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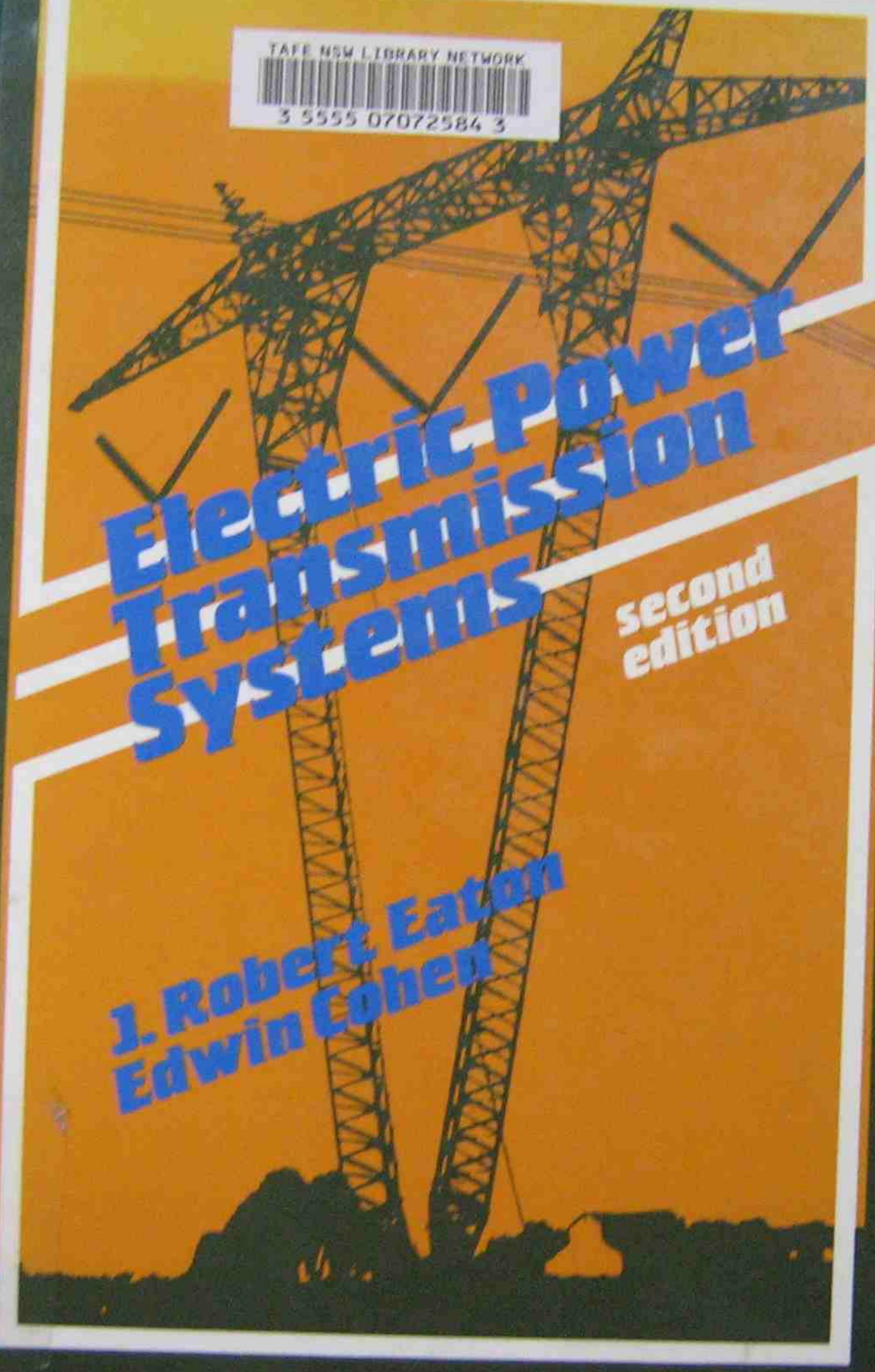

Electric Power Transmission Systems

second edition

J. Robert Eaton
Edwin Cohen

Electric Power Transmission Systems

Second Edition

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Preface

This book is intended to give a first-level presentation of the technical aspects exhibited by electric systems which transmit power from the generators to the loads. It should be of value to the technologist who builds, maintains, and operates electric power equipment; to the student engineer who later goes on to more advanced study in preparation for design and analysis of power systems; and to those persons whose technical problems are closely associated with the electric power industry.

This second edition of the book is an expanded version of the first one, laying greater emphasis on those aspects of power systems which concern a broader spectrum of engineers and technologists in the performance of their tasks. In particular, the calculation of short-circuit currents due to symmetrical faults and its impact on the ratings of circuit-interrupting devices have been expounded. Besides, a new chapter on distribution has been added, the analytical determination of transmission-line voltages has been stressed, and the load-flow problem has been introduced.

Problems have been added in this edition requesting the student to use a computer for their solution. Some are simple enough to be solved with a hand-held programmable calculator; others are more involved requiring the formation of a data base; a few require an iterative algorithm. It is hoped that these problems will spur the student to a greater use of the computational facilities at his disposal.

It is assumed that the reader has had a basic course in electric circuit theory. His or her knowledge of mathematics should include elementary

algebra and calculus, and complex numbers. Chapter 2 summarizes most of the relations used in the remainder of the book.

The first edition of the book was produced by the first author under the sponsorship of the American Electric Power System. The second edition was prepared by the second author while on sabbatical leave from his institute.

The authors acknowledge the assistance of many organizations that made available data presented in this book.

The Indiana and Michigan Electric Company provided many photographs and circuit diagrams.

Public Service Indiana provided photographs of an ac generator and a damaged circuit breaker.

Westinghouse Electric Corporation provided tables of overhead line constants, data on transformer impedances, and a photograph of programmable controller.

Anaconda Wire and Cable Company supplied pictures of typical overhead and underground cables.

The Institute of Electrical and Electronics Engineers granted permission for publication of a table of machine reactances from ANSI/IEEE Standards.

Some of the diagrams of circuit breakers are adaptations of more detailed diagrams published in bulletins of Allis Chalmers Manufacturing Company and General Electric Company.

Edwin Cohen

Electric Power Transmission Systems

chapter 1

The Electric Power System

1-1. REQUIREMENTS OF AN ELECTRIC SUPPLY SYSTEM

A great amount of effort is necessary to maintain an electric power supply within the requirements of the various types of customers served. Large investments are necessary, and continuing advancements in methods must be made as loads steadily increase from year to year. Some of the requirements for electric power supply are recognized by most consumers, such as proper voltage, availability of power on demand, reliability, and reasonable cost. Other characteristics, such as frequency, wave shape, and phase balance, are seldom recognized by the customer but are given constant attention by the utility power engineers.

The voltage of the power supply at the customer's service entrance must be held substantially constant. Variations in supply voltage are, from the consumer's view, detrimental in various respects. For example, below-normal voltage substantially reduces the light output from incandescent lamps. Above-normal voltage increases the light output but substantially reduces the life of the lamp. Motors operated at below-normal voltage draw abnormally high currents and may overheat, even when carrying no more than the rated horsepower load. Overvoltage on a motor may cause excessive heat loss in the iron of the motor, wasting energy and perhaps damaging the machine. Service voltages are usually specified by a nominal value and the voltage then maintained close to this value,

deviating perhaps less then 5 percent above or below the nominal value. For example, in a 120-volt residential supply circuit, the voltage might normally vary between the limits of 115 and 125 volts as customer load and system conditions change throughout the day.

Power must be available to the consumer in any amount that he may require from minute to minute. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric power company. As electrical energy cannot be stored (except to a limited extent in storage batteries), the changing loads impose severe demands on the control equipment of any electrical power system. The operating staff must continually study load patterns to predict in advance those major load changes that follow known schedules, such as the starting and shutting down of factories at prescribed hours each day.

The demands for reliability of service increase daily as our industrial and social environment becomes more complex. Modern industry is almost totally dependent on electric power for its operation. Homes and office buildings are lighted, heated, and ventilated by electric power. In some instances loss of electric power may even pose a threat to life itself. Electric power, like everything else that is man-made, can never be absolutely reliable. Occasional interruptions to service in limited areas will continue. Interruptions to large areas remain a possibility, although such occurrences may be very infrequent. Further interconnection of electric supply systems over wide areas; continuing development of reliable automated control systems and apparatus; provision of additional reserve facilities; and further effort in developing personnel to engineer, design, construct, maintain, and operate these facilities will continue to improve the reliability of the electric power supply.

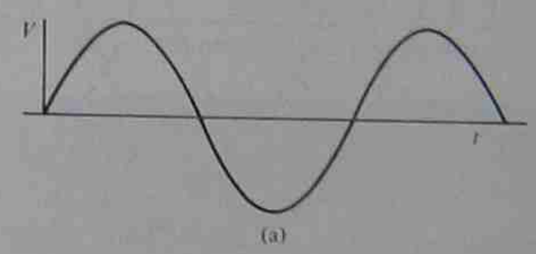
The cost of electric power is a prime consideration in the design and operation of electric power systems. Although the cost of almost all commodities has risen steadily over the past many years, the cost per kilowatt-hour of electrical energy has actually declined. This decrease in cost has been possible because of improved efficiencies of the generating stations and distribution systems. Although franchises often grant the electric power company exclusive rights for the supply of electric power to an area, there is keen competition between electric power and other forms of energy, particularly for heating and for certain heavy-load industrial processes.

The power-supply requirements just discussed are all well known to most electric power users. There are, however, other specifications to the electric power supply which are so effectively handled by the power companies that consumers are seldom aware that such requirements are of importance.

The frequency of electric power supply in the United States is almost entirely 60 hertz (formerly cycles per second). The frequency of a system is

dependent entirely upon the speed at which the supply generator is rotated by its prime mover. Hence frequency control is basically a matter of speed control of the machines in the generating stations. Modern speed-control systems are very effective and hold frequency almost constant; deviations are seldom greater than 0.02 hertz.

In an ac system the voltage continually varies with time, at one instant being positive and a short time later being negative, going through 60 complete cycles of change in each second. Ideally a plot of the time change should be a sine wave, as shown in Fig. 1-1a. In poorly designed generating



(a)

(b)

FIG. 1-1. (a) A voltage which varies sinusoidally with time. (b) A voltage wave shape which contains a fifth harmonic.

equipment, harmonics may be present and the wave shape may be somewhat as shown in Fig. 1-1b. The presence of harmonics produces unnecessary losses in the customer's equipment and sometimes produces hum in nearby telephone lines. The voltage wave shape is basically determined by the construction of the generation equipment. The power companies put specification limitations on the harmonic content of generator voltages and so require equipment manufacturers to design and build their machines to minimize trouble from this effect.

Practically all major power equipment is supplied by three-phase circuits. Three-phase circuits are essentially three single-phase circuits each of which has its own sine wave of voltage. If phase balance is perfect, each of

the three voltages is of the same magnitude but displaced in time from the other two by one third of a cycle. Modern three-phase generators are designed to have almost perfect phase balance, as shown in Fig. 1-2.

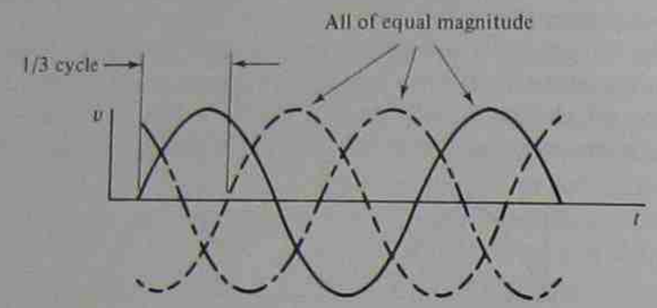


FIG. 1-2. The three voltage waves produced by a balanced three-phase generator.

Voltage unbalances produce unnecessary losses in three-phase motors and reduce the maximum starting torque. Few customers are aware of the problem of phase balance except in those rare instances where abnormal conditions are encountered.

Practically all consumers use the electric power supply to operate motors, transformers, and other devices in which iron is magnetized by currents from the electric power system. The currents that magnetize the iron do not influence the electric power bill (except where power-factor clauses apply) and so are seldom recognized by the customer. Nevertheless, provision must be made in the power system for supplying these magnetizing currents, and so their supply must be considered in specifying the characteristics of the generating, transmission, and distribution facilities that deliver power to the customer.

1-2. MINIMUM POWER SYSTEM

Electric power systems may be of great complexity and spread over large geographical areas. There is, however, a minimum system that can function as an electric power supply as shown in Fig. 1-3. The system consists of an energy source, a prime mover, a generator, and a load. Supervising it is some sort of a control system.

The *energy source* may be coal, gas, or oil burned in a furnace to heat water and generate steam in a boiler; it may be fissionable material which, in a nuclear reactor, will heat water to produce steam; it may be water in a pond at an elevation above the generating station; or it may be oil or gas burned in an internal combustion engine.

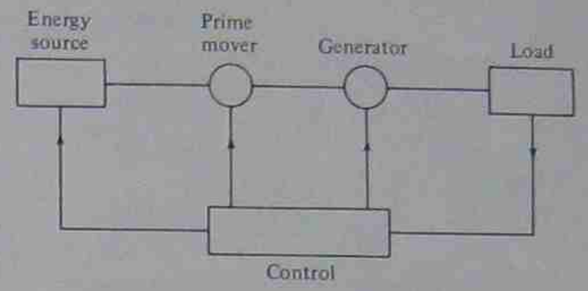


FIG. 1-3. The minimum electric power system.

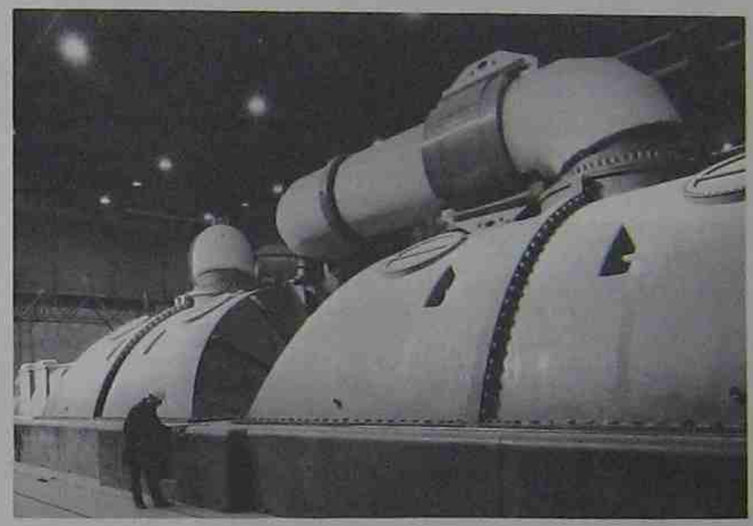


FIG. 1-4. A large steam turbine which drives a generator.

The *prime mover* may be a steam-driven turbine (Fig. 1-4), a hydraulic turbine or water wheel (Fig. 1-5), or an internal combustion engine (Fig. 1-6). Each one of these prime movers has the ability to convert energy in the form of heat, falling water, or fuel into rotation of a shaft, which in turn will drive the generator.

The *generator* may be an ac machine (or alternator) (Fig. 1-7), the type of machine that supplies most of the electric power used today. In special cases the generator may be a dc machine (Fig. 1-8).

The electrical *load* on the generator in Fig. 1-3 may be lights, motors, heaters, or other devices, alone or in combination. Probably the load will vary from minute to minute as different demands occur.

The *control system* functions to keep the speed of the machines sub-

FIG. 1-5. The rotor of a 204,000 H.P. water wheel.

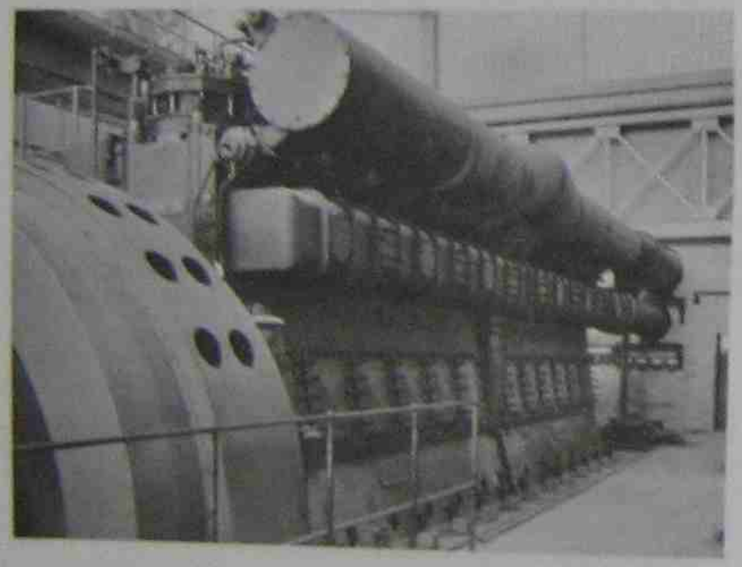


FIG. 1-6. A diesel engine.

stantially constant and the voltage within prescribed limits, even though the load may change. To meet these changing load conditions, it is necessary for fuel input to change, for the prime-mover input to vary, and for the torque on the shaft from the prime mover to the generator to change

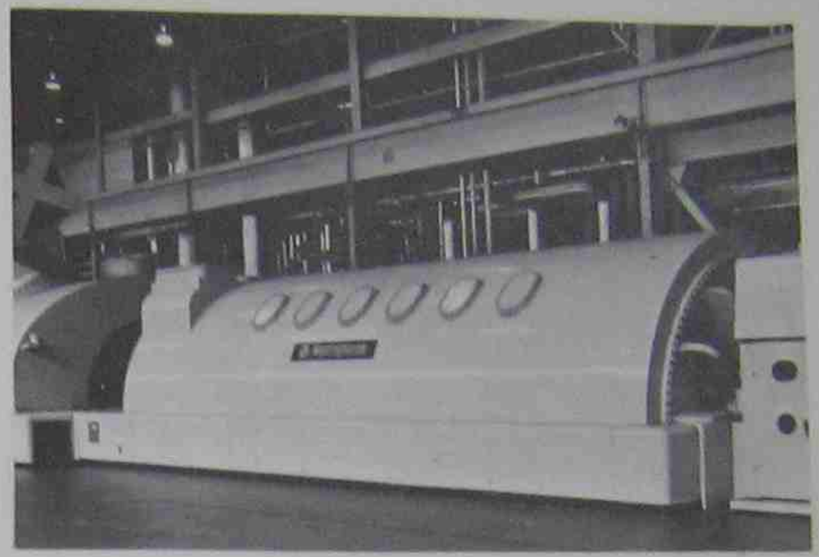


FIG. 1-7. An ac-generator rated 430,000 kVA, 24 kV, 3600 RPM.

FIG. 1-8. A dc-generator rated 6 kW, 240 V, 1800 RPM.

in order that the generator may be kept at constant speed. In addition, the field current to the generator (alternator) must be adjusted to maintain constant output voltage. The control system may include a man stationed in the power plant who watches a set of meters on the generator-output terminals and makes the necessary adjustments manually. In a modern station, the control system is a *servomechanism* that senses generator-output conditions and automatically makes the necessary changes in energy input and field current to hold the electrical output within certain specifications.

1-3. MORE COMPLICATED SYSTEMS

In most situations the load is not directly connected to the generator terminals, as shown in Fig. 1-3. More commonly the load is some distance from the generator, requiring a power line connecting them, as shown in Fig. 1-9.

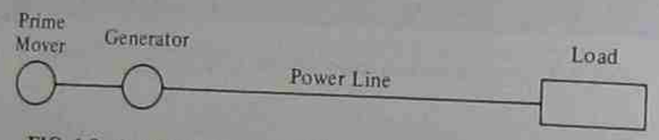


FIG. 1-9. A generator connected by a power line to a distant load.

The situation is now more complex. It is desirable to keep the electric power supply at the load within specifications. However, the controls are near the generator, which may be in another building, perhaps several miles away.

If the distance from the generator to the load is considerable, it may be desirable to install transformers at the generator and at the load end, and to transmit the power over a high-voltage line (Fig. 1-10). For the same

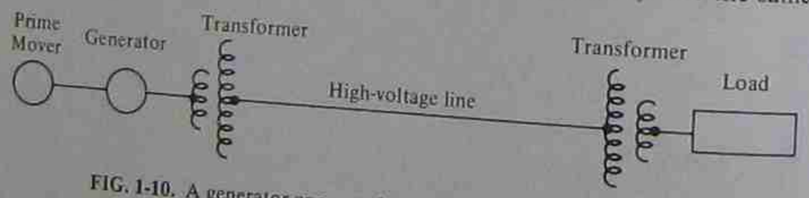


FIG. 1-10. A generator connected through transformers and a high-voltage line to a distant load.

power, the higher-voltage line carries less current, has lower losses for the same wire size, and provides more stable voltage conditions at the load. A *power transformer* is shown in Fig. 1-11, and a *high-voltage line* in Fig. 1-12. In some cases an overhead line may be be unacceptable. Instead it may be advantageous to use an *underground cable* (Fig. 1-13). With the power system shown in Fig. 1-9 or 1-10, the power supply to the load must

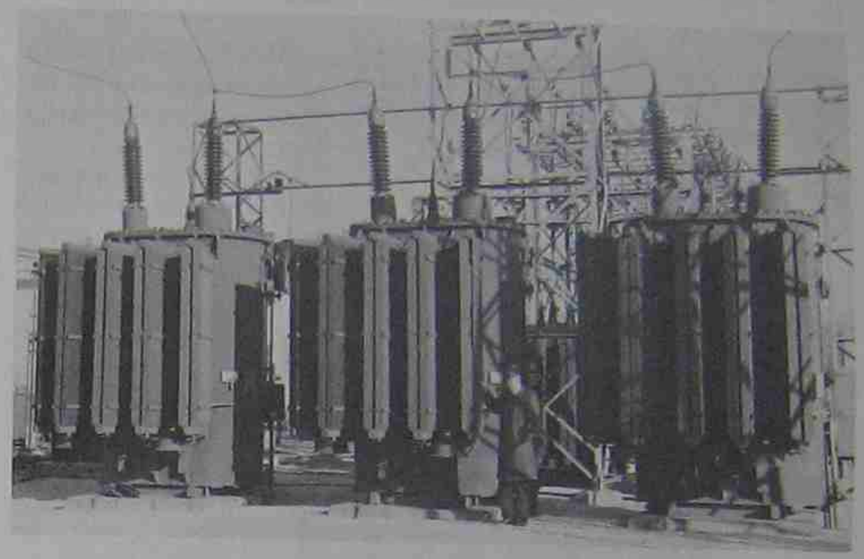


FIG. 1-11. A 138-kV transformer bank.

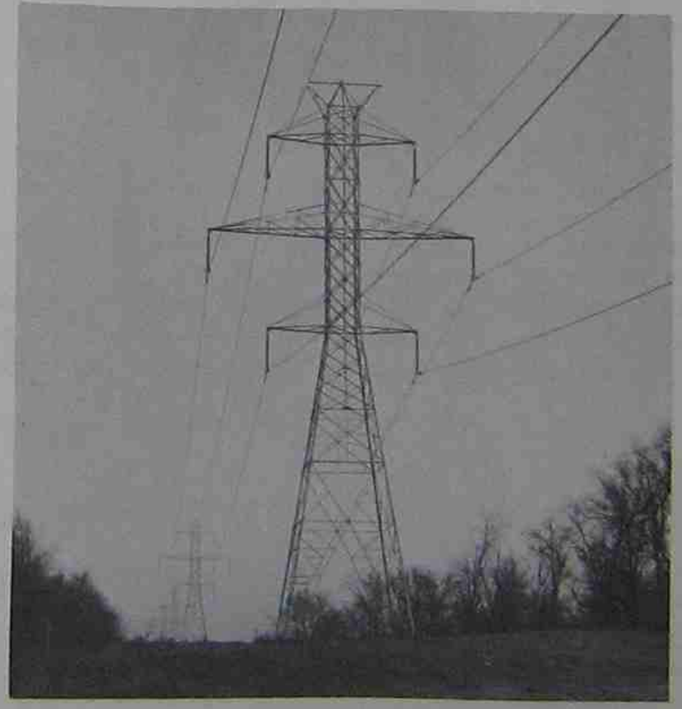


FIG. 1-12. A double-circuit 345-kV transmission line.

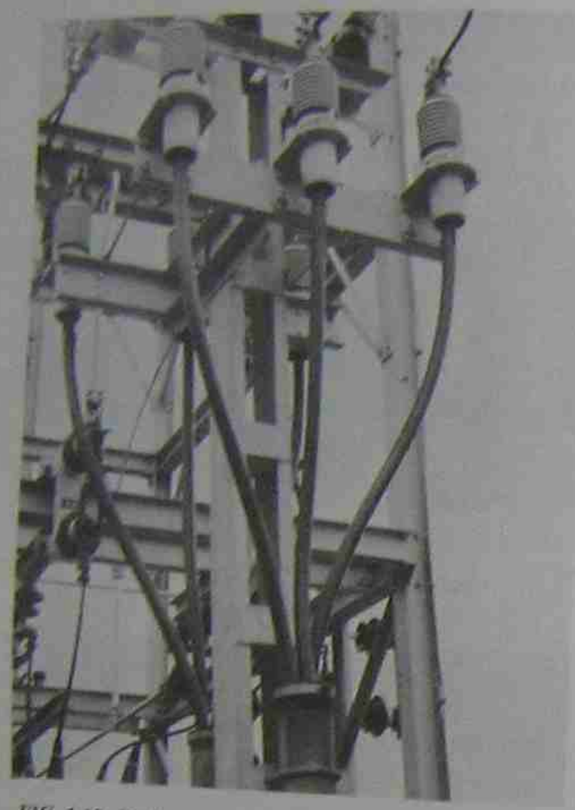


FIG. 1-13. Underground cables used to supply urban loads.

be interrupted if, for any reason, any component of the system must be removed from service for maintenance or repair.

Additional system load may require more power than the generator can supply. Another generator with its associated transformers and high-voltage line might be added, resulting in the system shown in Fig. 1-14.

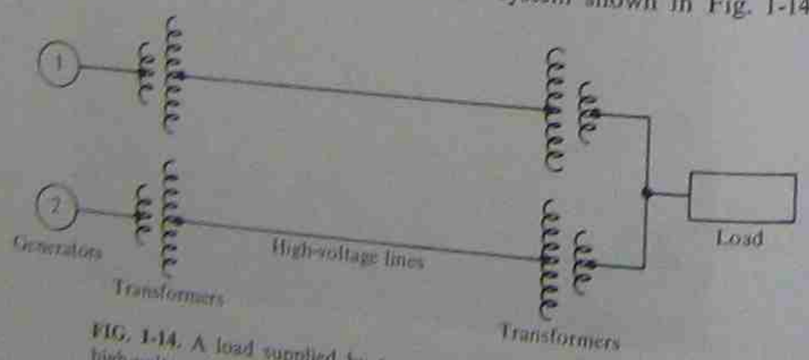


FIG. 1-14. A load supplied by two generators through separate high-voltage lines.

(*Note:* In Fig. 1-14 the prime movers of the two generators are not shown. As the discussion from now on will be confined to the electrical part of the system, the necessary prime movers will not be shown on the diagrams.)

It can be shown that there are some advantages in making ties between the generators (1) and at the ends of the high-voltage lines (2 and 3), as shown in Fig. 1-15. This system will operate satisfactorily as long as no trouble develops or no equipment needs to be taken out of service.

The above system may be vastly improved by the introduction of

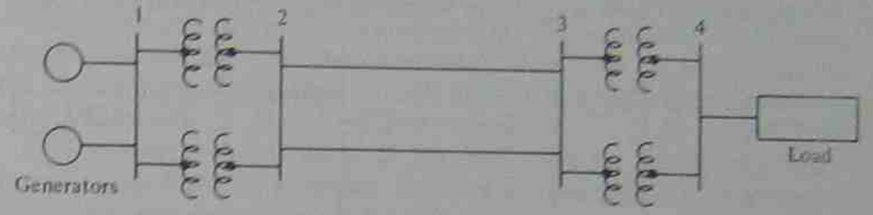


FIG. 1-15. The system of Fig. 1-14 with parallel operation of the generators, of the transformers, and of the transmission lines.

FIG. 1-16. A 345-kV oil circuit-breaker.

circuit breakers (Fig. 1-16), which may be opened and closed as needed. Circuit breakers added to the system, Fig. 1-17, permit switching out of service any selected piece of equipment without disturbing the remainder of the system. With this arrangement any element of the system may be deenergized for maintenance or repair by operation of circuit breakers. Of course, if any piece of equipment is taken out of service, the total load must then be carried by the remaining equipment. Attention must be given to avoid overloads during such circumstances. If possible, outages of equipment are scheduled at times when load requirements are below normal.

Figure 1-18 shows a system in which three generators and three loads

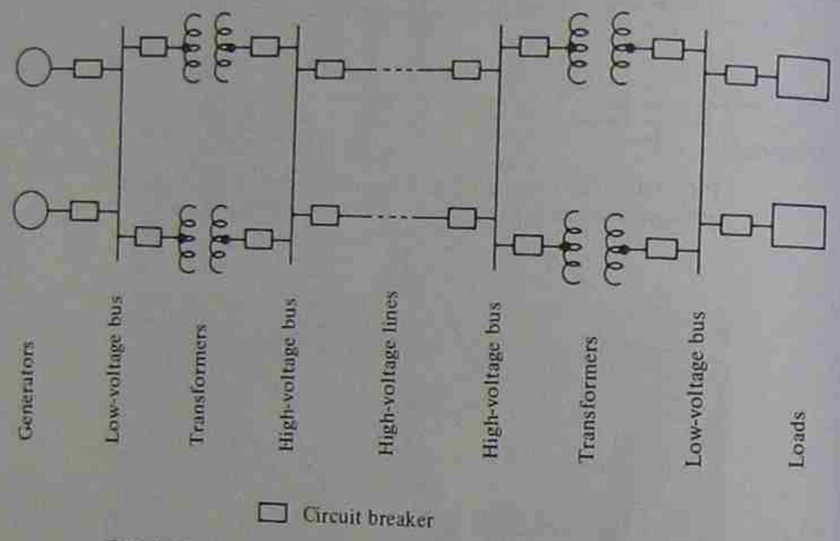


FIG. 1-17. The system of Fig. 1-15 with necessary circuit-breakers.

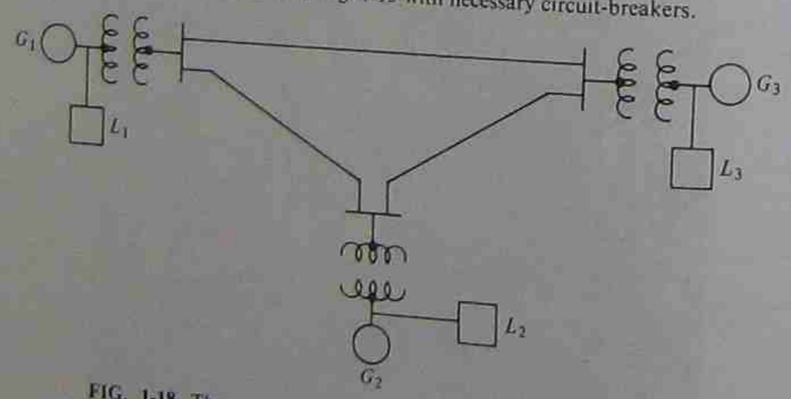


FIG. 1-18. Three generators supplying three loads over high-voltage transmission lines.

are tied together by three transmission lines. No circuit breakers are shown in this diagram, although many would be required in such a system.

1-4. SOME TYPICAL SYSTEM LAYOUTS

The generators, lines, and other equipment which form an electric system are arranged depending on the manner in which load grows in the area and may be rearranged from time to time. Probably no two systems are exactly the same. However, there are certain plans into which a particular system design may be classified. Three types are illustrated: the radial system, the loop system, and the network system. All of these are shown without the necessary circuit breakers. In each of these systems, a single generator serves four loads.

The *radial system* is shown in Fig. 1-19. Here the lines form a "tree" spreading out from the generator. Opening any line results in interruption of power to one or more of the loads.

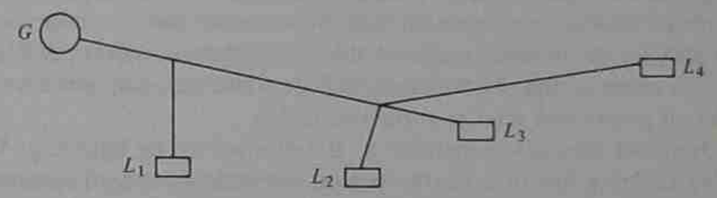


FIG. 1-19. A radial power system supplying several loads.

The *loop system* is illustrated in Fig. 1-20. With this arrangement all loads may be served even though one line section is removed from service. In some instances during normal operation, the loop may be open at some point, such as A. In case a line section is to be taken out, the loop is first closed at A and then the line section removed. In this manner no service interruptions occur.

Figure 1-21 shows the same loads being served by a *network*. With this arrangement each load has two or more circuits over which it is fed.

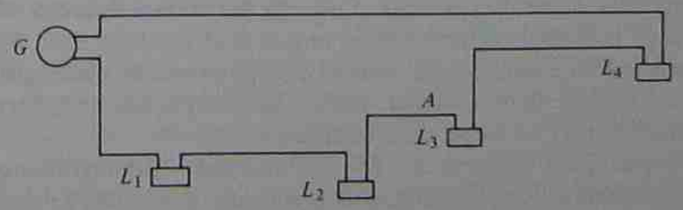


FIG. 1-20. A loop arrangement of lines for supplying several loads.

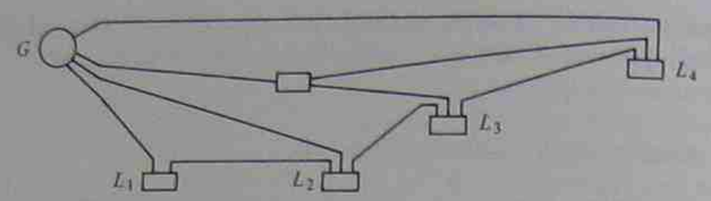


FIG. 1-21. A network of lines supplying several loads.

Distribution circuits are commonly designed so that they may be classified as radial or loop circuits. The high-voltage transmission lines of most power systems are arranged as networks. The interconnection of major power systems results in networks made up of many line sections.

1-5. HAZARDS TO POWER SYSTEM OPERATION

The operation of electric power systems may be disturbed as the result of a number of causes. The troubles on the electric circuits are usually in the form of broken conductors or circumstances in which conductors are temporarily (or permanently) connected to each other or to ground. Regardless of the cause of the disturbances, such troubles seriously interfere with the flow of power and require corrective action.

Overhead lines are vulnerable to troubles set up by lightning. When lightning strikes a line or a nearby object, a *transient voltage* is created on the line. High-voltage circuits have large spacings between conductors and from conductors to grounded objects, such as towers. Direct strokes to such lines are usually diverted to ground through overhead ground wires and may cause no interference with operation. Occasionally strokes terminate directly on the power conductors and introduce on them transient voltages of such magnitude that *arcover* across insulator strings may result. Once an arc is established, power current flows through it until the circuit is deenergized. Lightning voltages may be of high magnitude but are of very short duration; their time is measured in microseconds. As a result, their effects are most noticeable at the point where the stroke occurs. Distribution lines, which operate at perhaps 12 kV or less, are mounted on relatively small insulators which may be flashed over by the voltage induced on a line even though the lightning stroke does not contact the line. Such resulting arcs interfere with operation and usually are eliminated by deenergizing the line. When the line is deenergized, the arc is extinguished and, very commonly, the line may be reenergized immediately.

Overhead lines are subjected to wind and sleet. Although designed to withstand ordinary storm loading, it is practically impossible to design for the extreme condition of sleet or wind loading. As a result, occasional line

failures occur as a result of these causes. Failures resulting from wind or sleet are usually of such nature that repairs must be made before the line may be reenergized.

Foreign objects may contact a line and cause damage which necessitates removal of the line from service. Airplanes may fly into a line, an automobile may knock down a pole, a construction worker may run a crane into a line, or an excavator may dig up a cable. Birds, squirrels, snakes, and other animals occasionally short-circuit lines and cause outages.

Generators, transformers, lines, or other components may be switched out of service for normal or routine maintenance. When switching operations occur, transients are set up on the power system which sometimes produce serious overvoltages. Such overvoltages in turn may cause flashover of insulators or puncture of solid insulation.

Equipment sometimes fails from no particular direct cause. Failure may be due to inadequate design, to previous overloads, or to natural deterioration of equipment.

Human errors may produce power-system outages. Switches may be opened unintentionally cutting off loads; temporary grounding electrodes may be put on energized circuits by mistake; equipment handled by hot-line devices may be dropped. Such occasions, although rare, must be considered as hazard possibilities in power-system design.

1-6. NEED FOR AUXILIARY EQUIPMENT

Circuit breakers such as those shown in Fig. 1-16 are necessary to deenergize equipment either for normal operation or on the occurrence of short circuits. Circuit breakers must be designed to carry normal-load currents continuously, to withstand the extremely high currents that occur during faults, and to separate contacts and clear a circuit in the presence of a fault. Circuit breakers are rated in terms of these duties.

When a circuit breaker opens to deenergize a piece of equipment, one side of the circuit breaker usually remains energized, as it is connected to operating equipment. Since it is sometimes necessary to work on the circuit breaker itself, it is also necessary to have means by which the circuit breaker may be completely disconnected from other energized equipment. For this purpose *disconnect switches* (Fig. 1-22) are placed in series with the circuit breakers. By opening these disconnects, the circuit breaker may be completely deenergized, permitting work to be carried on in safety.

Various *instruments* are necessary to monitor the operation of the electric power system. Usually each generator, each transformer bank, and each line has its own set of instruments, frequently consisting of *voltmeters*, *ammeters*, *wattmeters*, and *varmeters*.

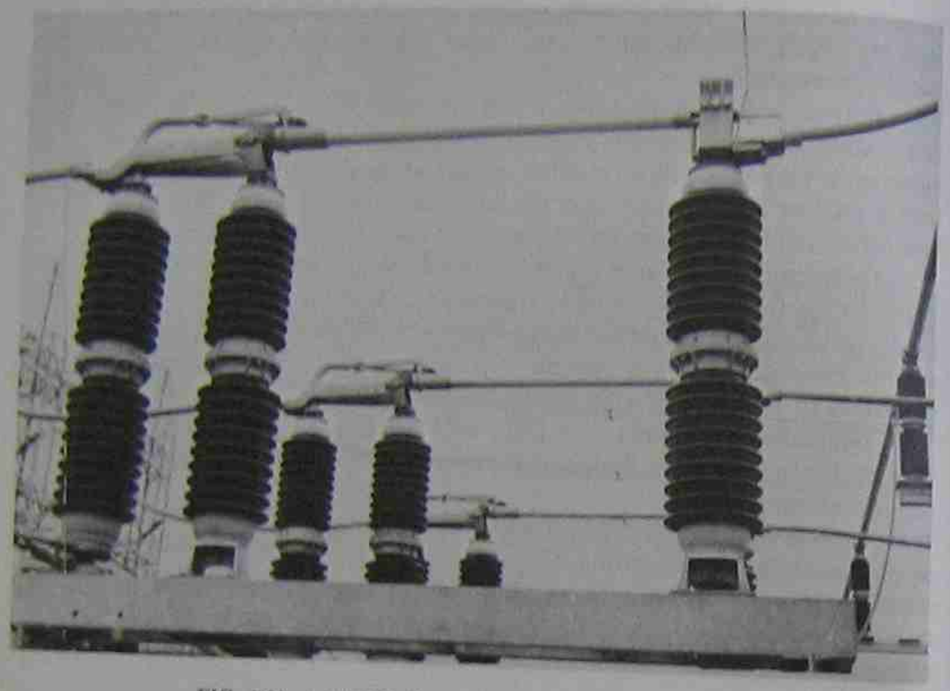


FIG. 1-22. A 138-kV disconnect switch. The horizontal bar may be swung upward, hinging at the left support.

When a fault occurs on a system, conditions on the system undergo a sudden change. Voltages usually drop and currents increase. These changes are most noticeable in the immediate vicinity of the fault. On-line *analog computers*, commonly called *relays* (Fig. 1-23) monitor these changes of conditions, make a determination of which breakers should be opened to clear the fault, and energize the trip circuits of those appropriate breakers. With modern equipment, the relay action and breaker opening causes removal of the fault within three or four cycles after its initiation.

The instruments that show circuit conditions and the relays that protect the circuits are not mounted directly on the power lines but are placed on *switchboards* in *control houses*. Instrument transformers are installed on the high-voltage equipment, by means of which it is possible to pass on to the meters and relays representative samples of the conditions on the operating equipment. The primary of a potential transformer is connected directly to the high-voltage equipment. The secondary provides for the instruments and relays a voltage which is a constant fraction of the voltage on the operating equipment and is in phase with it. Similarly, a current transformer is connected with its primary in the high-voltage circuit. The secondary winding provides a current which is a known fraction of the power-equipment current and is in phase with it. Instrument transformers are shown in Figs. 1-24 and 1-25.

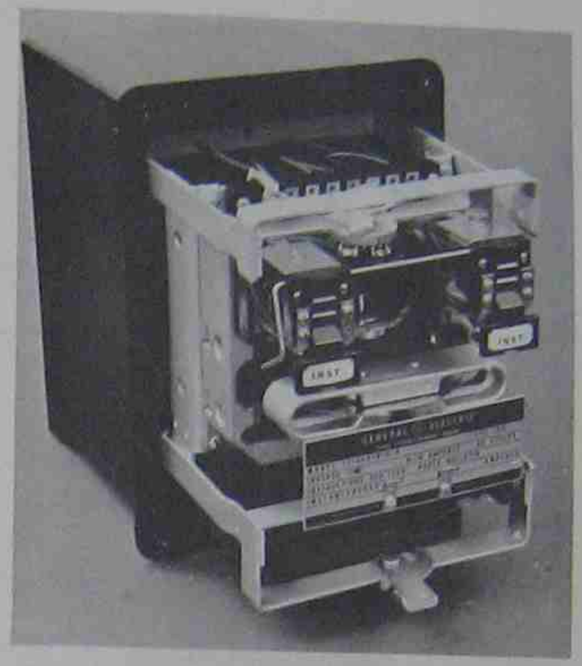


FIG. 1-23. A relay for detecting currents of excessive value.

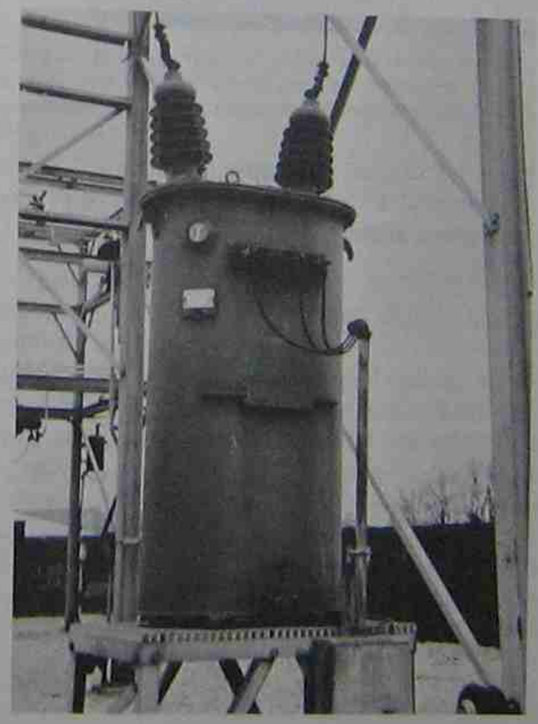


FIG. 1-24. A 24-kV potential transformer.

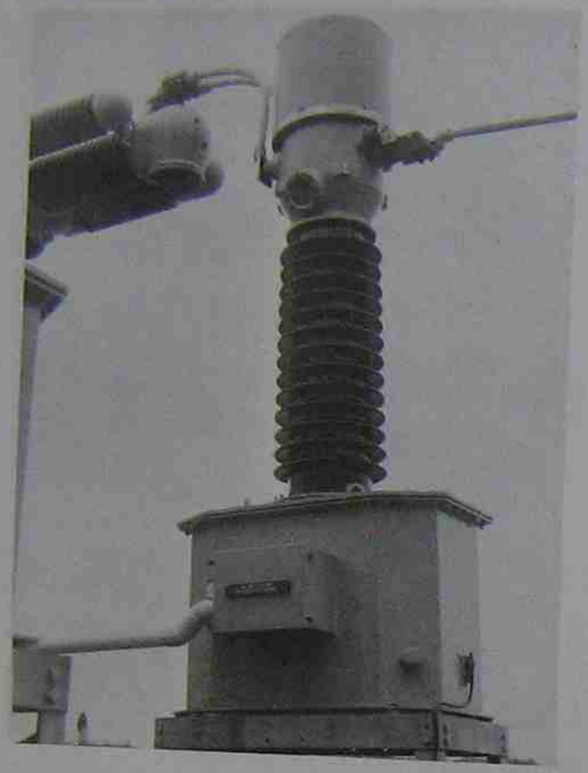


FIG. 1-25. A current transformer on a 138-kV circuit.

Bushing potential devices and capacitor potential devices serve the same purpose as potential transformers but usually with less accuracy in regard to ratio and phase angle.

1-7. ONE-LINE AND THREE-LINE DIAGRAMS

Thus far, a power circuit has been represented by a single line on a diagram. This is called a *one-line diagram*. Actually, practically all power circuits consist of three conductors, and circuit breakers and disconnects must be installed in each conductor. The total circuit of a three-phase transformer bank, a three-phase circuit breaker, three-blade disconnect switches, and a three-conductor transmission line is shown in Fig. 1-26a. The one-line diagram is shown in Fig. 1-26b. One-line diagrams are used very extensively, the reader realizing that each device shown is really installed in triplicate.

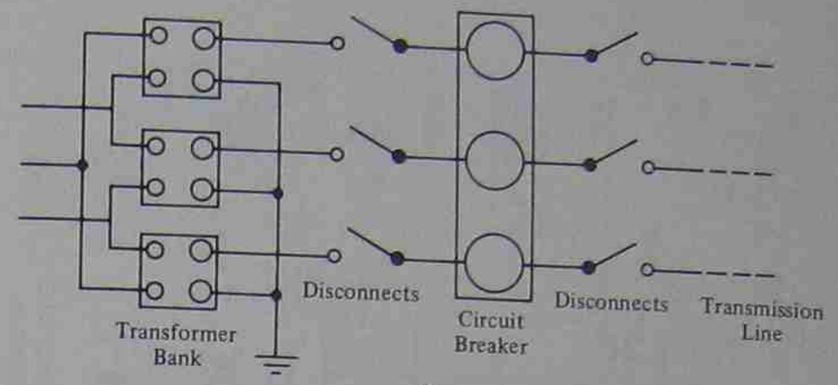


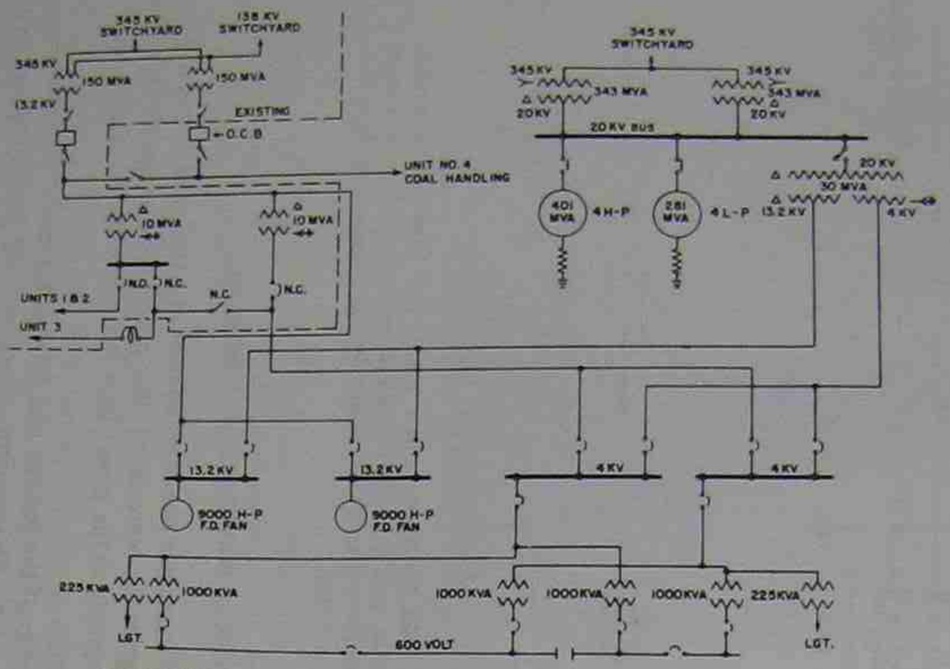
FIG. 1-26. (a) A three-phase transformer bank, the disconnect switches, and a 3-pole circuit-breaker connecting to a 3-phase transmission line. (b) A one line diagram representing the system of Fig. 1-26(a).

1-8. SOME TYPICAL POWER SYSTEM DIAGRAMS

The layout of the major power equipment in a station is shown in Fig. 1-27. On this diagram is represented the power-system equipment from the generator terminals to the power lines that carry the electrical energy away from the plant.

A diagram of the Indiana and Michigan Electric Co. power system is shown in Fig. 1-28. This diagram shows only the generating and switching stations and the lines joining them. No details of the equipment within the stations are shown.

Practically all the electric power systems of the United States lying east of the Rocky Mountains are interconnected. Similarily, those west of the Rocky Mountains are interconnected. A section of the enormous interconnected power systems of the United States is shown in Fig. 1-29.



SIMPLIFIED MAIN ONE-LINE DIAGRAM UNIT NO. 4

FIG. 1-27. A simplified one-line diagram showing the circuits necessary for handling the output of a single generator and the main auxiliary equipment required for its operation.

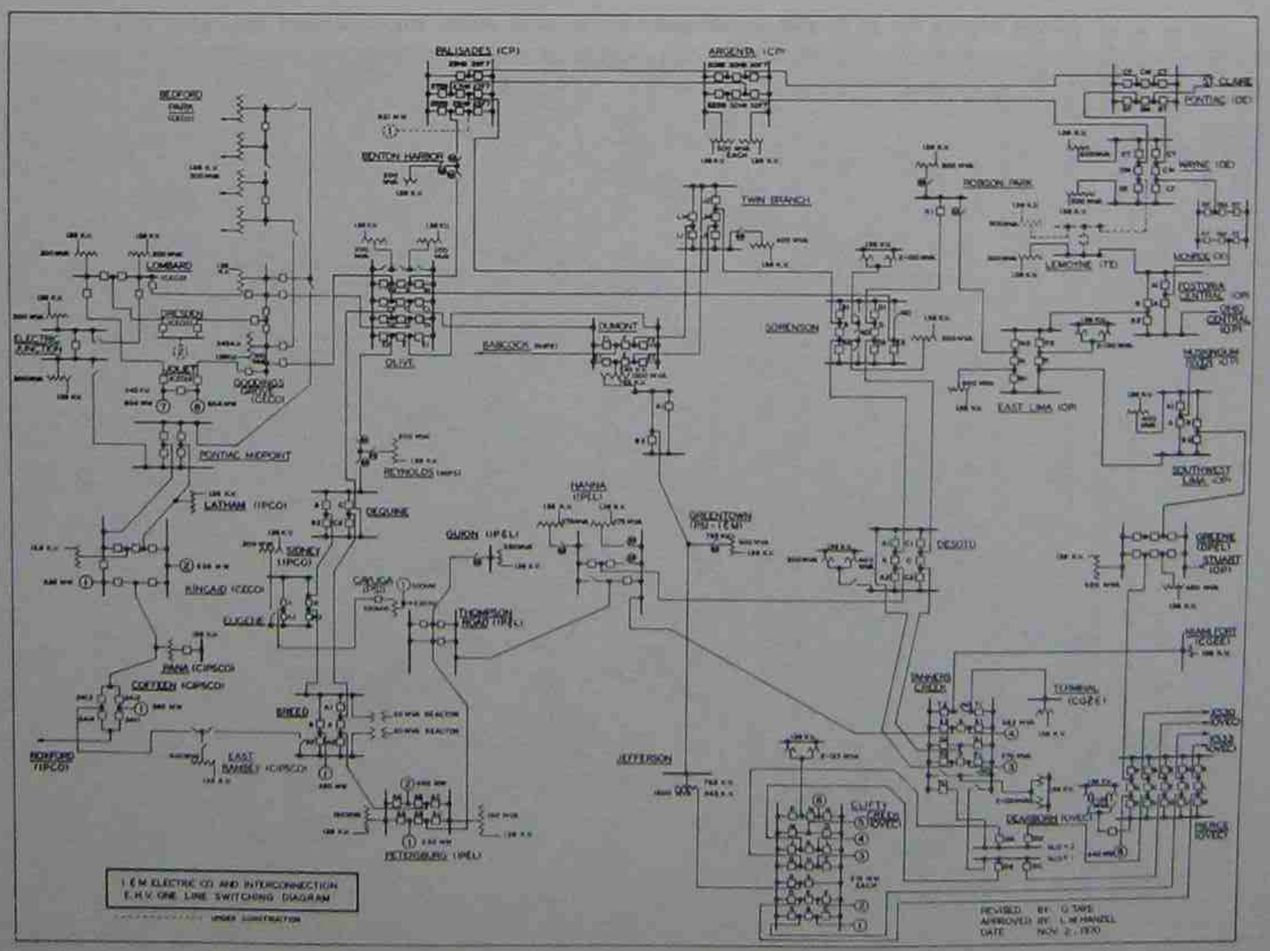


FIG. 1-28. The principal lines and interconnections of the Indiana and Michigan Electric Company.

FIG. 1-29. The interconnected power lines of the northeastern section of the United States.

1-9. COMMUNICATION SYSTEMS

The operation of an extensive power system demands effective communications between the many stations. As a consequence, every power system also operates a communications system. The communication circuits are used for voice transmission, for the remote operation of switches and other control equipment, for the transmission of meter readings to central supervisory offices, and for relaying.

In some instances the electric power companies have constructed and maintained their own wire circuits. In other cases they may lease lines from the local telephone company. The power lines themselves may be used as communication channels by superimposing on them voltages of high frequency (30 to 200 kilohertz), which is modulated in such a fashion as to carry the intelligence desired. Microwave channels (Fig. 1-30), operating at frequencies from 2 to 6 gigahertz, may carry several hundred communication channels, involving voice, telemetering, computer control, and other functions.

FIG. 1-30. A micro-wave transmitting and receiving tower.

chapter 2

Fundamentals of Electric Circuits

2-1. PURPOSE

In the study of any subject, the writer assumes a certain knowledge on the part of the reader. This chapter summarizes that information on electric circuits which the reader presumably has previously learned. It includes a discussion of units, symbols, notation, basic laws, certain derived relations, graphical representation, and electric circuit behavior which usually is covered in an elementary course in electricity. In subsequent chapters this information is used as needed without further comment or justification.

A study of this chapter affords the reader an opportunity to assess his preparation for further study. Hopefully, it provides a review of those basics of electricity which the reader may need in the pursuit of a study of the subject of electric power supply. All discussions presented in the remainder of this book are based on the material of this chapter.

2-2. SYSTEM OF UNITS

All subject development is in the framework of the MKS system of units. In certain instances, however, practical considerations suggest the presentation of calculations in terms of the English system (inches, pounds, etc.).

2-3. NOTATION

Table 2-1 shows a list of *physical quantities*, the units in which they are expressed, and the designating symbol. It may be noted that a few of the letter symbols are used to represent more than one quantity (such as use of L for length and also for inductance). This notation is in accordance with common practice. The relations in which these symbols are used are stated in such a fashion that no misunderstanding results.

Table 2-1. *Symbols, Units and Abbreviations*

Quantity	Symbol	Unit (MKS system)	Abbreviation
1. MASS	M	kilogram	kg
2. LENGTH	l	meter	m
3. TIME	t	second	s
4. FORCE	F	newton	N
5. CHARGE	Q, q	coulomb	C
6. CURRENT	I, i	ampere	A
7. ELECTROMOTIVE FORCE	E, e	volt	V
8. POTENTIAL DIFFERENCE	V, v	volt	V
9. ENERGY	W, w	joule	J
10. POWER	P, p	watt	W
11. RESISTANCE	R	ohm	Ω
12. CONDUCTANCE	G	mho	mho
13. RESISTIVITY	ρ	ohm-meter	Ω-m
14. CONDUCTIVITY	σ	mho per meter	mho/m
15. TEMPERATURE COEFFICIENT OF RESISTANCE	α	per degree	°C
16. MAGNETIC FLUX	Φ	weber	Wb
17. MAGNETIC FLUX DENSITY	B	webers per square meter	Wb/m²
18. MAGNETOMOTIVE FORCE	$\mathcal{F}$	ampere-turn	At
19. MAGNETIC INTENSITY	H	ampere-turns per meter	At/m
20. RELUCTANCE	$\mathcal{R}$	ampere-turns per weber	At/Wb
21. PERMEANCE	$\mathcal{P}$	webers per ampere-turn	Wb/At
22. PERMEABILITY	μ	henrys per meter	H/m
23. SELF-INDUCTANCE	L	henry	H
24. MUTUAL INDUCTANCE	M	henry	H
25. ELECTRIC FLUX	Ψ	line	
26. ELECTRIC FLUX DENSITY	D	lines per square meter	
27. ELECTRIC FIELD INTENSITY	$\mathscr{E}$	volts per meter	V/m
28. PERMITTIVITY	ϵ	farads per meter	F/m
29. CAPACITANCE	C	farad	F
30. ELASTANCE	S	daraf	
31. FREQUENCY	f	hertz (cycles per second)	Hz
32. ANGULAR VELOCITY	ω	radians per second	rad/s
33. PHASE ANGLE	ϕ	degree, radian	° rad
34. INDUCTIVE REACTANCE	X_L	ohm	Ω

Quantity	Symbol	Unit (MKS system)	Abbreviation
35. CAPACITIVE REACTANCE	X_C	ohm	Ω
36. IMPEDANCE	Z	ohm	Ω
37. INDUCTIVE SUSCEPTANCE	B_L	mho	mho
38. CAPACITIVE SUSCEPTANCE	B_C	mho	mho
39. ADMITTANCE	Y	mho	mho
40. REACTIVE POWER	P_q	reactive volt ampere	VAR
41. APPARENT POWER	P_s	volt-ampere	VA
42. POWER FACTOR	F_p		
43. REACTIVE FACTOR	F_q		

It may be noted in Table 2-1 that voltage, current, and power are represented by the letter symbols V, I, and P, each presented in both uppercase and lowercase letters. Uppercase letters represent voltage, current, and power where all are constant, as in dc circuits. In ac circuit work, uppercase V and I represent effective values, whereas uppercase P represents average values. V_m and I_m represent the *crest*, or *maximum*, values of sinusoidally varying voltage and current.

Lowercase v, i, and p represent instantaneous values of voltage, current, and power when these quantities are varying with time. Hence they may be used as *instantaneous values* of these quantities in an ac circuit.

Where needed, *double-subscript notation* is used in the representation of current and voltage. V_{xy} represents the voltage of point X with respect to point Y. I_{CD} represents the current flowing through a circuit element from C to D. Note that in the circuit of Fig. 2-1, the voltage V_{AB} gives rise to the current I_{AB}.

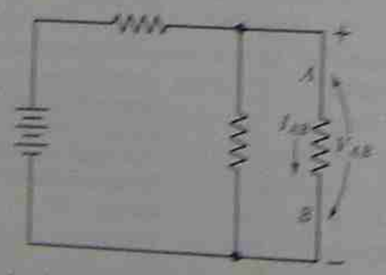


FIG. 2-1. A circuit element illustrating the polarity of the voltage and the direction of the current flow.

2-4. ELECTRIC-CIRCUIT RELATIONS

There are many well-known relations of electric circuits, some of which are regarded as basic, others are derived. The division between the two classes depends somewhat on the point of view. It is the intention here to list those relations of general importance, regardless of the classification into which they might fall.

a. General Circuit Relations. The charge q passing a point X (Fig. 2-2) during an interval of time t is

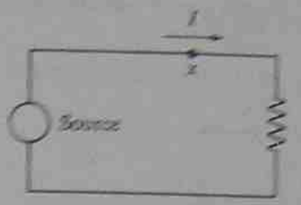


FIG. 2-2. A current I flowing past the point X.

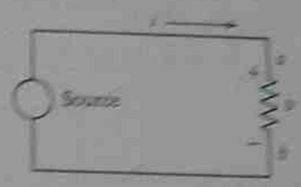


FIG. 2-3. A circuit element carrying the current i in the presence of the voltage V.

$$q = It \tag{2-1}$$

provided that the current is constant over time, t. If the current is time-varying, integration over time is necessary,

$$q = \int_0^t i\,dt \tag{2-2}$$

from which it follows that

$$i = \frac{dq}{dt} \tag{2-3}$$

The power input p to a circuit element ab (Fig. 2-3) is

$$p = vi \tag{2-4}$$

where v is the voltage across the element and i is the current through it.

The energy w delivered to the circuit element during t is

$$w = Pt \tag{2-5}$$

if the power P is constant over time, t. If the power is time-varying, then

$$w = \int_0^t p\,dt \tag{2-6}$$

b. Relations Applying to Resistors. The voltage v applied across a resistor is

$$v = iR \tag{2-7}$$

where i is the current through the resistor and R the value of the resistance.

The power p delivered to the resistor is

$$p = vi = i^2R = \frac{v^2}{R} \tag{2-8}$$

The resistance of a body of material of length l and uniform cross section A (Fig. 2-4) is

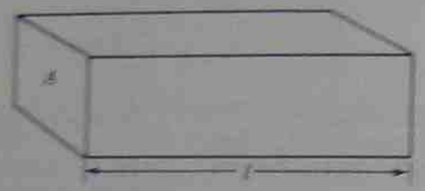


FIG. 2-4. A bar of resistance material of cross section A, length l, and resistivity ρ.

$$R = \rho \frac{l}{A} \tag{2-9}$$

where ρ is the resistivity of the material (see Table A-1).

If the resistance of a resistor at temperature T_1 is R_1, then its resistance R_2 at temperature T_2 is

$$R_2 = R_1[1 + \alpha(T_2 - T_1)] \tag{2-10}$$

where α is the temperature coefficient of resistance at T_1.

When several resistors, R_1, R_2, and R_3 (Fig. 2-5), are connected in series, their equivalent resistance is

$$R_{eq} = R_1 + R_2 + R_3 \tag{2-11}$$

FIG. 2-5. Three resistors in simple series arrangement.

The conductance G of a resistor is

$$G = \frac{1}{R} \tag{2-12}$$

When several resistors are connected in parallel (Fig. 2-6), their equivalent conductance is the sum of the individual conductances

$$G_{eq} = G_1 + G_2 + G_3 \tag{2-13}$$

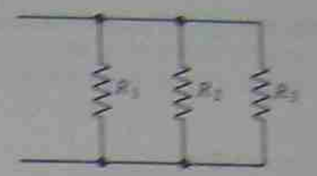


FIG. 2-6. Three resistors in parallel arrangement.

The equivalent resistance may be determined from the relation

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \tag{2-14}$$

c. Relations Applying to Magnetic Devices. The magnetomotive force $\mathcal{F}$ produced by a coil of N turns carrying a current I (Fig. 2-7) is

$$\mathcal{F} = NI \tag{2-15}$$

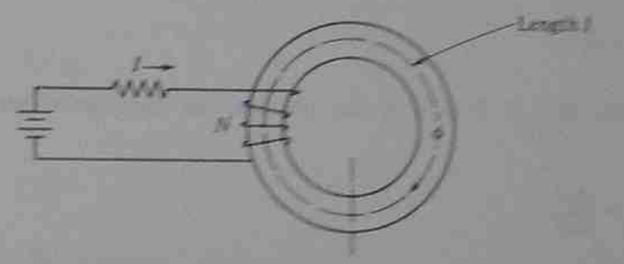


FIG. 2-7. A ring of magnetic material of length l, cross-section A, and permeability μ on which is wound a coil of N turns carrying a current I.

The magnetic flux Φ that will be produced is

$$\Phi = \frac{\mathcal{F}}{\mathcal{R}} \tag{2-16}$$

where $\mathcal{R}$ is the reluctance of the magnetic path.

The reluctance $\mathcal{R}$ of a body of material of length l and uniform cross section A is

$$\mathcal{R} = \frac{1}{\mu} \frac{l}{A} \tag{2-17}$$

where μ is the permeability of the material. For free space, $\mu = \mu_0 = 4\pi \times 10^{-7}$ henrys per meter. The relative permeability is μ/μ_0.

The permeance $\mathscr{P}$ of a magnetic path of reluctance $\mathscr{R}$ is

$$\mathscr{P} = \frac{1}{\mathscr{R}} \tag{2-18}$$

The magnetic flux density B is

$$B = \frac{\Phi}{A} \tag{2-19}$$

where Φ, the magnetic flux, is assumed to be uniform over the area A.

The magnetic field intensity H is related to the magnetomotive force $\mathscr{F}$ by

$$H = \frac{\mathscr{F}}{l} \tag{2-20}$$

The permeability μ of a magnetic material is

$$\mu = \frac{B}{H} \tag{2-21}$$

If the ratio of B to H is *not* constant, the incremental permeability μ_Δ is

$$\mu_\Delta = \frac{\Delta B}{\Delta H} \tag{2-22}$$

Suppose that a magnetic field of flux density B passes from one pole face of a magnetic material across an air gap to another similar pole face of magnetic material (Fig. 2-8). A force F is produced between the two pole faces such that

$$F = \frac{B^2 A}{2\mu_0} \tag{2-23}$$

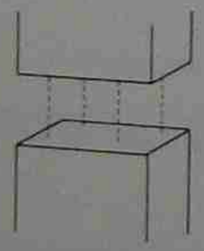


FIG. 2-8. Two magnetic poles, each of cross-section A, between which there is a magnetic field whose flux density is B.

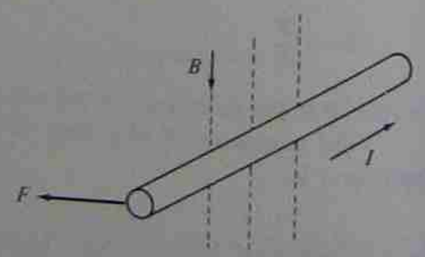


FIG. 2-9. A conductor of length l, carrying a current I, which is at right angles to a magnetic field of flux density B.

where A is the area of the pole faces and μ_0 is the permeability of free space.

The force F produced on a conductor of length l carrying a current I at right angles to a magnetic field of density B (Fig. 2-9) is

$$F = BIl \tag{2-24}$$

where F is at right angles to both B and I.

Assume a magnetic flux Φ linking a coil of N turns. If the flux changes, a voltage v is generated in the coil:

$$v = N\frac{d\Phi}{dt} \tag{2-25}$$

If the flux considered is set up by a current i in the coil itself (Fig. 2-7), then

$$\Phi = \frac{\mathscr{F}}{\mathscr{R}} = \frac{Ni}{\mathscr{R}}$$

and

$$v = \frac{NN}{\mathscr{R}}\frac{di}{dt}$$

or

$$v = L\frac{di}{dt} \tag{2-26}$$

where the self-inductance L is

$$L = \frac{N^2}{\mathscr{R}} \tag{2-27}$$

From Eq. (2-26),

$$i = \frac{1}{L}\int v\,dt \tag{2-28}$$

When current I flows in an inductor of value L, the energy stored in the magnetic field is

$$W = \frac{1}{2}LI^2 \tag{2-29}$$

Consider Eq. (2-25). If the flux Φ is set up by a current i_2 in a coil of turns N_2, which has a common magnetic circuit with coil 1 (Fig. 2-10), then

$$\Phi = \frac{\mathscr{F}_2}{\mathscr{R}} = \frac{N_2 i_2}{\mathscr{R}}$$

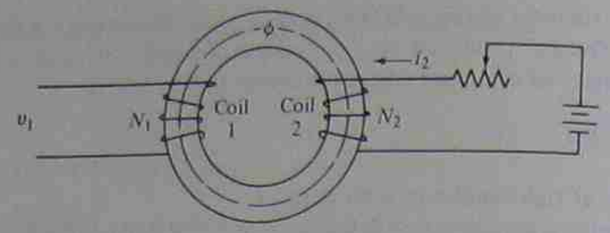


FIG. 2-10. Two coils, one with N_1 turns, the other with N_2 turns wound on the same magnetic core.

and

$$v_1 = N_1 \frac{N_2}{\mathscr{R}} \frac{di_2}{dt}$$

$$v_1 = M_{12} \frac{di_2}{dt} \tag{2-30}$$

where M_{12} is the mutual inductance between coil 1 and coil 2.

When several inductors, L_1, L_2, and L_3, are connected in series (Fig. 2-11), the equivalent inductance is

$$L_{eq} = L_1 + L_2 + L_3 \tag{2-31}$$

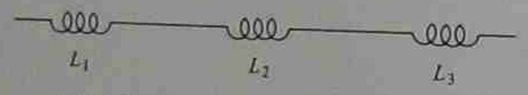


FIG. 2-11. Three inductors connected in series.

When several inductors are connected in parallel (Fig. 2-12), the equivalent inductance may be determined from the relation

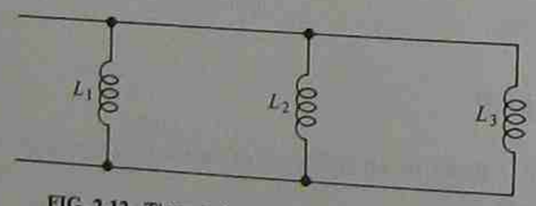


FIG. 2-12. Three inductors connected in parallel.

$$\frac{1}{L_{eq}} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \tag{2-32}$$

d. Relations Applying to Electric-Field Devices. If a charge Q is placed in a region of electric-field intensity $\mathscr{E}$ (Fig. 2-13), a force F is produced. Then

$$F = Q\mathscr{E} \tag{2-33}$$

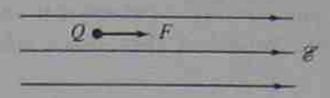


FIG. 2-13. A body carrying an electric charge Q in an electric field of intensity $\mathscr{E}$.

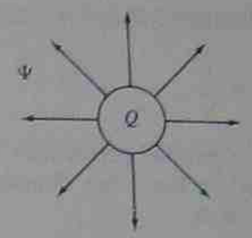


FIG. 2-14. A body carrying an electric charge Q from which ψ electric field lines emanate.

A body has on it a charge Q. From this body there will be ψ lines of electric flux (Fig. 2-14)

$$\psi = Q \tag{2-34}$$

The density D of the field lines will be

$$D = \frac{\psi}{A} \tag{2-35}$$

if the electric flux is uniform over the area A.

The permittivity ϵ of a dielectric material is

$$\epsilon = \frac{D}{\mathscr{E}} \tag{2-36}$$

For free space, $\epsilon = \epsilon_0 = 10^{-9}/36\pi$ farads per meter. The relative permittivity is ϵ/ϵ_0.

Two conducting bodies A and B, separated by a dielectric, form a *capacitor* (Fig. 2-15). If one carries a charge $+Q$ and the other a charge $-Q$

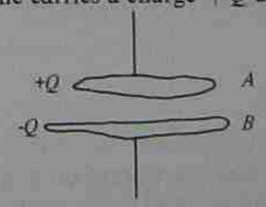


FIG. 2-15. A capacitor formed by two conducting bodies separated by a dielectric.

while the voltage between them is V, the capacitance C between the two bodies is

$$C = \frac{Q}{V} \tag{2-37}$$

The elastance S of a capacitor is

$$S = \frac{1}{C} \tag{2-38}$$

Two parallel plates each of area A and spacing d (where d is small compared to the other dimensions) form a capacitor (Fig. 2-16), whose capacitance is

$$C = \epsilon \frac{A}{d} \tag{2-39}$$

where ϵ is the permittivity of the material separating the two plates.

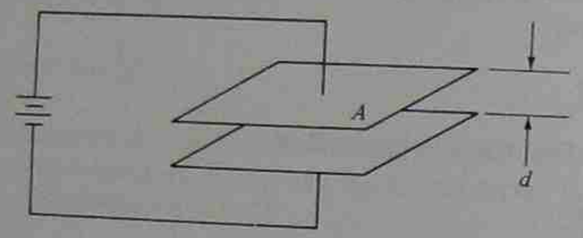


FIG. 2-16. Two parallel conducting plates of area A separated a distance d by a dielectric of permittivity ϵ.

In a parallel-plate system as just described, the electric field intensity $\mathscr{E}$ is

$$\mathscr{E} = \frac{V}{d} \tag{2-40}$$

where V is the voltage between the two plates.

If the voltage on a capacitor is changing with time, the current required to change the charge is

$$i = \frac{dQ}{dt} = C\frac{dv}{dt} \tag{2-41}$$

From Eq. (2-41) it follows that the voltage on a capacitor is

$$v = \frac{1}{C}\int i\,dt \tag{2-42}$$

The energy W stored in the capacitor is

$$W = \tfrac{1}{2}CV^2 \tag{2-43}$$

If several capacitors, $C_1, C_2, C_3, \ldots$, are connected in parallel (Fig. 2-17), the equivalent capacitance is

$$C_{eq} = C_1 + C_2 + C_3 + \cdots \tag{2-44}$$

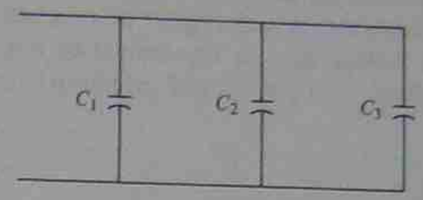


FIG. 2-17. Three capacitors connected in parallel.

If several capacitors, $C_1, C_2, C_3, \ldots$, are connected in series (Fig. 2-18), the equivalent elastance S_{eq} will be

$$S_{eq} = S_1 + S_2 + S_3 + \cdots \tag{2-45}$$

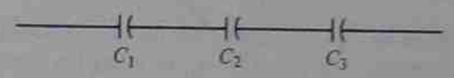


FIG. 2-18. Three capacitors connected in series.

or the equivalent capacitance may be determined from

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \tag{2-46}$$

The dielectric strength (DS) of an insulating material is

$$\text{DS} = \mathscr{E}_{BD} \tag{2-47}$$

where $\mathscr{E}_{BD}$ is the electric-field intensity at which the dielectric loses its insulating property and permits ready passage of current through it, a condition known as *dielectric breakdown*.

2-5. RELATIONS PERTAINING TO AC CIRCUITS

a. Representation of Sinusoidally Varying Quantities. The currents and voltages in well-designed ac circuits vary with time following almost perfect sinusoidal patterns. A sinusoidally varying voltage (or current) may be represented in several ways. The voltage may be expressed mathematically as

$$v = V_m \cos(2\pi ft + \phi_1) \tag{2-48}$$

or

$$v = V_m \sin (2\pi ft + \phi) \tag{2-49}$$

where V_m is the maximum (or crest) value of the voltage, f the frequency, and ϕ the angular displacement with respect to an arbitrary reference.

The sinusoidal voltage may be represented by a graph in which the magnitude of the voltage, v, is plotted with reference to time, t, as shown in Fig. 2-19.

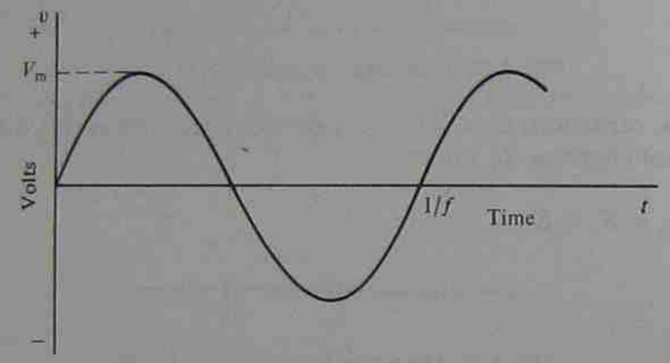


FIG. 2-19. A graph showing the voltage in an ac- circuit which varies with time as a sine wave.

A voltage may be represented by *a phasor*, as in Fig. 2-20. Here the line segment (phasor) A is assumed to have a length representative of V_m and to rotate around the point O, the angle increasing with time according to the relation

$$\phi_t = 2\pi ft + \phi_1 \tag{2-50}$$

If we now make a plot of the horizontal projection A_h of the phasor as it varies with time, the trace which will result will conform to Eq. (2-48). If, instead, we make a plot of the vertical projection A_v of the phasor as it varies with time, the trace which will result will conform to Eq. (2-49). Present practice (followed in this textbook) favors the use of the horizontal projection and the interpretation of Eq. (2-48).

Since the phasor A has a length representative of V_m (but not necessarily equal to it), it is common practice to draw phasors expressed in terms of the effective value of the voltage rather than the maximum value:

$$V_{eff} = \frac{V_m}{\sqrt{2}} = 0.707 V_m \tag{2-51}$$

A phasor may be expressed in several ways. We shall use the symbol $\bar{A}$ to represent a phasor of length A set at a particular angle ϕ with respect to a reference, as in Fig. 2-21. We may express $\bar{A}$ in complex notation. In rectangular form

$$\bar{A} = m + jn \tag{2-52}$$

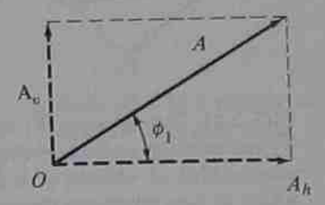


FIG. 2-20. A phasor representing a voltage which varies sinusoidally with time. The magnitude of the voltage is A.

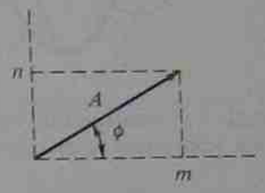


FIG. 2-21. A phasor of length A, whose horizontal component is m, whose vertical component is n, and which makes an angle ϕ with the reference axis.

indicating that phasor $\bar{A}$ may be regarded as the sum of two phasors at right angles to each other ($j = \sqrt{-1}$). Or we may write

$$\bar{A} = A\underline{/\phi} \tag{2-53}$$

which is the *polar form* of Eq. (2-52). Or we may write

$$\bar{A} = Ae^{j\phi} \tag{2-54}$$

which is the *exponential form* of Eq. (2-52).

b. Addition of Sine Waves. Two (or more) sinusoids v_1 and v_2 may be added when represented by either of the three methods of expression just described. For example,

$$v_t = V_{1m} \cos (2\pi f_1 t + \phi_1) + V_{2m} \cos (2\pi f_2 t + \phi_2) \tag{2-55}$$

If f_1 is equal to f_2, mathematical manipulation will show that v_t is a sinusoid of the same frequency:

$$v_t = V_{tm} \cos (2\pi ft + \phi_3) \tag{2-56}$$

The two waves of Eq. (2-55) are shown graphically in Fig. 2-22. These two waves may be added point by point to give v_t as shown.

The two waves of Eq. (2-55) may be represented by phasors (Fig. 2-23). By adding the phasors, following the law of vector addition, a new phasor V_t

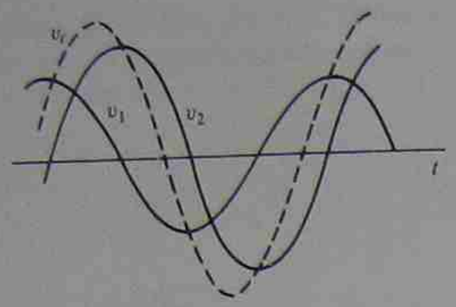


FIG. 2-22. Two sine waves (of voltage) v_1 and v_2 which when added point by point give the total v_t.

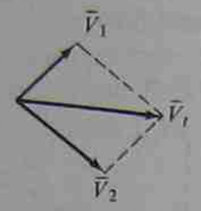


FIG. 2-23. Two phasors $\bar{V}_1$ and $\bar{V}_2$ representing sine waves which when added as vectors, give $\bar{V}_t$, which in turn represents the sum.

is produced which properly represents the sum. This addition may be performed either graphically or analytically.

c. Resistance. The expression relating voltage and current in a resistor is

$$v = iR \tag{2-7}$$

If the current through the resistor is a sinusoid represented by

$$i = I_m \cos 2\pi ft \tag{2-57}$$

then

$$\begin{aligned} v &= I_m R \cos 2\pi ft \\ &= V_m \cos 2\pi ft \end{aligned} \tag{2-58}$$

where

$$V_m = I_m R$$

or

$$V = IR \tag{2-59}$$

where V and I are effective values.

A comparison of Eqs. (2-57) and (2-58) shows that the wave of voltage is in phase with the wave of current (Fig. 2-24). On a phasor diagram, the voltage and current are represented as shown in Fig. 2-25a, where both phasors are along the line of reference, or as in Fig. 2-25b, where both are

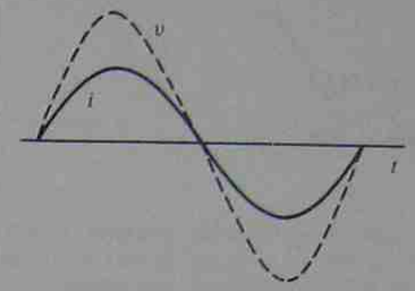


FIG. 2-24. In a resistor, the sine waves of current and voltage are in phase with each other.

FIG. 2-25. Phasor diagrams showing the current and voltage of a resistor in phase with each other. (a) Phasors are on the reference axis. (b) Phasors are at an angle with the reference axis.

at an angle with reference. Since it is presumed that these phasors rotate with time, either position is correct. The *relative* position of the two phasors is of importance.

In phasor notation

$$\bar{V}_R = I_R R \tag{2-60}$$

The power to the resistor,

$$p = vi \tag{2-4}$$

when averaged over a complete cycle is

$$P_R = VI = I^2 R \tag{2-61}$$

where V and I are effective values.

d. Inductance. In an inductor

$$v = L \frac{di}{dt} \tag{2-26}$$

If, as in the case of the resistor, the current is represented by

$$i = I_m \cos 2\pi ft \tag{2-57}$$

then

$$v = I_m L 2\pi f(-\sin 2\pi ft) \tag{2-62a}$$

$$v = V_m \cos(2\pi ft + 90) \tag{2-62b}$$

where

$$V_m = I_m 2\pi fL \tag{2-63}$$

or

$$V_m = I_m X_L \tag{2-64}$$

where X_L, the inductive reactance, is

$$X_L = 2\pi fL \tag{2-65}$$

A comparison of Eqs. (2-57) and (2-62) shows that the wave of voltage is 90 degrees ahead of the wave of current (or the current is 90° behind the voltage), Fig. 2-26.

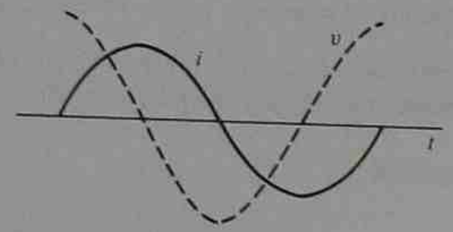


FIG. 2-26. In an inductor, the sine wave of current lags the sine wave of voltage by 90°.

On a phasor diagram, the voltage and current are represented as shown in Fig. 2-27a or b. From this diagram and Eq. (2-64) it follows that if the current and voltage are represented by phasors, then

$$\bar{V}_L = jX_L\bar{I} = j2\pi fL\bar{I} \tag{2-66}$$

where the j indicates a 90° displacement.

The instantaneous power to the inductor,

$$p = vi \tag{2-5}$$

when averaged over a complete cycle is

$$P_L = 0 \tag{2-67}$$

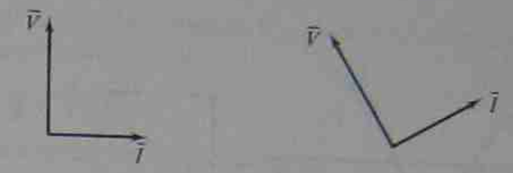


FIG. 2-27. Phasor diagrams showing the current through an inductor lagging the voltage across it by 90°. (a) The current phasor is on the reference axis. (b) The current and voltage phasors are displaced from the reference axis.

e. Capacitance. In a capacitor

$$v = \frac{1}{C}\int i\,dt \tag{2-42}$$

If, as in the case of the resistor, the current is represented by

$$i = I_m \cos 2\pi ft \tag{2-57}$$

then

$$v = I_m \frac{1}{2\pi fC} \sin 2\pi ft$$

or

$$V = V_m \cos(2\pi ft - 90°) \tag{2-68}$$

where

$$V_m = I_m \frac{1}{2\pi fC} \tag{2-69}$$

or

$$V_m = I_m X_C \tag{2-70}$$

where X_C, the capacitive reactance, is

$$X_C = \frac{1}{2\pi fC} \tag{2-71}$$

A comparison of Eqs. (2-57) and (2-68) shows that the wave of voltage is 90 degrees behind the wave of current (Fig. 2-28).

On a phasor diagram, the voltage and current are shown as in Fig. 2-29a or b. From this diagram and Eq. (2-71) it follows that if the current

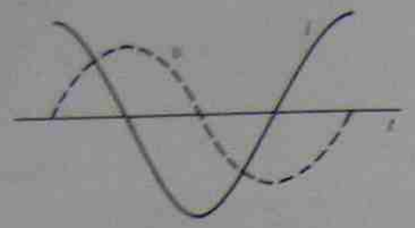


FIG. 2-28. In a capacitor, the sine wave of current leads the sine wave of voltage by 90°.

FIG. 2-29. Phasor diagrams showing the current of a capacitor leading the voltage across it by 90°. (a) The current phasor is on the reference axis. (b) The current and voltage phasors are displaced from the reference axis.

and voltage are represented by phasors, then

$$\bar{V}_C = -jX_C I_C = \frac{-j}{2\pi fC} I_C \tag{2-72}$$

where the $-j$ indicates a $-90°$ displacement.

The instantaneous power to the capacitor,

$$p = vi \tag{2-5}$$

when averaged over a complete cycle is

$$P_C = 0 \tag{2-73}$$

I. Series Combinations of Resistance, Inductance, and Capacitance. Consider a resistor in series with an inductor carrying a sinusoidally varying current I (Fig. 2-30a). As the current is common to both circuit elements, it will be used as reference in the phasor diagram (Fig. 2-30b). The voltage across the resistor, V_R, is in phase with I,

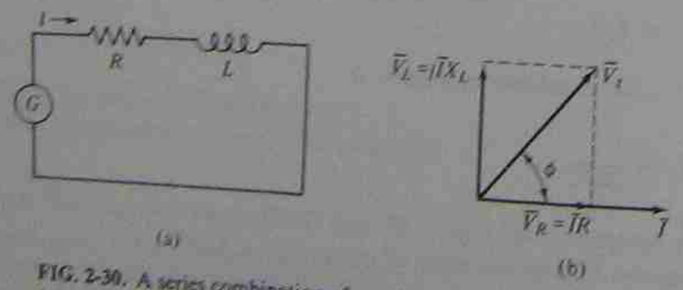


FIG. 2-30. A series combination of a resistor R and an inductor L. (a) The circuit diagram. (b) The phasor diagram.

while the voltage across the inductor, V_L, leads the current by 90°. By phasor addition, the total voltage V_t is

$$V_t = \sqrt{V_R^2 + V_L^2} \tag{2-74}$$

which leads the current by the phase angle

$$\phi = \arctan \frac{V_L}{V_R} \tag{2-75}$$

Since (in phasor notation)

$$\bar{V}_R = IR \tag{2-60}$$

$$\bar{V}_L = I j2\pi fL = I jX_L \tag{2-66}$$

$$\bar{V}_t = I(R + jX_L) = IZ \tag{2-76}$$

then Z, the circuit impedance, is

$$Z = R + jX_L \tag{2-77}$$

Next, consider a resistor in series with a capacitor in an ac circuit (Fig. 2-31a). An analysis of the phasor diagrams for this circuit (Fig. 2-31b)

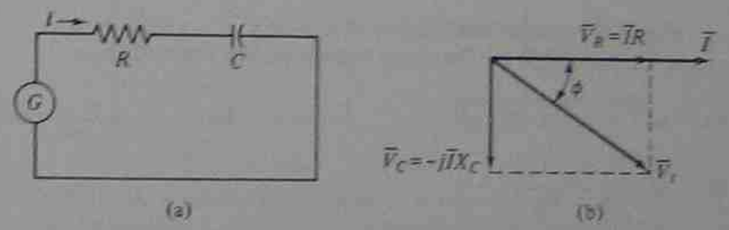


FIG. 2-31. A series combination of a resistor R and a capacitor C. (a) The circuit diagram. (b) The phasor diagram.

shows that

$$V_t = \sqrt{V_R^2 + V_C^2} \tag{2-78}$$

which lags the current by the phase angle

$$\phi = -\arctan \frac{V_C}{V_R} \tag{2-79}$$

$$\bar{V}_R = IR \tag{2-60}$$

$$\bar{V}_C = -jX_C I = \frac{-j}{2\pi fC} I \tag{2-72}$$

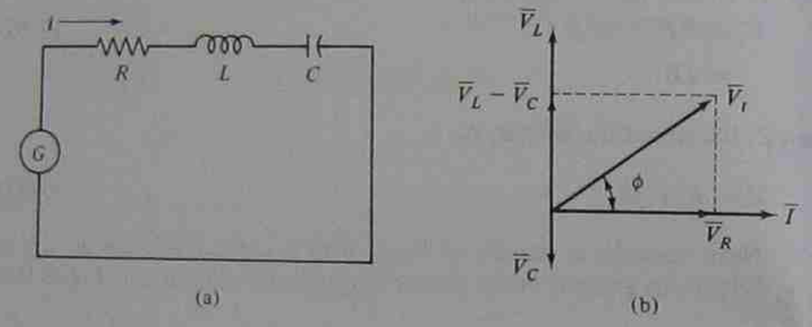
and

$$\bar{V}_t = \bar{I}(R - jX_C) = \bar{I}Z \tag{2-80}$$

where

$$Z = R - jX_C \tag{2-81}$$

A similar analysis of an ac circuit consisting of a series combination of a resistor, an inductor, and a capacitor (Fig. 2-32a) and the corresponding phasor diagram (Fig. 2-32b) shows that



(a) (b)

FIG. 2-32. A series combination of a resistor R, an inductor L, and a capacitor C. (a) The circuit diagram (b) The phasor diagram.

$$V_t = \sqrt{V_r^2 + (V_L - V_C)^2} \tag{2-82}$$

$$\phi = \arctan \frac{V_L - V_C}{V_R} \tag{2-83}$$

In phasor notation

$$\bar{V}_t = I\left(R + j\omega L - \frac{j}{\omega C}\right) \qquad \omega = 2\pi f \tag{2-84}$$

$$\bar{V}_t = IZ \tag{2-85}$$

where

$$Z = R + jX_L - jX_C \tag{2-86}$$

An RLC series circuit (Fig. 2-32a) is said to be *resonant* when

$$X_L - X_C = 0 \tag{2-87}$$

Then

$$Z = R \tag{2-88}$$

Since

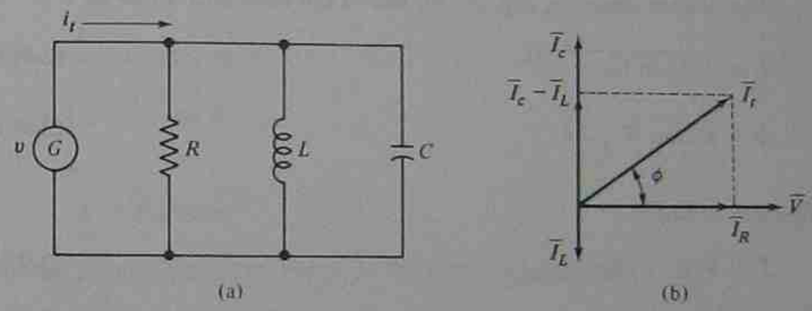
$$X_L = 2\pi f L$$

and

$$X_C = \frac{1}{2\pi f C}$$

it follows that a circuit may be brought to resonance by a proper adjustment of either inductance, capacitance, or frequency.

g. Parallel Combinations of Resistance, Inductance, and Capacitance. Consider an ac circuit in which a resistor, an inductor, and a capacitor are in parallel (Fig. 2-33a). Note that V is



(a) (b)

FIG. 2-33. A parallel combination of a resistor R, an inductor L, and a capacitor C. (a) The circuit diagram. (b) The phasor diagram.

common to R, L, and C and is therefore used as the reference in Fig. 2-33b. By Eq. (2-60),

$$I_R = \frac{\bar{V}}{R}$$

or

$$I_R = \bar{V}G \tag{2-89}$$

where

$$G = \frac{1}{R} \tag{2-90}$$

By Eq. (2-66),

$$\bar{I}_L = \frac{\bar{V}}{jX_L} = \bar{V}(-jB_L) \tag{2-91}$$

where

$$B_L = \frac{1}{X_L} = \frac{1}{2\pi fL} \tag{2-92}$$

By Eq. (2-72),

$$I_C = \frac{\bar{V}}{-jX_C} = \bar{V}jB_C \tag{2-93}$$

where

$$B_C = \frac{1}{X_C} = 2\pi fC \tag{2-94}$$

Note that R, X_L, X_C, G, B_L, and B_C are all *real* numbers, not complex.

The phasor diagram, Fig. 2-33b, shows the total current to be

$$I_t = \sqrt{I_R^2 + (I_C - I_L)^2} \tag{2-95}$$

$$\phi = \arctan \frac{I_C - I_L}{I_R} \tag{2-96}$$

In phasor notation,

$$\bar{I}_t = \bar{V}(G - jB_L + jB_C) \tag{2-97}$$

$$\bar{I}_t = \bar{V}\bar{Y} \tag{2-98}$$

where

$$\bar{Y} = G - jB_L + jB_C \tag{2-99}$$

A parallel circuit is said to be resonant when

$$-B_L + B_C = 0 \tag{2-100}$$

Then

$$Y = G \tag{2-101}$$

The condition of parallel resonance may be produced by a proper adjustment of either inductance, capacitance, or frequency.

h. Power, Apparent Power, and Reactive Power. From Eq. (2-61) it may be noted that in an ac circuit, the power to a resistor averaged over a cycle is

$$P_R = I^2R \tag{2-61}$$

where I is the effective value of the current.

From Eqs. (2-67) and (2-73), it may be noted that in an ac circuit the power to an inductor or to a capacitor averaged over a cycle is

$$P_L = 0 \tag{2-67}$$

$$P_C = 0 \tag{2-73}$$

As a consequence, to determine the power dissipated in an ac circuit it is necessary to look only at the power dissipated in the resistors.

In the series RLC circuit of Fig. 2-32 the power is given by

$$P = V_R I$$

However, we may write

$$V_R = V_t \cos \phi$$

or

$$P = V_t I \cos \phi \tag{2-102}$$

In the parallel circuit of Fig. 2-33 the power is given by

$$P = VI_R$$

Since

$$I_R = I_t \cos \phi$$

$$P = VI_t \cos \phi \tag{2-103}$$

It can be shown that in any circuit the active power is given by

$$P = VI \cos \phi \quad \text{watts} \tag{2-104}$$

where ϕ is the angle of the voltage $\bar{V}$ relative to the current $\bar{I}$. For an impedance, ϕ is its angle.

The apparent power, P_t, applying to all ac circuits, is

$$P_t = VI \quad \text{volt-amperes} \tag{2-105}$$

The reactive power, P_q, applying to all ac circuits, is

$$P_q = VI \sin \phi \quad \text{reactive volt-amperes} \tag{2-106}$$

The power factor, F_p, is

$$F_p = \cos \phi = \frac{P}{P_s} \tag{2-107}$$

The reactive factor, F_q, is

$$F_q = \sin \phi = \frac{P_q}{P_s} \tag{2-108}$$

A lagging load is one in which the current lags the voltage, as in an inductive circuit. A leading load is one in which the current leads the voltage, as in a capacitive circuit.

The reactive power supplied to an inductor is positive, that to a capacitor is negative.

A diagram showing a geometric relationship between P_s, P, and P_q is shown in Fig. 2-34. Here is may be noted that

$$P_s = \sqrt{P^2 + P_q^2} \tag{2-109}$$

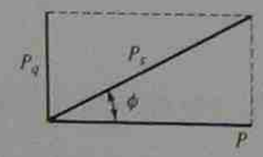


FIG. 2-34. A vector diagram (not a phasor diagram) showing the relationship between Apparent Power P_s, Active Power P, and Reactive (or Quadrature) Power P_q.

The vector power, S, is a complex number

$$S = P + jP_q = P_s \underline{/\phi} \tag{2-110}$$

which is proved to be

$$S = \bar{V}\bar{I}^* \tag{2-111}$$

where $\bar{I}^*$ is the conjugate of the current phasor $\bar{I}$.

Vector power is conserved in an electric circuit. This means that the total power supplied by the generators equals the total power absorbed by the resistors, and the total reactive power supplied by the generators equals the total reactive power absorbed by the reactances.

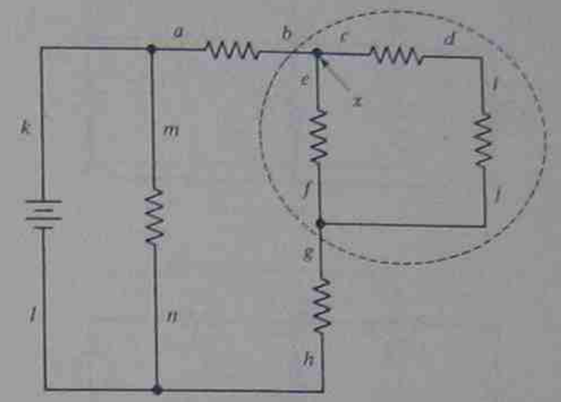


FIG. 2-35. A circuit to illustrate Kirchhoff's Voltage Law and Current Law.

$$V_{lk} + V_{ab} + V_{cd} + V_{dl} = 0$$

Here the path is closed, but it does not follow the branches of the circuit.

b. Kirchhoff's Current Law. The algebraic sum of all the currents to a point (or to a bounded region) is zero. This law is illustrated in Fig. 2-35 by writing (for point x)

$$I_{ab} + I_{dc} + I_{fe} = 0$$

It is further illustrated by writing (for the region bounded by the dashed line)

$$I_{ab} + I_{hg} = 0$$

c. Superposition Theorem. In a network containing several sources (voltage or current) the current in any branch may be determined by calculating the current in that branch in the presence of a single source while all other sources are reduced to zero, repeating the process for each source in turn, and then algebraically summing the several currents so calculated. This theorem is illustrated in Fig. 2-36. The current in branch X of (a) is the algebraic sum of the current in branch X determined in (b) plus the current in branch X determined in (c).

d. Thévenin's Theorem. In a network consisting of any number of sources and any number of branches, the behavior of a load attached to any two terminals mn may be analyzed by considering the network to be replaced by a simple circuit consisting of a single voltage source and a single impedance in series connection to the load.

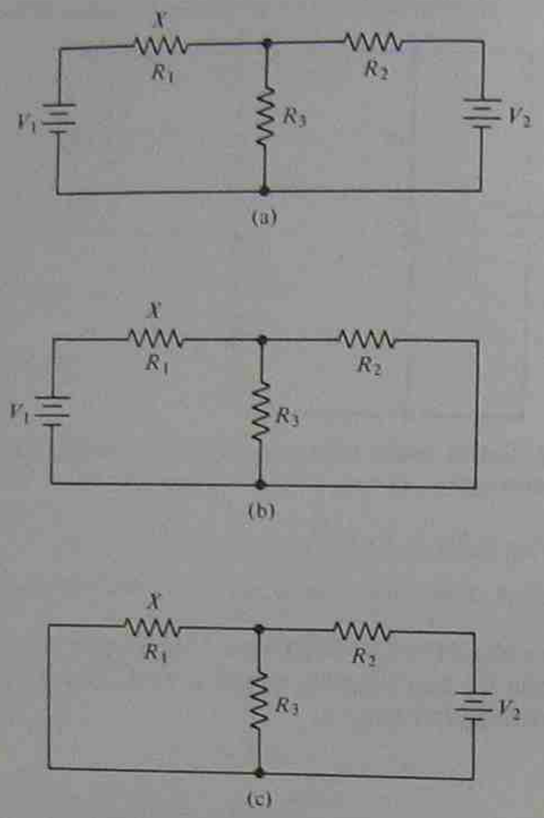


FIG. 2-36. Illustrating the Superposition Theorem. The current in Branch X of (a) is equal to the sum of the current in Branch X of (b) and the current in Branch X of (c).

The Thévenin voltage is the voltage measured between the load terminals mn on the total network but with no load on mn. The Thévenin impedance is that impedance measured between terminals mn of the network with all source voltages and source currents reduced to zero and with no load connected to mn. This theorem is illustrated in Fig. 2-37, in which (a) is the total circuit with the load connected. In (b) the Thévenin voltage is being measured. In (c) the Thévenin impedance is being measured. In (d) the Thévenin equivalent circuit is presented with the load connected.

e. Delta–Wye and Wye–Delta Transformations. Three points A, B, and C in an electric network may sometimes be interconnected by three impedances Z_{ab}, Z_{bc}, and Z_{ca} as shown in Fig. 2-38a. Such an arrangement of impedances is said to be *delta-connected*. In studies involving circuit reduction or in three-phase-circuit analysis, it is sometimes advan-

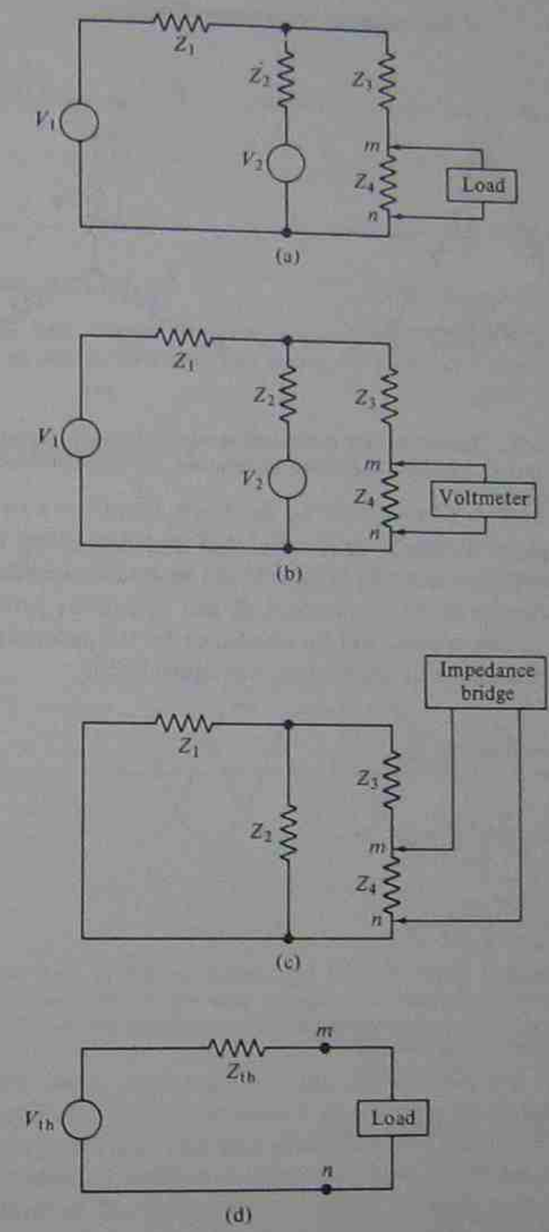


FIG. 2-37. Illustrating Thévenin s Theorem (a) A load is connected across two terminals mn of a complicated network. (b) The load is removed and the voltage V_{Th} between the terminals mn is measured. (c) The sources are removed and the impedance Z_{Th} between terminals mn is measured. (d) The Thévenin equivalent circuit.

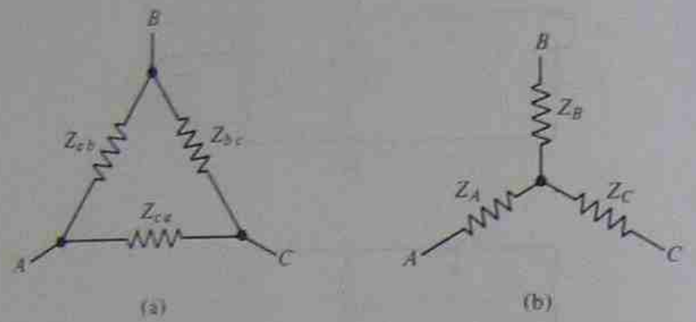


FIG. 2-38. Circuits that are equivalent in relationship to terminals *A*, *B*, and *C*. (a) Delta-connected impedances. (b) Wye-connected impedances.

tageous to replace the three delta-connected impedances by another set connected in wye (or star), Fig. 2-38b. If the new set has values properly selected, the behavior at the terminals *A*, *B*, and *C*, and the performance of the remainder of the system, will be unaffected by the substitution. It can be shown that the arrays of impedances are equivalent if

$$Z_A = \frac{Z_{ab}Z_{ca}}{Z_{ab} + Z_{bc} + Z_{ca}}$$

$$Z_B = \frac{Z_{bc}Z_{ab}}{Z_{ab} + Z_{bc} + Z_{ca}} \qquad (2\text{-}112)$$

$$Z_C = \frac{Z_{ca}Z_{bc}}{Z_{ab} + Z_{bc} + Z_{ca}}$$

or

$$Z_{ab} = \frac{Z_AZ_B + Z_BZ_C + Z_CZ_A}{Z_C}$$

$$Z_{bc} = \frac{Z_AZ_B + Z_BZ_C + Z_CZ_A}{Z_A} \qquad (2\text{-}113)$$

$$Z_{ca} = \frac{Z_AZ_B + Z_BZ_C + Z_CZ_A}{Z_B}$$

Sometimes the arrays of impedances discussed above are shown in a slightly different fashion, as indicated in Fig. 2-39. When presented in this manner the arrangements are sometimes designated as π-connected and *T*-connected, because of the diagram similarity to these two letters.

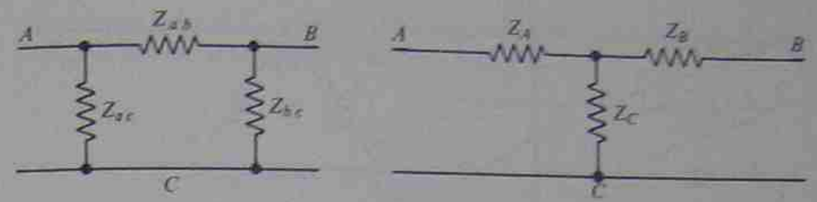


FIG. 2-39. Circuits that are equivalent in relationship to terminals *A*, *B*, and *C*. (a) π-connected (delta). (b) T-connected (Wye).

2-7. THREE-PHASE CIRCUITS

a. Three-Phase System of Voltages. A three-phase system of voltages is illustrated in Fig. 2-40. A set of coils, *ab*, *cd*, and *ef*, which might be three windings in an alternator or three secondary windings of

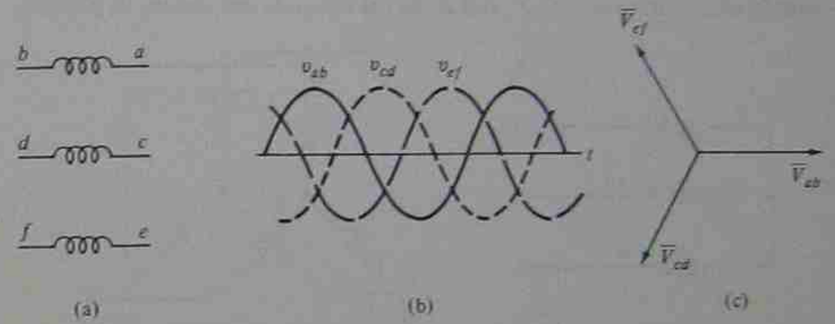


FIG. 2-40. A 3-phase system. (a) Coils in which voltages are generated. (b) The sine wave voltages produced in the three coils. (c) Phasor representation of the three voltages.

a transformer bank, is presented in (a). These coils are independent of each other and may be interconnected as desired. The voltages generated within these coils are presented as a time plot in (b) and as a phasor diagram in (c). This system of voltages is said to be *balanced* when effective values (or crest values) of the three waves are all of the same magnitude and the time displacement between each is one third of a cycle (120 degrees).

b. Delta Connection. The coils of Fig. 2-40 may be connected in delta as shown in Fig. 2-41 to form a three-phase supply with line conductors *X*, *Y*, and *Z*. In (a) the coils are shown as they would be connected physically. In (b) they are shown diagrammatically to emphasize the

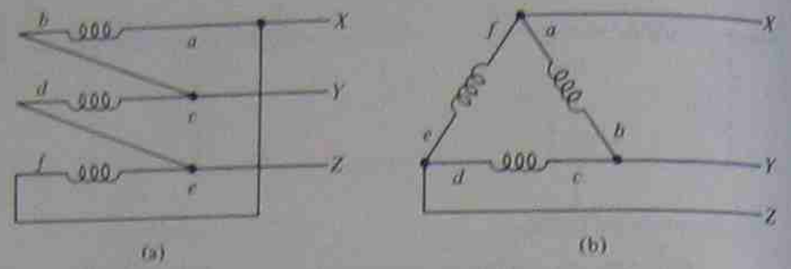


FIG. 2-41. Three coils connected in delta. (a) Physical arrangement. (b) Diagrammatic representation.

delta connection. The voltages between each pair of line conductors X, Y, and Z are each equal in magnitude to the voltage of either of the coils ab, cd, or ef.

c. Wye (or Star) Connection. The coils of Fig. 2-40a may be connected in wye (or star) as shown in Fig. 2-42 to form a three-phase supply with conductors X, Y, and Z. In (a) the coils are shown in physical

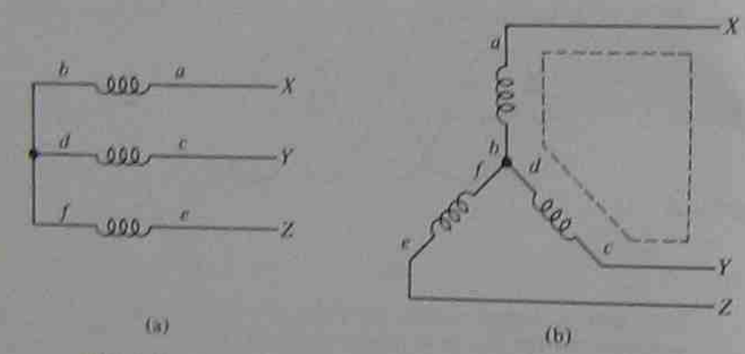


FIG. 2-42. Three coils connected in Wye. (a) Physical arrangement. (b) Diagrammatic representation.

arrangement. In (b) they are shown diagrammatically to emphasize the wye connection. In a balanced three-phase wye system, the voltages between each pair of line conductors X, Y, and Z are equal in magnitude and are 1.73 times the voltage of either of the coils ab, cd, and ef. This voltage relationship may be demonstrated by applying Kirchhoff's voltage law around the path shown by the dashed line:

$$\bar{V}_{ab} + \bar{V}_{dc} + \bar{V}_{xx} = 0$$

$$\bar{V}_{ab} + \bar{V}_{dc} = -\bar{V}_{xx} = \bar{V}_{xx}$$

The phasor sum of $\bar{V}_{ab}$ and $\bar{V}_{dc}$ (which is the same as the sum of $\bar{V}_{ab}$ and $-\bar{V}_{cd}$) is shown in the phasor diagram, Fig. 2-43.

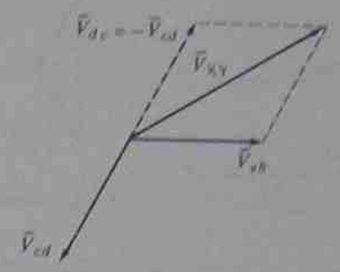


FIG. 2-43. Determination of the voltage between X and Y of the Wye connection, Fig. 2-42(b).

The common point of a wye connection is frequently termed the *neutral* and is designated by the letter N. The diagram of Fig. 2-42b might be shown as in Fig. 2-44.

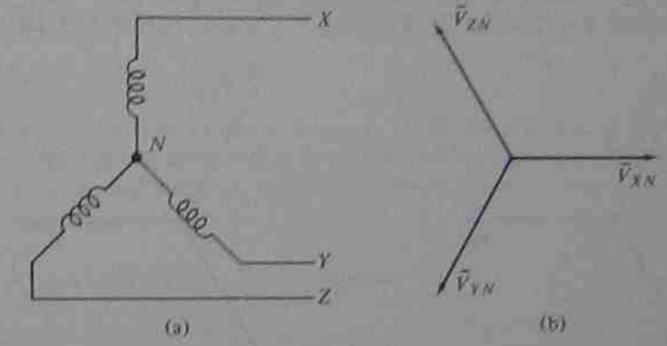


FIG. 2-44. The Wye-connected system. (a) The circuit showing the neutral. (b) The phasors of the line-to-neutral voltages. The phase sequence is XYZ.

d. Phase Sequence. The order in which each of the three voltages of a three-phase system reaches its positive crest determines the *phase sequence* of the system. Remembering that all phasors of a phasor diagram are assumed to rotate counterclockwise and that the positive crest of the sine wave is assumed to occur when the phasor is horizontal and to the right, it follows that the voltages of the system of Fig. 2-44b come up in the order X, Y, and Z. The phase sequence is therefore XYZ.

If the diagram of Fig. 2-42b had been labeled as shown in Fig. 2-45a (the designation X, Y, and Z is purely arbitrary), the phasor diagram would

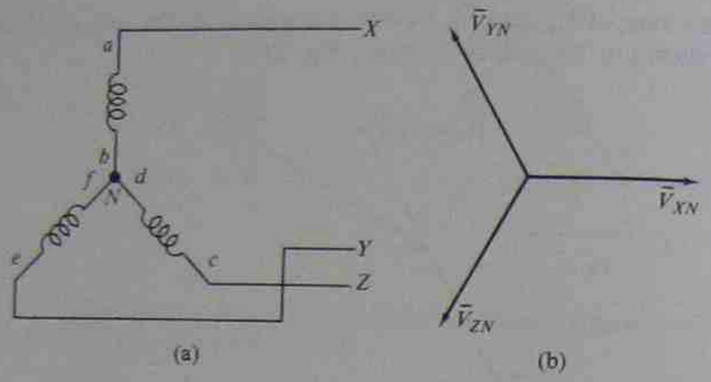


FIG. 2-45. The Wye-connected system with two terminals interchanged. (a) The circuit. (b) The phasors of the line-to-neutral voltages. The phase sequence is ZYX.

appear as in Fig. 2-45b. Thus it is seen that interchanging two leads (such as X and Y) reverses the phase sequence. Without interchanging connections, the phase sequence of a system may also be reversed by reversing the direction of rotation of the three-phase supply generator. This change would require Fig. 2-40c to be revised to Fig. 2-46a. Then Fig. 2-44b would

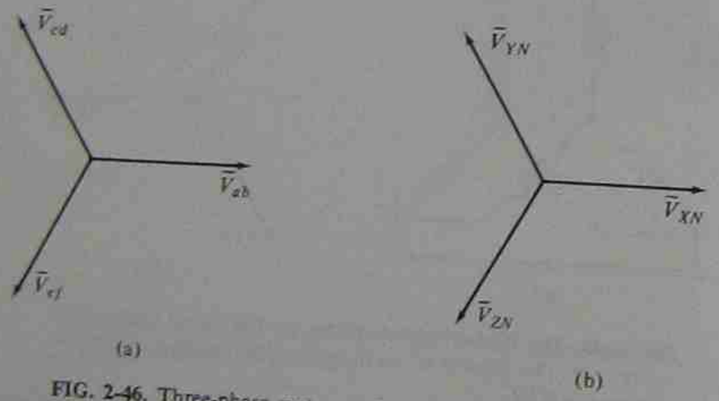


FIG. 2-46. Three-phase systems of phasors with the supply generator reversed in direction of rotation. (a) The phasors of coil voltage. (b) The phasors of line-to-neutral voltages. The phase sequence is ZYX.

be revised to Fig. 2-46b and the phase sequence would be ZYX. It must be concluded that the phase sequence of a system can be determined only after arbitrary conductor designations have been assigned.

e. Three-Phase Loads. Three-phase loads are usually connected to the supply lines in delta or in wye as shown in Fig. 2-47. If the

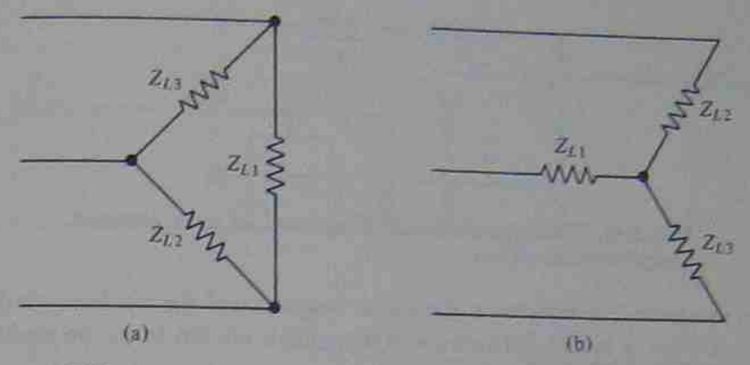


FIG. 2-47. Three-phase loads. (a) Delta connected. (b) Wye connected.

three impedances Z_{L1}, Z_{L2}, and Z_{L3} are identical, the loads are said to be *balanced*. When balanced three-phase loads are connected in delta, the line current is $\sqrt{3}$ times the current in an individual load impedance. In wye-connected systems, the line-to-line voltage is $\sqrt{3}$ times the voltage across any one individual load.

The power in a balanced three-phase load (wye or delta) is given by

$$P_{3\phi} = \sqrt{3}\, V_{LL} I_L \cos \phi \tag{2-114}$$

where V_{LL} is the line-to-line voltage, I_L is the line current, ϕ is the angle between the current and voltage in any one of the load impedances Z_L, and $\cos \phi$ is the power factor F_p of the load. The apparent power of a balanced three-phase load is

$$P_{s3\phi} = \sqrt{3}\, V_{LL} I_L \quad \text{volt-amperes} \tag{2-115}$$

2-8. EQUIVALENT CIRCUITS OF MACHINES

Many of the machines used in the electric power industry may be studied in regard to their performance in association with other equipment by replacing them with equivalent electric circuits. These electric-circuit models of the machines are usually developed on the basis of certain simplifying assumptions. These assumptions must be kept in mind when applying the models to the solution of power-system problems.

a. AC Generator. The circuit model of an ac generator (or alternator) is shown in Fig. 2-48. The voltage V_g is a fictitious generated voltage which is assumed to be dependent only on the speed of the machine and the value of the field current. The terminals PQ are the load terminals

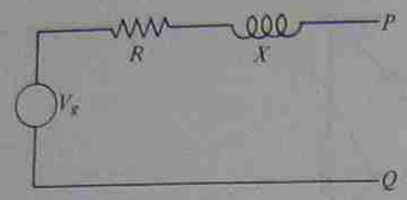


FIG. 2-48. The approximate equivalent circuit of an ac generator (or synchronous motor).

of the machine. The resistance R is the ac resistance of the machine winding. The reactance X is also fictitious, and its value is chosen to fit the problem, as follows:

X_s is termed the *synchronous reactance*, and this value is used in problems involving steady-state analysis.

X'_d is termed the *transient reactance*, and is used for problems involving sudden changes on the machine wherein numerical values are to be determined for a time approximately 10 cycles after the change is initiated.

X''_d is termed the *subtransient reactance*, and is used for problems involving sudden changes on the machine wherein numerical values are to be determined immediately after the change is initiated.

The different values of X are necessary because armature reaction does not follow immediately with the establishment of armature currents. Time is required for the generator field to change as a result of a change in the armature current.

b. Synchronous Motor. The circuit model of a synchronous motor is essentially the same as that of an ac generator. In Fig. 2-48, P and Q are the supply terminals and V_g is the internal voltage generated within the machine.

c. Two-Winding Transformer. The circuit model of a two-winding transformer is shown in Fig. 2-49a. Here R_1 and X_1 represent the primary winding resistance and leakage reactance, and R_2 and X_2 are the corresponding values for the secondary winding. The core-loss current and the magnetizing current are accounted for by the currents through R_c and X_m. The coupling between primary and secondary is assumed to be through the medium of a perfect transformer of turns ratio N_2/N_1.

For many purposes, a simpler model, Fig. 2-49b, may be used. Here the core-loss and magnetizing currents are neglected and the secondary impedance has been transferred to the low-voltage side and combined with

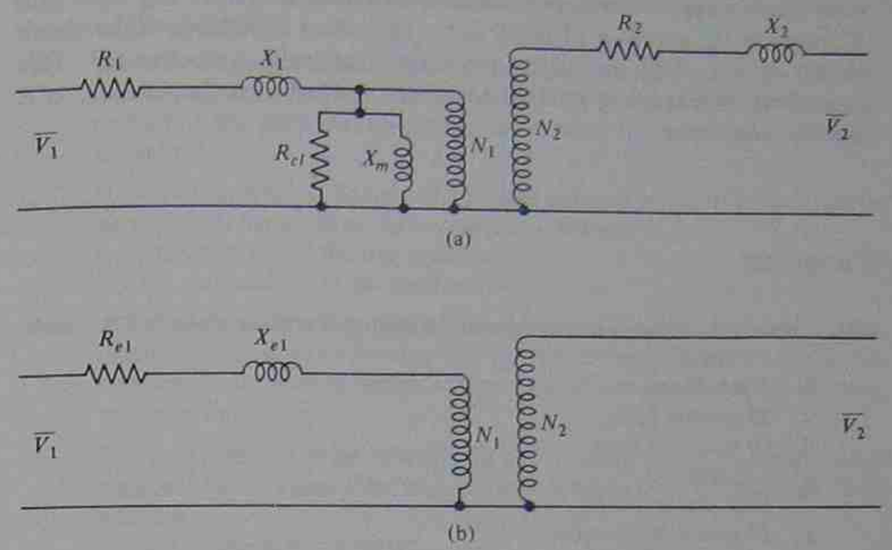


FIG. 2-49. The equivalent circuit of a two-winding transformer. (a) The complete representation. (b) A simplified circuit.

the primary impedance. Obviously R and X could be transferred to the secondary side (if desired) by multiplying by $(N_2/N_1)^2$.

$$R_{e1} = R_1 + R_2\left(\frac{N_1}{N_2}\right)^2$$

$$X_{e1} = X_1 + X_2\left(\frac{N_1}{N_2}\right)^2$$

d. Induction Motor. The circuit model of an induction motor is the same as that of a transformer except for the addition of a resistance R_s across the secondary terminals. R_s depends on the motor speed:

$$R_s = R_2\frac{n}{n_s - n}$$

where n_s is the synchronous speed and n the actual speed of the motor. For a frequency f and a number of poles p,

$$n_s = 120\frac{f}{p}$$

Under normal running conditions n is close to n_s in value, which makes R_s much larger than R_2. Thus, the voltage V_2 does not vary considerably. The

equivalent circuit is therefore sometimes simplified to that of Fig. 2-48 with V_g equal to V_2, and $R + jX$ equal to the equivalent impedance of the circuit shown in Fig. 2-49 having its secondary terminals short-circuited. This equivalent impedance is referred to as the blocked-rotor impedance, as it corresponds to $n = 0$.

PROBLEMS

2-1. Express the following quantities in the appropriate units of the MKS system.
   a. 15 inches.
   b. 6 pounds mass.
   c. 18 pounds force.
   d. 60 miles per hour.
   e. 3.5 days.
   f. 16.2 square inches.
   g. 32 pound feet torque.
   h. 45 foot pounds of work.
   i. 50 horsepower.
   j. 18,000 maxwells.
   k. 16 million electron volts.

2-2. Express the following in terms of English units.
   a. 4.2 kilometers.
   b. 650 joules.
   c. 85 kilowatts.
   d. 55 meters per second.
   e. 0.42 weber per square meter.
   f. 65 newtons.
   g. 15 meters per second per second.

2-3. A 12-V storage battery is charged at the rate of 9 amperes for 24 hours; calculate
   a. the total charge supplied to the battery.
   b. the total energy input.
   c. the ampere-hours.
   d. the size of the capacitor whose voltage would reach 12 volts after the charging period described above. Comment on this size.

2-4. A No. 10 copper wire has a diameter of 0.100 inch. Determine the resistance of 6 miles of No. 10 copper wire. The resistivity, ρ, is 10.2 ohms circular mils per foot, or 1.7×10^{-8} ohm-meter.

2-5. The resistance of a transformer winding is 0.076 ohm at 20°C. Determine its resistance when
   a. the unit has been deenergized and stored in a room at −30°F.
   b. the unit has been operated under overload and is at a temperature of 80°C. The temperature coefficient of resistance of copper is 3.9×10^{-3} per degree C.

2-6. Three 6-ohm resistors are connected in series. Three identical 6-ohm resistors are connected in parallel. The series-connected group is then connected in series with the parallel-connected group. What is the resistance of the total assembly?

2-7. Refer to Problem 2-6. Suppose the parallel group of resistors is connected in parallel with the series group of resistors. Calculate
   a. the resistance of the combination.
   b. the conductance of the combination.

2-8. A toroid-shaped iron core has a cross section of 6 square centimeters and a mean diameter of 18 centimeters. The relative permeability is 970. A 120-turn coil wound on the core carries a current of 3.8 amperes. Calculate the magnetic flux in the core.

2-9. The pole faces of a relay have an area of 1.5 square inches. By establishing a magnetic field between them it is desired to set up a force of 14 ounces. What must be
   a. the magnetic flux density?
   b. the total magnetic flux across the gap (neglect fringing)?

2-10. A 350-turn coil is wound on an iron core. When the current through the coil is 5 amperes, the flux in the core is 0.6 weber. What is the self-inductance of the coil?

2-11. Refer to Problem 2-10. A second coil of 200 turns is wound on the same core as described. What is the mutual inductance between the two windings?

2-12. A capacitor has a plate area of 24 square feet and an insulation thickness of 0.035 inch. The relative dielectric constant is 4.2. The insulation may be operated at a stress of 350 volts per mil. Determine
   a. the capacitance of the capacitor.
   b. the voltage at which it may be operated.
   c. the energy stored in it when operating at full voltage.

2-13. The voltage between two conductors of a transmission line is 765 kilovolts rms. What is the crest (maximum) value of the voltage? Calculate the value of this voltage
   a. averaged over a positive half-cycle.
   b. averaged over a complete cycle.

2-14. Two sine-wave voltages are added together. One voltage has an rms value of 75,000 volts, the other 50,000 volts. What will be the value of their sum if the first voltage leads the second by
   a. 0°?
   b. 60°?
   c. 90°?
   d. 180°?
   e. 270°?

2-15. A resistor of 6 ohms has applied across it a voltage of 500 volts. Calculate the current through the resistor if the frequency is
   a. 60 hertz.
   b. 60,000 hertz.

2-16. An inductor of 0.6 henry has 500 volts applied across it. Determine the current if the frequency is
   a. 60 hertz.
   b. 60,000 hertz.

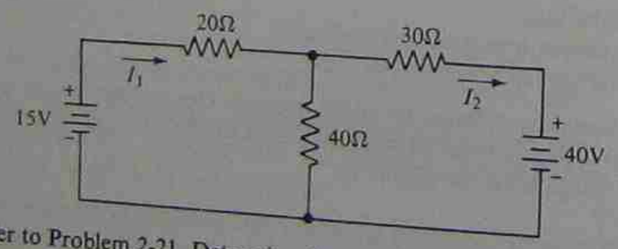
2-17. A capacitor of 6×10^{-6} farad has 500 volts applied across it. Determine the current if the frequency is
   a. 60 hertz.
   b. 60,000 hertz.

2-18. A 6-ohm resistor and an 8-ohm inductive reactor carry a 60-hertz current of 550 amperes. What is the total voltage across the series combination? Draw a phasor diagram showing the current, the voltage across each part, and the total voltage.

2-19. A 60-ohm resistor, a 50-ohm capacitive reactor, and a 30-ohm inductive reactor are connected in series. The series combination is connected to a 480-volt 60-hertz supply. Calculate
   a. the total series impedance.
   b. the value of the current.
   c. the voltage across each unit.
   d. the power dissipated in each unit.
   e. the total power.
   f. the power factor.
   g. Draw a phasor diagram showing the current, the voltage across each unit, and the total voltage.

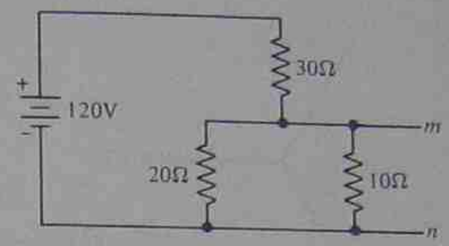
2-20. A resistor of 12 ohms and an inductive reactor of 16 ohms are connected across a 480-volt supply. Determine the power, the apparent power, and the reactive power supplied to the series combination.

2-21. Given the circuit shown, using Kirchhoff's voltage law, write the equations for the voltages around each mesh. From these equations, solve for I_1 and I_2.



2-22. Refer to Problem 2-21. Determine the current I_1 and I_2 using the method of superposition.

2-23. For the circuit shown, determine the Thévenin equivalent circuit applying to the terminals *mn*.

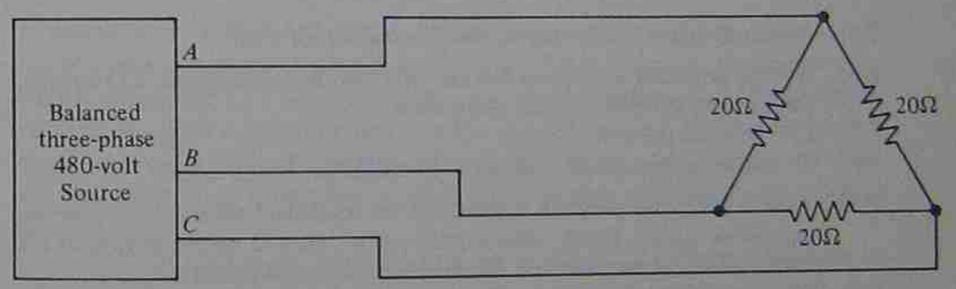


2-24. Explain how you could determine experimentally the Thévenin equivalent of the convenience outlet in your study room.

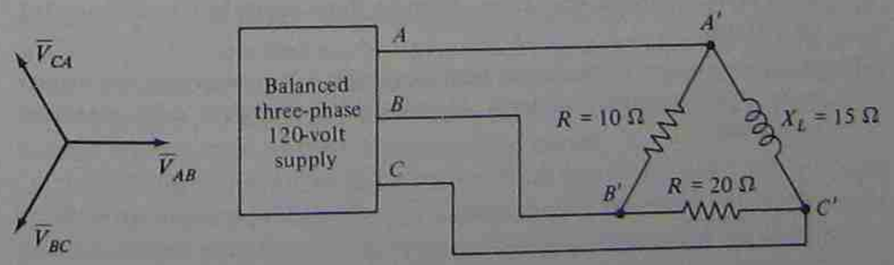
2-25. Three resistors of 6, 9, and 10 ohms are connected in delta. Find their equivalent wye connection.

2-26. Three resistors of 10, 16, and 25 ohms are connected in wye. Find their equivalent delta connection.

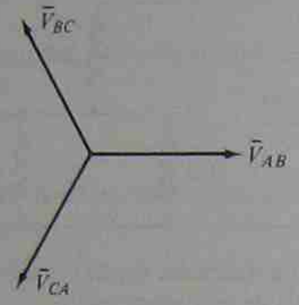
2-27. A group of three resistors are supplied by a balanced three-phase source as shown. Determine
   a. the current in each resistor.
   b. the current in each line conductor.
   c. the total power supplied to the load.



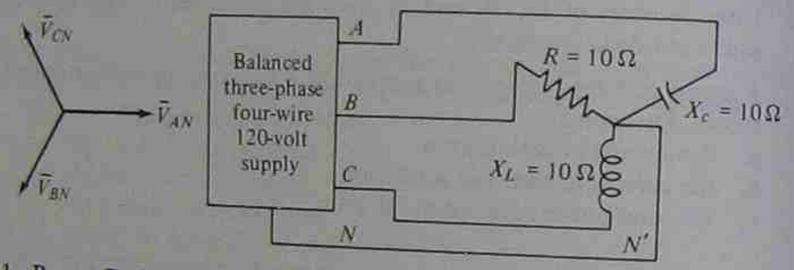
2-28. Solve for the current in each branch of the load (magnitude and phase angle). Determine the current in line AA'.



2-29. Repeat Problem 2-28 but assume that the phase sequence of the source is reversed, as shown in the accompanying phasor diagram.



2-30. Solve for the current in each branch of the load. Determine the current in line NN'.



2-31. Repeat Problem 2-30 assuming the phase sequence CBA.

2-32. A large generator is rated as follows: 300,000 kilovolt-amperes, 22 kilovolts, three phase, 0.8 power factor. Determine
a. the rated full-load current.
b. the maximum power output of the machine.

2-33. Write a computer program to calculate the equivalent resistance of a series-parallel dc circuit. Input: one resistance at a time and its connection to the partial circuit already entered. Output: the equivalent resistance.

2-34. Repeat Problem 2-33 for the equivalent impedance of an ac circuit.

2-35. Write a computer program that performs a delta-wye transformation. Input: three delta-connected resistances. Output: three equivalent wye-connected resistances.

2-36. Write a computer program that performs a wye-delta transformation. Input: three wye-connected resistances. Output: three equivalent delta-connected resistances.

chapter 3

The Basic Power Circuit

3-1. THE BASIC CIRCUIT AND SOME APPLICATIONS

A simple circuit that has many applications in analyzing the behavior of electric power systems is shown in Fig. 3-1. This is a simple, single-phase ac circuit consisting of a source voltage, $\bar{V}_s$; an impedance, Z; and a receiver voltage, $\bar{V}_r$. This simple circuit is worthy of note because it is the equivalent circuit representation of a number of different devices and serves as the basis for the analysis of a number of different problems associated with electric power supply.

This circuit may be used in studying problems of voltage regulation in which the supply voltage, $\bar{V}_s$, is held constant, the load current is varied, and the problem is to study the variations in the receiver voltage, $\bar{V}_r$, that will result. A somewhat similar problem would be to specify that the receiver voltage $\bar{V}_r$ is to be held constant while the load current varies, with the sending voltage, $\bar{V}_s$, specified as the unknown. In both problems it may be demonstrated that the power factor of the load will be of great significance. Losses in the power circuit and hence transmission efficiency may be calculated by reference to the resistance of the circuit.

With the behavior of this simple system clearly in mind, it is possible to develop important relations pertaining to the maximum power that may be transmitted over the circuit, the mechanical displacement between rotors

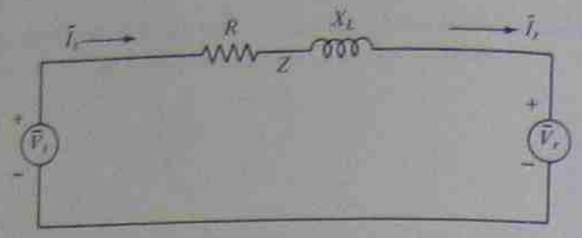


FIG. 3-1. The basic power circuit.

of synchronous machines at the two ends of the circuit, and the magnitude of fault currents which may result when short circuits develop on the system.

3-2. SYSTEMS TO WHICH THE BASIC CIRCUIT APPLIES

The diagram of Fig. 3-1 presents the circuit model of a number of important systems in the electric power field. It will be seen that the devices to which this circuit may be applied are quite diverse in nature. The values of R and X that must be used in a specific problem will be discussed in Chapter 4.

a. Extension Cord. Although an ordinary extension cord is seldom regarded as a device on which electric-circuit calculations need to be made, its equivalent circuit will be found to be that shown in Fig. 3-1. The voltage $\bar{V}_s$ is the source voltage at the terminals of the convenience outlet into which the cord is attached. The voltage $\bar{V}_r$ is the voltage at the load end of the extension cord. The resistance R is the resistance of the two conductors making up the extension cord, while the inductive reactance X_L is that which results from the magnetic field linking between the two conductors of the cord when current flows to the load.

b. Power Lines. The behavior of transmission lines and distribution circuits is frequently analyzed by the short-line method represented in the circuit of Fig. 3-1. Although most transmission lines and distribution lines are three-phase circuits, they may be analyzed on a single-phase basis, which justifies the use of this simple circuit. Here $\bar{V}_s$ is the voltage at the sending end of the line and $\bar{V}_r$ is the voltage at the receiving, or load, end of the line. The justification for using a single-phase model for solving a three-phase circuit problem will be discussed in more detail later in this chapter.

c. AC Generator. As was described in Chapter 2, the equivalent circuit of an ac generator is that shown in Fig. 2-48. This is seen to be the same circuit as that shown in Fig. 3-1, in which $\bar{V}_s$ has replaced $\bar{V}_g$ and $\bar{V}_r$ has replaced the voltage at the terminals PQ.

d. Synchronous Motor. The equivalent circuit of the synchronous motor is a modification of the basic circuit Fig. 3-1, in which $\bar{V}_s$ is now the voltage at the supply terminals and $\bar{V}_r$ has become $\bar{V}_g$, the voltage generated within the machine.

e. Transformer. The circuit model of the transformer was discussed briefly in Chapter 2 and presented in Fig. 2-49a. If the core loss and magnetizing current branches R_C and X_m are neglected, the circuit of Fig. 2-49b results. This circuit is similar to the basic circuit (Fig. 3-1) except for the perfect transformer at the output terminals. If Fig. 3-1 is used for a study of transformer behavior, the secondary voltage becomes $\bar{V}_r(N_2/N_1)$ and the secondary current becomes $\bar{I}(N_1/N_2)$.

When a transformer is represented by *per unit quantities* (to be discussed in Chapter 4), the circuit representation of Fig. 3-1 may be used directly.

f. Induction Motor. The equivalent circuit of an induction motor is approximated by the basic circuit of Fig. 3-1, in which the impedance is the blocked-rotor impedance of the motor and V_r is the generated voltage directly available for energy conversion.

g. Series Combinations of Several Devices. In actual power systems it is very common to find that several of the components previously discussed are connected in series or in parallel combination. A series arrangement of an ac generator, an overhead power circuit, and a synchronous motor are shown in Fig. 3-2. As the impedances representing them are in simple series combination, they may be added to form a single impedance extending from $\bar{V}_g$, the internal generated voltage of the alternator, to $\bar{V}_r$, the internal generated voltage of the motor.

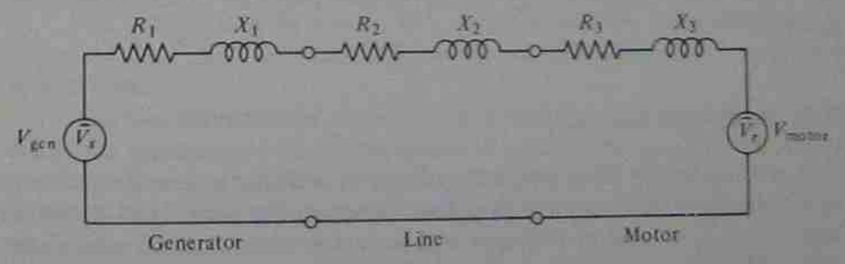


FIG. 3-2. Three basic power circuits in series.

h. Series–Parallel Combinations. The parallel combination of several devices, each represented by a simple impedance, may in turn be represented by a single equivalent impedance. Hence parallel combinations or series-parallel combinations of the circuit models of devices just discussed may be reduced to a simple circuit, as represented by Fig. 3-1.

i. Thévenin Equivalent of a Circuit. A complicated network such as that shown in Fig. 2-37a may have a load connected across two of its terminals such as m and n. For a study of the behavior of the load, the Thévenin equivalent of this system (Fig. 2-37d) may be used. This is another version of the basic circuit (Fig. 3-1).

3-3. EQUATIONS OF THE BASIC POWER CIRCUIT

The performance of the basic power circuit will be analyzed by phasor equations, by phasor diagrams, and by transmission diagrams. An interpretation of these diagrams will be further advanced in a later chapter. It may be noted from Fig. 3-1 that $\bar{I}_r$ and $\bar{I}_s$ are identical. For this reason there is no point in making a distinction between the two, and they will therefore be referred to simply as $\bar{I}$.

Writing Kirchhoff's voltage equation around the basic circuit (Fig. 3-1) there results

$$\bar{V}_s - \bar{I}Z - \bar{V}_r = 0$$

This equation may be solved for $\bar{V}_s$:

$$\bar{V}_s = \bar{V}_r + \bar{I}Z \tag{3-1}$$

It may also be solved for $\bar{V}_r$:

$$\bar{V}_r = \bar{V}_s - \bar{I}Z \tag{3-2}$$

Equations (3-1) and (3-2) may be regarded as the performance equations of the basic power circuit. They will be further analyzed in subsequent discussions.

3-4. PHASOR DIAGRAMS

The analysis of the basic circuit may begin by defining load-end conditions as $\bar{V}_r$ and $\bar{I}$, as represented in the phasor diagram Fig. 3-3a. Here it may be noted that $\bar{V}_r$ is used as reference and so is drawn horizontally and to the right. The current $\bar{I}$ is shown *lagging* the receiver voltage by the angle ϕ_r, implying that the load is a combination of resistance and inductive reactance. The power factor of the load is equal to the cosine of ϕ_r.

In Fig. 3-3b all terms of Eq. (3-1) are displayed. The $\bar{I}Z$ drop is shown leading the current $\bar{I}$ by the angle β, where β is the angle whose tangent is X/R, sometimes referred to as the angle of the line. The $\bar{I}Z$ drop is then added by phasor addition to $\bar{V}_r$ to produce $\bar{V}_s$. The angle ϕ_s is the angle between

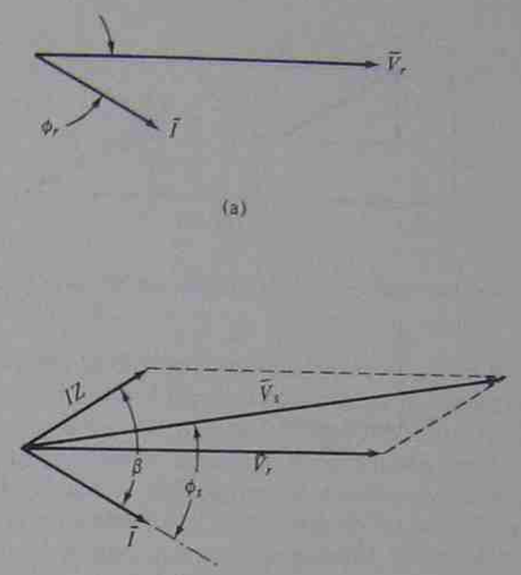


FIG. 3-3. Phasor diagram of the basic power circuit. (a) Receiver voltage and current. (b) The $\bar{I}Z$ drop added to receiver voltage gives sending-end voltage.

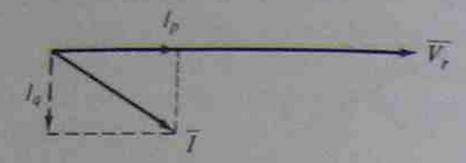
the sending-end voltage and the current. The power factor at the source terminals is given by cosine ϕ_s. Obviously the magnitude of the $\bar{I}Z$ drop is proportional to the magnitude of the current. It is also proportional to the magnitude of the line impedance.

The current may be divided into two components, one component I_p in phase with $\bar{V}_r$ and the other component I_q at right angles to $\bar{V}_r$, as shown in Fig. 3-4a.

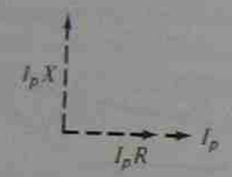
The line impedance is also made up of two components, the resistance R and the reactance X. The contribution to the $\bar{I}Z$ drop produced by the in-phase component of the current I_p flowing through the impedance is shown in Fig. 3-4b. The resistance drop is in phase with I_p and the inductive reactance drop leads I_p by 90°.

The contribution to the $\bar{I}Z$ drop occasioned by the quadrature component of current I_q is shown in Fig. 3-4c. The IR drop is in phase with this component of current and the IX drop leads it by 90°.

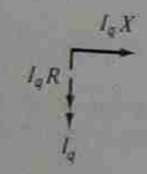
The influence of the four components of the $\bar{I}Z$ drop taken collectively is shown in Fig. 3-4d. Here it may be noted that the two components I_pR and I_qX add directly in line with reference and so contribute substantially toward an increase of the magnitude of $\bar{V}_s$. The component I_pX adds at right angles



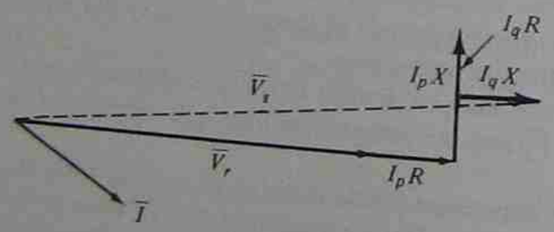
(a)



(b)



(c)



(d)

FIG. 3-4. Detailed phasor diagram of Eq. (3-1). Receiver current lagging receiver voltage. (a) Current divided into components I_p and I_q. (b) The I_pR and I_pX drops. (c) The I_qR and I_qX drops. (d) The total diagram showing V_s.

to $\bar{V}_r$ and the component I_qR subtracts at 90° from $\bar{V}_r$. These two components therefore tend to cancel each other. Since their resultant is at right angles to $\bar{V}_r$, it adds but little in increasing the magnitude of $\bar{V}_s$.

Figure 3-5 represents a condition similar to that just described except

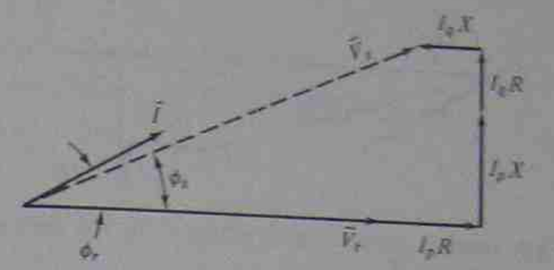


FIG. 3-5. Detailed phasor diagram of Eq. (3-1). Receiver current leading receiver voltage.

that here the current to the load *leads* the receiver voltage by the angle ϕ_r. This situation would apply if the load consisted of resistance and capacitive reactance. The diagram shows the four components of the $\bar{I}Z$ drop drawn in proper relation to the receiver voltage. It may be noted that I_pX and I_qR add at right angles to $\bar{V}_r$ and so make a limited contribution to the magnitude of $\bar{V}_s$. The term I_pR adds directly to $\bar{V}_r$, in contrast the term I_qX subtracts from it. Under these circumstances it is quite possible to have the magnitude of $\bar{V}_s$ smaller than the magnitude of $\bar{V}_r$.

Turning to Eq. (3-2) it may be seen that the receiver voltage may be considered as the difference between the sending-end voltage and the $\bar{I}Z$ drop. When drawing a phasor diagram representing this equation, it is convenient to use $\bar{V}_s$ as reference and then to subtract the $\bar{I}Z$ drop from it, as shown in Fig. 3-6. In this particular diagram $\bar{I}$ is shown *lagging* $\bar{V}_s$. By appropriate changes, a similar diagram could be drawn in which $\bar{I}$ leads $\bar{V}_s$.

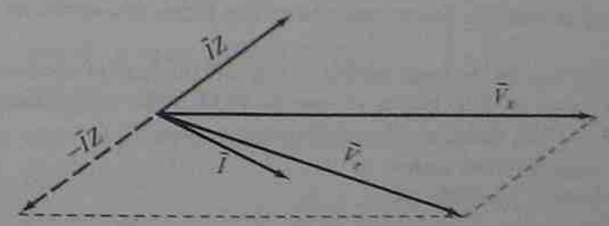


FIG. 3-6. Phasor diagram of Eq. (3-2).

Figure 3-7 shows a diagram similar to that of Fig. 3-6 except that the four components contributing to the $\bar{I}Z$ drop are clearly displayed. For a lagging power factor, $\bar{V}_r$ is always smaller in magnitude than $\bar{V}_s$.

Figure 3-8 is a phasor diagram of Eq. (3-2) for the condition in which the current *leads* the sending-end voltage. The contributions of the four components of the $\bar{I}Z$ drop are shown in the diagram. Note that with a leading load and an inductive reactance in the line, it is possible for the receiver voltage to be greater in magnitude than the sending-end voltage.

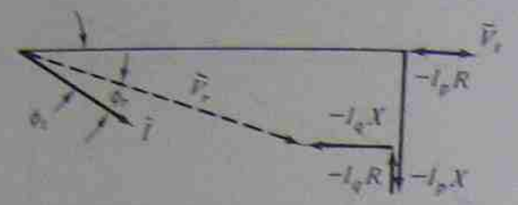


FIG. 3-7. Detailed phasor diagram of Eq. (3-2). The current I lags sending-end voltage $\bar{V}_s$.

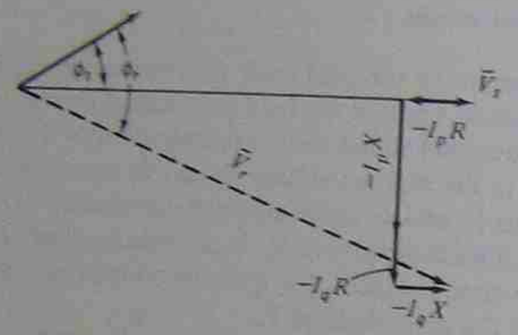


FIG. 3-8. Detailed phasor diagram of Eq. (3-2). The current $\bar{I}$ leads sending-end voltage $\bar{V}_s$.

Figures 3-3 to 3-8 were all drawn assuming that the impedance of the basic circuit (Fig. 3-1) was a resistance in series with an inductive reactance. Similar diagrams could be drawn for the situation in which the impedance is a resistance in series with a capacitive reactance. Capacitive impedances are seldom found in electric power circuits of the types discussed in Section 3-2.

EXAMPLE 3-1. In the basic circuit of Fig. 3-1 the load consumes 1500 W at a power factor of 0.80 and a voltage of 460 V. The transmission impedance $Z = 2 + j5\ \Omega$. Calculate the sending-end voltage V_s for:

a. a lagging power factor.
b. a leading power factor.

Solution:

a. $\arccos 0.80 = 36.9°$

$$I = \frac{1500}{460 \times 0.8} = 4.08 \text{ A}$$

$$\bar{V}_r = 460 \underline{/0°} \text{ V}$$

$$\bar{I} = 4.08 \underline{/-36.9°} = 3.26 - j2.45 \text{ A}$$

$$I_p = 3.26 \qquad I_q = -2.45$$

$$\bar{V}_s = \bar{V}_r + \bar{I}Z$$
$$= 460 \underline{/0°} + (4.08 \underline{/-36.9°})(2 + j5)$$
$$= 460 \underline{/0°} + (4.08 \underline{/-36.9°})(5.39 \underline{/68.2°})$$
$$= 460 \underline{/0°} + 22.0 \underline{/31.3°}$$
$$= 460 + 18.8 + j11.4$$
$$= 479 + j11.4$$
$$= 479 \underline{/1.4°} \text{ V}$$

or,

$$\bar{V}_s = 460 + (3.26 - j2.45)(2 + j5)$$
$$= (460 + 6.52 + 12.3) + j(-4.9 + 16.3)$$

$I_pR = 6.52$ $I_qX = 12.3$ direct parts of $\bar{I}Z$

$I_qR = -4.9$ $I_pX = 16.3$ quadrature parts of $\bar{I}Z$

$$\bar{V}_s = 479 + j11.4$$
$$= 479 \underline{/1.4°}$$

Note how the quadrature parts of $\bar{I}Z$ contribute insignificantly to the magnitude V_s.

b. $\bar{I} = 4.08 \underline{/36.9°} = 3.26 + j2.45$

$$I_p = 3.26 \qquad I_q = 2.45$$

$$V_s = 460 \underline{/0°} + (4.08 \underline{/36.9°})(5.39 \underline{/68.2°})$$
$$= 460 \underline{/0°} + 22.0 \underline{/105.1°}$$
$$= 460 + (-5.73 + j21.2)$$
$$= 454 + j21.2$$
$$= 455 \underline{/2.7°} \text{ V}$$

or

$$\bar{V}_s = 460 + (3.26 + j2.45)(2 + j5)$$
$$= (460 + 6.52 - 12.3) + j(4.9 + 16.3)$$

$I_pR = 6.52$ $I_qX = -12.3$ direct parts of $\bar{I}Z$

$I_qR = 4.9$ $I_pX = 16.3$ quadrature parts of $\bar{I}Z$

$$V_r = 454 + j21.2$$
$$= 455 \angle 2.7^\circ \text{ V}$$

Here, too, the quadrature parts of $\bar{I}Z$ contribute insignificantly to the magnitude V_r. Observe also that $V_s < V_r$.

It sometimes occurs that the voltage $\bar{V}_r$ is given at the sending end, while the power P_r and power factor F_r are known at the receiving end. The determination of the receiving-end voltage $\bar{V}_r$ may then be achieved with the aid of a phasor diagram, taking into account certain geometric relationships. In an actual power network, this problem is much more complex due to the multiplicity of sending-end and receiving-end terminals. The solution in that case can be obtained with the help of a digital computer and comes under the name of load-flow solution. The procedure for the basic circuit of Fig. 3-1 will now be illustrated by means of an example.

EXAMPLE 3-2. In the basic circuit of Fig. 3-1 the load consumes 4000 W at a power factor of 0.8 lagging. The sending-end voltage is 600 V and the impedance $Z = 1 + j4\ \Omega$. Determine the load voltage.

Solution. Taking $\bar{V}_r$ as reference,

$$\bar{V}_r = V_r \angle \theta$$
$$\bar{V}_s = 600 \angle 0^\circ$$
$$Z = 1 + j4 = 4.12 \angle 76^\circ$$
$$\hat{I} = \frac{\bar{V}_s - \bar{V}_r}{Z} = \frac{600 \angle 0^\circ - V_r \angle \theta}{4.12 \angle 76^\circ}$$

$\arccos 0.8 = 36.9^\circ$

$$P_r = \frac{4000}{0.8} = 5000 \text{ VA}$$
$$S_r = 5000 \angle 36.9^\circ$$
$$= \bar{V}_r \hat{I}^*$$
$$= (V_r \angle \theta)\left(\frac{600 \angle 0^\circ - V_r \angle -\theta}{4.12 \angle -76^\circ}\right)$$

Hence,

$$\frac{600 \angle 0^\circ - V_r \angle -\theta}{4.12 \angle -76^\circ} = \frac{5000 \angle 36.9^\circ}{V_r \angle \theta}$$

Multiplying through by $4.12 \angle -76^\circ$,

$$600 \angle 0^\circ - V_r \angle -\theta = \frac{20{,}600 \angle -\theta - 39.1^\circ}{V_r}$$

or

$$V_r \angle -\theta = 600 \angle 0^\circ - \frac{20{,}600}{V_r} \angle -\theta - 39.1^\circ$$

Taking conjugates,

$$V_r \angle \theta = 600 \angle 0^\circ - \frac{20{,}600}{V_r} \angle \theta + 39.1^\circ$$

This equation is solved iteratively in the following manner: using an estimate of $\bar{V}_r$, the right-hand side of the equation produces a new estimate of $\bar{V}_r$. The latter is used in its turn in the equation to obtain another $\bar{V}_r$, and so on. The process is repeated until $\bar{V}_r$ remains practically constant. Taking $\bar{V}_r = 590 \angle 0^\circ$ as a starting estimate,

$$V_r \angle \theta = 600 - \frac{20{,}600}{590} \angle 0 + 39.1^\circ = 573.3 \angle -2.2^\circ$$

Repeating the procedure,

$$V_r \angle \theta = 600 - \frac{20{,}600}{573.3} \angle -2.2^\circ + 39.1^\circ = 571.7 \angle -2.2^\circ$$
$$V_r \angle \theta = 600 - \frac{20{,}600}{571.7} \angle -2.2^\circ + 39.1^\circ = 571.6 \angle -2.2^\circ$$

This, then, is the receiving-end voltage.

3-5. TRANSMISSION DIAGRAMS

The performance of the basic power circuit for *any* condition of receiver current loading may be represented by an extension of the phasor diagrams just discussed. A chart known as a *transmission diagram* permits the graphical determination of many of the responses of the basic circuit. The transmission diagram is described by reference to a basic circuit to which particular numerical values have been assigned.

Consider the circuit shown in Fig. 3-9, in which the impedance, Z, is $5 \angle 60^\circ\ \Omega$ and the receiver voltage V_r is 100 volts. Referring to Fig. 3-10, let $\bar{V}_r$, drawn to scale, be the reference phasor. Assume that the current $\bar{I}$ is in phase with $\bar{V}_r$ as shown, indicating that the load power factor is unity. On the assumption that the load current is 4 amperes, the $\bar{I}Z$ drop is properly represented by the line segment OA, which is 20 units long and lies along the line OM, which is located at a leading angle of 60° with respect to the current.

If the value of the current is now assumed to be 8 amperes and in phase with $\bar{V}_r$, the $\bar{I}Z$ drop will be properly represented by the phasor OB (40 units

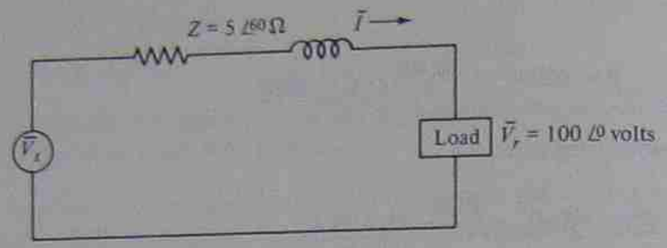


FIG. 3-9. The basic power circuit with the value of impedance Z and of receiver voltage V_r specified.

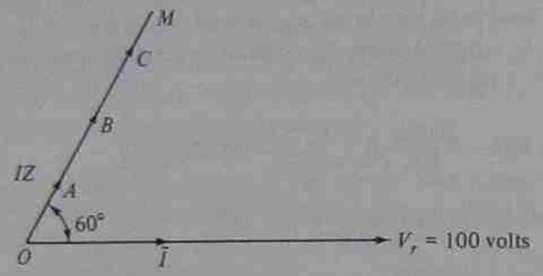


FIG. 3-10. Phasor diagram applying to Fig. 3-9 showing $\bar{V}_r = 100/\underline{0°}$ and the $\bar{I}Z$ drops for $\bar{I} = 4/\underline{0°}$, $\bar{I} = 8/\underline{0°}$, and $\bar{I} = 12/\underline{0°}$. (Scale: 1 cm = 20 volts.)

long), as shown in Fig. 3-10. Similarly a 12 ampere current would give rise to an $\bar{I}Z$ drop 60 units in length, as represented by the phasor OC.

According to Eq. (3-1), $\bar{V}_s$ is determined by the phasor addition of $\bar{V}_r$ and the $\bar{I}Z$ drop. Consequently, the line OM may be shifted to the right until it adds vectorially to the phasor $\bar{V}_r$, as shown in Fig. 3-11. For convenience we can label the points A, B, and C, in terms of the assumed currents 4, 8, and 12, as shown in Fig. 3-11.

Now a line drawn from O to A in Fig. 3-11 properly represents in magnitude and phase position the voltage $\bar{V}_s$ under a current loading of $\bar{I} = 4 \underline{/0°}$. Similarly, a phasor drawn from O to the point marked 12 represents the

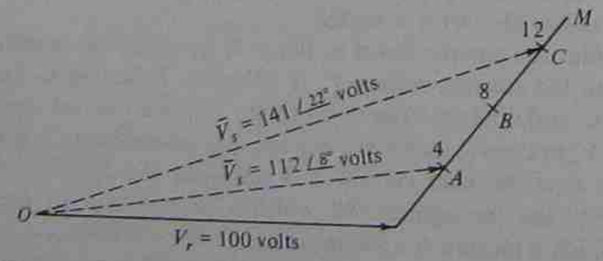


FIG. 3-11. The phasor diagram of Fig. 3-10 with the $\bar{I}Z$ drops added to $\bar{V}_r$ to give $\bar{V}_s$.

correct value of $\bar{V}_r$ for unity-power-factor loading of 12 amperes. We have constructed our transmission diagram for this system, although we are restricted to unity power factor at the load end of the line.

Let us now consider a zero-power-factor inductive load to be placed across the receiver terminal. The current $\bar{I}$ will not lag 90° behind the receiver voltage, $\bar{V}_r$ (Fig. 3-12). Again the $\bar{I}Z$ drop will be 60° ahead of the current and

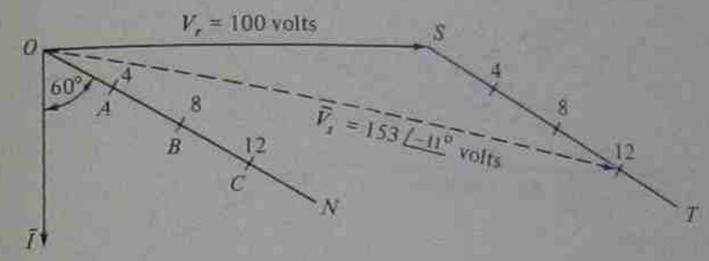


FIG. 3-12. Phasor diagram applying to Fig. 3-9 showing $\bar{V}_r = 100/\underline{0°}$ and the $\bar{I}Z$ drops for $\bar{I} = 4/\underline{-90°}$, $\bar{I} = 8/\underline{-90°}$, and $\bar{I} = 12/\underline{-90°}$.

so will lie along the line ON as shown. Line ON may be scaled off to give points A, B, and C, again corresponding to load currents of 4, 8, and 12 amperes. As in the previous example, line ON may be shifted to the right so that it takes up the position ST from the end of the phasor $\bar{V}_r$. Now a line drawn from O to the point 12 gives us the correct phasor value of $\bar{V}_s$ for the loading corresponding to a current of 12 amperes at zero power factor lag.

A similar diagram is shown in Fig. 3-13, except here the load current is assumed to be at 90° ahead of receiver voltage, $\bar{V}_r$, indicating a pure capacitive load at the receiver end. The $\bar{I}Z$ drop scaled as before is drawn 60° ahead of the current phasor.

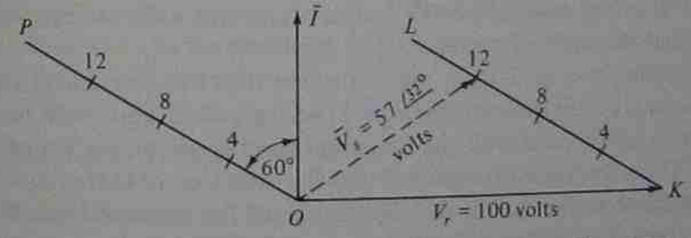


FIG. 3-13. Phasor diagram applying to Fig. 3-9 showing $\bar{V}_r = 100/\underline{0°}$ and the $\bar{I}Z$ drops for $\bar{I} = 4/\underline{90°}$, $\bar{I} = 8/\underline{90°}$, and $\bar{I} = 12/\underline{90°}$.

As before, the line OP may be transferred to the right so that it forms a phasor addition with $\bar{V}_r$ as shown by the line KL. Now a line drawn from O to the point marked 12 properly represents the phasor value of $\bar{V}_s$ with a 12 amperes, zero-power-factor leading load at the receiver end.

Obviously Figs. 3-11, 3-12, and 3-13 may be combined in a single diagram, as shown in Fig. 3-14. Now we can determine the phasor value of $\bar{V}_s$ for *any* condition of receiver loading corresponding to power factor 1.0, power factor 0 lag, and power factor 0 lead.

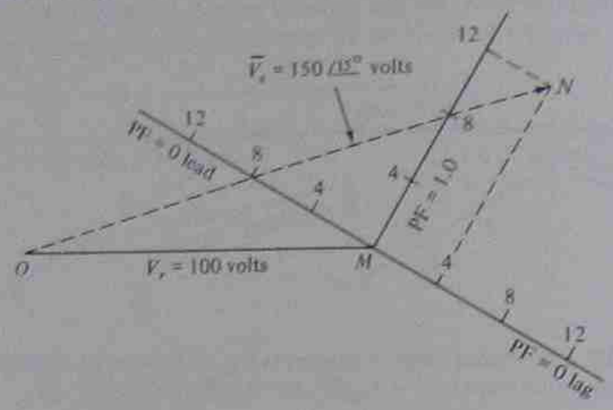


FIG. 3-14. Phasor diagram applying to Fig. 3-9 for $\bar{V}_r = 100/\underline{0°}$ and the $\bar{I}Z$ drops for current of any value.

Next let us suppose that the receiver load consists of two parts, one that draws a current of 12 amperes in phase with receiver voltage and one that draws a current of 4 amperes, zero-power-factor lag. Each of these currents causes its own individual $\bar{I}Z$ drop, each of which can be identified on the diagram of Fig. 3-14. The distance from M to N properly represents this total $\bar{I}Z$ drop. We can now conclude that the phasor ON properly represents the sending-end voltage when the load current is $12 - j4$.

The discussion of the preceding paragraph suggests that we might further revise our diagram by drawing a *grid* in the $\bar{I}Z$ area as shown in Fig. 3-15. On this diagram the line ON properly represents the sending-end voltage $\bar{V}_s$ when the receiver current is $8 + j8$.

Referring to Fig. 3-15, it may be noted that the area which has been divided into a grid is determined in grid *spacing* and in *angle* with respect to reference in accordance with the magnitude and angle of the impedance of the line. Thus, the angle between MP and the extension of OM is equal to the line impedance angle, that is, 60°. The length of the segment from M to the point marked 4 on MP is equal to four times the line impedance magnitude, that is, 20 volts. This segment is scaled as a voltage, but marked as a current. This is true of all the segments shown on the transmission diagram. We should remember that all the vectors being added on the diagram are voltages. For convenience, the diagram may be rotated counterclockwise so as to make MP vertical; this enables the use of regular graph paper in producing a transmission diagram.

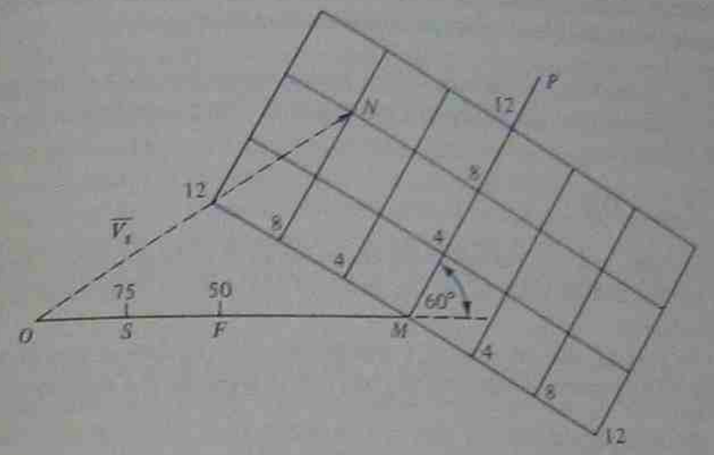


FIG. 3-15. The complete transmission diagram applying to Fig. 3-9 for $\bar{V}_r = 100/\underline{0°}$, $\bar{V}_r = 75/\underline{0°}$, and $\bar{V}_r = 50/\underline{0°}$.

The length OM is determined by the magnitude of the receiver voltage $\bar{V}_r$. Obviously this length would be only half as long if the receiver voltage had been 50 volts instead of 100 volts. We can therefore designate a point halfway between O and M (labeled on the diagram as F) and use this as the origin for problems in which the receiver voltage is assumed to be 50 volts. Another point, S, could be used as the origin of the diagram for problems in which the receiver voltage is assumed to be 75 volts. Other points along the line MO and its extension could be appropriately marked to be used as the origin of the diagram for problems involving any specified receiver voltage. Many other modifications of this diagram may be made.

It is left to the reader to work out the transmission diagram corresponding to Eq. (3-2). The usefulness of these diagrams will be apparent to the reader who works the problems given at the end of the chapter.

3-6. LOSSES AND THERMAL LIMITS

In the basic power circuit (Fig. 3-1) it may be noted that one of the components of the impedance is the circuit resistance. Resistance appears in all electric circuits (except those operated at extremely low temperatures) and is subject to limited control by the designer. The resistance of an electric conductor may be minimized by the use of low-resistivity materials, such as copper and aluminum, and by the selection of conductors of large cross-sectional area. The cross sections which may be used are frequently dictated by cost, weight, and volume considerations. In the most careful designs, the

resistance of the conductors is of significance and its effect on equipment behavior must be given adequate consideration.

a. Losses. Reference to the basic circuit (Fig. 3-1) shows that the current I flows through the circuit resistance R. The power loss in the circuit itself is therefore

$$P_{lost} = I^2R \tag{2-8}$$

In a machine or a line already built, the value of R is determined. The losses then are dependent entirely on the value of the current that flows through the resistance.

In general, the purpose of a power circuit is to deliver energy to the receiver. The power delivered to the receiver is given by the expression

$$P_r = V_r I \cos \phi_r \tag{3-3}$$

where ϕ_r is the angle between V_r and I. From this expression the current is seen to be

$$I = \frac{P_r}{V_r \cos \phi_r} \tag{3-4}$$

and

$$P_{lost} = \left(\frac{P_r}{V_r \cos \phi_r}\right)^2 R \tag{3-5}$$

Usually the voltage V_r is dicated by the rating of the load equipment and so must be held substantially constant. In some instances there is opportunity for the control of the power factor of the load. Obviously, the current I has its smallest possible value when the power factor is unity, a situation which exists when receiver voltage and current are in phase and the power factor angle ϕ_r is zero.

Many electrical machines (such as induction motors) contain iron which must be magnetized for the machines to function. The magnetizing currents, which lag the receiver voltage by 90°, are almost constant regardless of motor loading. The in-phase components of currents taken by motors increase as the motors are loaded. Hence the power factor of induction motor loads is less than unity and always lagging. It is possible to compensate for the quadrature lagging current by installing capacitors in parallel with the motor load. If the quadrature leading current of the capacitor is exactly equal to the quadrature lagging current of the motors, the power factor can be made equal to unity. At this unity power factor, the magnitude of the line current I is a minimum and losses are at a minimum.

Synchronous motors provide a means of regulating load power factor. By control of the magnitude of the field current supplied to the synchronous motor, the machine may draw a current having either a leading or a lagging component. If the synchronous motor is the only load on the end of a power circuit, the adjustment of the field current to produce unity power factor will minimize the current and consequently the losses in the power circuit. If the synchronous motor is in parallel with induction motors, which are drawing a lagging power factor current, the synchronous motor may be operated with excess field current thus drawing a leading current from the line, which, in combination with the other lagging motor currents, may result in unity power factor.

b. Thermal Effects. The I^2R losses represent electrical energy converted into heat within the conductor whose resistance is being considered. This liberated heat tends to increase the temperature of the conductor; the temperature increase depending on the rate at which heat is liberated and the ability of the surrounding environment to transfer this heat away. In some cases, as in generators or transformers, forced circulation of gas or oil over the conductors is necessary to hold temperatures to reasonable values.

In practically all electrical equipment, consideration must be given to the maximum temperature at which the conductors operate. In electrical machines and in power cables, the conductors are separated from each other and from grounded objects by means of solid insulation. The dielectric materials which form the insulation are, in most instances, organic materials that undergo chemical changes when subjected to high temperatures. Under extremely high temperatures, these materials will quickly char and lose their ability to serve as insulators. Insulation failure results in short circuits, and the destruction of the equipment may follow.

Overhead lines, for the most part, are constructed of *bare* conductors suspended on porcelain insulators. On such lines, the temperature of the conductors has no detrimental effect on the insulators. However, most power-line conductors are made of alloys of steel, aluminum, or copper, which are carefully heat-treated to develop maximum mechanical strength. Operation of these conductors at high temperatures may anneal the metal and seriously reduce conductor mechanical strength.

Damage to the solid insulation of machines, such as generators and transformers, and to metals of overhead conductors depends on the temperature reached during operation. The *ambient temperature* (the temperature of the surrounding environment) is of great importance in the operation and rating of electrical equipment. For example, a motor operating in a location where the temperature is −20°F may carry a much higher load without damage to its insulation than could a similar motor operating in a room

where the temperature is 120°F. Electrical insulation must be maintained below a certain temperature limit, regardless of the source of heat to it.

Because electrical machines operate in locations having vastly different ambient temperatures, different types of insulation may be required. The temperature of the surroundings plus the expected temperature rise during operation must be given consideration in specifying the insulation of an electrical machine.

c. **Efficiency.** Ideally, the line part of the basic power circuit (Fig. 3-1) would convey power from the sending end to the receiving end without losing any of it. In reality, the power absorbed by the line resistance R is a loss that is deducted from the sending-end power. Efficiency is an expression of the receiving-end power as a percentage of the sending-end power.

$$\text{Efficiency} = \frac{P_r}{P_s} \times 100 = \frac{P_r}{P_r + P_{\text{loss}}} \times 100$$

Obviously, the efficiency is at the most 100 percent.

3-7. BALANCED THREE-PHASE CIRCUIT ANALYSIS

In the discussion of the basic power circuit (Fig. 3-1) the statement was made that this circuit could be used in the analysis of balanced three-phase circuits. The justification of this statement is developed with reference to Fig. 3-16. A three-phase generator ABC is connected to a balanced three-phase load, abc, by means of a three-conductor transmission line. In each conductor of this line there is a resistance R and an inductive reactance, X_L. The balanced

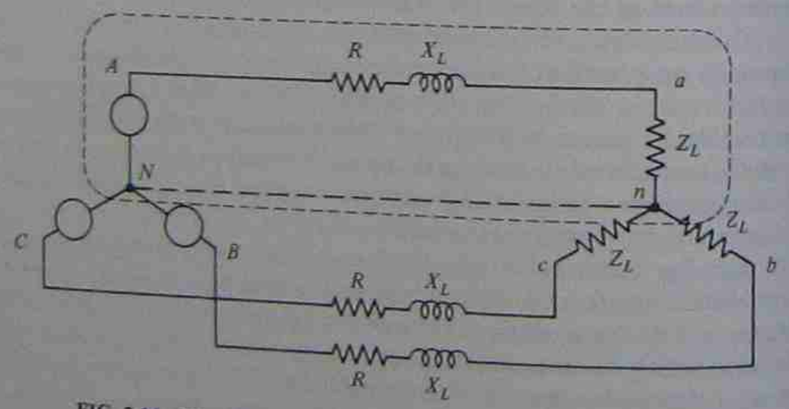


FIG. 3-16. Diagram of a three-phase generator (ABC) connecting through a three-phase line (R and X_L) to a three-phase load (abc).

three-phase load is represented by three identical impedances Z_L, which are here shown as star-connected. A neutral conductor, Nn, is shown connecting the neutral of the generator to the neutral of the load. Since this is a balanced source supplying a balanced load, the three load voltages and the three load currents will appear, when represented in a phasor diagram, as shown in Fig. 3-17. Writing Kirchhoff's current equation about the node n (Fig. 3-16) we find

$$\bar{I}_{Nn} + \bar{I}_{an} + \bar{I}_{bn} + \bar{I}_{cn} = 0$$

or

$$\bar{I}_{nN} = \bar{I}_{an} + \bar{I}_{bn} + \bar{I}_{cn} \tag{3-6}$$

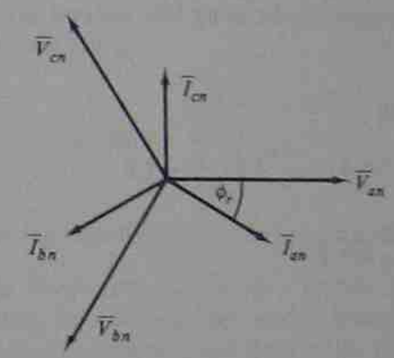


FIG. 3-17. A phasor diagram showing the three line-to-neutral voltages and three line currents of a balanced three-phase system.

The addition of the three currents represented by the right-hand side of this equation yields *zero*. Therefore, there will be no $I_{nN}Z_n$ drop in the neutral conductor and node N will be at the same potential as node n, even if the neutral conductor is removed. As a consequence, the A part of the circuit, enclosed by the dashed line, when redrawn as shown in Fig. 3-18, is

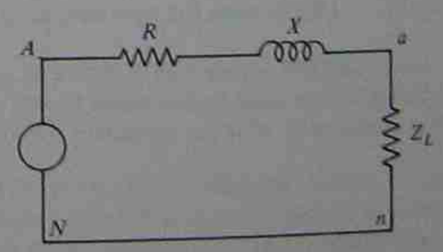


FIG. 3-18. The A-phase of the three-phase system, Fig. 3-16.

the basic power circuit. Hence we may write

$$\bar{V}_{AN} = \bar{V}_{ss} + \bar{I}_{As}Z \tag{3-7}$$

Since the circuit of Fig. 3-16 is a balanced three-phase circuit, any behavior established from an analysis of the A section of the circuit of Fig. 3-18 may be directly applied to either the B section or the C section. It is, of course, recognized that the voltages of the three sections and the currents of the three sections are identical in magnitude but are displaced from each other by one third of a cycle. The power supplied to the load Z_L in Fig. 3-18 is one third of the total three-phase load of Fig. 3-16.

This method of handling a problem involving a balanced three-phase system is sometimes termed the *line-to-neutral method* of solution. The impedance used is the line-to-neutral resistance and reactance (or the resistance and reactance per conductor). In using this method the following relations may be noted

$$V_{LL} = \sqrt{3}\, V_{LN} \tag{3-8}$$

$$P_{3\phi} = 3V_{LN}I_L \cos\phi = \sqrt{3}\, V_{LL}I_L \cos\phi \tag{3-9}$$

$$I_L = \frac{P_{3\phi}}{\sqrt{3}\, V_{LL} \cos\phi} \tag{3-10}$$

$$P_{\text{lost}} = 3I_L^2R \tag{3-11}$$

in which all terms are scalars.

Suppose that the load is made up of three identical impedances Z_Δ connected in delta. The delta load may be replaced by an equivalent wye-connected load made up of three impedances each of value Z_Y (as shown in Section 2-6e), where

$$Z_Y = \tfrac{1}{3}Z_\Delta \tag{3-12}$$

The new wye-connected load may be handled as described above. Equations (3-8), (3-9), (3-10), and (3-11) apply both for wye- and delta-connected loads.

EXAMPLE 3-3. A balanced three-phase load of 3000 kW, power factor 0.8 lag, is supplied at 22,000 V (line to line) over a line having a resistance of 3 Ω and an inductive reactance of 10 Ω per conductor (or line to neutral). Calculate the

a. line current.
b. phase angle.
c. line-to-neutral voltage.
d. impedance volt drop in line.

e. line-to-neutral source voltage.
f. line-to-line source voltage.
g. power lost in all three lines.

Solution. a. $I = \dfrac{P_{3\phi}}{\sqrt{3}\, V_{LL} \cos\phi} = \dfrac{3{,}000{,}000}{\sqrt{3} \times 22{,}000 \times 0.8} = 98.6$ A

b. $\phi = \cos^{-1} 0.8 = 37°$

c. $\bar{V}_{LN} = \dfrac{V_{LL}}{\sqrt{3}} = \dfrac{22{,}000}{\sqrt{3}} = 12{,}700\ \underline{/0°}$ (reference)

d. $\bar{I} = I(\cos\phi - j\sin\phi) = 98.6(0.8 - j.6) = 79 - j59.2$
$Z = 3 + j10$
$\bar{I}Z = (79 - j59.2)(3 + j10) = 829 + j613$

e. $\bar{V}_{s(\text{line to neutral})} = \bar{V}_r + \bar{I}Z$
$= 12{,}700 + 829 + j613$
$= 13{,}530 + j613 = 13{,}530\ \underline{/2.6°}$

f. $V_{s(\text{line to line})} = \sqrt{3}\, V_{s(L-N)} = \sqrt{3} \times \overline{13{,}530}$ (3-7)
$= 23{,}400$ V line to line

g. The total power lost is

$P = 3I_L^2R$
$= 3(98.6)^2 \times 3 = 87{,}500$ W (3-11)

3-8. SINGLE-PHASE EQUIVALENT OF A THREE-PHASE SYSTEM

In Section 3-7 it was shown that a three-phase system made up of a balanced three-phase generator, a balanced line, and a balanced three-phase load could be studied by considering only one third of the system and so analyzing it on a line-to-neutral basis. The behavior of the three-phase system may also be analyzed using the single-phase equivalent circuit shown in Fig. 3-19.

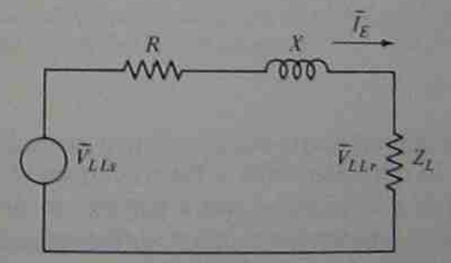


FIG. 3-19. The single-phase equivalent of the three-phase system, Fig. 3-16.

This circuit differs from Fig. 3-18 in that the voltages used at both the sending and receiving ends are line-to-line voltages instead of line-to-neutral voltages, as previously used. The impedance of the load, Z_L, at the receiver end is identical to that previously used, but because of the higher voltage impressed

across it, the power consumed in this load is equal to the total three-phase load assumed in Fig. 3-16. The line impedance is identical to that in one of the three conductors.

In the single-phase equivalent circuit the line current is seen to be

$$I_E = \frac{P_{3\phi}}{V_{LLr}\cos\phi_r} \tag{3-13}$$

In comparison to Eq. (3-10) it may be seen that the current in the single-phase equivalent circuit, I_E, is

$$I_E = \sqrt{3}\, I_L \tag{3-14}$$

The power lost in the equivalent circuit is

$$P_{\text{lost}} = I_E^2 R = 3I_L^2 R \tag{3-15}$$

which is the same as in the actual circuit as given by Eq. (3-11).

From Fig. 3-19 we may write the relation

$$\bar{V}_{LLs} = \bar{V}_{LLr} + \bar{I}_E Z \tag{3-16}$$

If we multiply each term of Eq. (3-7) by the factor $\sqrt{3}$ we obtain

$$\sqrt{3}\,\bar{V}_{AN} = \sqrt{3}\,\bar{V}_{an} + \sqrt{3}\,\bar{I}_{Aa} Z \tag{3-17}$$

It may be noted that (in terms of scalar values)

$$\sqrt{3}\,V_{AN} = V_{LLs}$$
$$\sqrt{3}\,V_{an} = V_{LLr}$$
$$\sqrt{3}\,I_{Aa} = I_E$$

Hence the single-phase equivalent-circuit solution gives the correct value of the losses and the correct scalar value of the sending-end line-to-line voltage.

In summary, it may be stated that a system consisting of a balanced three-phase generator connected to a balanced three-phase load (either star- or delta-connected) through a three-phase line may be analyzed by a single-phase equivalent circuit. The voltages in this single-phase equivalent circuit are equal in magnitude to the corresponding line-to-line voltages of the actual three-phase circuit. The losses in the equivalent single-phase circuit are identical to the losses in the three-phase circuit. The current in the equivalent single-phase circuit has a magnitude equal to $\sqrt{3}$ times that of the line current in the actual three-phase circuit.

EXAMPLE 3-4. Solve Example 3-3 by the single-phase equivalent method.

Solution:

$$P = 3000 \text{ kW}$$

$$\text{power factor} = 0.8 \text{ lag}$$

$$V_r = 22{,}000 \text{ V} \qquad \text{(reference)}$$

$$Z = 3 + j10 = 10.5 \underline{/73.3^\circ}\ \Omega$$

$$I_E = \frac{P_{3\phi}}{V_{LL}\cos\phi} \tag{3-13}$$
$$= \frac{3{,}000{,}000}{22{,}000 \times 0.8}$$

$$\bar{I}_E = 171 \underline{/-37^\circ} \text{ A}$$

$$\bar{V}_{LLS} = \bar{V}_{LLr} + \bar{I}_E Z \tag{3-16}$$
$$= 22{,}000 \underline{/0^\circ} + (171 \underline{/-37^\circ})(10.5 \underline{/73.3^\circ})$$
$$= 22{,}000 \underline{/0^\circ} + 1790 \underline{/36.3^\circ}$$
$$= 22{,}000 + 1440 + j1060$$
$$= 23{,}440 + j1060 = 23{,}450 \underline{/2.6^\circ} \text{ V}$$

The power lost is

$$P = I_E^2 R \tag{3-15}$$
$$= (171)^2 \times 3 = 87{,}500 \text{ W}$$

Note that the calculated sending-end (line-to-line) voltage and the losses agree with the values found in Example 3-3.

3-9. TRANSMISSION-LINE EQUIVALENCE; A BETTER CIRCUIT MODEL

In Section 3-2 it was stated that the basic circuit (Fig. 3-1) was useful as the short-line representation of an electric power circuit. This representation is adequate for most overhead-distribution circuit problems and for many high-voltage transmission-line problems, particularly if the line length is less than 50 miles. It is inadequate, however, for some distribution circuit problems, for many high-voltage transmission-line problems (particularly for those involving circuits greater than 50 miles in length), and for problems involving cable circuits of even shorter length. In many cases where the short-line representation is inadequate, the π-line or T-line representation will give

satisfactory results. For some advanced studies even these representations are inadequate.

The short-line method of solution is sometimes inadequate because it fails to represent the capacitance present in all power circuits. In some problems this capacitance is of little importance; in others it plays an important role. Two conducting bodies separated by a dielectric constitute a capacitor. An overhead transmission line consists of three power conductors supported above the ground, which itself is a conductor. In addition, there may be one or two ground wires. Obviously capacitance exists between every pair of these conducting bodies, giving a capacitance array that may be very complicated. In underground cables, the distance between conducting bodies is very short and the dielectric separating them has a permittivity several times as great as air. The capacitance per mile of underground cables is much greater than the capacitance per mile of overhead lines.

For the present discussion we shall consider only single-phase systems and balanced three-phase systems carrying balanced three-phase loads. For problems of this sort, the multicapacitor system associated with overhead lines and cables may be simplified to a circuit arrangement in which a single capacitor appears between each conductor and neutral. The capacitance, like the line resistance and inductance, is distributed throughout the line length, a portion appearing in every meter of the length. However, it may be shown by mathematical analysis (not included here) that the capacitance, the resistance, and the inductance may be *lumped* to form relatively simple equivalent circuits. One of these lumped-circuit arrangements is known as the π-line representation; the other is known as the T-line representation.

In the π-line representation, the circuit of Fig. 3-16 is modified to become the circuit shown in Fig. 3-20. It may be noted in this figure that a

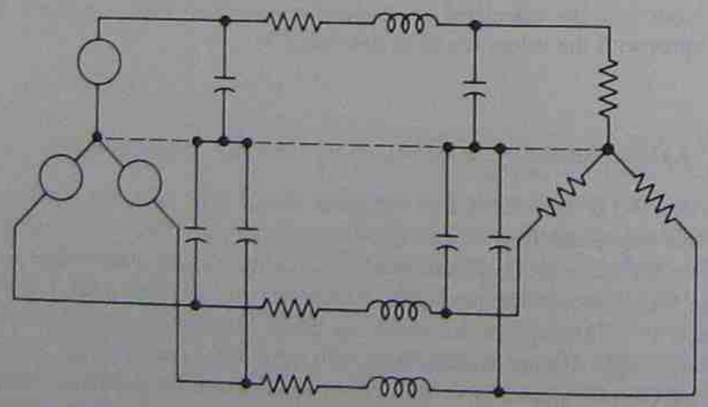


FIG. 3-20. A three-phase system showing the resistance, the inductance, and the capacitance of the transmission line. Pi-line representation.

capacitor is shown between line and neutral on each of the three conductors at both ends of the circuit. The line-to-neutral representation or the single-phase equivalent of this circuit is shown in Fig. 3-21.

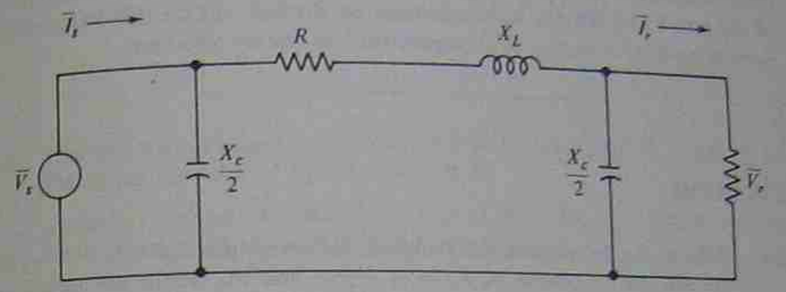


FIG. 3-21. The line-to-neutral (or single-phase equivalent) representation of the three-phase system, Fig. 3-20. R, L, and C are the total circuit resistance, inductance, and capacitance per conductor. The π-line representation.

In the π-line representation (Fig. 3-21) the resistance and inductive reactance are represented exactly as in the short-line method. Here R represents the resistance and X_L the series inductive reactance of a single conductor for the length of the line. The line-to-neutral capacitance for the length of line is determined and half of this value is put at each end of the line. It should be noted in Fig. 3-21 that the sending-end current, I_s, is not the same as the receiver-end current, I_r, and a distinction must be made between them.

The line-to-neutral (or the single-phase equivalent) of a transmission circuit represented by the T-line method is shown in Fig. 3-22. Here the total

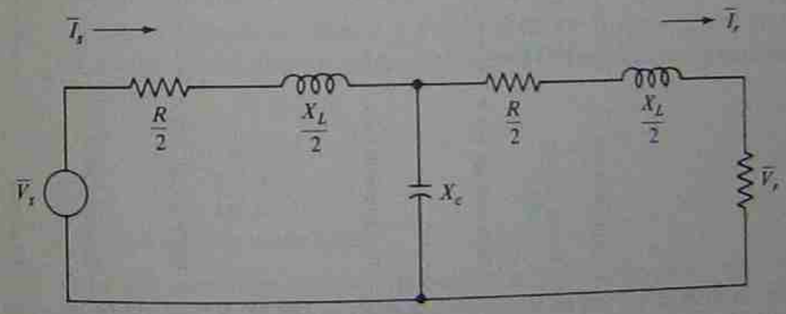


FIG. 3-22. The T-line representation of a transmission system.

resistance and the total inductive reactance of the line have been divided into two parts. The total capacitance of the circuit is connected between line and neutral at the midpoint. Again I_s differs from I_r and must be accordingly designated.

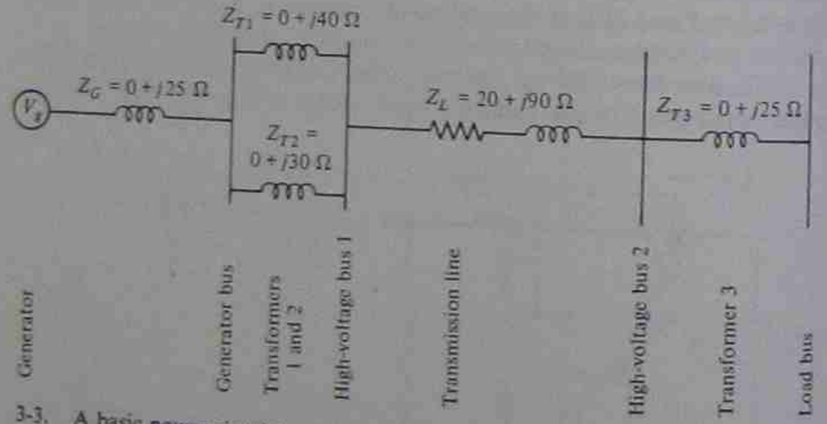
The π and T representations of transmission lines will be discussed in more detail in later chapters.

In some advanced problems it is necessary to recognize that the line resistance, inductance, and capacitance are distributed throughout every meter of the entire line length. Relations may be worked out on this basis which provide an exact solution to transmission-line circuit behavior.

PROBLEMS

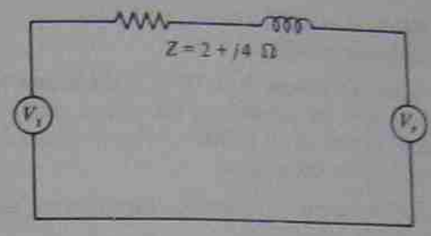
3-1. Refer to Fig. 3-2. Assume that the generator has an impedance $Z_G = 0 + j20$, the line an impedance of $Z_L = 15 + j50$, and the motor an impedance $Z_M = 0 + j40$. Calculate the impedance of the basic circuit which may be considered for analysis.

3-2. A power system is represented by an equivalent diagram as shown. All impedances have been referred to the same voltage level.
   a. Determine the basic circuit considering the generator bus voltage as V_s and the load bus voltage as V_r.
   b. Determine the basic circuit considering the generator internal voltage V_g as V_s and the load bus voltage as V_r.



3-3. A basic power circuit is as shown. Let $\bar{V}_r = 120\ \underline{/0^\circ}$ V. Determine the value of $\bar{V}_s$ when
   a. $\bar{I}_r = 10\ \underline{/0^\circ}$ A.
   b. $\bar{I}_r = 10\ \underline{/-90^\circ}$ A.
   c. $\bar{I}_r = 10\ \underline{/90^\circ}$ A.

   Draw a phasor diagram for each case.



3-4. Consider a basic power circuit in which $Z = 3 + j10\ \Omega$ and $\bar{V}_r = 240\ \underline{/0^\circ}$ V. Determine the value of $\bar{V}_s$ if $\bar{I}_r = 4 - j8$ A.

3-5. Consider the circuit in which $Z = 3 + j8\ \Omega$, $\bar{V}_r = 200\ \underline{/0^\circ}$ V, and $P_r = 1200$ W. Determine the values of $\bar{V}_s$ and P_s when
   a. receiver power factor = 1.0.
   b. receiver power factor = 0.6 lag.
   c. receiver power factor = 0.6 lead.

3-6. Consider the circuit in which $Z = 3 + j8\ \Omega$, $\bar{V}_r = 240\ \underline{/0^\circ}$ V, and $\bar{I}_r = 10\ \underline{/-30^\circ}$ A. Solve for $\bar{V}_s$ and P_s. Draw a phasor diagram.

3-7. Consider the circuit in which $Z = 3 + j8\ \Omega$, $\bar{V}_r = 240\ \underline{/0^\circ}$ V, and Z_r = (load impedance) $= 7 + j22\ \Omega$. Calculate
   a. receiver current $\bar{I}_r$.
   b. receiver voltage $\bar{V}_r$.
   c. receiver power factor F_{pr}.
   d. receiver power P_r.
   e. receiver volt-amperes P_{rr}.
   f. receiver reactive volt-amperes P_{qr}.

3-8. Consider the circuit in which $Z = 3 + j8\ \Omega$, $\bar{V}_r = 240\ \underline{/0^\circ}$ V, $P_r = 1000$ W, and $F_{pr} = 0.8$ lag. Solve for $\bar{V}_s$.

3-9. Consider the circuit in which $Z = 6 + j8 = 10\ \underline{/53^\circ}\ \Omega$ and $\bar{V}_r = 500\ \underline{/0^\circ}$ V. On a single phasor diagram solve graphically for $\bar{V}_s$ for each of the following conditions:
   a. $\bar{I}_r = 20\ \underline{/0^\circ}$ A.
   b. $\bar{I}_r = 20\ \underline{/90^\circ}$ A.
   c. $\bar{I}_r = 20\ \underline{/-90^\circ}$ A.
   d. $\bar{I}_r = 20\ \underline{/-45^\circ}$ A.

   Check all answers analytically.

3-10. Draw a transmission diagram applying to a basic power circuit in which $Z = 20.0\ \underline{/75^\circ}\ \Omega$. Use $\bar{V}_r$ as reference. Draw a grid line for each 50 A, from 0 to 300 A. On the V_r line, mark appropriate points for $V_r = 5000$, 10,000, and 15,000 V. Use a scale of 1 cm = 1000 V. From the diagram determine $\bar{V}_s$ for each of the following conditions:
   a. $V_r = 10{,}000$ V; $I_r = 150$ A; $F_{pr} = 1.0$.
   b. $V_r = 15{,}000$ V; $\bar{I}_r = 200 + j100$ A.

c. $V_r = 10{,}000$ V; $P_r = 2000$ kW; $F_{pr} = 0.8$ lag.
Check all answers analytically.

3-11. Refer to the circuit of Problem 3-10. What is the largest load of 0.707 power factor lag which may be carried on the circuit while maintaining V_r at 12,500 V while V_s is limited to 16,000 V? For this load condition determine also P_s and the losses in the circuit.

3-12. For the circuit of Problem 3-10, draw a transmission diagram using $\bar{V}_s$ as reference. Solve for $\bar{V}_r$ when
a. $V_s = 10{,}000$ V; $I_s = 200$ A; $F_{ps} = 1.0$.
b. $V_s = 15{,}000$ V; $\bar{I}_s = 150 + j200$.
c. $V_s = 15{,}000$ V; $\bar{I}_s = 250 \angle -30°$.
d. With the answer to part c, refer to the diagram of Problem 3-10. Does this give you $V_s = 15{,}000$ V, as expected?
Check all answers analytically.

3-13. A transmission circuit has an impedance of $Z = 3 + j14\ \Omega$. Load end conditions are $V_r = 5000$ V and $P_r = 250$ kW. Determine transmission losses and transmission efficiency for each of the four conditions:
a. Receiver current lags receiver voltage by 30°.
b. Receiver current lags receiver voltage by 60°.
c. Receiver current leads receiver voltage by 30°.
d. Receiver current is in phase with receiver voltage.

3-14. A three-phase transmission line has an impedance $Z = 6 + j20\ \Omega$ per conductor. Load-end conditions are $V_{LL,r} = 13{,}800$ V, P_r (three phase) = 1200 kW, and power factor = 0.8 lag. Solve for sending-end voltage, current, power factor, power, and transmission loss using the line-to-neutral method.

3-15. Repeat Problem 3-14 using the single-phase equivalent method.

3-16. Write a computer program that produces the sending-end voltage, given various receiving-end conditions. Use it to solve Problems 3-9 and 3-10.

3-17. Write a computer program that produces the receiving-end voltage, given various sending-end conditions. Use it to solve Problem 3-12.

3-18. Write a computer program that produces the receiving-end voltage, given the sending-end voltage and the receiving-end power and power factor. Use it to solve Problem 3-8.

chapter 4

Percent and Per Unit Quantities

4-1. INTRODUCTION

The use of the MKS system dictates that problems related to electric circuits should be solved in terms of volts, amperes, volt-amperes, and ohms. Answers to problems pertaining to electric power systems are almost always required in terms of these quantities. However, in the process of computations, it is frequently more convenient to express these electrical quantities in terms of "percent" or "per unit" of some arbitrarily chosen base. The electrical characteristics of machines are usually specified by the designers and manufacturers in terms of percent or per unit.

4-2. THE PERCENT SYSTEM

The *percent system* will be illustrated by means of an example. Consider an impedance Z (Fig. 4-1) which is assumed to have a constant value of 40 ohms regardless of the voltage impressed across it. Let us assume that we shall use this 40 ohms as reference and so declare it to be 100 percent impedance, as shown. The value of other impedances may then be specified as a certain percentage of this reference value.

Next, suppose that because of the design of this impedance or because of some operating practice, we declare the voltage associated with this impedance to be arbitrarily set at 200 volts. That is, 200 volts will be declared to be

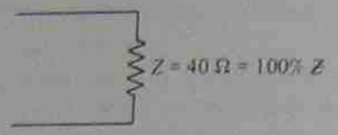


FIG. 4-1. A simple impedance, Z.

100 percent voltage. Since 200 volts (100 percent voltage) applied to the 40-ohm impedance (100 percent impedance) gives rise to a current of 5 amperes, it is logical to declare 5 amperes to be 100 percent current. Further, since 5 amperes at 200 volts implies 1000 volt-amperes, it follows that this value should represent 100 percent volt-amperes.

Those values which are declared to be 100 percent are termed *base values*. In summary, for this example,

base impedance	40 ohms	100% Z
base voltage	200 volts	100% V
base current	5 amperes	100% I
base volt-amperes	1000 volt-amperes	100% VA

Problems pertaining to conditions other than those described above might be specified in terms of these base quantities. A 50-ohm impedance would be specified as

$$Z = 125\%$$

a current of 4 amperes would be specified as

$$I = 80\%$$

and a voltage of 150 volts would be specified as

$$V = 75\%$$

The percent system presents some inconsistencies when values expressed in this fashion are inserted into mathematical equations. For example, we may write

$$V = IZ$$

If I is 80 percent (4 amperes) while Z is 150 percent (60 ohms), the relation above would yield

$$V = IZ = 80 \times 150 = 12{,}000\%$$

This result implies a voltage of 24,000 volts whereas the answer should be 240 volts.

Although it is common practice to express quantities in many instances as a percent, computations are much more readily made in a modification of the percent system, known as the *per unit system*.

4-3. THE PER UNIT SYSTEM

The *per unit system* is similar to the percent system except that all quantities are expressed as *decimal fractions* instead of percentages. Base quantities then have the value unity instead of 100 percent.

For the tabulation given in Section 4-2 we now write

base impedance	40 ohms	1.0 pu
base voltage	200 volts	1.0 pu
base current	5 amperes	1.0 pu
base volt-amperes	1000 volt-amperes	1.0 pu

It then follows that

50 ohms is 1.25 pu impedance
4 amperes is 0.8 pu current
150 volts is 0.75 pu voltage

The per unit system has the distinct advantage that, with it, all basic circuit relations apply. For example, if I is 0.8 pu (4 amperes) and Z is 1.50 pu (60 ohms), it follows that

$$V = IZ$$
$$= 0.8 \times 1.50 = 1.2 \text{ pu V}$$

It is now seen that 1.2 pu volts corresponds to 240 volts, the correct answer.

In summary, when expressed in per unit quantities,

$$V_{base} = I_{base} Z_{base} \tag{4-1}$$
$$VA_{base} = V_{base} I_{base} \tag{4-2}$$

If any two of the four quantities in these equations are specified, the other two may be evaluated immediately. In most instances, base voltage and base volt-amperes are specified. Base current and base impedance may then be calculated. Actual values and per unit values are related by

$$Z_{ohms} = Z_{pu} Z_{base} \tag{4-3}$$
$$I_{amps} = I_{pu} I_{base} \tag{4-4}$$
$$V_{volts} = V_{pu} V_{base} \tag{4-5}$$
$$VA_{volt\ amps} = VA_{pu} VA_{base} \tag{4-6}$$

The per unit system simplifies many of the problems of circuit analysis. In the conventional form of calculation using volts and amperes, the solution of a system involving power lines of several different voltage levels requires all impedances which are to be added to be transferred to a single voltage level. In the per unit system, the different voltage levels entirely disappear and a power network involving generators, transformers, and lines (of different voltage levels) reduces to a system of simple impedances, each one of which is essentially the general power circuit discussed in Chapter 3. Furthermore, machines such as generators and transformers, when described in the per unit systems, have their characteristics specified by almost the same number, regardless of the rating of the machines. For example, a 20-kVA transformer may have 6 percent (0.06 pu) reactance and a 200,000-kVA transformer may have 6 percent (0.06 pu) reactance. This percent reactance is the percent of rated voltage dropped across the leakage reactances when rated current flows.

4-4. SPECIFICATION OF GENERATORS

Consider the equivalent circuit of a generator as discussed in Section 2-8a and as represented in Fig. 4-2. Let it be assumed that the rating of the generator is

1000 VA 200 V

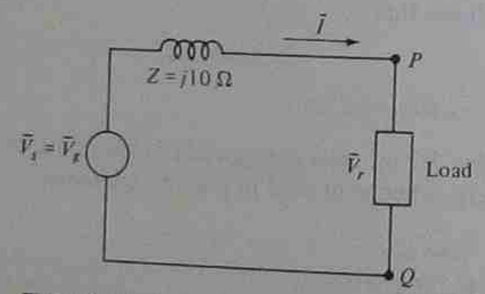


FIG. 4-2. The equivalent circuit of a generator.

From this we may calculate the rated single-phase current as

$$I = \frac{VA}{V} = \frac{1000}{200} = 5\text{A}$$

The load impedance necessary to produce this rated current and rated volt-ampere output at rated voltage is

$$Z_L = \frac{V_r}{I} = \frac{200}{5} = 40\ \Omega$$

For this machine we can define base quantities as follows:

base volt-amperes	1000 VA
base volts	200 V
base current	5 A
base impedance	40 Ω

For problems associated with this machine, volt-amperes, voltage, current, and impedance may be expressed as a percentage of base values or as a decimal fraction of base value (per unit).

From Fig. 4-2 it may be noted that the internal impedance of the generator is shown as 10 ohms. This is 25 percent, or 0.25, of Z_B. Hence we could say that on the basis of the machine rating, the internal impedance of the generator is 25 percent or 0.25 per unit.

Let us again examine the generator, but this time let us assume that the load terminals are short-circuited as shown in Fig. 4-3. Let us now ask the

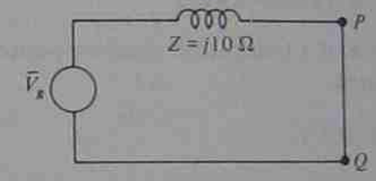


FIG. 4-3. The generator of Fig. 4-2 with its terminals short-circuited.

question: What value of V_g is necessary to produce rated full-load current in the machine? Since the rated full-load current is 5 amperes and the impedance of the machine is 10 ohms, it follows that

$$V_g = IZ = 5 \times 10 = 50\text{ V}$$

Thus it is seen that the voltage required is 25 percent of the *rated* terminal voltage. Expressing this as a decimal fraction, we may say that the voltage required to circulate full-load current is 0.25 times rated voltage. In the terminology of per unit quantities we say that this voltage is 0.25 per unit.

It may be noted that the voltage required to circulate full-load current with the machine short-circuited at the terminals expressed in per unit is exactly equal to the impedance of the machine expressed in per unit.

The rating of a machine, such as a generator, is determined not only by the design of the machine but also by the condition of operation to which it is to be subjected. Suppose, for example, that the machine of Fig. 4-2 is to be used in an application where it will never be run more than 5 minutes during any 1-hour period. For this short-time operation, the machine might easily be rated 2500 volt-amperes. However, since nothing else is changed,

the equivalent circuit of Fig. 4-2 still applies, for the ohms impedance of the machine is unaffected by the nameplate specifications. Under this new condition of operation we can now write

base volt-amperes	2500 VA
base voltage	200 V
base current	12.5 A
base impedance	16 Ω

The per unit Z of the machine is now 10 divided by 16, the actual impedance divided by the base impedance, or 0.625 per unit. Any numerical problems involving volts, volt-amperes, amperes, and ohms (not per unit quantities) worked out by the new base quantities should give the same numerical answers as before because the machine is unchanged by a change in base rating.

4-5. SPECIFICATION OF TRANSFORMERS

The per unit impedance of a transformer deserves particular attention. Consider a transformer rated

2000 VA 200/400 V

for which the approximate equivalent circuit, with all impedances referred to the low-voltage side, is shown in Fig. 4-4. Let us determine the per unit

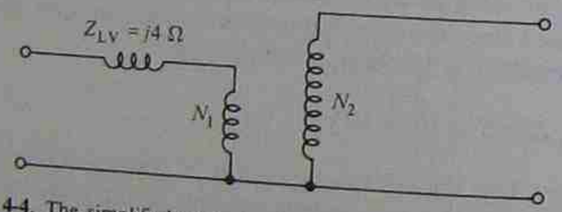


FIG. 4-4. The simplified equivalent circuit of a transformer with all series impedances transferred to the low-voltage side.

impedance of this transformer considering base quantities to be the rated values. That is, we shall determine the per unit quantities on the transformer's own base. On the low-voltage side,

base volt-amperes	2000 VA
base voltage	200 V
base current	10 A
base impedance	20 Ω

The impedance of the transformer (in pu) is

$$Z_{pu} = \frac{Z_{ohms}}{Z_{base}} = \frac{4}{20} = 0.20 \text{ pu}$$

Next let us consider the transformer with its impedance referred to the high-voltage side:

$$Z_{HV} = Z_{LV}\frac{N_2^2}{N_1^2} = Z_{LV}\frac{V_2^2}{V_1^2}$$
$$= 4\frac{400^2}{200^2} = 16\ \Omega$$

The equivalent circuit then is as shown in Fig. 4-5. Base quantities on the high-voltage side are

base volt-amperes	2000 VA
base voltage	400 V
base current	5 A
base impedance	80 Ω

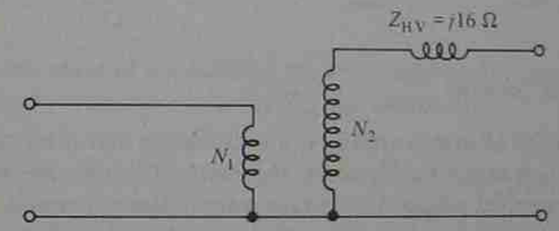


FIG. 4-5. The transformer of Fig. 4-4 with all series impedances transferred to the high-voltage side.

The impedance of the transformer (in pu) viewed from the high-voltage side is

$$Z_{pu} = \frac{16\ \Omega}{80\ \Omega} = 0.20 \text{ pu}$$

Hence it is seen that the per unit impedance is the *same* regardless of the side from which it is viewed. This statement (demonstrated here for a particular case) may be shown to apply generally, for *all* two-winding transformers. The equivalent circuit of the transformer is thus the simple circuit, Fig. 4-6.

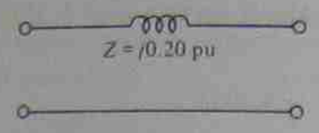


FIG. 4-6. The simplified equivalent circuit of a transformer expressed in per unit.

4-6. SPECIFICATION OF LINES AND CABLES

Using known wire size and spacing the designer of an overhead line and cable circuit is able to calculate the ohms impedance of the circuit. To convert this impedance to per unit impedance it is necessary to determine base ohms for the circuit. This is done by assuming an arbitrary base voltampere rating and an arbitrary base voltage rating. The volt-ampere rating may be that assigned to other pieces of equipment on the system. The voltage rating is usually the nominal voltage of the line as determined by the voltage rating of the transformer supplying the circuit. The base impedance may then be determined from Eqs. (4-1) and (4-2). With line impedance (in ohms) calculated, the per unit impedance of the line may be determined from Eq. (4-3) as

$$Z_{pu} = \frac{Z_{ohms}}{Z_{base}} = Z_{ohms}\frac{VA_{base}}{V^2_{base}} \tag{4-7}$$

4-7. CHANGE OF BASE

While the choice of base is arbitrary, it is advisable that it be made so as to produce per unit values readily comprehended by the user. In the case of the voltage, the nominal voltage at a certain point of the power system is usually found to be a convenient base value. Once a voltage base has been selected for a point in the system, the remaining voltage bases are no more independent; they are determined by the various transformer turns ratios. For example, if on the high-voltage side of a 4800/240-volt transformer the base voltage is 5000 volts, on the low-voltage side the base voltage must be 5000 (240/4800) = 250 volts.

As for the volt-ampere base, a unique value is assigned to the whole power system under study. This base is arbitrary. If the system is energized by a single generator, it is convenient (not necessary) to take the volt-ampere rating of the generator for base. In a more complex system, the total load value rounded off to a power of 10 may be selected. Thus, for a refinery or a small industrial complex, a convenient base may be 10 MVA.

Ordinarily the manufacturer of a machine expresses its characteristics in terms of per unit quantities using as bases the rated volt-amperes and rated

voltage of the machine. These bases may differ from those selected for the system under study, and it will be necessary to express the characteristics of each machine in terms of the system base quantities. This is readily accomplished by remembering that the actual impedance of a machine depends only on the materials and construction, and is unchanged by a change in the rating of the machine. However, if the base is changed, the per unit impedance of the machine takes on a new value.

Suppose that a manufacturer states that a machine has Z_{1pu} per unit impedance based on its own volt-ampere and voltage rating, which we shall define here as system 1 and in which we shall represent base quantities as VA_{B1} and V_{B1}. The question may be asked: What is the per unit impedance of this machine Z_{2pu} in a new base system 2, in which base quantities are defined as VA_{B2} and V_{B2}?

In system 1, from Eq. (4-3),

$$Z_{ohms} = Z_{1pu}Z_{B1} = Z_{1pu}\frac{V_{B1}}{I_{B1}} = Z_{1pu}\frac{V_{B1}}{VA_{B1}/V_{B1}}$$

$$= Z_{1pu}\frac{V^2_{B1}}{VA_{B1}}$$

Similarly, in system 2,

$$Z_{ohms} = Z_{2pu}\frac{V^2_{B2}}{VA_{B2}}$$

Since the actual ohms of the machine are unchanged by a change of base, we can equate these two expressions for Z_{ohms} to obtain

$$Z_{1pu}\frac{V^2_{B1}}{VA_{B1}} = Z_{2pu}\frac{V^2_{B2}}{VA_{B2}}$$

Solving for Z_{2pu} we obtain

$$Z_{2pu} = Z_{1pu}\frac{V^2_{B1}}{V^2_{B2}}\frac{VA_{B2}}{VA_{B1}} \tag{4-8}$$

This equation provides us with a means for expressing the per unit impedance of a machine in one base when its per unit impedance has already been expressed on a different base.

4-8. AN EXAMPLE SYSTEM

To illustrate the use of the per unit method in the analysis of system problems, consider the assembly of components shown in Fig. 4-7. Note that machines 1 and 2 are both rated 250 volts, as is the primary of transformer *A*. If this is

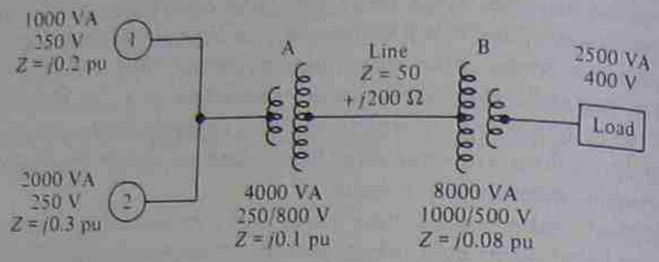


FIG. 4-7. An example power system with the characteristics of each component expressed independently.

taken as the base voltage for this part of the system, the line has a base voltage of 800 volts as determined by the turns ratio of transformer *A*. Transformer *B* was obviously not designed for this particular installation, as it is rated at a higher voltage than necessary. However, its turns ratio is proper to supply the load at its rated voltage, 400 volts.

To solve a problem involving this system by the per unit method, it is necessary to determine the impedance of all components on the same base. The base selected is arbitrary. For illustration, let 5000 VA be chosen as the base and determine the per unit impedance of each part. The determination for the machines and transformers may be made using Eq. (4-8), while that for the line may be made by Eq. (4-7).

Machine 1

$$Z_{pu(5000)} = j0.2\frac{250^2}{250^2}\frac{5000}{1000} = j1.0 \text{ pu}$$

Machine 2

$$Z_{pu(5000)} = j0.3\frac{250^2}{250^2}\frac{5000}{2000} = j0.75 \text{ pu}$$

Transformer *A*

$$Z_{pu(5000)} = j0.1\frac{250^2}{250^2}\frac{5000}{4000} = = j0.125 \text{ pu}$$

Line

$$Z_{pu(5000)} = (50 + j200)\frac{5000}{800^2} = (0.39 + j1.56) \text{ pu}$$

Transformer *B*

$$Z_{pu(5000)} = j0.08\frac{1000^2}{800^2}\frac{5000}{8000} = j0.078 \text{ pu}$$

Load

$$VA_{pu(5000)} = \frac{2500}{5000} = 0.5 \text{ pu}$$

The entire system may now be represented by the impedance diagram of Fig. 4-8, in which *all* components are represented on a common 5000-VA base. It is seen that the system is now a simple combination of several basic power circuits, which may be further simplified if desired.

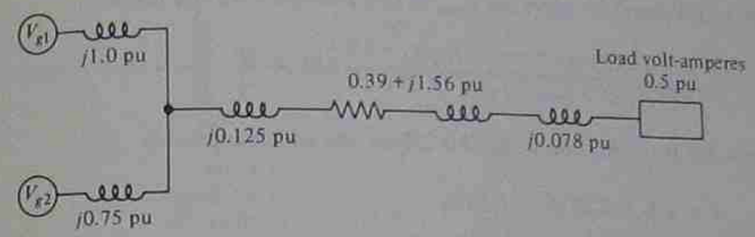


FIG. 4-8. The example system of Fig. 4-7 with the impedance of each component expressed on a 5000-VA base.

4-9. THREE-PHASE SYSTEMS; PER UNIT ANALYSIS

The previous discussion of per unit quantities was limited to single-phase machines and single-phase lines. This analysis may be readily extended to three-phase systems. Referring to the discussion on the single-phase equivalent of a three-phase system (Section 3-8), it was shown that all three-phase problems involving balanced systems may be worked on a single-phase circuit basis. In the single-phase equivalent circuit, all values are correct except the value of current, which is higher by the factor $\sqrt{3}$. From this we conclude that *any* problem involving balanced three-phase systems may be worked in terms of per unit quantities on a single-phase basis. When the solutions obtained in terms of per unit volts, per unit amperes, per unit volt-amperes, and per unit ohms are put into volts, amperes, volt-amperes, and ohms, all values are correct except the currents. The currents calculated from the single-phase equivalent diagram may then be reduced by dividing by $\sqrt{3}$ to obtain the correct numerical values applying in the actual three-phase system.

Suppose, for example, that in a system rated 1000 VA, 200 volts, the current is 2.4 pu. If this is a single-phase system, the base current is

$$I_B = \frac{VA_B}{V_B} = \frac{1000}{200} = 5 \text{ A}$$

and the actual current is

$$I = I_{pu}I_B = 5 \times 2.4 = 12 \text{ A}$$

If this is a three-phase system, the actual current is $12/\sqrt{3} = 6.95$ A.

This problem may also be approached by considering that in a three-phase system, the expression for volt-amperes is

$$VA = \sqrt{3}\, V_{LL} I_L \tag{2-113}$$

We could therefore solve for I_{base} in this relation with the result

$$I_{base\ 3\phi} = \frac{VA}{\sqrt{3}\, V_{LL}} = \frac{1000}{\sqrt{3} \times 200} = 2.88 \text{ A}$$

Then, for the condition where I is 2.4 pu, the actual current is

$$I = 2.4 \times 2.88 \text{ A} = 6.95 \text{ A}$$

In general, for a three-phase system there are two base values for each quantity. For the volt-ampere base, $VA_{B\phi h}$ is the value per phase, and VA_B is the value for the three phases

$$VA_B = 3\, VA_{B\phi h}$$

For the voltage base, V_{BLN} is the value from line to neutral, and V_B the value from line to line

$$V_B = \sqrt{3}\, V_{BLN}$$

For the current base, $I_{B\Delta}$ is the value in a branch of a delta connection, and I_B the value in a branch of a wye connection (the line value)

$$I_B = \sqrt{3}\, I_{B\Delta}$$
$$= \frac{VA_{B\phi h}}{V_{BLN}} = \frac{VA_B}{\sqrt{3}\, V_B}$$
$$I_{B\Delta} = \frac{VA_{B\phi h}}{V_B} = \frac{VA_B}{3V_B}$$

For the impedance base, $Z_{B\Delta}$ is the value of a branch in a delta connection, and Z_B the value of a branch in a wye connection

$$Z_B = \frac{Z_{B\Delta}}{3}$$
$$= \frac{V_{BLN}}{I_B} = \frac{V_{BLN}^2}{VA_{B\phi h}} = \frac{V_B^2}{VA_B}$$
$$Z_{B\Delta} = \frac{V_B}{I_{B\Delta}} = \frac{V_B^2}{VA_{B\phi h}} = \frac{3V_B^2}{VA_B}$$

The per unit value of an impedance is the same whether we consider it in its delta-connected form or the equivalent wye connection.

EXAMPLE 4-1. Consider the three-phase system shown in Fig. 4-9. Draw for it an impedance diagram, expressing all impedances in per unit referenced to

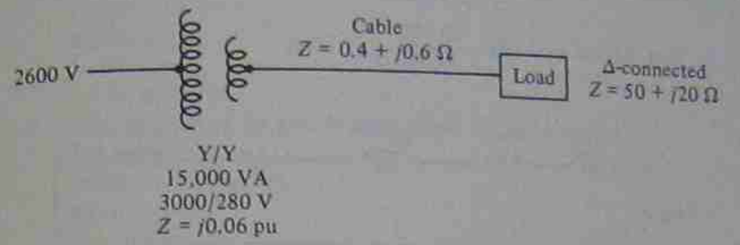


FIG. 4-9. An example of a three-phase system with component characteristics expressed independently.

a common base of 20,000 volt-amperes and 2600 volts on the high-voltage side. Using this impedance diagram, calculate the high- and low-voltage line currents.

Solution.

V_{base} on h.v. side $= 2600$ V

V_{base} on l.v. side $= 2600 \dfrac{280}{3000} = 242.7$ V

Transformer:

$$Z_{pu} = j0.06 \frac{(3000)^2}{(2600)^2} \frac{20{,}000}{15{,}000} = j0.107 \text{ pu}$$

Cable:

$$Z_{pu} = (0.4 + j0.6) \frac{20{,}000}{(242.7)^2} = 0.136 + j0.204 \text{ pu}$$

Load:

$$Z_{pu} = (50 + j20) \frac{20{,}000/3}{(242.7)^2} = 5.66 + j2.26 \text{ pu}$$

or

$$\text{equivalent wye impedance} = \frac{50 + j20}{3}\ \Omega$$

$$Z_{pu} = \frac{50 + j20}{3} \frac{20{,}000}{(242.7)^2} = 5.66 + j2.26 \text{ pu}$$

The resulting impedance diagram is shown in Fig. 4-10. The per unit current is

$$I = \frac{1.0}{(0.136 + 5.66) + j(0.107 + 0.204 + 2.26)} = 0.158 \text{ pu}$$

h.v. line current $= 0.158 \dfrac{20{,}000}{\sqrt{3}(2600)} = 0.70$ A

l.v. line current $= 0.158 \dfrac{20{,}000}{\sqrt{3}(242.7)} = 7.5$ A

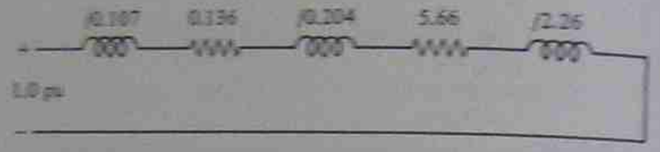


FIG. 4-10. Impedance diagram for the system of Fig. 4-9 with all values expressed on a common base.

4-10. BASE QUANTITIES IN TERMS OF KILOVOLTS AND KILOVOLT-AMPERES

The subject of per unit quantities has been presented so far in terms of volt-amperes, volts, amperes, and ohms. In power-system practice it is common to refer to ratings in terms of kilovolt-amperes and kilovolts. Equations (4-1) to (4-7) are readily modified to accommodate this notation:

$$kV_B = \frac{I_B Z_B}{1000} \tag{4-9}$$

$$kVA_B = kV_B I_B \tag{4-10}$$

$$Z_{ohms} = Z_{pu} Z_B \tag{4-11}$$

$$I_A = I_{pu} I_B \tag{4-12}$$

$$kV_{ex} = V_{pu} kV_B \tag{4-13}$$

$$kVA_{ex} = kVA_{pu} kVA_B \tag{4-14}$$

$$Z_{pu} = \frac{Z_{ohms}}{Z_B} = Z_{ohms} \frac{kVA_B}{kV_B^2 1000} \tag{4-15}$$

$$Z_{2pu} = Z_{1pu} \frac{kV_{B2}^2}{kV_{B1}^2} \frac{kVA_{B2}}{kVA_{B1}} \tag{4-16}$$

When the volt-ampere base is in megavolt-amperes,

$$Z_{pu} = Z_{ohms} \frac{MVA_B}{kV_B^2} \tag{4-17}$$

PROBLEMS

4-1. Consider a system in which base volt-amperes = 200 kVA and base voltage = 10,000 V.
   a. Calculate base current and base impedance.
   b. Express each of the following in terms of per unit values:
      12,000 volts
      90,000 watts
      600 ohms
      90 amperes
   c. Express each of the following in terms of percent values:
      250 volts
      450 kilovolt-amperes
      800 ohms
      10 amperes

4-2. Consider a system in which base impedance = 80 ohms and base current = 125 amperes.
   a. Calculate base kVA and base voltage.
   b. Express each of the following in terms of actual amperes, volts, ohms, or volt-amperes.
      $Z = 1.1$ pu
      $I = 27\%$
      $V = 0.75$ pu
      $VA = 36.7$ pu

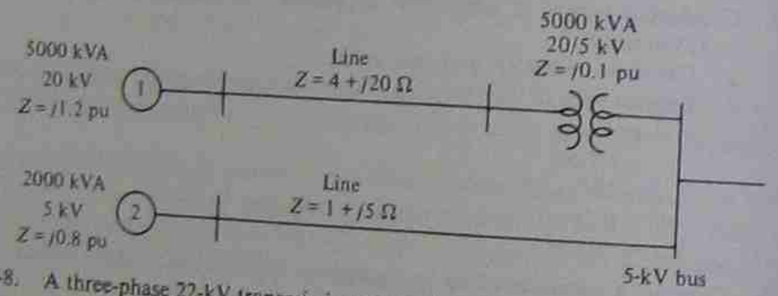
4-3. Consider a system in which base current = 400 amperes and base voltage = 25,000 volts.
   a. Calculate the actual voltage across a resistor of 4.2 pu Ω carrying a current of 2.5 pu A.
   b. A load has 80 percent voltage impressed across it. The current is 120 percent and the power is 60 percent. Calculate the power factor.
   c. An impedance has 0.40 pu V impressed across it. The current is 1.4 pu A and the power consumed is 0.45 pu W. Calculate the value of R and X expressed in pu ohms and in actual ohms.

4-4. A transformer is rated 75,000 kVA, 345/138 kV, and 8 percent impedance.
   a. The transformer, under certain load conditions, carries 0.6 pu A in the high-voltage winding. What actual current does this represent? What current must be present in the low-voltage winding? Express this current in pu amperes.
   b. What is the impedance of the transformer (in ohms) referred to the high-voltage side? Referred to the low-voltage side?
   c. The low-voltage terminals of the transformer are short-circuited and 0.22 pu voltage is applied to the high-voltage winding. Determine the high-side and the low-side currents that result. Express each in pu amperes and in actual amperes.
   d. What will be the IZ drop in the transformer if a current of 1.2 pu flows in the high-voltage winding?

4-5. A transformer is rated 5000 VA, 400/100 V, and 12 percent impedance.
   a. What is the impedance of the transformer (in ohms) referred to the high side? Referred to the low side?
   b. If for intermittent duty the transformer is re-rated 7500 VA, what will be the new percent impedance?
   c. The same transformer is supplied to a customer who has ordered a 300/75-V machine. What will be its new volt-ampere and percent impedance rating?

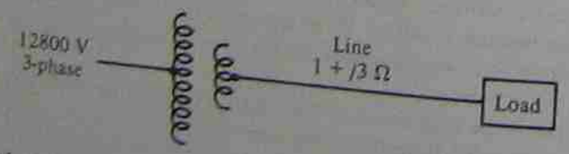
4-6. A transmission line has a series impedance of $Z = 10 + j40\ \Omega$. Calculate the pu impedance of this line under the following conditions:
   a. Operating voltage 600 V, base volt-amperes 40,000 VA.
   b. Operating voltage 11,000 V, base volt-amperes 5,000,000 VA.
   c. Operating voltage 22 kV, base volt-amperes 50,000 kVA.

4-7. Redraw the system showing all impedances on a 10,000-kVA base.



4-8. A three-phase 22-kV transmission circuit has an impedance $Z = 0.05 + j.40$ pu on a 10,000-kVA base. At the receiver end conditions are $V_r = 1.1$ pu, $P_r = 0.4$ pu, and $F_p = 0.8$ lag. Determine V_s and I_s in terms of volts and amperes.

4-9. The three-phase load shown is a delta-connected impedance of 250% $F_p = 0.9$ lag, with reference to a base of 400 kVA and 2 kV. The transformer is Y/Y-connected, 200-kVA, 13/2.6-kV, with $Z = j5\%$. Using the transformer rating as a base, find in per unit and amperes the current in a branch of the load.



4-10. Two three-phase loads are fed from the same power source. Load 1 absorbs 0.4 pu of power at a power factor of 0.8 lag. Load 2 absorbs 0.63 pu of power at a power factor of 0.9 lag. All per unit values are referenced to the same base. Find the combined power factor of the load.

4-11. Given a power system with all its nodes numbered consecutively (1, 2, 3, . . .), let the voltage and volt-ampere bases of the system be specified at node 1. Write a computer program that determines the per unit impedance of each element of the power system. Inputs: each element, its nature (transformer, line, motor, . . .), the nodes to which it is connected, its ratings (voltage and volt-ampere), its impedance (per unit or ohmic value).

4-12. Use the computer program of Problem 4-11 to determine the per unit impedances of Problem 4-7.

4-13. Use the computer program of Problem 4-11 to determine the per unit impedances of Problem 4-9.

4-14. Use the computer program of Problem 4-11 to determine the per unit impedances of the system shown in Fig. 4-7.

chapter 5

Circuit Constants

5-1. INTRODUCTION

The behavior of electric power systems may be accurately predicted by calculations based on electric circuit theory. Chapter 2 presented circuit models of many of the important components of an electric power system. Chapter 3 showed the basis for the analysis of the behavior of these components operated as individual devices or interconnected into systems. If numerical calculations are to be made, it is necessary to assign values to each circuit element under consideration. The purpose of this chapter is to provide information by which it is possible to assign correct values to each resistance, inductance, and capacitance which appears in the circuit models of lines, transformers, generators, loads, and other components of electric power systems. The characteristics of overhead lines and underground cable circuits may be determined with great accuracy from the specifications of the conductors to be used and their geometric arrangement. The characteristics of generators and transformers may be predicted by the designer before the machines are constructed or they may be determined by tests after the machines have been assembled. In preliminary studies of power-system design, it is sometimes desirable to consider machines that have not been designed or built. For such studies it is frequently satisfactory to use machine constants typical of a selected voltage and kilovolt-ampere rating.

5-2. OVERHEAD LINES

The circuit model of an overhead line operating under balanced conditions of source voltage and loading was shown in Fig. 3-20. The line resistance and inductive reactance are of importance in almost all problems. For some studies it is possible to omit the capacitance and thus simplify the equivalent circuit diagram and the computations that may be made from it. This section deals with the determination of the resistance, inductive reactance, and the capacitive reactance of overhead lines based on the length of the circuit, the conductors used, and the spacing between the conductors as they are mounted on the supporting structures.

a. Resistance. The resistance of a conductor may be calculated from the relation

$$R = \rho \frac{l}{A} \tag{2.9}$$

where ρ is the resistivity of the material, l the length of the conductor, and A the cross section of the conductor.

In practice, several different systems of units are used in the calculation of resistance. In the MKS system, ρ is expressed in ohm-meters, length is expressed in meters, and area is expressed in square meters. Another system (CGS) expresses ρ in micro-ohm-centimeters, length in centimeters, and area in square centimeters. Another system commonly used among electric power engineers expresses resistivity in ohms circular *mils* per foot (sometimes designated as ohms per circular mil foot), length in feet and area in circular mils. Table A-1 (see Appendix A) summarizes two of these systems of notation and gives the value of ρ for several materials of importance in power-system work. (*Note:* A circular mil is the area of a circle having a diameter of 1 mil or 0.001 inch. The area of a circle having a diameter of 8 mils is 64 circular mils. Areas expressed in circular mils are very commonly used for conductors that have a circular cross section, such as those used in overhead lines.)

The application of Eq. (2-9) yields the resistance of a conductor at 20°C when the value of ρ as given in Table A-1 is applied. The resistance of a conductor at any temperature may be determined by applying Eq. (2-10):

$$R_2 = R_1[1 + \alpha(T_2 - T_1)] \tag{2-10}$$

In this equation R_2 is the resistance at temperature T_2. R_1 is the resistance at temperature T_1, 20°C. Values of the temperature coefficient of resistance are given in Table A-1.

EXAMPLE 5-1. Calculate the resistance of a cylindrical aluminum conductor having the following dimensions:

length: 300 ft = 9140 cm

diameter: 0.250 in. = 250 mils = 0.635 cm

Solution. Using ρ in micro-ohm-centimeters, length must be expressed in centimeters and area in square centimeters:

$$R = \rho \frac{l}{A}$$

$$R = 2.83 \times 10^{-6} \frac{9140}{0.635^2 (\pi/4)} = 0.0816\ \Omega$$

Using ρ in ohms cir mil per foot, length must be in feet and area in circular mils:

$$R = 17.0 \frac{300}{250^2} = 0.0816\ \Omega$$

The solution attained in Example 5-1 is for a conductor temperature T_1 of 20°C. Suppose in operation a new temperature T_2 of 130°C is observed. The resistance R_2 is

$$\begin{aligned} R_2 &= R_1[1 + \alpha(T_2 - T_1)] \\ &= 0.0816[1 + 0.0039(130 - 20)] \\ &= 0.0816(1 + 0.429) = 0.117\ \Omega \end{aligned}$$

There are certain limitations in the use of Eq. (2-9) for calculating the resistance of transmission-line conductors. A slight error is introduced if the conductors are stranded rather than solid, for the individual strands are slightly longer than the length of the cable itself. When alternating current flows in a solid conductor the current does not distribute itself uniformly over the conductor cross-sectional area but tends to be of greater density near the surface of the conductor. This nonuniform distribution of current results in increased losses and causes the ac resistance of the conductor to be somewhat higher than the dc resistance. This effect is particularly noticeable in solid conductors of large cross section. It increases in importance as frequency is increased. This behavior, known as *skin effect*, causes the resistance of conductors at radio frequencies to be many times that observed with direct current. At power frequency (60 hertz) the effective resistance is only a few percent greater than that observed with dc.

In many instances, stranded conductors and composite conductors such as those shown in Fig. 5-1 are used in overhead construction practice. The composite conductor consists of a center core of high-strength material

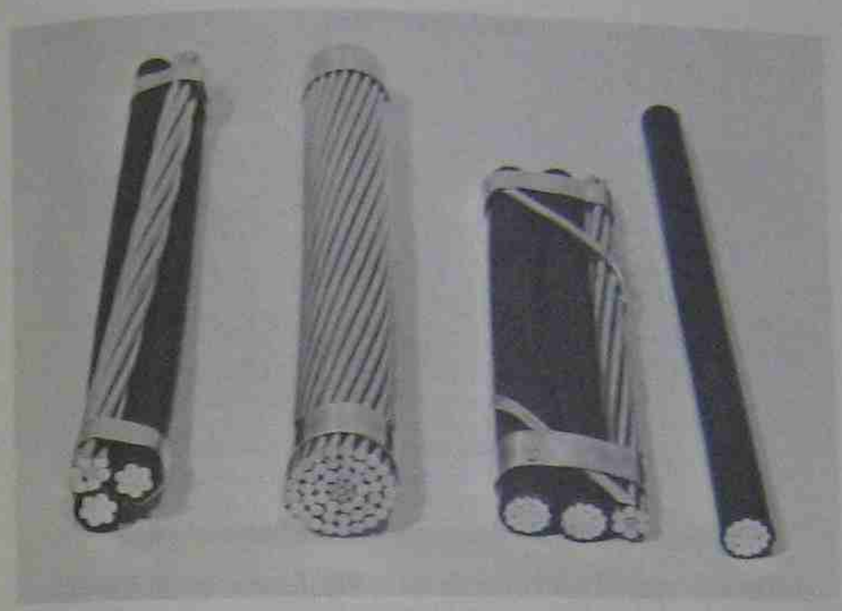


FIG. 5-1. Some typical conductors used on overhead power lines.

such as steel (which has a relatively high resistivity) surrounded by one or more layers of low-resistivity metal (commonly aluminum). The distribution of current between the steel and aluminum is not directly determinable by resistance calculations and so the effective resistance can only be approximated by Eq. (2-9). Advanced calculations and tests have been carried out to determine the effective resistance of all the composite conductors offered for use in overhead-line construction. These values are available in tabular form, such as Tables A-2 and A-3 in Appendix A. Tables of this sort in use in the United States usually give the resistance of conductors per thousand feet or the resistance per mile.

b. Inductance and Inductive Reactance. The physical nature of inductance may be described by reference to the single-phase line shown in cross section in Fig. 5-2. Here a current is assumed to flow out in conductor *A* and to return in conductor *B*. These currents set up magnetic field lines that link between the conductors as shown. When the current changes, the flux changes and a voltage is induced in the circuit. If the current changes sinusoidally as it does in a conventional ac circuit, the voltage induced is referred to as the *IX* drop. As there is only a single turn in this circuit, the magnetic flux per ampere of current in the circuit is equal to the circuit inductance.

It is of interest to note the location of the magnetic field lines shown in Fig. 5-2. Note that most of them are in the air space between the conductors. There are, however, some magnetic field lines within the conductors themselves.

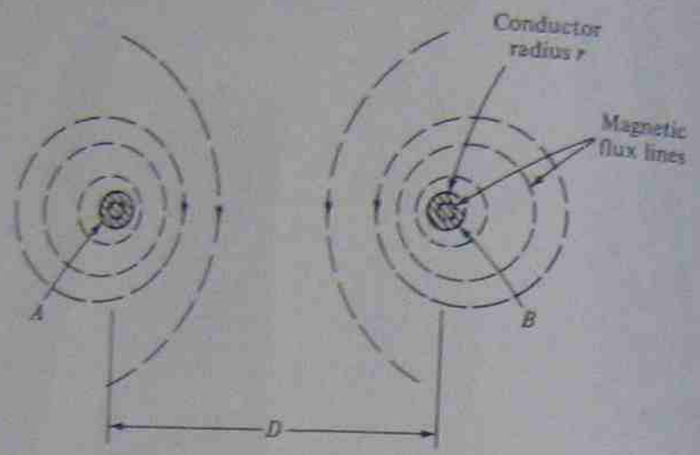


FIG. 5-2. The magnetic field associated with a single-phase line.

The inductance of a circuit as shown in Fig. 5-2 may be calculated from electromagnetic field relations, a subject beyond the scope of the present discussions. Assuming solid conductors carrying direct current, the inductance per meter is found to be

$$L = 2 \times 10^{-7}\left(\log_e \frac{D}{r} + \frac{1}{4}\right) \tag{5-1}$$

In this equation L is the inductance line to neutral (or the inductance per conductor) in henrys per meter of line length, D the spacing between the centers of the conductors, and r the radius of the conductors.

In the derivation of Eq. (5-1) the term $\frac{1}{4}$ arises from a consideration of the flux within the *solid* conductors. For many purposes it is desirable to eliminate this term by the introduction of a concept called the *geometric mean radius*, GMR. A physical interpretation of the geometric mean radius is illustrated in Fig. 5-3. Here the solid conductors A and B of Fig. 5-2 have been replaced by hollow tubes. The hollow tubes have a radius, termed the *geometric mean radius*, of value somewhat smaller than the radius r of the conductors in Fig. 5-2. Since there is no current within the hollow tubes, there is also no magnetic flux internal to these tubes. The magnetic flux *external* to the hollow tube in that small region between GMR and r contributes to the inductance of the circuit, an amount equal to that of the internal flux as shown in Fig. 5-2. The use of the concept of geometric mean radius permits revising Eq. (5-1) and rewriting it as Eq. (5-2). For solid conductors carrying direct current, the GMR is 0.779 times the physical radius:

$$L = 2 \times 10^{-7} \log_e \frac{D}{\text{GMR}} \quad \text{henrys/meter} \tag{5-2}$$

$$L = 0.741 \times 10^{-3} \log_{10} \frac{D}{\text{GMR}} \quad \text{henrys/mile} \tag{5-3}$$

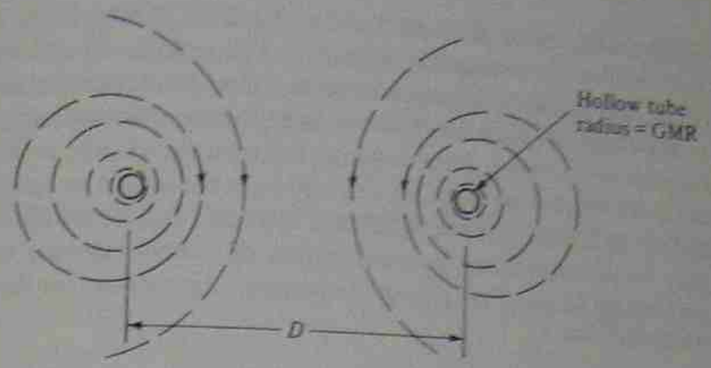


FIG. 5-3. A single-phase line with conductors of hollow tubes illustrating the meaning of geometric mean radius.

With the inductance known, we may apply Eq. (2-65),

$$X_L = 2\pi f L \tag{2-65}$$

and write an expression for the inductive reactance line to neutral (or per conductor):

$$X_L = 2\pi f 0.741 \times 10^{-3} \log_{10} \frac{D}{\text{GMR}} \quad \text{ohms/mile} \tag{5-4}$$

The use of the geometric mean radius of conductor simplifies inductance and inductive reactance calculations. The geometric mean radii of stranded conductors and of composite conductors are difficult to determine by calculation or test. Fortunately, the geometric mean radii of the conductors commonly used in overhead-line construction have been determined and are available as shown in Tables A-2 and A-3.

c. Capacitance and Capacitive Reactance. The physical nature of the capacitance of a transmission circuit is illustrated with reference to Fig. 5-4. The two conductors, A and B, similar to those of Fig. 5-2, are

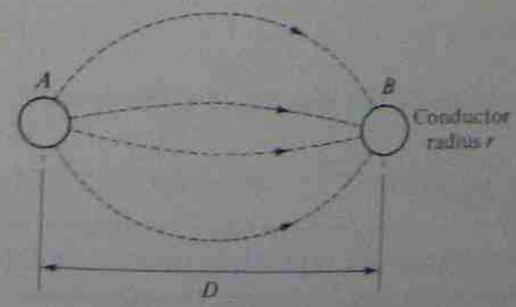


FIG. 5-4. The electric field associated with a single-phase line.

separated by a dielectric and hence form a capacitor. If a positive voltage $+V$ is put on A while a negative voltage $-V$ is put on B, a charge $+q$ appears on A and a charge $-q$ appears on B. Electric field lines extend from A to B as shown in the diagram. If the voltage V changes in magnitude, the value of q must also change. Hence, during the time the voltage is changing, a current i flows lengthwise in the conductors from the source to bring about the change in the charge q on the conductor surfaces. The capacitance of this circuit may be calculated by a consideration of electromagnetic fields (a subject beyond the scope of the present discussion). Expressions for the capacitance are as follows:

$$C = \frac{2\pi\epsilon}{\log_e (D/r)} \quad \text{farad/meter} \qquad \epsilon = \frac{10^{-9}}{36\pi}\ \text{F/m} \quad \text{for air} \tag{5-5}$$

$$C = \frac{0.0388}{\log_{10} (D/r)} \quad \text{microfarad/mile} \tag{5.6}$$

where C is the line-to-neutral capacitance (or per conductor), ϵ the permittivity of the dielectric ($10^{-9}/36\pi$ for air), D the distance between the centers of the conductors, and r the physical radius of each conductor.

The line-to-neutral capacitance may be better understood by reference to Fig. 5-5. Here the two conductors A and B are shown with a neutral between them. The capacitance C as given by Eqs. (5-5) and (5-6) is as shown on Fig. 5-5. The capacitance between A and B is $\frac{1}{2}C$.

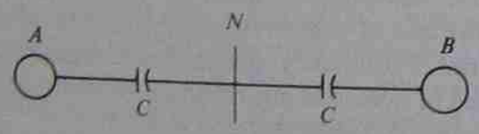


FIG. 5-5. The two conductors of a single-phase line with a neutral plane between them.

The capacitive reactance X_C is given as

$$X_C = \frac{1}{2\pi f C} \tag{2-71}$$

When this equation is combined with Eq. (5-6) there results

$$X_C = \frac{10^6}{2\pi f \times 0.0388} \log_{10} \frac{D}{r} \quad \text{ohm-miles} \tag{5.7}$$

Note that the units given for the capacitance reactance in Eq. (5-7) are ohm-miles. As the length of the line l increases, the capacitance C increases and hence X_C decreases.

d. Constants of Single-Phase Lines. The π-line circuit model of a single-phase line, represented with a neutral, is shown in Fig. 5-6. In this diagram R, L, and C represent the resistance, inductance, and capacitance of the line per unit length and l is the line length. The values of these

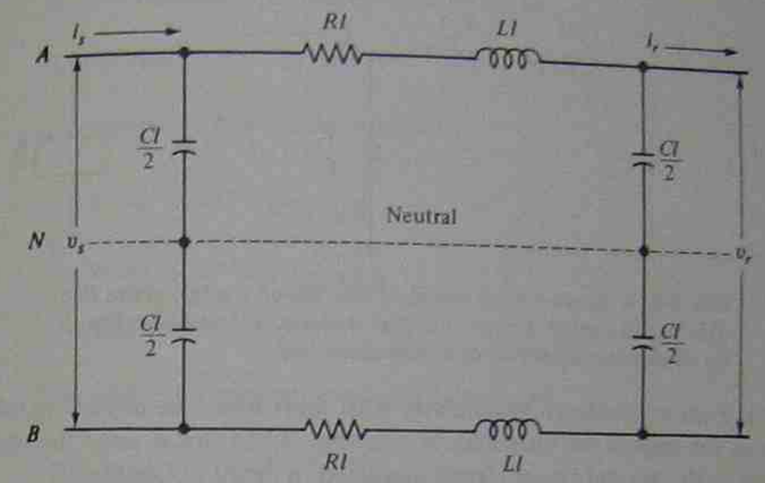


FIG. 5-6. A line-to-neutral model of a single-phase line of length l showing resistance, inductance, and capacitance.

constants may be determined by Eqs. (2-9), (5-3), and (5-6). Note that half of the total line capacitance is placed at each end. For the solutions to problems involving sinusoidal currents and voltages, L and C must be replaced by X_L and X_C, resulting in the diagram shown in Fig. 5-7. X_L and X_C are values for unit length of line.

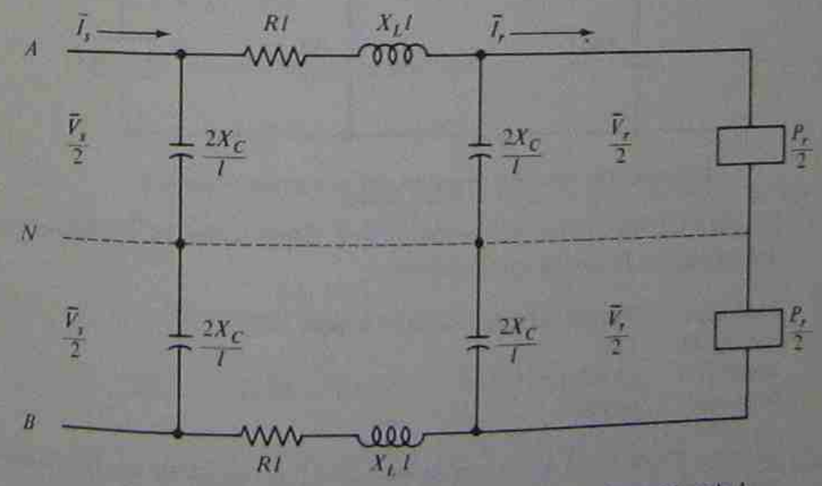


FIG. 5-7. A line-to-neutral model of a single-phase line of length l, showing resistance, inductive reactance, and capacitive reactance.

A study of Fig. 5-7 shows that the A to N section of this circuit behaves exactly like the B to N section, except that the voltages and currents are 180° displaced from each other in the two sections. It is therefore quite sufficient to study only a single line-to-neutral diagram, as shown in Fig. 5-8.

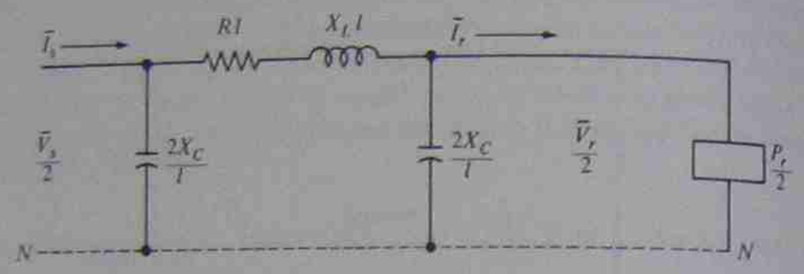


FIG. 5-8. A line-to-neutral model of one leg of a single-phase line. This may be used as the line-to-neutral model of a three-phase line or the single-phase equivalent of a three-phase line.

For many problems, particularly with short lines, the capacitive reactances at the ends of the lines may be omitted. When this is done the circuit reduces to the general power circuit discussed in detail in Chapter 3.

For some purposes it may be desirable to handle a single-phase line on a total circuit basis rather than on a line-to-neutral basis. For this purpose the diagram of Fig. 5-7 may be modified by the simple omission of the neutral conductor, which of course may not be present physically. The diagram may then be simplified to that of Fig. 5-9. Note that in this diagram all voltages and impedances are *twice* the values of those shown in Fig. 5-8.

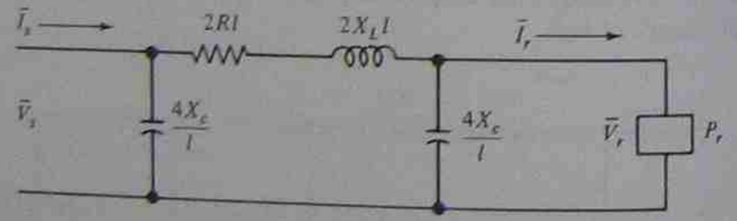


FIG. 5-9. The complete circuit model of a single-phase line.

EXAMPLE 5-2. Determine the constants and π-line model of a single-phase line having the following specifications:

conductor	300,000 cir mil, 19-strand copper
spacing D	12 ft
length l	25 miles
frequency	60 Hz

Solution. From Table A-2 it may be seen that this conductor has the following characteristics:

outside diameter	0.629 in. ($r = 0.0262$ ft)
geometric mean radius	0.01987 ft
resistance per mile	0.1966 Ω (at 25°C)

R_t, total resistance (per conductor) is $R \times l$, or

$$R_t = 0.1966 \times 25 = 4.92\ \Omega$$

The inductance (per conductor) is

$$L = 0.741 \times 10^{-3} \log_{10} \frac{D}{\text{GMR}} \tag{5-3}$$

$$= 0.741 \times 10^{-3} \log_{10} \frac{12}{0.01987}$$

$$= 2.06 \times 10^{-3}\ \text{H/mile}$$

The total inductance per conductor is, therefore,

$$L_t = L \times l = (2.06 \times 10^{-3})(25)$$

$$= 51.5 \times 10^{-3}\ \text{H}$$

The capacitance (per conductor) is

$$C = \frac{0.0388}{\log_{10} (D/r)} \tag{5-6}$$

$$= \frac{0.0388}{\log (12/0.0262)}$$

$$= 0.0146\ \mu\text{F/mile}$$

The total capacitance per conductor is

$$C_t = C \times l = 0.0146 \times 25 = 0.365\ \mu\text{F}$$

The π-line circuit model (line to neutral) with half of the capacitance on each end is as shown in Fig. 5-10. If the line operates at 60 Hz, the impedances are

$$X_L = 2\pi fL = 2\pi 60 \times 51.5 \times 10^{-3} = 19.4\ \Omega$$

$$X_C = \frac{1}{2\pi fC} = \frac{10^6}{2\pi 60 \times 0.365/2} = 14{,}500\ \Omega$$

and the line may be represented (line to neutral) as in Fig. 5-11. On a total line basis, these values are all increased by the factor 2, and the circuit becomes as shown in Fig. 5-12.

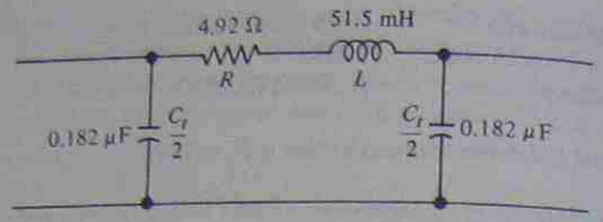


FIG. 5-10. π-line circuit model showing resistance, inductance, and capacitance, line-to-neutral.

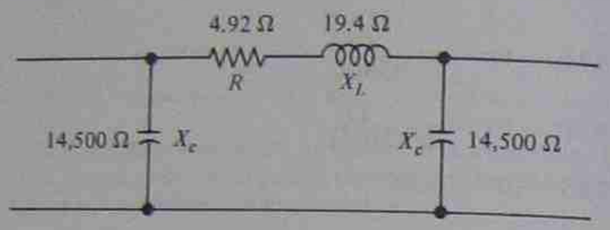


FIG. 5-11. Sixty-hertz line-to-neutral circuit model of Fig. 5-10.

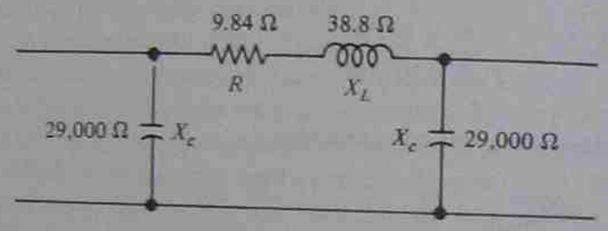


FIG. 5-12. Total circuit model.

e. Constants of Three-Phase Lines. The equations for calculating the resistance, inductive reactance, and capacitive reactance of a single-phase line on a line-to-neutral (or per conductor) basis apply equally well to the determination of these quantities for a three-phase line treated on a line-to-neutral basis, as was discussed in Section 3-7. As shown in Section 3-8, the line-to-neutral circuit model may be used as the single-phase equivalent of the three-phase circuit by appropriate modifications of currents and voltages.

Equations (5-4) and (5-7) for the calculations of inductive reactance and capacitive reactance each involve the term D, the distance between conductors. In a three-phase circuit, shown in cross section in Fig. 5-13, there are three conductors, X, Y, and Z, which have unequal separation. Symmetry may be in good measure regained by transposition. This consists of interchanging the conductor positions at regular intervals along the line. For lines that are transposed (and with but little error for lines that are not transposed) the distance D may be determined by the relation

$$D = \sqrt[3]{D_{XY}D_{YZ}D_{ZX}} \tag{5-8}$$

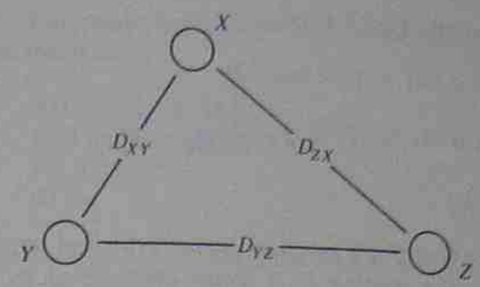


FIG. 5-13. A three-phase power line with unequal spacings between the three conductors X, Y, and Z.

On ultra-high-voltage (UHV) lines, the conductors X, Y, and Z may each be made up of several cables, as shown in Fig. 5-14, a type of construction known as *bundle conductors*. If all of these smaller cables are identical and are symmetrically spaced around a circumscribing circle as shown, it is possible to calculate an *equivalent conductor radius*. For inductive reactance

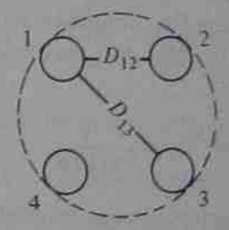


FIG. 5-14. A conductor formed by a bundle of four cables.

calculations the equivalent geometric mean radius is given by Eq. (5-9). In this equation GMR_1 is the GMR applying to the individual cables making up the bundle. Capacitive reactance calculations are made using an equivalent radius given by Eq. (5-10), in which r_1 is the physical radius of the individual cables making up the bundle. With these two modifications, Eqs. (5-4) and (5-7) may be used to calculate the inductive reactance and the capacitive reactance per mile of line.

$$\text{GMR}_{eq} = \sqrt[n]{\text{GMR}_1 D_{12} D_{13} \cdots D_{1n}} \tag{5-9}$$

$$r_{eq} = \sqrt[n]{r_1 D_{12} D_{13} \cdots D_{1n}} \tag{5-10}$$

f. Tables of Line Constants. Data have been prepared in tabular form which make possible determination of overhead-line constants without resorting to use of equations for calculation. The construction of these tables may be explained by reference to Eqs. (5-4) and (5-7). From the well-known relation

$$\log \frac{A}{B} = \log A + \log \frac{1}{B}$$

it is possible to rewrite Eq. (5-4) as

$$X_L = 2\pi f \times 0.741 \times 10^{-3} \log_{10} D + 2\pi f \times 0.741 \times 10^{-3} \log_{10} \frac{1}{\text{GMR}} \tag{5-11}$$

$$X_L = X_d + X_a \tag{5-12}$$

We may note that (for a given frequency) the first term of Eq. (5-11) is dependent only on the spacing D, a factor determined by the geometrical arrangement of the conductors. The second term of Eq. (5-11) (for a given frequency) is dependent only on the GMR, a value which depends upon the particular conductor design selected for the line. It is therefore possible to make a tabulation (Table A-4) in which the value of

$$X_d = 2\pi f \times 0.741 \times 10^{-3} \log_{10} D \tag{5-13}$$

is represented for each of a number of different values of D covering the range of conductor separations that might be expected in practical line construction. Other tabulations (Tables A-2 and A-3) may be prepared showing the value of

$$X_a = 2\pi f \times 0.741 \times 10^{-3} \log_{10} \frac{1}{\text{GMR}} \tag{5-14}$$

for each of the many conductor designs available for use in construction. Now, to determine X_L for a given line design, it is only necessary to select the appropriate value of X_d from Table A-4 and to add it to the appropriate value of X_a obtained from Table A-2 or A-3.

The preparation of tables for the determination of capacitive reactance may be explained by rewriting Eq. (5-7) as

$$X_a = \frac{10^6}{2\pi f \times 0.0388} \log_{10} D + \frac{10^6}{2\pi f \times 0.0388} \log_{10} \frac{1}{r} \tag{5-15}$$

$$X_c = X'_d + X'_a \tag{5-16}$$

$$X'_d = \frac{10^6}{2\pi f \times 0.0388} \log_{10} D \tag{5-17}$$

$$X'_a = \frac{10^6}{2\pi f \times 0.0388} \log_{10} \frac{1}{r} \tag{5-18}$$

Values of X'_d are shown in Table A-5. Values of X'_a are shown in Tables A-2 and A-3. To determine the capacitive reactance for a mile of line it is only necessary to select the appropriate value of X'_a and add to it the appropriate value of X'_d.

EXAMPLE 5-3. Determine the constants of a three-phase line having the following specifications:

conductor	900,000 cir mil ACSR
spacing	14 ft horizontally ○ 14 ft ○ 14 ft ○
length l	125 miles
frequency	60 Hz

Solution. For computation purposes the spacing D is determined by

$$D = \sqrt[3]{D_{XY} D_{YZ} D_{ZX}} = \sqrt[3]{14 \times 14 \times 28} = 17.6 \text{ ft} \tag{5-8}$$

From here on the determination of the impedance values for the circuit model could proceed by the method shown in Example 5-2. Instead, we shall make use of tabular values. From Table A-3 we obtain the following values:

resistance per mile (60 Hz) = 0.104 ohm
$X_a = 0.393$ ohm/mile
$X'_a = 0.0898$ megohm-mile

From Table A-4 we obtain for $D = 17.6$ ft, 60 Hz,

$X_d = 0.3480$ ohm/mile (by interpolation)

From Table A-5 we obtain for $D = 17.6$ ft, 60 Hz,

$X'_d = 0.0851$ megohm-mile

Then, by Eq. (5-12),

$X_L = X_d + X_a = 0.348 + 0.393 = 0.741$ ohm per mile

and, by Eq. (5-16),

$X_c = X'_d + X'_a = 0.0851 + 0.0898 = 0.1749$ megohm-miles

The line-to-neutral circuit model may now be formed (see Fig. 5-15) exactly as was done for the single-phase line (Fig. 5-8).

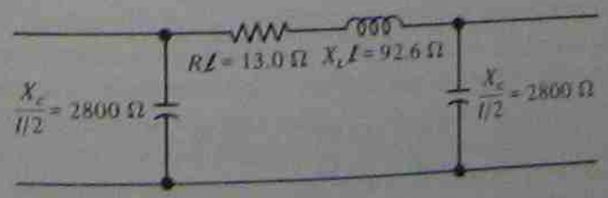


FIG. 5-15. π-line circuit model of line, Example 5-3. Line-to-neutral.

Problems pertaining to balanced three-phase loads may be solved using the circuit model of Example 5-2, as was discussed in Section 3-7. The capacitor on the right may be regarded as an addition to the load, the one on the left as an addition to the load seen by the source. For some problems the capacitors on the ends of the model may be neglected.

Figure 5-15 may also be regarded as representing the single-phase equivalent of the three-phase system. Computations may be handled as discussed in Section 3-8, with consideration being given to the capacitors as discussed in the preceding paragraph. A calculation of this type follows.

EXAMPLE 5-4. Suppose that the three-phase load on the end of the line is 12,000 kilowatts, unity power factor, supplied at 120 kilovolts (Fig. 5-16).

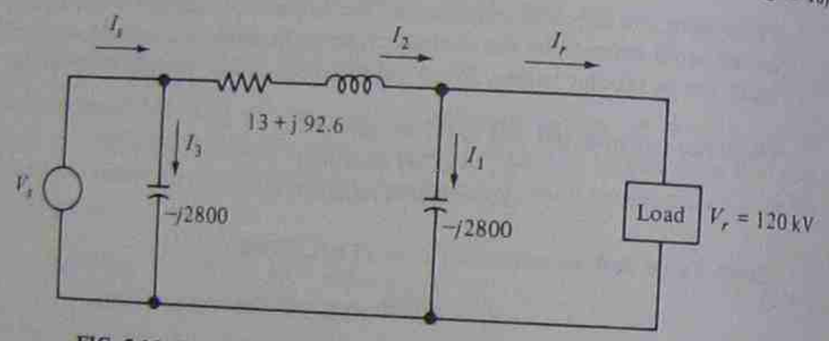


FIG. 5-16. Line of Example 5-3 carrying load. Single-phase equivalent model.

Considering the single-phase equivalent solution,

$$\bar{V}_r = 120{,}000 \underline{/0^\circ} \text{ V}$$

$$I_r = \frac{P}{V \cos \phi} = \frac{12{,}000{,}000}{120{,}000 \times 1} = 100 \text{ A}$$

$$\bar{I}_r = 100 \underline{/0^\circ} \text{ A}$$

$$\bar{I}_1 = \frac{\bar{V}_r}{-jX_{C1}} = \frac{120{,}000 /0^\circ}{-j2800} = j42.9 \text{ A}$$

$$\bar{I}_2 = \bar{I}_r + \bar{I}_1 = 100 + j42.9 = 109 \underline{/23.2^\circ} \text{ A}$$

$$\bar{V}_s = \bar{V}_r + \bar{I}_2 Z$$
$$= 120{,}000 + (100 + j42.9)(13 + j92.6)$$
$$= 120{,}000 - 2670 + j9820$$
$$= 117{,}300 + j9820 = 117{,}700 \underline{/4.8^\circ} \text{ V}$$

$$\bar{I}_3 = \frac{\bar{V}_s}{-jX_{C3}} = \frac{117{,}300 + j9820}{-j2800} = -3.51 + j41.9 \text{ A}$$

$$\bar{I}_s = \bar{I}_2 + \bar{I}_3$$
$$= 100 + j42.9 - 3.51 + j41.9 = 96.5 + j84.8$$
$$= 128.5 \underline{/41.3^\circ} \text{ A}$$

$$\cos \phi_s = \cos(41.3^\circ - 4.8^\circ) = \cos 36.5^\circ = 0.804$$
$$P_s = V_s I_s \cos \phi_s = 117{,}700 \times 128.5 \times 0.804$$
$$= 12{,}160 \text{ kW}$$

In the actual three-phase system (see Section 3-8),

$$I_r = \frac{100}{\sqrt{3}} = 57.7 \text{ A}$$

$$I_s = \frac{128.5}{\sqrt{3}} = 74.2 \text{ A}$$

5-3. CABLES—PORTABLE, OVERHEAD, UNDERGROUND

Insulated cables have many applications in the field of electric power. Small cables are used as extension cords around offices, homes, and factories. Larger cables are used for connections to machines that are movable over restricted distances. In some instances *portable cables* carry quite heavy electrical loads, as for example the case of electrically driven drag lines, which require several thousand horsepower for operation. *Overhead cables* find application in distribution circuits where tree conditions or proximity to buildings and other structures make the use of open-wire lines impracticable. *Underground cables* are used in many situations, including major transmission circuits between large stations. Some cable power circuits operate at 765 kilovolts and carry loads of several hundred megawatts. Cables of even higher voltage will probably become available soon.

The characteristics of cables are quite different from those of overhead lines of the same voltage class. As the conductors of cables are much closer together than are those of overhead lines, the inductance and inductive reactance of cables are much smaller than similar quantities for overhead lines. In some instances the resistance of a cable may be larger in magnitude than its inductive reactance. The close spacing of conductors and the presence of solid insulation between them results in the capacitance of cables being much greater per unit length than that of overhead lines. As a consequence, the capacitive reactance of cables is much lower. For this reason care must be taken in using the short-line method of solution for problems involv-

ing cable circuits. Even though a cable is only a few miles long, many problems will demand the use of the π-line or T-line circuit model for satisfactory computation.

a. Typical Power Cables. Some typical power cables are shown in Fig. 5-17.

FIG. 5-17. Some typical insulated power cables.

The conductors of insulated cables are almost always made of copper. For the same resistance per foot of length, conductors of copper are smaller than conductors of aluminum, with the result that a smaller weight of insulating material is required. Even though copper is, under present market conditions, more expensive than aluminum, the savings in the cost of insulation and the increased flexibility of smaller diameters make copper preferable to aluminum in the design of most high-voltage power cables. Underground cables using sodium as the conductor material are in limited use as distribution primary feeders.

The insulation used in power cables depends upon the application and cost. Portable cables are commonly insulated with natural or artificial rubber, a material that will stand repeated flexing even at very low temperatures. However, because of rapid deterioration of chemical structure, it cannot be used at high temperatures. Cables to be used at high temperatures may be insulated with asbestos or glass fiber.

High-voltage cables for carrying large blocks of power are frequently insulated with *oil-impregnated paper*. Other materials, such as cross-linked polyethylene, are coming into very general use for this purpose. Cables have been built using a gas, such as sulfur hexafluoride, under pressure for the insulation.

b. Calculation of Cable Constants. A *coaxial cable* consists of a center conductor (solid, stranded, or hollow) which is separated by insulation from a hollow cylindrical outer conductor (Fig. 5-18). The resis-

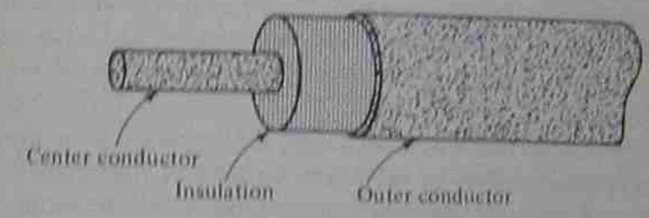


FIG. 5-18. A coaxial cable.

tance to the flow of direct current may be calculated by Eq. (2-9), proper consideration being given to the area of the center conductor and the area of the outer conductor. For alternating current flow, the resistance will be higher, increasing by a few percent for 60 hertz to several hundred percent for high frequencies due to skin effect.

The inductance of a coaxial cable may be determined with fair accuracy by

$$L = 0.741 \times 10^{-3} \log_{10} \frac{D_o}{D_i} \quad \text{henrys/mile} \tag{5-19}$$

where D_o is the inside diameter of the outer conductor and D_i the outside diameter of the inner conductor. The capacitance of a coaxial cable may be determined by

$$C = \frac{0.0388k}{\log_{10} (D_o/D_i)} \quad \text{microfarads/mile} \tag{5-20}$$

where k is the relative permittivity which may have a value from 1.0 to 6.0, depending on the material of the insulation.

Coaxial cables find limited application in the electric power field. Those of the types shown in Fig. 5-17 are in common use. The constants of such cables cannot be determined by simple mathematic relations.

c. Tables of Cable Constants. The manufacturers and users of electric cables have determined the cable constants by advanced mathematical methods and by tests. Table A-6 presents the circuit constants of cables of selected designs. For reliable computations, data on cable constants for a particular design should be obtained from the manufacturer.

5-4. CHARACTERISTICS OF SYNCHRONOUS MACHINES

When a synchronous machine is being designed, studies are made which predict the machine's characteristics. After it is built, the machine is tested to determine conformance with the design expectations. From both design and test data, the manufacturer can supply very accurate data on the operating characteristics of the machine. This information can then be used to supply the constants needed in the electric-circuit models of the machine (Section 2-8a).

Engineers concerned with the design and operation of synchronous machines have made studies of the characteristics of machines of different sizes and have found that machine characteristics follow certain patterns dependent on machine kilovolt-ampere rating, voltage, speed, and field construction. Table A-7 lists some of the machine characteristics, arranged according to basic machine features.

In listing typical machine constants, it may be noted that the values given are in percent or per unit rather than in ohms, either of which may be used with the circuit model (Fig. 2-48). The use of percent or per unit quantities in expressing machine characteristics makes possible a great simplification in the tabulation of characteristics.

Each machine constructed has a nameplate rating of voltage and kilovolt-ampere capacity, which form the base quantities for the per unit system applied to each individual machine.

5-5. TRANSFORMER CHARACTERISTICS

The impedance of transformers, when expressed in terms of per unit on their own base, fall in the range from 0.01 to 0.30 per unit. When transformers are classified in terms of voltage and kilovolt-ampere rating, their per unit impedances fall into even narrower ranges. The per unit impedance of almost any single phase transformer may be determined approximately from Table A-8 and Fig. 5-19. From the table it may be noted that smaller low-voltage

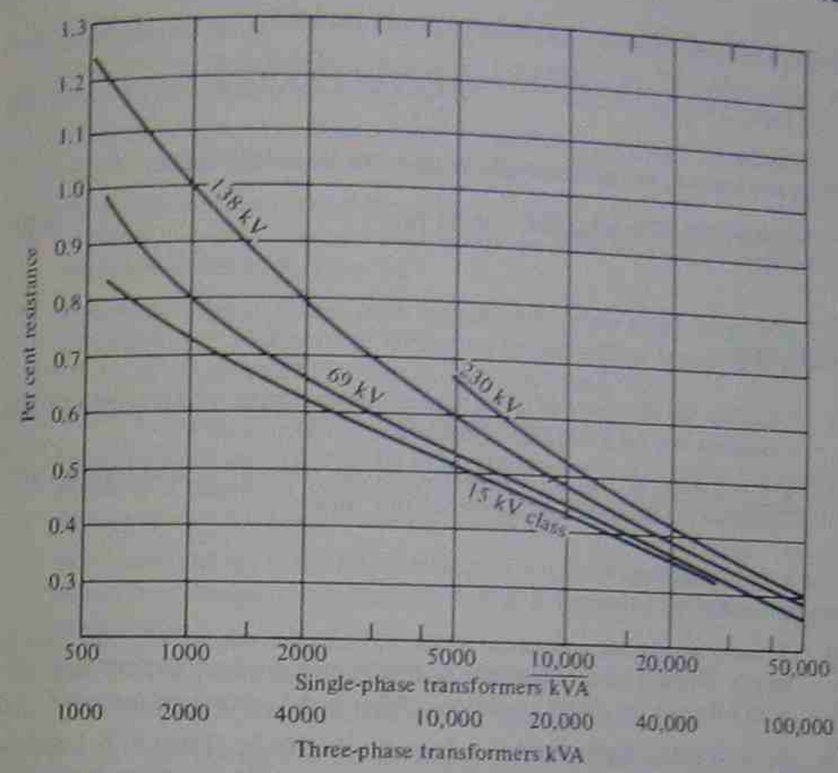


FIG. 5-19. Percent resistance of transformers based on kVA ratings.

transformers have somewhat lower per unit impedance than larger high-voltage transformers.

5-6. CHARACTERISTICS OF INDUCTION MOTORS

The per unit subtransient reactance of an induction motor is the inverse of its blocked-rotor current at rated voltage and frequency. More accurately, it is, with reference to Fig. 2-49, the short-circuit reactance

$$X'' = X_1 + \frac{X_m X_2}{X_m + X_2} \quad \text{per unit} \tag{5-21}$$

This reactance falls in the range 0.15 to 0.25, the lower figure applying to the larger motors (over 50 hp).

The per unit reactance is supposed to be based on the motor rated voltage and rated input volt-ampere. However, the latter rating is often not specified; instead, the rated mechanical output power in horsepower is. For

an input-output efficiency η and input power factor F_p,

$$\text{Input kVA} = \frac{(\text{mechanical output hp})(0.746 \text{ kW/hp})}{\eta F_p} \tag{5-22}$$

When not known, the product ηF_p is taken to be 0.746, that is,

$$\text{Input kVA} = \text{mechanical output hp} \tag{5-23}$$

PROBLEMS

5-1. Calculate the resistance of a bar of hard-drawn copper whose cross section is a square 4 mm on a side and whose length is 120 m at 20°C.

5-2. The diameter of No. 2 hard-drawn copper wire is 0.258 in. (Table A-2). Calculate the resistance of 2 miles of this wire
   a. at 20°C.
   b. at −50°F.
   c. at 120°F.

5-3. A transmission-line conductor is 556,500 circular mil ACSR, 105 miles in length. What is its dc resistance at 25°C small currents, at 50°C large currents? Repeat for 60-Hz conditions. What is the percentage increase?

5-4. A No. 4 solid copper wire has a diameter of 0.204 in. (Table A-2). Calculate the diameter of an aluminum wire having the same resistance per unit of length.

5-5. A single-phase 2-mile line is contructed of No. 2 solid copper wire spaced 5 ft between centers. Solve for the inductance and the 60-Hz inductive reactance per conductor using Eq. (5-1).

5-6. Determine the GMR of a No. 2 solid conductor. Repeat Problem 5-5 using Eq. (5-4).

5-7. Repeat Problem 5-5 using Eq. (5-12) and taking values of X_d and X_a from the tables in Appendix A.

5-8. A 105-mile three-phase 60-Hz 138-kV transmission line is constructed of 556,500 circular mil ACSR conductor spaced 17.5 ft horizontally. Calculate
   a. the equivalent spacing.
   b. the 60-Hz inductive reactance per conductor.

5-9. Refer to Problem 5-5. Solve for the capacitance and the 60-Hz capacitive reactance per conductor using Eqs. (5-6) and (5-7).

5-10. Repeat Problem 5-9 using Eq. (5-16) and taking values of X'_d and X'_a from the appendix tables.

5-11. A 105-mile three-phase 60-Hz transmission line is constructed of 556,500 circular mil ACSR conductor spaced 17.5 ft horizontally. Determine the capacitive reactance per conductor.

5-12. From the results of Problems 5-2, 5-7, and 5-10, construct the π-line equivalent circuit (line to neutral Fig. 5-8) for the single-phase line. Also, construct the total circuit equivalent, Fig. 5-9.

5-13. From the results of Problems 5-3, 5-8, and 5-11, construct the π-line representation (Fig. 5-8) of the 105-mile three-phase line.

5-14. On the basis of the thermal limitations (only) as indicated by "Approximate Current-Carrying Capacity," what maximum kVA load could be carried on the 105-mile line of Problem 5-8?

5-15. Assume that the maximum kVA load at unity power factor is carried on the 105-mile line of Problem 5-8. What sending-end voltage is needed to provide 138 kV at the receiver? Neglect the line capacitance.

5-16. Repeat Problem 5-15, considering the line capacitance.

5-17. How much change in the 60-Hz inductive reactance per mile of line is occasioned by a change in wire size from No. 6 AWG to 1,000,000 circular mil, the line spacing assumed to remain constant?

5-18. How much change in the 60-Hz inductive reactance per mile of line is occasioned by a change of spacing from 4 to 40 ft, assuming the same conductor in all cases?

5-19. Repeat Problem 5-17, with reference to capacitive reactance.

5-20. Repeat Problem 5-18, with reference to capacitive reactance.

5-21. A 15-kV 60-Hz overhead line is constructed of 4/0 copper conductor spaced 4 ft horizontally. Compare the line constants of this overhead line with those of a three-conductor, belted, paper-insulated cable of similar conductor size and voltage rating.

5-22. Determine the R and X (in percent, in per unit, and in ohms) of transformers rated as follows:

3 kVA	2500/240 V
100 kVA	2300/240/120 V
100 kVA	69/22 kV
50,000 kVA	230/138 kV class, oil immersed, self-cooled
50,000 kVA	230/69 kV class, oil immersed, forced oil cooled with forced air cooler

5-23. Determine the synchronous impedance (percent, per unit, and ohms) of a 60,000-kVA 20-kV 3600-rpm turbine generator.

5-24. Determine the reactance (percent, per unit, and ohms) of a 1000-hp 2.4-kV 1160-rpm induction motor.

5-25. Write a computer program that produces the inductive and capacitive reactances per mile of a line, given the distances between conductors and the radius of each conductor.

chapter 6

Assemblies of Power-System Components

6-1. INTRODUCTION

In previous chapters, equivalent circuits of many power-system components were presented and methods described for determining numerical values of the circuit constants that must be assigned for computational purposes. Using the per unit system, it was demonstrated that the constants of different components could be reduced to a unified system of representation. From an examination of the equivalent circuits of the various power-system components, it is obvious that each possesses certain behavior characteristics similar to those described for the basic power circuit. The performance of the basic power circuit was analyzed briefly, by graphical methods, using a transmission diagram based on the phasor representation of voltage and current in the basic power circuit (Chapter 3).

In this chapter we shall look at assemblies of power-system components which on closer examination are seen to be more complicated than the basic power circuit. However, familarity with the behavior of the basic power circuit substantially aids in understanding the behavior of the more complicated components operating individually or in combination with other devices. The practicing power engineer may observe that some of the material presented in this chapter seldom finds direct application in his daily activities. The material of this chapter is presented primarily because of its value in developing an understanding of power-system behavior.

6-2. FOUR-TERMINAL NETWORKS—SPECIAL CASE

A four-terminal network is any assembly of electrical components having two terminals defined as the *input* terminals and two other terminals, defined as the *output* terminals (Fig. 6-1a). In this section we confine our

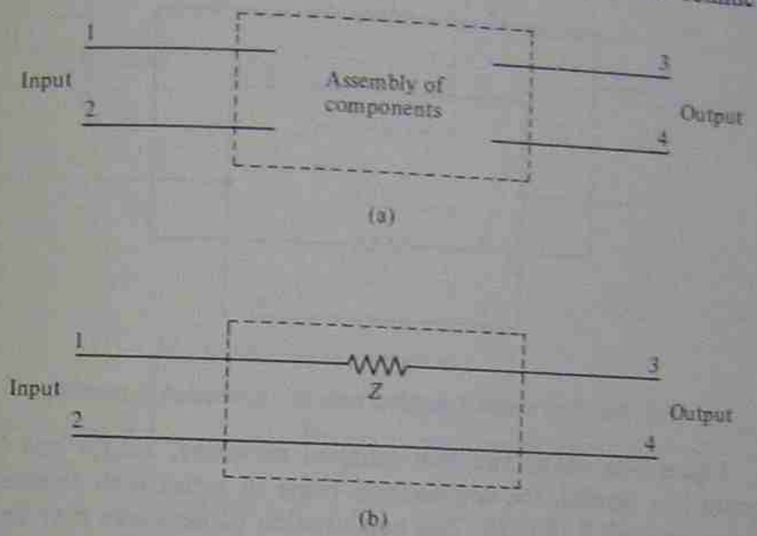


FIG. 6-1. Four terminal networks. (a) A general circuit. Internal connections are not shown. (b) The basic power circuit.

attention to the very simple form of the four-terminal network shown in Fig. 6-1b. It may be noted that in this (special) case, there is within the network no impedance terminating on the conductor, 2-4. It may be recognized at once that the general power circuit is a four-terminal network of this special class.

a. Series, Parallel, and Series–Parallel Connections of Networks. Figure 6-2 shows two four-terminal networks, 1,2,3,4 and 5,6,7,8, connected in simple series (tandem) arrangement. It is obvious that this combination may be reduced to a single four-terminal network containing a single impedance of magnitude Z_a plus Z_b.

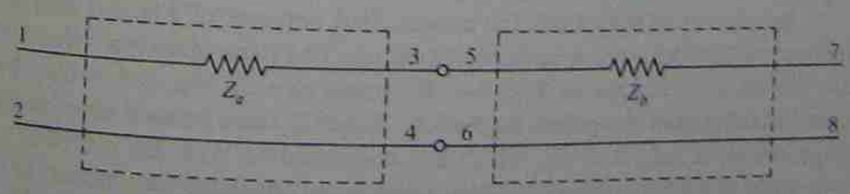


FIG. 6-2. Two simple 4-terminal networks connected in tandem.

Figure 6-3 shows two four-terminal networks 1,2,3,4 and 5,6,7,8 connected in parallel. Again it is obvious that this combination may be reduced to a single network in which there appears an impedance equal to the parallel combination of Z_a and Z_b.

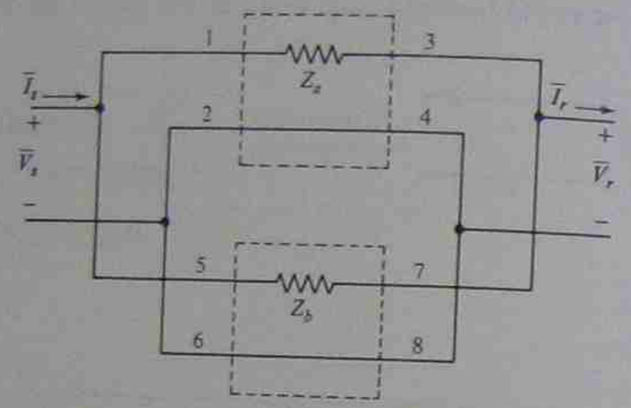


FIG. 6-3. Two simple 4-terminal networks connected in parallel.

Figure 6-4a shows two four-terminal networks, 1,2,3,4 and 5,6,7,8, connected in parallel, the combination being in series with another four-terminal network 9,10,11,12. This combination of networks may be represented in a simpler fashion as shown in Fig. 6-4b. The series–parallel combination of impedances Z_a, Z_b, and Z_c may be reduced to a single equivalent impedance (Fig. 6-1b), which is then the simplest version of the basic power circuit.

b. Networks of Lines from Source to Receiver. A more complicated form of a four-terminal network is shown in Fig. 6-5. Here it may be noted that an extensive array of impedances forms a connection between terminals 1 and 3. Note that again there are no impedances connected to line 2–4. Such an array might be a line-to-neutral representation or an equivalent single-phase representation of a three-phase system in which a number of interconnected overhead lines run from a single source 1–2 to a single receiver 3–4. A representation of this sort implies that the capacitance of the lines is being neglected.

By successive reductions the complicated network of Fig. 6-5 may be reduced to the form of the basic power circuit. The steps of such a reduction are shown by reference to Fig. 6-6. By inspection of Fig. 6-5 it may be noted that between the points marked X, Y, and Z there exists a set of three impedances, Z_e, Z_b, and Z_d, which are connected in wye. By means of a wye–delta transformation, Eq. (2-111), these impedances may be replaced by a delta connection of three other impedances, Z_k, Z_l, and Z_m, shown in Fig.

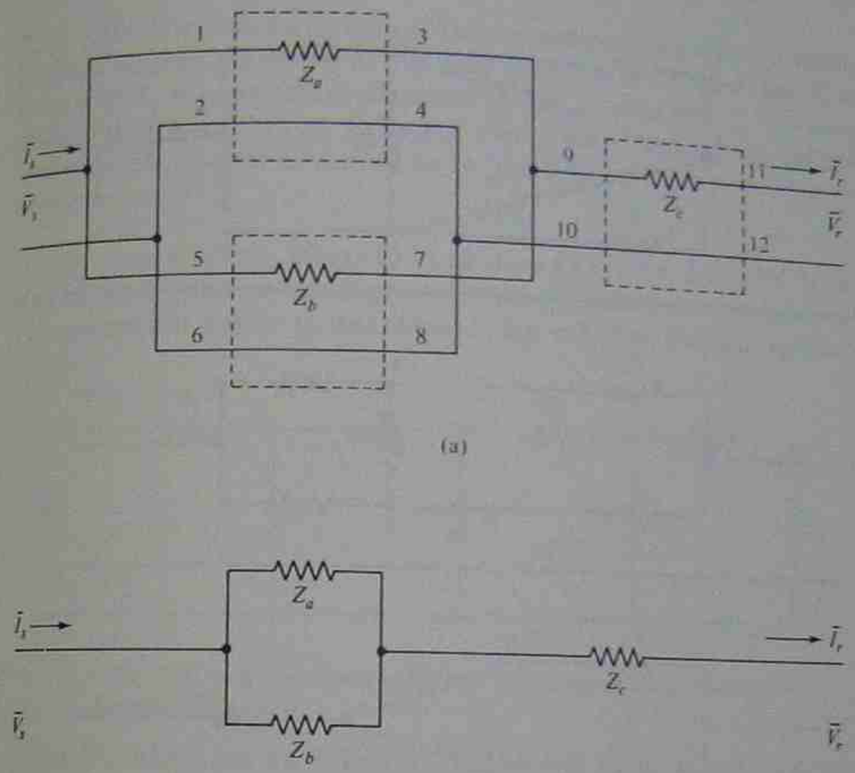


FIG. 6-4. Two simple 4-terminal networks connected in parallel, the combination in tandem with a third simple network. (a) The complete system. (b) A simplified circuit.

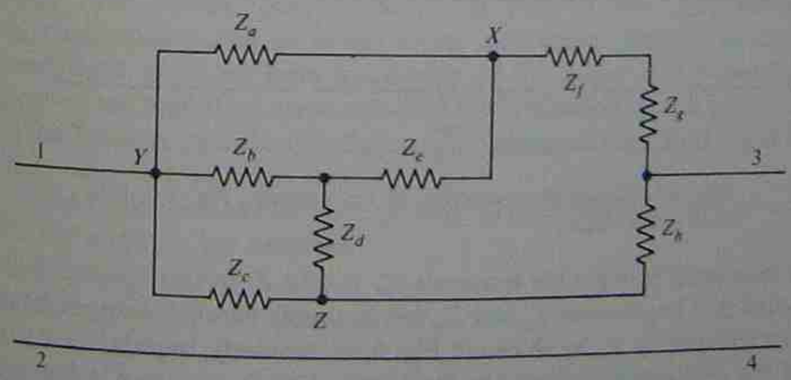


FIG. 6-5. A complicated array of impedances forming a 4-terminal network. Note that terminals 2 and 4 are directly connected.

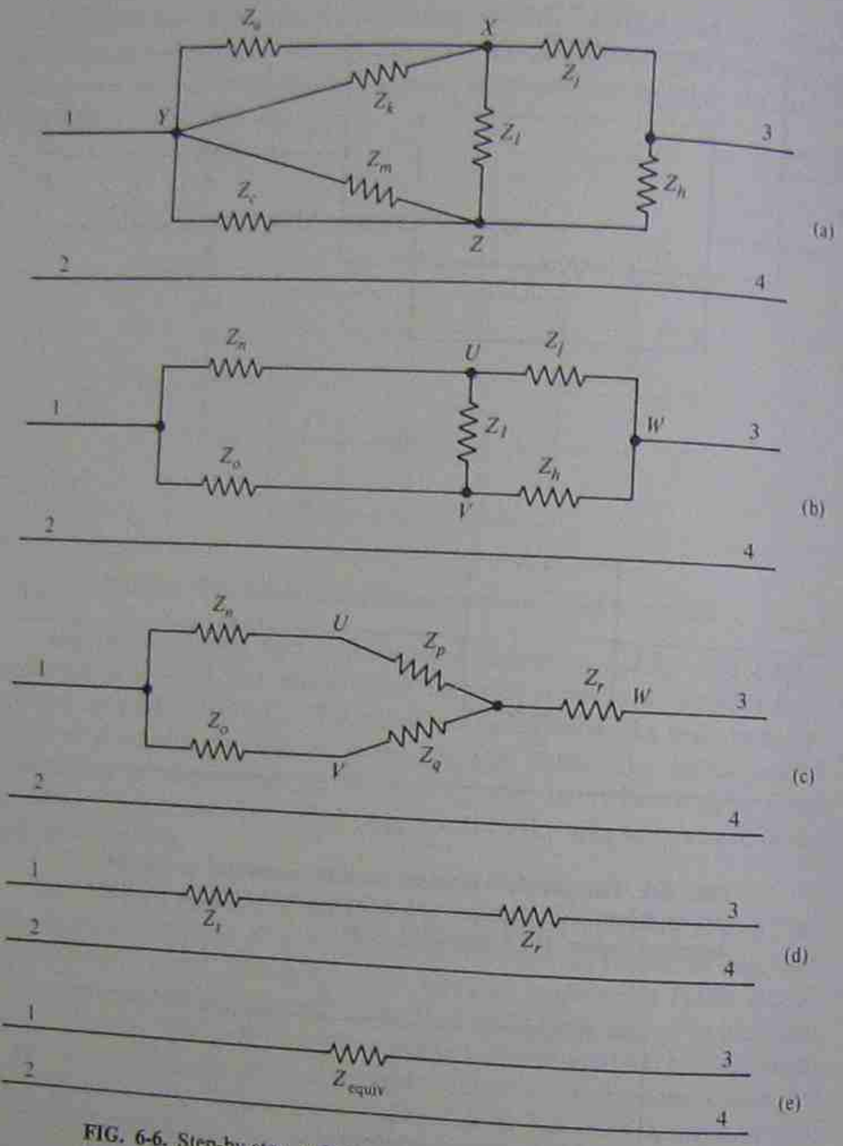


FIG. 6-6. Step-by-step reduction of the network, Fig. 6-5, to a basic power circuit.

6-6a, connected between the terminals X, Y, and Z. In this diagram it may be noted that impedances Z_a and Z_k are in simple parallel arrangement and can be replaced by Z_n, as shown in Fig. 6-6b. Similarly, impedances Z_m and Z_c of Fig. 6-6a may be replaced by their equivalent Z_o, as shown in Fig. 6-6b.

On inspection of Fig. 6-6b it may be seen that between the terminals U, V, and W there is a delta arrangement of three impedances, Z_j, Z_l, and

Z_h. A delta–wye transformation of these impedances, Eq. (2-110), results in a new diagram, as shown in Fig. 6-6c. Here it may be noted that Z_n in series with Z_p is in parallel combination with Z_o in series with Z_q. Reducing these to their equivalent Z_r yields Fig. 6-6d. This in turn may be reduced to the final equivalent circuit shown in Fig. 6-6e, which is now the basic power circuit.

c. Line with Distributed Loads—The Ladder Network. In distribution circuit practice, there sometimes occurs a *ladder-circuit arrangement* similar to that shown in Fig. 6-7. This diagram represents

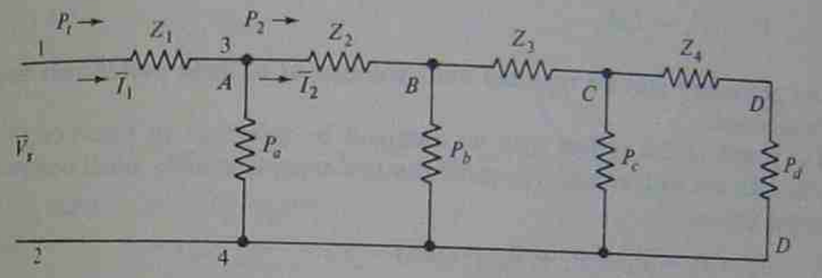


FIG. 6-7. A ladder network similar to a distribution circuit feeding several loads.

a long line which has loads connected at several points spaced randomly along its length. This arrangement may be regarded as a series of basic power circuits each in turn having as its load another circuit. For example, between terminals 1,2,3,4 we observe a single impedance Z_1 forming a basic power circuit. The load on this circuit is the entire system to the right of terminals 3-4. A problem of practical importance may be illustrated by means of this network. Suppose that at the source station the voltage V_s is known. Suppose also that from station instruments the total power output and its power factor are known. Suppose further that at each load point we have knowledge of the power and power factor. As one of the important responsibilities of distribution-system operation, it may be desirable to calculate the supply voltage at each load point. This can be done in a series of steps.

Let V_s be used as reference. I_1 may be determined in terms of magnitude and angle by the relations

$$\bar{I}_1 = \frac{P_t}{V_s F_{pt}} \underline{/\theta_t} \qquad \theta_t = \cos^{-1} F_{pt}$$

The voltage at point A may then be calculated by the relation

$$\bar{V}_a = \bar{V}_s - \bar{I}_1 Z_1 = V_a \underline{/\beta_a}$$

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The magnitude and angle of the current supplied to the load at A may be calculated by the relations

$$\bar{I}_a = \frac{P_a}{V_a F_{pa}} \underline{/\theta_a + \beta_a} \qquad \theta_a = \cos^{-1} F_{pa}$$

The current I_2 and the voltage at load B may then be calculated by the relations

$$\bar{I}_2 = \bar{I}_1 - \bar{I}_a$$

$$\bar{V}_b = \bar{V}_a - \bar{I}_2 Z_2$$

The procedure may be repeated until voltages at all load points have been determined.

The losses in the system may be obtained by reference to Equation (6-1), although not with accuracy because the loss term is usually small compared to the others.

$$P_t = P_a + P_b + P_c + P_d + \text{losses} \tag{6-1}$$

A determination of greater accuracy might be made by calculating the losses in each line section from known currents and circuit resistances.

It is obvious that this problem could also be worked by beginning at the extreme load end of the line if the conditions there were known or assumed. A calculation proceeding through this system from right to left would then give information as to the required conditions at the source station.

EXAMPLE 6-1. Determine voltage condition on a system of the type shown in Fig. 6-7, assuming that

$V_s = 5000$ V

$P_1 = 600$ kW 0.8 power-factor lag

$Z_1 = 4 \underline{/70^\circ}\ \Omega$

$P_2 = 400$ kW 0.707 power-factor lag

$Z_2 = 2.5 \underline{/60^\circ}\ \Omega$

Solution.

a. At the source,

$$I_1 = \frac{P_1}{V_s \cos \varphi_1} = \frac{600{,}000}{5000 \times 0.8} = 150 \text{ A}$$

Considering V_s as reference,

$$\bar{V}_s = 5000 \underline{/0^\circ} \text{ V}$$

$$I_1 = 150 \underline{/-36.9^\circ} \text{ A}$$

$$I_1 Z_1 = 150 \underline{/-36.9^\circ} \times 4 \underline{/70^\circ} = 600 \underline{/33.1^\circ} \text{ V}$$

$$\bar{V}_A = \bar{V}_s - I_1 Z_1 = 5000 \underline{/0^\circ} - 600 \underline{/33.1^\circ}$$

$$= 5000 + j0 - (503 + j328)$$

$$= 4497 - j328$$

$$= 4510 \underline{/-4.2^\circ} \text{ V}$$

b. At A,

$$I_2 = \frac{P_2}{V_A \cos \varphi_2} = \frac{400{,}000}{4510 \times 0.707} = 125 \text{ A}$$

Since $\bar{V}_A = 4510 \underline{/-4.2^\circ}$ V,

$$I_2 = 125 \underline{/-45^\circ - 4.2^\circ} = 125 \underline{/-49.2^\circ} \text{ A}$$

$$I_2 Z_2 = 125 \underline{/-49.2^\circ} \times 2.5 \underline{/60^\circ} = 313 \underline{/10.8^\circ} = 307 + j58.7 \text{ V}$$

$$\bar{V}_B = \bar{V}_A - I_2 Z_2 = 4497 - j328 - (307 + j58.7)$$

$$= 4190 - j387$$

$$= 4210 \underline{/-5.3^\circ} \text{ V}$$

This method of solution could be carried on to all sections of the line if desired.

6-3. FOUR-TERMINAL NETWORKS; A, B, C, D CONSTANTS

a. General Four-Terminal Network. The general four-terminal network is described with the aid of Fig. 6-8. This network is described by two source-terminals between which there is a voltage V_s and through which a current I_s flows, as shown in the diagram. There are also

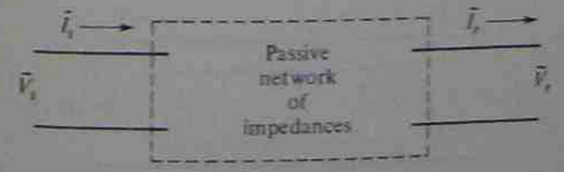


FIG. 6-8. The general 4-terminal network consisting of passive impedances connected in any fashion.

two receiver-terminals between which the voltage is $\bar{V}_r$ and through which the current $\bar{I}_r$ flows. The network consists of any arrangement of electrical components. We shall limit this discussion to any array in which all are passive elements; that is, there are no current or voltage sources within the network. Unlike the simple network treated in Section 6-2, the arrangement of components may be such that the current $\bar{I}_s$ is quite different from the current $\bar{I}_r$.

From general network theory (not presented here) it can be shown that, at the terminals, the behavior of the network may be specified by equations having the form

$$\bar{V}_s = A\bar{V}_r + B\bar{I}_r \tag{6-2}$$

$$\bar{I}_s = C\bar{V}_r + D\bar{I}_r \tag{6-3}$$

$$AD - BC = 1 \tag{6-4}$$

In general, all terms in these equations are *complex numbers*. For a given network, A, B, C, and D are constants. From Eqs. (6-2) and (6-3) it may be concluded that if values are assigned to any two of the terms $\bar{V}_s$, $\bar{V}_r$, $\bar{I}_s$, and $\bar{I}_r$, the other two of the four terms are uniquely determined. Equation (6-4) shows that A, B, C, and D are themselves interrelated.

It is the purpose of this section to analyze the nature of four-terminal networks and to become familiar with their characteristics. In many instances a complicated four-terminal network may, on examination, be found to be an assembly of simpler four-terminal networks. In this situation it is possible to approach the determination of the values of A, B, C, and D for the complicated network by manipulating the constants applicable to the several simpler networks forming the whole. We shall, therefore, determine the constants of several of the simple basic networks and then examine some of the methods by which they may be put into combination to form more complicated systems.

b. Series Impedance. Our study of the basic power circuit containing a simple series impedance (Fig. 6-9) is, in fact, an analysis of one of the elementary forms of the four-terminal network. For the network in

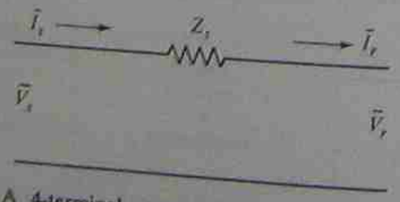


FIG. 6-9. A 4-terminal network consisting of a single series impedance.

Fig. 6-9 we may write expressions for $\bar{V}_s$ and $\bar{I}_s$ in terms of $\bar{V}_r$ and $\bar{I}_r$ as follows:

$$\bar{V}_s = \bar{V}_r + Z_s\bar{I}_r$$

$$\bar{I}_s = 0\bar{V}_r + \bar{I}_r$$

A comparison of these two equations with Eqs. (6-2) and (6-3) permits us to write the A, B, C, and D constants as follows:

$$A = 1.0 \qquad B = Z_s \qquad C = 0 \qquad D = 1.0 \tag{6-5}$$

c. Shunt Admittance. Another simple four-terminal network consists of a single shunt admittance, Y_p, connected as shown in Fig. 6-10.

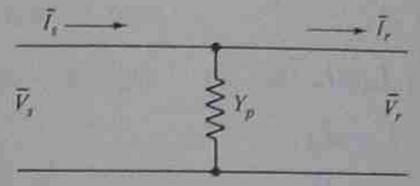


FIG. 6-10. A 4-terminal network consisting of a single shunt admittance.

For this network we may write expressions for $\bar{V}_s$ and $\bar{I}_s$ in terms of $\bar{V}_r$ and $\bar{I}_r$ as follows:

$$\bar{V}_s = \bar{V}_r + 0\bar{I}_r$$

$$\bar{I}_s = Y_p\bar{V}_r + \bar{I}_r$$

Again comparing these equations with Eqs. (6-2) and (6-3) we may declare values of A, B, C, and D as follows:

$$A = 1.0 \qquad B = 0 \qquad C = Y_p, \qquad D = 1.0 \tag{6-6}$$

d. Two Four-Terminal Networks in Tandem. Two four-terminal networks may be connected in tandem as shown in Fig. 6-11, to form a new four-terminal network. Here it is assumed that network

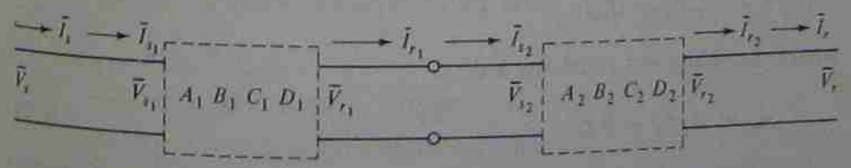


FIG. 6-11. Two general 4-terminal networks connected in tandem.

1 has the constant A_1, B_1, C_1, and D_1, while network 2 has the the constant A_2, B_2, C_2, and D_2. The two in combination form a system that has input $\bar{V}_s$ and $\bar{I}_s$ and output $\bar{V}_r$ and $\bar{I}_r$. Considering only network 2 we may write

$$\bar{V}_{s2} = A_2\bar{V}_{r2} + B_2\bar{I}_{r2} = A_2\bar{V}_r + B_2\bar{I}_r$$

$$\bar{I}_{s2} = C_2\bar{V}_{r2} + D_2\bar{I}_{r2} = C_2\bar{V}_r + D_2\bar{I}_r$$

Considering only network 1 we may write

$$\bar{V}_{s1} = A_1\bar{V}_{r1} + B_1\bar{I}_{r1}$$

$$\bar{I}_{s1} = C_1\bar{V}_{r1} + D_1\bar{I}_{r1}$$

Noting that

$$\bar{V}_s = \bar{V}_{s1} \qquad \bar{I}_s = \bar{I}_{s1}$$

$$\bar{V}_{r1} = \bar{V}_{s2} \qquad \bar{I}_{r1} = \bar{I}_{s2}$$

$$\bar{V}_{r2} = \bar{V}_r \qquad \bar{I}_{r2} = \bar{I}_r$$

we may write that

$$\bar{V}_s = A_1(A_2\bar{V}_r + B_2\bar{I}_r) + B_1(C_2\bar{V}_r + D_2\bar{I}_r)$$

$$\bar{I}_s = C_1(A_2\bar{V}_r + B_2\bar{I}_r) + D_1(C_2\bar{V}_r + D_2\bar{I}_r)$$

Collecting terms necessary to put the expressions for $\bar{V}_s$ and $\bar{I}_s$ in standard form we have

$$\bar{V}_s = (A_1A_2 + B_1C_2)\bar{V}_r + (A_1B_2 + B_1D_2)\bar{I}_r \tag{6-7}$$

$$\bar{I}_s = (C_1A_2 + D_1C_2)\bar{V}_r + (C_1B_2 + D_1D_2)\bar{I}_r \tag{6-8}$$

these equations in turn may be rewritten as

$$\bar{V}_s = A_{eq}\bar{V}_r + B_{eq}\bar{I}_r$$

$$\bar{I}_s = C_{eq}\bar{V}_r + D_{eq}\bar{I}_r$$

where the equivalent constants are

$$A_{eq} = A_1A_2 + B_1C_2 \tag{6-9}$$

$$B_{eq} = A_1B_2 + B_1D_2 \tag{6-10}$$

$$C_{eq} = C_1A_2 + D_1C_2 \tag{6-11}$$

$$D_{eq} = C_1B_2 + D_1D_2 \tag{6-12}$$

The above equations permit us to evaluate the equivalent A, B, C, and D constants for two known networks connected in tandem. Attention must be directed to the facts that the order in which the networks are connected in tandem is of importance. If in Fig. 6-11 the two networks 1 and 2 had been interchanged in position, the equivalent constants would be different from those given in Eqs. (6-9) to (6-12).

EXAMPLE 6-2. Determine the equivalent $ABCD$ constants of network 1 connected in tandem with network 2 as indicated in Fig. 6-12.

Solution.

a. In network 1, by Eq. (6-5),

$$A_1 = 1.0 \qquad B_1 = 20\angle 30^\circ\ \Omega \qquad C_1 = 0\mho \qquad D_1 = 1.0$$

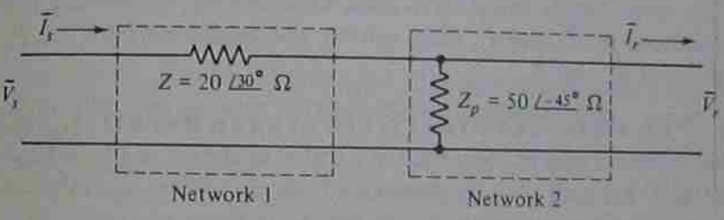


FIG. 6-12. Two networks in tandem, Example 6-2.

b. In network 2,

$$Y_P = \frac{1}{Z_P} = \frac{1}{50\angle -45^\circ} = 0.02\angle 45^\circ \text{ mho}$$

By Eq. (6-6),

$$A_2 = 1.0 \qquad B_2 = 0 \qquad C_2 = 0.02\angle 45^\circ \qquad D_2 = 1.0$$

c. Combining the two networks, by Eq. (6-9),

$$\begin{aligned} A_{eq} &= A_1A_2 + B_1C_2 \\ &= 1.0 \times 1.0 + 20\angle 30^\circ \times 0.02\angle 45^\circ \\ &= 1.0 + 0.4\angle 75^\circ = 1.0 + 0.104 + j0.386 \\ &= 1.104 + j0.386 = 1.17\angle 19.3^\circ \end{aligned}$$

By Eq. (6-10),

$$B_{eq} = A_1B_2 + B_1D_2$$
$$= 1.0\underline{/0^\circ} \times 0 + 20\underline{/30^\circ} \times 1.0\underline{/0^\circ}$$
$$= 20\underline{/30^\circ}\ \Omega$$

By Eq. (6-11),

$$C_{eq} = C_1A_2 + D_1C_2$$
$$= 0 \times 1.0 + 1.0 \times 0.02\underline{/45^\circ}$$
$$= 0.02\underline{/45^\circ}\ \mho$$

By Eq. (6-12),

$$D_{eq} = C_1B_2 + D_1D_2$$
$$= 0 \times 0 + 1.0 \times 1.0$$
$$= 1.0\ \underline{/0^\circ}$$

The same results could have been obtained by considering receiver-end conditions as $\bar{V}_r$ and $\bar{I}_r$, then solving the ladder network for $\bar{V}_s$ and $\bar{I}_s$ in terms of $\bar{V}_r$ and $\bar{I}_r$.

e. Two Four-Terminal Networks in Parallel. Two four-terminal networks may be connected in parallel as shown in Fig. 6-13. A new four-terminal network may be determined which will be equivalent in performance to the two networks in parallel. Note that

$$\bar{V}_{s1} = \bar{V}_{s2} = \bar{V}_s$$
$$\bar{V}_{r1} = \bar{V}_{r2} = \bar{V}_r$$

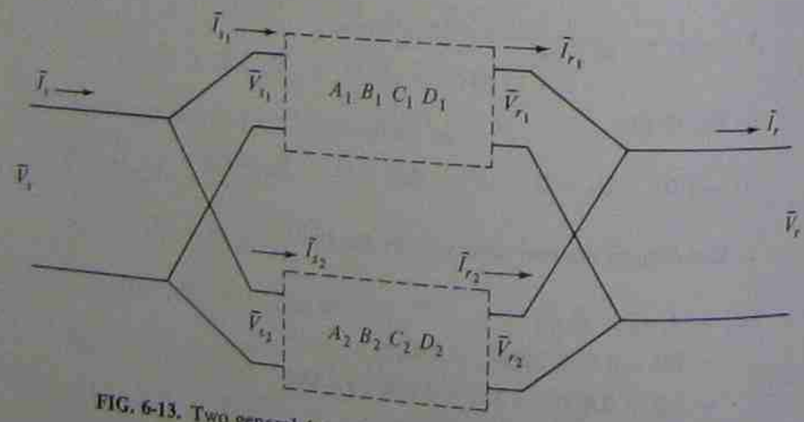


FIG. 6-13. Two general 4-terminal networks connected in parallel.

$$\bar{I}_s = \bar{I}_{s1} + \bar{I}_{s2}$$
$$\bar{I}_r = \bar{I}_{r1} + \bar{I}_{r2}$$

By a consideration of the above relations and by manipulations somewhat like those made for the tandem arrangement, it may be shown that the four-terminal network equivalent to that shown in Fig. 6-13 will have constants as follows:

$$A_{eq_p} = \frac{A_1B_2 + A_2B_1}{B_1 + B_2} \tag{6-13}$$

$$B_{eq_p} = \frac{B_1B_2}{B_1 + B_2} \tag{6-14}$$

$$C_{eq_p} = C_1 + C_2 + \frac{(A_1 - A_2)(D_2 - D_1)}{B_1 + B_2} \tag{6-15}$$

$$D_{eq_p} = \frac{B_2D_1 + B_1D_2}{B_1 + B_2} \tag{6-16}$$

EXAMPLE 6-3. Refer to Example 6-2. Consider that network 1 is connected in parallel with network 2. Determine the equivalent *ABCD* constants.

Solution.

By Eq. (6-13),

$$A_{eq_p} = \frac{A_1B_2 + A_2B_1}{B_1 + B_2} = \frac{1.0 \times 0 + 1.0 \times 20\underline{/30^\circ}}{20\underline{/30^\circ} + 0} = 1.0\ \underline{/0^\circ}$$

By Eq.(6-14),

$$B_{eq_p} = \frac{B_1B_2}{B_1 + B_2} = \frac{20\underline{/30^\circ} \times 0}{20\underline{/30^\circ} + 0} = 0\ \Omega$$

By Eq. (6-15),

$$C_{eq_p} = C_1 + C_2 + \frac{(A_1 - A_2)(D_2 - D_1)}{B_1 + B_2}$$
$$= 0 + 0.02\underline{/45^\circ} + \frac{(1.0 - 1.0)(1.0 - 1.0)}{20\underline{/30^\circ} + 0}$$
$$= 0.02\underline{/45^\circ}\ \mho$$

By Eq. (6-16),

$$D_{eq_p} = \frac{B_2D_1 + B_1D_2}{B_1 + B_2} = \frac{0 \times 1.0 + 20\underline{/30^\circ} \times 1.0}{20\underline{/30^\circ} + 0}$$
$$= 1.0\ \underline{/0^\circ}$$

It may be noted that these two networks in parallel have the identical characteristics of network 2 alone.

f. More Complicated Networks. The determination of the *ABCD* constants of complicated networks may involve considerable detailed computation. If the network can be broken up into a group of simpler four-terminal networks that are in series, in parallel, or in series–parallel arrangement, the relations so far presented will permit evaluation of the constants.

For some configurations it will be necessary to resort to general network analysis and make a solution through the application of Kirchhoff's voltage law and Kirchhoff's current law. For such determinations it is frequently desirable to use digital computers. The solutions of problems of this kind are beyond the interest of the present discussion. However, it is important to note that methods are available for calculating the *ABCD* constants of any generalized four-terminal network.

g. Experimental Determination of *ABCD* Constants. If a four-terminal network has been constructed and can be tested, its *ABCD* constants may be readily determined regardless of the complexity of the network. Two tests are sufficient: one in which the receiver terminals are *open-circuited* and one in which the receiver terminals are *short-circuited*.

When the receiver terminals are open-circuited (Fig. 6-14) I_r is 0 and Eqs. (6-2) and (6-3) reduce to

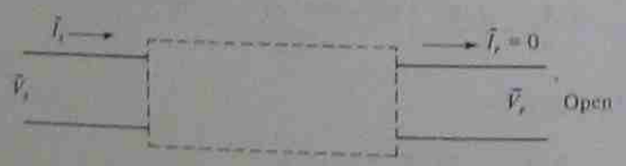


FIG. 6-14. A 4-terminal network. The receiver terminals are open-circuited for test. $\bar{I}_r = 0$.

$$\bar{V}_s = A\bar{V}_r$$

$$\bar{I}_s = C\bar{V}_r$$

The values of A and C may be determined from measured phasor values of $\bar{V}_s$, $\bar{I}_s$, and $\bar{V}_r$.

In the second test, the receiver terminals are short-circuited (Fig. 6-15) and measurements made of the phasor values of $\bar{V}_s$, $\bar{I}_s$, and $\bar{I}_r$. The constants B and D are then determinable from the relations

$$\bar{V}_s = B\bar{I}_r$$

$$\bar{I}_s = D\bar{I}_r$$

FIG. 6-15. A 4-terminal network. The receiver terminals are short-circuited for test. $\bar{V}_r = 0$.

EXAMPLE 6-4. Determine the *ABCD* constants of a network on which the following test results have been observed.

a. Receiver open-circuited, $\bar{I}_r = 0$:

$\bar{V}_s = 100 \angle 0°$ V

$\bar{V}_r = 70.7 \angle -45°$ V

$I_s = 1.41 \angle -45°$ A

b. Receiver short-circuited, $\bar{V}_r = 0$:

$\bar{V}_s = 100 \angle 0°$ V

$I_s = 2.0 \angle -90°$ A

$I_r = 2.0 \angle -90°$ A

Solution:

From a,

$$\bar{V}_s = A\bar{V}_r$$

$$100 \angle 0° = A \times 70.7 \angle -45°$$

$$A = 1.41 \angle 45°$$

and

$$I_s = C\bar{V}_r$$

$$1.41 \angle -45° = C \times 70.7 \angle -45°$$

$$C = 0.02 \angle 0° \text{ } \mho$$

From b,

$$\bar{V}_s = B\bar{I}_r$$

$$100 \angle 0° = B \times 2.0 \angle -90°$$

$$B = 50 \angle 90° \ \Omega$$

and

$$\bar{I}_s = D\bar{I}_r$$

$$2.0\angle -90^\circ = D \times 2.0\angle -90^\circ$$

$$D = 1.0\angle 0^\circ$$

h. *ABCD* Constants of a π Circuit. The π-line representation of a transmission circuit with capacitance considered has been discussed on several previous ocassions. Other circuits arranged in this general form are frequently found in power-system practice. The common occurrence of the π circuit justifies its special treatment in terms of generalized circuit constants.

The π-network is shown in general form in Fig. 6-16. Note that the shunt branches are designated as admittances Y_1 and Y_2, the series branch as an impedance Z. This is merely a matter of convenience in notation.

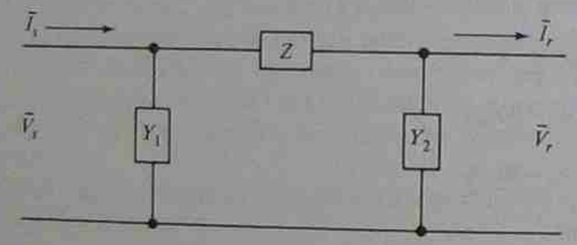


FIG. 6-16. A π-circuit 4-terminal network.

The π-circuit may be treated as the tandem connection of three four-terminal networks as shown in Fig. 6-17. The *ABCD* constants of part (b) may be determined from Eq. (6-5); the *ABCD* constants of parts (a) and (c) may be determined from Eq. (6-6). Knowing the *ABCD* constants of parts (a) and (b) it is possible to combine them in tandem to form a new network by the method described in Section 6-3d. This new network may then be

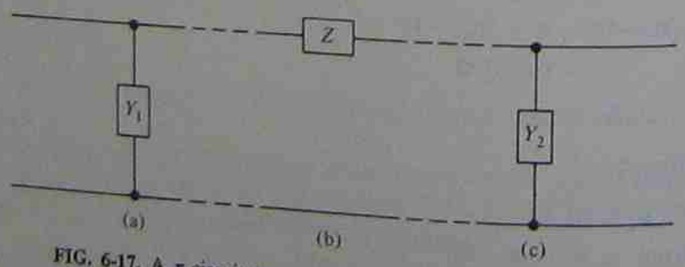


FIG. 6-17. A π-circuit treated as three 4-terminal networks connected in tandem.

combined in tandem with part (c) to give the *ABCD* constants of the total π circuit.

An alternative method for determining the *ABCD* constants of the π circuit is illustrated by means of Fig. 6-18. Here it will be assumed that

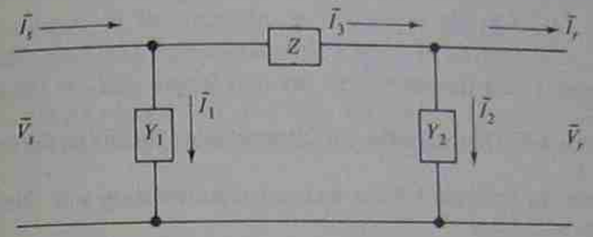


FIG. 6-18. A π-circuit labeled for the determination of *ABCD* constants.

the values of $\bar{V}_r$ and $\bar{I}_r$ are both known. From these known terminal conditions the behavior of each part of the ladder network is determined until eventually $\bar{V}_s$ and $\bar{I}_s$ have been expressed in terms of $\bar{V}_r$ and $\bar{I}_r$. The development proceeds as follows:

$$\bar{I}_2 = \bar{V}_r Y_2$$

$$\bar{I}_3 = \bar{I}_r + \bar{I}_2 = \bar{I}_r + \bar{V}_r Y_2$$

$$\bar{V}_s = \bar{V}_r + \bar{I}_3 Z = \bar{V}_r + (\bar{I}_r + \bar{V}_r Y_2)Z$$

$$\bar{I}_s = \bar{I}_3 + \bar{I}_1 = \bar{I}_3 + \bar{V}_s Y_1 = \bar{I}_r + \bar{V}_r Y_2 + [\bar{V}_r + (\bar{I}_r + \bar{V}_r Y_2)Z]Y_1$$

Putting this into the standard form of Eqs. (6-2) and (6-3) we observe that

$$\bar{V}_s = (1 + Y_2 Z)\bar{V}_r + Z\bar{I}_r$$

$$\bar{I}_s = (Y_2 + Y_1 + Y_1 Y_2 Z)\bar{V}_r + (1 + ZY_1)\bar{I}_r$$

From these equations it follows that

$$A_\pi = 1 + Y_2 Z \tag{6-17}$$

$$B_\pi = Z \tag{6-18}$$

$$C_\pi = Y_2 + Y_1 + Y_1 Y_2 Z \tag{6-19}$$

$$D_\pi = 1 + ZY_1 \tag{6-20}$$

From these equations, the π-line representation of a transmission circuit

(Fig. 5-8) may be expressed by *ABCD* constants by observing that

$$Z = (R + jX_L)l \tag{6-21}$$

$$Y_1 = Y_2 = j\frac{l}{2X_c} \tag{6-22}$$

where X_L and X_c are the reactances per unit length and l is the line length.

EXAMPLE 6-5. Determine the *ABCD* constants applying to the line of Example 5-3.

Solution. In Example 5-3 the π-circuit representation was shown to be as in Fig. 6-19. Here

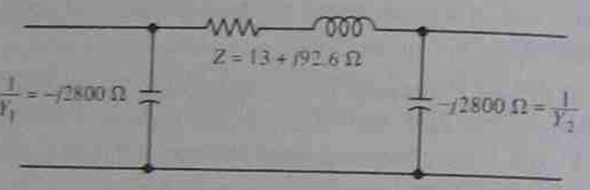


FIG. 6-19. Circuit diagram for Example 6-5.

$$Z = 13 + j92.6 = 93.5/\underline{82^\circ}\ \Omega$$

$$Y_1 = \frac{1}{-j2800} = 0.000357/\underline{90^\circ}\ \text{mho}$$

$$Y_2 = \frac{1}{-j2800} = 0.000357/\underline{90^\circ}\ \text{mho}$$

Then

$$A_\pi = 1 + Y_2Z = 1 + 93.5/\underline{82^\circ} \times 0.000357/\underline{90^\circ}$$
$$= 1 + 0.0334/\underline{172^\circ} = 1 - 0.033 + j0.00465$$
$$= 0.967 + j0.00465 = 0.967/\underline{0.3^\circ}$$

$$B_\pi = 93.5/\underline{82^\circ}\ \Omega$$

$$C_\pi = Y_1 + Y_2 + Y_1Y_2Z$$
$$= 0.000357/\underline{90^\circ} + 0.000357/\underline{90^\circ} + 0.000357/\underline{90^\circ} \times 0.000357/\underline{90^\circ} \times 93.5/\underline{82^\circ}$$
$$= -0.0000017 + j0.000702$$
$$= 0.000702/\underline{90.1^\circ}\ \mho$$

$$D_\pi = A_\pi = 0.967/\underline{0.2^\circ}$$

6-4. TRANSMISSION DIAGRAMS DERIVED FROM *ABCD* CONSTANTS

A brief discussion of transmission diagrams related to the basic power circuit was presented in Section 3-5. The diagrams presented there will be further developed in this section as related to the more general circuit arrangements that may be expressed through *ABCD* constants.

a. Comparison of Basic Power Circuit with Generalized Circuit. The equations describing the basic power circuit are

$$\bar{V}_s = \bar{V}_r + \bar{I}_r Z$$

$$\bar{I}_s = \bar{I}_r$$

As has been previously pointed out, these equations arise from a consideration of a network consisting of a single series impedance. Under this circumstance the sending-end current is exactly equal to the receiving-end current.

The equations describing the generalized four-terminal network are

$$\bar{V}_s = A\bar{V}_r + B\bar{I}_r \tag{6-2}$$

$$\bar{I}_s = C\bar{V}_r + D\bar{I}_r \tag{6-3}$$

These more complicated equations arise when connections exist, as in power-system practice, from line to neutral. These connections appear when we consider items such as line capacitance, fixed loads within the network, and shunt reactors.

Generalized circuit constants may be developed from a consideration of impedance expressed in ohms, voltage expressed in volts, and currents expressed in amperes. If the analysis is made on this basis, term A of Eq. (6-2) must be dimensionless; term B will have dimensions of ohms because its product with current must be volts. Similarly, in Eq. (6-3) term C will have dimensions of mhos, for its product with volts must be amperes, and the term D must be dimensionless.

If the analysis of the network has been made on the basis of per unit quantities A, B, C, and D will all be dimensionless. In general, all these quantities will be complex numbers.

b. Transmission Diagram Construction. In Section 3-5, a method was outlined by which the basic power circuit could be analyzed graphically with the aid of a transmission diagram. A similar method of study may be employed with the generalized four-terminal net-

work, although the construction of the transmission diagram is somewhat more complicated. Furthermore, it is necessary to construct a diagram pertaining to current in addition to the diagram pertaining to voltage. The construction of these diagrams will be illustrated for a circuit in which the following *ABCD* constants apply. These constants are quite typical of a power system consisting of a generator, transformer, high-voltage transmission line, and step-down transformer:

$$A = \mathrm{A}\,\underline{/\alpha} = 0.80\,\underline{/6^\circ}\ \text{pu}$$

$$B = \mathrm{B}\,\underline{/\beta} = 0.50\,\underline{/80^\circ}\ \text{pu}$$

$$C = \mathrm{C}\,\underline{/\gamma} = 0.25\,\underline{/70^\circ}\ \text{pu}$$

$$D = \mathrm{D}\,\underline{/\delta} = 1.10\,\underline{/-2^\circ}\ \text{pu}$$

The start of the construction of the voltage diagram is illustrated in Fig. 6-20. Using $\bar{V}_r$ as reference and assuming it to have a value of $1.0\,\underline{/0^\circ}$ pu,

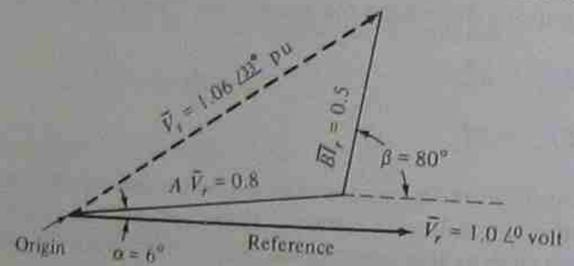


FIG. 6-20. A phasor diagram for determining $\bar{V}_s$ under the conditions that

$$\bar{V}_r = 1.0\,\underline{/0^\circ}$$

$$I_r = 1.0\,\underline{/0^\circ}$$

$$A = 0.8\,\underline{/6^\circ}$$

$$B = 0.5\,\underline{/80^\circ}$$

the phasor of $\bar{V}_r$ is laid out to scale horizontally as shown. $A\bar{V}_r$, which now has the value $0.80\,\underline{/6^\circ}$, is laid out on the diagram as shown. Next assume the receiver current to be $1.0\,\underline{/0^\circ}$ pu. Now $B\bar{I}_r$ takes on the value $0.50\,\underline{/80^\circ}$. The phasor $B\bar{I}_r$ is added to the tip of the phasor $A\bar{V}_r$ in accordance with Eq. (6-2). The phasor $\bar{V}_s$ now represents in magnitude and phase position

the source end voltage under the conditions of receiver voltage being $1.0\,\underline{/0^\circ}$ and receiver current $1.0\,\underline{/0^\circ}$.

Following the procedure outlined in Section 3.5, phasors of $B\bar{I}_r$ may be located to correspond with $\bar{I}_r$, having the values $1.0\,\underline{/-90^\circ}$ and $1.0\,\underline{/+90^\circ}$, corresponding to load-power factors of 0 lag and 0 lead. The diagram may now be expanded to account for any chosen value of receiver current by the addition of the grid shown in Fig. 6-21. Since the value of $A\bar{V}_r$ is directly proportional to the magnitude of $\bar{V}_r$, origins corresponding to different values of $\bar{V}_r$ may be designated as shown on the diagram.

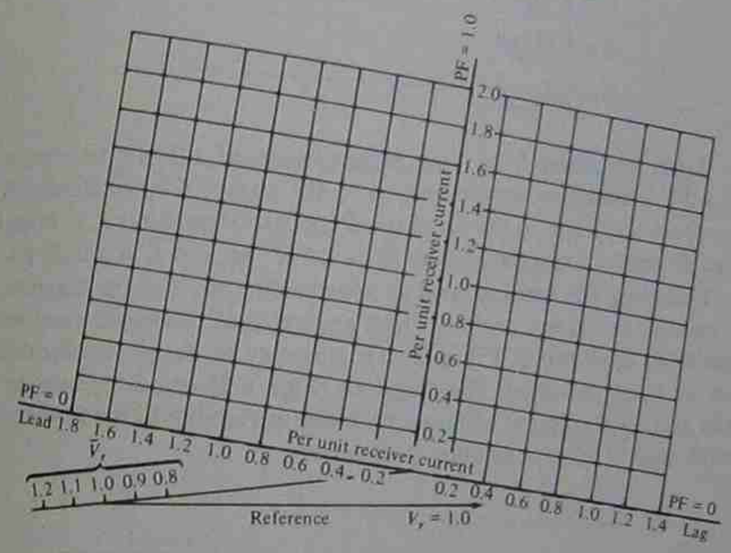


FIG. 6-21. A voltage diagram relating $\bar{V}_s$ to $\bar{V}_r$ and $\bar{I}_r$ for the conditions

$$A = 0.8\,\underline{/6^\circ}$$

$$B = 0.5\,\underline{/80^\circ}$$

The construction of the current diagram follows a similar procedure (Fig. 6-22). Again $\bar{V}_r$ is used as reference and so is laid out horizontally. Assuming $\bar{V}_r$ to be $1.0\,\underline{/0^\circ}$ pu, the phasor $C\bar{V}_r$ is evaluated $(0.25\,\underline{/70^\circ})$ and laid out to scale from the origin of the diagram as shown.

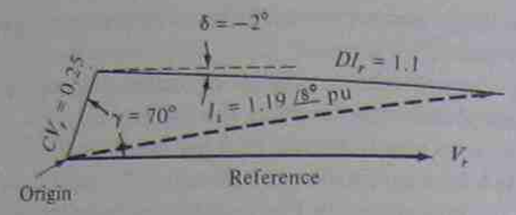


FIG. 6-22. A phasor diagram for determining $\bar{I}_1$ under the conditions that

$\bar{V}_r = 1.0 \angle 0°$

$I_r = 1.0 \angle 0°$

$C = 0.25 \angle 70°$

$D = 1.1 \angle -2°$

Again assuming I_r to have a magnitude of 1.0 pu, the phasor $D\bar{I}_r$ ($1.1 \angle -2°$) is added in vector fashion to the phasor $C\bar{V}_r$ as shown. A line drawn from the origin to the tip of the $D\bar{I}_r$ phasor represents $\bar{I}_1$ in magnitude and angle on the assumption that $\bar{V}_r$ is $1.0 \angle 0°$ pu and $\dot{I}_r$ is $1.0 \angle 0°$ pu.

Following the method used in constructing the voltage diagram, it is now possible to draw a grid on which any value of receiver current may be represented, as shown in Fig. 6-23. Origins may be designated for different values of V_r as indicated. The diagrams (Figs. 6-21 and 6-23) may be used for the graphical solution of many problems pertaining to the four-terminal network with $ABCD$ constants as specified.

6-5. GRAPHICAL ANALYSIS OF THE FOUR-TERMINAL NETWORK

The transmission diagrams (Figs. 6-21 and 6-23) may now be used to analyze some of the characteristics of the four-terminal network which are of interest to the electric-system operator.

It is very commonly recognized that electric power must be delivered to the customers in any desired amount, while voltage and frequency are held within specified limits. Those persons directly associated with system operation are aware that another quantity, reactive power (or quadrature power), has a great influence on the control of voltage and on system losses and in some systems requires the same attention in system dispatch as does the flow of power itself. Reactive power may be positive or negative. Reactive power fed to a receiver is said to be *positive* when the receiver current

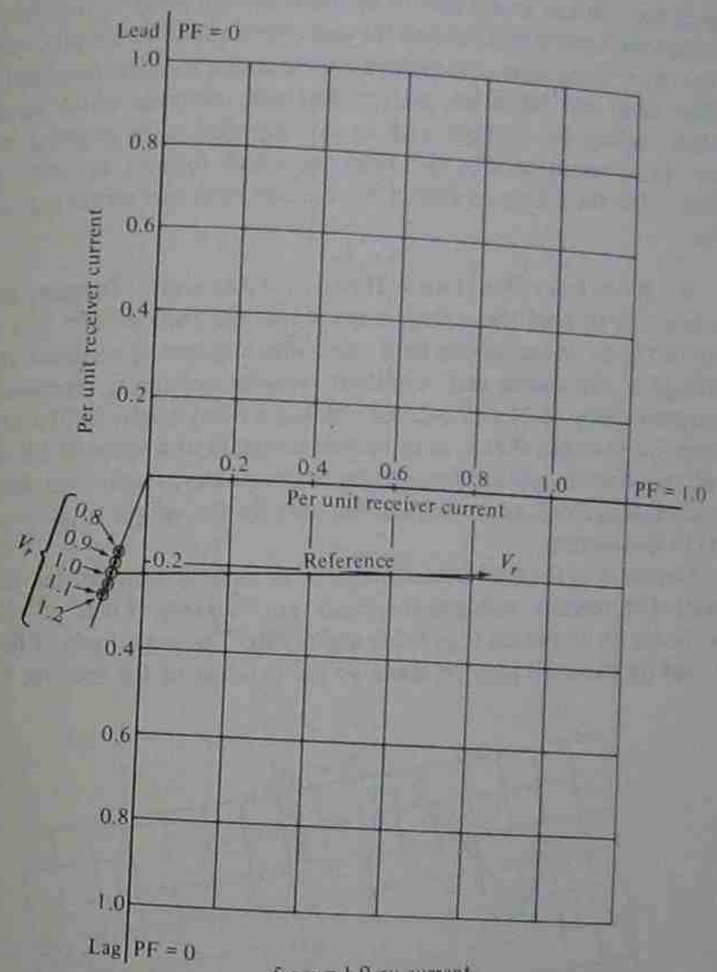


FIG. 6-23. A current diagram relating $\bar{I}_1$ to $\bar{V}_r$ and $\bar{I}_r$ for the conditions

$C = 0.25 \angle 70°$

$D = 1.1 \angle -2°$

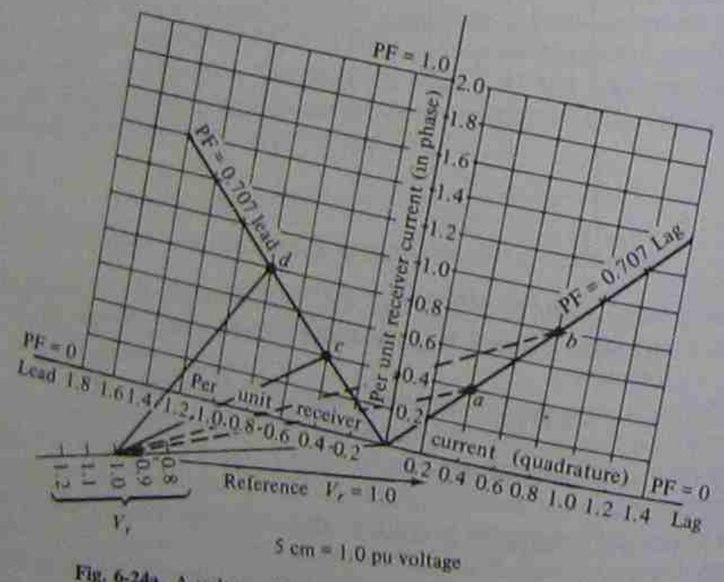
lags the receiver voltage. It is *negative* when the receiver current *leads* the voltage.

Transformers, induction motors, and all equipment having iron cores that must be magnetized by currents supplied by the power system require

lagging currents and so are said to be supplied with positive reactive power. The electrical equipment found on the customers' premises are predominately of this type. Capacitors, overexcited synchronous motors, overhead transmission lines, and cables are all supplied with currents which have components leading the voltage, and so are supplied with negative reactive power. In the analysis of system behavior which follows, attention should be directed to the effects on system response of both real power and reactive power.

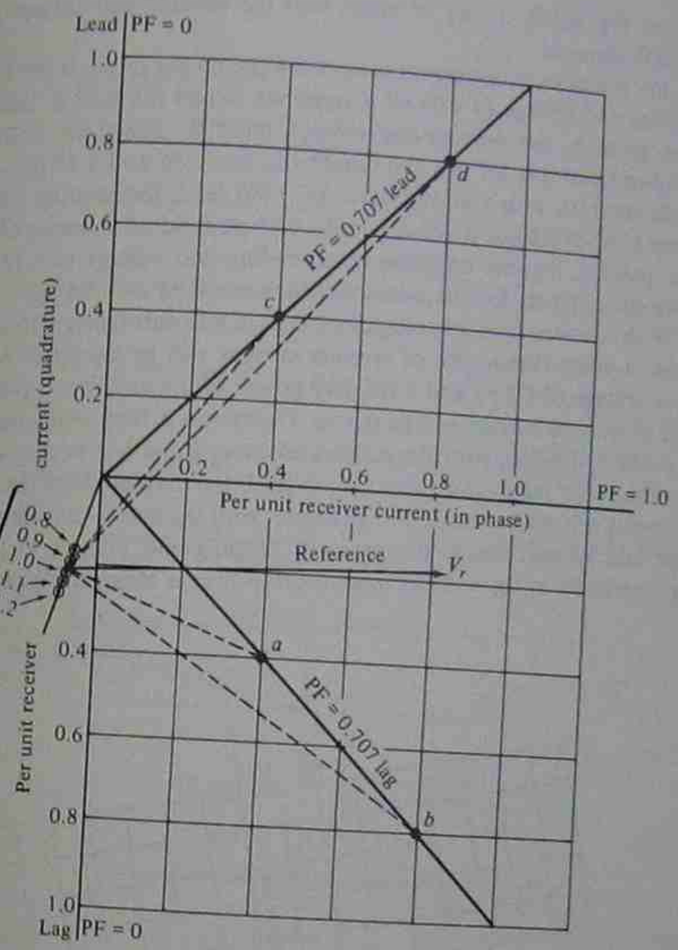
a. Receiver Voltage Held Constant. In many respects it is desirable to hold the voltage constant at the receiver end of a power circuit. To do so under varying load conditions requires appropriate changes of voltage at the source end. Constant receiver voltage is represented on the diagrams, Figs. 6-21 and 6-23 by holding a fixed origin for the analysis. Assume, for example, that V_r is to be held constant at a value of 1.0 regardless of variations in power demands by the customer. In the two diagrams, the points designated as V_r=1.0 will be used as the origin in all measurements in this section.

Assume that the load power factor is to be held constant but that the kilowatt and reactive volt-ampere loads are variable. Lines of constant power factor are shown on Figs 6-24a and 6-24b. The magnitude of the kilowatt load (in per unit) may be taken as the product of the receiver voltage



5 cm = 1.0 pu voltage

Fig. 6-24a. A voltage diagram emphasizing receiver power factor 0.707 lag and 0.707 lead.



5 cm = 1.0 pu current

FIG. 6-24b. A current diagram emphasizing receiver power factor 0.707 lag and 0.707 lead.

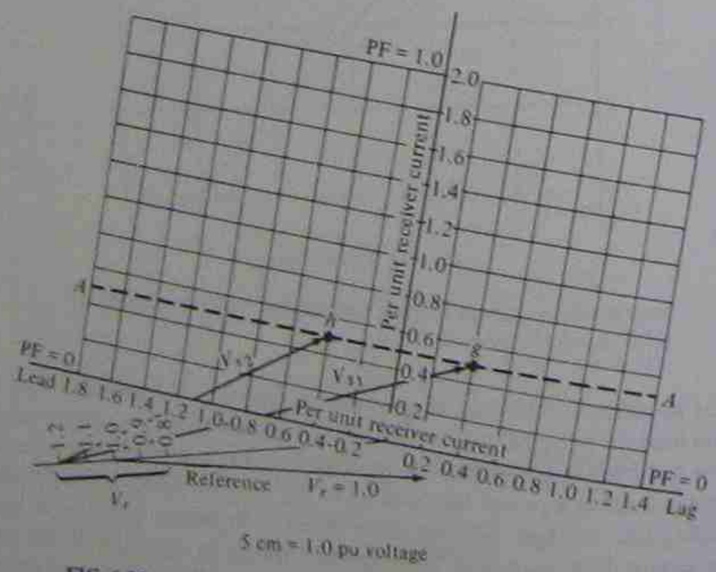
and the in-phase component of the receiver current. The magnitude of the reactive load (in per unit) may be taken as the product of the receiver voltage and the quadrature component of receiver current. It may be noted that an increase in load at a power factor of 0.707 lag requires a substantial increase in sending-end voltage. For the same increase in power supplied at unity power factor, less change in sending-end voltage is required. If the load power factor is 0.707 lead, an increase in power requires almost no change in the magnitude of the sending-end voltage. By reference to the current

diagram, Fig. 6-24b, it may be noted that the sending-end current changes as load is changed.

For example, with a power load of 0.4 pu, power factor 0.707 lag, point a, sending-end voltage of 1.06 pu is required. When the load is increased to 0.8 pu, point b, the sending-end voltage must be raised to 1.32 pu. The sending-end currents for the two conditions are 0.56 and 1.15 pu.

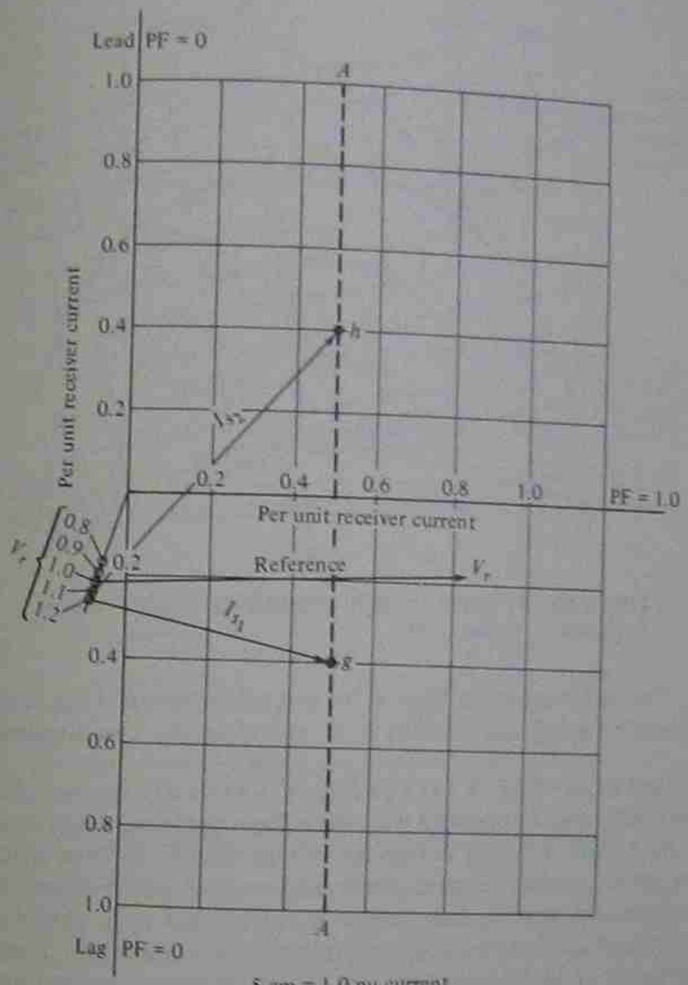
In contrast, with a power factor of 0.707 lead, the sending voltage for a power load of 0.4 pu, point c, is only 0.71 pu, and an increase of load to 0.8 pu, point d, requires an increase in sending-end voltage to 0.72 pu. The sending-end currents for the two conditions are 0.85 and 1.47 pu.

With constant receiver voltage, a constant kilowatt receiver load implies that the in-phase component of receiver current will be constant. Assume a receiver voltage of 1.2 pu and a receiver power of 0.6 pu. The in-phase component of receiver current will be 0.5 pu. Operation is then along line AA on Figs. 6-25a and 6-25b, with the origins taken at $V_r = 1.2$. It may be noted that as the power factor shifts from lag to lead, the magnitude of the required sending-end voltage decreases. For example, with the above-assumed receiver voltage and kilowatt load, the required sending-end voltage and current change markedly as the receiver quadrature power is changed. With quadrature power at a value of 0.48 pu positive (lag), point g, the required sending-end voltage and current are 1.24 and 0.66 pu, respectively. When the quadrature power is changed to 0.48 pu negative (lead), point h, the required sending-end voltage and current are 0.89 and 0.97 pu, respectively.



5 cm = 1.0 pu voltage

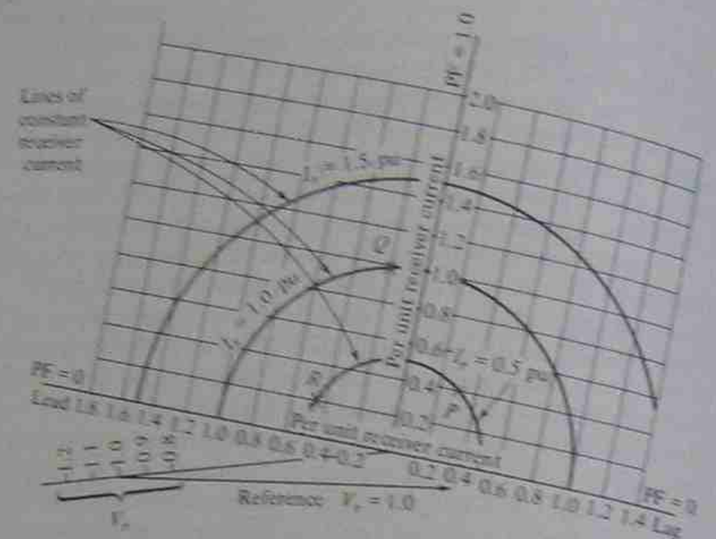
FIG. 6-25a. A voltage diagram emphasizing an in-phase component of receiver current of value 0.5 pu.



5 cm = 1.0 pu current

FIG. 6-25b. A current diagram emphasizing an in-phase component of receiver current of value 0.5 pu.

With constant receiver voltage, a constant value of receiver current implies a constant kilo-volt-ampere load, with a freedom of variation in power



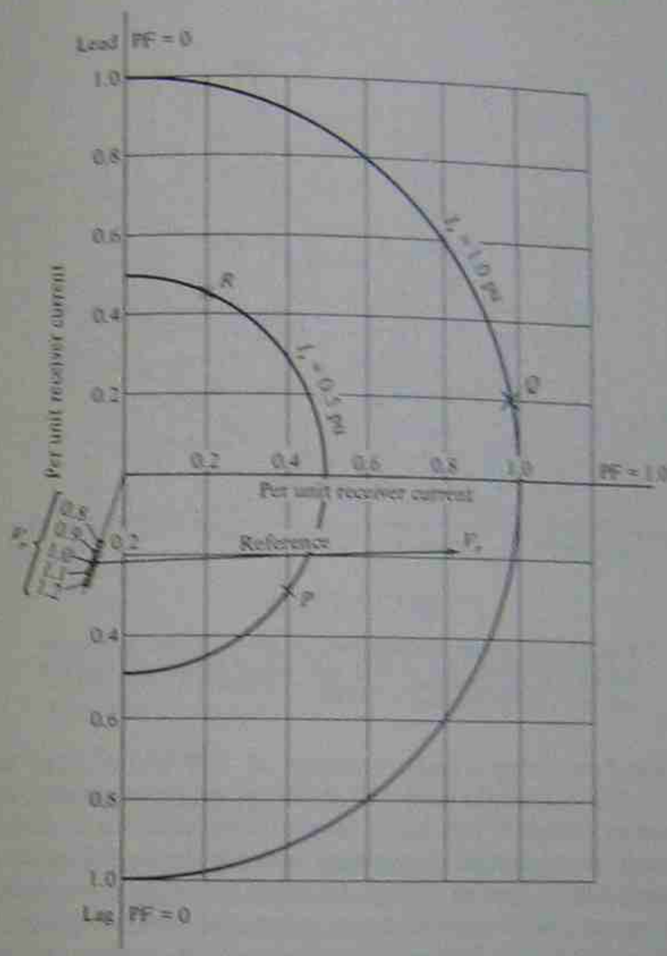
5 cm = 1.0 pu voltage

FIG. 6-26a. A voltage diagram emphasizing receiver current magnitudes of special values.

factor. The circles drawn in Figs. 6-26a and 6-26b represent this condition. Corresponding points are listed as *P*, *Q*, and *R* on the two diagrams.

b. Sending-End Voltage, V_s, Constant. In some instances a power system may be operated with the voltage held constant at the source end of the system. Changes in receiver voltage then result from changes in receiver power, receiver reactive power, and receiver power factor. As previously discussed, sending-end voltage is represented by a phasor drawn from a selected origin to an operating point in the current grid. If sending-end voltage is to be held constant, the length of this phasor must remain constant.

Consider the case of a variable kilowatt load at constant power factor, 0.707 lag, for example, as shown in Fig. 6-27. As load is increased, the right-hand end of the $\bar{V}_r$ phasor will move to the right while its other end will move up the $A\bar{V}_r$ line, the magnitude of $\bar{V}_r$ being determinable by the position of the lower end of the phasor $\bar{V}_r$. When receiver voltage is 1.0 pu and receiver power is 0.1 pu (point *A*) the required sending-end voltage is 0.9 pu. If this sending-end voltage is held constant while receiver load (at power factor 0.707 lag) is increased until the in-phase component of current is 0.4 pu, point *B*, the origin of the diagram must move to point *b*, indicating

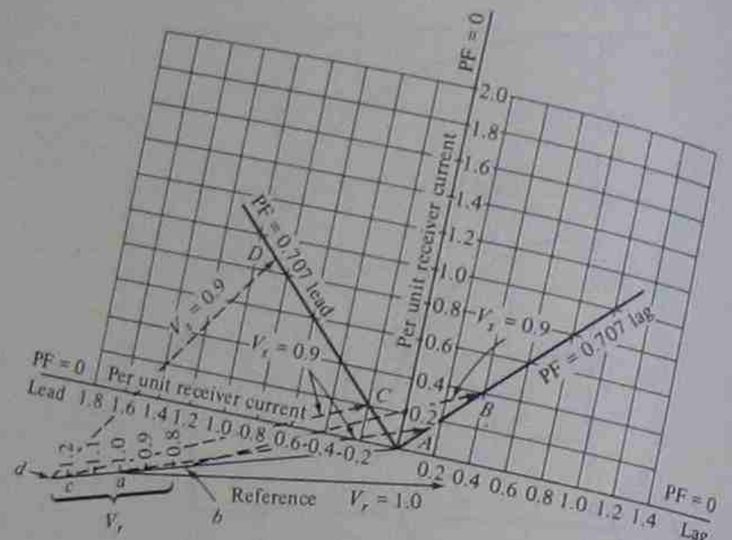


5 cm = 1.0 pu current

FIG. 6-26b. A current diagram emphasizing receiver current magnitudes of special values.

a receiver voltage of 0.75 pu. It is obvious that under this circumstance, increases in load bring about a rapid decrease in receiver voltage.

If, however, the power factor is 0.707 lead, an increase of load will cause the phasor representing $\bar{V}_r$ (shown dashed) to move in such fashion that its lower end changes position very little. With sending-end voltage held constant at 0.9 pu (as in the previous example) when the in-phase component of receiver current is 0.2 (point *C*), the origin of the diagram

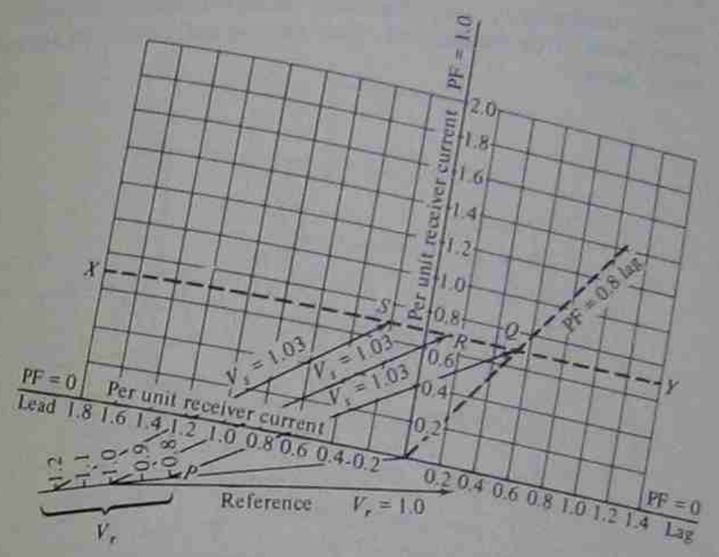


5 cms = 1.0 pu voltage

FIG. 6-27. A voltage diagram used to show changes in receiver voltage due to changes in load and power factor. Sending-end voltage V_s is held constant at 0.9 pu.

is at point c, indicating a receiver voltage of 1.18 pu. A large increase in the receiver current (to point D) shifts the origin to point d, indicating a receiver voltage of 1.25 pu. It may be concluded that if sending-end voltage is held constant on this system, increases in lagging power-factor load rapidly depress receiver voltage. Increases in leading power-factor load (at least over a limited range) cause an increase of receiver voltage. Hence for this system it may be concluded that, with a constant sending-end voltage, at lagging power factor, increases of load reduce receiver voltage much more than do increases of leading power-factor load.

With the aid of Fig. 6-28, voltage controlled by capacitor loading at the receiver end may be illustrated. Suppose that the in-phase component of receiver current remains constant at 0.7 per unit. Suppose further that initially the power factor is 0.8 lag and the receiver voltage is low, 0.8 per unit. The sending-end voltage, 1.03 pu, is then represented by the phasor PQ extending from the origin, $V_r = 0.8$, to the current indicated. Now assume capacitors are added in parallel with the load at the receiver end, thus adding negative reactive volt-amperes. With constant in-phase current, each increment of capacitor added moves the operating point to the left along the dashed line, XY. As the operating point is moved to the left, the lower end



5 cms = 1.0 pu voltage

FIG. 6-28. A voltage diagram used to show changes in receiver voltage due to changes in capacitor switching at the load end. V_s is held constant at 1.03 pu.

$V_r = 1.1$ pu.

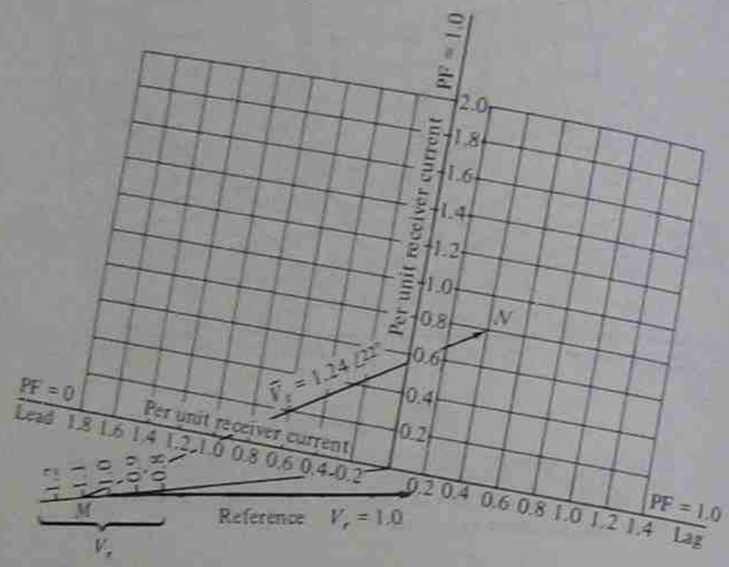
$I_r = 0.8 - j0.4$ pu.

of the phasor $\bar{V}_s$ (which is of constant length) will slide down the $A\bar{V}_r$ line defining new origins, each one corresponding to an increased value of V_r. For example, if the capacitor current is 0.8 pu, the terminal point S will be defined and a new origin corresponding to $V_r = 1.2$ pu will be required. Thus it is seen that, by switching capacitors, almost any desired value of receiver voltage may be attained. Obviously the same effect could be realized by the use of an overexcited synchronous condenser which draws a current leading its supply voltage by almost 90°.

c. Sending-End Conditions. The transmission diagrams (Figs. 6-29a and 6-29b) make possible a determination of sending-end voltage, current, and power factor once receiver-end conditions are selected.

EXAMPLE 6-6. Suppose the receiver-end voltage is 1.10 pu while receiver-end current is $0.8 - j0.4$ per unit. On Fig. 6-29a, the line MN represents the sending-end voltage in magnitude and phase position relative to $\bar{V}_r$. In Fig.

6-29b the line PQ represents sending-end current in magnitude and phase position relative to V_r. The difference of these two angles determines the power factor at the sending end. Thus sending-end conditions are completely defined.



5 cms = 1.0 pu voltage

FIG. 6-29a. Determination of sending-end voltage.

In this example it may be noted that $\bar{V}_s = 1.24 \angle 22°$ and $\bar{I}_s = 0.99 \angle -12°$. From these data it may be determined that at the sending end,

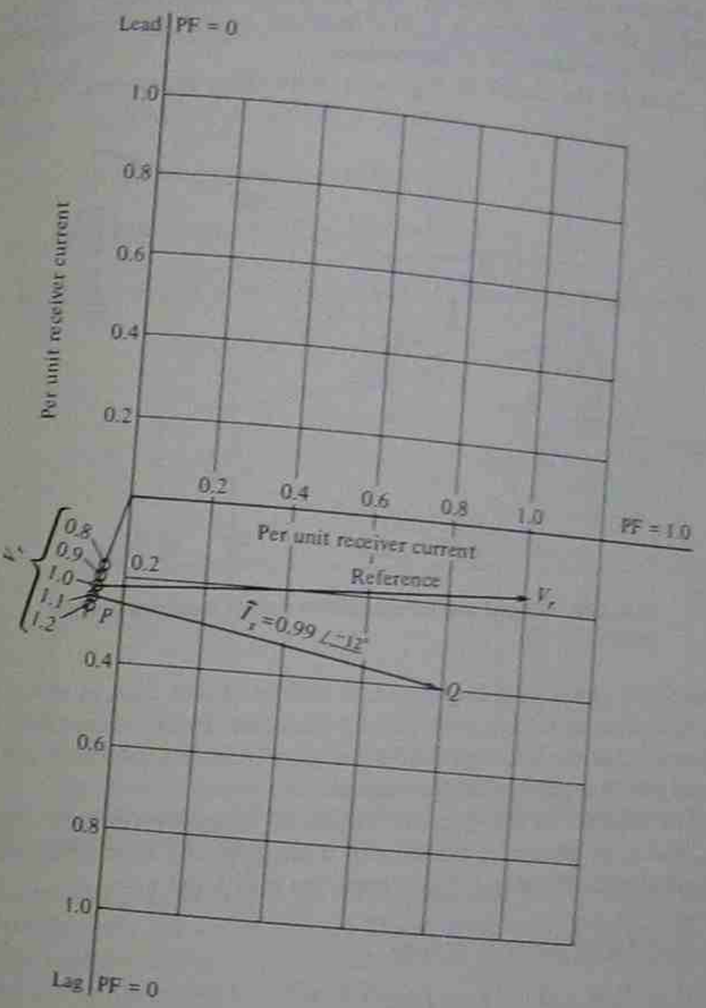
power factor $= \cos(22° + 12°) = 0.83$ lag

$$\text{power} = V_s I_s \cos\phi_s$$
$$= 1.24 \times 0.99 \times 0.83 = 1.015 \text{ pu}$$

$$\text{reactive power} = V_s I_s \sin\phi$$
$$= 1.24 \times 0.99 \times 0.56 = 0.687 \text{ pu}$$

$$\text{system losses} = P_s - P_r = 1.015 - 0.88 = 0.135 \text{ pu}$$

d. Other Problems. The transmission diagrams of the type just discussed will be examined in more detail in Chapter 7. With these diagrams it becomes possible to define power limits and to define criteria for stability of system operation.



5 cms = 1.0 pu current

FIG. 6-29b. Determination of sending-end current.

6-6. SYSTEMS WITH SEVERAL SOURCES

The discussion so far has been confined to a power system that connects a single source to a single receiver. With present-day interconnection practice, many situations exist in which several sources supply one or more loads. A detailed treatment of interconnected power networks is beyond the pres-

ent objective of this discussion. However, a simple example will be presented to show that even in a multimachine case, the understanding of simple circuit behavior is of importance.

Consider the circuit of Fig. 6-30. Here three generators, 1, 2, and 3,

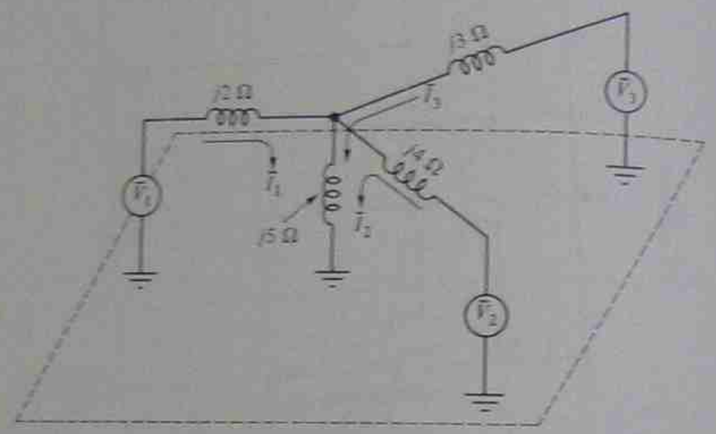


FIG. 6-30. A 3-machine interconnected system supplying a single load.

are supplying power to a single load. It will be shown that, in effect, there is an equivalent tie joining each pair of machines. In this illustration, let it be assumed that the line impedances are pure inductive reactance and that the load also is a pure inductive reactor.

The solution of this network begins by assigning the three currents I_1, I_2, and I_3 as shown by the arrows. Then applying Kirchhoff's voltage law around each of these defined loops, we may write

$$\begin{aligned} \bar{V}_1 &= \bar{I}_1 j2 + (\bar{I}_1 + \bar{I}_2 + \bar{I}_3) j5 \\ \bar{V}_2 &= \bar{I}_2 j4 + (\bar{I}_1 + \bar{I}_2 + \bar{I}_3) j5 \\ \bar{V}_3 &= \bar{I}_3 j3 + (\bar{I}_1 + \bar{I}_2 + \bar{I}_3) j5 \end{aligned} \tag{6-23}$$

These equations may be rearranged and put in standard form as shown in Eqs. (6-24):

$$\begin{aligned} \bar{V}_1 &= j7\bar{I}_1 + j5\bar{I}_2 + j5\bar{I}_3 \\ \bar{V}_2 &= j5\bar{I}_1 + j9\bar{I}_2 + j5\bar{I}_3 \\ \bar{V}_3 &= j5\bar{I}_1 + j5\bar{I}_2 + j8\bar{I}_3 \end{aligned} \tag{6-24}$$

These three simultaneous equations may be solved for $\bar{I}_1$, $\bar{I}_2$, and $\bar{I}_3$ by substitution, by determinants, or by matrix inversion with a digital computer to yield

$$\begin{aligned} \bar{I}_1 &= -j0.305\bar{V}_1 + j0.0974\bar{V}_2 + j0.130\bar{V}_3 \\ \bar{I}_2 &= j0.974\bar{V}_1 - j0.201\bar{V}_2 + j0.0649\bar{V}_3 \\ \bar{I}_3 &= j0.130\bar{V}_1 + j0.0649\bar{V}_2 - j0.247\bar{V}_3 \end{aligned} \tag{6-25}$$

Refer now to Fig. 6-31. If Kirchhoff's current law is used to write

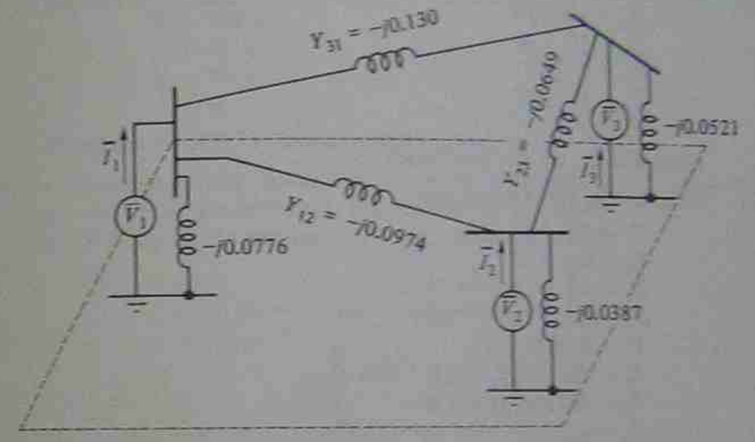


FIG. 6-31. A system equivalent to that of Fig. 6-28 as concerns current in each of the three machines. Each pair of machines is interconnected by a general power circuit.

the equations for $\bar{I}_1$, $\bar{I}_2$, and $\bar{I}_3$, it will be seen that the resulting equations are exactly those shown in Eqs. (6-25). It must be concluded, therefore, that the network of Fig. 6-31 is equivalent, as far as machine terminals are concerned, to the network of Fig. 6-30.

Note that between the buses of each pair of generators there is a simple series circuit. The information we have gained regarding power flow over the general power circuit and over the generalized network helps us to understand the interchange of power between generating stations on a complicated power system.

PROBLEMS

6-1. Refer to Fig. 6-3. Assume that

$$Z_a = 0 + j20$$
$$Z_b = 10 + j15$$

Determine Z_{eq} for this combination.

6-2. Refer to Fig. 6-4. Assume that

$Z_a = 0 + j60$
$Z_b = 0 + j30$
$Z_c = 0 - j15$

Determine Z_{eq} for this combination.

6-3. Refer to Fig. 6-5. Assume that

$Z_a = 15 + j0$
$Z_b = 10 + j0$
$Z_c = 60 + j0$
$Z_d = 10 + j0$
$Z_e = 10 + j0$
$Z_f = 5 + j0$
$Z_g = 15 + j0$
$Z_h = 0$

Determine Z_{eq} for this combination.

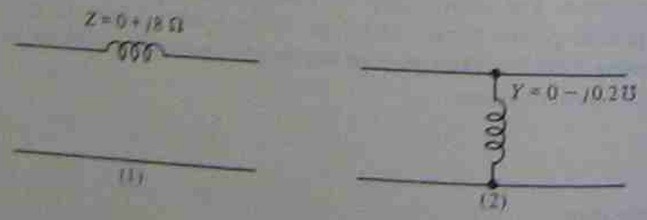
6-4. Refer to Fig. 6-7. Assume that

$Z_1 = 0.5 + j2$
$Z_2 = 0.5 + j3$
$Z_3 = 0.5 + j3$
$Z_4 = 0.5 + j2$
$V_s = 5000$ V
$P_a = 500$ kW, $f_p = 1.0$
$P_b = 500$ kW, $f_p = 1.0$
$P_c = 0$
$P_d = 0$

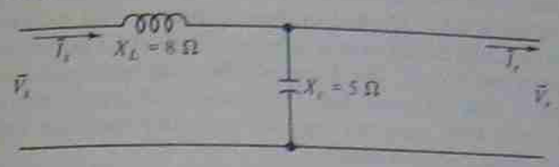
Solve for V_r, P_r, f_{pr}, and losses.

6-5. Consider the two four-terminal networks 1 and 2. Determine the *ABCD* constants of the two networks in combination if

a. 1 and 2 are in tandem.
b. 2 and 1 are in tandem.
c. 1 and 2 are in parallel.



6-6. Refer to the circuit shown. Assume that $\bar{V}_r$ and $\bar{I}_r$ are of known values. Solve for $\bar{V}_s$ and $\bar{I}_s$. From these solutions determine the *ABCD* constants of this circuit.



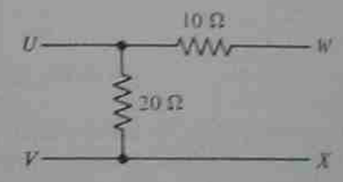
6-7. A four-terminal network of resistors is tested with the following results:

Receiver terminals open-circuited	Receiver terminals short-circuited
$V_s = 100$ V	$V_s = 100$ V
$I_s = 15$ A	$I_s = 30$ A
$V_r = 75$ V	$V_r = 0$
$I_r = 0$	$I_r = 20$ A

Determine the *ABCD* constants of the network.

6-8. Consider the circuit shown. Determine the *ABCD* constants, considering

a. *UV* the source terminals, *WX* the receiver terminals.
b. *WX* the source terminals, *UV* the receiver terminals.



6-9. A 105-mile 138-kV three-phase line has the following constants:

$R = 0.168\ \Omega$/mile
$X_L = 0.795\ \Omega$/mile
$X_C = 187{,}700\ \Omega$-miles

a. Draw the π-line representation of this line.
b. Change the values in the representation to correspond to per unit quantities on a 50,000-kVA 138-kV base.
c. Construct transmission diagrams applying to this system. Use a scale of 10 cm = 1 pu voltage for the voltage diagram and 10 cm = 1 pu current for the current diagram.

6-10. From the diagrams of Problem 6-9, make the following determinations. All are balanced three-phase conditions.

a. $P_r = 0.90$, receiver power factor 1.0, $V_r = 1.1$. Solve for $\bar{V}_s$, I_s, F_{ps}, and P_s.
b. $P_{rr} = 60{,}000$ kVA, receiver power factor 0.8 lag, $V_r = 130$ kV. Solve for $\bar{V}_s$ and I_s in volts and amperes.
c. $I_r = 1.0 + j0.5$ pu, $V_r = 1.1$ pu. Solve for $\bar{V}_s$ and I_s.

6-11. Solve Problem 6-10 analytically, using the *ABCD* constants obtained in Problem 6-9.

6-12. Refer to Fig. 6-21. The system is operating with a connected load that draws a current of $0.6 - j0.4$ pu regardless of receiver voltage. The receiver voltage is 0.9 pu. It is desired to raise receiver voltage to 1.1 pu without changing the sending-end voltage. The change will be made by adding a capacitor load in parallel with connected load. What value of capacitance current will be required? How many pu ohms of capacitive reactance will this require? Solve graphically and analytically.

6-13. Refer to Fig. 6-30. Assume that $\bar{V}_1 = 10\underline{/0^\circ}$ V, $\bar{V}_2 = 8\underline{/0^\circ}$ V, and $\bar{V}_3 = 6\underline{/0^\circ}$ V. Solve for the current that flows in $\bar{G}_1$. Make this calculation by referring to Fig. 6-31.

6-14. Write a computer program that produces the sending-end conditions (voltage, current, power, and power factor) given the *ABCD* constants of the transmission system and any variety of receiving-end conditions.

6-15. Solve Problem 6-10 using the program developed in Problem 6-14.

6-16. Solve Problem 6-12 using the program developed in Problem 6-14.

chapter 7

Power Limits—Stability

7-1. STATEMENT OF THE PROBLEM

Electrical engineers in many fields of application are concerned with the maximum amount of power that can be delivered at the terminals of a circuit or a machine. The power engineer is particularly interested in this problem, for he must work under certain restrictions which may not apply to his counterpart in the communication or electronics field.

A classical problem presented in all elementary textbooks on electrical circuits is described with the aid of Fig. 7-1. In the diagram it may be seen that a voltage source V_s is connected through a resistor R to the terminals PQ, across which is connected the variable load resistor R_L. If the voltage source is a battery, the resistor R is the sum of the internal resistance of the battery and the resistance of the connecting leads to the load terminals. The problem (as usually stated) is to determine the value of the load resistance R_L which will result in maximum power being delivered to the load. It is easily shown that the power to the load is a maximum when the load resistance R_L is equal in magnitude to the combined source and circuit resistance R,

$$R_L = R \tag{7-1}$$

A similar problem is presented when an ac source is connected through the impedance Z_t to the load terminals PQ, Fig. 7-2. As is shown in elemen-

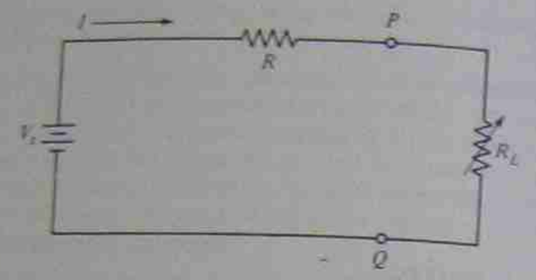


FIG. 7-1. A dc circuit for the study of maximum power transfer.

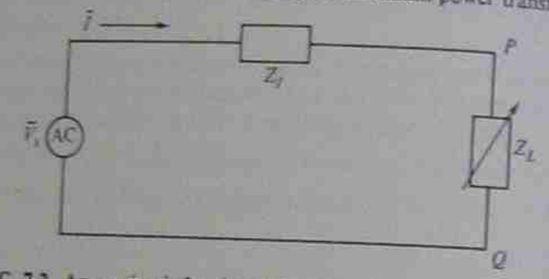


FIG. 7-2. An ac circuit for the study of maximum power transfer.

tary textbooks, the power delivered to the load is a maximum when

$$Z_L = \text{conjugate of } Z_I \tag{7-2}$$

The simple analysis of the maximum power-transfer problem as described by Figs. 7-1 and 7-2 may be adequate for the communication engineer or the electronic circuit designer. The power engineer must give attention to some additional details. In both circuits, under condition of maximum power delivery to the load, only 50 percent of the power output from the source reaches the load, a similar amount being lost in the resistor R of Fig. 7-1 or in the impedance Z_I of Fig. 7-2. In Fig. 7-1 the voltage at the load terminals is just 50 percent of that of the source. In Fig. 7-2 the voltage at the terminals of the load may be less or greater than the source voltage, depending on the nature of the impedance Z_I.

In power-system practice, loads may be in thousands of kilowatts. A system design in which, with maximum power transfer, the losses in the system were equal to the delivered load would be rejected as being uneconomical. A further complication would result because of the heat dissipated within the power-system equipment.

The power engineer is further restricted by the necessity of supplying variable loads from zero to maximum at or near a constant value of voltage. The power engineer in searching for the maximum capabilities of his system must keep in mind that the light output of lamps is greatly reduced when they

are operated below rated voltage. With voltage below normal, induction motors, operating at rated torque draw abnormally high currents, which result in decreased efficiency and may result in damage from over-heating. Under conditions of low voltage, starting torque is below normal, and under extreme conditions motors may stall under load.

The maximum power-transfer problem in the electric power system is further complicated by the presence of synchronous machines. If attempts are made to transfer excessive amounts of power between synchronous machines, the machines may pull out of step with each other and delivery of power to customers will be severely impaired.

In describing power limits, it is obvious that power-system operators must give attention to many factors that may be ignored by designers who work with electronic-type equipment. This chapter will examine the power-supply capabilities of circuits when operating within the restrictions imposed by the nature of electric-power generation and utilization equipment.

7-2. ASYNCHRONOUS LOADS (LAMPS, HEATERS, INDUCTION MOTORS)

The magnitude of the power which may be transmitted from a source to asynchronous loads such as lamps, heaters, and induction motors is influenced by the range of voltage that is available by control of the source equipment, the range of voltage which may be tolerated by the load, and by the characteristics of the circuit extending from source to receiver. Restrictions may also be imposed by the current-carrying ability of the components comprising the power circuit.

The behavior characteristics of a general four-terminal network (Fig. 7-3) were discussed in detail in Chapter 6. The transmission diagram for a

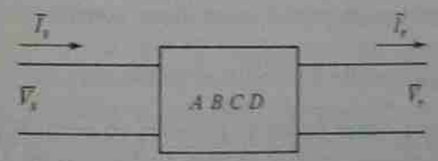


FIG. 7-3. A four-terminal network with *ABCD* constants.

typical network was presented in Chapter 6 and is shown in Fig. 7-4. With the aid of this diagram, the power limits of the system to which it applies may be readily defined when source voltage, load voltage, and load power factor are specified.

As an example, suppose that receiver voltage must never fall below 0.8 pu. (This is a low value for a power application.) Assume further that source voltage is held at 1.0 pu. Conforming to these restrictions the arc of a

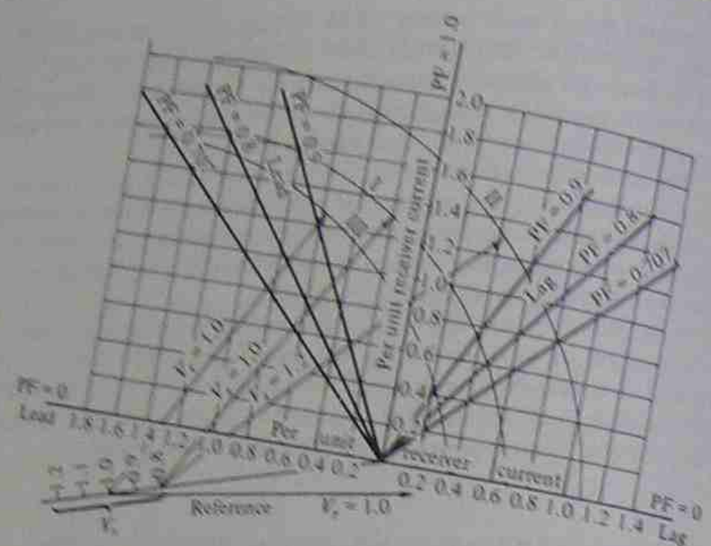


FIG. 7-4. A transmission diagram for the study of power transfer.
Curve I: $V_s = 0.8$ pu, $V_r = 1.0$ pu
Curve II: $V_s = 0.8$ pu, $V_r = 1.2$ pu
Curve III: $V_s = 1.0$ pu, $V_r = 1.0$ pu

circle I may be drawn with center at $V_s = 0.8$ and with a radius of 1.0, as shown in Fig. 7-4.

Considering the load power factor to be 0.9 lag, it may be noted that for this power factor, an in-phase component of current of 0.75 pu is indicated. Hence the maximum power under these conditions is

$$P_{max} = I_{in\ phase} V_r = 0.75 \times 0.8 = 0.60 \text{ pu}$$

Similarly, if the load power factor is assumed to be 0.707 lag, the in-phase component of the receiver current is seen to be 0.50 pu and the maximum power is

$$P_{max} = 0.50 \times 0.8 = 0.40 \text{ pu}$$

If the load power factor is assumed to be 0.8 lead, the in-phase component of receiver current is seen to be 1.65 pu and the maximum power is

$$P_{max} = 1.65 \times 0.8 = 1.32 \text{ pu}$$

If in the above examples the load on the system is (for a particular

power factor) lower than P_{max}, then the receiver voltage V_r may be greater than the specified value of 0.8 pu or the source voltage V_s may be reduced to a value less than 1.0 pu.

Curve II of Fig. 7-4 is drawn with $V_s = 0.8$ and $V_r = 1.2$ pu. It may be noted that for each assumed load power factor, the in-phase component of the receiver current is of higher value than before, implying higher load limits. Curve III is drawn on the assumption that the receiver voltage V_r is 1.0 pu, while the sending voltage V_s is 1.0 pu. Under these restrictions only very low values of power at lagging power factor may be carried by the system.

By an extension of the method described in the preceding paragraphs it is possible to determine the maximum load capability of this system with any desired restrictions placed on source-end voltage and receiver-end voltage. In some instances, a detailed analysis of the voltage and current associated with each component of the transmission circuit would be required to assure that no damage would be caused by voltages or currents beyond the rating of the individual circuit elements comprising the networks.

7-3. SYNCHRONOUS LOADS

When two or more synchronous machines are in operation on the same power system, a new limitation on maximum power transfer must be considered. This problem will be discussed in an elementary form by assuming two synchronous machines, one at the source end of our system and one at the receiver end. On examination of this system, it is found that a power-transfer limit exists, even though voltages can be held at specified values at both ends of the system. If an attempt is made to exceed this power limit, the machines will pull out of step and cease to run in synchronism. If the machine at the source end is a generator while the one at the receiver end is a synchronous motor, loss of synchronism will cause the synchronous motor to stall. If the machines at the ends of the line are both generators driven by prime movers, loss of synchronism will be followed by wild fluctuations of current and voltage (hunting) within the transmission network, accompanied by a power transfer from source to receiver which is alternately positive and negative, with an average value substantially zero. When synchronism is lost, it is invariably necessary to separate the machines by opening circuit breakers and resynchronizing them. During the period when the machines are out of step and while they are being resynchronized, customer service may be seriously impaired.

The discussion that follows refers to an analysis of the behavior of two synchronous machines operating with an intervening transmission network. The analysis will apply in principle to several different systems, such as two generators operating on the same station bus, two generators geographically

separated but tied together through a transmission circuit, or a generator supplying a synchronous motor.

7-4. THE INFINITE BUS

In studying the two-machine stability problem, the analysis may be simplified considerably by assigning to one of the machines some very special and idealized characteristics. This machine, commonly referred to as an *infinite bus*, is assumed to be uninfluenced in some of its behavior regardless of the loading put upon it. It is assumed to run at constant frequency, corresponding exactly to the nominal frequency of the system. The magnitude of its voltage remains constant at any specified value and its phase position is unchanged regardless of the power and power-factor demands that may be put upon it. Because of the assumed complete stability of the voltage of the infinite bus, it is used as reference in any graphical or analytical studies of system performance.

Although the infinite bus is a fictional device used for introductory system stability analysis, there are circumstances in actual power systems which closely approximate the infinite bus concept. Present-day large interconnected power networks operate at almost constant frequency. A small generator connected to a large network would have little influence on the voltage of the network, regardless of the condition of operation of the generator. Similarly, a small synchronous motor connected to a larger interconnected system would have little influence on the voltage magnitude or phase position of the large network, even though the loading of the motor was varied over wide limits. In each of these examples the large network is a close approximation to an infinite bus.

7-5. GENERATOR CONNECTED TO INFINITE BUS

A study of the stability problem begins with an analysis of the behavior of a generator connected through a line to an infinite bus (Fig. 7-5a). In looking at the diagram of the electrical elements forming this system, it is obvious that we are dealing again with a general power circuit (Fig. 7-5b), shown in simpler form in Fig. 7-5c. For this circuit we can write the well-known equation

$$E_s = E_r + IZ \tag{7-3}$$

where the voltage E_s is the internal voltage generated by the moving rotor of the generator.

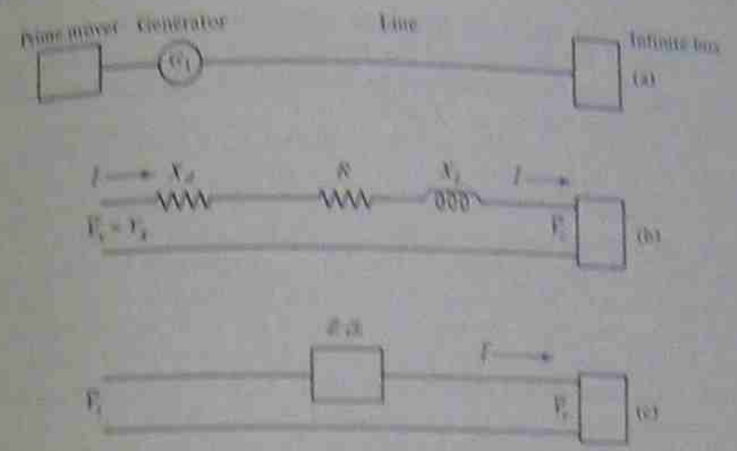
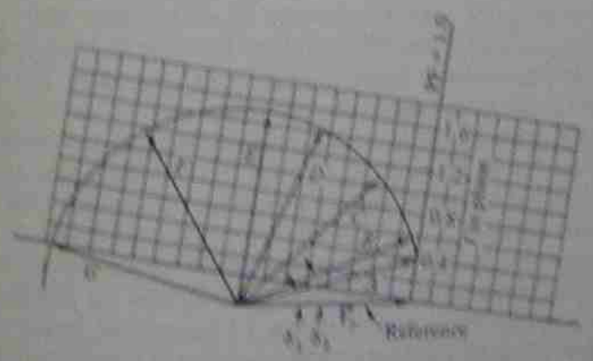


FIG. 7-5. A generator connected to an infinite bus. (a) Schematic diagram showing components. (b) Diagram showing circuit constants. (c) The system reduced to the basic power circuit.

a. Graphical Analysis. In Section 3-5 we developed the transmission diagram presented as Fig. 3-15. A diagram of this type (Fig. 7-6) is used here as the basis of a graphical analysis of the power-transfer characteristics of the general power circuit. This diagram is presented on a per unit basis for which $Z = 0.6\ /80^\circ$ pu. It should be pointed out that the (almost) horizontal lines on the grid represent constant values of the in-phase component of receiver current. Hence, for constant receiver voltage, these lines represent constant receiver power, since

$$P_r = I_{in\ phase} V_r$$



Scale 2.5 cm = 1.0 pu voltage

FIG. 7-6. A transmission diagram showing the change of I_{in} even with increase of the displacement angle δ.

Suppose the system is operating under the following conditions: $V_r = 1.0$ pu, I_r (in phase) $= 0.4$ pu, power factor 1.0, $P_r = 0.4$ pu. The source-end voltage $\bar{V}_s$ is represented by the phasor A, which has magnitude 1.06 pu and lies at angle $\delta_1 = 13°$ relative to $\bar{V}_r$.

As shown in Fig. 7-5b, the source voltage, $\bar{V}_s$, is really the generated voltage, $\bar{V}_g$, set up by the moving rotor in the generator. For many problems it may be assumed that this voltage generated within the machine has a magnitude that is proportional to the field current and a phase position that is dependent on the rotor position. In Fig. 7-6, $\bar{V}_g$, represented by phasor A, is shown as leading $\bar{V}_r$. Hence it may be concluded that the field structure of the generator is advanced by the angle δ_1 ahead of the rotor of that generator which we have called the infinite bus. Suppose that with no other change, the throttle of the prime mover driving generator G_1 (Fig. 7-5a) is opened slowly. The increased mechanical torque produced by the prime mover at first exceeds the electrical restraining torque in the generator. Because of this unbalance of torques, the prime mover and its generator increase in speed very slightly. As the rotor (the field structure) of the generator advances in position, the generated voltage $\bar{V}_g$ will also advance to position B (Fig. 7-6) while its magnitude is unchanged.

It may be noted that in this new position (B), the in-phase component of $\bar{I}_r$ is now 0.6 pu and the power received by the infinite bus is now 0.6 pu. The increased electrical output of the generator G_1 may exactly match the increase in torque described for the prime mover. If such is the case, operation will be stable with the new displacement angle δ_2 between $\bar{V}_g$ and $\bar{V}_r$. Since both $\bar{V}_g$ and $\bar{V}_r$ are considered to be of constant magnitude, it may be noted that the phasors A and B are radii of a circle whose center is at the origin corresponding to $V_r = 1.0$.

Further increases of the throttle opening and input power of the prime mover cause the rotor of generator G_1 to advance, and $\bar{V}_g$ takes on new positions, such as C and D. Each time the throttle is opened an additional amount, the electrical output of generator G_1 increases. The torque due to electromagnetic forces within the generator rises to meet the increased torque of the prime mover and the power delivered to the infinite bus increases. Note that in positions B, C, and D, the infinite bus is accepting power, and so has the appearance of a load on the system. This load is of leading power factor.

Suppose that by careful adjustment of the prime-mover throttle the position of the generator rotor advances until $\bar{V}_g$ is at the position E. Here the in-phase component of the current is 1.5 pu and the power received is 1.5 pu. What will be the result of a further increase of throttle opening?

An increase in the mechanical torque supplied by the prime mover again causes the rotor to speed up slightly and so advance in position relative to the rotor of the infinite bus. However, as $\bar{V}_g$ advances to a new position

E, the in-phase component of receiver current decreases and the power delivered to the infinite bus decreases.

As the generated voltage $\bar{V}_g$ advances in position, the output of generator G_1 decreases, the electrical torque within the machine decreases, and the amount by which the mechanical torque exceeds the electrical torque increases rapidly. This excess net torque causes a further increase in speed and a further advancement in the angle δ.

When $\bar{V}_g$ advances beyond the point G, the in-phase component of receiver current becomes negative and the infinite bus begins supplying power to the system. This further increases the acceleration of the rotor of generator G_1. The generator will increase in speed and the phasor representing $\bar{V}_g$ rotates relative to $\bar{V}_r$ with increasing speed. Synchronism between the two machines has been lost. As $\bar{V}_g$ takes on *different* positions, the currents in the circuits swing wildly and voltage measured at any point other than the terminals will rise and fall at slip frequency. The only recourse to remedy the situation is to separate the generator from the infinite bus by opening a circuit breaker, and then to resynchronize the generator to the bus.

It is seen that the condition for maximum received power occurs when $\bar{V}_g$ is at the position E. This corresponds to a phase angle δ between $\bar{V}_g$ and $\bar{V}_r$ equal to the impedance angle θ of Z.

b. Analytical Approach. The problem of the stability of two machines tied together through a general power circuit may be carried out analytically using Fig. 7-7. Note that in this diagram all complex quantities

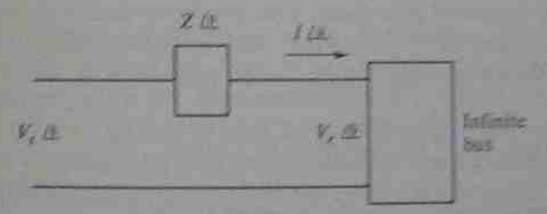


FIG. 7-7. A source voltage $\bar{V}_s$ connected through a basic power circuit to an infinite bus.

have been expressed in polar form; that is,

$$\bar{V}_r = V_r \angle 0° \quad \text{(reference)} \tag{7-4}$$

$$\bar{V}_s = V_s \angle \delta \tag{7-5}$$

$$Z = Z \angle \theta \tag{7-6}$$

$$\bar{I} = I \angle \varphi \tag{7-7}$$

Writing Kirchhoff's voltage equation around the loop we have

$$\bar{V}_s - \bar{I}Z - \bar{V}_r = 0$$

Solving for $\bar{I}$ in this equation and expressing all terms in polar form yields

$$\bar{I} = I\underline{/\psi} = \frac{V_s\underline{/\delta} - V_r\underline{/0^\circ}}{Z\underline{/\theta}} = \frac{V_s}{Z}\underline{/\delta - \theta} - \frac{V_r}{Z}\underline{/-\theta} \tag{7-8}$$

$$\bar{I}^* = I\underline{/-\psi} = \frac{V_s}{Z}\underline{/\theta - \delta} - \frac{V_r}{Z}\underline{/\theta} \tag{7-9}$$

The vector power received, P_{sr}, is the product of $\bar{V}_r$ and $\bar{I}^*$.

$$P_r + jP_{qr} = \frac{V_rV_s}{Z}\underline{/\theta - \delta} - \frac{V_r^2}{Z}\underline{/\theta} \tag{7-10}$$

The real power and reactive power received are then

$$P_r = \frac{V_rV_s}{Z}\cos(\theta - \delta) - \frac{V_r^2}{Z}\cos\theta \tag{7-11}$$

$$P_{qr} = \frac{V_rV_s}{Z}\cos(\theta - \delta) - \frac{V_r^2}{Z}\sin\theta \tag{7-12}$$

Since θ is the circuit impedance angle, hence fixed, the maximum value of P_r occurs when the first term of Eq. (7-11) is maximum (i.e., when $\delta = \theta$), as realized in the graphical procedure. This condition does not result in maximum power supplied by V_r (unless $\theta = 45^\circ$), as shown below.

The vector power supplied, P_{rs}, is the product of $\bar{V}_s$ and $\bar{I}^*$.

$$P_s + jP_{qs} = \frac{V_s^2}{Z}\underline{/\theta} - \frac{V_sV_r}{Z}\underline{/\theta + \delta} \tag{7-13}$$

The real power and reactive power supplied are then:

$$P_s = \frac{V_s^2}{Z}\cos\theta - \frac{V_sV_r}{Z}\cos(\theta + \delta) \tag{7-14}$$

$$P_{qs} = \frac{V_s^2}{Z}\sin\theta - \frac{V_sV_r}{Z}\sin(\theta + \delta) \tag{7-15}$$

Since θ is fixed, the maximum value of P_s occurs when the second term of Eq. (7-14) is maximum (i.e., when $\delta = 180^\circ - \theta$).

If the resistance in the circuit impedance is neglected, then

$$\theta = 90^\circ \tag{7-16}$$

Under this circumstance the expressions for received power, Eq. (7-11), and for supplied power, Eq. (7-14), reduce to

$$P_r = P_s = \frac{V_sV_r}{Z}\sin\delta \tag{7-17}$$

This sinusoidal relationship between power received and displacement angle δ is shown in Fig. 7-8. Such a plot is known as a *power–angle diagram.*

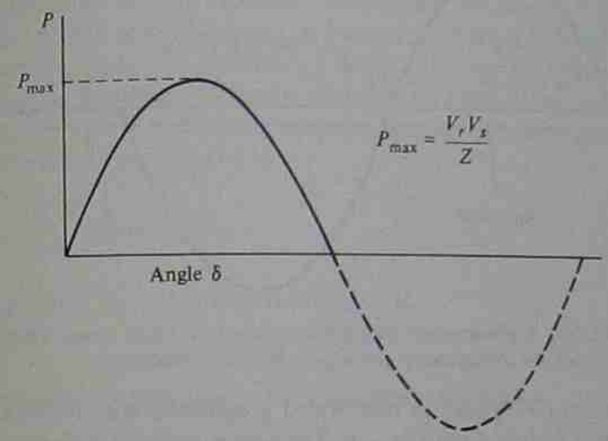


FIG. 7-8. A power-angle diagram applying to a basic power circuit in which the impedance is pure inductive reactance.

This simplified version of the power-angle relationship is rather widely used in stability studies. From this curve it can be seen that maximum receiver power is attained when the displacement angle is 90°. As the angle is increased beyond 90°, receiver power drops off rapidly and becomes zero at 180°. Beyond this angle, receiver power becomes negative, which implies that the infinite bus is supplying power to the system instead of accepting power from it. It is of importance to note that if the resistance of the circuit is assumed to be zero, there are no losses in the circuit and source power is exactly equal to receiver power. Besides, the received (and sent) power is positive if δ is positive, independently of the magnitude of V_s and V_r. Thus, power flows from the bus whose voltage is leading.

If the resistance in the circuit impedance is not neglected, then

$$\theta < 90^\circ \tag{7-18}$$

In this case, Eq. (7-11) can be expressed as

$$P_r = \frac{V_r}{Z}[V_s\cos(\theta - \delta) - V_r\cos\theta] \tag{7-19}$$

The corresponding power-angle diagram is a sine function as in Fig. 7-8, shifted to the left by an angle $90° - \theta$ and lowered by $V_r^2 \cos \theta / Z$, as shown in Fig. 7-9.

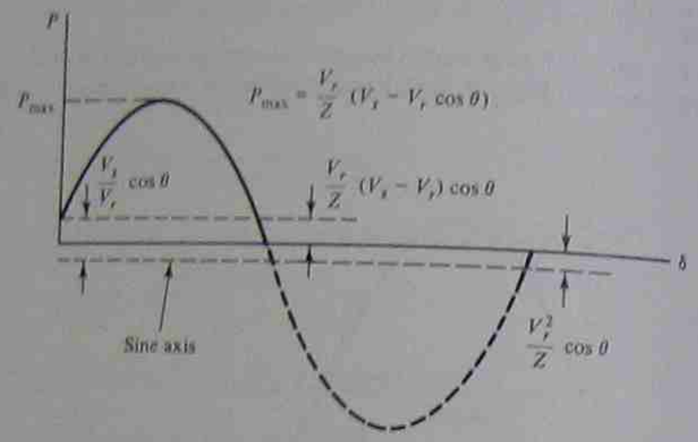


FIG. 7-9. A power-angle diagram applying to a basic power circuit in which the impedance is not a pure inductive reactance.

Equation (7-19) may be interpreted graphically with reference to Fig. 7-10, which is derived from Fig. 7-6. The power received P_r is equal to V_r/Z times the difference between the projection of V_s and the projection of V_r along the in-phase current axis. The power received is maximum when AC

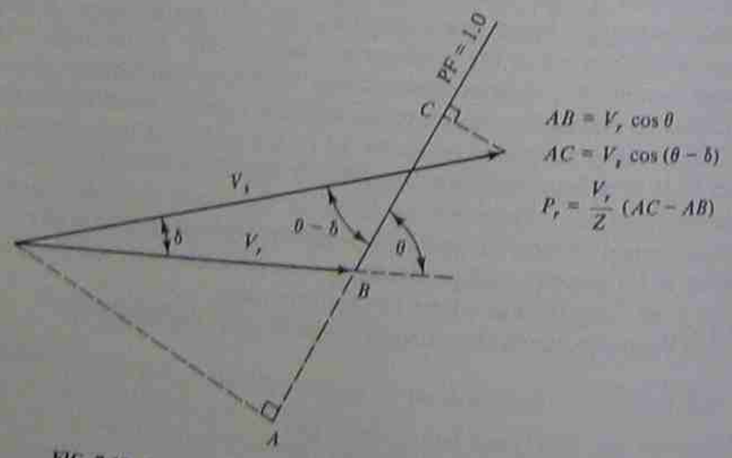


FIG. 7-10. A partial transmission diagram showing the projections of V_s and V_r along the in-phase current line.

is maximum. This occurs when V_s is parallel to the in-phase current axis, that is, when $\delta = \theta$.

An examination of Figs. 7-8 and 7-9 reveals that for a given received power two power angles are possible. However, only one of these angles permits stable generator operation. Under steady-state operation stability is achieved when the system forces the angle δ back to its steady-state value after a temporary perturbation. When δ is less than θ, an increase in δ results in increased received power, i.e., an increase in the generator output. Since the generator input has not changed, deceleration results and δ is brought back to its original value. Likewise, a decrease in δ leads to a reduction of received power and, hence, acceleration back to the original value of δ. Following the same argument, it can be seen that no stable steady-state operation is possible with $\delta > \theta$. For stable steady-state operation, then, $dP_r/d\delta$ must be positive. From Eq. (7-11),

$$\frac{dP_r}{d\delta} = \frac{V_r V_s}{Z} \sin(\theta - \delta) \tag{7-20}$$

Since θ is positive, $dP_r/d\delta$ is positive for $\delta < \theta$.

7-6. INFINITE BUS SUPPLYING A SYNCHRONOUS MOTOR

A problem similar to the one just discussed is that in which a synchronous motor is supplied from an infinite bus (Fig. 7-11a). The circuit diagram is shown in Fig. 7-11b. Here it may be noted that the source voltage is the volt-

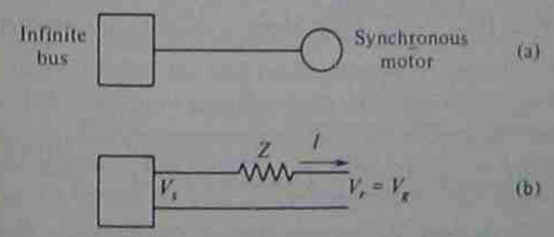


FIG. 7-11. A synchronous motor supplied from an infinite bus. (a) Schematic diagram. (b) Circuit diagram.

age of the infinite bus, while the receiver voltage is the generated voltage within the synchronous motor. If the synchronous motor is tied directly to the infinite bus, the impedance Z is simply the impedance of the synchronous motor itself. If the motor is supplied over lines or through transformers, the impedances of these devices are included in the impedance Z shown on the diagram.

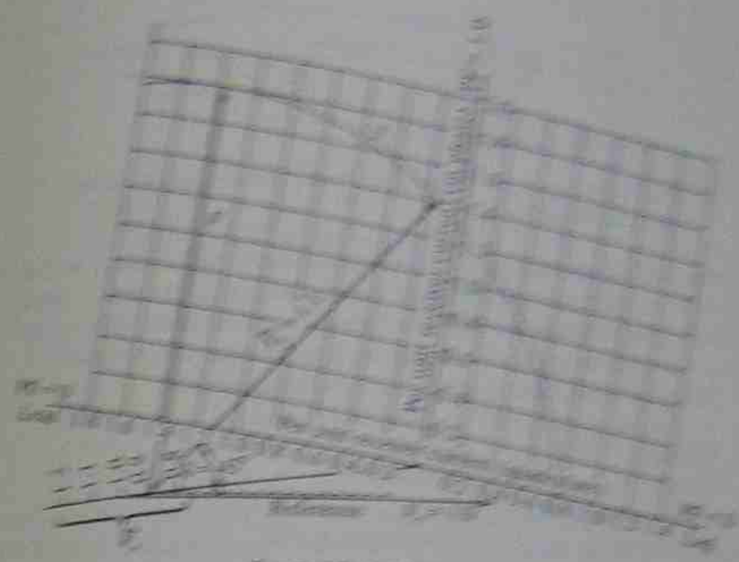


FIG. 7-12. A transmission diagram used to determine maximum power transfer.

$$P_{r_1} = 1.1 \text{ pu}$$
$$P_{r_2} = 0.9 \text{ pu}$$

component of receiver current is 1.4 pu. Receiver power is therefore

$$P_{r_{max}} = V_r I_{r,max} = 0.9 \times 1.4 = 1.26 \text{ pu}$$

Other angular positions of the phasor $\bar{V}_r$ may be taken and the receiver power calculated, thus providing information for plotting the power-angle diagram.

It may be noted that for this particular system and with the particular voltages specified, maximum power occurs when the $\bar{V}_r$ phasor is in position 2, for here the in-phase component of receiver current is a maximum. By examination it may be noted that $P_{max} = V_r I_{r,max\,cos\,\theta}$ is dependent on the values assigned to V_s and V_r, and on the magnitudes and angles of the constants A and B.

An analytical study of the power transfer through a generalized $ABCD$ network may be made but will not be presented here. Suffice it to say that the received power is maximum when δ is equal to β, the angle of network constant B.

7-8. TRANSMISSION DIAGRAM OF A LONG TRANSMISSION LINE

Consider a power circuit in which a generator is connected to an infinite bus through a transformer and a long line as shown in Fig. 7-13. Although the transmission characteristics of this system can only be determined by an

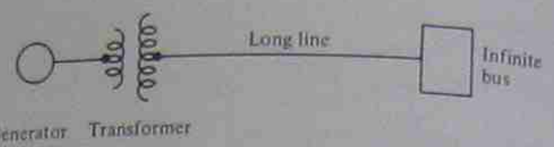


FIG. 7-14. A generator connected through a transformer and a long line to an infinite bus.

analysis of the total system, the transmission line itself, if long, will have a dominant influence on the behavior characteristics of the entire system. It is therefore informative to study the transmission characteristics of the line alone. A specific example will be used to illustrate the line behavior.

Consider a line having the following characteristics:

voltage	230 kV
length l	300 miles
equivalent spacing	40 ft
conductor	1,590,000 cm ACSR

Using the tables in Chapter 5 we find that

$$R = 0.0684\ \Omega/\text{mile}$$
$$X_L = 0.8066\ \Omega/\text{mile}$$
$$X_C = 0.1909\ \text{M}\Omega\text{-miles}$$

Considering the π-line representation of the transmission line, Eqs. (6-21) and (6-22) indicate the following:

$$Z = (R + jX_L)l = (0.0684 + j0.8066)300 = 243\ \underline{/85.2^\circ}\ \text{ohms}$$

$$Y_1 = Y_2 = j\frac{l}{2X_C} = j\frac{300}{2 \times 0.1909 \times 10^6} = 0.786 \times 10^{-3}\ \underline{/90^\circ}\ \text{mhos}$$

The values of A and B for the π-line representation are given by Eqs. (6-17) and (6-18) as

$$A = 1 + Y_2Z = 1 + 0.786 \times 10^{-3}\ \underline{/90^\circ} \times 243\ \underline{/85.2^\circ}$$
$$= 1 + 0.191\ \underline{/175.2^\circ} = 0.810\ \underline{/1.1^\circ}$$

$$B = Z = 243\ \underline{/85.2^\circ}\ \text{ohms}$$

With the values of A and B known, a transmission diagram may be constructed as shown in Fig. 7-15. Note that this diagram is for the single-phase equivalent circuit and is constructed in terms of volts, ohms, and amperes instead of per unit quantities. Obviously, if a base kVA had been

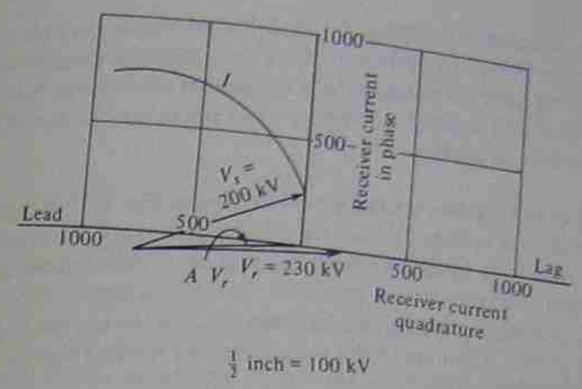


FIG. 7-15. The transmission diagram of a 300-mile, 230-kV transmission line.

chosen, the diagram could have been constructed in terms of per unit values. This diagram indicates that if the receiver current is 250 amperes at a power factor of 1.0 (57,500 kilowatts) the required sending-end voltage will be 200 kilovolts.

Suppose that the values of sending-end voltage V_s and receiver voltage V_r are held constant while power input is increased. The vector $\bar{V}_r$ will rotate describing the arc, I. This arc indicates a maximum possible value of the in-phase component of receiver current of 750 amperes (172,000 kilowatts). Analytically, the maximum received power occurs when $\delta = 85.2^\circ$.

$$\bar{V}_r = 202\ \underline{/85.2^\circ} = 0.810\ \underline{/1.1^\circ} \times 230\ \underline{/0^\circ} + 243\ \underline{/85.2^\circ} \times \bar{I}_r \times 10^{-3}$$

$$\bar{I}_r = 1070\ \underline{/45.3^\circ} = 753 + j761\ \text{A}$$

To make better use of his equipment, the transmission engineer looks for methods of increasing the power limits of his system. This search has led to many improvements in transmission-circuit design.

7-9. METHODS OF INCREASING TRANSMISSION-SYSTEM CAPABILITIES

Various methods are available for increasing the transmission capabilities of circuits. Some of these methods are illustrated with reference to the transmission line described in Section 7-8, even though the line is only a part of the necessary system.

a. Multiple Circuits. Referring to the line described in Section 7-8, it is obvious that building a second circuit would bring about a doubling

of the transmission capabilities, for each line would be capable of carrying the maximum power, as previously described. Multiple circuits are in common use. They have the additional advantage that service may be maintained over one line, with reduced capability, while the other line is out of service for maintenance or repair.

b. Raising Line Voltage. Referring to Fig. 7-15, it may be noted that if the receiver voltage V_r is increased, the phasor AV_r increases proportionately. Assuming again an initial loading of 57,500 kilowatts at unity power factor, receiver current decreases but V_s increases. This increased value of V_s provides an increased maximum value of the in-phase component of receiver current. Combining this with increased receiver voltage results in increased maximum power transfer.

c. Use of Shunt Reactors. Shunt inductive reactors of proper size may be installed at each end of the line (Fig. 7-16), thereby effectively

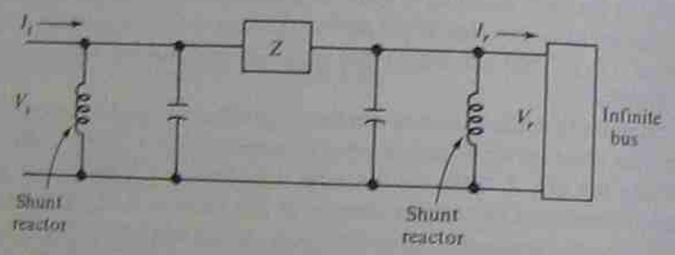


FIG. 7-16. The π-line representation of the 230-kV transmission line with shunt reactors at the terminals.

balancing out the line capacitance and reducing the value of Y in Eq. (6-22) to zero. Under this circumstance the value of A becomes 1.0 and the transmission diagram changes to that shown in Fig. 7-17.

Again assuming a receiver voltage V_r of 230 kilovolts and a receiver current of 250 amperes, unity power factor (57,500 kilowatts), it may be noted that V_s is 245 kilovolts, a value substantially higher than that required as indicated in Fig. 7-15. Operating with this value of sending-end voltage, power transfer may be increased until the in-phase component of receiver current is 850 amperes, corresponding to a maximum power limit of 196,000 kilowatts. The effect of the shunt reactors is even more favorable if the analysis is made considering the impedance of the generator and transformer at the source end.

When the system is equipped with reactors as described above, the source generator must operate at a higher voltage, which means that it has a stronger field. A high value of field strength tends to provide stable operation.

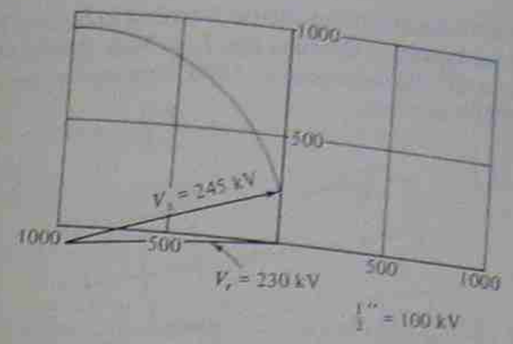


FIG. 7-17. The transmission diagram of the 230-kV transmission line with shunt reactors.

It may be noted that the long line with shunt reactor compensation has the behavior characteristics of the general power circuit.

d. Reducing Line Reactance By Means of Series Capacitors. It may be noted that in the construction of transmission diagrams for either the short-line representation or the π-line representation of a transmission line, the spacing between the lines of the grid is determined by the series impedance of the line. Any means of reducing this impedance reduces the spacing between grid lines, from which it follows that power limits are increased.

One method of reducing the series impedance is installation of series capacitors in the line, usually located at the midpoint (Fig. 7-18).

Referring to the transmission line of Section 7-8, the installation of a series capacitor of 120 ohms results in a total series impedance of

$$\begin{aligned} Z_t &= (R + jX_L)l - jX_C \\ &= (0.0684 + j0.8066)300 - j120 \\ &= 20.5 + j122 = 124 \underline{/80.5^\circ} \text{ ohms} \end{aligned}$$

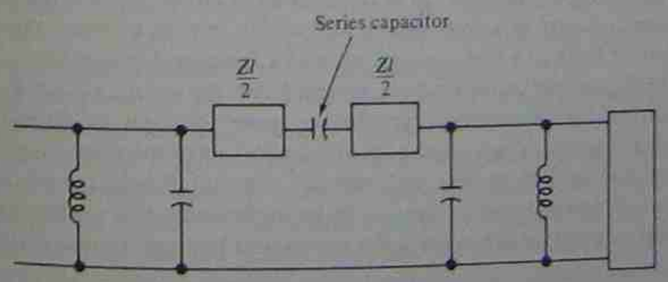


FIG. 7-18. The π-line representation of the 230-kV transmission line with shunt reactors and a series capacitor.

With reactor compensation also (as described in Section 7-9c) the transmission diagram appears as shown in Fig. 7-19. Note that for the same initial load conditions (57,500 kilowatts at 230 kilovolts) the maximum power transfer is 390,000 kilowatts.

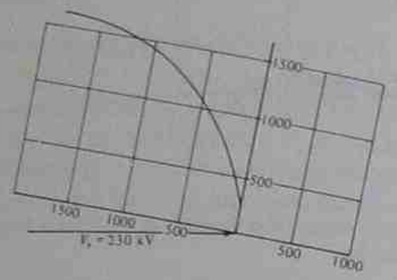


FIG. 7-19. The transmission diagram of the 230-kV transmission line with shunt reactors and a series capacitor.

e. Reducing Line Reactance By Means of Bundle Conductors. Although the use of bundle conductors on transmission lines is primarily to reduce corona loss and radio interference, it also has the advantage of reducing line reactance and so increasing the power limit of the line. Corona is the ionization of air in the vicinity of a conductor due to the intense electric field that may be created by the conductor voltage. Suppose a conductor of a given physical radius (and with a particular value of geometric mean radius GMR_1) is replaced by four cables of equal total conductance spaced apart as described in Section 5-2e. The new value of the geometric mean radius GMR_{eq} as given by Eq. (5-9) is greater than GMR_1. Hence the inductive reactance as given by Eq. (5-4) is reduced slightly, with a corresponding increase in the maximum power-transfer capability of the line.

f. Use of Voltage Regulators. Automatic voltage regulators may substantially increase the steady-state stability limits of a system, as will be illustrated with Fig. 7-20. In (a) is shown the circuit to be considered. A generator connects to a low-voltage bus, which in turn connects through a transformer bank to a high-voltage bus and a long transmission line.

In discussions so far we have assumed that the source voltage V_g (Fig. 7-20b) is held constant while we observe power changes as displacement angle is advanced. It is a good approximation to assume that voltage V_g is proportional to field current and remains constant if field current is held constant. If power-angle studies are to be made under this circumstance, it is proper to consider the entire series impedance between V_g and the infinite bus.

In power-system practice it is quite common to readjust field current

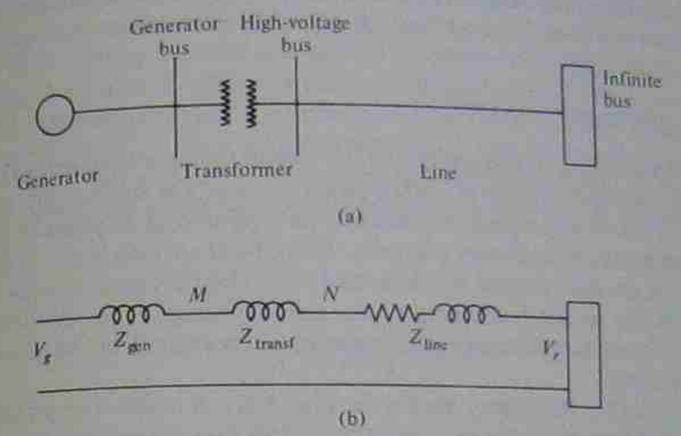


Fig. 7-20. A simple power system showing all buses. (a) Schematic. (b) Circuit diagram.

and so change V_g as loading on the machine is increased. This change in field current may be accomplished by an automatic voltage regulator. If the automatic voltage regulator is set to hold a constant value of voltage on the generator bus (point M, Fig. 7-20b), power limits are determined by a consideration of the series impedance from the point M to the infinite bus. Obviously because of the lower value of the total series impedance Z, this mode of operation will give higher power limits than would be obtained by holding V_g (field current) constant.

A still more favorable situation is observed if the voltage regulator controlling the field current of the generator is set to hold at a constant value the voltage on the high-voltage bus, N. Now the only impedance that needs to be considered in the problem is that which lies between point N and the infinite bus.

It is the operating practice of some companies to set their voltage regulators to hold constant a voltage which may be regarded as at a point somewhere between M and N. Local considerations determine the exact point to be held constant by action of the voltage regulator.

If, in the example just cited, the power output of the generator is to be increased while an automatic voltage regulator holds generator bus voltage at a constant value, it is necessary for field current to be increased with each increment of power output. In some instances it is impossible to realize the full power limit predicted by graphical analysis or by the equations because of field-circuit limitations. In every machine the maximum value of V_g is limited by the maximum possible output voltage of the excitor supplying the field, by the resistance of the field circuit, and by the saturation of the mag-

sonic circuit. All these factors must be evaluated when one attempts to determine the steady-state power limits of a particular machine.

7-10. TRANSIENT STABILITY

The discussion in this chapter up to the present time has been limited to the steady-state performance of electric power circuits. The study of this type of behavior is of importance in predicting the response of a system on which load changes are made very gradually. This type of analysis is also of importance as an introduction to the behavior of electric power systems when subjected to sudden load changes or to sudden changes in circuit configuration. Some of the elementary problems of transient analysis will be introduced in this section.

Consider the system shown in Fig. 7-21, in which the problem is simplified by considering reactances only. This diagram represents a generator connecting to a bus and then through a parallel combination of two lines to an infinite bus. X_s represents the reactance of the machine and X_{L1} and X_{L2} the reactances of the two lines.

By suitable circuit reduction the system of Fig. 7-21a may be reduced to the general power circuit in which a single impedance Z appears between the generated voltage V_s and the infinite bus (Fig. 7-7). Assuming that V_s, V_∞

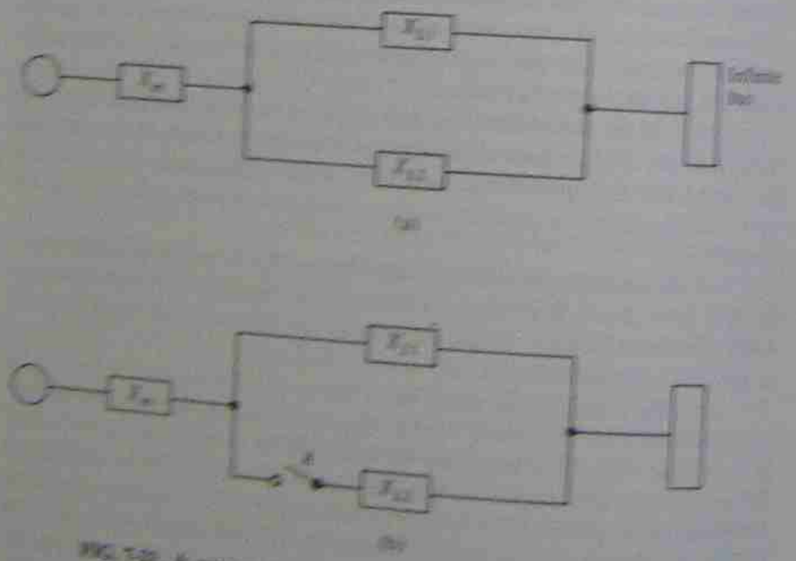


FIG. 7-21. A generator connecting through two parallel lines to an infinite bus. (a) Both lines closed. (b) One line closed, one open.

and Z are known, reference to Eq. (7-13) permits the plotting of a power-angle diagram as shown by (a) in Fig. 7-22.

Now suppose that line 2 is opened by action of a circuit breaker A, resulting in a system as shown by the circuit diagram, Fig. 7-21b. Under this new arrangement the value of Z in the equivalent circuit between V_s and the infinite bus is $j(X_s + X_{L1})$ a value greater than with both lines in service (Fig. 7-21a). With one line out of service and with the resultant increase in the value of Z, the power-angle diagram will be as indicated by curve (b) in Fig. 7-22.

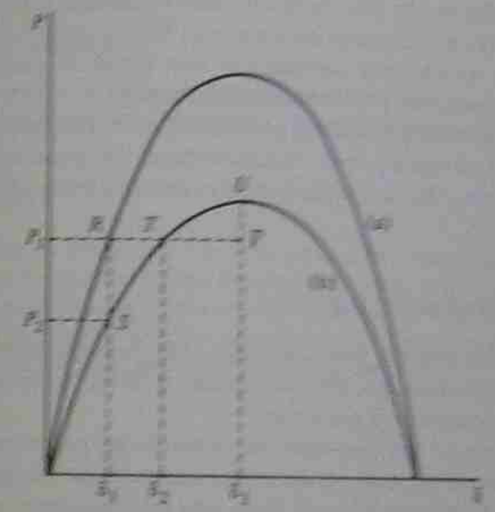


FIG. 7-22. The power-angle diagram of the system shown in Fig. 7-21. (a) Both lines closed. (b) One line closed, one open.

Assume that under a particular set of operating conditions and with both lines in service (Fig. 7-21a), the power being delivered to the infinite bus is P_1, as indicated on Fig. 7-22. This implies that the generated voltage V_s leads the voltage of the infinite bus by the angle δ_1. The rotor of the machine then is at a particular location with respect to the rotor of the infinite bus.

Next suppose that the switch A suddenly opens, giving us the circuit indicated by Fig. 7-21b. Since the angular displacement of the rotor cannot change instantly, immediately after the opening of the breaker the rotor displacement is still at the angle δ_1, which implies that the power delivered to the load and the power output of the generator has dropped to the value P_2. This sudden change in the output of the generator could not be immediately recognized by the governor on the prime mover, with the result that shaft torque will remain unchanged following the switching operation. Now the power input to the generator from the shaft is P_1 while the power output into

the electric circuit is P_2, the difference between the two being available for accelerating the rotor. With a slight increase in speed, the rotor angle will increase, eventually reaching the value at which shaft power and electrical power will again balance. However, during the time the shift has been made from δ_1 to δ_2, the rotor has been accelerating. When the angle δ_2 is reached, the rotor is running slightly above synchronous speed. It will therefore continue to advance in the direction of δ_3. However, in the region between δ_2 and δ_3 the electrical output exceeds the shaft input, with the result that the rotor slows down.

It can be shown for this particular case (although it will not be done here) that the rotor will advance until the area TUV is equal to the area RST. Oscillation will be observed around the new point of stability, δ_2, with eventual stable operation at this rotor displacement.

The study of transient stability problems involves an analysis of electric-circuit behavior combined with considerations of transients in rotating mechanical systems. This subject is treated in detail in more advanced courses and textbooks.

7-11. SYSTEMS WITH MANY MACHINES

Present-day power systems have extensive interconnections which result in many synchronous machines, generators, and motors, being electrically connected through complicated networks.

The analysis of the two-machine problem as presented above is an oversimplification of the case, inasmuch as one machine was presumed to be of infinite size. If two machines of finite size are considered, any change in either of the machines affects the other with complicating results. More advanced methods than have been presented here must be used even in this simple case.

Large electric power networks bring about the interconnection of many machines in different plants at widely separated points. The steady-state and transient analysis of such systems, involving many lines and transformers, is a highly specialized subject. Methods of study using digital computers must be continually revised as system growth adds to the complexity of the problem.

PROBLEMS

7-1. Determine the maximum power that may be delivered by a 12-V storage battery which has an internal resistance of 0.05 Ω. Under maximum power conditions, what will be the power loss within the battery and what will be the terminal voltage?

7-2. Determine the maximum power that may be delivered by a 10-kVA transformer whose primary voltage is held constant at 1.1 pu volts. The impedance of the transformer is 2 percent resistance and 4 percent reactance. Under maximum power conditions, what will be the power loss within the transformer, the terminal voltage, and the current?

7-3. Refer to the transmission diagram presented in Fig. 6-21. With $V_r = 1.0$ pu, draw curves showing the magnitude of V_s for receiver power P_r ranging from 0 to 1.2 pu, the power factor assumed to be
   a. unity.
   b. 0.707 lag.
   c. 0.707 lead.
   Also solve analytically.

7-4. For the system of Problem 7-3, assume that $V_s = 1.1$. Draw curves of V_r for receiver power ranging from 0 to 1.2 pu, the power factor assumed to be
   a. unity.
   b. 0.8 lag.
   c. 0.8 lead.

7-5. The system of Problem 7-3 is to carry a unity-power-factor customer load which varies from 0 to 1.6 pu. Sending-end voltage is held constant at 1.1 pu. Receiving-end voltage is held constant at 1.0 pu by adjusting a reactive load which is in parallel with the customer load. Determine the reactive volt-amperes (lag or lead) necessary if the customer load is
   a. 0
   b. 0.5 pu.
   c. 1.0 pu.
   d. 1.3 pu.

7-6. A generator with an internal impedance of $(0.05 + j.80)$ pu is connected to an infinite bus, whose voltage is 1.0 pu. Construct a transmission diagram and draw a power angle curve assuming that V_g is 1.1 pu. What is the maximum power received and what will be the circuit loss at this power? Also solve analytically.

7-7. Refer to Problem 7-6. Assume that the generator is connected to the infinite bus through a line whose impedance is $Z_L = 0.2 + j0.5$. What is the maximum power that may be transferred to the infinite bus?

7-8. Refer to the transmission diagram Fig. 6-21 and consider it applying to a generator connected to an infinite bus. Assume that the infinite bus voltage is 1.1 pu. Calculate the rotor-displacement angle when the received power is 1.4 pu, assuming that the generator voltage is
   a. 0.85 pu.
   b. 1.10 pu.

7-9. Compare the maximum power transfer for the transmission line described in Section 7-8 with and without shunt reactors. Assume that in each case $V_s = 245$ kV and $V_r = 230$ kV.

7-10. Refer to the capacitor-compensated line in Section 7-9d. Suppose that by mistake the capacitive reactance is made 300 Ω. Draw a transmission diagram for this condition, and from it analyze system performance.

7-11. Refer to the system of Fig. 7-21 and the power angle diagram Fig. 7-2c. Assume that after switch S is opened, all transients have disappeared and the system is operating stably at the angle δ_2. Switch A is now closed. Analyze the system response.

chapter 8

Faults on Power Systems

Each year new designs of power equipment bring about increased reliability of operation. Nevertheless, equipment failures and interference by outside sources occasionally result in faults on electric power systems. On the occurrence of a fault, current and voltage conditions become abnormal, the delivery of power from the generating stations to the loads may be unsatisfactory over a considerable area, and if the faulted equipment is not promptly disconnected from the remainder of the system, damage may result to other pieces of operating equipment.

8-1. DESCRIPTION OF A FAULT

A *fault* is the unintentional or intentional connecting together of two or more conductors which ordinarily operate with a difference of potential between them. The connection between the conductors may be by physical metallic contact or it may be through an arc. At the fault, the voltage between the two parts is reduced to zero in the case of metal-to-metal contact, or to a very low value in case the connection is through an arc. Currents of abnormally high magnitude flow through the network to the point of fault. These short-circuit currents will usually be much greater than the designed thermal ability of the conductors in the lines or machines feeding the fault. The resultant rise in temperature may cause damage by the annealing of conductors

and by the charring of insulation. In the period during which the fault is permitted to exist, the voltage on the system in the near vicinity of the fault will be so low that utilization equipment will be inoperative. It is apparent that the power-system designer must anticipate points at which faults may occur, be able to calculate conditions that exist during a fault, and provide equipment properly adjusted to open the switches necessary to disconnect the faulted equipment from the remainder of the system. Ordinarily it is desirable that no other switches on the system are opened, as such behavior would result in unnecessary modification of the system circuits.

A distinction must be made between a *fault* and an *overload*. An overload implies only that loads greater than the designed values have been imposed on the system. Under such a circumstance the voltage at the overload point may be low, but not zero. This undervoltage condition may extend for some distance beyond the overload point into the remainder of the system. The currents in the overloaded equipment are high and may exceed the thermal design limits. Nevertheless, such currents are substantially lower than in the case of a fault. Service frequently may be maintained, but at below-standard voltage.

Overloads are rather common occurrences in homes. For example, a housewife might plug five waffle irons into the kitchen circuit during a neighborhood party. Such an overload, if permitted to continue, would cause heating of the wires from the power center and might eventually start a fire. To prevent such trouble, residential circuits are protected by fuses or circuit breakers which open quickly when currents above specified values persist. Distribution transformers are sometimes overloaded as customers install more and more appliances. The continuous monitoring of distribution circuits is necessary to be certain that transformer sizes are increased as load grows.

Faults of many types and causes may appear on electric power systems. Many of us in our homes have seen frayed lamp cords which permitted the two conductors of the cord to come in contact with each other. When this occurs, there is a resulting flash, and if breaker or fuse equipment functions properly, the circuit is opened.

Overhead lines, for the most part, are constructed of bare conductors. These are sometimes accidentally brought together by action of wind, sleet, trees, cranes, airplanes, or damage to supporting structures. Overvoltages due to lightning or switching may cause flashover of supporting insulators, thereby establishing an arc from the conductor to the support or from conductor to conductor. Contamination on insulators sometimes results in flashover even during normal voltage conditions.

The conductors of underground cables are separated from each other and from ground by solid insulation, which may be oil-impregnated paper or a plastic such as polyethylene. These materials undergo some deterioration with age, particularly if overloads on the cables have resulted in their operation at elevated temperatures. Any small void present in the body of the insulating material will result in ionization of the gas contained therein, the products of which react unfavorably with the insulation. Deterioration of the insulation may result in failure of the material to retain its insulating properties, and short circuits will develop between the cable conductors. The possibility of cable failure is increased if lightning or switching produces transient voltages of abnormally high values between the conductors.

Transformer failures may be the result of insulation deterioration combined with overvoltages due to lightning or switching transients. Short circuits due to insulation failure between adjacent turns of the same winding may result from suddenly applied overvoltages. Major insulation may fail, permitting arcs to be established between primary and secondary windings or between a winding and grounded metal parts such as the core or tank.

Generators may fail due to breakdown of the insulation between adjacent turns in the same slot, resulting in a short circuit in a single turn of the generator. Insulation breakdown may also occur between one of the windings and the grounded steel structure in which the coils are embedded. Breakdown between different windings lying in the same slot results in short-circuiting extensive sections of the machine.

Fault may be classified as permanent or temporary. *Permanent faults* are those in which insulation failure or structure failure produces damage that makes operation of the equipment impossible and requires repairs to be made. *Temporary faults* are those which may be removed by deenergizing the equipment for a short period of time; short circuits on overhead lines frequently are of this nature. High winds may cause two or more conductors to swing together momentarily. During the short period of contact, an arc is formed which may continue as long as the line remains energized. However, if automatic equipment can be brought into operation to deenergize the line quickly, little physical damage may result and the line may be restored to service as soon as the arc is extinguished. Arcs across insulators due to overvoltages from lightning or switching transients usually can be cleared by automatic circuit-breaker operation before significant structure damage occurs. Because of this characteristic of faults on lines, many companies operate following a procedure known as high-speed reclosing. On the occurrence of a fault, the line is promptly deenergized by opening the circuit breakers at each end of the line. The breakers remain open long enough for the arc to clear, and then reclose automatically. In many instances service is restored in a fraction of a second. Of course, if structure damage has occurred and the fault persists, it is necessary for the breakers to reopen and lock open.

For the purpose of this discussion, one specialized type of fault is given primary consideration, the balanced three-phase fault. This type of fault exists when all three conductors of a three-phase line (or a machine) are

brought together simultaneously into a short-circuit condition. Faults of this type are not particularly common, but their study enables us to comprehend a whole group of problems that short-circuit conditions present to the power-system operator. Other types of faults, which are much more difficult to analyze, are discussed briefly in Section 8-7.

Balanced three-phase faults, like balanced three-phase loads, may be handled on a line-to-neutral basis or on an equivalent single-phase basis. Problems may be solved either in terms of volts, amperes, and ohms, or in terms of per unit quantities. The handling of faults on single-phase lines is of course identical to the method of handling three-phase faults on an equivalent single-phase basis.

8-2. NEED FOR CALCULATING FAULT CONDITIONS

Faults on power systems are unpredictable both as to location and time of occurrence. When a system study is made to determine the behavior during a fault, it is necessary to assume the location of the fault, the configuration of lines, transformers, and generators that exists previous to the fault, and in some cases the loading of the system. For a system of some complexity, the possibilities of assignment of initial conditions combined with a choice of fault location may result in a very large number of required solutions. These studies provide the engineer with information by which he can design to assure the prompt disconnection of faulted equipment with a minimum of damage and a minimum of disturbance to the operation of the remaining system.

Circuit breakers and fuses are used to disconnect faulted equipment. Since the current to the faulted equipment is abnormally high, these devices are asked to interrupt currents far greater in magnitude than those observed during normal operation. The circuit-interrupting process consists of parting a pair of contacts between which an electric arc is drawn, then processes must be brought into play to extinguish the arc. The greater the arc current and the higher the voltage of the circuit, the more difficult is the problem of arc extinction. Breakers and fuses are rated in terms of the normal circuit voltage, the continuous currents they may carry, and the short-circuit currents they may interrupt. Under short-circuit conditions a circuit breaker may open successfully, provided the current to be interrupted is within the design value. However, when asked to interrupt a current well above the design value, the arc between the parting contacts may not extinguish and the breaker may be destroyed by gas pressure built up within it (Fig. 8-1). Ordinary plug fuses, such as those used in entrance boxes in residences, will interrupt currents far above their continuous rating. On typical residential circuits, such fuses, when short circuits occur, will blow without breaking their

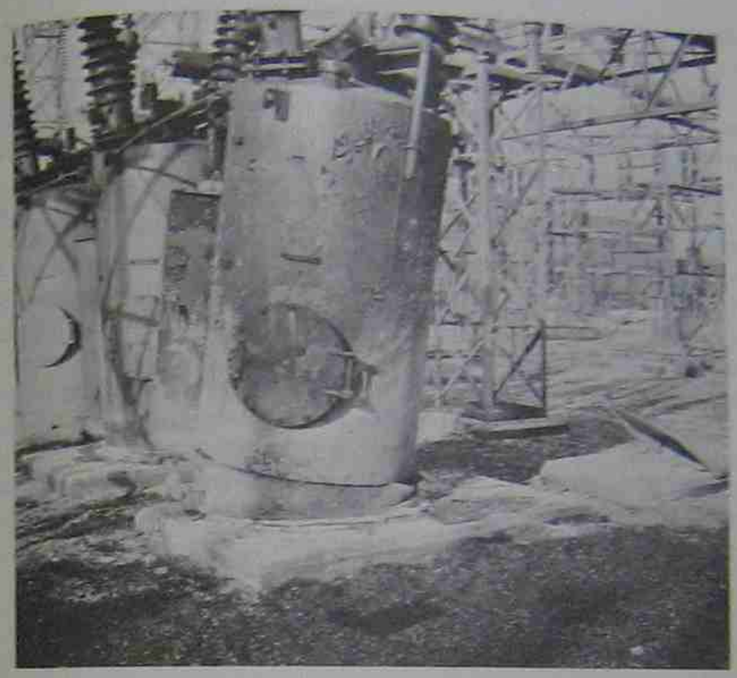


FIG. 8-1. A circuit breaker damaged by short-circuit currents which exceeded its interrupting rating.

transparent windows. However, if misapplied on industrial circuits where short-circuit currents may be thousands of amperes, the blowing of a fuse may produce the sound and violence of a shotgun blast.

As systems grow and new generators, lines, and transformers are added, short-circuit current values increase. It may become necessary to replace breakers and fuses with ones of higher current-interrupting capacity to avoid failures.

In order that circuit breakers operate promptly to disconnect faulted equipment, it is necessary to have a system that may recognize the presence of a fault, determine which piece of equipment is faulted, and supply energy to the mechanisms which will trip the appropriate breakers. In some of the simplest systems using low-voltage breakers, the power current itself flows through the trip coil of the breaker. If the current exceeds a certain specified value, the breaker is tripped and the circuit opened. On complicated networks, a system of on-line computers (known to the power man as relays) receives a continuous indication of the current and voltage on all lines, transformers, and generators connected to the many station buses. On the occurrence of a fault, the fault condition is recognized by the abnormal

voltage and current conditions then in existence. The relay contacts close to supply tripping current to those breakers necessary to clear the fault. If these relays are to be adjusted for proper functioning, it is necessary for the power engineer to know in advance the values and phase positions of the currents and voltages resulting from fault conditions. The subject of relays is treated in more detail in Chapter 11.

A force exists between a current-carrying conductor and every current-carrying conductor near it. These forces must be given consideration in the design of station buses, transformer windings, and machine windings. For two parallel conductors the force per unit length is directly proportional to the product of the current in each of the two conductors and inversely proportional to their separation. Equipment must be designed to withstand the forces resulting from the extremely high currents that exist during faults.

Overhead conductors, underground cables, transformer windings, and generator coils may be damaged by excessive temperature, either through the annealing of the conductor metal or through damage to insulation. In some cases the current during a fault, even though promptly cleared, may be so great that overheating of a conductor may occur.

8-3. FAULT CONDITIONS FROM CIRCUIT PARAMETERS

The circuit conditions during a fault may be calculated directly from known circuit parameters. On simple circuits, the problem is straightforward and easily accomplished. On complicated networks, digital computers are used to solve the required mathematical relations. A few examples will demonstrate the general method of attack.

a. Simple Series Circuit. A circuit representative of a distribution line is shown in Fig. 8-2a. Assume that the sending-end voltage is held constant at 4800 volts and the line impedances are as indicated. Load points are at *A*, *B*, and *C*.

In many instances the short-circuit currents which flow during faults are much greater than normal load currents, permitting load currents to be neglected (Fig. 8-2b). An important exception is synchronous motor load and, to a certain extent, three-phase induction motors. These motors act as generators during faults, converting their kinetic energy to electrical power as they slow down. Faults may be simulated at a station by closing switch *P*, *Q*, or *R*. Table 8-1 shows the system conditions existing for a fault at each of the three points, *A*, *B*, and *C*. Obviously faults could occur between stations. The resulting conditions at the stations may be determined once the location of the fault point is assumed.

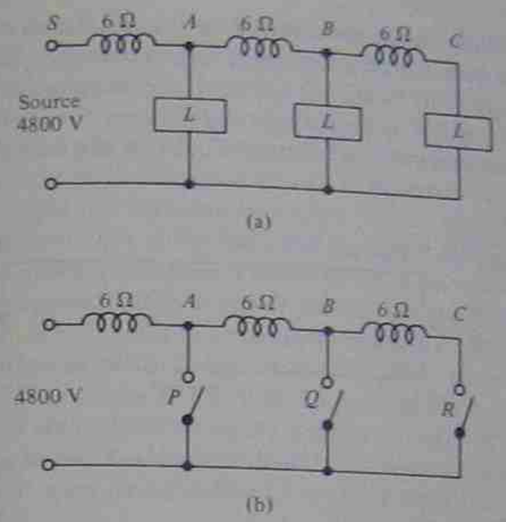


FIG. 8-2. A distribution circuit with three load points. (a) Normal circuit. (b) Loads are ignored. Short circuits may be produced by closing switches *P*, *Q*, or *R*.

Table 8-1. *Fault Condition on Fig. 8-2*

	Fault at *A*	Fault at *B*	Fault at *C*
CURRENT (amperes)			
S to *A*	800	400	266
A to *B*	0	400	266
B to *C*	0	0	266
VOLTAGE (volts)			
At *A*	0	2400	3200
At *B*	0	0	1600
At *C*	0	0	0

b. Faults on Networks. Figure 8-3a shows a simple network consisting of a transformer bank supplying a load over two parallel lines, on one of which a fault is assumed to exist. Figure 8-3b shows the assumed values of circuit constants in per unit values. The load is again neglected. This circuit may be reduced by a series of steps, shown in Fig. 8-3c and d, to a simple circuit in which the fault current may be determined. Once the magnitude of fault current is known, its division between the two line sections may be determined. Finally, the voltage at each bus and the current in each line may be evaluated as shown in Fig. 8-3e.

So far the discussion has centered on the calculation of currents and voltages in the presence of a fault at a known location. When an actual fault occurs, usually its location is unknown and the piece of faulted equipment must be identified by the currents and voltages observed at the stations during the fault. From Fig. 8-3e it is obvious that the faulted line could be

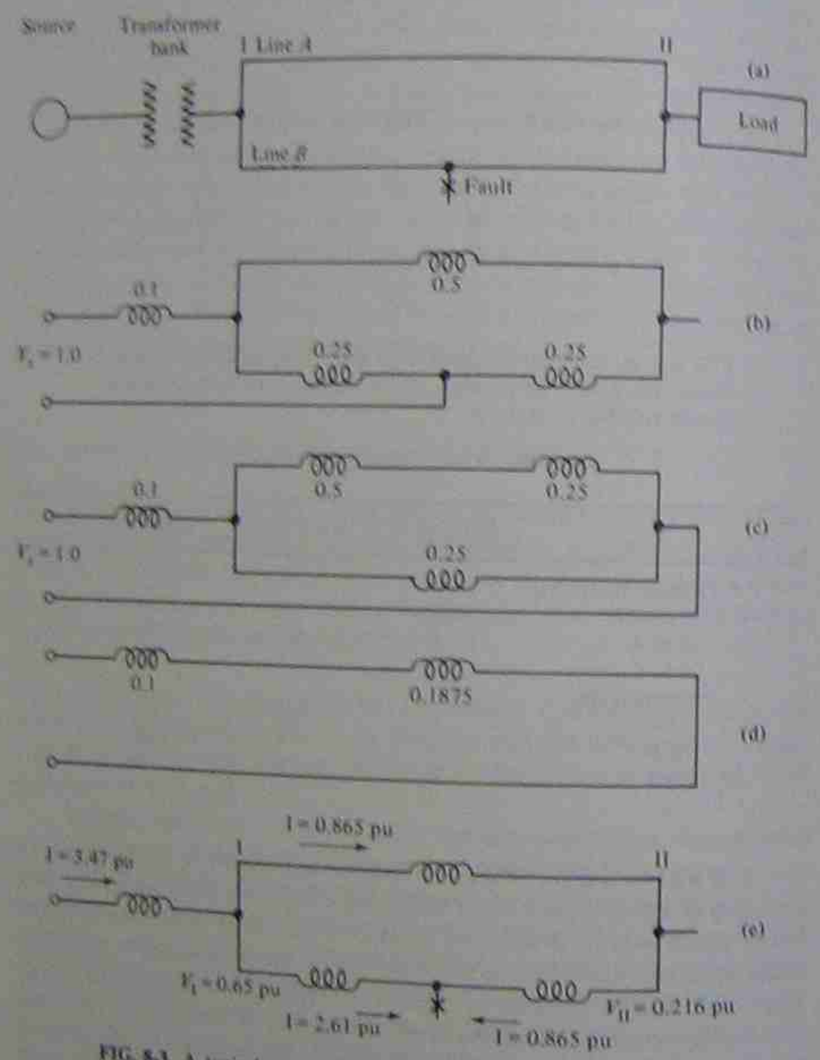


FIG. 8-3. A typical small power system with fault. (a) One line diagram. (b) Single-phase equivalent circuit under fault conditions. (c) and (d) Steps in system reduction for fault calculations. (e) Calculated currents in each line and voltages at each bus.

identified at bus I simply on the basis of current magnitudes. At bus II, the two lines carry current of equal magnitude. Other means of recognizing the faulted line are needed.

c. General Approach. Thévenin's theorem discussed in Section 2-6d affords a general procedure for obtaining fault currents in any network. The idea is to obtain the Thévenin equivalent of the network at the fault point before the occurrence of the fault. For the power system of Fig. 8-3a, the single-phase impedance diagram is shown in Fig. 8-4a, where F is the fault point and N the neutral. Since F and N are not connected, the Thévenin equivalent circuit of Fig. 2-37d becomes that shown in Fig. 8-4b. V_{FN} is the open-circuit voltage at point F; this is usually taken to be the nominal voltage, i.e., $1.0\underline{/0^\circ}$ as shown in Fig. 8-4f. To find the Thévenin impedance, all voltage sources are replaced by short circuits as in Fig. 8-4c. Reduction of the impedance as in Fig. 8-4d leads to the Thévenin impedance of Fig. 8-4e. The Thévenin equivalent circuit at point F in the absence of a fault is finally shown in Fig. 8-4f.

A fault at point F is now simulated by connecting F to N in Fig. 8-4a and f. For a three-phase system, this corresponds to tying all three lines together (possibly to ground) and is referred to as a symmetrical short circuit. The resulting current is 3.48 pu, as found in Fig. 8-3e. Clearly, then, the procedure basically involves the determination of the Thévenin impedance at the fault point, the reciprocal of that impedance being the fault current in pu.

So far only generators have been considered as sources of short-circuit currents. Indeed, they constitute the main sources of such currents. However, motors often contribute significantly to a fault current, sometimes upward of 10 percent. While a generator can, in principle, feed current to a fault indefinitely until it, or some other part of the system, breaks down, a motor cannot. The reason is that a generator is driven by a mechanical prime mover, such as a turbine, which can run independently of the electric power system. Thus, a generator can keep on operating fully in the presence of a fault, producing a voltage at its terminals all the while.

On the other hand, an electric motor derives its power from the electric power network and needs a voltage level close to rated to drive its mechanical load. When a short circuit occurs, the voltage drops to a low value, practically cutting off the flow of electric power to the motor. The latter does not stop instantaneously, however, due to its inertia and that of its load. If the motor magnetic field is still present, it will generate a voltage high enough to deliver power to the network and feed the fault at the expense of the kinetic energy of the motor and its load. The motor then slows down and its ability to feed the fault diminishes. If the motor magnetic field disappears when a fault occurs, no voltage is generated and no power flows to the fault. The kinetic

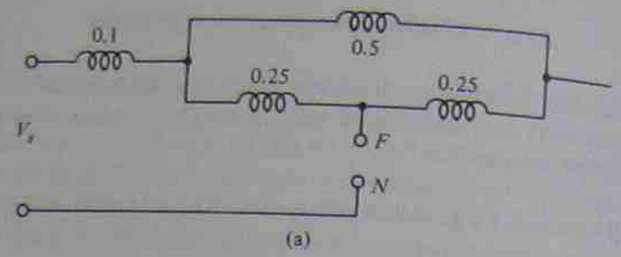


FIG. 8-4. Illustration of the application of Thévenin's theorem to a power system. (a) Single-phase equivalent circuit in the absence of a fault. (b) Thévenin equivalent at fault point. (c) Voltage source replaced by short circuit. (d) Impedance reduction. (e) Thévenin impedance. (f) Final Thévenin equivalent.

energy is expended on friction or some other mechanical outlet. In any event, a motor contribution to a short-circuit current is temporary.

The magnetic field in a synchronous motor is set up by a current drawn from a dc source. When the motor terminal voltage drops drastically due to a fault in the network, the dc current is fully available to allow the motor to act as a generator capable of feeding the fault over a period of up to a few minutes, that is, until the motor speed has dropped considerably. By contrast, the magnetic field in an induction motor is set up by the terminal voltage as in a transformer. As the terminal voltage collapses, so does the field a very short time later. An induction motor thus acts as a generator for a very short period of time, about 3 or 4 cycles.

The first step in the calculation of a short-circuit current is the determination of an impedance diagram. It is customary at this point to ignore all nonmotor loads, as well as small motors. Every element appearing on the one-line diagram of the network is replaced, between the same two nodes, by its per unit impedance. Since the purpose is to obtain the Thévenin impedance, all voltages induced in generators and motors are eliminated. Thus, all generator and motor impedances are to be inserted between a generator (motor) terminal point and the system neutral. The latter is often referred to as the *reference bus*. Then, to determine the Thévenin impedance at a fault point F, one finds the equivalent impedance between F and the neutral.

The short-circuit current at F is the reciprocal of the Thévenin impedance.

$$I_{sc}\ (\text{in pu}) = \frac{V_{FN}}{Z_{FN}} = \frac{1.0}{\text{Thévenin impedance (in pu)}}$$

It is important to note at this point that this is not the short-circuit current value used in selecting a circuit-breaker rating. For this purpose the short-circuit current value calculated as explained above is augmented by a multiplying factor of value between 1.0 and 1.6, for reasons discussed in the next two sections.

The per-unit impedances used in the impedance diagram must all be referenced to the same volt-ampere base. This means converting the per-unit impedance designated for each piece of equipment from its volt-ampere rating to the common volt-ampere base (see Section 4-7). Unless explicitly specified, the volt-ampere rating of generators and motors is $\sqrt{3}\ VI$, where V is the line voltage rating and I the full-load current rating. When the rated current of a motor is not known, the volt-ampere rating is calculated as follows:

$$\text{kVA base} = \frac{\text{horsepower rating} \times (0.747\ \text{kW/hp})}{\text{full-load efficiency} \times \text{power factor}} \qquad (8\text{-}1)$$

When the denominator in Eq. (8-1) is not known, the following kVA bases are adopted:

Induction motor or 0.8-power-factor synchronous motor:

$$\text{kVA base} = \text{horsepower rating} \tag{8-2}$$

1.0-power-factor synchronous motor:

$$\text{kVA base} = 0.8 \times \text{horsepower rating} \tag{8-3}$$

Equations (8-2) and (8-3) subsume an efficiency of 93.3 percent.

EXAMPLE 8-1. Calculate the symmetrical short-circuit current at point F in Fig. 8-5 given the following data:

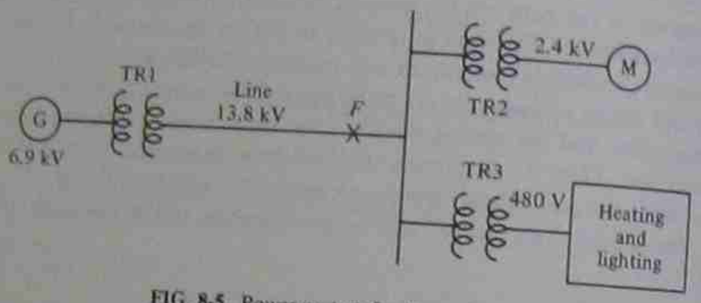


FIG. 8-5. Power system for Example 8-1.

Generator: 6.9 kV, 20,000 kVA, $Z = (2 + j35)\%$

Motor: induction, 2.4 kV, 6000 hp, $Z = (2 + j25)\%$

TR1: 6.9/13.8 kV, 20,000 kVA, $Z = (0.6 + j5)\%$

TR2: 13.8/2.4 kV, 7000 kVA, $Z = (1 + j6)\%$

TR3: 13.8/0.48 kV, 14,000 kVA, $Z = (1.5 + j8)\%$

Line: $Z = 0.08 + j0.24\ \Omega$

Solution. Let kVA_B be 20 MVA. Per-unit impedances are:

Generator: $Z = (0.02 + j0.35)$ pu

Motor: $$Z = (0.02 + j0.25) \times \frac{20{,}000}{6000}$$
$$= (0.0667 + j0.833) \text{ pu}$$

TR1: $Z = (0.006 + j0.05)$ pu

TR2: $$Z = (0.01 + j0.06) \times \frac{20{,}000}{7000}$$
$$= (0.0286 + j0.171) \text{ pu}$$

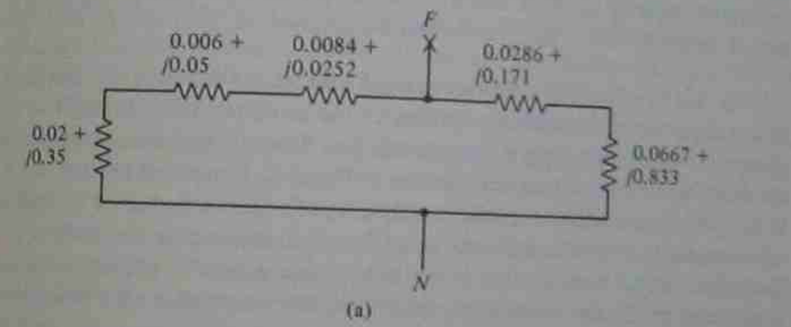
Line: $$Z = (0.08 + j0.24) \times \frac{20}{(13.8)^2}$$
$$= (0.0084 + j0.0252) \text{ pu}$$

The heating and lighting load is neglected. The impedance diagram is now produced as in Fig. 8-6a and reduced as in Fig. 8-6b. From Fig. 8-6c the Thévenin equivalent impedance at point F is $0.3\ \underline{/85.1^\circ}$ pu.

Base current at F $= \dfrac{20{,}000}{\sqrt{3} \times 13.8} = 837$ A

Short-circuit current $= \dfrac{1.0}{0.3} = 3.33$ pu

Short-circuit current $= 3.33 \times 837 = 2790$ A



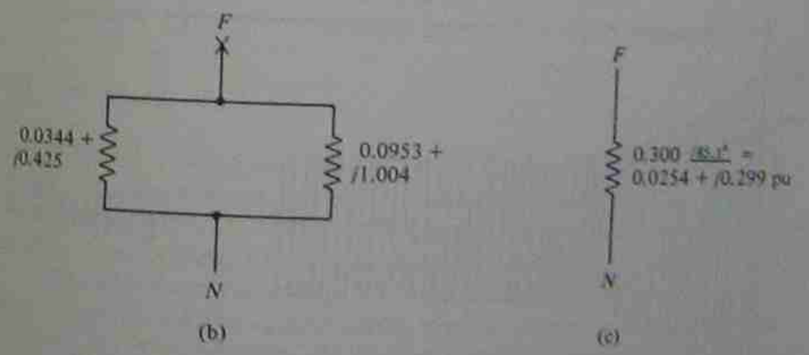


FIG. 8-6. Impedance diagram for the network of Fig. 8-5. (a) As viewed at point F. (b) Impedance reduction. (c) Thévenin impedance at point F.

8-4. SYNCHRONOUS MACHINE IMPEDANCE

In Section 2-8a the equivalent circuit model (or Thévenin equivalent) of an ac generator was shown (Fig. 2-48) as a generated voltage connected to the machine terminals through a resistance and an inductive reactance. This is, indeed, a gross oversimplification of a rather complicated electrical machine. However, this model serves for many purposes, particularly if the constants in the equivalent circuit are chosen to fit the particular problem at hand. Table A-7 was presented with but little discussion of the data. The application of the various values of inductive reactance listed in this table will now be presented. The value to be selected depends upon whether conditions of steady state or rapid change are being considered.

a. Problems of Steady State. Steady-state conditions are assumed in those problems in which changes of load are made very gradually, such as over a period of several minutes or more. Studies pertaining to voltage regulation and to steady-state stability limits fall in this class. For problems of this type it is proper to use the inductive reactance given in Table A-7 under the heading X_d. This refers to the direct axis reactance or, as some writers prefer to call it, the synchronous reactance, X_s.

b. Calculations Involving Fault Conditions. Suppose that a short circuit is suddenly applied to the terminals of a three-phase ac generator. The power-frequency current that flows in any one of the three windings will vary with time as shown in Fig. 8-7. Note that the current is initially of high magnitude, falls in value rapidly in the first 5 to 15 cycles, and eventually comes to a steady value 2 or 3 seconds after the start of the fault. This actual performance is not that which would be expected from a consideration of the equivalent circuit of the alternator. However, the

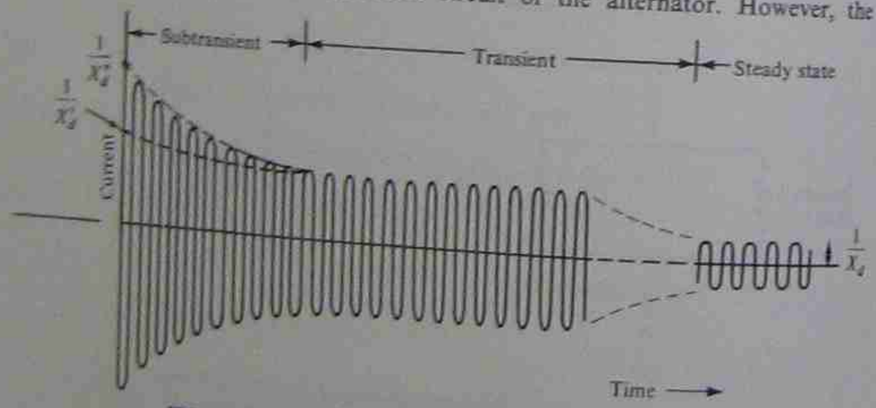


FIG. 8-7. The current in a short-circuited ac generator decreases with time.

equivalent circuit will predict expected current values at any desired point in time if the proper value of alternator impedance is selected.

It is frequently desirable to determine the 60-hertz component of current which exists *immediately* after the initiation of the fault. This current influences the relays that provide system protection and determines the largest electromagnetic forces set up. It is the current involved in the determination of the interrupting capability of fuses and of breakers which open with extremely high speed. For slower breakers it is the current involved in the determination of the momentary capability of closing a faulty circuit when open, and of withstanding large mechanical stresses when closed. In the solution of problems of this sort it is necessary to use the inductive reactance X_d'', which is designated as the *subtransient reactance*. It may be noted that for all machines, X_d'' is *much smaller* than X_d.

In certain power-system problems, attention is given to the magnitude of the current 10 or 12 cycles after the initiation of the fault. Intentional time delay in the operation of relays and circuit breakers may result in this current being of importance in determining the current interrupting ratings of breakers. Hence it is necessary to calculate the value of the current in a circuit after the early rapid decrease in current value. For problems of this type, the *transient reactance* X_d' should be used in calculations. As would be expected, the value of X_d' is intermediate between the values of X_d and X_d''.

When a short circuit is permitted to continue for an extended period of time, transients disappear and the current magnitude reaches a steady state. For calculations of current magnitude under this condition, the generator is assigned the impedance X_d, as indicated in Section 8-4a.

The phenomena that occur within a synchronous machine which make necessary the use of these three different values of reactance involve transients in the field and in the rotor of the ac machine. An analysis of this behavior is beyond the scope of the present discussion.

8-5. DC OFFSET

In Section 8-4 we described the behavior of an ac generator with regard to power-frequency currents and their variation with time following the occurrence of a short circuit. Another effect, known as *dc offset* when applied to ac generators, is common to all inductive circuits subjected to sudden changes.

Consider the circuit of Fig. 8-8, in which the closing of switch S results in a dc source voltage applied across a series resistance–inductance combination. As is well known, the current behavior following closing of the switch is as shown in Fig. 8-9a. Note that initially the current is zero and that finally it has the value V/R. This behavior is dictated by the fact that the current through an inductor cannot change by a finite value in zero

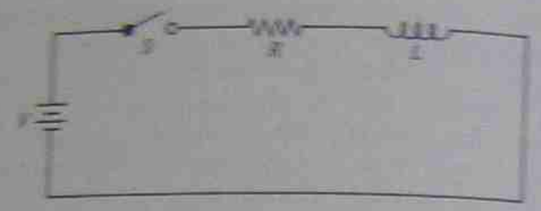


FIG. 8-8. A simple *RL* circuit which is energized from a dc source by closing the switch *S*.

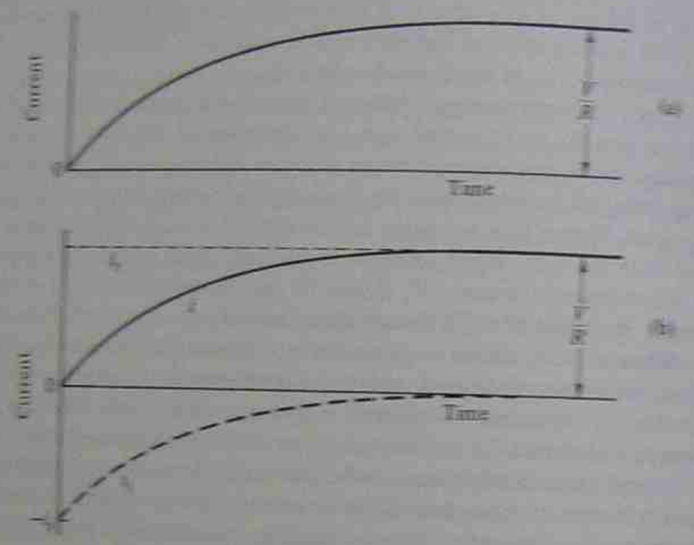


FIG. 8-9. The buildup of current in the circuit of Fig. 8-8. (a) The actual current. (b) The current decomposed into a steady-state current i_s and a transient current i_t which, if added, give the total current i.

time. Since the current is zero before the switch is closed, it must rise from zero by a smooth curve. Then, after all transients have disappeared, the final value of the current is limited only by the circuit resistance R. The duration of the transient depends on the ratio L/R. The larger L/R is, the longer the transient period.

The current through the inductor–resistor circuit may be considered to be the sum of two currents, as shown in Fig. 8-9*b*. The steady-state current, i_s, is assumed to be present from time $t = 0$, the start of the transient. A transient current, i_t, begins with a value $-i_s$ and decreases in value with time. Then

$$i = i_s + i_t$$

at $t = 0$,

$$i = 0$$

at $t = \infty$,

$$i = i_s = \frac{V}{R}$$

The same type of behavior applies in the presence of an ac source (Fig. 8-10). Now the steady-state current i_s is an alternating current (Fig. 8-11). The transient current i_t is of such magnitude that at $t = 0$, $i = i_s - i_t = 0$.

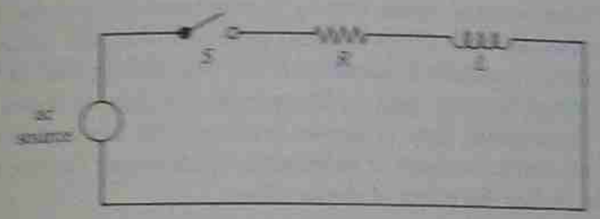


FIG. 8-10. A simple *RL* circuit which is energized from an ac source.

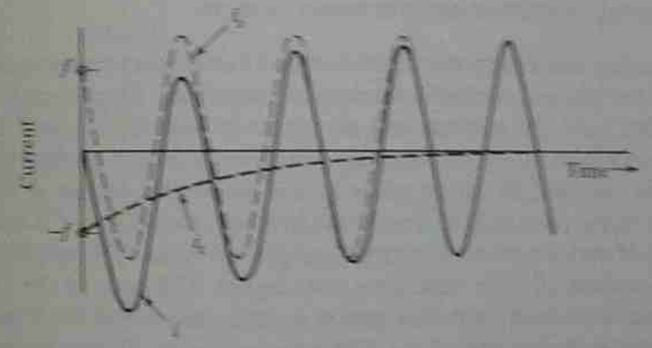


FIG. 8-11. The current in the circuit of Fig. 8-10 following the closing of switch *S*.

i_s = the steady-state current
i_t = the transient current
i = the total current

As in the dc case, let it be assumed that the steady-state current exists at full value from the instant the switch is closed (Fig. 8-11). Its value is determined by the source voltage and the impedance Z of the circuit. Note that in the example shown, the steady-state current i_s has a value of f at $t = 0$, the instant the switch is closed. Hence a transient current i_t of value

$-f$ must be present. The transient current and the steady-state current are added together to give the actual current i, as shown.

When an ac generator is short-circuited on the occurrence of a fault, the resulting current contains both the steady-state ac component and the transient component. The magnitude of the transient component is dependent, as was shown in Fig. 8-11, on the point on the steady-state current wave where the fault happens to strike. The magnitude is greatest when the fault occurs at a point corresponding to the crest of the steady-state current; it is zero when the fault occurs at a point corresponding to the zero of the steady-state current. As can be seen from Fig. 8-11, the transient behavior of the circuit may cause the actual current to rise to a value substantially greater than that predicted by generator subtransient reactance considerations alone. This effect is known as *dc offset*. Due to its exponentially decaying nature, its presence is most seriously felt in the first cycle following the occurrence of a fault. Therefore, its impact is heaviest on the interrupting duty of fuses and high-speed circuit breakers, and on the momentary duty of slower breakers. As for the interrupting duty of slower breakers, the importance of the dc offset depends on the moment of interruption; the longer the interruption is delayed, the weaker the effect of the dc offset.

8-6. DUTIES OF CIRCUIT-INTERRUPTING DEVICES

Specifications concerning circuit breakers and fuses must necessarily take into account the moment at which interruption is expected. Short-circuit currents in the first cycle (the subtransient) are larger in both their ac and dc offset components than those occurring, say, 10 cycles later (the transient).

The duration of the dc offset in the simple RL circuit of Fig. 8-10 depends on the ratio L/R. In a network, however, this duration is a complex function of various network parameters. For the sake of simplicity, the dc offset is considered to be dependent only on the X/R ratio of the Thévenin impedance at the fault point. For greater accuracy the ANSI/IEEE Standards require the determination of the Thévenin reactance X after removing all resistances from the impedance diagram, and the Thévenin resistance R after removing all reactances. These values of X and R are then used to determine the equivalent X/R ratio at the fault point. For simplicity X may be replaced by Z in that ratio, where Z is the Thévenin impedance magnitude used in the calculation of the ac short-circuit current in Section 8-3c.

With reference to Fig. 8-7, calculation of currents in the subtransient region requires the use of X''_d, and in the transient region X'_d. The number of machine parameters needed for the calculations is reduced by the aforementioned standards, which require the use of impedances as per Table A-9.

The momentary duty of slow breakers must at least be equal to the

short-circuit current at their location, calculated as in Section 8-3c and multiplied by a factor of 1.6. For the interrupting duty of slow breakers, the multiplying factor is obtained from curves similar to that displayed in Fig. 8-12. This curve is given here only as an illustration; for the actual curves one should consult the appropriate standard. The interrupting duty of fuses and fast breakers is taken to be the same as the momentary duty of slow breakers.

EXAMPLE 8-2. For the problem of Example 8-1, assuming that the given generator and motor reactances are subtransient reactances, find the momentary and interrupting duties.

Solution. Impedances for momentary duty based on factors given in Table A-9 are the same as those shown in Fig. 8-6a. Hence,

AC short-circuit current = 2790 A

Momentary-duty current = $2790 \times 1.6 = 4460$ A

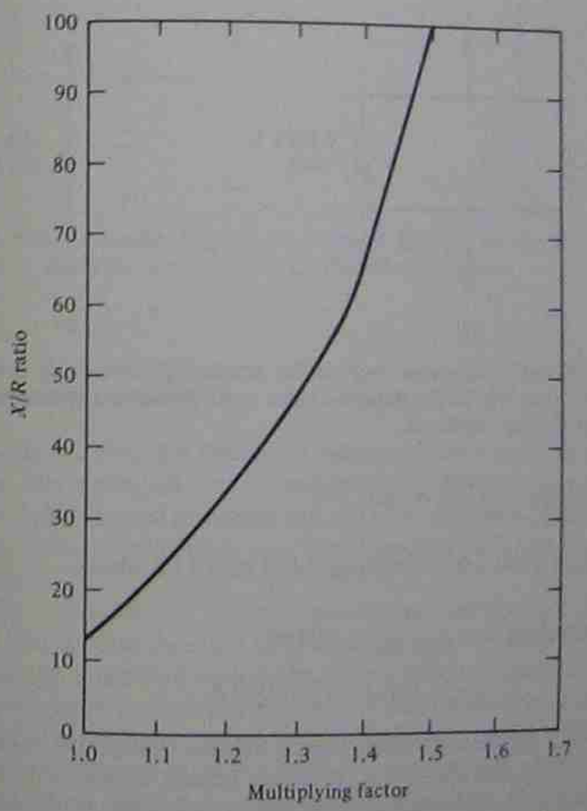


FIG. 8-12. Multiplying factor for a particular interrupting speed of circuit breaker.

For interrupting duty the motor impedance is multiplied by 1.5 (see Table A-9). The impedance diagram is displayed in Fig. 8-13 and the resistance diagram in Fig. 8-14.

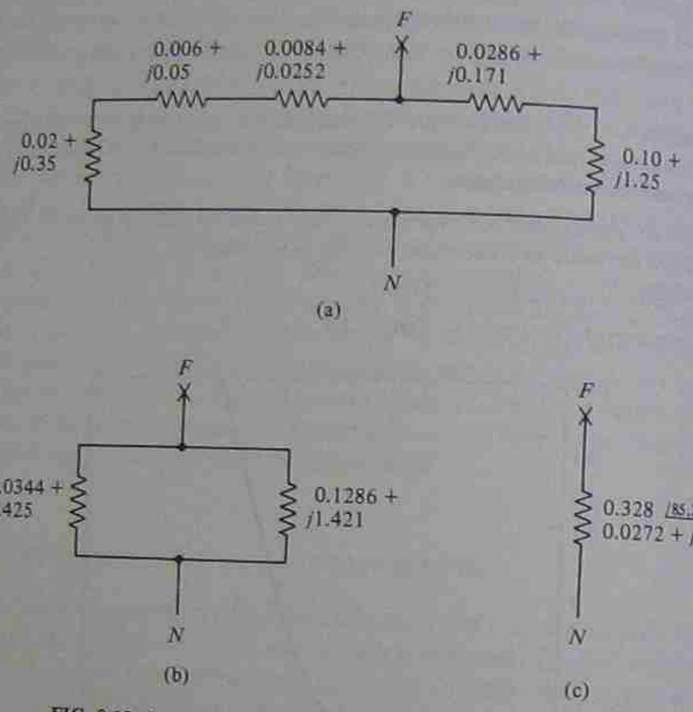


FIG. 8-13. Impedance diagram for calculating interrupting duty in Example 8-2. (a) As viewed at point *F*. (b) Impedance reduction. (c) Equivalent impedance.

$$X/R \text{ ratio} = \frac{0.328}{0.0271} = 12.1$$

From Fig. 8-12 the multiplying factor equals 1.0. Hence,

$$\text{Interrupting duty} = \frac{1.0}{0.328} = 3.05 \text{ pu}$$

$$= 3.05 \times 837 = 2550 \text{ A}$$

Thus, a high-speed breaker located at point *F* should be capable of interrupting or making 4460 A. A slower breaker should be capable of withstanding the mechanical stresses resulting from 4460 A, of closing the circuit on 4460 A, and of interrupting 2550 A.

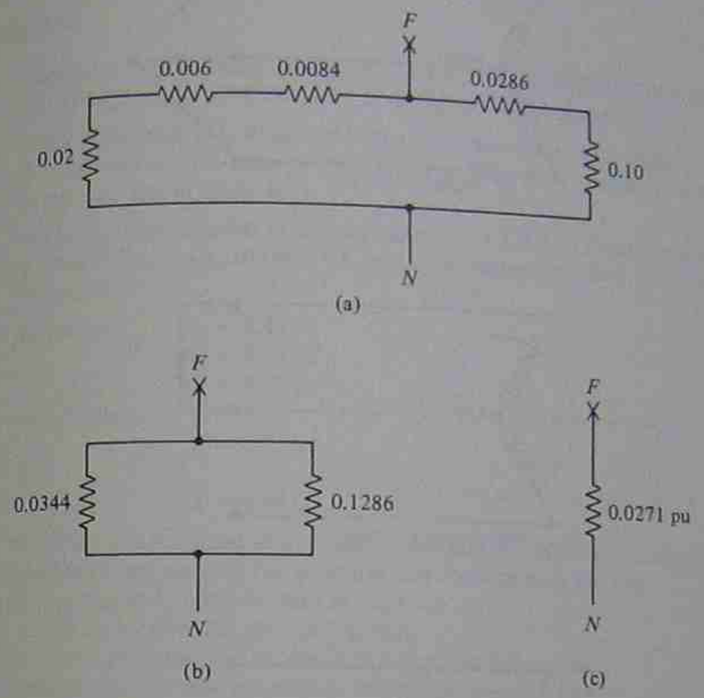
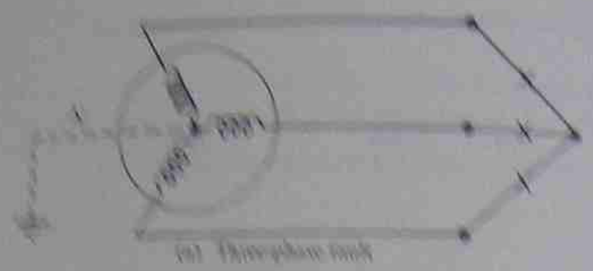


FIG. 8-14. Resistance diagram for Example 8-2. (a) As viewed at point *F*. (b) Resistance reduction. (c) Equivalent resistance.

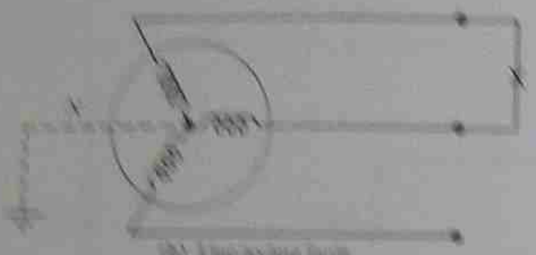
8-7. UNSYMMETRICAL FAULTS ON THREE-PHASE SYSTEMS

As stated in Section 8-1, this discussion relates primarily to balanced three-phase faults. For these, all three conductors are assumed to be brought together into a short circuit simultaneously. As was described earlier, calculations for such faults may be made on a line-to-neutral basis or a single-phase equivalent basis.

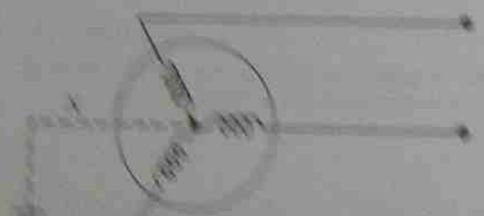
Actually, the faults that occur on generators, transformers, and transmission and distribution lines are seldom of this type. Figure 8-15 shows a generator (neutral grounded) with faults of four different types, all of which must be considered in power-system design. A calculation procedure known as the *method of symmetrical components* provides a means for determining the currents and voltages to be expected at any point on a system on the occurrence of faults of the types illustrated in Fig. 8-15. The study of this subject is not discussed in detail here.



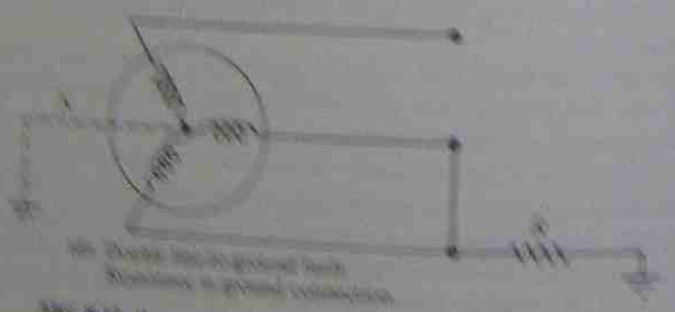
(a) Three-phase fault



(b) Line-to-line fault



(c) Line-to-ground fault.
Resistance in ground connection.



(d) Double line-to-ground fault.
Resistance in ground connection.

8B, 8-18. Some typical types of fault on a three-phase system.

PROBLEMS

8-1. Determine typical values of X_d, X'_d, and X''_d (expressed in per unit and in ohms) applying to a 100,000-kVA 20-kV turbine-driven generator.

8-2. Refer to Problem 8-1. What will be the initial rms value of the 60-Hz current flowing with a three-phase fault at the terminals of the generator? Express in per unit and in amperes.

8-3. A power system consists of a 12-kV generator, a 138/12-kV transformer, and a 138-kV line. On a 100,000-kVA base these components have the following reactances:

generator $X_d = 2.40$ pu
$X'_d = 0.30$ pu
$X''_d = 0.18$ pu

transformer $X = 0.26$ pu

line $X = 0.80$ pu

Consider a three-phase short circuit at the load end of the line. Calculate the current (in amperes) in the generator and the current in the line
a. immediately after the start of the fault.
b. 10 cycles after the start of the fault.
c. 2 sec after the start of the fault if breakers fail to clear.
Assume that the internal voltage of the generator is 1.1 pu.

8-4. A 5-kV three-phase distribution circuit is supplied by a 300-kVA 34.5-kV transformer. The line is 4/0 ACSR spaced 7 ft equilaterally. Assume that the voltage on the primary side of the transformer is held constant at 34 kV. Solve for the current (in amperes) on the high-voltage side and on the low-voltage side of the transformer for a fault on the 5-kV line
a. at the station end.
b. 4 miles distant from the station.
Neglect circuit resistance.

8-5. Refer to Fig. 8-3. What will be the fault current after the opening of a circuit breaker in line 4 at bus 1? What will be the voltage at bus 3?

8-6. Refer to Fig. 8-3. What will be the fault current if the fault occurs when line 4 is out of service? What will be the voltage at bus 3?

8-7. Refer to Fig. 8-4. Assume that each generator has an impedance of 1.0 pu and each line has an impedance of 0.5 pu. What is the fault current and what is the current in each line? Assume that each generator has an internal voltage of 1.2 pu.

8-8. Refer to Fig. 8-4. Assume that the fault point is moved to a location at the middle of the center line. Outline a method for calculating the fault current.

8-9. Two generators are operating on the same bus at 1.1 pu voltage. Other conditions are as follows:

	Generator 1	Generator 2
Reactance, pu	2.5	1.5
Load kW, pu	0.3	0.4
Power factor	1.0	0.8 lag

Solve for the internal generated voltage of each machine.

8-10. A 100,000-kVA 20-kV ac generator is short-circuited at its terminals. What is the maximum possible crest value of the current, dc offset considered? $X_d'' = 0.11$ pu.

8-11. A short-circuit current is given by

$$i = (0.6e^{-48t} + 0.8e^{-10t} + 1.4)\sin(377t + 0.35) - 0.96e^{-24t} \text{ per unit}$$

Plot this current against time in the initial half second. Identify the subtransient, transient, and steady-state intervals.

8-12. The three-phase short-circuit current resulting in phase A is, in per unit,

$$i_A = (0.4e^{-50t} + 1.0e^{-10t} + 1.6)\sin(377t + 50°) + Ke^{-20t}$$

Find K and the short-circuit currents in the other two phases.

8-13. For a three-phase short circuit at point F, determine the momentary and interrupting duties of the necessary circuit-protective devices. The base voltampere is 10,000 kVA.

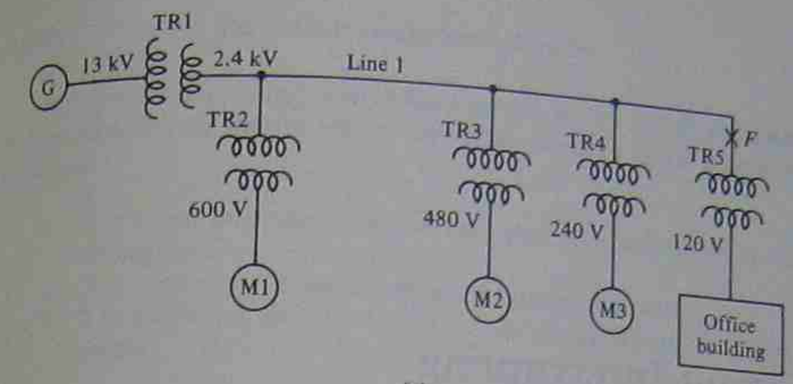
Generator G: 100 MVA, 13 kV, $X_d'' = 0.3$ pu, $X/R = 25$

Motor M1: synchronous, 3000 hp, 600 V, 0.8 pf, $X_d'' = 0.2$ pu, $X/R = 20$
M2: induction, 4000 hp, 480 V, $X_d'' = 0.25$ pu, $X/R = 12$
M3: induction, 2000 hp, 240 V, $X_d'' = 0.25$ pu, $X/R = 10$
M4: induction, 3000 hp, 240 V, $X_d'' = 0.25$ pu, $X/R = 10$

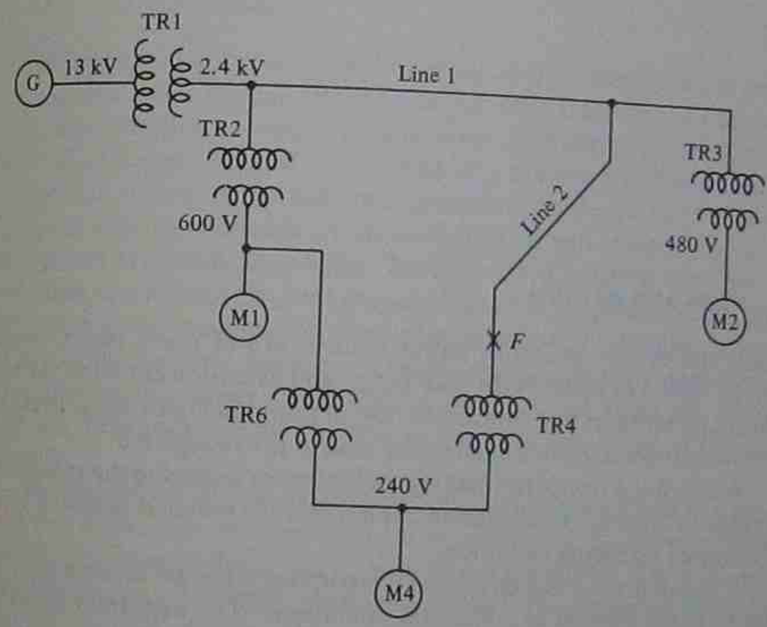
Transformer TR1: 13/2.4 kV, 20 MVA, $X = 0.1$, $X/R = 15$
TR2: 2.4/0.6 kV, 7000 kVA, $X = 0.08$, $X/R = 10$
TR3: 2.4/0.48 kV, 5000 kVA, $X = 0.08$, $X/R = 12$
TR4: 2.4/0.24 kV, 3000 kVA, $X = 0.07$, $X/R = 8$
TR5: 2.4/0.12 kV, 1000 kVA, $X = 0.06$, $X/R = 6$
TR6: 600/240 V, 3000 kVA, $X = 0.08$, $X/R = 10$

Line 1: $X = 0.03\ \Omega$, $R = 0.006\ \Omega$

Line 2: $X = 0.04\ \Omega$, $R = 0.01\ \Omega$



(a)



(b)

chapter 9

Circuit-Interrupting Devices

9-1. TYPES AND RATINGS

Circuit-interrupting devices in power systems are of many forms, ranging from the small key switches (in floor lamps and extension cords) to the enormous circuit breakers that control the flow of power in high-voltage networks. Three basic types of *circuit-interrupting devices* are recognized.

A *switch* is a device for making, breaking, or changing the connections in an electric circuit. This definition implies that the switch is used in a system in its normal operating condition.

A *circuit breaker* is a device for interrupting a circuit between separable contacts under normal or abnormal conditions. The abnormal conditions during which a circuit breaker may be asked to operate are primarily those which exist during short circuits. The circuit breaker is designed to withstand these short-duration, high-magnitude currents and to interrupt them if necessary.

A *fuse* is an overcurrent protective device with a circuit-opening fusible member directly heated and destroyed by the passage of overcurrent through it. Probably the most common application is in the service entrance boxes of residences, where fuses may be used to protect the main lines and each of the several individual circuits into the house. Fuses are also used in many applications on distribution primary circuits and to a limited extent on bulk-power high-voltage equipment.

All circuit-interrupting devices have certain design *ratings* that must be correlated with the duty to which they will be subjected. These ratings are as follows:

1. The power-frequency *voltage* of the circuit on which the device may be installed
2. The maximum *continuous current* the device may carry
3. The maximum *short-circuit current* the device is capable of interrupting

The short-circuit volt-ampere rating of the device is defined from the rated circuit voltage and the rated short-circuit current:

$$\text{VA} = \sqrt{3}\, V_{\text{rated}} I_{\text{rated}} \tag{9-1}$$

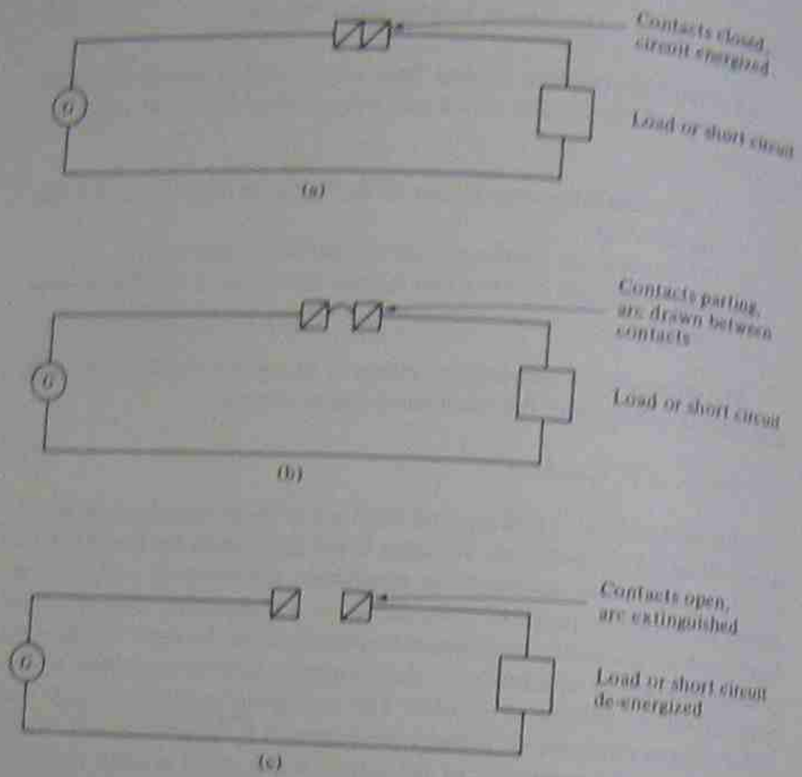
Switches, circuit breakers, and fuses are of great importance in power-system design and operation. Reliance is put upon them for the changes of circuit configuration necessary as generators, transformers, and lines are placed in service or removed from service to accommodate changes in load conditions or necessary maintenance operations. In the event of abnormal conditions such as overloads or short circuits, circuit-interrupting devices must operate as quickly as possible. The high-speed isolation of a fault is of importance to minimize (1) damage to equipment at the point of fault, (2) the disturbance to the remainder of the system which might produce instability and loss of synchronism between machines, and (3) the deterioration of the circuit-interrupting device itself. Circuit breakers and fuses are available which interrupt short-circuit currents in less than two cycles of the power frequency.

In residential 120-volt lighting circuits, a switch is located in only one of the two conductors to lamps and small appliances. In power circuits, a circuit-interrupting device is put in *each* power conductor. These are sometimes termed three-pole circuit breakers (or fuses). The discussion that follows refers, for the most part, to a *single-pole device*, it being understood that three such units will be provided on a three-phase installation.

9-2. THE CIRCUIT-INTERRUPTING PROCESS

The important steps in the circuit-interrupting process are described with the aid of Fig. 9-1.

1. The circuit is complete with current flowing across the interface of two metallic bodies known as contacts (Fig. 9-1a).
2. The contacts separate and an arc is established between the parting



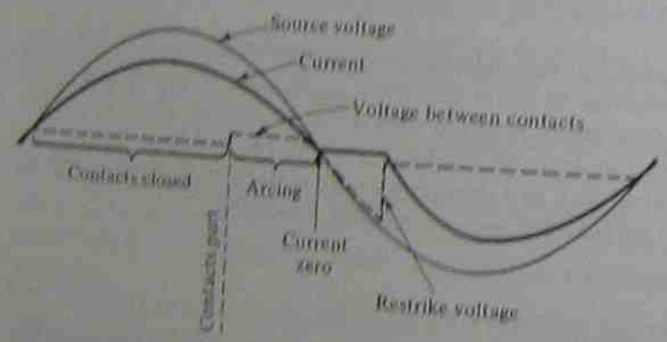


FIG. 9-1. Steps in the circuit opening process. (a) Contacts closed, circuit complete. (b) Contacts parted, circuit current flowing through an arc. (c) Contacts parted, arc extinguished, circuit open. (d) Current and voltage associated with the arc during the interruption process.

contacts (Fig. 9-1b). The voltage across the arc is low, usually much less than the crest value of the circuit voltage.

3. In accordance with the normal cyclic changes in an ac circuit, the circuit current (and thus the arc current) will come to zero.
4. Immediately following the instant of current zero the voltage between the parting contacts will reverse in polarity. To reestablish the arc current in the opposite direction, a finite value of voltage is necessary. The restriking voltage will be greater than the voltage originally across the arc, as described in step 2.
5. During the period of zero arc current (a finite time) the voltage between the arcing contacts rises at a rate depending on the nature of the circuit.
6. During this same period the voltage required to reignite the arc increases with time.
7. If the voltage of step 5 is greater than the voltage described in step 6, the arc restrikes, then continues until the next current zero to repeat the process with greater gap spacing between the parting contacts.
8. If, on the other hand, the voltage of step 6 is greater than that of 5 the arc fails to restrike and the circuit is interrupted (Fig. 9-1c).

Electrical conditions relating to arc behavior are diagrammed in Fig. 9-1d.

The design and operation of circuit breakers will be considered in Section 9-7 after the characteristics of arcs have been described. An understanding of the phenomena associated with arcs is helpful not only in regard to the operation of circuit-interrupting devices, but also in a study of lightning arresters, the sparkover of air across high-voltage insulators, and the puncture of solid insulation, as in generators, transformers, or cables.

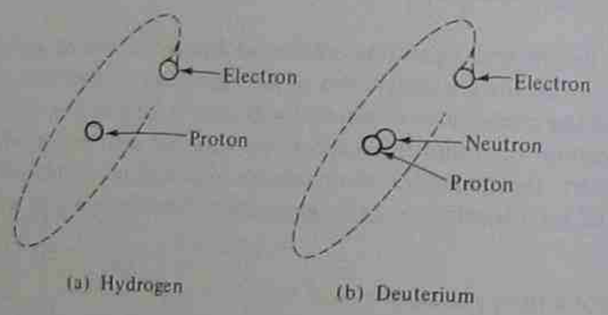
9-3. CONDUCTION PROCESS

It is a well-accepted theory that all matter as we know it is composed of three basic particles: protons, neutrons, and electrons. The arrangement of these particles in nuclei, atoms, molecules, solids, liquids, and gases accounts for the physical and electrical properties of all materials as we observe them. A *proton* has mass and carries a unit *positive* electric charge. A *neutron* has a mass almost equal to that of a proton but carries no electric charge. An *electron* has a mass much smaller than that of a proton and carries a unit *negative* electric charge.

The *nucleus* of the hydrogen atom is made up of a single proton. The nuclei of atoms of other elements consist of a grouping of protons and neutrons. Each *atom* consists of a nucleus surrounded by one or more electrons.

Figure 9-2 shows models of atoms of three different kinds. In Fig. 9-2a an atom of hydrogen is shown with the nucleus made up of a single proton around which spins a single electron. In Fig. 9-2b the model of the deuterium atom is shown with a nucleus consisting of one proton and one neutron. Again a single electron is shown in motion around the nucleus. Figure 9-2c shows the model of a helium atom. The nucleus consists of two protons and two neutrons, and around it move two electrons. Note that in each case in Fig. 9-2 the number of protons is equal to the number of electrons. As the chemical nature of the atom is determined by the number of protons, the deuterium atom and the hydrogen atom, each with one proton, have similar chemical properties but different mass. The helium atom, which has two protons, has chemical properties different from that of hydrogen. The atoms of other elements are similarly constructed, the number of protons in the nucleus being characteristic of the particular element.

All atoms in their normal state have protons and electrons of equal number. As each proton carries a unit positive charge and each electron carries a unit negative charge, it is obvious that each normal atom taken as a complete structure is *electrically neutral*. There are, however, many processes by which one or more electrons may be removed from a neutral atom. The



(a) Hydrogen (b) Deuterium

(c) Helium

FIG. 9-2. Models of simple atoms.

electrons are then free negatively charged particles. The remainder of the atom, with more protons than electrons, has a net positive charge and is known as a *positive ion*. The removal of an electron from a neutral molecule is called *ionization* and the two particles produced are called an *ion pair*. A gas in which there are many free electrons and positive ions is said to be *ionized*. In an electric field between two oppositely charged plates, the free electrons will drift toward the anode. The positive ions, if free to move, will drift toward the cathode. The movement of these particles results in a transfer of positive charge from anode to cathode and a transfer of negative charge from cathode to anode. The sum of these two charge movements constitutes current flow from anode to cathode.

The removal of one or more electrons from a neutral atom requires energy from an outside source. Since the negative charge on the electron is attracted by the positive charge on the positive ion, the two tend to reunite in a process called *deionization*. Energy is given off when an electron unites with a positive ion. Ionizing processes and deionizing processes are of great importance in the formation of arcs and in their extinction.

Metals in solid form are made up of an assembly of a great number of atoms. A characteristic of metals is that as the individual atoms combine, an electron detaches itself from each of the many, many atoms forming the solid. The remainder of each atom forms a positive ion. These positive ions arrange themselves in a fixed, closely spaced, orderly array through which the free electrons may move as shown in Fig. 9-3a. The free electrons move randomly about within the structure traveling at high velocity from one boundary of the crystal to another. If an electric field is applied across the crystal, as shown in Fig. 9-3b, the electrons will drift from the negative terminal toward the positive terminal. This condition we call a current flow from the positive terminal to the negative terminal. The large number of electrons that drift freely in the presence of an electric field accounts for the high conductivity (low resistivity) of metals such as silver, copper, and aluminum.

Nonmetallic solids such as glass or porcelain consist of a somewhat ordered array of atoms of several different kinds. In materials that are regarded as insulators, there are very, very few electrons which are free to drift in the presence of an electric field. The structure of this matter is such that all electrons are kept in close association with their parent atoms.

Gases consist of individual atoms, or small ordered groups of atoms known as molecules, which are moving in random fashion at high velocity. They collide with each other and with the walls of the containing vessel. As the average separation between individual molecules is very great compared to their diameter, they may move relatively long distances between collisions. In the normal state each molecule is electrically neutral and so has no tendency to drift in the presence of an electric field. In this situation a gas appears to be a perfect insulator. However, free electrons and positive ions introduced into

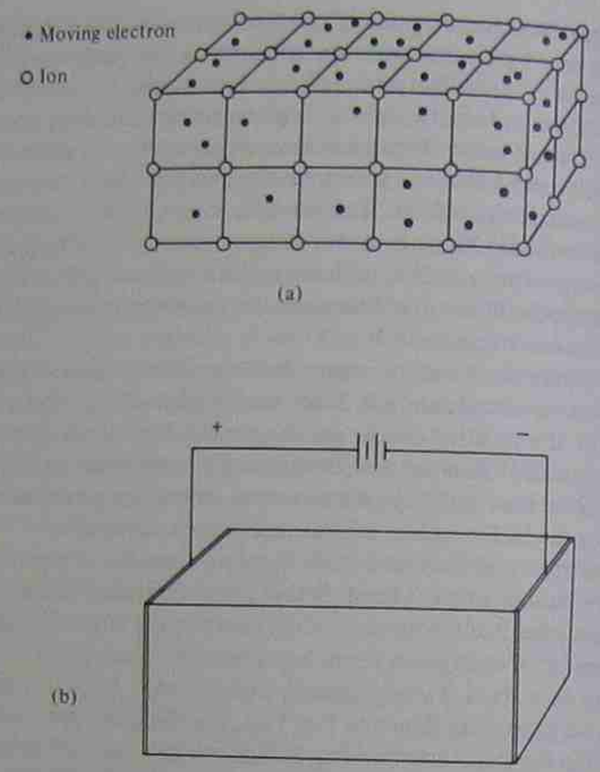


FIG. 9-3. Model of a metal. (a) The crystal structure showing fixed positive ions and moving electrons. (b) The metal has a voltage impressed across it.

the gas volume will render it conducting. The arcs used in arc welding and the arcs in circuit breakers during the circuit-interruption process are extreme examples of gases made conducting in this manner. The ionizing and deionizing processes that influence the conducting ability of a gas will now be discussed.

9-4. IONIZING PROCESSES

a. Radiation. All space on the earth is constantly bombarded and penetrated by very high energy submicroscopic particles. Some of these come from the sun and are known as *cosmic rays*. Others come from the disintegration of radioactive materials which are present in very minute quantities in the earth and even in all living organisms, including the human body. These

high-energy particles, when passing near the electrons of a neutral molecule, may knock off one or more electrons from the molecule. With each such event, one or more free electrons are produced and one positive ion is generated. Because this process is going on continuously, it is found that all gases are slightly conductive.

b. High Temperature. As a gas is raised in temperature, the molecules constituting the gas move at higher and higher velocity. If the temperature is high enough, the collision of two gas particles may result in the detachment of one or more electrons and the generation of a positive ion. It is found that the gases constituting a high-temperature flame are highly conductive.

c. Electron Collision. If an electric field is set up in a gas volume by applying a voltage between two electrodes, those electrons and positive ions generated by cosmic rays and radiation particles begin drifting; the electrons move toward the anode, the positive ions toward the cathode. As these particles drift, they collide with neutral gas molecules. If the energy gained by an electron in a free path between collisions is sufficient, the collision may result in the ionization of another gas molecule, hence the generation of another free electron and another positive ion. Ionization by electron impact is of very great importance in the breakdown of gases. In the presence of a high-strength electric field a single electron moving from the cathode to the anode may have many ionizing collisions, each one of which produces another free electron which has the same ionizing ability. Such a multiplication of free electrons is known as an *electron avalanche*. Ionization by electron collision increases rapidly as the voltage gradient in the gas volume is increased.

d. Emission from Metals. Electrons may be released into a gas volume from a metal surface. Metals that have high boiling points, such as tungsten or carbon, when raised to a high temperature by any method, may "boil out" many electrons into the gas volume. This is known as *thermionic emission*. Another process, thought to be *high field emission*, may cause the discharge of electrons from a metal surface at a small area known as a *cathode spot* even at relatively low temperatures. Thermionic emission and high field emission are of great importance in all high-current arcs.

9-5. DEIONIZING PROCESSES

Deionizing processes are those means by which the number of free electrons and positive ions in a gas volume are reduced. In an arc, if the activity of the deionizing processes exceeds the activity of the ionizing processes, the number

of free charged particles is reduced, the current in the arc diminishes, and arc extinction may result.

a. Electric Fields. The electric field between two plates of opposite potential continually removes charged particles from a gas volume, the free electrons moving toward the anode and the positive ions toward the cathode. At the anode the electrons enter into the metal, while at the cathode the positive ions each gain an electron from the metal surface to become a neutral gas molecule. If all ionizing processes were to cease, electric fields would quickly sweep all charged particles out of the gas volume.

b. Recombination. Recombination is the elimination of a free electron and a positive ion by their union to form a neutral gas molecule. Although in a highly ionized gas there may be many electrons and positive ions, recombination seldom occurs in the gas volume. It occurs readily at the surfaces of solids and liquids which are in intimate contact with the ionized gas.

c. Diffusion and Convection. Electrons and positive ions, in many respects, behave like ordinary gas molecules. They move from a region of high density by diffusion; they may be moved away from the region of ion-pair production by air currents.

d. Cooling. Cold air or other gases introduced into the highly ionized region of an arc does not eliminate charged particles directly but does reduce their number as it inhibits the formation of ion pairs due to high temperature collisions of gas molecules. Cooling is thought to be of great importance in the proper functioning of certain types of circuit breakers.

e. Electron Attachment. The molecules of electronegative gases tend to capture and hold free electrons which come close to them. The resulting particles, known as negative ions, in an electric field move toward the anode. However, because of their high mass, they do not gain sufficient energy between collisions with neutral gas molecules to produce ionization by collision. Hence the electrons trapped by this process are eliminated from producing new ion pairs.

The designers of electrical equipment use to their advantage the several processes of ionization and deionization. If a stable arc is required, as in an arc welder, conditions will be controlled to favor ionization and limit deionization. In a circuit breaker or in a lightning arrester, the problem is to eliminate the arc. Hence a design is chosen which favors deionization and discourages ionization.

9-6. ARCS AND ARC INTERRUPTION

Arcs may be started by several different methods. In the lightning flashover of transmission-line insulators, the extremely high voltage causes electric potential gradients in the air of such value that ionization by collision produces a condition known as sparkover. The spark quickly changes to the condition known as an arc as power-frequency current follows the breakdown path. In an electric welder system, the arc is started by separating two electrodes which are momentarily touched together. In a circuit breaker or fuse, the separation of the contacts results in an arc drawn between them. In relation to circuit-interrupting devices, we are not particularly interested in the mechanisms that start the arc. The characteristics of interest are those which may be used to bring about arc extinction.

A stable arc in a dc circuit is shown in Fig. 9-4. The current in the arc may be a fraction of an ampere or many thousands of amperes. The cathode is of first importance in the arc because it emits electrons in great numbers. The movement of these electrons to the anode accounts for perhaps 90 percent of the current. These electrons may be emitted from the cathode due to thermionic emission if the cathode is of high-melting-point material such as carbon or tungsten. They may be emitted from a *cathode spot* by field emission if the cathode is of copper or other material of relatively low melting temperature.

The electrons move out from the cathode and in collision with neutral gas molecules in region *A*, (where the electric gradient is high) bring about

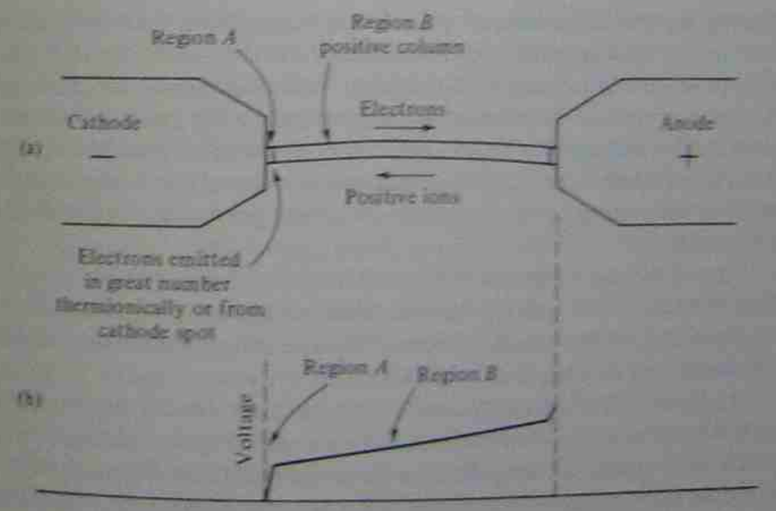


FIG. 9-4. Model of a dc arc. (a) Pictorial. (b) Voltage distribution.

ionization by collision. Now there are more electrons to move to the anode and some positive ions which move to the cathode. Region *B*, known as the *positive column*, is one of relatively uniform characteristics. The electric gradient in this region is quite low, but high enough to provide some ionization by electron collision. The new free electrons and positive ions are just enough to replace those lost laterally by diffusion out of the arc column and by recombination within it. At the anode, all current is due to the movement of electrons to it. These moving electrons cause some heating of the anode. The heavy positive ions arriving at the cathode at high velocities heat the cathode (if carbon) sufficiently to produce the high temperature necessary for thermal emission. On a copper cathode, their effect is to produce a cathode spot from which electrons are emitted.

The voltage across region *A* is 10 to 20 volts. The voltage across region *B*, the positive column, is proportional to its length, a few volts per centimeter.

If circuit conditions maintain the current constant while the spacing between anode and cathode is increased by the separation of the contacts, the voltage across the region *A* will remain substantially constant while the voltage across region *B*, the positive column, increases in proportion to its length. If the current is increased while spacing is held constant, slight changes of voltage across the arc will result in more copious emission from the cathode and more active ionization by collision in the positive column.

While the arc is maintained, deionizing agencies may be brought into play. Air may be blown across the positive column, carrying some of the ionized particles away while cooling the column. Oil may be sprayed into the arc or an insulating surface may be brought in contact with it, both providing increased recombination in the positive column. Electronegative gases may be introduced to capture some of the free electrons. All these processes require an increase in the gradient in the positive column if the arc is to continue to exist. In all circuits the gradient in the positive column is limited by the voltage which the circuit may provide between the arc terminals. Hence a point can be reached at which deionizing effects remove more charged particles than can be replaced by ionizing processes. In this case the arc will cease.

Theory indicates that an arc in a dc circuit of any voltage could be interrupted by a device that would introduce ample deionizing effects. However, practical limitations make it very difficult to design circuit breakers for use in dc circuits above a few thousand volts.

Arc interruption in an ac circuit is much more readily accomplished than in a dc circuit. In ac circuits, all currents and voltages go through cyclic changes. Hence ion-producing effects in the arc are variable, falling as current diminishes and ceasing at the time of current zero. Meanwhile, deionizing effects continue in full force. When the arc current comes to zero and the voltage across the contacts reverses in polarity, current in the new direction

is not immediately established. For a short period of time the current remains zero. The length of the period of current zero is dependent on (1) the separation of the contacts, (2) the activity of the deionizing effects, and (3) the rate at which the voltage rises.

It may be noted that items 1 and 2 contribute to the suppression of the arc. This effect is sometimes described by saying that the arc path "gains dielectric strength."

If the arc path gains dielectric strength faster than the voltage across the arc terminals rises in value, the arc is not reestablished but ceases. If the voltage rises faster than the dielectric strength, arc current will flow in the new direction, at least until the next current zero. If the arc contacts are moving apart, hopefully a spacing is reached at which the arc is extinguished. It may be concluded that the extinction of an arc is dependent not only on the arc-interrupting device, but also on the characteristics of the entire circuit which controls the rate of rise of *recovery voltage* following arc current zero. Recovery voltage is discussed in Section 9-9.

The behavior of an arc regarding its extinction (as just described) applies to circuit-interrupting devices of *all* voltage classes. Another effect, of importance in arc extinction in circuits of relatively low voltage, is now described.

When a breaker is closed, there is high mechanical pressure between the breaker contacts, with the result that these pieces of metal touch each other at many different points. As the pressure is removed, the number of points making contact reduces until eventually there is only one point of contact. Here the current density is very high and heating in a local area is very intense. On the final parting, a point on each contact is at very high temperature, a condition favorable to the emission of electrons from the electrode surface. If the contacts are made of high-melting-point material, electrons will be released by thermal emission and the temperature of the electrode maintained as positive ions move into it. When the potential between the electrodes reverses following current zero, thermal emission is picked up from the other electrode and the arc continues. However, the situation is quite different if the contacts are of low melting point, requiring that the electrons come from the metal by high field emission. The cathode spot does *not* hold over from one half-cycle to the next but must be reestablished following each current zero by phenomena within the arc itself. To do so requires a voltage across the arc, at least momentarily, of 300 to 400 volts. If the circuit is of such nature that it cannot provide this voltage, the arc ceases at the first current zero.

The behavior just described is easily illustrated by a set of experiments described in Fig. 9-5. Figure 9-5a shows a 120-volt dc circuit, a resistance *R*, and a pair of carbon electrodes. The resistance *R* may be of practically any value, perhaps 20 ohms. When the carbon contacts are parted, an arc is drawn between them, which continues until the electrodes are spaced a fair

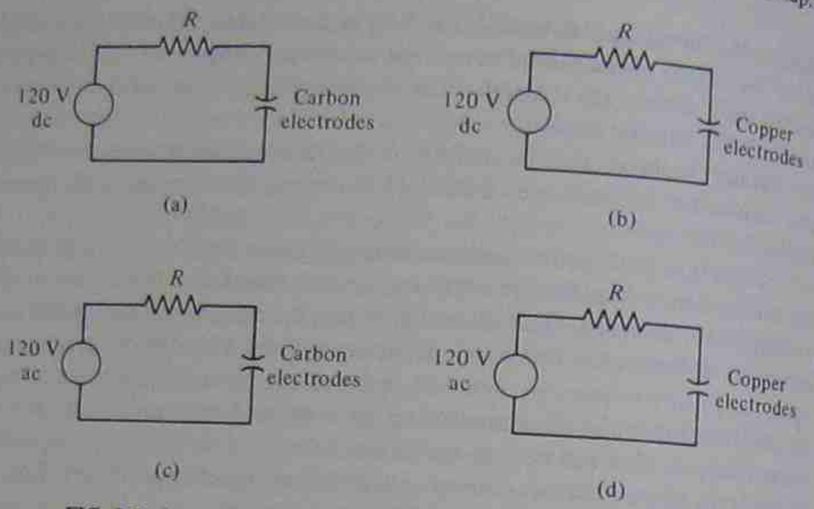


FIG. 9-5. An arc in a 120-volt circuit. (a) Dc source, carbon electrodes. (b) Dc source, copper electrodes. (c) Ac source, carbon electrodes. (d) Ac source, copper electrodes.

distance apart. Figure 9-5b shows a similar circuit but here the electrodes are copper. The behavior of this circuit is substantially the same as the one shown in Fig. 9-5a. Figure 9-5c is identical to the circuit of Fig. 9-5a except for the source, which is now an ac supply. When the electrodes are parted, again an arc is drawn, and its behavior is practically the same as that observed before. Figure 9-5d shows the same circuit except now the parting contacts are copper. As these contacts are pulled apart, there is a momentary flash but no continuing arc is established. Oscillographic records will show that the arc ceases with the first current zero. This behavior is explained by the fact that the 120-volt circuit has a crest value of 170 volts, substantially less than the 300 or 400 volts necessary to reestablish an electron supply by a cathode spot.

An oscillographic record of current and voltage in a circuit of Fig. 9-5c is shown as Fig. 9-6a. Note that only a small voltage, about 20 volts, is required to bring the thermionic cathode into full operation.

If the ac source voltage of Fig. 9-5d is increased, eventually a voltage is reached at which an arc can be reestablished between the copper electrodes following current zero. When this is done, an oscillographic record of current and voltage appears as shown in Fig. 9-6b. Notice that after current zero and voltage reversal, almost no current is observable until the voltage between contacts has reached 350 volts. Then, with the reestablishment of a cathode spot, current increases and arc voltage decreases.

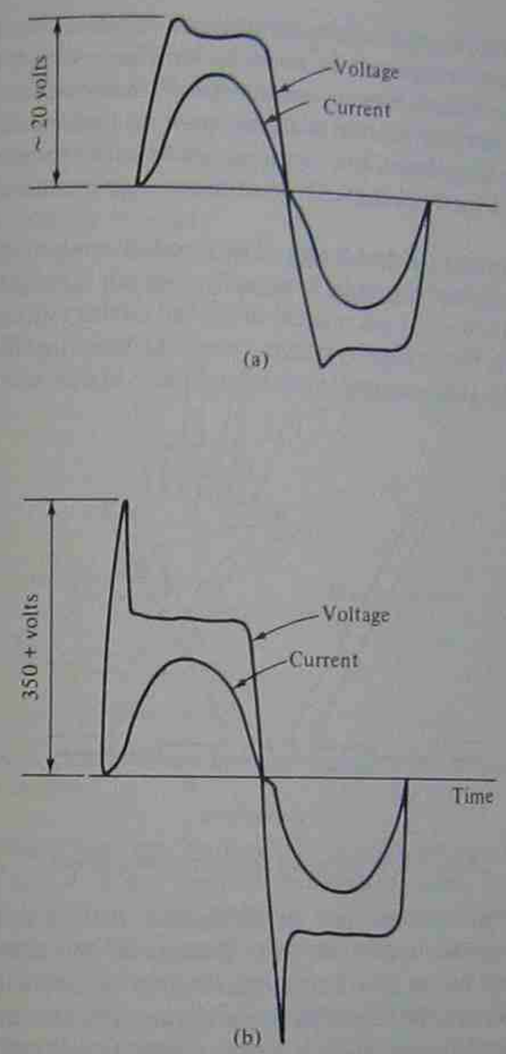


FIG. 9-6. The waveform of voltage and current in a short arc. (a) Between carbon electrodes. (b) Between electrodes of low melting point.

9-7. CIRCUIT-BREAKER DESIGNS

Designers of circuit breakers have resorted to many ingenious schemes to bring about arc interruption. Breakers for dc circuits rely principally on lengthening of the arc and subjecting it to deionizing effects. In breakers for

operation in low-voltage ac circuits, advantage is taken of the voltage required to establish a cathode spot. In breakers for medium-voltage ac circuits, the cathode-spot phenomena may be combined with methods for bringing about the lengthening and deionization of the arc path. In breakers for high-voltage circuits, arcs are lengthened, forced against oil-laden surfaces, and cooled by oil sprays or by air jets. Examples of several types of breakers follow.

a. Air Circuit Breakers. The simplest method of extinguishing an arc is by increasing its length. Eventually a length is reached at which the voltage required across the arc is equal to the full circuit voltage. With further increase in length, the deionizing effects exceed the ionizing effects and the arc ceases. Figure 9-7 shows a simple arc-interrupting device with which several

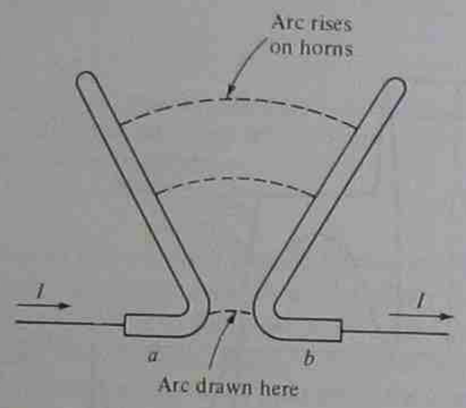


FIG. 9-7. A horn-gap arc-interrupting device.

arc-suppressing mechanisms may be illustrated. As the contacts *a* and *b* part, the arc is established at the base. Because of the heat generated, air currents cause the arc to rise. Furthermore, since electromagnetic forces in a loop tend to increase the area of the loop, the arc is further encouraged in its upward movement. The longer arc is readily cooled by convection air currents and by radiation, and the longer positive column requires a higher voltage. Each increase in length results in a higher voltage required to support the arc. Hopefully, in a circuit interrupter of this kind, the arc extinguishes before it reaches the top position on the contact horns.

Circuit breakers using the principles illustrated are frequently used in dc circuits and in low-voltage ac circuits. Coils carrying the *power current* may provide a magnetic field which aids in moving the arc toward the horn tips. Breakers of this type may be used to interrupt 100 amperes or more at several hundred volts.

The construction of a circuit breaker for use on a 120-volt ac circuit may be of very simple design. If the parting contacts are made of low-melting-

point material such as brass or copper, the arc will go out at the first current zero as the voltage is insufficient to reestablish a cathode spot after current reversal. The necessary insulation must be so positioned as to avoid charring from the heat of the arc. If charring occurs, the carbon produced may serve as an electrode from which electrons may be released thermionically and so reignite the arc following current zero. Several hundred amperes may be interrupted by a simple breaker.

An arc interrupter for a circuit of higher voltage may be constructed as shown in Fig. 9-8. This is a combination of magnetic blowout to lengthen the

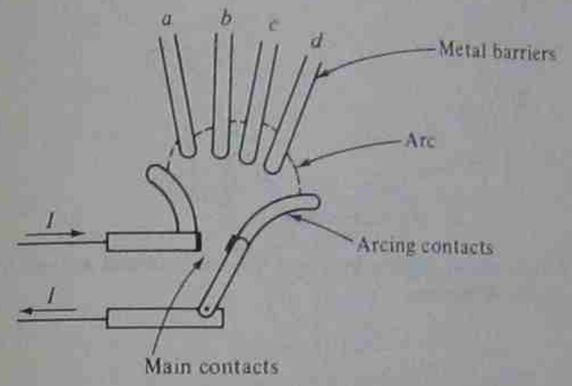


FIG. 9-8. A circuit breaker in which the arc is broken into several sections in series.

arc, with the lengthened arc broken into several sections by the metallic barriers *a*, *b*, *c*, and *d*. There are then five arcs in series. Each one of these arcs experiences the effect of lengthening, cooling, and, if low-melting-point materials are used, the necessity of reestablishing a cathode spot following current reversal. Breakers of such design interrupt currents of several thousand amperes in ac circuits operating at several hundred volts.

Another circuit-interrupter design is illustrated in Fig. 9-9. Again the arc is lengthened by magnetic blowout. The barriers are insulating fins between which the arc is forced. Another factor, recombination and cooling at insulator surfaces, tends to reduce the ionization within the arc path and so increase the voltage necessary for restriking following current zero. This design may be used to interrupt currents of 50,000 amperes in ac circuits operating at 10,000 volts.

b. Oil Circuit Breakers. In many circuit breakers, arcs are drawn under oil (Fig. 9-10). As the arc plays between the parting contact, oil is vaporized to produce a large bubble, which surrounds the arc. Decomposition of the oil may result in this gas containing a considerable amount of

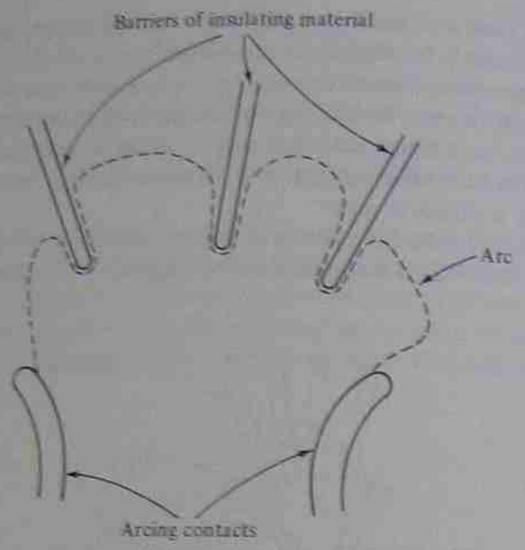


FIG. 9-9. A circuit breaker in which the arc is forced against transverse insulating barriers.

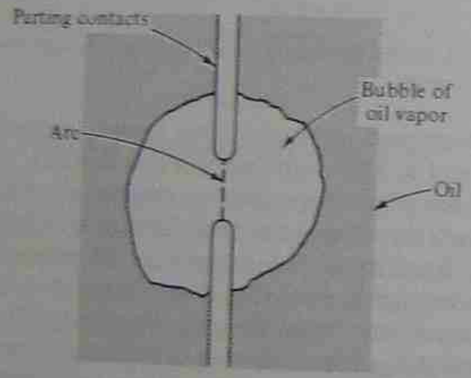


FIG. 9-10. An arc drawn under oil. A bubble of hydrogen surrounds the arc.

hydrogen, a gas unfavorable to ion-pair production. This form of arc interruption, therefore, depends on the lengthening and cooling of the arc and the introduction of a gas unfavorable to arcing.

A more advanced form of breaker in which the arc is drawn under oil is shown in Fig. 9-11. Here an insulating chamber filled with oil surrounds the closed contacts (Fig. 9-11a). When the moving contact is lowered, the arc is drawn out through the throat of the insulating chamber (Fig. 9-11b). The

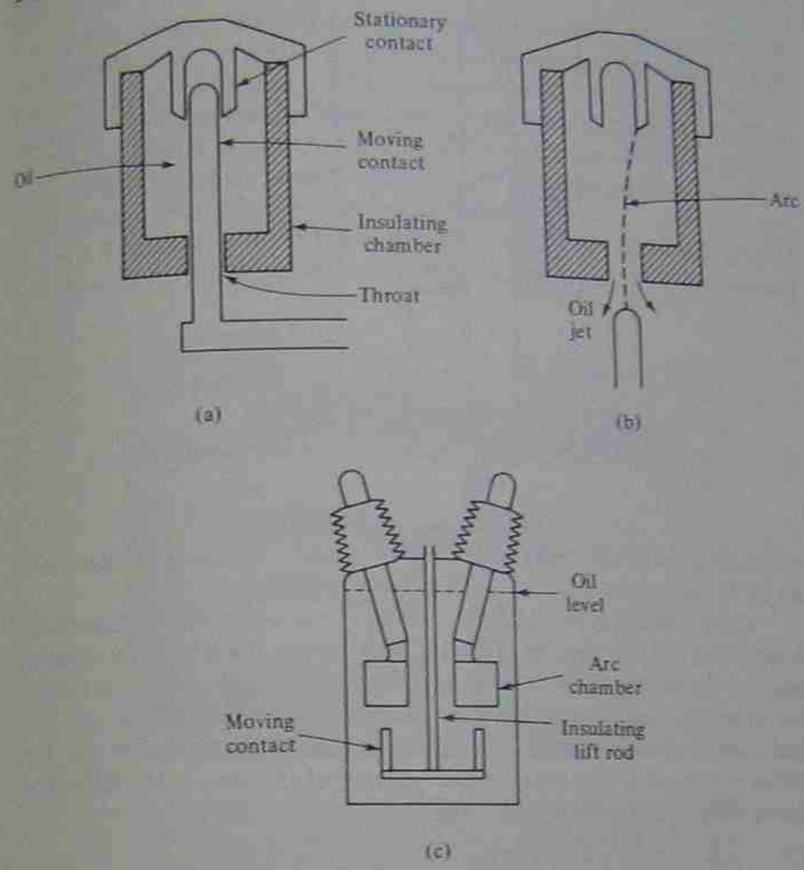


FIG. 9-11. A circuit breaker in which the arc is drawn under oil in a confining chamber. (a) Contacts closed, chamber full of oil. (b) Contacts open, arc drawn, oil being forced through arc region. (c) The complete breaker has two arc systems in series.

portion of the arc within the chamber generates gas which forces oil out through the throat, where it is in intimate contact with the arc to cool it, encourage recombination, and physically carry away the free electrons and positive ions. The arrangement of two sets of these parting contacts within a circuit breaker is shown in Fig. 9-11c.

Another version of the arc chamber in this type of breaker is shown in Fig. 9-12. Here the throat of the insulating chamber is made up of laminations between which oil may move radially into the arc path. In some designs, after the arc is drawn through the throat it is forced to move horizontally against barriers that are saturated with oil. Circuit breakers of this type have

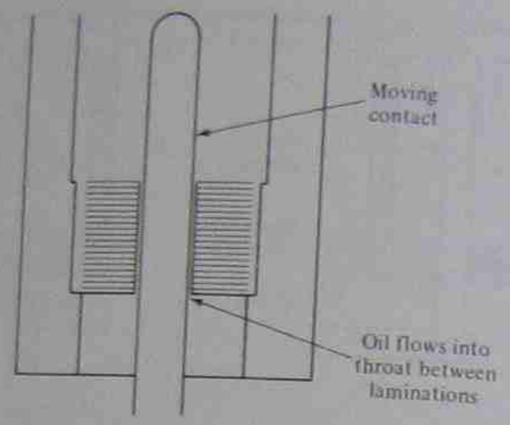


FIG. 9-12. An arc chamber in which oil is forced radially into the arc path.

been built to interrupt 10,000-ampere short-circuit currents in circuits operating at 500 kilovolts.

Circuit breakers in which the contacts part under oil are very effective in performing their function as circuit interrupters. They have the disadvantage that the oil they contain presents a fire hazard in case the tank is ruptured due to unexpected internal pressure. Furthermore, the inertia of the heavy operating mechanisms limits the rate at which breaker contacts may part, with a consequent time delay in the opening of the arc. A 345-kilovolt oil-circuit breaker is shown in Fig. 1-16.

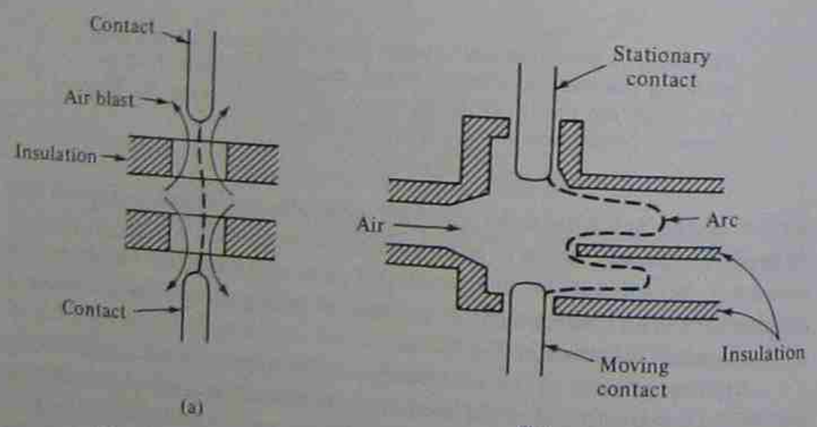
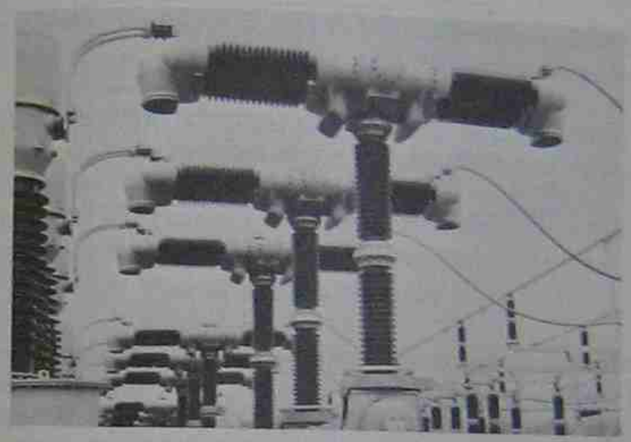


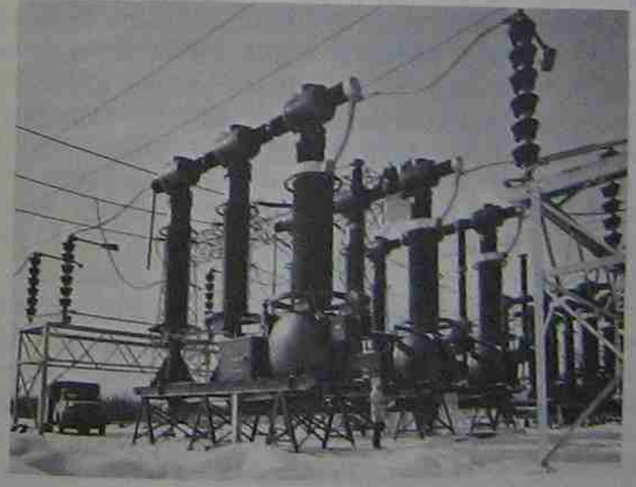
FIG. 9-13. An arc chamber in which an air blast is directed into the arc. (a) Parallel to the arc. (b) At right angles to the arc.

c. Air-Blast Breakers. The air-blast breaker is a type in which the hazard of fire is reduced to a minimum and contact parting speed may be made very great. As the arc is drawn, a high-pressure air blast cools the arc and removes the ionized gas from between the parting electrodes. In Fig. 9-13a the air blast is parallel to the arc. In Fig. 9-13b the air blast is at right angles to the arc and so tends to extend it and force it against an insulating barrier, with the attendant recombination effect.

A 138-kilovolt air-blast breaker is shown in Fig. 9-14a. In this breaker both the stationary and moving contacts are hollow tubes. As these contacts



(a)



(b)

FIG. 9-14. An air-blast circuit breaker. (a) For 138-kV service. (b) For 345-kV operation, several units are connected in series.

are parting, air under high pressure comes out of both and carries the arc products away from the contacts. On extra-high-voltage circuits, several air-blast units are connected in series to form a single circuit breaker (see Fig. 9-14b). Breakers capable of interrupting 40,000 amperes on 765-kilovolts ac circuits are in service.

Vacuum switches (Fig. 9-15) provide another scheme for circuit interruption. In all our discussions so far we have considered the behavior of the

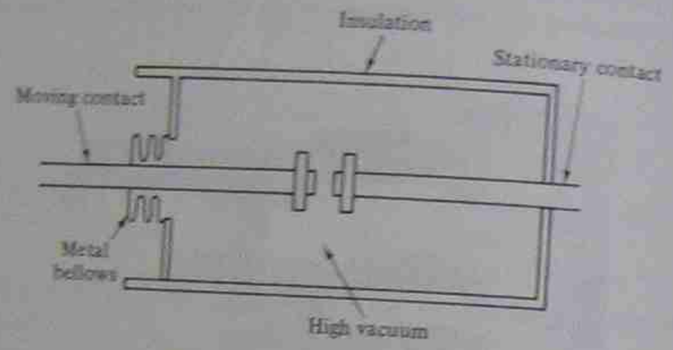


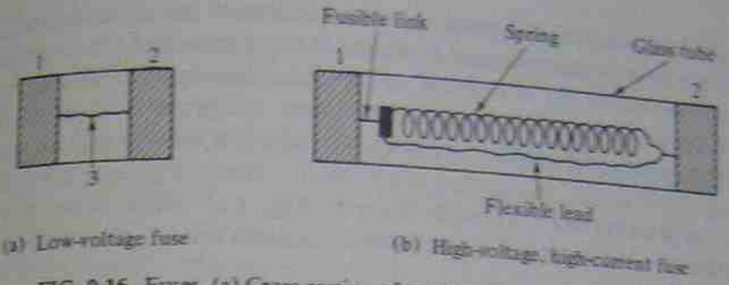
FIG. 9-15. A vacuum switch.

gas between the parting contacts. As described earlier, this gas is ionized by several different processes and so provides free electrons, which move to the anode, and positive ions, which move to the cathode. The positive ions coming to the cathode provide a mechanism by which electrons come out of the metal either thermionically or by high field emission. Practically all these phenomena disappear if the gas is removed from the space between the electrodes. The arc is interrupted at the first current zero and does not reignite. Vacuum breakers fail if leaks permit air to enter the interrupting chamber. The moving contacts are sealed by airtight metal bellows.

9-8. FUSES

A fuse, like a circuit breaker, is used to open a circuit in the event of an overload or short-circuit condition. Fuses are not ordinarily used to open and close circuits during normal operation. Unlike a circuit breaker, a fuse cannot be reclosed once it has opened. Its principal advantage is its low cost and high reliability.

Fuses used on low-voltage circuits are of very simple construction (Fig. 9-16a). Two end terminals, 1 and 2, are joined together by a metal fuse wire, 3, having a low melting point. With excessive current through the fuse wire, heat generated causes it to melt and clear the circuit. At higher voltage



(a) Low-voltage fuse (b) High-voltage, high-current fuse

FIG. 9-16. Fuses. (a) Cross section of cartridge fuse. (b) High-voltage fuse.

and current ratings, the fuse wire may be surrounded by a powder (such as boric acid) which aids in deionizing the arc produced following melting of the fuse.

Figure 9-16b shows a design used on higher voltage. A short fusible link is held under tension by a coil spring. A flexible wire joins the link to the right-hand terminal. When excessive current causes the fusible link to melt, the spring pulls the open contacts apart, increasing the length of the arc. An insulating nonflammable liquid such as carbon tetrachloride may fill the entire tube to assist in the deionizing process.

9-9. RECOVERY VOLTAGE

As shown by previous discussion, interruption of high current arcs in circuit breakers of electric power systems is dependent on the fact that the power current passes through zero value and reverses direction twice during each cycle. As the instant of current zero is approached, those factors tending to maintain ionization within the arc are diminishing and momentarily are nonexistent. Meanwhile, those factors that tend to deionize the arc path are very active. Hence at the instant that the voltage across the arcing contacts reverses polarity, the stability of the arc is uncertain. Whether or not the arc is reestablished depends on the rate at which ionizing effects are brought back into play. Those phenomena which supply the free electrons and positive ions to the arc column are very voltage dependent. Hence the probability of arc reestablishment is increased by a high rate of rise of voltage across the arc terminal. One writer has described the problem of arc interruption following current zero as a race between two opposing sets of forces: the deionizing effects that rapidly increase the dielectric strength of the arc path, and the rapidly increasing voltage appearing between the parting contacts. Whether or not the arc restrikes following current zero depends on the outcome of this race.

The rate at which voltage rises across the contacts of a circuit breaker following current zero depends entirely on the nature of the electric circuit

in which the current is flowing. A consideration of the circuit-interruption problem in some simple circuits illustrates the importance of *circuit configuration* on the rate of rise of recovery voltage following arc extinction at current zero. As seen from the following illustrations, the problem of circuit interruption is quite different in a resistive, an inductive, or a capacitive circuit.

a. Resistive Circuit. Refer to Fig. 9-17 which shows a circuit consisting of an ac power source whose terminals are 1-2, the contacts of a

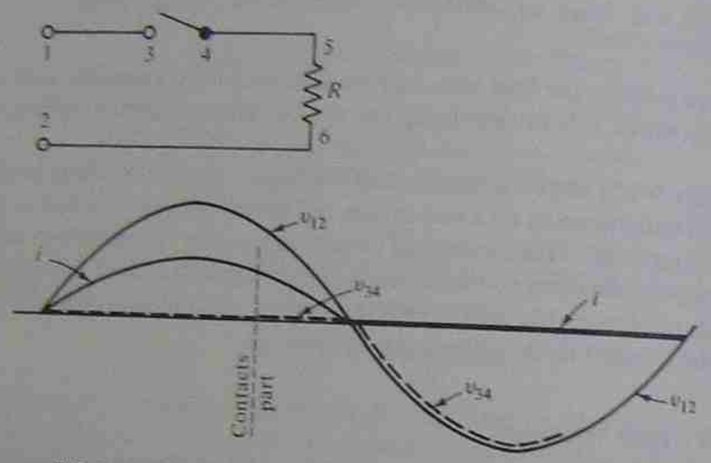


FIG. 9-17. Current interruption in a resistive ac circuit. (a) The circuit. (b) The current and voltage across the breaker contacts.

circuit breaker 3-4, and a resistor 5-6. From Kirchhoff's voltage law we may write

$$v_{12} = v_{34} + v_{56} \tag{9-2}$$

from which

$$v_{34} = v_{12} - v_{56} \tag{9-3}$$

When the contacts part, the voltage v_{34} is the voltage across the arc, perhaps less than 100 volts.

Assume that, following current zero, the circuit is interrupted; we may then write

$$i = 0 \qquad v_{56} = 0 \tag{9-4}$$

$$v_{34} = v_{12} \tag{9-5}$$

It is seen that in the resistive circuit, the voltage v_{34} available to cause restriking of the arc is exactly equal to the source voltage. Its rate of rise is determined from the characteristics of the source.

b. Capacitive Circuit. Figure 9-18a shows a capacitive circuit in which the parting contacts 3-4 are opening the circuit. Figure 9-18b shows

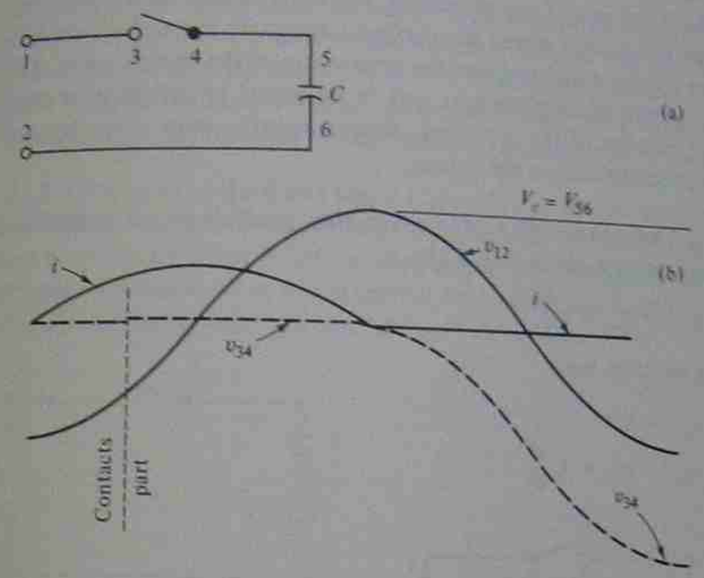


FIG. 9-18. Current interruption in a capacitive ac circuit. (a) The circuit. (b) The current and voltage across the breaker contacts.

the sequence of events following the parting of contacts and the interruption of current at the first current zero. From the relations

$$v_{12} = v_{34} + v_{56}$$

$$v_{34} = v_{12} - v_{56}$$

before current zero and neglecting arc drop,

$$v_{34} = 0$$

$$v_{56} = v_{12}$$

Note that in the capacitive circuit, current zero occurs at the instant of the crest value of the voltage wave. This means, then, that if the current ceases at the instant of current zero, the capacitor is left charged with a

voltage equal to the crest value of the ac supply, V_c. Then

$$v_{56} = V_c$$
$$v_{34} = v_{12} - V_c \tag{9-6}$$

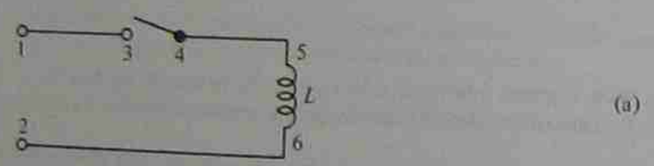
This equation shows that the voltage across the open contacts is the difference between the ac voltage and the dc voltage, as shown in Fig. 9-18b. Note that the initial rate of rise of voltage following current zero is relatively slow but that the voltage across the parting contacts at the end of one half-cycle reaches a value equal to twice the crest value of the supply wave. This high voltage across parting contacts may in an actual circuit breaker produce a delayed restrike of the arc. Such delayed restrike may give rise to serious transient conditions on the system.

c. Inductive Circuit. A similar analysis on an inductive circuit is made with the aid of Fig. 9-19:

$$v_{12} = v_{34} + v_{56}$$

Before contacts open,

$$v_{34} = 0$$
$$v_{56} = v_{12} = L\frac{di}{dt}$$



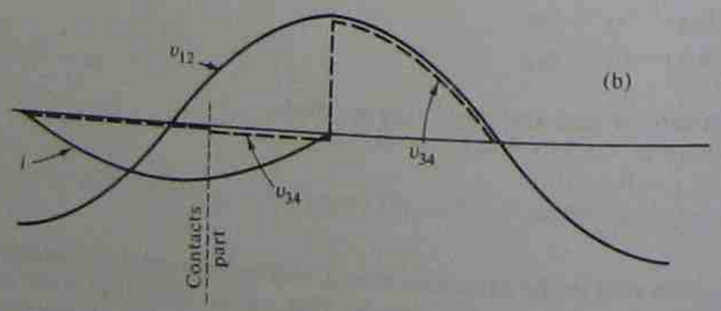


FIG. 9-19. Current interruption in an inductive ac circuit. (a) The circuit. (b) The current and voltage across the breaker contacts.

After contacts open,

$$i = 0 \tag{9-7}$$
$$L\frac{di}{dt} = 0 \tag{9-8}$$
$$v_{34} = v_{12} \tag{9-9}$$

If the circuit current ceases at the instant of current zero, the rate of change of current through the inductor drops suddenly to zero and the voltage across the inductor becomes zero. Therefore, the voltage across the arc goes from zero value to the crest value of the supply voltage wave in zero time. This sudden rise of the recovery voltage tends to cause restrike of the arc.

d. Resistance–Inductance Circuit. A similar analysis of a series resistance-inductance circuit may be made with the aid of Fig. 9-20. It is seen here that the presence of the resistance in the circuit shifts the point on the supply voltage wave at which current zero occurs and thereby reduces the recovery voltage appearing across the parting contact.

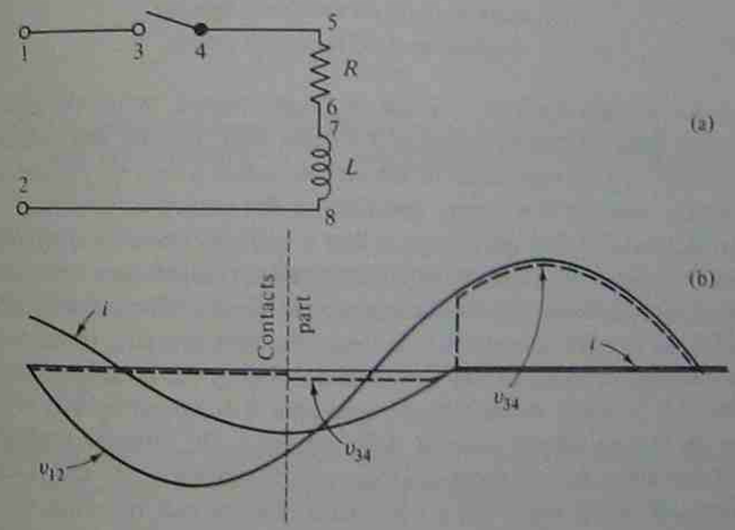


FIG. 9-20. Current interruption in a resistance-inductance circuit. (a) The circuit. (b) The current and voltage across the breaker contacts.

A similar analysis could be made on a resistance-capacitance circuit. Here again the recovery voltage would be found to be substantially reduced by the presence of the series resistors.

e. Resistance Switching. As shown in the discussion above, the presence of *series resistance* in a circuit reduces the rate of rise of recovery

voltage across the parting contacts of the switch. In some applications a resistor is momentarily switched into the circuit to aid in circuit interruption, as shown in Fig. 9-21. With this arrangement the main contacts of the breaker

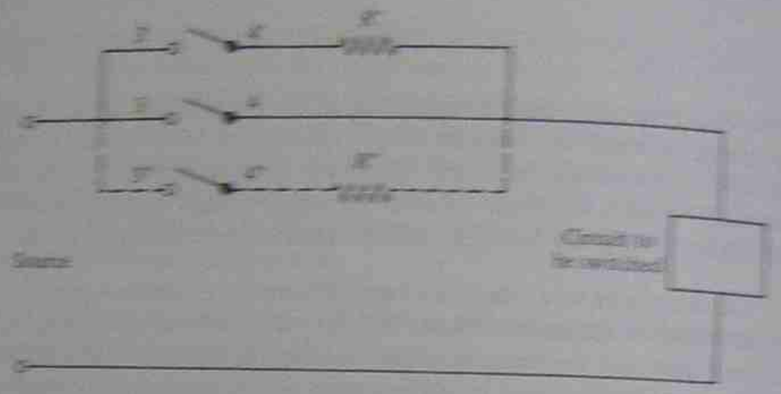


FIG. 9-21 Schematic diagram of a breaker with resistance switching.
3-4 Main contacts
3'-4' Auxiliary contacts for circuit opening
3''-4'' Auxiliary contacts for circuit closing

3-4 and the auxiliary contacts 3'-4' are originally closed. When the circuit is to be interrupted, the main contacts 3-4 open first, leaving the resistor *R* then in series with the remainder of the circuit. After a very short time delay the auxiliary contacts 3'-4' open, completing the circuit interruption. This arrangement has a further advantage in that it reduces transient overvoltages which may occur in the circuit to be interrupted. Transient overvoltages may also be generated when the circuit breaker is closed. These transients are reduced if the closure is made in two steps, the first bringing in the resistor as by the closing of contacts 3''-4'' followed quickly by the closing of the main contacts, 3-4. In some switching arrangements it is advantageous to use a resistor on closing whose value is different from the resistor used in the opening operation. In that event another set of contacts 3''-4'' and a resistor *R*'' (shown dashed in Fig. 9-21) are required. This circuit switching arrangement is particularly applicable to circuit breakers with which long transmission lines may be energized and deenergized.

c. Inductance-Capacitance Switching. Figure 9-22*a* shows a circuit arrangement representing the inductance of a transformer through which is supplied a static capacitor, *C*. Suppose that a short circuit occurs on a connecting transmission line as shown and the circuit breaker 3-4 is required to remove this short circuit. It may be shown analytically (though it will not be done here) that following the interruption of the current at

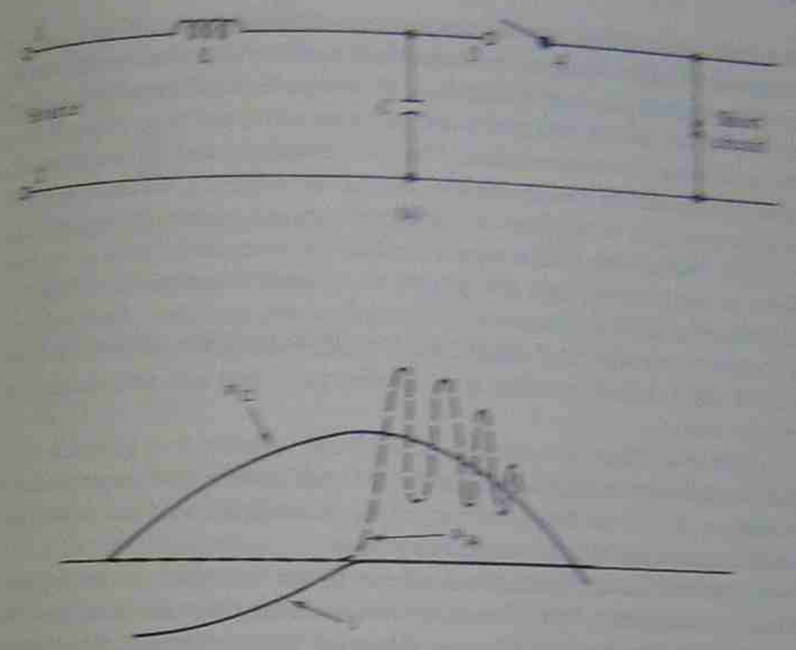


FIG. 9-22 Switching in the presence of series inductance and capacitance. (a) The circuit. (b) The current and voltage across the breaker contacts.

current zero, oscillatory voltage will appear across the contacts 3-4 (Fig. 9-22*b*). The (resonant) frequency of this oscillation is determined by

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{9-10}$$

This type of transient results in a high rate of rise of recovery voltage and must be considered in circuit-breaker application.

9-10. CIRCUIT-BREAKER CHARACTERISTICS

A circuit breaker is characterized in part by the class of insulating material used in its construction. The various classes are distinguishable not only by the kind of insulating material, but also by the environment in which they can operate.

At a given voltage each insulation class requires minimum clearance and creepage *paths*. The minimum clearance path is the minimum distance

that must be provided between conducting surfaces which differ in voltage; it is primarily dependent on the dielectric strength of the insulating material. Creepage denotes the undesirable flow of current between conductors, along the insulation surface; the minimum creepage paths are thus dependent on the environmental contamination. Besides clearance and creepage restrictions, the insulation classes impose diverse temperature limitations which must be respected at all times by the circuit breaker during its operation.

The main contacts of a circuit breaker are commonly made of copper, silver, or silver alloy, and are subject to diverse temperature limitations. Copper contacts are not normally fit for continuous operation; their temperature tends to rise with time. Most circuit-breaker contacts are therefore made of silver alloy, which provides good conductivity and low and stable temperature rise.

The rated dielectric strength of a circuit breaker is a measure of its ability to withstand voltages specified in the standards in both magnitude and waveshape. It ensures the proper operation of the breaker under dry or wet conditions, and under ac or impulse voltages.

A circuit breaker is usually designed to serve a certain system voltage called the nominal voltage. This is by reason of the limitations imposed by the insulation and by the arcing, as discussed earlier. These limitations are certainly not exceeded at lower voltages. Thus, a circuit breaker may be used in a system whose voltage is below nominal. Above nominal voltage, there is obviously a limit to the adequacy of a breaker; this is called the *rated maximum voltage*.

The rated short-circuit current of a breaker is the highest symmetrical current that it is capable of interrupting when used in a system carrying rated maximum voltage. If the system voltage is below rated maximum voltage, the breaker is then capable of interrupting a higher current obtained from the relation:

$$\text{Current-interrupting capability} = \text{rated short-circuit current} \times \frac{\text{rated maximum voltage}}{\text{system voltage}}$$

At this point it is appropriate to introduce an additional restriction known as the K-factor of a breaker. The relation above for the current-interrupting capability holds provided the resulting value does not exceed K times the rated short-circuit current, that is, as long as the system voltage is not more than K times smaller than the rated maximum voltage. Thus, under no circumstance does the current-interrupting capability exceed K times rated short-circuit current no matter how low the system voltage is. As an example, let a circuit breaker have a rated maximum voltage of 4.8 kV, a rated short-circuit current of 6000 A, and a K-factor of 2.2. This breaker is capable of

interrupting a current whose symmetrical component is 6000 A when used in a system whose voltage is 4800 V. For a system voltage of 4000 V, the current-interrupting capability is

$$6000 \times \frac{4800}{4000} = 7200 \text{ A}$$

The highest current-interrupting capability is

$$6000 \times 2.2 = 13{,}200 \text{ A}$$

which is available when the system voltage is

$$\frac{4800}{2.2} = 2180 \text{ V}$$

For a system voltage smaller than 2180 V, say 1800 V, the current-interrupting capability remains at 13,200 A.

A circuit breaker is also capable of closing and latching a faulted circuit provided the resulting current does not exceed $1.6K$ times the rated short-circuit current, where K is the breaker K-factor. In other words, the maximum peak should not exceed $2.7K$ times the rated short-circuit current (see Fig. 8-11). This capability is often referred to as the momentary rating of the breaker. The latter is, of course, expected to interrupt the circuit a short time later. The momentary rating of the breaker discussed above is

$$13{,}200 \times 1.6 = 21{,}100 \text{ A rms}$$

or

$$13{,}200 \times 2.7 = 35{,}600 \text{ A peak}$$

The *rated continuous current* of a breaker is that value of rms current at rated frequency which the breaker is capable of carrying continuously without exceeding any of the temperature limitations discussed earlier. For the example above, a reasonable value of rated continuous current might be 600 A.

9-11. FUSE CHARACTERISTICS

Fuses are broadly classified as non-current-limiting or current-limiting. Since all fuses limit excessive currents, this classification refers in reality to the manner in which the rating of a fuse is set forth in the standards. In most cases where it is applied, a current-limiting fuse opens the circuit before the first peak of the short-circuit current; a non-current-limiting fuse opens it one cycle or more after the fault inception.

The *continuous current rating*, or simply current rating, of a fuse is that current which it is capable of carrying indefinitely without deterioration or excessive temperature rise. Since the voltage affects the arcing occurring in a fuse after it has melted, a fuse also has a voltage rating (rms if ac). A fuse obviously can operate at current and voltage levels lower than rated.

A non-current-limiting fuse is usually specified only by its current, voltage, and frequency ratings. Besides, it is expected to blow within specified maximum times when subjected to overload currents of 135 and 200 percent. This type of fuse should not be used in situations where short-circuit currents may exceed 10,000 amperes.

Before we embark on a discussion of current-limiting fuses, we have to deal first with certain fundamental concepts. The *interrupting rating* of a fuse is the maximum rms short-circuit current which may possibly occur where the fuse is used. Thus, at a point in the electric circuit, if the calculated short-circuit current is 75,000 amperes, no fuse should be used with interrupting rating inferior to that value. Let a fuse be used with an interrupting rating of 100,000 amperes. This does not mean that the fuse would ever allow a 75,000-A fault current to flow through it, even for one cycle; that brings us now to the next definition.

The *peak let-through current* is the maximum current that a fuse allows to flow while it is interrupting the circuit. This current value is not a rms but a peak instantaneous value, as shown in Fig. 9-23. The duration of the current from the moment the short circuit occurs to the moment it is interrupted is

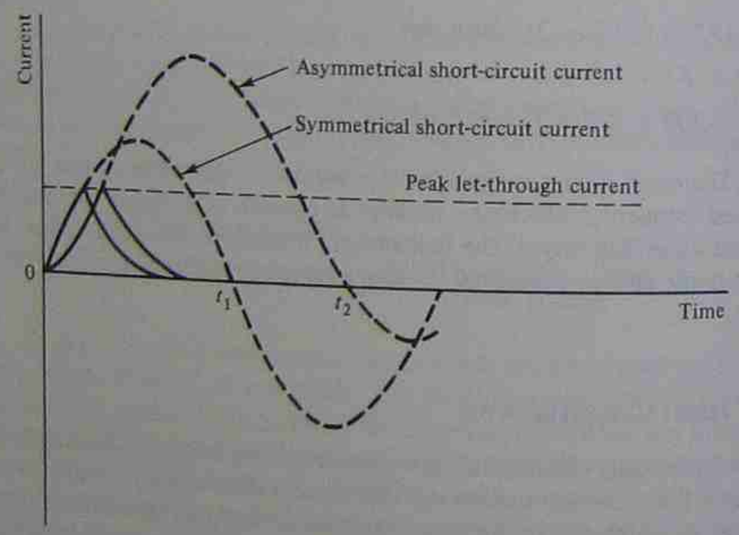


FIG. 9-23. Performance of a current-limiting fuse.

called the clearing time. This interval of time comprises two subintervals: the melting time and the arcing time, as shown in Fig. 9-24. The melting time is the time needed to melt the link in a fuse. The arcing time is the time elapsed from the melting of the link to the interruption of the circuit; it is dependent on the circuit reactance and voltage as discussed in Section 9-9. The peak let-through current is then the maximum current occurring during clearing time provided current limiting takes place.

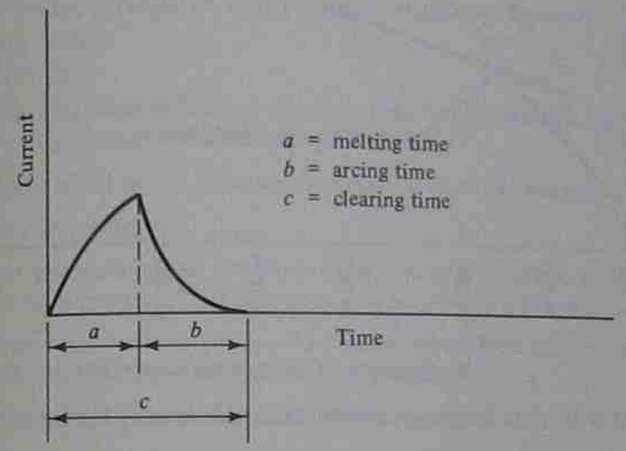


FIG. 9-24. Current passed by a current-limiting fuse as it interrupts a circuit.

Current limiting is said to occur if the clearing time at rated voltage is smaller than the first half cycle of the symmetrical or asymmetrical current wave, i.e., $0 - t_1$ or $0 - t_2$ in Fig. 9-23. If the short-circuit or overload current is below a certain threshold value, the current in its entirety is passed by the fuse until interruption, in which case no current limiting occurs. Figure 9-25 shows the dependency of the peak let-through current on the short-circuit current. Note the points where current limiting becomes effective.

The overcurrent flowing through a fuse also flows through the circuit elements to be protected by the fuse. The time taken by a fuse to clear the fault is an important factor in providing suitable protection to the equipment fed through the fuse. But time alone is not enough in trying to ascertain the damage caused by excessive current; the current value must also be taken into account. It would be convenient to deal with a single factor in determining protection.

Damage to a circuit element results from overheating caused by the energy dissipated in the element resistance during fuse clearing time. This energy is I^2Rt, where I^2 is the average of the current squared (square of the

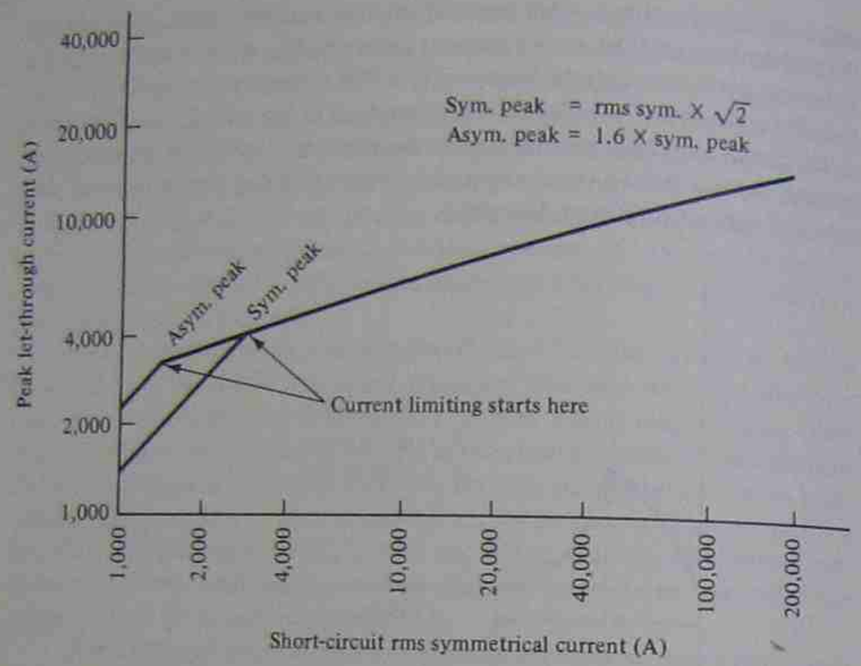


FIG. 9-25. Peak let-through current characteristic using log-log scale.

rms current) and t is the clearing time. A common factor for all circuit elements connected in series with a fuse is obviously I^2t. This factor is the *thermal energy let-through* and is expressed in ampere-squared-seconds.

In order to provide selective protection, two fuses used to carry in some cases the same fault current must be so sized that the fuse closer to the fault point blows first. The I^2t of that fuse during clearing time should be incapable of damaging the fuse farther from the fault point. Thus, two I^2t values are defined for a fuse: melting I^2t, which depends solely on current regardless of voltage, and clearing I^2t, which depends on voltage and power factor since both affect arcing time.

A fuse is therefore characterized by a melting I^2t and by a clearing I^2t at a given voltage and power factor. The clearing I^2t of a fuse must be smaller than the maximum I^2t of the equipment that it purports to protect.

As for ratings, a current-limiting fuse is usually specified by current, voltage, frequency, interrupting capability, and current-limiting capability. Its size and shape preclude its replacing a non-current-limiting fuse. In fact, some fuses are rated in the same manner as current-limiting fuses and yet are classified as non-current-limiting because they can fit in fuse holders intended for non-current-limiting fuses.

PROBLEMS

9-1. A 100,000-kVA 18-kV three-phase four-pole turbine generator is to be equipped with a breaker at its terminals. Specify the ratings of the breaker.

9-2. Suppose the generator of Problem 9-1 is to be operated on the same bus with two other similar generators. How will its breaker requirement be affected?

9-3. Describe the process of circuit interruption in a breaker on an ac system.

9-4. What are the principal carriers of electric charge when current flows
   a. in a metal?
   b. in an arc?

9-5. What is the basic difference between copper and porcelain which explains their vastly different conductivity (or resistivity)?

9-6. List some of the things in nature that may produce free electrons.

9-7. What is an ion pair?

9-8. List and describe those processes in an arc which tend to maintain or increase the numbers of free electrons and positive ions present.

9-9. List and describe those processes in an arc which tend to suppress the numbers of free electrons and positive ions present.

9-10. List five mechanisms used by circuit-breaker designers in an effort to suppress arcs.

9-11. Explain why it is much easier to interrupt an arc in an ac circuit than in a dc circuit.

9-12. Compare the problem of interrupting 1000 A in a 120-V ac circuit with that of interrupting 100 A in a 1200-V ac circuit.

9-13. What is meant by "recovery voltage"? What controls its rate of rise?

9-14. Assume that a device were developed that would interrupt arc current at the instant of *crest* value. Make a sketch showing the rise of recovery voltage
   a. in a resistive circuit.
   b. in a capacitive circuit.
   c. in an inductive circuit.

9-15. Refer to Fig. 9-22. Consider that L is the leakage inductance of a 25-kVA 22/5-kV transformer viewed on the 5-kV side. Let C be a 10-kVA capacitor bank for power-factor correction. What will be the frequency of oscillation when contacts 3-4 are opened?

9-16. A circuit breaker has the following features: rated maximum voltage 15 kV, rated short-circuit current 5500 A, K-factor 2.3, rated continuous current 600 A. Determine its suitability to the following situations:
   a. 13.8-kV system, symmetrical short-circuit current 5800 A, continuous current 800 A.

b. 13.2-kV system, symmetrical short-circuit current 6200 A, continuous current 550 A.
c. 12.4-kV system, symmetrical short-circuit current 8000 A, continuous current 500 A.
d. 7.5-kV system, symmetrical short-circuit current 10,000 A, continuous current 1000 A.
e. 4.8-kV system, symmetrical short-circuit current 15,000 A, continuous current 600 A.

9-17. From Fig. 9-25 determine the maximum peak let-through current of the fuse for a short-circuit symmetrical current of:
a. 9000 A rms.
b. 2000 A rms.
Compare the answers with the amplitude of the short-circuit currents.

chapter 10

System Instrumentation

10-1. SYSTEM MONITORING

A modern electric power system is an assembly of many components each of which influences the behavior of every other part. Proper functioning of the system as a whole makes it necessary to monitor conditions existing at many different points on the system in order to assure optimum operation.

The concern of the customers is primarily that the frequency and voltage of the supply are held within certain rather narrow limits. Since frequency of the system is the same everywhere, it may be monitored by a single frequency meter located at any convenient point. In contrast, the voltage of the system may be quite different at different points. Consequently, it is necessary to make continuous observation of the voltage at certain key points on the system in order to provide acceptable service.

Efficient operation of the system is obtained by assigning proper load schedules to each of the generators on the system. Newer plants, although individually more efficient, may be located at points on the system where their loading occasions large system losses. It is desirable to operate with a division of the load between generators such that the total cost of fuel consumed is minimized. To provide reliability of the power supply in the event of unexpected conditions, it is desirable to have the total kilowatt rating of all machines in operation somewhat greater than the total load plus losses.

This excess of generation, known as *spinning reserve*, is then available for picking up suddenly applied customer loads or to pick up the load dropped by a generator that must be removed from service for emergency maintenance.

Instrumentation is necessary to permit billing of customers for energy used. Many interconnections exist between different power systems. Instruments must be provided at interchange points to permit billing for energy transferred from one system to another. The continuous monitoring of energy transfer is necessary to assure that interchanged power is within the limits of contract agreements.

The continuous measurement of conditions on major pieces of equipment is necessary to avoid damage due to overload. As load increases from month to month, points at which additional capacity of equipment is required may be recognized and provision made for the installation of additional equipment. Thus instrumentation serves as a guide for future construction in a growing power system.

Occasionally, under emergency conditions, a system operator observes that his system load exceeds the ability of the available generating and transmission equipment. He is then faced with the problem of *load shedding* or, more properly, *load conservation*. It is then necessary to drop selected loads where service interruption is least objectionable. In such an event, he relies on the many instruments which provide information relative to system-operation conditions.

Instruments may sound alarms as advance warnings of conditions requiring action to avoid damage to equipment operating beyond its design limitation. In the event of extreme conditions such as power-system faults, defective equipment is switched out of service automatically. Instruments that continuously monitor current, voltage, and other quantities must be able to identify the faulted equipment and to bring about operation of the circuit breakers which remove it from service, while leaving in service all other equipment on the operating system.

The many different electrical devices on a power system and those owned by the customers are designed for operation within certain specified ranges. Operation outside these designed limits is undesirable, as it may result in inefficiency of operation, excessive deterioration, or (in extreme cases) the destruction of the device. Careful attention to the conditions under which equipment is operating may indicate corrective action that must be taken.

Overcurrent on all electrical devices is undesirable, as it produces excessive temperatures, inefficient operation, and reduced service life. Overcurrent in residential circuits may bring about disconnection of the circuit by fuse or breaker action. Overcurrent in motors may damage insulation, with possible early insulation failure.

Undervoltage considerably reduces the efficiency of incandescent lamps and may result in nonoperation of fluorescent lamps. Undervoltage

of the power supply to motors may result in excessive currents in the motors, with possible damage to windings.

Overvoltage increases the light output of lamps but in many instances seriously shortens useful life. Overvoltage applied to motors and transformers may result in excessive losses within the iron, with possible damage to the iron or to the adjacent winding insulation.

Overspeed of rotating machines may result in structural damage to rotating parts. The overspeed of the customers' production equipment may result in an inferior quality of the product.

An out-of-step condition existing between two generators or between a generator and a synchronous motor results in an interruption of useful power transfer between the two machines. An out-of-step condition should be recognized promptly and the machines separated from each other. They may then be resynchronized and brought back into service.

Instruments of many different types must be installed at many locations on a power system and on the premises of the many customers. With such instruments, conditions existing on the system may be continuously monitored.

10-2. INSTRUMENTS FOR SYSTEM MONITORING

The instruments used for system monitoring include the following:

voltmeters	synchroscopes
ammeters	relays
wattmeters	varmeters
watt-hour meters	automatic oscillographs
frequency meters	

The meters may be *indicating* or *recording*. The instruments may in turn control automatic equipment for regulating voltage, frequency, power output, or power interchange on tie lines. In many modern systems, instrument readings are transmitted from many points on the operating system to control centers. At these control centers the reading of instruments from the remote points may be displayed as an aid to the system dispatcher. In some instances data from selected instruments are fed into a computer which determines plant loading for the most economic system operation. The computer then transmits signals to the various generators to load each machine to the predetermined value.

The transmission of instrument readings from point to point on a power system may be accomplished by several different methods. Leased or private telephone lines may provide circuits for information transmission.

Channels of communication may be provided by carrier current systems using the power conductors as the medium of transmission. In other instances, microwave circuits may be utilized. The system used for the transmission of instrument readings may also be used for voice transmission and for supervisory control.

10-3. INSTRUMENT CIRCUITS

Residental loads on electric power systems are ordinarily supplied by circuits that nominally operate at 120–240 volts. The currents that flow in these circuits may be as much as 100 or 150 amperes. The watt-hour meters which measure energy on these circuits have potential coils designed for operation at 120–240 volts and current coils which carry full-load current. In contrast, the watt-hour meters, wattmeters, voltmeters, ammeters, and other instruments used in power-system stations and substations and the instruments used on the systems of large industrial customers are, almost without exception, equipped with potential coils designed to operate at approximately 120 volts and with current coils designed to carry normal working currents of approximately 5 amperes. The 120-volt, 5-ampere line of instrumentation is accepted as standard. If voltages of power circuits, with values in some instances greater than 500 kilovolts, are to be measured by instruments with 120-volt coils, and if power-system currents measured in thousands of amperes are to be measured by instruments with 5-ampere current coils, it is necessary that some sort of voltage-sampling and current-sampling devices be interposed between the operating electric power system and the instruments that measure its performance. Potential transformers, capacitor potential devices, and bushing potential devices, connected to the high-voltage power system, supply to the instruments voltages that are a known fraction of the system voltage. Ideally the voltages supplied to the instruments are in phase with the system voltages which they represent. Similarly, current transformers and similar devices must supply instrument currents which are a known fraction of the power-system currents and which ideally are in phase with the power-system currents. Figure 10-1 shows a typical installation in which a single-phase load (or a line-to-neutral load) is supplied from an ac source. A potential transformer rated 72,000/120 volts provides a voltage supply for the potential coils of the voltmeter and the wattmeter. A current transformer rated 1000/5 amperes supplies current to the current coils of the instruments.

A consideration of Fig. 10-1 illustrates many advantages in the use of instrument transformers in power circuits. The power circuits themselves may be arranged in the switchyard almost independently of the location chosen for the instruments. Since the leads from the instrument transformers to the instruments themselves are subjected to voltages and currents of rela-

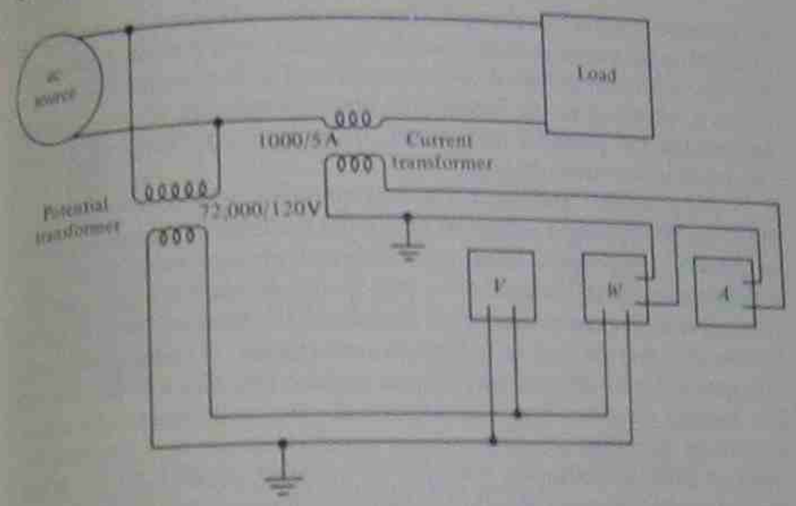


FIG. 10-1. A voltmeter, an ammeter, and a wattmeter connected to a power circuit through instrument transformers.

tively low magnitude, these connections may be constructed of wire of relatively small size and with minimum insulation. As a safety measure one side of each secondary circuit is grounded. The instruments may be located as desired in a control house, and the secondary leads run to them with relatively little hazard to the equipment or to the operating personnel.

10-4. VOLTAGE SUPPLY TO INSTRUMENTS

Several different types of devices may be connected to high-voltage circuits to supply the 120-volt circuits of the measuring instruments. All these systems have certain requirements in common. Ideally the voltage supplied to the instrument circuits should be a known fraction of the voltage on the power circuit and in phase with it. The device must insulate the power circuit from the instrument circuit, permitting one side of the instrument circuit to be grounded. If the voltage supplied by the instrument winding is exactly that fraction of the power-system voltage as indicated by the nameplate (such as 72,000 to 120) the device is said to have *zero ratio error*. If the output voltage is exactly in phase with the power-system voltage, the *phase-angle error* is said to be zero. Actually these ideal conditions are seldom attained in practice. The ratio and phase-angle errors may be of considerable concern, as they affect the accuracy with which the measuring instruments indicate the behavior of the power system itself. Ratio and phase-angle errors may change as the

power-system voltage is changed. They are also influenced by the loading imposed on the potential transformer by the leads from it to the instruments and the instrument potential coils themselves. The load imposed on such a device is spoken of as the *burden*. The potential-reducing devices discussed here include the potential transformer, the capacitor potential device, and the bushing potential device.

The potential transformer (Fig. 1-24) provides the most accurate sampling of the power-system voltage of any of the available devices. It is also the most costly. The potential transformer is, in fact, merely a power transformer of full voltage rating designed for a very small secondary load, perhaps 200 volt-amperes. The equivalent circuit diagram of the transformer discussed in Section 2-8c may be used to analyze its performance. A transformer design that provides relatively low magnetizing current, low core-loss current, and low leakage reactance has extremely small ratio and phase-angle errors. Because of their high accuracy, voltage transformers are used almost exclusively to provide instrument potential in metering installations for billing to commercial customers or between interconnecting systems. Where installed for billing purposes, they are also used to supply the potential coils of indicating and recording instruments and relays.

Capacitor potential devices provide a less expensive method of obtaining a potential supply for instruments. However, greater phase-angle and ratio errors are inherent with this type of device. Their use, therefore, is limited to applications in which a high degree of accuracy is not required. Such devices are used to a considerable extent to supply potential to the voltmeters and wattmeters used to monitor electrical conditions within a system and to provide the voltage for the potential coils of protective relays. The capacitor potential device consists of a high-voltage capacitor shown in Fig. 10-2a contained in a porcelain weather shed associated with an impedance matching network (Fig. 10-2b). The impedance matching network as shown here consists of a transformer and adjustable resistors, inductors, and capacitors. Designs vary from one manufacturer to another but all provide a means for adjusting the output voltage to conform in ratio and phase angle to the high-side voltage. This adjustment may vary with the burden placed upon the device, and so adjustments may be required with the burden connected exactly as it will be operated.

Because the impedance-matching section is essentially a resonant circuit, ratio and phase-angle errors may change with applied voltage. Such changes may be particularly troublesome if there are nonlinear circuit elements associated with the secondary circuit, such as the iron-core potential circuits of relays. These ratio and phase-angle error changes may be of particular importance during fault conditions, when circuit voltage may drop to a small fraction of the normal value. It is, of course, during these

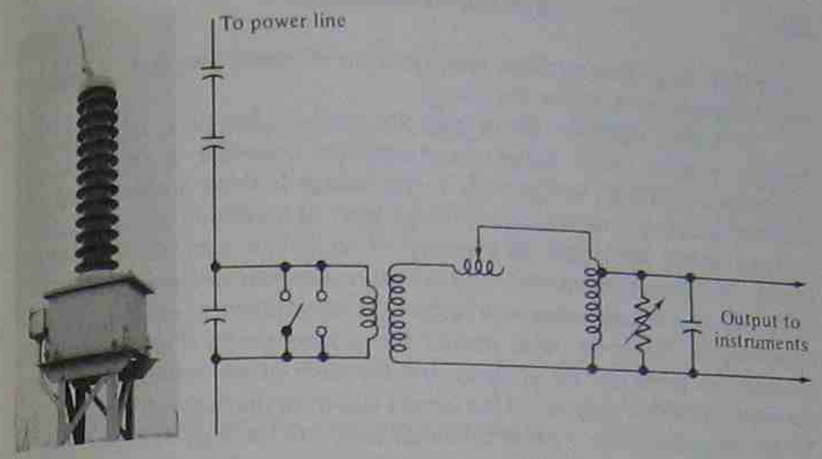


FIG. 10-2. A capacitor potential device. (a) The high voltage capacitor. (b) The impedance matching network.

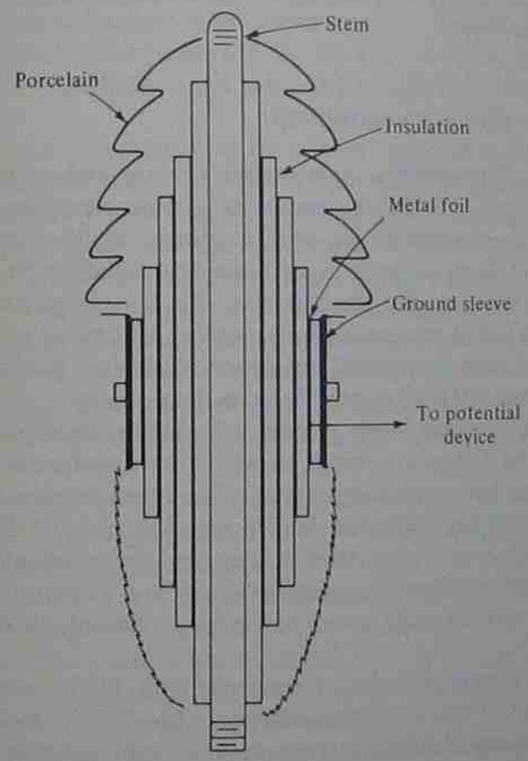


FIG. 10-3. The construction of a capacitor-type high-voltage bushing.

times that relays must perform their function of identifying fault locations and removing the defective equipment.

A *bushing potential device* uses the capacitance of a high-voltage bushing in place of the high-voltage capacitor described in the previous paragraphs. As shown in Fig. 10-3, a high-voltage bushing is constructed of a central metal stem on which is wound a layer of insulating material. After building up this layer, perhaps a quarter of an inch, a layer of metal foil is put on. This process is repeated until the entire insulator system is assembled. In operation, a voltage appears on each of the metal layers, the lowest voltage appearing on that metal layer nearest the ground sleeve. The capacitance between this particular metal sleeve and the stem of the bushing serves as the capacitor which couples the instrument circuit to the high-voltage circuit. As the capacitance here is lower than that built into the high-voltage capacitors of the capacitor potential device, this device is less intimately connected to the power line. As a consequence, the ratio and phase-angle errors of bushing potential devices are considerably greater than those of capacitor potential devices. Hence they are used only in those locations where such error may be tolerated.

10-5. CURRENT SUPPLY TO INSTRUMENT

The current supply to switchboard instruments, relays, and similar equipment is most commonly provided by means of *current transformers*. Current transformers are iron-core devices with a primary winding consisting of a small number of turns of large current-carrying capacity. This winding is insulated from the core and the secondary for full power-circuit voltage. The secondary winding consists of a large number of turns of relatively small wire. The turns ratio is adjusted to supply 5 amperes to the instrument circuit when rated full-load current flows in the primary.

The current flowing in the primary of a current transformer is determined entirely by the power circuit in which the transformer is installed. This current is substantially independent of the characteristics of the transformer itself or of the secondary burden imposed upon it. However, for purposes of analysis it is convenient to treat the current transformer in the conventional fashion, beginning with the secondary current and adding to it the exciting current to determine the primary-current, turns ratio considered.

The equivalent circuit of the transformer (Fig. 10-4) serves to describe the performance of the current transformer. Ideally, the secondary of a current transformer should be short-circuited. Actually the impedance placed on it is very low, consisting of one or more instrument current coils and the connecting leads. Referring to the equivalent circuit, it is seen that if the

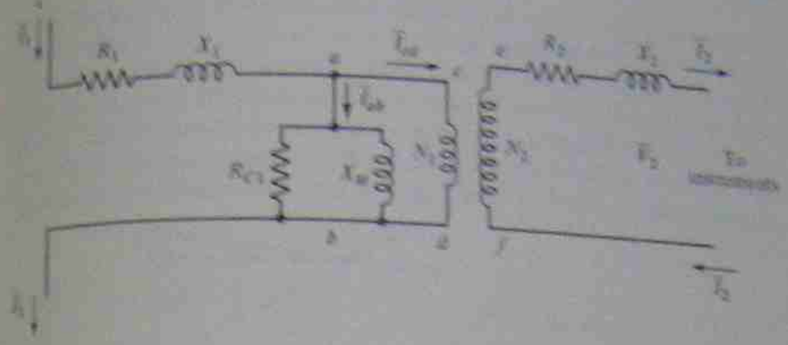


FIG. 10-4. The equivalent circuit of a current transformer.

transformer is short-circuited, the output voltage is zero and the voltage across the section a-b which accounts for the core loss and magnetizing currents is very low. If the transformer exciting current is so low that it may be neglected, it follows that the secondary current will be equal to the primary current multiplied by the turns ratio, N_1/N_2. Thus under the condition of zero burden on the transformer, the ratio and phase-angle errors will be very small.

If the connecting leads from the current transformer to the instruments are long and if several instrument current coils are placed in series, the transformer secondary load impedance is of importance and the burden on the transformer is said to be high. In order to circulate current in the secondary circuit to the instruments, a significant voltage must be present across the transformer secondary output terminals. To produce this voltage there must be a flux in the core, and to produce the flux there must be exciting current. As a consequence, the primary current, which is the sum of the load current and the exciting current, will be greater than the secondary-current, turns ratio considered. As a result a phase-angle and ratio error appears (Fig. 10-5).

The core and windings of a current transformer are relatively inexpensive. However, if the transformer is to be used for measuring the current on a high-voltage circuit, insulation and shielding for full line voltage must be provided between the primary and the core and between the primary and secondary windings. This results in a very substantial increase in the cost of a transformer. To minimize the insulation cost, bushing-type current transformers were developed. These transformers utilize the bushings which penetrate circuit breaker and power transformer cases as the insulation for the current transformers. A bushing-type current transformer is shown diagramatically in Fig. 10-6a. The power conductor whose current is to be measured penetrates once through a large-diameter ring-shaped laminated

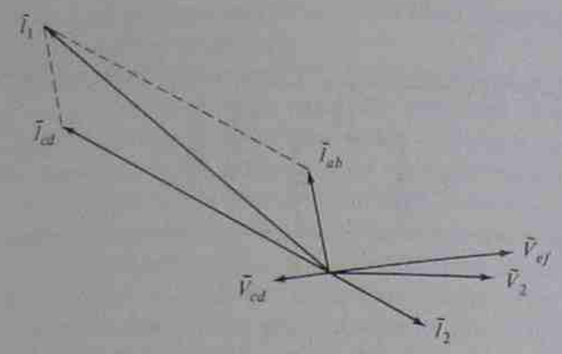
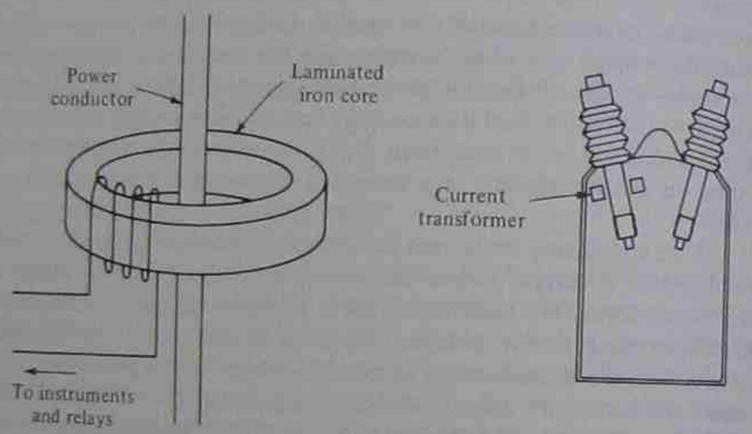


FIG. 10-5. A phasor diagram showing the voltages and currents associated with a current transformer.



(a) Construction (b) Circuit breaker with current transformer

FIG. 10-6. A bushing type current transformer. (a) Basic structure. (b) Installation in a circuit breaker.

iron core. The secondary winding on this core connects to the associated instruments and relays.

Figure 10-6b shows the cross section of an oil circuit breaker with a current transformer in place. It may be noted that the breaker bushing provides the insulation between the power conductor and the secondary winding.

As may be seen from Fig. 10-6a, the bushing-type current transformer consists of a single primary turn rather loosely linked with the secondary. As a result, the transformer leakage reactance is relatively high. This gives rise to increased ratio and phase-angle errors inherent in the bushing-type current transformer as compared with the ones of conventional design.

Errors are particularly large during conditions of system faults, when short-circuit currents may be 10 or more times the rated full-load current of the current transformer. Under fault conditions, the iron of the core may reach saturation with an attendant sudden increase in the value of the magnetizing current. As the secondary current is the primary current minus the exciting current, the current supplied to instruments will be less than the value indicated by the transformer turns ratio alone. Figure 10-7 shows typical performance curves for bushing-type current transformers. Transformers of this type are used primarily in connection with switchboard indicating instruments and relays. They are seldom used where high accuracy is required.

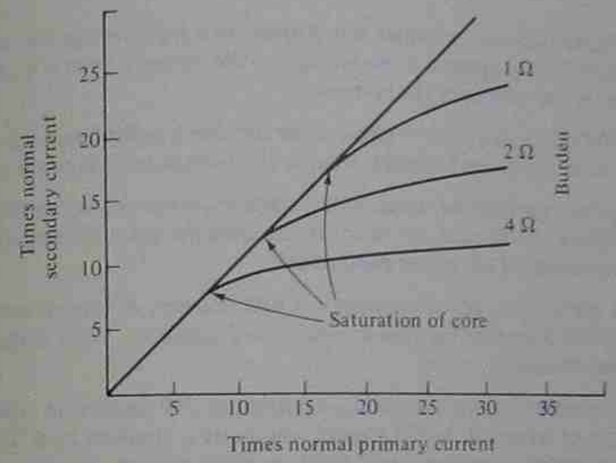


FIG. 10-7. Performance curves of a bushing-type current-transformer showing the effect of burden.

The principal problem of measuring current in a high-voltage circuit lies not in the current measurement itself but in the transfer of the information to a circuit which may be conveniently connected to switchboard equipment. For example, a relatively inexpensive ammeter could be connected directly into a power conductor. Its reading might be observed by looking through a telescope. This arrangement would, of course, not provide circuitry for switchboard equipment. Several schemes have been developed for measuring the current with the measuring equipment itself tied directly to and operating at the same voltage as the power equipment. The current readings are then transmitted over a radio channel or over a light beam to a low-voltage circuit leading to switchboard equipment. These systems permit the simplest form of high-voltage insulation between the measuring system and the instrument circuits (perhaps a single column of porcelain insulators) but require the complexity of the information transmission circuitry. How-

ever, this type of current-measuring system is particularly attractive on extra-high-voltage circuits, where circuit-breaker design is of such form (see Section 9-7c) that no high-voltage entrance bushings are required.

PROBLEMS

10-1. A 72,000/120-volt potential transformer on a high-voltage line supplies a switchboard voltmeter. If the voltage on the power system is 68,000 volts, what is the reading of the voltmeter?

10-2. A 5000/120-volt potential transformer supplies a switchboard voltmeter. If the voltmeter reads 130 volts, what is the voltage on the power system?

10-3. A current transformer, rated 2000/5 amperes, is on a power conductor and supplies a switchboard ammeter. If the ammeter reads 2.1 amperes, what is the current in the power conductor?

10-4. The current in a power conductor is 650 amperes. A current transformer rated 400/5 amperes supplies a switchboard ammeter. What is the reading of the ammeter?

10-5. A single-phase power line carries a current of 350 amperes at 69,000 volts, 0.8 power factor lag. A switchboard wattmeter is supplied by a 72,000/120-volt potential transformer and 400/5 amperes current transformer. What is the reading of the wattmeter?

10-6. A wattmeter having a full scale reading of 500 watts connects to a power circuit through a 1000/5-amperes current transformer and a 138,000/120-volts potential transformer. The wattmeter is rescaled to indicate power-circuit quantities directly. What will then be the full scale reading of the wattmeter?

10-7. A bushing potential device having a nominal rating of 500,000/120 volts is improperly adjusted, with the result that the output voltage to the switchboard instrument is 8 percent low. With the switchboard instrument reading 104 volts, what is the voltage on the line?

10-8. A bushing potential device rated 72,000/120 volts is properly adjusted for ratio but has an improper phase-angle adjustment, which results in the secondary voltage being 10 degrees behind the primary voltage. This device is connected to a single-phase power line to provide potential for a switchboard wattmeter. Current to the wattmeter is supplied by a 200/5-amperes current transformer. On the line the voltage is 69,000 volts, the current is 180 amperes, and the power factor is 1.0. What is the actual power on the line, and what is the power as determined from the switchboard wattmeter?

10-9. Repeat Problem 10-8 but assume that the power factor is 0.5 lead.

10-10. A bushing-type current transformer is rated 400/5 amperes. During a fault, the short-circuit current is 8000 amperes. What current flows in the switchboard instruments if the impedance of the instruments and connecting leads is
a. 1 ohm?
b. 4 ohms?

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chapter 11

Relays and Relay Systems

11-1. GENERAL

A relay is a device that responds to variations in the conditions in one electric circuit to affect the operation of other devices in the same or in another electric circuit. The earliest forms of relays were electromechanical devices, a type that gained general acceptance because of its simplicity and rugged construction. Power-system relays must be highly reliable, for they may go for long periods without attention but must be ready to operate with speed and accuracy on demand. Most relays in service on electric power systems today are of this type.

Relays and relay systems using vacuum tubes were developed but were never generally accepted. The inherent uncertainties of vacuum tubes (which sometimes burned out or experienced a change in performance characteristics) made them somewhat unsuited for power-system protection.

Solid-state, or static, relays have, in the past few years, been developed to the point where they are highly acceptable for power-system protection. Circuit designs have been developed in which operating characteristics are almost entirely independent of those variations of component characteristics that result from temperature changes or age. The response time of solid-state relays may be made as short as desired; in fact, the basic components themselves have such fast response that it is frequently necessary to add delay

circuits to avoid false operations due to momentary transients on the power circuits. The various functions necessary in relay applications can each be accomplished by solid-state circuitry of different designs. Integrated circuits are progressively making inroads into these designs, offering greater flexibility, sophistication, and reliability. It is quite difficult to show solid-state circuitry basic to a particular function; it is outside the scope of this book. This is, however, discussed in relation to phase comparison in Section 11-11. Because of their increasing acceptance by designers, programmable controllers are also discussed.

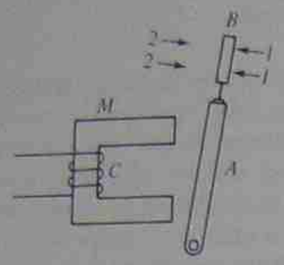
The principles of protection of electric power circuits are quite independent of the relay designs which may be applied. For example, if the current to an electric circuit or a machine is greater than that which can be tolerated, it is necessary to take remedial action. The device for recognizing the condition and initiating corrective measures would be termed an overcurrent relay regardless of the mechanisms by which the function would be accomplished. Because the functions of electromechanical devices are easily described, their performance will serve as a basis for presenting a description of relays and relay systems in general.

11-2. BASIC RELAY TYPES

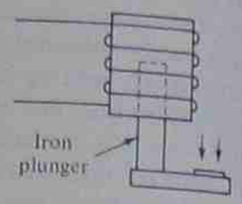
Most of the electromechanical relays in use may be classified into a few basic types. Each of these has moving contacts that may be made to open one or more circuits, to close one or more circuits, or to do both. Each of these devices is ordinarily in the normal state and moves into the operate state on the occurrence of certain electrical changes in the coils of the relays.

a. Moving-Armature Relay. The *moving-armature relay* is shown in Fig. 11-1a. A coil *C* is wound on a core of magnetic material *M*. A movable armature *A* carries with it a movable contact *B*. With no current in the coil, the contact *B* rests against the contacts 1-1, connecting them together. Gravity or a spring holds the armature in the position shown. If current through the coil is slowly increased, a point is reached at which the armature *A* suddenly rotates to the left, opening contacts 1-1 and closing contacts 2-2. The minimum current at which this motion may be initiated is termed the *pickup current*. If the current is now slowly reduced, a value will be found at which the armature will drop back to its original position. This is termed the *drop-out*, or *release*, *value*.

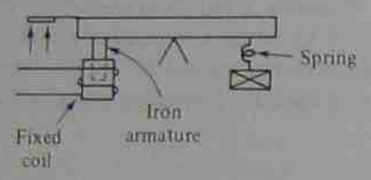
b. Solenoid. A *solenoid relay* is shown in Fig. 11-1b. A fixed coil surrounds a movable iron plunger. The plunger is held away from a sym-



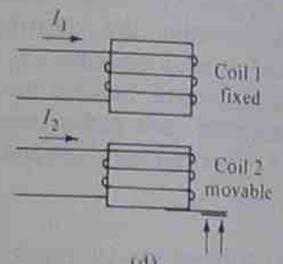
(a)



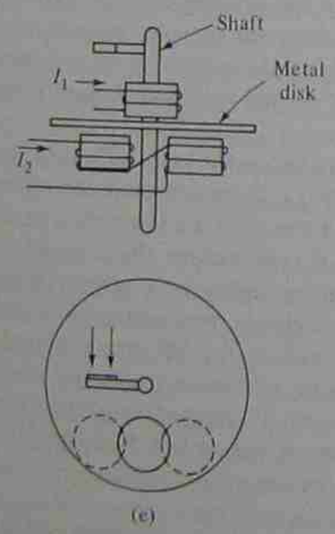
(b)



(c)



(d)



(e)

FIG. 11-1. Electromechanical relay types. (a) Moving armature. (b) Solenoid. (c) Balance beam. (d) Mutually interacting coils. (e) Induction disc, elevation and plan.

metrical position in the coil by gravity or by a spring. When current of sufficient value flows in the coil, the iron core is drawn into the coil, thus closing the contacts as shown. Obviously such an arrangement could be made to open contacts by a simple position change. Again the pickup current is greater than the release current. The plunger in any selected position experiences a force proportional to the square of the current (or to the square of the voltage across the coil).

c. Balance Beam. An iron armature is fastened to a *balance beam* as shown in Fig. 11-1c. The armature is drawn into a fixed-position coil when current flows in the coil. Various contact and spring arrangements are possible.

d. Mutually Interacting Coils. Two coils, one fixed and one movable, are positioned so that their magnetic fields interact (Fig. 11-1d). If the currents are of constant direction, the force between them will be proportional to the algebraic product of the two currents and may result in drawing the coils together or thrusting them apart. If ac currents flow in the coils, the force action will be proportional to the product of the two current values and the cosine of the angle Δ between them:

$$F = K_M I_1 I_2 \cos \Delta \tag{11-1}$$

e. Induction Disc or Induction Cup. The *induction-disc relay* operates on the principle of the induction motor. As illustrated with Fig. 11-1e, currents displaced in time flowing through coils displaced in space give rise to a moving magnetic field which passes through the movable disc. This moving magnetic field sets up within the disc currents which result in force action on the disc, tending to make it rotate. In this type of relay the coils above the disc may carry one current and the coils below the disc carry another current independently. If these currents are displaced from each other by the angle Δ, the torque produced on the disc is

$$T = K_D I_1 I_2 \sin \Delta \tag{11-2}$$

If the two sets of coils are in series and so carry the same current, no torque results. However, a resistor or a capacitor in parallel with one set of coils causes its current to shift out of phase with the other and so gives rise to torque. Other methods of phase shifting are used.

The coils of induction relays are usually provided with taps which enable the selection of pickup current. This permits proper protection coordination, as discussed later in the chapter, even after changes in load layout have taken place during years of service.

11-3. RELAY TIMING

Any of the basic relay types may be modified to control the time interval between the instant from relay pickup to the closing of the contacts. For the most part these modifications consist of mechanical accessories associated with the relays.

a. Instantaneous. An *instantaneous relay* is one in which no intentional time delay has been provided. Figure 11-2a represents an instantaneous solenoid type of relay. Certainly there will be a short time interval between the instant of pickup and the opening or closing of the contact, but no intentional time delay has been added.

b. Inverse Time. An *inverse-time solenoid relay* is shown in Fig. 11-2b. A dashpot (either hydraulic or pneumatic) attached to the moving

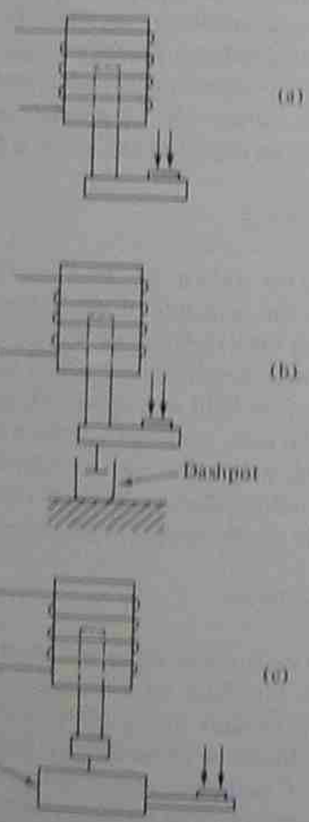


FIG. 11-2. Relay timing mechanisms. (a) Instantaneous. (b) Inverse time. (c) Timed.

plunger slows its upward motion. At a current value just equal to pickup the plunger moves slowly and the time delay is at a maximum. At higher values of coil current, the pull on the plunger is greater and the time delay is shortened. Each increase in current shortens the time delay, hence the name, inverse time relay.

In the induction-disc relay, inverse time delay may be introduced by positioning a permanent magnet so that its field penetrates the disc. When the disc moves, currents set up in it produce a drag on the disc, which slows its motion.

c. Timed. In some applications it is desirable to have a definite time interval between the instant of pickup and the closing of contacts. This may be accomplished as shown in Fig. 11-2c, in which the movement of the plunger of the relay trips a clock escapement mechanism. This mechanism, after a definite preset time, causes operation of the relay contacts.

Various other schemes of relay timing are in use. In some instances relays are equipped with mechanisms to control the time interval between the instant of dropout conditions in the coil to the restoration of contacts in their normal position. The use of time delays in both trip and restore is illustrated in some of the examples later in the chapter.

11-4. RELAY-SYSTEM EXAMPLES

Several examples will be presented to show some of the principles of applications of relays to the control of circuits. Special types of relays to be discussed later will be applied to more complicated systems.

A simple relay system is shown in Fig. 11-3. The output of a light-sensitive photovoltaic cell is connected to the coil of a moving-armature relay. When light strikes the cell the relay picks up, closing contacts and completing the circuits from the battery through the motor. If the light decreases to such a value that the current in the coil is below the release value, the armature returns to the normal position opening the contacts of the relay

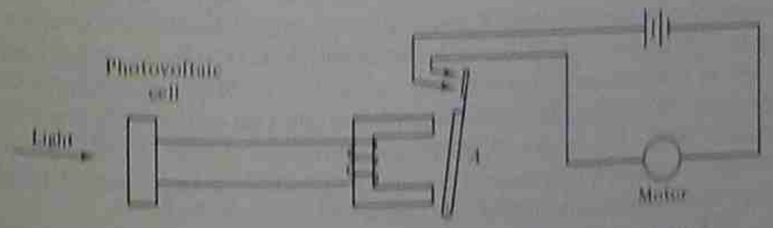


FIG. 11-3. A relay system by which a photo cell controls the operation of a motor.

and deenergizing the motor. It is evident that by replacing the relay with one in which the contacts were closed in the normal position and open in the operate position, the sequence of events could be reversed. With light on the cell the motor is shut down and runs only when the cell is dark.

Figure 11-4 is a modification of Fig. 11-3, in which a solenoid type of relay has been added in a connection by which it serves as a seal-in relay.

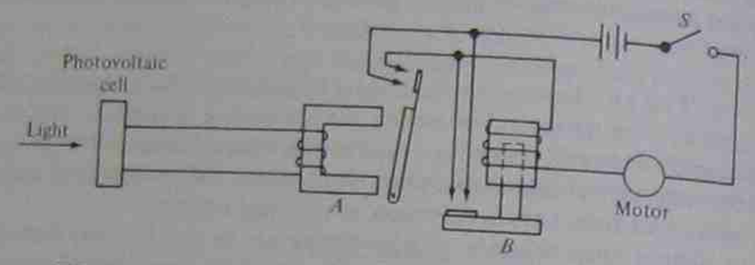


FIG. 11-4. A system similar to that of Fig. 11-3 but with the addition of a seal-in relay.

Note that when relay *A* closes contacts, the current from the battery to the motor must flow through the operating coil of relay *B*. When its contacts close, it short-circuits the contacts of relay *A*, making further operation of that relay of no consequence. Relay *B* will remain in the contacts closed position until switch *S* is opened, interrupting the current to the motor and to the coil of relay *B*. Seal-in relays have many applications in the electric power field.

A third example of relay applications is shown in Fig. 11-5. Three independent circuits may be identified in this diagram. The first is a power circuit connecting the generator to the load. A circuit breaker provides a means for opening this circuit. A current transformer provides a small sample of the power current to the relay coil, I. A potential transformer provides a small sample of the potential of the power circuit to the coil of relay II. The movable contacts of the circuit breaker are carried on an insulating operating rod, which in turn is provided with other devices. A second circuit provides a connection between battery *X* and a solenoid-operated latch on the operating rod. In normal conditions with the circuit breaker closed, relays I and II are in the contacts-open position, while the auxiliary contacts on the operating rod are closed. In parallel with the trip coil of the latch is another solenoid relay, III, whose contacts are normally closed. A third circuit provides a connection through a manually operated closing switch *T* to the circuit-breaker closing solenoid.

If the breaker is open, it may be closed by momentarily closing switch *T*, thus energizing the closing solenoid and lifting the operating rod into the

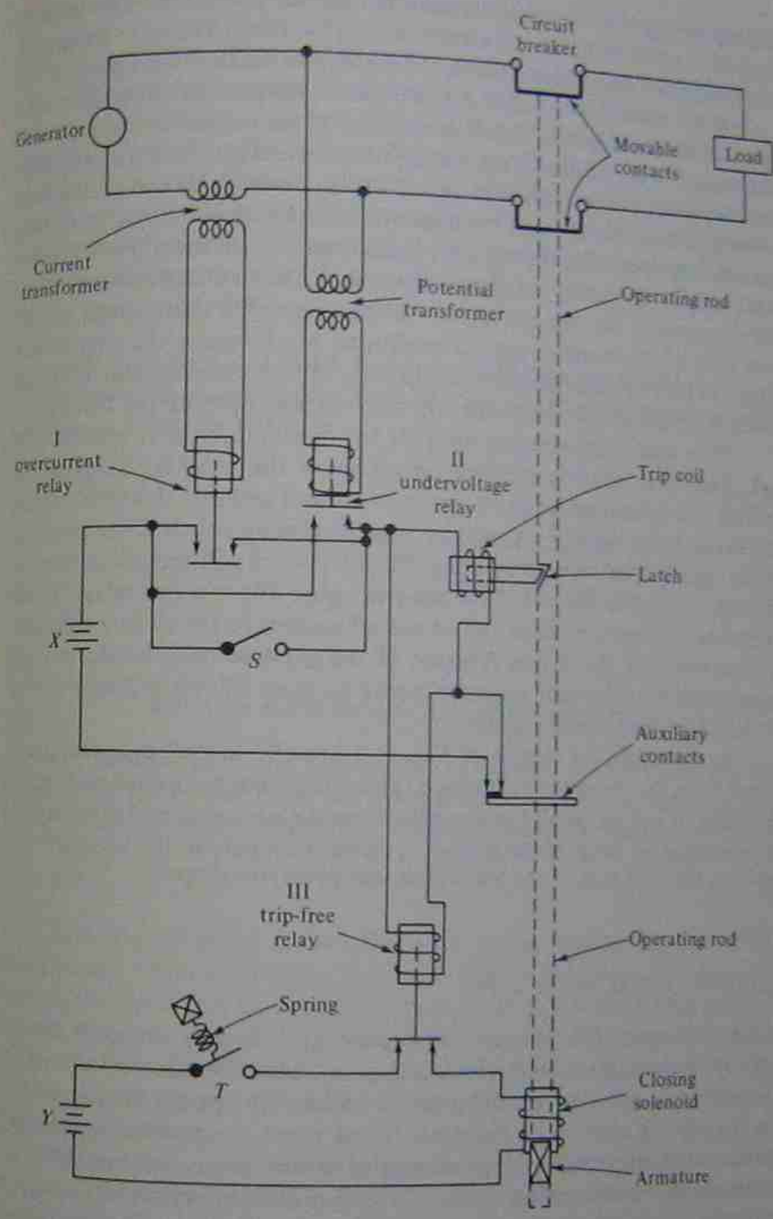


FIG. 11-5. A system for opening and closing a circuit breaker.

latch position, simultaneously closing the auxiliary contacts. The breaker may be opened manually by closing switch *S*, which connects battery *X* to the trip coil and triggers the latch, letting the breaker fall open.

If the breaker is closed, it may be opened automatically on the occurrence of abnormal power circuit conditions. If the current is too high, the over-current relay I will pick up, closing contacts and thus energizing the trip coil. Similarly, if the breaker is closed and the voltage of the circuit goes below a predetermined value, the undervoltage relay II will drop out, closing contacts and energizing the trip coil. In each case, when the trip coil is energized and the operating rod moves downward, the auxiliary contacts open, thereby opening the trip-coil circuit. In the event of a short circuit on the load side of the breaker, circuit conditions would cause the overcurrent relay I to pick up and the undervoltage relay II to drop out, either of which could complete the circuit to the trip coil, thereby opening the breaker.

Note that circuit-opening relay III has its coil in parallel with the trip coil. This is to provide trip-free operation of the breaker. Suppose the breaker has opened under short-circuit conditions and that this short circuit still exists. If the breaker is closed by hand by closing switch *T*, the presence of the fault will be detected by relays I and II, which will provide current to the trip coil and to the coil of the *trip-free relay*. The trip-free relay, III, on operating will open contacts and so cut off current to the closing solenoid. A time delay on the restore function of the trip-free relay would provide opportunity for the station operator to take his hand off switch *T* before relay III falls back into closed position.

In summary, the circuits of Fig. 11-5 provide control over the power circuit from the generator to the load. This circuit can be opened and closed manually. It will be opened automatically on the occurrence of overcurrent, undervoltage, or both. If the breaker is closed manually in the presence of a fault on the load side of the breaker, it will promptly reopen.

11-5. FUNCTIONAL RELAY TYPES

Basic relay types were presented in Section 11-2. It may be noted that in each of these relays a single force exists to cause operation of the relay. In more advanced types, several different forces may operate simultaneously on the moving element of the relay. These more complicated relays may serve special functions in the protection of electric power systems. Most of these special-function relays are produced by modifying either of two types of basic relays: the balance beam or the induction disc. The discussion presented here refers to the balance-beam type of relay.

Three types of coil arrangements may be used to influence the beam position. The first is a fixed coil wound with many turns of wire across which

normal circuit voltage might be impressed, which will be called a voltage coil. This coil, when energized, produces a force on an armature attached to the beam. The second, a fixed coil with a small number of turns of relatively large wire designed to carry continuously a current of at least 5 amperes, will be designated as a current coil. The current coil will operate on an armature attached to the balance beam. The third type of arrangement, designated the watt element, consists of a fixed current coil positioned to interact with a movable potential coil attached to the beam. A voltage coil, a current coil, and a watt element may be used individually or in combination on a single balance beam. In some cases a spring will be attached to the balance beam to provide a restraining force.

a. Voltage Coil and Spring. A balance beam with a voltage coil and spring is shown in Fig. 11-6. The torque that is set up electrically, which tends to tip the beam, is

$$T_e = K_e V^2 \tag{11-3}$$

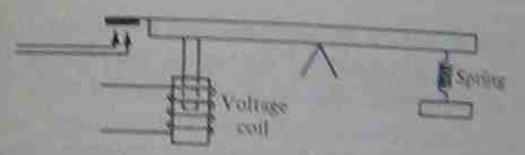


FIG. 11-6. A balance beam relay, voltage controlled.

where K_e depends upon the construction of the coil, the armature, and the length of the lever arm. When the beam is in the equilibrium condition, the torque produced by the spring T_s is exactly equal to the electric torque, or

$$K_e V^2 = T_s \tag{11-4}$$

As a starting point, assume that with normal voltage on the coil the forces on the beam are exactly balanced. Now if the spring tension is increased, the beam tips clockwise and remains in this position with normal voltage. However, if the voltage is increased, a point will be reached where the electric torque exceeds the spring torque and the beam tips counterclockwise, closing the relay contacts. This then provides the structure of a relay for detecting *overvoltage*.

Beginning again with normal voltage and with the beam in the balanced position, let the spring tension be decreased until the beam tips counterclockwise. It remains counterclockwise as long as the voltage is of normal value. However, if the voltage is reduced, a point is reached at which the beam rotates in a clockwise direction. This, then, is a structure by which *undervoltage* may be detected.

b. Current Coil and Spring. A balance beam with a current coil and spring is shown in Fig. 11-7. The torque produced by the current coil T_c is

$$T_c = K_c I^2 \tag{11-5}$$

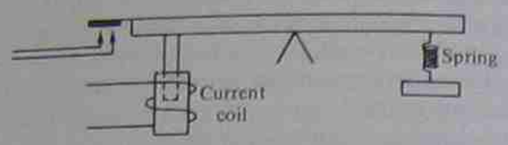


FIG. 11-7. A balance beam relay, current controlled.

The electric torque is equal to the spring torque T_s and the beam is balanced when

$$K_c I^2 = T_s \tag{11-6}$$

By the same arguments as were presented in Section 11-5a, it may be shown that by proper adjustment of the spring, the relay of Fig. 11-7 may become either an overcurrent relay or an undercurrent relay.

c. Watt Element and Spring. A balance beam with two mutually interacting coils and a spring is shown in Fig. 11-8a. The electrically generated torque was given by Eq. (11-1) as

$$T = K_M I_1 I_2 \cos \Delta \tag{11-1}$$

In the application to be considered here, coil 1 may be made of many turns of fine wire and be connected across a voltage supply V through a series impedance Z_s. The current I_1 will then lag the voltage V by some angle, depending on the total impedance of the series circuit made up of the coil and the impedance Z_s. Assume that the current I_1 lags the voltage V by the angle θ (Fig. 11-8b). If the current I_2 lags the voltage V by the angle ϕ, currents I_1 and I_2 are separated by the angle $\phi - \theta$, and the electrically generated torque is

$$T_e = K_e V I_2 \cos (\phi - \theta) \tag{11-7}$$

where $K_e V = K_M I_1$.

When the beam is balanced, the electric torque is equal to the spring torque

$$K_e V I_2 \cos (\phi - \theta) = T_s$$

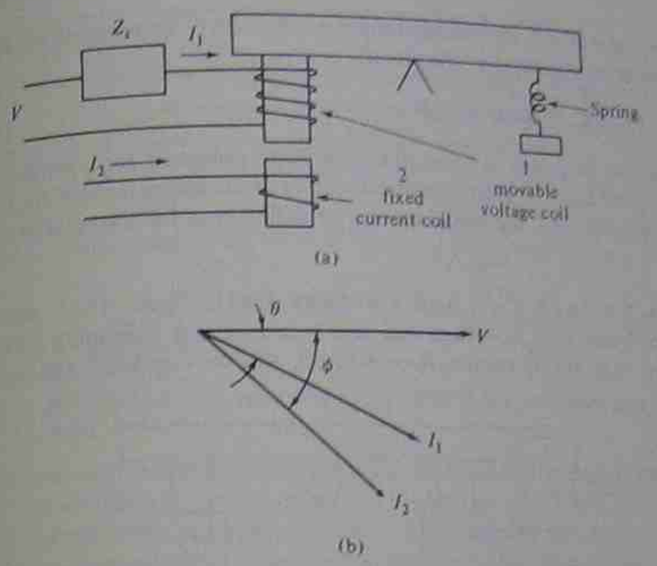


FIG. 11-8. A balance beam relay with mutually interacting coils.

Again by proper adjustment of the spring, the relay can be made to operate on either an excess value or a deficiency of the electrically generated torque. The voltage coil may be connected to any potential terminals and the current coil may be connected into any current-carrying conductor. The electric torque nevertheless will be as given by Eq. (11-7). Two mutually interacting coils with this arrangement are commonly termed a *watt element*.

If the current and voltage coils of a watt element are connected to a power circuit as shown in Fig. 11-9, in which Z_s is chosen of such a value

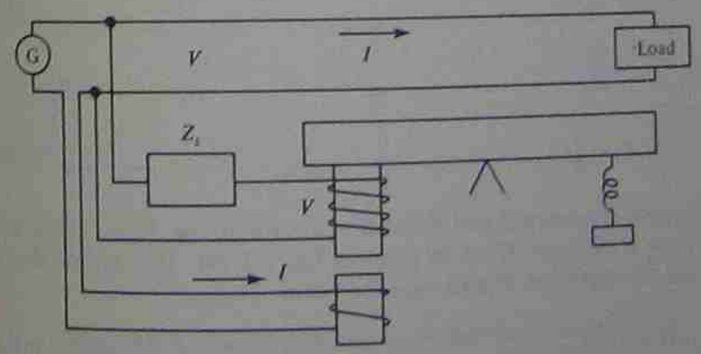


FIG. 11-9. A balance beam relay connected to respond to the interaction of the current and voltage in a power circuit.

as to make $\theta = 0$, the electric torque produced will be proportional to the power being delivered by the circuit:

$$T_e = K_e VI \cos\phi = K_e P \tag{11-8}$$

If the flow of power reverses, the electrically generated force on the relay will reverse and will be in the same direction as the spring force. If the spring force is made zero, the relay becomes an indicator of the direction of power flow.

d. Voltage Coil and Current Coil. Figure 11-10 shows a balance beam with a voltage coil and a current coil generating opposing torques. Any spring torque, if used at all, will be very small and may be

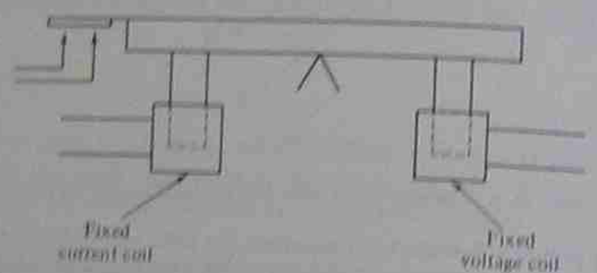


FIG. 11-10. A relay actuated by a current coil and restrained by a voltage coil.

neglected. The beam is balanced when the torque produced by the current coil is equal to the torque produced by the voltage coil. The contacts close when

$$K_i I^2 > K_v V^2$$

$$\frac{V^2}{I^2} < \frac{K_i}{K_v} \tag{11-9}$$

$$\frac{V}{I} < \sqrt{\frac{K_i}{K_v}} \tag{11-10}$$

If this relay is connected into a circuit as shown in Fig. 11-11, the contacts will close if the ratio V/I is as given in Eq. (11-10). This means that for balance the impedance Z must have the value

$$Z_B = \sqrt{\frac{K_i}{K_v}} \tag{11-11}$$

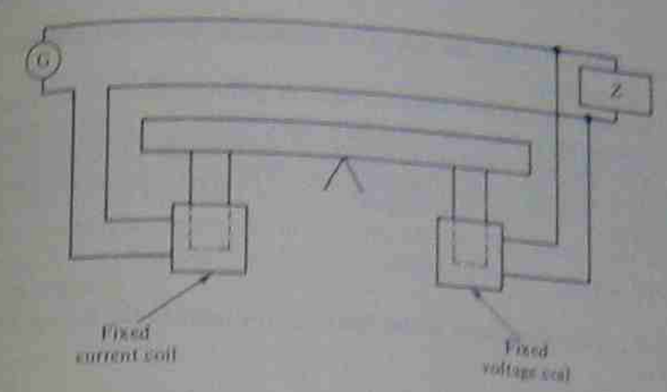


FIG. 11-11. A relay responsive to the value of the impedance in a power circuit.

If the value of Z present in the circuit is Z_B, the beam will be exactly balanced. If Z is greater than Z_B, the beam will tip to the right. If it is less than Z_B, the beam will tip in the opposite direction. Thus this relay properly connected is able to sense if circuit impedance is greater or less than some specified value. It is known as an *impedance relay*.

An application of this relay when connected into a power system may be illustrated by reference to Fig. 11-12. The system consists of two generating stations joined by an overhead line. Loads are not shown. Near the center of the line a relay is connected with its current coil in series with the line and

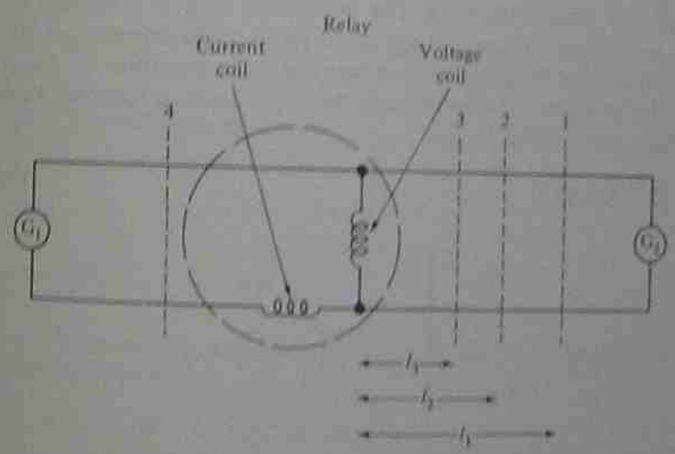


FIG. 11-12. A power system with an installed impedance relay. The relay is responsive, dependent on the location of the fault.

its potential coil across the line. For simplicity, instrument transformers have been omitted.

Suppose that a short circuit occurs at point 1, distance l_1 from the relay, making the voltage between conductors zero at that point. Generators G_1 and G_2 will supply current to the fault, but only the current I_1 from G_1 will flow through the current coil of the relay. The voltage across the potential coil will be

$$V_r = I_1 Z_{l1} \tag{11-12}$$

where Z_{l1} is the impedance of the line from the relay to the fault point. Its value is

$$Z_{l1} = l_1 z_u \tag{11-13}$$

in which z_u is the impedance per unit length of line.

At some particular length of line, l_2,

$$l_2 z_u = Z_B = \sqrt{\frac{K_i}{K_v}} \tag{11-14}$$

With the fault at position 2, the relay beam will just balance. If the fault is moved to position 3, the relay beam will tip to the left (Fig. 11-10) to close contacts. It is seen, therefore, that the relay will close contacts for any fault less than distance l_2 from the relay location. It will also respond to a fault at position 4, in which case only short-circuit current I_2 supplied by generator G_2 will pass through the relay. The impedance relay is influenced by the scalar value of the voltage and the scalar value of the current and is in no way influenced by the phase relation between these quantities.

The impedance of a line is made up of two parts, a real part R and an imaginary part jX (Fig. 11-13):

$$Z = R + jX \tag{11-15}$$

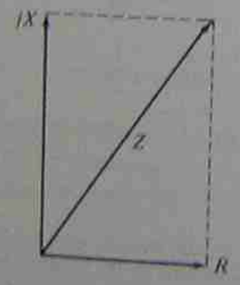


FIG. 11-13. An impedance diagram showing R, X, and Z.

However, the relay responds only to the scalar value of the impedance:

$$Z = \sqrt{R^2 + X^2} \tag{11-16}$$

The operating characteristics of the impedance relay may be displayed on an R–X diagram as a circle of radius Z_B, centered at the origin, as shown in Fig. 11-14. At any time that the voltage on the potential coil of the relay and the current through the current coil of the relay are such as to indicate an impedance that falls within the circle, the beam of the relay will tip to the left and so close contacts.

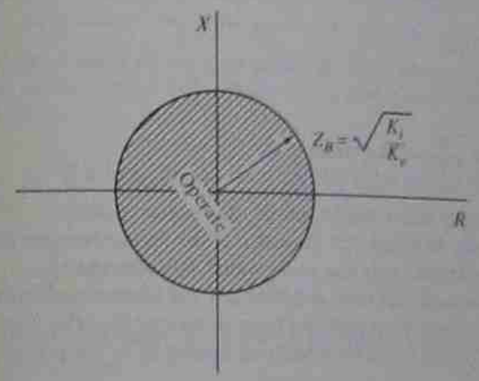


FIG. 11-14. A diagram in the R-X plane showing the region of operation of an impedance relay.

EXAMPLE 11-1. Suppose that an impedance relay is designed with characteristics

$K_i = 128$ newton-meters/ampere^2

$K_v = 2$ newton-meters/volt^2

Then

$$Z_B = \sqrt{\frac{128}{2}} = \sqrt{64} = 8\ \Omega$$

Let it be connected, as shown in Fig. 11-12, into a circuit in which the impedance per unit length is

$$z = 0.2 + j0.75 = 0.77\ \underline{/75^\circ}\ \Omega/\text{mile}$$

If a short circuit occurs at position 1, a distance

$l_1 = 15$ miles

the impedance of the line from the relay to the fault point is

$$Z_{11} = 0.77 \times 15 = 11.5\ \Omega$$

As this is greater than the value of Z_B, the relay will not operate.

Next suppose that the fault is at position 3, distance 4 miles from the relay. The impedance of the line from the relay to the fault point is

$$zl_3 = 0.77 \times 4 = 3.08\ \Omega$$

As this value is less than Z_B, the relay will operate.

If the fault point is at a distance l_2 from the fault such that

$$Z = zl_2 = Z_B$$

then

$$l_2 = \frac{Z_B}{z} = \frac{8}{0.77} = 10.4 \text{ miles}$$

Now the relay beam will be just at the balance point.

It may be noted that the angle of the line impedance did not enter into the computations; only the *scalar* value was considered.

If the fault had been at position 4, the short-circuit current through the relay would have been supplied from generator G_2. The voltage on the relay, and its response, could have been calculated as in the previous cases.

e. Voltage Coil and Watt Element. A balance beam relay may be constructed with a voltage coil and a watt element as indicated in Fig. 11-15. The beam will tip to the left when

$$K_w V_P I \cos(\phi - \theta) > K_v V_v^2 \tag{11-17}$$

This type of relay might be connected as shown in Fig. 11-16. Now

$$V_P = V_v = V$$

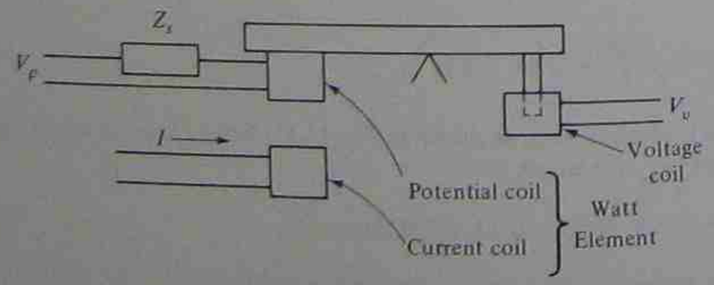


FIG. 11-15. A relay actuated by a watt element and restrained by a voltage coil.

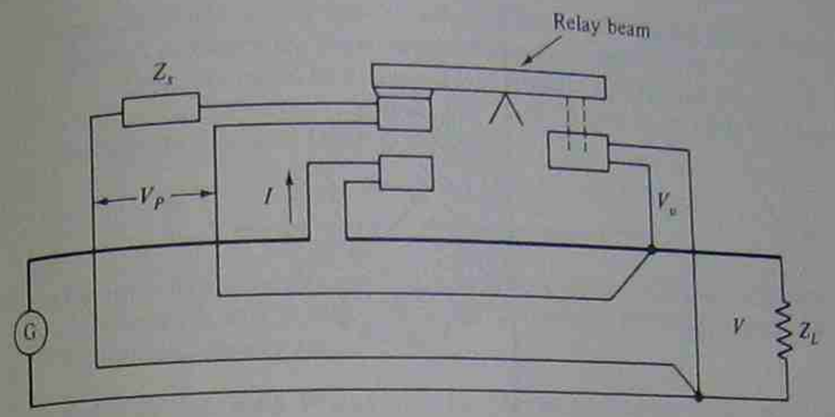


FIG. 11-16. A relay of the type shown in Fig. 11-15 connected to respond to the current and voltage of a power system. The circuit connection.

Solving (11-17) for the impedance seen by the relay under the condition of balance we find

$$\frac{V}{I} < Z_B = \frac{K_w}{K_v} \cos(\phi - \theta) \tag{11-18}$$

If Z_s is chosen such that the current in the potential coil is in phase with the voltage V_1, then

$$\theta = 0 \tag{11-19}$$

and

$$Z_B = \frac{K_w}{K_v} \cos\phi \tag{11-20}$$

It is seen that the magnitude of Z_B depends on ϕ, the angle between the current and the voltage associated with the load impedance Z_L. ϕ is, in fact, the angle of this impedance. Equation (11-20) is the polar form of a circle which when drawn on an R–X diagram appears as shown in Fig. 11-17. The circle passes through the origin and has a diameter K_w/K_v.

EXAMPLE 11-2. Suppose that the relay in Fig. 11-16 has the constants

$K_w = 50$

$K_v = 0.5$

The diameter of the circle (Fig. 11-17) is 100. If the load impedance Z_L has the value

$Z = 90 + j0$

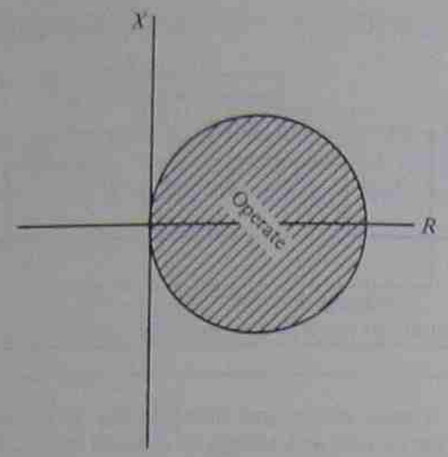


FIG. 11-17. The region of operation of the relay of Fig. 11-16 for $\theta = 0$.

its value falls within the circle and the relay will operate. On the other hand, if the load impedance Z_L is

$$Z = 0 + j20$$

its value falls outside the circle and the relay will *not* operate.

If Z_s is of such a value that θ is not zero, the circle shifts as shown in Fig. 11-18 with diameter unchanged and still passing through the origin.

If a relay of this type is used to detect short circuits in a line section, it may be desirable to adjust Z_s to such a value that

$$\theta = \tan^{-1} \frac{X_{line}}{R_{line}} \tag{11-21}$$

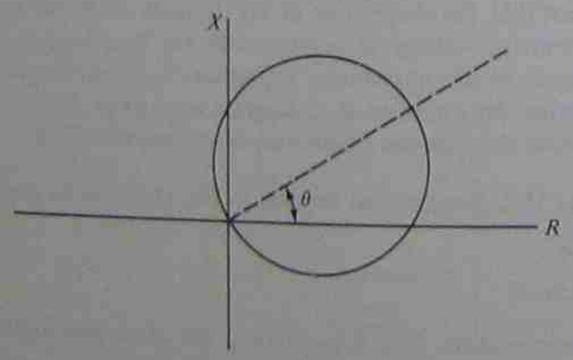


FIG. 11-18. The region of operation of the relay of Fig. 11-16 with θ nonzero.

Then the Z of the line, for any value of line length, will fall on the circle diameter, providing the situation with the most reliable response.

This relay might be connected into a system with two power sources in a fashion similar to that shown in Fig. 11-12. It may be seen that the relay responds for values of l such that

$$0 < lz < \frac{K_w}{K_v} \tag{11-22}$$

The relay does not respond if lz is greater than K_w/K_v, and it does not respond if l is negative, that is, if $\phi - \theta > 90°$. This relay is sometimes spoken of as a *directional distance relay*.

f. Current and Watt Coils. A balance-beam relay may be constructed with a current coil and a watt element as shown in Fig. 11-19.

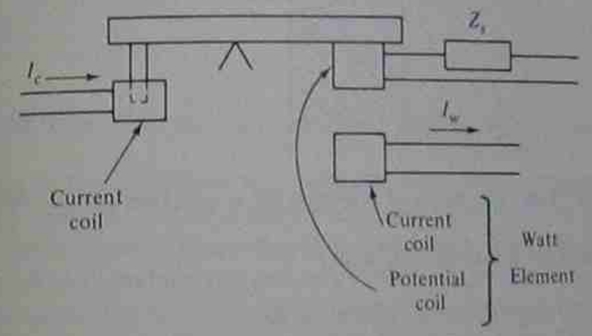


FIG. 11-19. A relay actuated by a current coil and restrained by a watt element.

When forces are balanced,

$$K_i I_c^2 = K_w V I_w \cos(\phi - \theta) \tag{11-23}$$

If the two current coils are in series so that $I_c = I_w = I$, then

$$\frac{K_i}{K_w} = \frac{V}{I} \cos(\phi - \theta)$$

$$\frac{K_i}{K_w} = Z \cos(\phi - \theta) \tag{11-24}$$

If Z_s is chosen such that

$$\theta = 0 \tag{11-25}$$

$$\frac{K_i}{K_w} = Z \cos\phi = R \tag{11-26}$$

When a relay of this type is connected in a power circuit supplying an impedance Z_L, the balance point is determined by the resistance component of the impedance, the reactive component producing no influence. The performance characteristic may be shown on an R–X diagram (Fig. 11-20). From this it is seen that the relay will respond under all conditions in which current and voltage values indicate a resistance of any value less than K_i/K_w, including negative values.

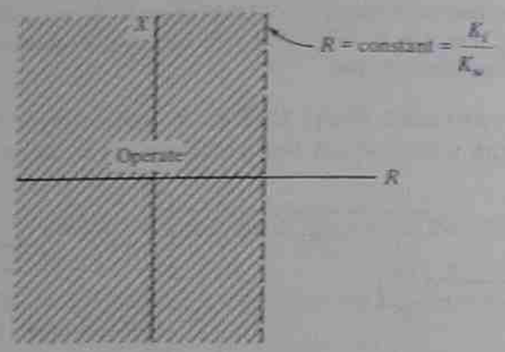


FIG. 11-20. The region of operation for a resistance distance relay.

If this relay is adjusted to make

$$K_i = 10 \text{ N-m/A}^2 \qquad K_w = 5 \text{ N-m/W}$$

then $R = 2\ \Omega$.

Such a relay would close contacts in a circuit in which the voltage and the current were of such magnitudes and phase position as to make the impedance seen by the relay appear to be $1.2 + j20$. It would not close contacts if the impedance was $2.2 + j1.0$. A current and voltage condition that makes the impedance appear to be $-2.2 - j1.0$ would cause relay operation. This relay might be termed a *resistance distance relay* because it is responsive to particular values of resistance in the circuit to which it is connected.

If the impedance Z_r of the watt element is made highly inductive such that

$$\theta = 90° \tag{11-27}$$

$$\frac{K_i}{K_w} = Z \cos(\phi - 90)$$

$$\frac{K_i}{K_w} = Z \sin \phi = X \tag{11-28}$$

The response of this relay is as shown in Fig. 11-21. The relay will operate for all values of X less than K_i/K_w, including negative values. This is known as a *reactance distance relay*.

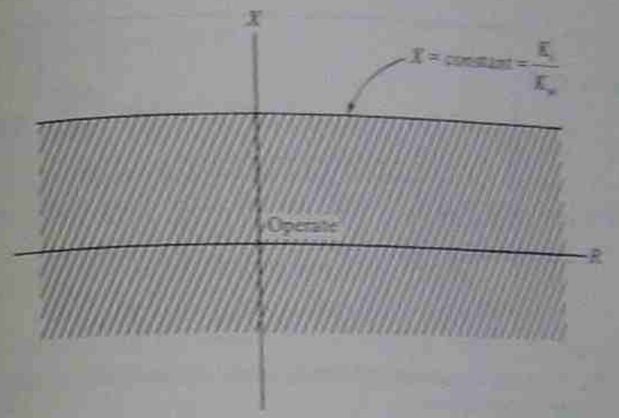


FIG. 11-21. The region of operation of a reactance distance relay.

Relays of this type have an advantage when used to measure the distance to the point of fault on a transmission line. The inductive reactance of a faulted line is directly proportional to line length. The resistance of the faulted circuit may include the resistance of the arc at the fault point and, in some instances, the resistance of a tower footing or other connections to the earth (see Chapter 13). Hence a distance measurement by a reactance relay is more reliable than a measurement made by a simple impedance relay. For example, a reactance relay would give the same response to an impedance of $Z_1 = 2 + j12$ as to an impedance of $Z_2 = 15 + j12$.

11-6. RELAY CONNECTIONS TO POWER EQUIPMENT

In Section 11-5 the relay current coils were shown connected in series with the power circuits while the potential coils were connected directly across the power-circuit terminals. These direct connections would be found only in low-voltage, low-power circuits. As indicated earlier, most instrument current coils are designed for nominal operation at 5 amperes; most potential coils are designed for nominal operation at 120 volts. If power-system values exceed these standard values, instrument transformers or similar devices must be employed. Figure 11-22 shows a balance-beam impedance relay connected to a 24-kV power circuit. A 300/5-ampere current transformer provides a current of appropriate value to the current coil of the relay. A 24,000/120-volt potential transformer provides voltage of proper value to

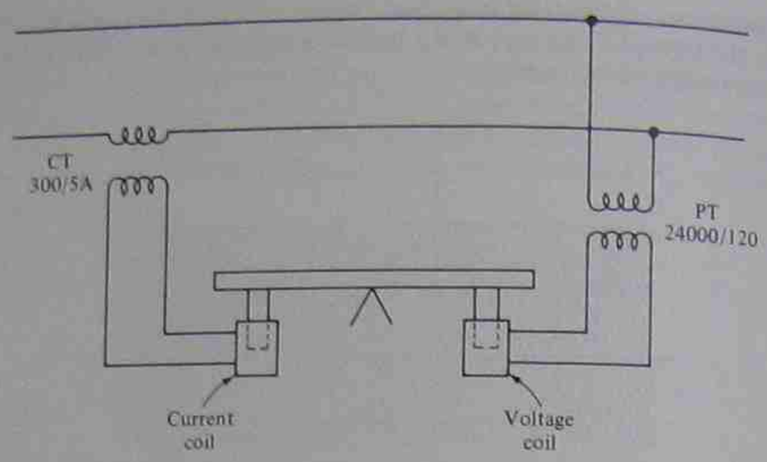


FIG. 11-22. An impedance relay connected to a power circuit through instrument transformers.

the potential coil of the instrument. For such an arrangement we may write

$$V_{line} = V_{relay} K_{pt} \tag{11-29}$$

$$I_{line} = I_{relay} K_{ct} \tag{11-30}$$

where K_{pt} and K_{ct} are the potential transformer ratio and the current transformer ratio, respectively. The apparent impedance of the line as indicated by voltage and current in the line is

$$Z_{line} \frac{V_{line}}{I_{line}} = \frac{V_{relay} K_{pt}}{I_{relay} K_{ct}} \tag{11-31}$$

Equation (11-32) shows the relations between the impedance of the line as indicated by its voltage and current, and the impedance seen by the relay as indicated by the voltage and current impressed across it.

$$Z_{line} = Z_{relay} \frac{K_{pt}}{K_{ct}} \tag{11-32}$$

In the example shown in Fig. 11-22, a fault at some distance from the station might result in a current of 5000 amperes simultaneously with a voltage of 7500 volts. This would indicate a power-line impedance to the point of fault of

$$Z_L = \frac{V}{I} = \frac{7500}{5000} = 1.5\,\Omega$$

On the relay, the voltage would be

$$V_{relay} = \frac{V_{line}}{K_{pt}} = \frac{7{,}500}{24{,}000/120} = 37.5\text{ V}$$

and the relay current would be

$$I_{relay} = \frac{I_{line}}{K_{ct}} = \frac{5000}{300/5} = 83.3\text{ A}$$

(if there is no ratio error. See Fig. 10-7.)

The impedance seen by the relay due to conditions at its terminals is

$$Z_{relay} = \frac{V_{relay}}{I_{relay}} = \frac{37.5}{83.3} = 0.45\,\Omega$$

Applying Eq. (11-32), the impedance of the line may be recalculated from relay values and instrument transformer ratios as

$$Z_L = 0.45 \frac{24{,}000/120}{300/5} = 1.5\,\Omega$$

the correct value.

Other types of relays might be similarly connected to the power system through instrument transformers. The performance of the relays as determined by the electrical quantities supplied to them may be interpreted in terms of the performance of the power equipment by a suitable consideration of the instrument transformer ratios.

11-7. PROTECTION OF GENERATORS

This section presents for illustration several schemes for protecting generators by relays which are able to detect improper circuit behavior. Various other schemes are in use. The systems presented are somewhat oversimplified, for in each case instrument transformers are shown connected to the relays in the simplest arrangement possible. Actually several different types of relays may protect the same machine and one instrument transformer may supply several different relays as well as indicating instruments.

In previous discussions, current transformers were shown as two winding transformers (which they are), as indicated in Fig. 11-23a. For simplicity, henceforth current transformers will be indicated as shown in Fig. 11-23b. The diagram shows only the secondary of the transformer.

a. Generator Differential Protection. Current differential protection is a scheme by which the currents measured at two points

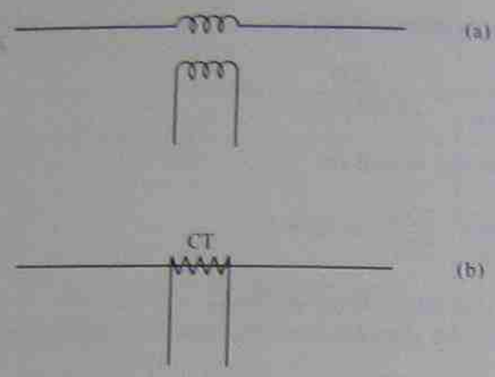


FIG. 11-23. Representation of a current transformer. (a) Two-winding representation. (b) Conventional representation.

are compared. These currents under normal conditions are equal but may become unequal on the occurrence of a fault. This scheme applied to one winding of a generator is shown in Fig. 11-24. A current transformer at the neutral end of the winding has its secondary connected in series with an identical transformer at the terminal end of the winding. A current relay is connected as shown. In normal operation the currents at both ends of the winding are equal and in phase. The secondary current around the loop then is the same at all points and no current flows through the relay coil.

If a fault develops at *M* (within the winding) which causes current to flow from the winding to the grounded frame or to another winding, the current at the neutral end differs from the current at the terminal end. The current in the secondary circuit to the left of the relay must correspond to the current in the neutral end of the winding, while the current to the right of

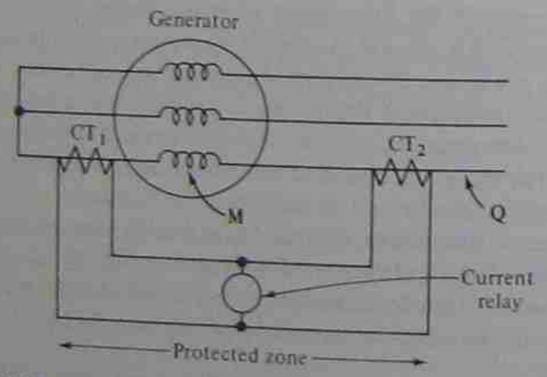


FIG. 11-24. Current differential protection of a generator. Protection on only one conductor is shown.

the relay must correspond to the current at the terminal end. The difference of these two currents must pass through the relay current coil. This relay then closes its contacts to clear the generator from the system. This usually involves opening the generator breaker, opening the field circuit, and closing the throttle on the prime mover driving the generator.

Note that this relay system responds to a ground fault at any point between CT_1 on the generator neutral and CT_2 on the machine terminal. The system does not respond to a fault at *Q*, for now the currents in CT_1 and CT_2 are identical and the difference current to the relay is zero. The region in which a fault causes operation of a relay is known as the *protected zone*.

The above arrangement assumes that the two current transformers CT_1 and CT_2 are identical, a situation that really never exists. If ratio errors in one are slightly different from those in the other, relay current may be present during normal operation and particularly during faults external to the generator. To avoid this difficulty, the relay is modified to respond to the differential current in terms of its fractional relation to the current flowing in the generator winding (Fig. 11-25). Thus under heavy load, a greater dif-

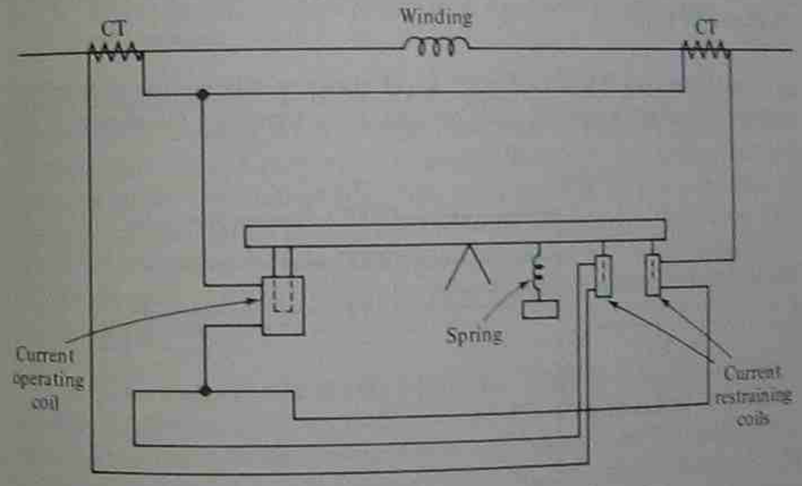


FIG. 11-25. A percent differential protection relay system.

ferential current through the relay operating coil is required for its operation than under light load conditions. Such a relay is termed a *percent differential relay*.

b. Split-Winding Protection. A balanced winding differential protection scheme may be used on large generators which have two parallel paths through the machine for each winding. As shown in Fig. 11-26,

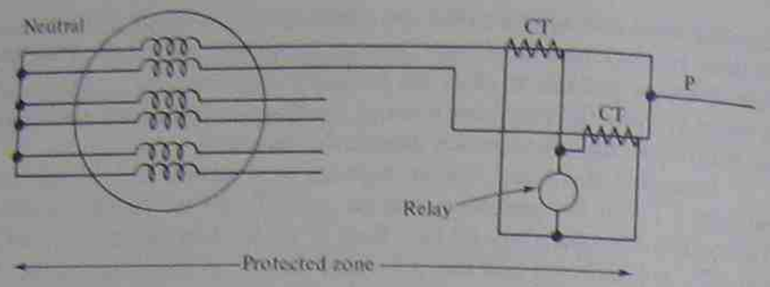


FIG. 11-26. Protection of a generator with two paths for each winding.

a current transformer connected in each branch of the winding permits a comparison of the path currents. If these two path currents differ by a predetermined amount, the relay operates to clear the generator from the system. A percent differential relay may be used in this application.

The protected zone for the system of Fig. 11-26 extends from the machine neutral to the current transformers on the machine terminals. A fault at *P*, outside the protected zone, will not cause operation of the relay shown. An additional relay system would be necessary to initiate the clearing of a fault at this point.

c. Ground Fault. Figure 11-27 shows a scheme for protecting a generator against a ground fault on one of its terminals (as shown by the

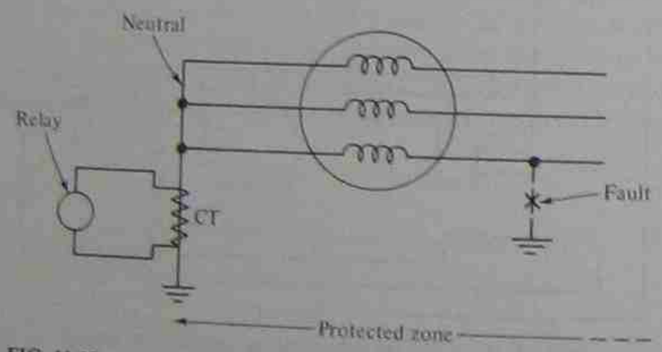


FIG. 11-27. Ground fault protection of a generator (neutral current measurement).

dashed line) or within the winding itself. Such a condition will cause current to flow in the neutral ground terminal, which will be detected by an overcurrent relay. The protected zone extends from the machine neutral to an indefinite distance out on the lines connecting directly to the machine terminals.

Another scheme for generator ground-fault protection is shown in Fig. 11-28. A potential transformer is connected between the generator neutral and ground. Across the secondary of this transformer is connected an impedance *Z* and an overvoltage relay, as shown. Under normal conditions, a small current flows in the impedance as unbalances in the power system

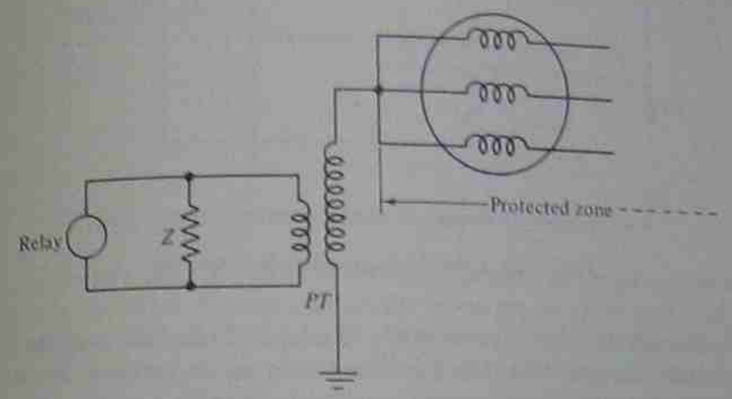


FIG. 11-28. Ground fault protection of a generator (neutral voltage measurement).

cause the machine neutral to be slightly different from zero potential. The voltage across the relay is low. On the occurrence of a ground fault, the machine neutral rises to a value equal to normal line-to-ground voltage, causing operation of the overvoltage relay. The relay operates for a ground fault at any point on the system directly connected to the generator terminals. This scheme of protection has the advantage that the current in the fault is low, being controlled in magnitude by the value of the impedance *Z* in the potential transformer secondary.

d. Ground-Fault Differential. Another scheme for generator-fault protection is shown in Fig. 11-29. The secondaries of each of the three current transformers connected at the terminals of the machine are connected in parallel. Under ordinary operation, the currents flowing in the generator leads and hence the currents flowing in the secondary windings add to zero and no current flows to the relay. Similarly, under normal conditions the neutral current is zero and no current is supplied by the neutral lead current transformer to the relay. If a ground fault develops at *A* external to the generator protective scheme, the sum of the currents at the terminals of the generator is exactly equal to the current in the neutral connection and the current supplied to the relay is zero. However, for a ground fault at *B* or within a winding, these currents are not equal and the difference current

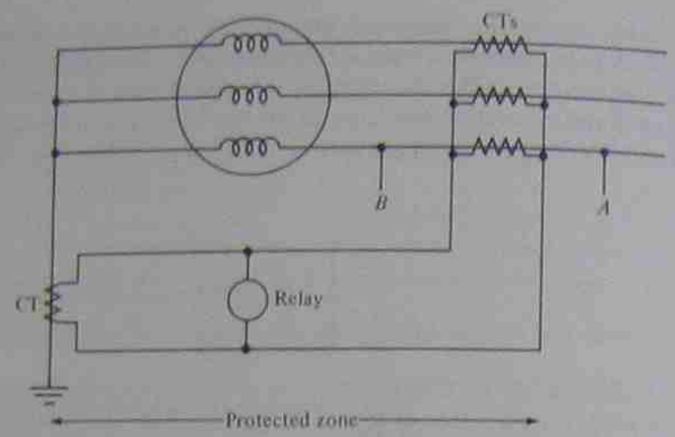


FIG. 11-29. Differential ground fault protection.

flows through the relay. Operation of the relay will clear the machine from the system. The protected zone is limited to the region between the neutral and the current transformers on the machine terminals.

c. Other Relay Schemes. Other relay schemes used for generator protection include overcurrent protection, reversed power, reversed vars, excess temperature, loss of bearing oil pressure, and many other abnormal operating conditions.

11-8. BUS PROTECTION

Two methods of bus protection are described: one a differential scheme, the other a fault bus scheme. Various other arrangements are in use.

a. Differential Protection. In normal operation the sum of all currents coming to a bus must equal zero. If the sum of these currents (for a given conductor) is not equal to zero, it must be concluded that there is an unwanted connection (short circuit) to ground or to another one of the three conductors. Figure 11-30 shows the scheme of protection for a bus fed by a generator and supplying two lines. The system is shown for the *A* conductor. Similar systems would be required for the other two conductors. The secondaries of the current transformers in the generator lead, in line 1, and in line 2 are all connected in parallel. The protective relay is connected across this parallel connection. A current in the relay indicates a fault within the protected region and initiates opening of the generator breaker and each of the line breakers.

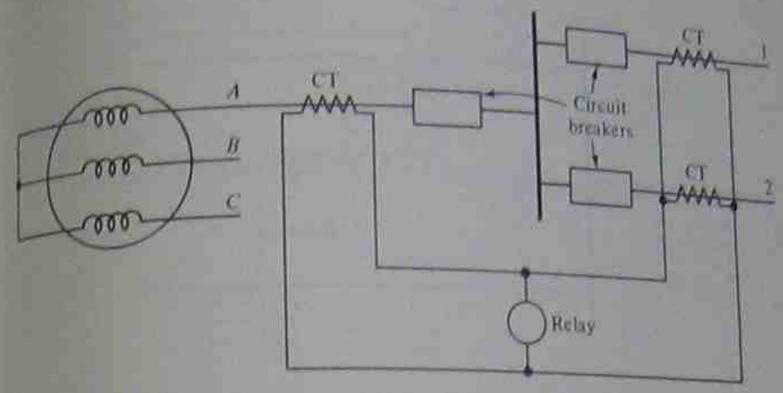


FIG. 11-30. Current differential protection of a station bus.

b. Fault Bus Protection. It is possible to design a station so that the faults which develop are entirely line-to-ground faults or at least the probability of such faults is much greater than the probability of line-to-line faults. Particularly on generator buses and other high-capability, relatively low voltage circuits, a grounded metal barrier may surround each conductor throughout its entire run in the bus structure. With this arrangement every fault that might occur must involve a connection between a conductor and a grounded metal part. A somewhat less certain arrangement may be obtained in open construction by making spacing between adjacent conductors great compared to spacing over insulators to ground. Again faults that occur will almost certainly be from a conductor to the supporting structure.

In each of the preceding cases the metal supporting structure, known as the fault bus, is grounded through a current transformer as shown in Fig. 11-31. A fault involving a connection between a conductor and the grounded supporting structure will result in current flow through this current transformer and actuation of the relay connected to its secondary. Operation of this relay will result in tripping all breakers connecting equipment to the bus. An impedance Z in series with the current transformer serves to limit the value of the short-circuit current during a line-to-ground fault.

11-9. TRANSFORMER PROTECTION

Transformers are very commonly protected by current differential schemes such as the one illustrated in Fig. 11-32. Neglecting exciting currents, the current in the primary of the transformer is related to the current in the secondary by the turns ratio. This ratio must be considered in selecting the current transformers for the current differential protective scheme. As shown

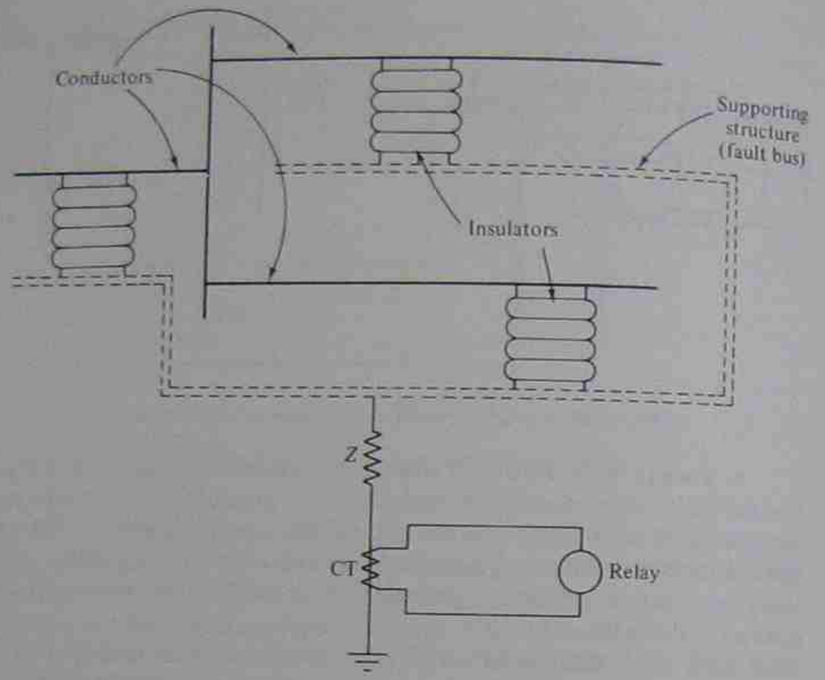


FIG. 11-31. Fault bus protection.

in the diagram, the current transformer on the 24-kV winding of the transformer has a rating of 1000/5 amperes. On the 120-kV side of the transformer the current transformer has a rating of 200/5 amperes. During normal loading, the secondaries of these current transformers carry identical currents and may be interconnected with a current differential relay, as shown in Fig. 11-32. If a fault develops within the transformer, the currents will not balance and the differential relay functions to clear the breakers on both sides of the transformer. The protected zone extends from the current transformers on the high-voltage side to those on the low-voltage side of the power transformer.

Current differential relays may function improperly on closing of the breaker (either high side or low side) to energize the transformer after it has been out of service. Depending on the condition of the residual magnetism left in the transformer core due to previous operation and the point on the wave at which the closing breaker makes contact, initial magnetizing currents may be quite large, as much as eight times normal full-load current. These initial in-rush currents quickly diminish in value to the normal no-load excitation currents. However, since these initial in-rush currents exist in one winding only, an unbalance of currents between primary and secondary

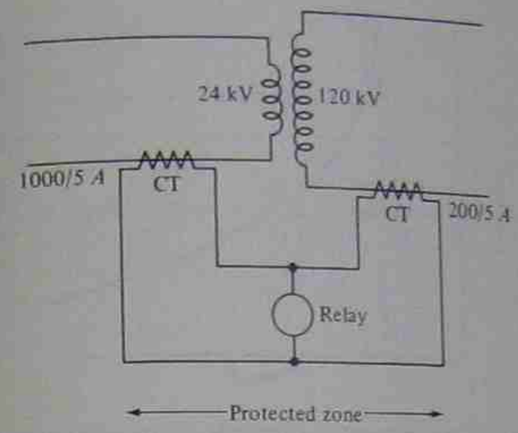


FIG. 11-32. Current differential protection of a transformer.

exists which may cause tripping of the differential relay. To avoid this improper tripping on closing, differential relays are sometimes made slow in operation for a few seconds following the closing of the breaker which reenergizes the transformer. In some systems, advantage is taken of the fact that initial in-rush currents are nonsinusoidal. Hence it is possible to design a relay system that discriminates between them and the nearly sinusoidal currents of a short circuit.

11-10. RELAY PROTECTION OF LINES

A great number of schemes are in use for the protection of overhead line and cable circuits. A few of these are discussed in this section. The descriptions presented pertain essentially to general principles rather than to details of the protection systems. In some cases two or more systems are used in combination to accomplish the desired selection. In other cases one complete system may be superimposed on top of another, both of which are capable of affording circuit protection. Duplicate, or redundant, protection systems are in use on many of the most important high-voltage circuits.

a. Inverse-Time Overcurrent Protection. As shown in Section 11-3b, a simple overcurrent relay may be modified to make its response time inversely proportional to the value of the current above minimum pickup. Such a relay has a performance characteristic curve, shown in Fig. 11-33. At values of current less than pickup, the relay never operates. At higher values the time of operation decreases steadily with increase of current.

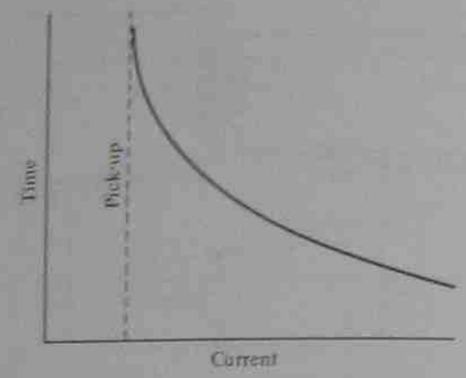


FIG. 11-33. The time-current characteristic of an inverse-current relay.

It is important to note that the melting time of the current-sensitive element in a fuse may be described by a characteristic similar to that of Fig. 11-33. At currents less than the normal rated value, the fuse will not blow. At currents above this value the current-sensitive element will melt, the time for melting being inversely related to the current value. For this reason, the present discussion of line protection by inverse-time overcurrent relays is equally applicable to circuit protection by fuses.

In applying relays for circuit protection, it is necessary to consider not only the time for the relay to operate but the time for the breaker to clear the fault after its trip coil is energized. In the case of the fuse, it is necessary to consider both the time to melt the fusible link and the time to clear the arc following the separation of contacts. These periods are shown diagrammatically in Fig. 11-34. It is important to note that in the relay–breaker combination (Fig. 11-34a) the operation is irretrievably initiated when the relay contacts close, although it is not completed until the arc in the breaker is interrupted. Similarly, in the case of the fuse (Fig. 11-34b), the fuse operation is irretrievably initiated when the fusible link melts, but the operation is not completed until the arc between the opening contacts is extinguished.

The importance of the behavior of breakers (or fuses) is made evident by considering the protection of a small power system supplied by a single source and provided with several sectionalizing points (Fig. 11-35). Although there may be loads at numerous points, their presence is neglected, the assumption being that currents due to faults are much greater than the normal-load currents.

In Fig. 11-35, sectionalizing points are indicated at *A*, *B*, and *C*. A protection scheme is desired in which, on the occurrence of a fault, a minimum interruption to the system results. For example, with a fault at *P*, the breaker (or fuse) at *C* should open. However, if it fails to clear, the breaker

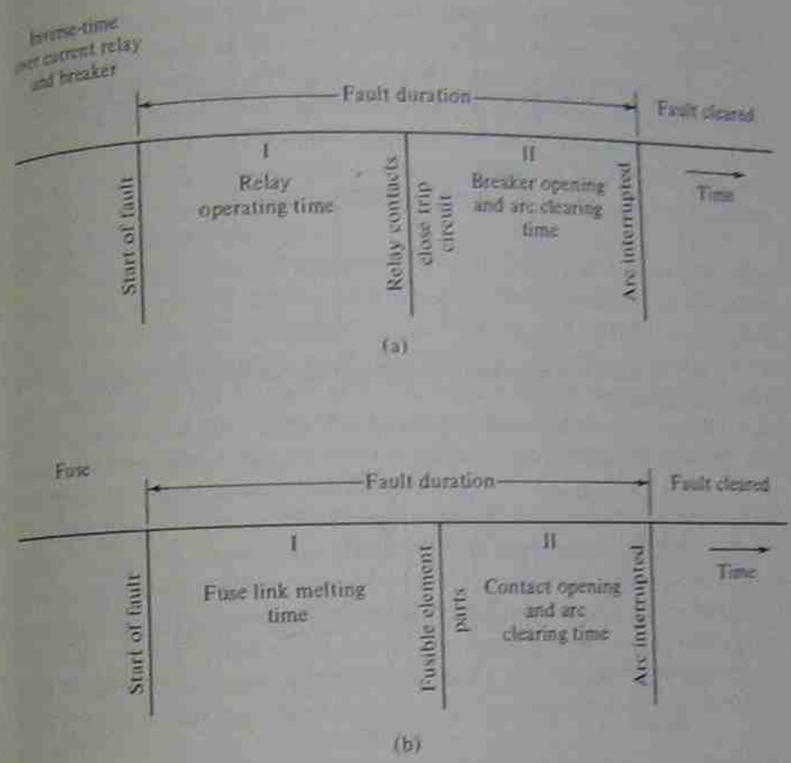


FIG. 11-34. Diagramatic representation of the sequence of events in clearing a fault. (a) Relay and breaker. (b) Fuse.

at *B* should open as backup protection. To accomplish this behavior, the relays at the three different locations require different trip settings. If fuses are used, the fuse characteristics must be similarly selected. The discussion from here on refers to a breaker-protection scheme, although all statements apply equally to a fuse-protection scheme.

Suppose the relays at points *A*, *B*, and *C* are given settings such that their performance characteristics are as indicated by (a), (b), and (c) of Fig. 11-36. The solid lines are the relay tripping times, whereas the dashed lines are obtained by adding the breaker clearing time, assuming it to be constant under all conditions.

Suppose that with a fault at *P* the short-circuit current is 100 amperes. The relay at *C* will close its contact in time T_1 and the breaker will clear the arc in time T'_1. With this same current the relay at *B* will close its contact at time T_2 and the breaker will clear the fault at time T'_2. The breaker at *A*

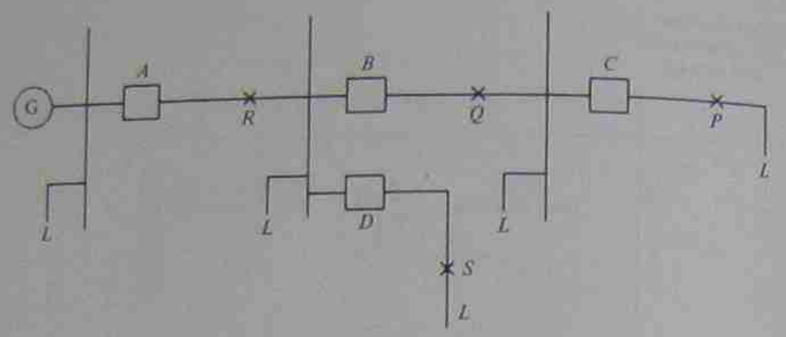


FIG. 11-35. A power system for describing relay selectivity and backup protection.

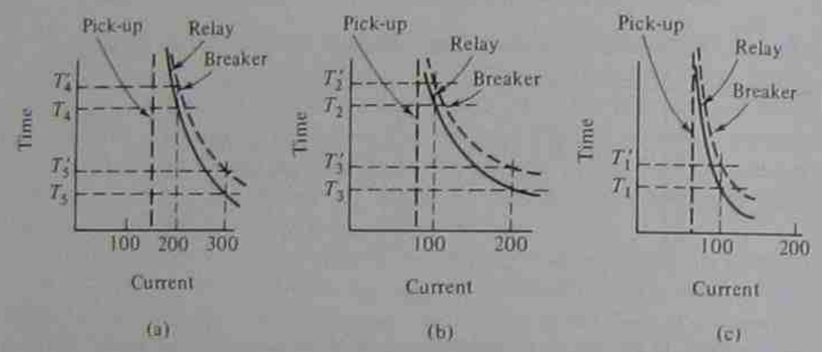


FIG. 11-36. The operating characteristics of the relay-breaker combinations of the system, Fig. 11-35.

would not operate with 100 amperes flowing in it, as this is less than the pickup current of the relay at A.

Note that the time T_1', the total fault-clearing time of the relay–breaker combination at C, is less than T_2, the relay time at B. If all equipment functions satisfactorily, the breaker at C operates to clear the fault and the breaker at B remains closed. However, if (due to a malfunction) the breaker at C fails to clear the fault, the breaker at B clears it in time T_2'. With this particular fault the breakers at B and C are properly coordinated. However, if T_1' had been greater than T_2, both breakers, B and C, would operate, interrupting unnecessarily any load connected between the two breakers.

A fault at Q results in a higher value of fault current, because the line impedance from the generator to the fault point is less than before. Assuming the fault current to be 200 amperes, the relay at B closes contacts in time T_3 and the breaker clears the fault at time T_3'. Similarly, with 200 amperes fault current the relay at A will close contacts in time T_4, and the breaker will

clear the fault in time T_4'. Since T_3' is less than T_4, the proper functioning of the breaker at B results in the fault being cleared before the relay contacts at breaker A are closed. Hence breaker A normally will not operate.

A fault at S on the branch circuit results in behavior similar to that at Q, except that breaker D should respond instead of breaker B.

A fault at R, with a fault current assumed to be 300 amperes, will result in the relay at A closing contacts in time T_5, with breaker operation clearing the fault at time T_5'.

The example above illustrates a function known as *backup protection*, which is very important in relay-system design. Note that a fault at P combined with the failure of operation of the breaker at C results in a slightly delayed action of the breaker at B. If a fault at Q is combined with the improper functioning of the breaker at B, the trouble will be cleared by operation of the breaker at A. It is seen that faults are cleared even in the event of the malfunctioning of a relay or breaker. All properly designed relay systems afford backup protection to adjacent zones.

The proper selection of clearing times which permits the breaker nearest a fault to open before the relay providing backup protection has had a chance to close its contacts is known as *protection coordination*. This coordination is made possible by the variation in the minimum value of pickup current among relays, as well as by the difference in steepness of the time-current curves. Thus, the pickup currents of relays A, B, and C are 150, 80, and 65 A, respectively; the time-current characteristics are progressively steeper for A, B, and C.

For proper coordination it was previously stated that, say, T_1' must be smaller than T_2. In practice, $T_1' < T_2'' < T_2$, where T_2'' is called the relay reset time. This is due to the fact that, as the moving parts of a relay travel toward the closed-contact position, they reach a point beyond which inertia alone is capable of bringing them to that position even if the relay coil gets deenergized. The reset time is the time needed to reach that critical position.

b. Impedance Relays With Directional Elements. The problem of relaying of overhead lines and cable circuits becomes more complicated when there are two or more generating stations on the system. Figure 11-37 shows a two-generator system with several sectionalizing points. The loads at each station are not shown. Impedance relays with inverse time

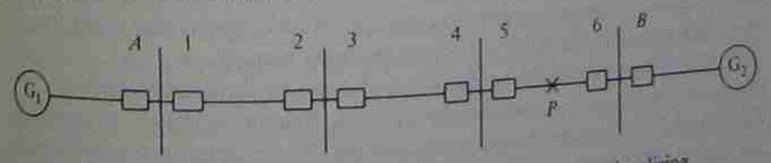


FIG. 11-37. A power system with two sources and four sectionalizing points.

delay and a directional element are assumed at each breaker. Both must close contacts to trip the breaker. It is assumed that the directional elements on all odd-numbered breakers will pick up on the occurrence of a fault to their right. The directional element on all even-numbered breakers will pick up for faults to their left. The selection of the eligible breaker that should trip in the event of a fault is determined by the impedance relays.

Consider a fault at P. The directional element of breaker 1 operates as the fault is to the right. The current and voltage conditions on the impedance relay are such as to indicate the impedance $z_s I_{1P}$, which is the impedance of the line from breaker 1 to the fault point P. Let it be assumed that this is outside the operating range of the impedance relay on breaker 1.

As viewed by breaker 2, the fault is in the wrong direction for tripping and the directional element does not operate, thereby blocking breaker trip.

At breaker 3 the directional element operates to permit tripping. The impedance relay responds to the impedance $z_s I_{3P}$. Assume that this is just barely within the operating range of the impedance relay. This relay tends to close its contacts but will be slow in operation.

At breaker 4, the fault is in the wrong direction for the directional element to close contacts.

At breaker 5, the directional element operates to permit tripping. The impedance seen by the impedance relay is $z_s I_{5P}$. As this impedance is low, it falls well within the region of operation of the impedance relay. Hence this relay operates quickly to provide trip current for the breaker. In case breaker 5 fails to trip, breaker 3 will trip after a time delay, thus providing backup protection.

At breaker 6 the directional element operates to permit tripping. The impedance relay on this breaker sees low fault impedance and quickly closes tripping contacts. Should this breaker fail to open, the protective scheme on generator G_2 should cause breaker B to open.

The scheme just described was illustrated by a relatively simple power system consisting of several series-connected line sections. The method is equally applicable to networks in which there may be multiple parallel lines, closed loops, and numerous generating stations. Each breaker is set to trip if its directional element responds, indicating the location of the fault to be in the appropriate direction. The impedance relay closes contacts quickly if current and voltage conditions indicate low impedance between the breaker and the fault. Tripping occurs after an appreciable time delay if the impedance indicates that the fault is beyond the next station.

The above description referred to the use of impedance relays, a type which has found very extensive application. Reactance relays, described in Section 11-5f, might have been used instead. The reactance relays have the advantage that they respond only to the reactance of the circuit, a value that

is unaffected by the presence of fault circuit resistance, a factor which may be of importance if long arcs form the short circuit at the fault point.

It has been assumed that the impedance (or reactance)-measuring relays have inverse-time characteristics. Distance-measuring relays, in which the timing is by steps, have been designed and are in extensive use. If the impedance seen by the relay is in a certain low range, the closing of tripping contacts will be without intentional time delay, or instantaneously. If the impedance measured is in a somewhat greater range, a fixed time delay is introduced. If the impedance is in a still greater range, a longer fixed time delay is introduced. If the impedance is beyond this third range, no operation results. Relays of this type are spoken of as *step-distance relays*.

In application the step-distance relay is frequently set to be instantaneous over about 80 per cent of the line it protects. If the measured impedance indicates the fault to be in the far end of the protected section or in the next section, tripping time is increased. The third step operation extends from the second circuit section into the third. This range is illustrated in Fig. 11-38. With this arrangement each breaker provides backup protection for two other breakers.

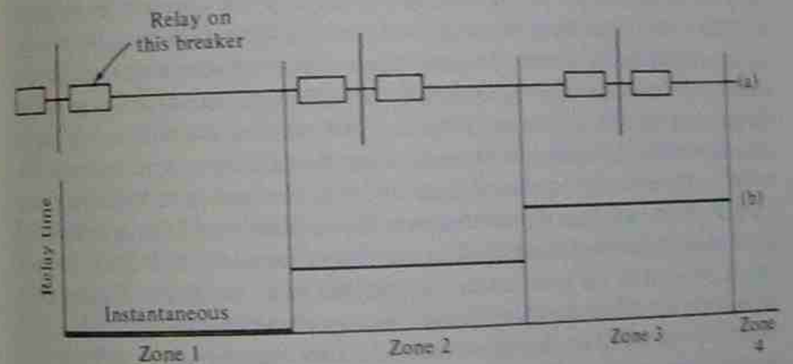


FIG. 11-38. Step-distance relays applied to a power system. (a) The system. (b) The time steps of one relay for faults at different locations.

c. Directional Comparison. The *directional comparison method* of relay protection is illustrated by means of Fig. 11-39. Here it is assumed that a fault exists at point P. The operation of the directional relay element provided on each breaker is indicated by the arrow. A directional element that does not operate for a fault at P is indicated by the letter O. It is evident that if one could stand in the middle of a line section and view the directional elements on each end of the section, it would be possible to determine if the fault were in that section or external to it. The directional element of breaker

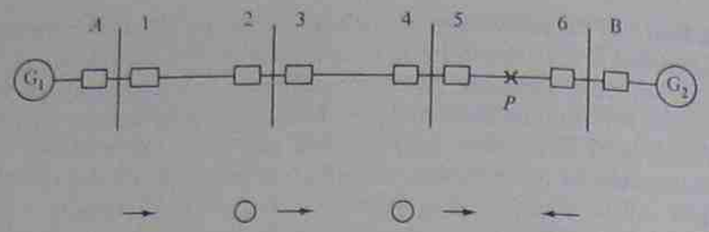


FIG. 11-39. A power system for illustrating a system of directional comparison protection.

1 has operated. The directional element on breaker 2 at the other end of the line section is open, indicating that the fault is not in this section. Similarly, the closed position of the directional element on breaker 3 and the open position on breaker 4 indicates that the fault is external to the line between 3 and 4. The directional element on breaker 5 is closed, and similarly the directional element on breaker 6 is closed, indicating that the fault is between the two breakers and that both breakers should trip.

The basic principle of directional comparison is very simple and positive. A difficulty arises in attempting to view the directional elements at both ends of the lines simultaneously. If the line terminals are not far apart geographically, a wire communication circuit between them may permit automatic comparison of relay positions with high-speed removal of the faulted line section. However, if the line sections are 100 miles or more in length, wire communication channels may be expensive and perhaps unreliable. Here it may be desirable to utilize a channel in a high-frequency carrier system, which is transmitted over the conductors of the power circuit itself. Abnormal conditions existing on the occurrence of a fault activate relays on each of the breakers in line sections near the fault. These relays, unless blocked from operation, cause tripping of the breakers. The blocking signals is controlled by the directional relays on each breaker, and is transmitted from one end of a protected section to the other by carrier or by microwave. If a directional element determines that the fault is not in the direction of the protected section, a signal is transmitted which blocks breaker operation at both ends of the section. If the directional elements at both ends of the line indicate that the fault is in the direction of the protected section, no blocking signal is transmitted from either end, and both breakers trip. The sequence of events is made clear by study of Fig. 11-39.

At breaker 1 the directional element indicates that the fault may be in the line section from 1 to 2. This breaker trips if no blocking signal is received. No blocking signal is transmitted to breaker 2.

At breaker 2 the directional element shows that the fault is not in the line section. A carrier signal is transmitted which blocks tripping of both

breaker 1 and breaker 2. Behavior at breakers 3 and 4 is similar to that at 1 and 2 respectively.

At breaker 5 the directional element indicates the possibility of a fault in the line section. No blocking signal is transmitted. The directional element at breaker 6 also indicates the possibility of the fault in the protected section. No blocking signal is transmitted. After a very short time delay, both breakers 5 and 6 trip.

The transmission of a *blocking signal* between stations (rather than a tripping signal) provides more reliable fail-safe operation. A fault in the middle of the line might interfere with carrier frequency transmission and so make impossible the transmission of a tripping signal. A blocking signal needs to be transmitted only if the line is in good condition.

A failure of the blocking signal equipment causes the opening of a line section on which no fault exists. However, this type of false operation is preferable to the failure to clear a faulted section.

d. Phase-Comparison Protection. The presence of a fault in a line section may be detected by comparing the phase position of the currents as observed at each of the two ends of the line, in a manner somewhat similar to differential protection. The comparison of these currents is made over carrier channels or microwave channels. The method is illustrated by reference to a short section of power system (Fig. 11-40). In column (a) behavior is described for a fault assumed at point *P*. The current flowing *into* the line section at circuit breaker *A* is as shown on line 1. If this current is of sufficient magnitude, a carrier signal is transmitted which goes to the relaying system of breaker *A* and over a communication circuit to the relaying system of breaker *B*. As indicated on line 3, carrier transmission is only during the positive half-cycle of the current wave.

The current flowing *into* the line section at breaker *B* is as indicated in line 2. This current is of different magnitude than the current at *A* but is almost in phase with it. If it is of sufficient magnitude, there will be carrier transmission to the relay equipment at *B* and over the communication circuit to the relay equipment at *A*. This transmission occurs only during the positive half-cycle of the current flow at *B*, as shown on line 4. The carrier transmissions at *A* from *A* and from *B* are added and rectified to yield an output signal, as shown on line 5. When the signal has a zero value for a specified time (measured in milliseconds) as at T, auxiliary equipment causes the trip circuit of the breaker to be energized. At breaker *B*, both signals are received and are processed in the same fashion.

Next consider a fault assumed at *Q*. In column (b), Fig. 11-40, behavior is described for this condition. The current flowing *into* the line section at breaker *A* is as shown in line 1. This causes carrier transmission as shown in

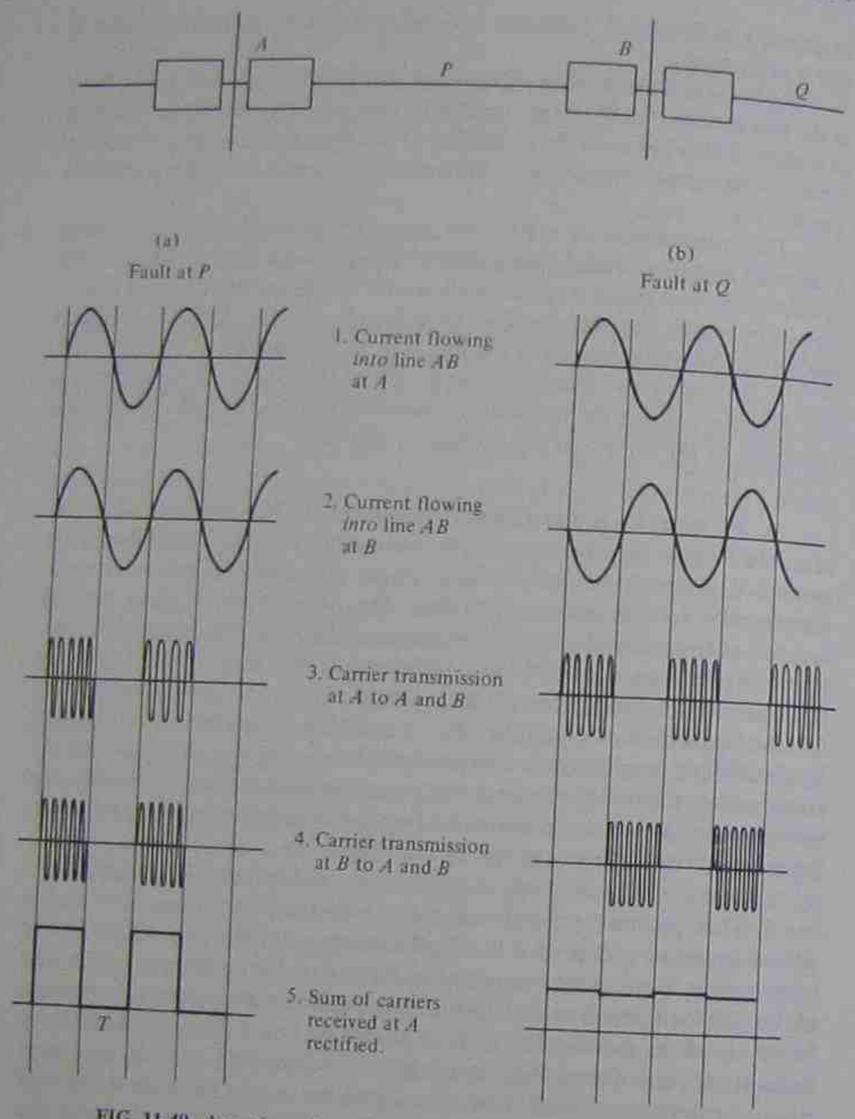


FIG. 11-40. A section of a power system for illustrating phase comparison protection.

line 3. This carrier transmission is received by the relay equipment at both breakers *A* and *B*.

At breaker *B* the current *into* the protected section is as indicated by line 2. Note that it is 180° out of phase with the current into the line section

at *A*. This causes carrier transmission (during the positive half-cycle only), as shown in line 4. This carrier is transmitted to the relaying equipment at both *A* and *B*, as before. The sum of the *A* carrier and *B* carrier added and rectified results in a signal, as shown in line 5. This signal maintains a non-zero value throughout the entire cycle, preventing the auxiliary equipment from energizing the trip circuit to the breaker. Similar behavior at breaker *B* results in no signal to the trip-coil circuit of that breaker.

It may be noted that with this phase-comparison arrangement, a trip signal is available with a fault in the *line* section, but none is available if the fault is exterior. In the event of failure of the carrier equipment, the affected line section will be opened even though no fault exists on it. Solid-state equipment applied to such a system provides very high speed reliable relay protection.

11-11. SOLID-STATE RELAYING

Designers of electronic circuits have developed systems using solid-state components that duplicate the functions of the many electromechanical relay types that have been discussed. The circuitry used for a particular function may be considerably different as developed by different designers. No attempt is made here to present a group of solid-state relay designs corresponding to the electromechanical ones described. For purposes of illustration, the broad operations necessary in the phase-comparison system are outlined.

a. Functions Necessary in the Phase-Comparison Method of Circuit Protection. A *level response circuit* recognizes that the current magnitude is indicative of a fault condition. The output of this level circuit is necessary to *permit* carrier transmission.

A *half-wave rectifier* produces an output only during the positive half-cycle of the current wave.

A *switching circuit* responds to signals from the level circuit and the rectifier circuit to cause transmission of carrier only during the positive half-cycle of the current wave.

A circuit is necessary to add carrier transmission received from the two ends of the protected section.

The added carriers must be rectified to produce either a constant output for blocking or a pulsating output allowing tripping depending on the time displacement of the two carriers.

b. Programmable Controllers. A programmable controller (PC), Fig. 11-41, is a microprocessor-based solid-state device capable of performing logical operations toward the control or protection of industrial

FIG. 11-41. A programmable controller.

equipments and processes. It is well suited for operation in an industrial environment, as, unlike minicomputers, it needs no particular conditioning of its physical or electrical environment. Its programming is often based on the relay ladder concept, but may also use fundamental digital gate logic.

A typical programmable controller is made up of three main components:

1. A processor which performs all the logical operations, makes decisions, and coordinates all control actions based on input information received from the various PC input terminals. These terminals reflect the status of switches, pushbuttons, limit switches, photodiodes, optical isolators, and so on, used in the controlled system. The processor is essentially the brain of the system. Its operation is determined by a program stored in its read-only memory (ROM). The program is prepared and entered by the user who may easily modify it any time.
2. A power supply which meets the energy needs of the processor and many of the input and output (I/O) devices.

3. Input/output modules which interface between the various I/O devices such as switches, solenoids, lamps, relays, etc., and the processor. In order to prevent transients traveling on the long wires connecting the I/O modules to the external devices from perturbing the processor operation, all input and output circuits are usually isolated by means of photodiodes or transformers.

The programmable controller operation is cyclic in nature. The same broad functions are performed sequentially over and over again. The sequence of operations varies among controllers; however, a basic one comprises three stages as follows:

1. All inputs are probed in binary fashion, i.e., they may either be found ON or OFF. The information is stored in input registers. Once this stage is completed, the content of the input registers stays fixed independently of any changes that may subsequently occur at the input terminals. Inputs are thus probed once in a cycle. This operation is enabled by a *scanner*.
2. The scanner then turns to the program lines stored in the ROM and enables the execution of one line at a time. Each line requires effecting one or more logical operations between input, output, or internally defined variables. The values of the output variables are determined by some of these logical operations. They are not immediately used to update the outputs; rather, they are stored in output registers.
3. Once all program lines have been executed, the scanner then turns to the output modules and enables the output registers to update the status of the various outputs. The scanner then turns again to the inputs as in stage 1 above.

In the scheme above input changes are not taken into account during program execution (stage 2) but only once at the beginning of each cycle (stage 1). Similarly, changes in the content of the output registers during program execution affect the outcome of following program lines but do not find their way to the actual outputs. The latter are affected by the last content of the output registers in the cycle (stage 3).

Clearly, the speed at which inputs are acknowledged and outputs are changed depends on the cycle time, which in turn depends on the number of program lines. A controller cycle may thus take 30 milliseconds, objectionable in some processes when one considers that a solenoid valve takes about 1 millisecond to operate. This problem is alleviated in programmable controllers in which the three stages of a cycle are divided into substages which are interleaved: probing of 12 inputs, followed by execution of 32 program

lines, followed by updating of 12 outputs, then probing of the next set of 12 inputs, and so on. In other words, the cycle is divided into subcycles, each having its own three stages. If a subcycle runs out of any of the three substages, it simply proceeds with the remaining ones to the end. In this scheme each input or output is still updated only once during each cycle, but the result of the updating is made available to the logic of the following subcycles.

The fundamental instructions of a programmable controller are:

Load Accumulator (LDA)
Load Accumulator with Complement (LDAC)
AND
AND Complement (ANDC)
OR
OR Complement (ORC)
Store (STO)

The first two operations, LDA and LDAC, transfer data from a designated I/O or internally defined variable into the accumulator. The latter is used to retain the result of each subsequent operation. The next four operations in the list above (AND, ANDC, OR, ORC) are logical operations between the accumulator data and a designated I/O or internal variable data; the result goes into the accumulator. The last operation, STO, transfers data from the accumulator into a designated output; the accumulator content remains unchanged.

In addition to the "real" inputs and outputs, a number of variables are defined as internal I/O by the program. The purpose of these internally defined variables is usually to record in memory for subsequent use the occurrence of an event, such as particular sequences of inputs. The values of these internal variables are usually stored in a random-access memory (RAM).

Skipping certain parts of a program is made possible by a conditional *jump* instruction. This feature is crucial to decision making as it provides alternative subprograms depending on the status of the control job at hand. Other instructions are also available depending on the degree of complexity of the controller. They tend to simplify the program steps and allow more efficient utilization of the various memories.

Programmable timers are often made available and may be incorporated in the logic. They make possible the insertion of delays in the determination of the outputs. Counters provide control based on the number of times a particular variable changes status.

Compared with many relay-controlled circuits currently in use, small-scale programmable controllers are cost-competitive replacements for relay systems requiring as few as 10 relays. In addition, they offer increased flexibility and ease of use. For the same inputs and outputs, changes in sequence

of operation can be achieved by changes in program, not by rewiring, as in the case of relays.

PROBLEMS

11-1. The current in a certain ac circuit should be held at 800 A. Show a relay system which will sound an alarm if the current falls to 750 A. Choose a balance-beam relay showing the necessary coil or coils, spring, contacts, and any instrument transformers necessary.

11-2. Show the complete setup of a relay system for use in a 240-V ac circuit which will sound an alarm if the voltage rises above 260 V or falls below 220 V.

11-3. A gasoline-driven 120-V 5-kW ac generator is connected through a breaker to a large 120-V system. Show a relay system that will energize the trip coil of the breaker in the event that the gasoline engine runs out of fuel and power flows from the large systems to the 5-kW generator, driving it as a motor.

11-4. Show a relay system which will sound an alarm if the voltage of a circuit exceeds 70 V. The alarm should continue even though the voltage later drops below 70 V.

11-5. Refer to Fig. 11-5. What would be the result if, on closing the circuit breaker, the auxiliary contacts failed to close? Explain.

11-6. Refer to Fig. 11-5. Assume that with the circuit breaker closed, a test man, by mistake, opens the potential transformer secondary circuit. Explain the result.

11-7. Show a relay arrangement which might be used to sound an alarm 5 min after the power supply fails.

11-8. Refer to the circuit of Fig. 11-11. Tests on the relay itself show that the torque on the beam due to 5 A in the current coil is just balanced by that due to 120 V on the voltage coil. Which way will the beam tip if the load impedance Z is
a. $6 + j9$?
b. $15 + j20$?
c. $20 + j20$?
For this system what is the ratio K_i/K_v?

11-9. Refer to the system of Fig. 11-22, but assume the following values: PT ratio: 69,000/120, CT ratio: 400/5, $K_i/K_v = 36$. Assume that the voltage between conductors is 58 kV. What conductor current is necessary to produce a balance of the relay beam?

11-10. Draw a diagram showing the relay of Fig. 11-16 connected for operation on a 12-kV circuit on which the current is normally 200 A. Assume that the relay itself has 120-V potential coils and a 5-A current coil. Assume that $\theta = 0$. What must be the value of the ratio K_v/K_i to make the relay responsive to line impedances from $Z = 0$ to $Z = 20$?

11-11. Refer to Fig. 11-15. The potential coil of the watt element has a resistance of 45 Ω and an inductance of 0.15 mH.
   a. What must be the value of the impedance Z_r to make $\theta = 0$?
   b. What must be the value of Z_r to make the relay match a line in which the impedance per mile is $z = 0.15 + j.75\ \Omega$?

11-12. A reactance relay is so constructed that K_i/K_v is 75. On test, 60 V is applied to the potential circuit while a current of 3.5 A lagging the voltage by 40° is passed through the current coils. Will the relay operate? Explain.

11-13. Draw a diagram of a relay system that will protect a generator, providing trip current to the breaker in case of
   a. a fault within the generator.
   b. excess load current.
   c. power flow from the system to the generator (reverse power).
   Show all necessary CT's and PT's. Design the system on a line-to-neutral basis.

11-14. Refer to Figs. 11-35 and 11-36. Assume that with a fault at P, the relay contacts at breaker C close but the breaker is sluggish in operating. How much delay could be tolerated without resulting in the unnecessary opening of breaker B? If both breaker C and breaker B are sluggish, how much delay could be tolerated without the unnecessary opening of breaker A?

11-15. Refer to Fig. 11-39. Suppose that, owing to a failure of equipment, no blocking signal is transmitted from breaker 4. Explain the results.

Chapter 12

Electrical Insulation

12-1. PURPOSE

Insulation is required to keep electrical conductors separated from each other and from other nearby objects. Ideally, insulation should be totally nonconducting, for then currents are totally restricted to the intended conductors. However, insulation does conduct some current and so must be regarded as a material of very high resistivity. In many applications, the current flow due to conduction through the insulation is so small that it may be entirely neglected. In some instances the conduction currents, measured by very sensitive instruments, serve as a test to determine the suitability of the insulation for use in service.

Although insulating materials are very stable under ordinary circumstances, they may change radically in characteristics under extreme conditions of voltage stress or temperature or under the action of certain chemicals. Such changes may, in local regions, result in the insulating material becoming highly conductive. Unwanted current flow brings about intense heating and the rapid destruction of the insulating material. These insulation failures account for a high percentage of the equipment troubles on electric power systems. The selection of proper materials, the choice of proper shapes and dimensions, and the control of destructive agencies are some of the problems of the insulation-system designer.

12-2. INSULATING MATERIALS

Many different materials are used as insulation on electric-power systems. The choice of material is dictated by the requirements of the particular application and by cost. In residences, the conductors used in branch circuits and in the cords to appliances may be insulated with rubber or plastics of several different kinds. Such materials can withstand necessary bending, are relatively stable in characteristics, and are inexpensive. They are subjected to relatively low electrical stress.

High-voltage cables are subjected to extreme voltage stress; in some cases several hundred kilovolts are impressed across a few centimeters of insulation. They must be manufactured in long sections, and must be sufficiently flexible as to permit pulling into ducts of small cross section. The insulation may be oil-impregnated paper, varnished cambric, or synthetic materials such as polyethylene.

The coils of generators and motors may be insulated with tapes of various kinds. Some of these are made of thin sheets of mica held together by a binder, and others are of fiber glass impregnated with insulating varnish. This insulation must be capable of withstanding quite high operating temperatures, extreme mechanical forces, and vibration.

The insulation on power-transformer windings is commonly paper tape and pressboard operated under oil. The oil saturates the paper, greatly increasing its insulation strength, and, by circulating through ducts, serves as an agent for carrying away the heat generated due to I^2R losses and core losses in the transformer. The transformer insulation is subjected to high electric stress and to large mechanical forces. The shape and arrangement of conducting metal parts is of particular concern in transformer design.

Overhead lines are supported on porcelain insulators. Between the supports air serves as insulation. Porcelain is chosen because of its resistance to deterioration when exposed to the weather, its high dielectric strength, and its ability to wash clean in rain.

12-3. INSULATION BEHAVIOR

When insulation is placed between two metallic conductors A and B connected to a voltage source (Fig. 12-1), several phenomena associated with the insulation may be identified. The insulation, or dielectric, influences the capacitance between the plates, a current of low magnitude flows through the body of the insulation, a leakage current flows over the surface of the insulation, and if the voltage is great enough, sudden changes in the body of the insulation may make it highly conductive.

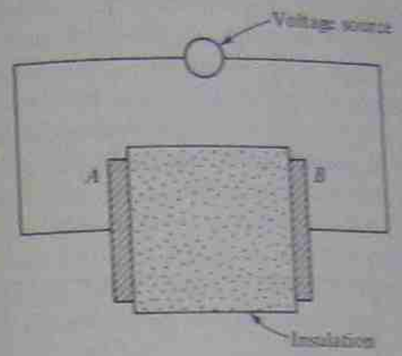


FIG. 12-1. Insulation under electrical stress between two metal electrodes.

a. Capacitance and Dielectric Hysteresis. As is well known, the presence of a dielectric between two conducting plates increases the measured capacitance between these plates. The behavior of the electrons and protons comprising the dielectric accounts for this capacitance increase. This phenomenon is worth investigating, for it explains some other characteristics of insulation of interest.

As discussed in Chapter 9, all matter is made up of protons, electrons, and neutrons. In the normal state, these particles are grouped as atoms or molecules in which the number of electrons (each with unit negative charge) and the number of protons (each with unit positive charge) are equal, therefore, each group is electrically neutral. However, each of these particles experiences a force due to its interaction with any charges placed on nearby plates. We say that the charged particles respond to the electric field set up between the plates.

In a perfect insulator, the electrons and protons are held together in the atoms and molecules and are not free to drift from one plate to another. However, in the presence of an electric field, they may move very slight distances, the electrons toward the anode, the protons toward the cathode. This situation is illustrated in greatly simplified form in Fig. 12-2a. This diagram shows a group of polar molecules. Each of these is neutral, but each has an extra electron at one end and an extra proton at the other. These may be moving with respect to each other but at some instant have a position as shown. Let us confine our attention to the polar molecule at P.

Next let charges be put on A and B by connection to a voltage source as shown in Fig. 12-2b. The molecule P rotates, taking up a new position with the electron displaced toward A and the proton toward B, under influence of the electric field.

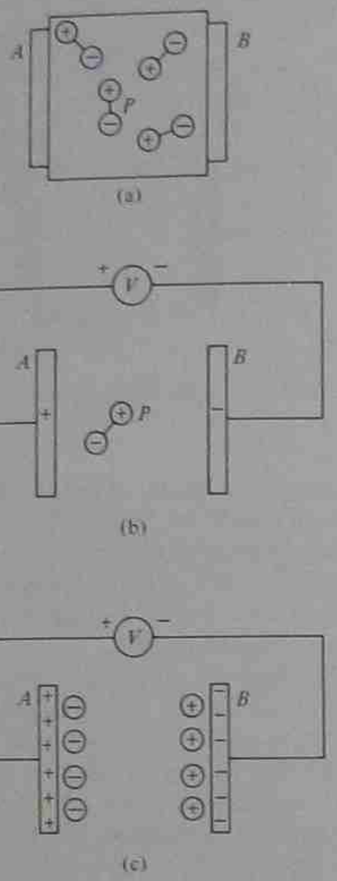


FIG. 12-2. The effect of electrical stress of insulation. (a) Some polar molecules under normal conditions. (b) The polar molecule *P* changes position under stress. (c) The charge layers adjacent to the electrodes.

The effect of the many, many electron-proton pairs in the dielectric volume, moving as shown by the example *P*, is to produce an effect shown in Fig. 12-2c. Adjacent to the anode *A* there is an excess number of electrons in the dielectric; near the cathode *B* is an excess number of protons in the dielectric. These charges partially neutralize the effect of the charge originally placed on the plate and additional charges move from the voltage source to *A* and *B* as the charges in the dielectric take on their new positions. Hence, for the same voltage between the plates, the charges that have moved from the source to the plates have been increased as a result of the presence of the dielectric. The capacitance between the plates is greater, therefore, than it would be without the dielectric.

Whenever a system of particles is moved from one position to another (such as system *P* from the position shown in Fig. 12-2a to that of Fig. 12-2b), there are forces which restrict the motion, and time is required to make the change. Such is the case in dielectrics. In some materials the change is made in a fraction of a microsecond; in others it may take several hours. During the period of change, the capacitance appears to increase and current flows in the external circuit. It is sometimes stated that charge is "soaking" into the dielectric. The phenomenon is known as dielectric absorption.

When the voltage source is disconnected from plates *A* and *B* and the voltage between them is made zero by a short-circuiting connection (Fig. 12-3a), the displaced particles in the dielectric tend to go back to their

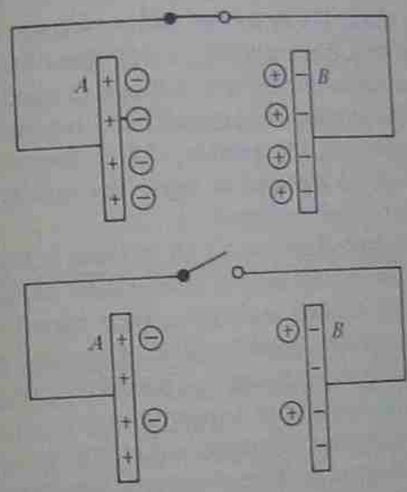


FIG. 12-3. Charge conditions in a capacitor that has been energized. (a) Immediately after being short-circuited. (b) After the short circuit is removed.

normal state. However, if it took a long time to get them oriented, it will take a long time to get them back into the normal state. Hence the condition shown in Fig. 12-3a may persist for some time, a charge remaining on each plate equal in effect to the charge remaining in the dielectric adjacent to the plates.

Next suppose that the short circuit is removed. Forces continue to restore the dielectric to its neutral state. With the circuit open, the charges held on the plates cannot be removed. As the dielectric returns to its normal condition, the trapped charges on the plates produce a voltage between *A* and *B*. This voltage may be a serious hazard to a workman who expected the capacitance between the plates to be discharged by the short-time application of a short circuit. This hazard is particularly serious on equipment of high capacitance such as high-voltage cables, static capacitors, and generator

windings. For this reason, it is always desirable to keep such equipment continuously short-circuited when workmen are to be in physical contact with the presumably deenergized equipment.

Referring again to Fig. 12-2a and b, the movement of particles, such as the polar molecule *P*, may result in the movement of other nonpolar molecules. If the molecular motion is increased, the temperature of the material is increased. If the power supply is an ac source, each reversal of voltage will tend to cause a reversal of the position of the polar molecules and electrical energy from the source will be converted to heat in the insulation. This loss is known as *dielectric hysteresis*. It increases with frequency and with applied voltage. It must be considered in high-voltage cable design.

b. Conduction Currents. When voltage is applied between two plates separated by a dielectric (Fig. 12-1), those few free electrons that are present in the insulation drift from cathode to anode. This is termed a conduction current (from anode to cathode) and represents power loss into the insulation. In insulation, the number of free electrons is low, and as a result the resistivity of the material is high. The number of free electrons may be increased by several processes.

An increase in temperature causes an increase in the thermal agitation of the molecules of the insulation. As temperature increases, an increased number of electrons are broken loose from their parent molecules and are free to drift in the presence of an electric field. The resistivity of the material decreases with an increase in temperature. This is in contrast to metals, where resistivity increases with increase of temperature.

Insulating materials have chemical structures designed to have high electrical resistance. Changes in these structures may result in a substantial reduction of the resistance. Chemical changes may result from periods of elevated temperature, from the action of light, or from attack by certain chemicals.

The exposure of insulation to radiation particles (as from nuclear reactors) increases the number of free electrons, and so causes a temporary reduction of resistivity. Under extreme exposure, chemical changes resulting from radiation damage may permanently lower insulation resistance.

c. Surface Leakage Currents. Leakage currents flow along paths between electrodes over the surface of the insulating material. The magnitude of these currents is in no way related to the resistivity of the material itself. The value of the leakage current depends on the applied voltage, the insulation material, the surface contamination, and the moisture content of the air. On seriously contaminated high-voltage line insulator surfaces, leakage currents may be as much as 100 milliamperes.

d. Insulation Breakdown. Insulation may undergo a very sudden change in characteristics in a process known as *breakdown*. Consider the arrangement shown in Fig. 12-4. Two parallel-plane electrodes *A* and *B*

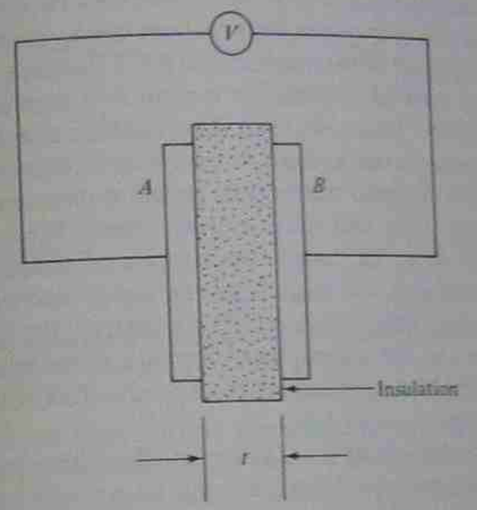


FIG. 12-4. Insulation of thickness t being stressed by applied voltage V.

are separated by a sheet of dielectric of thickness t. A variable voltage source V provides a difference of potential between A and B. Suppose the voltage is slowly raised. At first the conduction current is very low, perhaps measurable in microamperes. With increased applied voltage, the current suddenly increases, and the insulation takes on the character of a metallic conductor. This is termed insulation breakdown. On examination, a small damaged place may be found extending through the insulation sheet. Perhaps there will be some charring and perhaps there will be a hole.

The voltage at which such breakdown occurs is called the *breakdown*, or *puncture*, *voltage*, V_p, and the electric field intensity $\mathscr{E}_p$ at that point is known as the *breakdown gradient* or puncture strength of the insulation.

$$\mathscr{E}_p = \frac{V_p}{t} \tag{12-1}$$

where t is the insulation thickness.

The puncture strength of a particular material is not a constant but varies with the thickness of the sample, the shape and geometry of the electrodes, and the *rate* of application of voltage. Where no other information is specified, the puncture strength usually refers to that determined by

tests using plane circular electrodes and applying voltage at a rate such that breakdown may occur in less than 2 or 3 minutes.

Two mechanisms of breakdown are of importance. Both may occur at the same time, although one or the other may be dominant. As mentioned in the previous paragraphs, under voltage stress, an increase in temperature causes an increase of the conductance (or a decrease in the resistance) of the insulating material. Conduction current flow implies a release of energy in the insulation. Under electrical stress near the puncture value, a local region may increase in temperature because heat is released faster than it is carried away. The increased temperature causes an increase in the conductance of that local area, and more current flows, thereby increasing the temperature even more. Of course, the increase of temperature will cause increased conduction of heat away from the region and a stable condition may result. However, if the voltage is further increased, the temperature may continue to rise and the current may continue to increase until chemical changes destroy the insulation and puncture results. This is sometimes called *thermal breakdown*.

Another mechanism of breakdown involves the acceleration of free electrons in an insulation volume to the energy level at which they, in collision with neutral molecules, knock other electrons free of the parent molecule, thus forming electron *avalanches*, as was discussed in Section 9-4c. In solids, these high-speed electrons break chemical bonds and so bring about chemical changes. In gases, the high-speed electrons generate ion pairs. The movement of the resulting charged particles, if sufficiently intense, produces sparkover and arcs. This may be termed breakdown by electron collision.

e. Volt–Time Characteristics of Breakdown. Both mechanisms of insulation breakdown described above require energy to be delivered from the voltage source to the insulation volume. This means that time is required for breakdown. The lower the applied voltage, the more slowly does the breakdown process proceed, and the longer the time to reach breakdown. At voltages below a critical value, the rate of energy dissipation by normal thermal conduction and convection processes is sufficient to prevent the growth of the breakdown process. At stresses below this critical value, insulation may operate indefinitely without breakdown.

Insulation is sometimes tested by applying a voltage above the critical value and observing the time which elapses before breakdown. Then a second experiment is performed with a different value of test voltage. This is repeated and finally a curve is drawn showing the time to breakdown plotted against applied voltage.

For solid insulation where the breakdown process is basically thermal, the curve shows a characteristic like that in Fig. 12-5a. Note that for voltages just above the critical value, V_c, the time lag of breakdown may be measured in minutes or even hours.

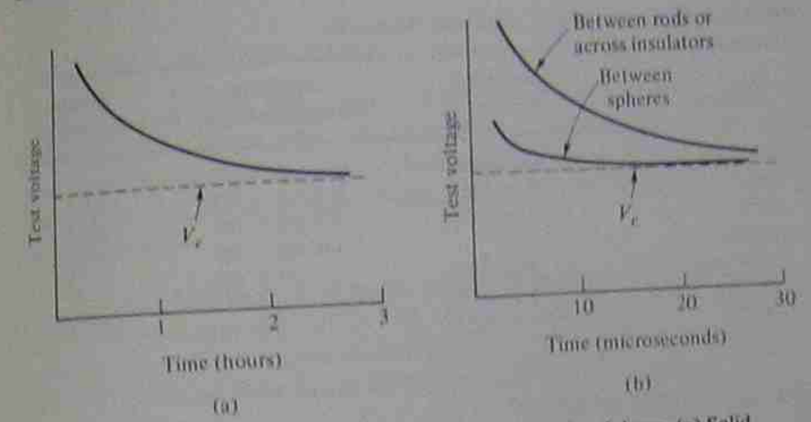


FIG. 12-5. Volt-time characteristics of insulation breakdown. (a) Solid insulation. (b) Air between spheres and between rods.

For gaseous insulation, where the breakdown process is basically by electron collision, the volt–time curve appears as shown in Fig. 12-5b. Note that the time here is measured in microseconds. The shape of the electrodes of the test system influences the shape of the curve. Between closely spaced spheres, where the electric field is almost uniform, the time lag is very small. Between rod gaps, where the electric field is very nonuniform, the time lag is greater.

f. Insulation Deterioration. Insulation in service may deteriorate, a fact which implies that periodic checks of insulation condition must be made to avoid equipment failure due to breakdown of insulation.

The conductivity of solid and liquid insulation increases rapidly with moisture content. Designs and maintenance procedures must be such as to minimize the amount of moisture that may be absorbed.

Chemical changes due to excessive temperature and due to exposure to chemicals, sunlight, and nuclear radiation may permanently impair the value of solid and liquid insulation.

Gaseous insulation, such as air, loses strength as particle density is decreased, either by a reduction of pressure or by an increase in temperature. Some gases, such as sulfur hexafluoride, lose insulation strength if contaminated with air, moisture, or conducting particles.

g. Typical Insulation Characteristics. The relative permittivity, puncture strength, and resistivity of several materials of importance in electric power are shown in Table 12-1. The puncture strength and resistivity will vary considerably, dependent on purity, manufacturing processes used, and moisture content. For comparison, the resistivity of copper is also shown.

Table 12-1. *Characteristics of Insulating Materials*

Material	Resistivity, ohm-cm	Puncture Strength, volts/cm	Relative Permittivity
AIR	Very high	3×10^4	1.0
GLASS	2×10^{13}	$0.5–3.0 \times 10^6$	5.4–9.9
MICA	2×10^{17}	$3.5–7.0 \times 10^6$	2.5–8.6
PAPER		$1.0–4.0 \times 10^5$	2.0–2.6
PORCELAIN	3×10^{14}	1.0×10^5	5.7–6.8
RUBBER	1×10^{15}		2.0–3.5
COPPER	1.6×10^{-6}		

12-4. LIMITATIONS ON DESIGN

The insulation of an electric power system is of critical importance from the standpoint of service continuity. As mentioned before, probably more major equipment troubles are traceable to insulation failure than to any other cause. It might be argued that equipment should be overinsulated in terms of present practice. There are, however, other factors in addition to direct cost that argue against the use of higher insulation levels.

In cables, insulation is operated at very high stress. If insulation thickness were increased, more material would be required. In addition, larger-diameter cables would require more lead for covering, would be more difficult to handle, and lengths that could be put on reels would be reduced. In addition, electrical insulation is also good thermal insulation. Increased insulation thickness increases the problem of heat removal from the power conductors and requires a reduction of their current rating.

Increased thickness of insulation in transformers increases the size of coils and cores and increases copper and iron losses. The larger spacing between coils results in increased per unit impedance.

Increasing the number of suspension units in transmission line insulators necessitates an increase in cross-arm length, which in turn requires heavier structures and perhaps wider rights of way.

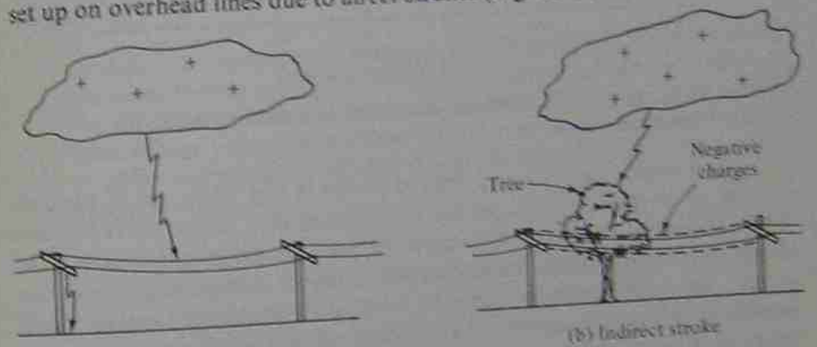
Similar statements could be made regarding other equipment, such as generators, instrument transformers, and circuit breakers. An arbitrary increase in insulation strength results in increased costs of associated parts and, in many instances, less satisfactory operating characteristics.

Because of the problems associated with equipment designs that attempt to utilize overly generous insulation, efforts are made in other directions. Manufacturers attempt to produce insulation of uniformly high quality, operators attempt to maintain the insulation with minimum deterioration, and designers attempt to plan systems in which overvoltages due to transient conditions are limited to values only slightly above the system operating voltage.

12-5. SOURCES OF OVERVOLTAGES

Overvoltages on power systems are traceable to three basic causes: lightning, switching, and contact with circuits of higher voltage rating. The power-system designer seeks to minimize the number of these occurrences, to limit the magnitude of the voltages produced, and to control their effects on operating equipment.

a. Lightning. Lightning results from the presence of clouds which have become charged by the action of falling rain and vertical air currents, a condition commonly found in cumulus clouds. Voltages may be set up on overhead lines due to *direct* strokes (Fig. 12-6a) and due to indirect



(a) Direct stroke (b) Indirect stroke

Note: Clouds may be of either polarity

FIG. 12-6. Lightning stroke to a line. (a) Direct. (b) Indirect.

strokes (Fig. 12-6b). In a direct stroke, the lightning current path is directly from the cloud to the subject equipment—an overhead line in Fig. 12-6a. From the line, the current path may be over the insulators and down the pole to ground. The voltage set up on the line may be that necessary to flash over this path to ground.

In the indirect stroke, the current path is to some nearby object, such as the tree shown in Fig. 12-6b. The voltage appearing on the line is explained as follows: As the cloud comes over the line, the positive charges it carries draw negative charges from distant points and hold them bound on the line under the cloud in position as shown. The voltage on the line is zero, assuming that the line is not energized. If the cloud is assumed to discharge on the occurrence of the stroke in zero time, the positive charges suddenly disappear, leaving the negative charges unbound. Their presence on the line implies a negative voltage with respect to ground.

On the occurrence of a stroke, lightning clouds do not discharge in zero time. Instead, the stroke current rises from zero value to maximum value (perhaps 50,000 amperes) in a few microseconds and is completed in

a few hundred microseconds. For many test and design purposes, the voltage set up on the line due to lightning is assumed to be as shown in Fig. 12-7. Here it may be noted that the crest value of the voltage is reached in 1.2 microseconds and the 50 percent point on the tail of the wave is reached in 50 microseconds. Obviously all voltages set up by natural lightning discharges do not conform to this specification.

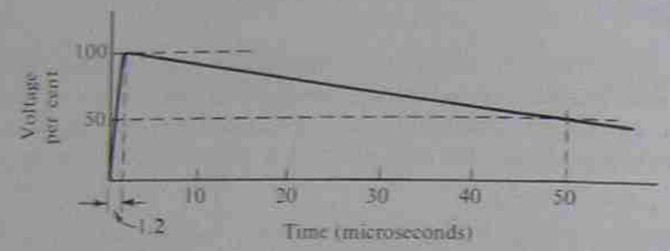


FIG. 12-7. A 1.2 × 50 test wave used to simulate a lightning-produced voltage.

Direct lightning strokes to lines as shown in Fig. 12-6a are of concern on lines of all voltage class, as the voltage that may be set up is in most instances limited by the flashover of the path to ground. Increasing the length of insulator strings merely permits a higher voltage before flashover occurs. The most generally accepted method of protection against direct strokes is by use of the *overhead ground wire* (Fig. 12-8). For simplification only one ground wire and one power conductor are shown.

The ground wire is placed *above* the power conductor at such a position that practically all lightning-stroke paths will be to it instead of to the power conductor. Stroke current then flows to ground, most of it passing through

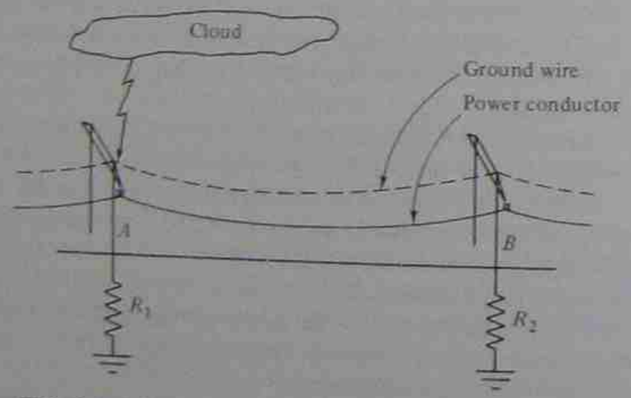


FIG. 12-8. A lightning stroke to a transmission line with overhead ground wire.

the tower footing ground resistance R_1 while a smaller part goes down the line and to ground through the adjacent tower footings. The tower rises in voltage due to the current I_1 through the resistance R_1 to a value which is (as a first approximation)

$$V_t = I_1 R_1 \tag{12-2}$$

Approximately this voltage appears between the tower and the power conductor (which was not struck). If this voltage is less than that required to cause insulator flashover, no trouble results. Protection by this method is improved by using two carefully placed ground wires and by making tower footing ground resistance of low value. Ground resistance is discussed in Chapter 13.

EXAMPLE 12-1. Suppose the lightning current which flows to ground through the tower footing is 25,000 A. If the tower footing resistance is 10 Ω, using Eq. (12-2), the potential of the tower rises to 250,000 V. This is the approximate voltage across the insulator string. However, if the ground resistance is 25 Ω, the voltage is 625,000 V, and insulator flashover will be more probable.

The lightning record of lines supported on towers 80 to 90 feet tall substantiates the simple theory of line protection just presented. The poorer record of lines on towers over 100 ft in height indicates that other factors, perhaps the inductance of the path down the tower, should be considered.

Indirect strokes produce relatively low voltages on lines. They are of real concern on low-voltage lines supported on small insulators. They are of little importance on high-voltage lines whose insulators can withstand hundreds of kilovolts without flashover.

b. Switching Transients. Overvoltages may result from switching operations on the closing of circuit breakers, or if restriking occurs within the breaker, on circuit-opening operations. A simple circuit to explain the nature of switching transients is shown in Fig. 12-9. In this circuit L

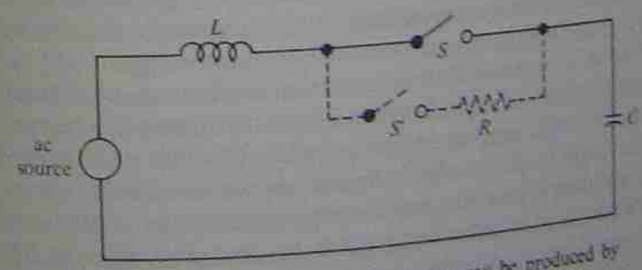


FIG. 12-9. A circuit in which overvoltages may be produced by switching.

might represent the inductance of a transformer while C represents the capacitance of a transmission line. When the switch S is closed, oscillations will result in a voltage of frequency

$$f = \frac{1}{2\pi\sqrt{LC}} \tag{12-3}$$

appearing across the capacitor. The magnitude of this voltage depends on the magnitude of the voltage left on the capacitor due to previous operation, the voltage of the ac source, and the point on the wave at which the switch makes contact. The magnitude of the overvoltage may be controlled by (1) causing the switch to close at the most favorable point on the wave, or (2) inserting resistance in the circuit by closing an auxiliary switch S' (shown dashed) a short interval of time before the main contact S closes. Both methods are in use on major power systems.

c. Contact With Circuits of Higher Voltage. *Lines of different voltage class are sometimes carried on the same structures. Necessary crossings of lines of different voltage class bring these lines in close proximity to each other. Under these circumstances, conductor or support failure or extreme loading due to wind and sleet may bring lines in contact with each other. In practice the higher voltage line is placed above the lower voltage line, and because of its greater importance, the higher voltage line may be more liberally designed. However, contact between circuits does occasionally occur. Such contacts are recognized by the relays as faults, and circuit breakers are opened to clear the trouble. For short periods of time the lower-voltage line may be subjected to overvoltage.*

Contact between circuits of different voltage class may also result from failure of the winding-to-winding insulation in transformers. Here, again, the trouble should be recognized by the protective system and the faulted equipment removed by operation of circuit breakers or fuses.

During the short interval of time between the establishment of contact between circuits and the removal of the defective equipment, an overvoltage may be imposed on the low-voltage circuit. The magnitude of this overvoltage may be limited by lightning arresters or by protective gaps.

A point of extreme concern is at the distribution transformer that supplies residential load. Here, flashover of the transformer bushings or failure of the insulation between primary and secondary windings might cause primary voltage (perhaps 12 kilovolts) to appear on the circuits into homes, thus creating a serious fire hazard and a danger to the lives of the occupants. This problem is quite effectively solved by providing primary lightning arresters and by grounding them, the transformer case, and the secondary neutral at the transformer. A ground connection is also placed on the secondary neutral on the customer's premises. Principally by the ground connections, the danger of serious overvoltages is greatly reduced. An accidental connection between primary and secondary circuits results in a ground fault on the primary and the "blowing" of the primary fuses.

The grounding of the secondary neutral of residential distribution circuits greatly reduces the overall hazard to people and property. However, a source of danger still exists which is not generally recognized and which accounts for a few deaths each year. Figure 12-10 shows a typical distribution

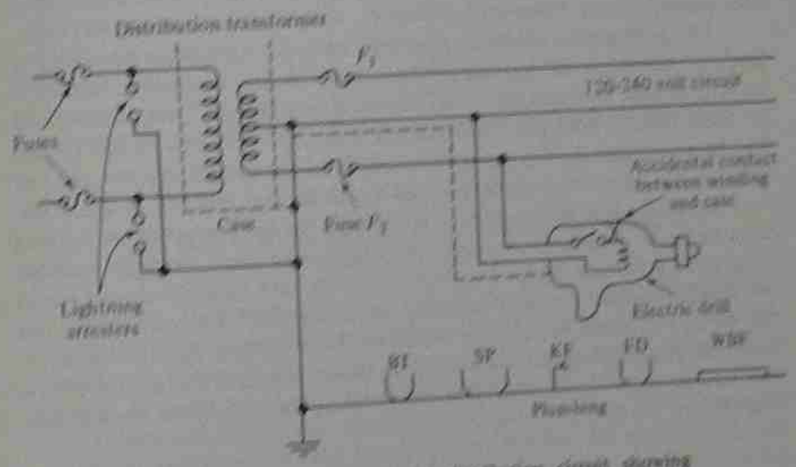


FIG. 12-10. *A typical residential distribution circuit showing equipment which is directly connected to the circuit neutral.*

BT Bathtub
SP Swimming Pool
KF Kitchen Faucet
FD Furnace Duct
WBF Wet Basement Floor.

transformer supplying a 120-240 volt circuit into a home. The secondary neutral, being tied to ground, is also directly connected through the grounded piping of plumbing fixtures and furnaces to such equipment as bathtubs (BT), swimming pools (SP), kitchen faucets (KF), furnace ducts (FD), and wet basement floors (WBF). A person in contact with any of these is tied directly to one side of a 120-volt circuit. If at the same time he touches the other (or hot) side of the circuit, he is directly across the supply. A contact with the hot side of the circuit may be made with a metal floor lamp or metal receptacle in which an unnoticed wiring defect exists. Figure 12-10 illustrates a situation that occurred near the home of one of the authors. A man used an electric drill in which there was an accidental contact between one terminal

of the drill-motor and the metal case. Unfortunately he chose to use the (defective) drill while standing in a swimming pool. When he pulled the trigger of the drill to close the motor switch, the case of the drill was then connected directly to the hot side of the 120-volt circuit. The man was electrocuted.

The importance of ground leads on portable tools and appliances may be illustrated from the above example. Had there been such a ground lead (shown dashed) on the (defective) drill the closing of the switch would have produced a short circuit on the 120-volt circuit. This trouble would have been cleared by the "blowing" of fuse F_2 without injury to the workman.

The person who works on grounded equipment, touches plumbing or pipes, or stands on the surface of the ground should remember that he is making contact with one side of an electric power circuit. Great care should be taken that he does not make contact with the other side of the circuit. The hazard is particularly great if the hands of the person are wet, for wet skin readily conducts current into the liquid-flooded interior of the body.

Specially designed equipment is available for the protection of workers such as boiler repairmen, miners, and others who must work in intimate relation to grounded equipment. Portable tools have been developed which are doubly insulated, greatly reducing the probability of a contact between the energized conductor and the hands of the workman. Another arrangement provides high-speed opening of the power circuit if current (of even a few milliamperes) flows to ground rather than returning in the neutral conductor.

12-6. TRAVELING WAVES

As described in Section 12-5a, the voltages set up on lines by lightning rise from zero to maximum value in a few microseconds. Transients due to switching produce voltages that rise very rapidly, although not as fast as those due to lightning. These voltages may be transmitted many miles over lines and may produce overvoltages in stations far from their origin. The propagation of an electrical disturbance down a line is very rapid but at a measurable rate. When very rapid voltage changes are involved, it is helpful to look at the circuit behavior in terms of *traveling waves* rather than by conventional methods of analysis.

A transmission line (overhead or cable) has a certain inductance per unit length L and certain capacitance per unit length C. For this analysis, resistance and leakage will be neglected. The inductance and the capacitance are distributed all along the line. Each section, even a very short length of line, possesses both L and C. If the line is divided up into small sections of length Δx, the inductance of that section will be $L\Delta x$ and the capacitance

will be $C\Delta x$. A line which is divided into small sections in each of which the inductance and capacitance are lumped is shown in Fig. 12-11. The length Δx may be made as short as desired; thus uniform distribution of the line constants may be represented as closely as desired.

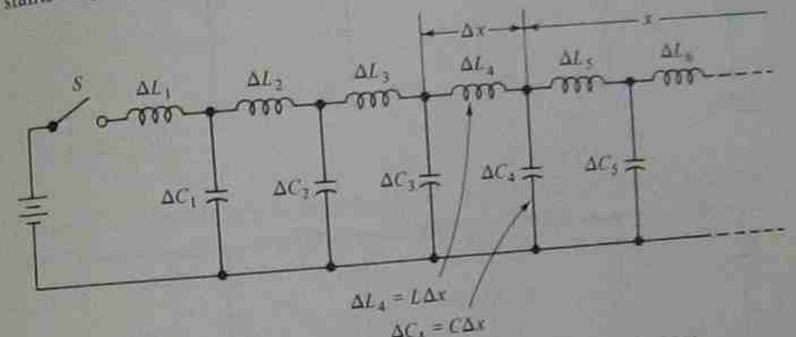


FIG. 12-11. A transmission line shown as incremental sections of inductance and capacitance.

Suppose the switch S is closed at time $t = 0$. The nature of inductance is such that time is required to establish a current of significant magnitude through the inductor ΔL_1. After this current is established, time will be required to build up a voltage on the capacitor ΔC_1. Only after voltage appears here will current start building in inductor ΔL_2. It is obvious that the conditions which exist at the source end of the line are not immediately observed at the far end of the line. The propagation of the source-end voltage and current conditions down the line is termed a *traveling wave*. The velocity of propagation, the relation between current and voltage at any point, the energy transmitted, the energy stored in a section of line, and other relations may be determined from two simple differential equations, derived below.

In Fig. 12-12a we may examine the voltages which exist in an incremental section. At distance x from the far end of the line, assume that the voltage is v and the current is i. At distance $x + \Delta x$ the voltage is $v + \Delta v$. The value of Δv may be written

$$\Delta v = L\,\Delta x \frac{di}{dt} \tag{12-4}$$

In Fig. 12-12b we may examine the currents which exist in an incremental section:

$$\Delta i = C\,\Delta x \frac{dv}{dt} \tag{12-5}$$

If Δx is made very short, these equations take on the differential form:

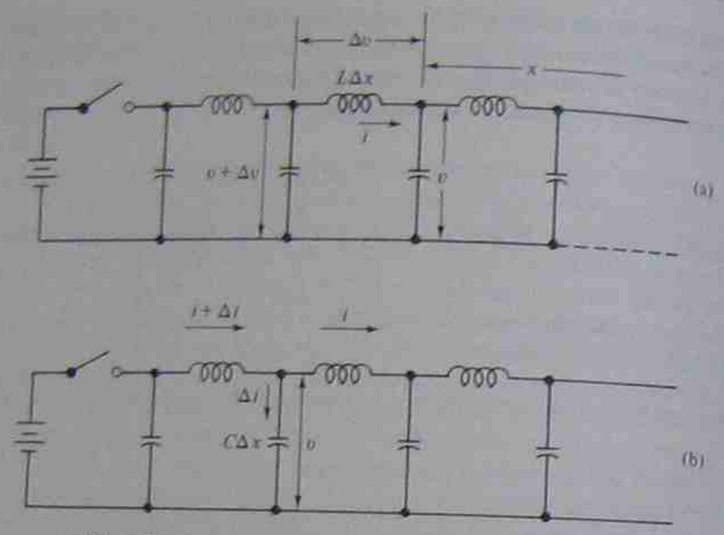


FIG. 12-12. An incremental section of a line. (a) Voltage conditions. (b) Current conditions.

$$\frac{\partial v}{\partial x} = L\frac{\partial i}{\partial t} \tag{12-6}$$

$$\frac{\partial i}{\partial x} = C\frac{\partial v}{\partial t} \tag{12-7}$$

These are the basic equations, from which much can be learned about traveling waves.

The relation between voltage and current in a traveling wave may be determined by the following steps. Dividing Eq. (12-6) by Eq. (12-7) yields

$$\frac{\partial v}{\partial i} = \frac{L}{C}\frac{\partial i}{\partial v}$$

Then

$$\frac{(dv)^2}{(di)^2} = \frac{L}{C}$$

$$\frac{dv}{di} = \sqrt{\frac{L}{C}}$$

or

$$dv = \sqrt{\frac{L}{C}}\,di$$

and, on integrating,

$$v = \sqrt{\frac{L}{C}}\,i \tag{12-8}$$

$$v = Z_c i \tag{12-9}$$

where

$$Z_c = \sqrt{\frac{L}{C}} \tag{12-10}$$

is termed the characteristic impedance of the line. Note that it is a constant relating v and i, and so has the character of a resistor.

The *velocity* of propagation U may be determined from the relation

$$U = \frac{dx}{dt}$$

From Eq. (12-6),

$$\frac{\partial x}{\partial t} = \frac{1}{L}\frac{\partial v}{\partial i}$$

From Eq. (12-7),

$$\frac{\partial v}{\partial i} = \frac{1}{C}\frac{\partial t}{\partial x}$$

Then

$$\frac{dx}{dt} = \frac{1}{LC}\frac{dt}{dx}$$

$$\frac{(dx)^2}{(dt)^2} = \frac{1}{LC}$$

$$U = \frac{dx}{dt} = \frac{1}{\sqrt{LC}} \tag{12-11}$$

The power P flowing past any point is

$$P = vi = \frac{v^2}{Z_c} = i^2 Z_c \tag{12-12}$$

The energy stored in the inductance of the line, per unit length, is

$$W_L = \tfrac{1}{2}Li^2$$

The energy stored in the capacitance of the line, per unit length, is

$$W_c = \tfrac{1}{2}Cv^2$$

The total energy stored in the line, per unit length, is

$$W = W_L + W_c = \tfrac{1}{2}Li^2 + \tfrac{1}{2}Cv^2$$

Since

$$v = i\sqrt{\frac{L}{C}}$$

$$v^2 = i^2\frac{L}{C}$$

and

$$W = \tfrac{1}{2}Li^2 + \tfrac{1}{2}Li^2$$
$$= Li^2 \qquad (12\text{-}13)$$

Similarly,

$$W = Cv^2 \qquad (12\text{-}14)$$

If typical values are substituted into Eqs. (12-10) and (12-11), it is found that the characteristic impedance and velocity of propagation on overhead lines and cable circuits are approximately as given in Table 12-2.

Table 12-2. *Characteristics of Overhead and Cable Lines*

	Characteristic Impedance Z, ohms	Velocity of Propagation U miles/sec	feet/μ sec
OVERHEAD LINE	400	186,000	1000
CABLE	50	90,000	500

Let us examine the time behavior of the overhead line shown in Fig. 12-11 when it is energized by closing the switch S, connecting it to a constant 2000-volt source. This line is shown redrawn in Fig. 12-13a, simplified by the omission of the inductors and capacitors. This line has a characteristic impedance of 400 ohms, a velocity of propagation of 1000 feet per microsecond, and is assumed to be 5000 feet in length.

Suppose now that the switch S is closed at $t = 0$. A voltage and current profile along the line will appear as in Fig. 12-13b. A voltage and current

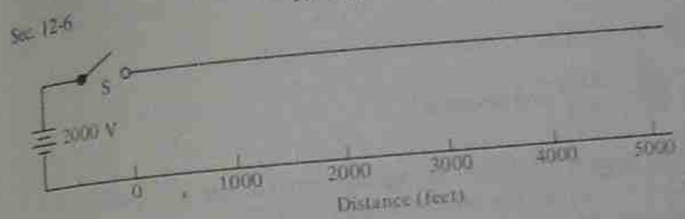


FIG. 12-13. A transmission line being energized by switching on a constant voltage source. (a) The circuit arrangement. (b) Voltage and current conditions at $t = 0+$. (c) Voltage and current conditions at $t = 1$ μsec. (d) Voltage and current conditions at $t = 4$ μsec. (e) Voltage and current conditions, line open circuited at terminal, $t = 6$ μsec. (f) Voltage and current conditions, line short circuited at terminal, $t = 6$ μsec.

exist at the right-hand terminal of the switch, but at other points on the line the voltage and current are zero.

At time $t = 1.0$ μ sec, the voltage and current condition on the line has propagated 1000 feet and the profiles appear as in Fig. 12-13c. In the line section from 0 to 1000 feet, the voltage is at all points 2000 volts and the

current is

$$i = \frac{v}{Z_c} = \frac{2000}{400} = 5 \text{ amperes}$$

At all points beyond 1000 feet, voltage and current are still zero.

At time $t = 4\ \mu$sec the profiles appear as in Fig. 12-13d. Now the voltage is 2000 volts from S to the 4000-foot point, and the current over this same distance is 5 amperes. Beyond the 4000-foot point, voltage and current are still zero.

What happens when the wave comes to the end of the line? The behavior will depend on the method of terminating the line. Energy continues to flow down the line from the power source.

If the line is open-circuited, there can be no current flow at the end, and so all received energy must be stored in the line capacitance. At $t = 6\mu$ sec, the conditions on the line will be as shown in Fig. 12-13e. The voltage from 0 to 4000 feet is 2000 volts and the current is 5 amperes. From 4000 to 5000 feet, the voltage is 4000 volts and the current is zero. This new condition is moving to the left.

If the line is short-circuited at the end, there can be no voltage at the end of the line and all received energy must be stored in the line inductance. At $t = 6\ \mu$sec, the conditions on the line will be as shown in Fig. 12-13f. The voltage from 0 to 4000 feet is 2000 volts and the current is 5 amperes. From 4000 to 5000 feet, the voltage is zero and the current is 10 amperes. The new condition is moving to the left.

The behavior of the line may be analyzed as if an incident wave propagates down the line and reflects when it comes to the end, the reflected wave then propagating to the left. For the incident wave, v_i and i_i,

$$v_i = Z_c i_i \tag{12-9}$$

and for the reflected wave, v_r and i_r,

$$v_r = -Z_c i_r \tag{12-15}$$

(Note that in the reflected wave, the current is flowing to the left, hence the negative sign.)

The voltage v and the current i where both waves exist are

$$v = v_i + v_r \tag{12-16}$$

$$i = i_i + i_r \tag{12-17}$$

where v_i and i_i apply to the incident waves and v_r and i_r apply to the reflected waves.

Refer to Fig. 12-14a, which shows a line terminated by a resistor R.

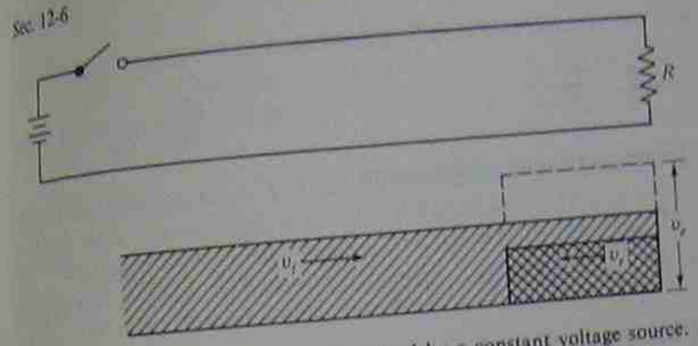


FIG. 12-14. A line being energized by a constant voltage source. The line is terminated by a resistor R. (a) The circuit arrangement. (b) Voltage conditions on the line after reflection.

In Fig. 12-14b an incident voltage wave v_i and a reflected voltage wave v_r are shown. The power carried to the right by the incident wave is

$$P_i = \frac{v_i^2}{Z_c} \tag{12-18}$$

The power carried to the left by the reflected wave is

$$P_r = \frac{v_r^2}{Z_c} \tag{12-19}$$

The voltage v_e on the end of the line at the resistor is

$$v_e = v_i + v_r$$

and the power P_R absorbed by the resistor is

$$P_R = \frac{v_e^2}{R} = \frac{(v_i + v_r)^2}{R} \tag{12-20}$$

Then

$$P_i = P_r + P_R \tag{12-21}$$

$$\frac{v_i^2}{Z_c} = \frac{v_r^2}{Z_c} + \frac{(v_i + v_r)^2}{R}$$

$$\frac{v_i^2 - v_r^2}{Z_c} = \frac{(v_i + v_r)^2}{R}$$

$$\frac{(v_i - v_r)(v_i + v_r)}{Z_c} = \frac{(v_i + v_r)^2}{R}$$

$$\frac{v_i - v_r}{Z_c} = \frac{v_i + v_r}{R}$$

from which the voltage of the reflected wave is

$$v_r = v_i \frac{R - Z_C}{R + Z_C} \tag{12-22}$$

and the voltage at the end of the line is

$$v_e = v_i + v_r$$

$$= 2v_i \frac{R}{R + Z_C} = 2v_i \frac{1}{1 + Z_C/R} \tag{12-23}$$

This equation has the form of the expression for the voltage across R in the circuit of Fig. 12-15.

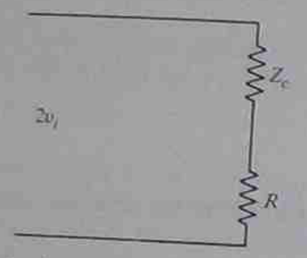


FIG. 12-15. The circuit equivalent of a line terminated in a resistor.

The current through the resistor at the end of the line is

$$i_e = \frac{v_e}{R} = \frac{2v_i}{R + Z_C} \tag{12-24}$$

Suppose the line of Fig. 12-13 is terminated with a resistance of 600 ohms. When the 2000-volt, 5-ampere incident wave reaches the end, a reflection will occur. The voltage of the reflected wave will be, by Eq. (12-22),

$$v_r = v_i \frac{R - Z}{R + Z} = 2000 \frac{600 - 400}{600 + 400}$$

$$= 400 \text{ V}$$

The voltage at the end of the line will be, by Eq. (12-23),

$$v_e = 2v_i \frac{R}{R + Z} = 2 \times 2000 \frac{600}{600 + 400} = 2400 \text{ V}$$

The current in the reflected wave is, by Eq. (12-15),

$$i_r = \frac{-v_r}{Z_C} = -\frac{400}{400} = -1.0 \text{ A}$$

The current through the resistor is by Eq (12-24)

$$i_R = \frac{v_e}{R} = \frac{2400}{600} = 4 \text{ A}$$

Note that if the resistance R at the end of the line is less than Z_C, the reflected voltage wave will be negative and the reflected current wave will be positive.

This mathematical analysis is consistent with the behavior described in Fig. 12-13e and f. If R is infinite (open circuit), by Eq. (12-23), the voltage at the end of the line becomes

$$v_e = 2v_i \frac{1}{1 + Z_C/R} = 2v_i$$

If R is zero,

$$v_e = 2v_i \frac{R}{R + Z_C} = 0$$

Several facts of immediate importance appear from the knowledge of traveling waves here presented.

1. Refer to Fig. 12-8. The effect of current flow to the ground at resistance R_2 is not felt until sufficient time has elapsed for a wave to travel from tower A to B and return. With long spans, this may be several microseconds. This may allow sufficient time for the lightning-produced voltage to rise to a value sufficiently high to cause flashover of the insulators at tower A.
2. Reference to Eq. (12-23) shows that if a line is open at the end ($R = \infty$), the voltage at that point will be $2v_i$. Hence terminal

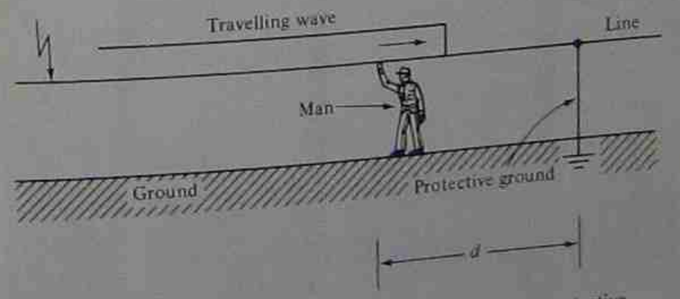


FIG. 12-16. A man working on a line between his protective grounds and the source of a traveling wave.

equipment on an open-ended line may experience a voltage higher than that of the initial traveling wave which produced it.

3. A set of grounds put on a line to protect workmen from lightning-produced voltages must be placed either at the location where the men are working or between the workmen and the lightning source. If placed as shown in Fig. 12-16, the workmen will be subjected to full incident wave voltage for the period required for the wave to travel from the men to the ground and return, a distance $2d$.

12-7. LIGHTNING ARRESTERS

Electric power equipment is subjected to overvoltages from various causes, and the equipment must have adequate insulation to avoid failure. If the overvoltages can be limited to values only slightly greater than the normal operating voltage, favorable designs may be attained. The effects of excessive insulation were discussed in Section 12-4.

Lightning arresters, Fig. 12-17, are devices put on electric power equipment to limit overvoltages to a value less than they would be if the arresters were not present. Ideally a lightning arrester should be off the line under normal operation, switch onto the line when the voltage is perhaps 20 per-

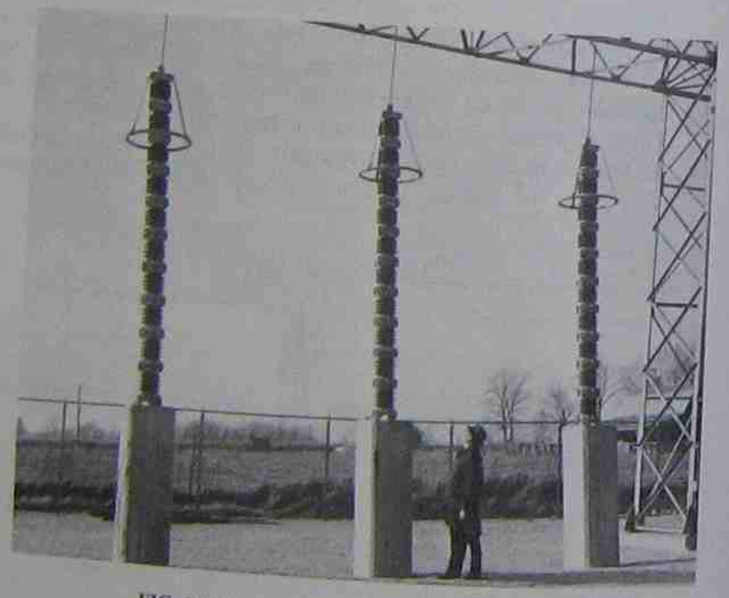


FIG. 12-17. A set of 138 kV lightning arresters.

cent above normal value, limit the voltage to this value regardless of the nature or source of the overvoltage, and switch off of the line when the disturbance is past and normal voltage has been restored.

The basic form of a lightning arrester is shown in Fig. 12-18. A spark

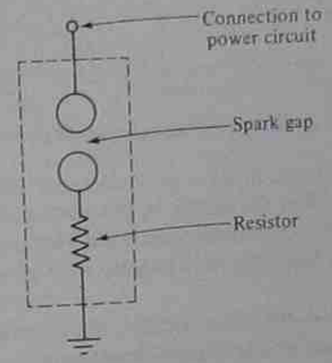


FIG. 12-18. A basic lightning arrester.

gap is connected in series with a resistor. The gap is set at a sparkover value greater than normal line voltage, hence the gap is normally non-conducting. On the occurrence of an overvoltage, the gap sparks over, and then the voltage across the arrester terminals is determined by the IR drop in the arrester. The resistor limits the current flow, avoiding the effect of a short circuit. When the overvoltage condition has passed, the arc in the gap should cease, thus disconnecting the arrester from the circuit. If the arc does not go out, current continues to flow through the resistor, and both the resistor and the gap may be destroyed.

The ohmic value of the resistor is of importance. If it is low, the voltage across it is low during the flow of transient current through it and the device functions effectively as a protection against overvoltage. However, the power follow current through the gap will be high and will be difficult to interrupt. The arrester shown in Fig. 12-18 has the disadvantage that the voltage across it increases linearly with the current flow through it. Thus severe lightning transients will cause proportionately high voltages across the arrester terminals. Nonlinear resistors have been developed for lightning-arrester use. These resistors have current–voltage characteristics somewhat as shown in Fig. 12-19. With this behavior, it may be noted that the resistance drops as voltage (or current) is increased. Suppose a line is terminated in an arrester. Equation (12-23) gives the voltage across its terminals as

$$v_a = 2v_i \frac{1}{1 + Z_c/R} \tag{12-23}$$

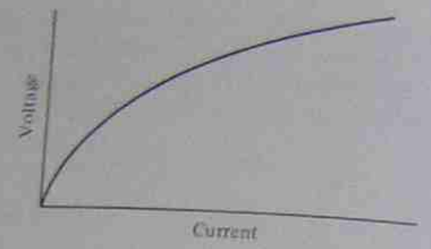


FIG. 12-19. The volt-ampere relationship in the non-linear resistor of an arrester.

It may be noted that as R is decreased, v_a becomes a smaller fraction of v_r. Hence an arrester with a nonlinear resistance element permits across its terminals a voltage that increases only slightly with an increase of the value of the incident wave.

As pointed out in a previous section, the arrester resistor must be disconnected from the line immediately following the end of the overvoltage condition. The interruption of the power follow current by the gap presents the same basic problems as the interruption of the arc in an opening circuit breaker. In one respect the problem is more difficult. In the arrester the arcing contacts are fixed in position, rather than moving apart as in the circuit breaker. In another respect the problem is less difficult. Although the nonlinear resistor of the arrester passes high-magnitude currents during periods of overvoltage, the current with normal voltage across the arrester terminals is proportionately smaller. Hence the power-frequency currents to be interrupted are much smaller than in a circuit breaker.

Figure 12-18 showed the basic elements of a lightning arrester. For application on high-voltage circuits, a large number of these basic elements may be put in series to form the arrester. This design has the advantage that standard parts may be used for arresters of different voltage rating. It also has the advantage that arc interruption is done through a series of gaps, an arrangement discussed in Chapter 9. The spark gaps used in the arresters are designed to have small time lag, uniform breakdown voltage, and favorable arc-extinction characteristics.

A lightning-arrester spark gap of one design is shown in Fig. 12-20. Two diverging metal electrodes A and B are mounted on a disc of vitreous material such as porcelain. Another piece of similar material fits closely on top of the electrodes. Sparkover occurs across the small gap G. The arc moves out progressively into positions 1, 2, and 3. This movement is assured by a magnetic field set up vertically in the arc space by the flow of arrester current through coils placed above and below the gap. The narrow slot between the porcelain supports decreases in thickness toward arc position 3. Arc-extinguishing forces are then the lengthening of the arc and the deioniz-

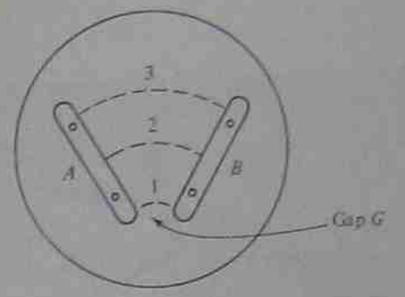


FIG. 12-20. The confined spark-gap of a lightning arrester.

ing effect of the arc confined to the narrow region between the porcelain discs. In some instances arc extinction occurs before the first zero of the power-frequency current.

Arresters must be placed very near the equipment to be protected. In many instances arresters are mounted directly on the tanks of large power transformers. If placed at a distance from the equipment to be protected, traveling-wave conditions may result in a voltage at the equipment much higher than that permitted at the arrester.

12-8. TRANSMISSION-LINE INSULATION

The conductors of overhead transmission lines Fig. 12-21 are supported by porcelain insulators and are insulated from each other by air between the points of attachment.

Modern porcelain insulators are designed and manufactured in such a fashion that in themselves they are almost perfect in operation. Very seldom is porous or cracked porcelain found. Flashover of line insulators is almost always traceable to the breakdown of the air around them due to overvoltage from lightning or other causes. Insulators whose surfaces are contaminated and then moistened by light rain or fog may flash over even under normal-operating-voltage conditions. If an insulator is cracked or porous and permits lightning or power-frequency current to pass through the body of the insulator, it may be shattered, with the resultant dropping of the line.

The air between the conductors of a high-voltage transmission line is under electrical stress. This stress is relatively great immediately adjacent to the conductors and very low midway between them. When the stress in the air exceeds about 30 kilovolts/cm, breakdown occurs within that area where the high stress exists. Hence on a transmission line it is possible to have dielectric breakdown of the air around the conductors without total breakdown between conductors. This condition is termed *corona*.

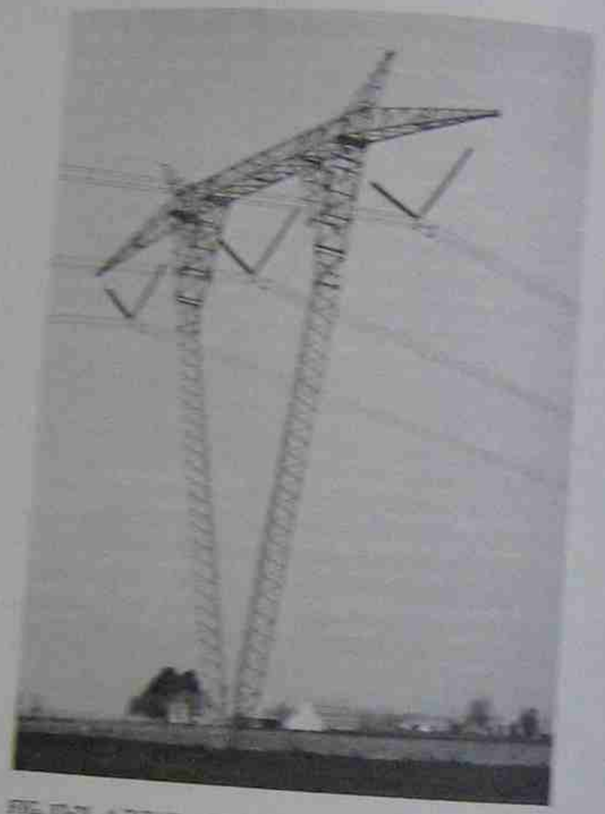


FIG. 12-21. A 765 kV transmission line showing the ground wires, bundle conductors, and V-string insulators.

Corona on transmission lines produces power loss, generates ozone and acid compounds of nitrogen, and produces radio interference and audible noise. These effects are easily tolerated if of low level but can become very annoying if excessive. A great amount of experimental work has been done to study these effects, for they present limiting factors in the voltage at which lines may be operated. Present-day designs permit these effects but attempt to control their levels to a point where they are relatively unobjectionable.

PROBLEMS

12-1. Two parallel plates each 30 by 30 cm are separated by a distance of 0.35 cm. What will be the capacitance between the plates if the dielectric between them is

a. air?
b. glass?

12-2. Refer to Problem 12-1. What will be the approximate value of the voltage necessary to cause puncture or breakdown of the insulation?

12-3. Refer to Problem 12-1. Assume that the insulation is glass. With 25,000 volts dc between the plates, what will be the leakage current and the power loss in the insulation? Will the power loss be greater or less if the test voltage is alternating? Explain.

12-4. A 12-kilovolt power-factor correction capacitor bank has been removed from service by opening a circuit breaker. Consider the point on the wave where the breaker current is interrupted and determine the value (if any) of the voltage that might remain on the capacitor.

12-5. An underground cable connected to an overhead line is taken out of service for maintenance. A safety ground connection is put on the line. Next the cable is disconnected from the line. Describe any hazard which may exist.

12-6. Compare the mechanism of breakdown in the puncture of transformer insulation and in the breakdown of an air gap.

12-7. A transformer bushing has a protective air spark gap in parallel with it. On test the voltage is raised to a value well above that at which this equipment is designed to operate and although held for 30 seconds, no breakdown has occurred. If the test is continued at constant voltage and breakdown later occurs, which piece of equipment, the bushing or the spark gap, would you expect to be the one that failed? Explain.

12-8. For test, a standard wave (Fig. 12-7) is impressed on a power circuit. As the wave travels down the line, how many feet will it be (at any instant) from the point on the line at which the voltage first starts to rise and the point at which the voltage is a maximum? Assume that circuit to be

a. an overhead line.
b. a cable.

12-9. On the basis of the calculated inductance and capacitance per mile line-to-neutral, determine the characteristic impedance and velocity of propagation on a line consisting of 500,000 cir mil copper spaced 12 feet horizontally.

12-10. What is the characteristic impedance and velocity of propagation of a coaxial cable with rubber insulation? The diameter of the outer conductor is 0.8 cm and that of the outer conductor is 2.1 cm.

12-11. The insulators on a transmission line will flash over at 600 kilovolts. In a section of this line the tower footing ground resistance is 18 ohms. What minimum value of lightning stroke current to the ground wire will result in insulator flashover?

12-12. Refer to Problem 12-11. If the stroke contacts the power conductor itself, what minimum value of current will cause flashover? (*Hint:* Consider the stroke current to the line to divide, setting up two traveling waves that flow in opposite directions from the point of contact.)

12-13. An overhead line is terminated by a resistor of 250 ohms. A lightning-produced traveling wave has a voltage of 400 kilovolts. Determine the power in the incident wave, in the reflected wave, and the power absorbed by the resistor. Consider $Z_c = 400$ ohms.

12-14. A long overhead line ($Z_c = 400$ ohms) connects to a long cable ($Z_c = 50$ ohms). A 250-kilovolt traveling wave originates on the line and propagates toward the junction. What will be the voltage at the junction? (*Note:* A long transmission circuit looks like a simple resistor as far as traveling waves are concerned.)

12-15. Repeat Problem 12-14 but assume that the 250-kilovolt traveling wave originates in the cable.

12-16. Describe four locations in your own experience where use of an ungrounded power tool would be particularly hazardous.

chapter 13

Grounding Electric Circuits Effectively

13-1. GROUNDING PRACTICE

In many types of electrical systems it is necessary to install in the ground electrodes or systems of electrodes, which serve as electrical connections to the earth. Such a connection is ordinarily referred to as a *ground*. Any device that is directly connected to a ground is said to be *grounded*. Grounds are required on power systems, on radio broadcast stations, on telephone systems, on lightning rods, and on the steel frames of large buildings.

Many of the devices associated with an electric power system are grounded. In residences, the entrance box and the secondary neutral are grounded. Ground terminals are provided in many of the convenience outlets which may be used to supply portable tools. In a residence, the ground consists of a connection to the water system, if it is available. In some instances, wires embedded in the footings of the building provide a connection to the earth. Driven rods are sometimes required.

At the transformers supplying distribution secondary circuits, a ground connection is provided. To this is connected the secondary neutral and in many instances the transformer case and the lightning arresters. Grounds are provided on the handles that operate airbreak disconnect switches and on regulators and similar pieces of equipment. Transmission lines with overhead ground wires have a ground connection at each supporting structure to which the ground wire is connected.

In generating and switching stations the frames of all generators and motors, the tanks of transformers and oil circuit breakers, and the cases of instruments and relays are grounded. The steel frames of buildings, the steel supporting structures in switchyards, and the fences which surround the stations are all grounded. By having all these parts connected to the same ground, the possibility of a dangerous voltage difference between parts is virtually eliminated.

Grounds are also provided at many points which form part of the electric circuits themselves. The neutrals of wye-connected generators and transformers may be solidly connected to ground or connected to ground through an impedance. Lightning arresters and shunt reactors are solidly grounded. The secondaries of current transformers and potential transformers have a ground at one point on each of the circuits.

The ground-electrode system of a generating or switching station may consist of an extensive network of buried conductors and driven ground rods. Great care is taken in the design and construction of these ground mats to make certain that their resistance is but a small fraction of an ohm.

In normal operation, the electrical connections to the earth (or grounds) carry currents of very low magnitude. These continuous small currents are frequently traceable to minor unbalances which exist in the transmission and distribution lines of the system. The electrical connections to the earth are of primary importance during those short intervals of time when faults exist on the system or when overvoltages arise due to lightning or switching transients. During these *abnormal* periods, which are of short duration, the current conducted through the ground connections may be of magnitudes measured in many thousands of amperes.

Ideally, the resistance of a ground should be zero. Then the flow of current through it causes no rise in the potential of the ground point measured relative to other points on the earth distant from the ground connection. It is, of course, impossible to install a ground-electrode system in the earth which has zero resistance, even with unlimited expenditure of material and effort. It is difficult to define a particular ohmic value of the ground connection which may be considered adequate; a lower value is always preferred. If the resistance to ground is finite (and it always is), current flow through the ground connection results in (1) a rise in potential of the equipment tied to the ground point measured relative to contacts with the earth at distant points, and (2) electric potential gradients measured horizontally on the earth's surface particularly in close proximity to the ground-electrode system. Both results present a shock hazard to personnel and an insulation damage hazard to equipment. These hazards are reduced as the resistance of the ground connection is lowered, but they can never be entirely eliminated.

13-2. GROUND RESISTANCE

The physical structure of a ground-electrode system may take many different forms. It may be a buried plate or a driven rod; it may be a group of two or more driven rods or a system of buried horizontal wires; it may be a combination of buried wires and driven rods. The concept of ground resistance may be demonstrated by considering the simplest form of an electrode, a metal hemisphere buried flush with the surface of the earth (Fig. 13-1).

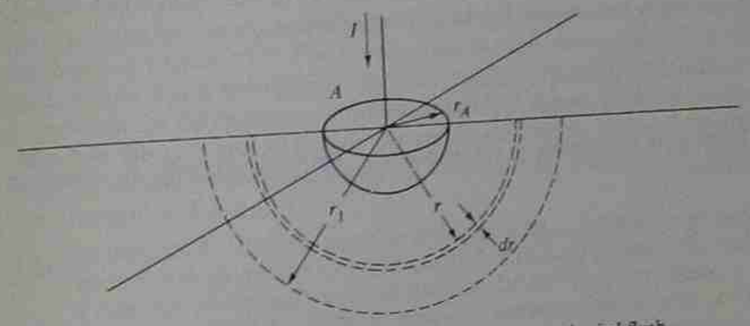


FIG. 13-1. A hemispheric metal electrode of radius r_A buried flush with the surface of the earth.

Assume that a current I from some source (not shown) enters this electrode and flows out radially into the surrounding ground, which is assumed to be of uniform resistivity and of infinite extent. The resistance of this ground connection may be calculated by reference to the well-known relation

$$R = \rho \frac{l}{A} \tag{13-1}$$

in which R is the resistance between two faces of a conducting body of resistivity ρ, length l, and of uniform cross-sectional area A at right angles to the current flow. In the case of the current path in the ground, its cross-sectional area is *not* uniform but increases with increasing distance from the electrode center. The cross-sectional area at right angles to the current flow may be seen to be that corresponding to the area of a hemisphere of radius r. Hence

$$A = 2\pi r^2 \tag{13-2}$$

Since this cross-sectional area applies only for the length dr (Fig. 13-1) of

the current path, Eq. (13-1) must be modified to

$$dR = \rho \frac{dr}{2\pi r^2} \tag{13-3}$$

The incremental resistance dR may be interpreted as the resistance between opposite faces of a thin hemispheric shell of radius r and thickness dr. The resistance between the metal hemisphere A of radius r_A and an imagined hollow metal hemispheric electrode of radius r_1 is obtained by summing the resistances of an infinite number of thin shells which might be placed between A and the large hemisphere:

$$R = \int dR = \int_{r_A}^{r_1} \rho \frac{dr}{2\pi r^2} \tag{13-4}$$

When this expression is integrated and limits substituted, an expression results

$$R = \frac{\rho}{2\pi}\left(\frac{1}{r_A} - \frac{1}{r_1}\right) \tag{13-5}$$

This, then, is the resistance of a path through a volume of earth between a hemispheric electrode of radius r_A and a larger one of radius r_1.

EXAMPLE 13-1. Suppose a metallic hemisphere of radius 25 centimeters is buried flush with the surface of soil whose resistivity is 5000 ohm-centimeters. Calculate the resistance between this hemisphere and a hemispheric metal shell of radius 250 centimeters.

Solution. Substituting in Eq. (13-5) yields

$$R = \frac{5000}{2\pi}\left(\frac{1}{25} - \frac{1}{250}\right)$$

$$= \frac{5000}{2\pi}(0.040 - 0.004) = 28.6 \text{ ohms}$$

If the radius r_1 in Eq. (13-5) is made very great, the equation reduces to

$$R = \frac{\rho}{2\pi r_A} \tag{13-6}$$

Equation (13-6) gives a physical interpretation of the meaning of the ground resistance of an electrode buried in the earth. The ground resistance of a hemispheric electrode (or any other form of electrode that may be chosen) is the resistance from the metallic electrode itself through a path of ever-increasing cross section to an imagined hemispheric electrode of infinite

radius. For practical considerations, it is not necessary to have an electrode of infinite radius as just described. Referring to Eq. (13-5), it may be noted that if r_1 is 10 times the value of r_A, the calculated resistance R is 90 percent of the value given by Eq. (13-6). From this it may be concluded that most of the resistance of an earth connection resides in that soil volume which is very close to the ground electrode.

13-3. EXPRESSIONS FOR GROUND RESISTANCE

An expression for the ground resistance of a buried hemispheric electrode was developed in Section 13-2. The mathematics for this development was relatively simple, but a hemispheric electrode shape is seldom used in practice. Expressions for the resistance of practical electrode shapes have been derived from field theory, a subject beyond the present discussion. The various equations for ground resistance of a number of commonly used electrode shapes are presented in Table 13-1.

EXAMPLE 13-2. Using the equation given in Table 13-1, calculate the resistance of a single ground rod of length 10 feet (305 centimeters) and radius $\frac{1}{2}$ inch (1.27 centimeters) in soil of resistivity 200,000 ohm centimeters.

Solution.

$$R = \frac{\rho}{2\pi L}\left(\log_e \frac{4L}{a} - 1\right)$$

$$= \frac{200{,}000}{2\pi \times 305}\left(\log_e \frac{4 \times 305}{1.27} - 1\right) = 612\,\Omega$$

13-4. PRACTICAL VALUES OF RESISTIVITY

In the formulas for ground resistance presented in Table 13-1, an assumption is made that the soil is perfectly homogeneous and that the resistivity is of some known value throughout the earth volume surrounding the electrode. This is practically never the case. Many factors influence the value of the resistivity, among which may be listed chemical composition of the soil, moisture content, and temperature. If one were to examine the soil in the vicinity of a ground electrode, one might find significant variations in all three of these parameters as one penetrates into the earth.

a. Soil Composition. As shown by Table 13-2, soils of different nature have vastly different values of electrical resistivity, the range being greater than 1,000 to 1. Particularly in glaciated country, where layers of soil have been pushed on top of other soil, stratification may exist. Almost every conceivable combination of strata may be found. Low-resistivity top-

Table 13-1. *Formulas for Calculation of Resistances to Ground**
(Approximate formulas including effects of images. Dimensions must be in centimeters when resistivity is in ohm-centimeters.)

	Hemisphere, radius a	$R = \frac{\rho}{2\pi a}$
•	One ground rod, Length L, radius a	$R = \frac{\rho}{2\pi L}\left(\log_e \frac{4L}{a} - 1\right)$
• •	Two ground rods, $s > L$, spacing s	$R = \frac{\rho}{4\pi L}\left(\log_e \frac{2L}{a} - 1\right) + \frac{\rho}{4\pi s}\left(1 - \frac{L^2}{3s^2} + \frac{2}{5}\frac{L^4}{s^4} - \cdots\right)$
••	Two ground rods, $s < L$, spacing s	$R = \frac{\rho}{4\pi L}\left(\log_e \frac{4L}{a} + \log_e \frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} - \cdots\right)$
—	Buried horizontal wire, Length $2L$, depth $s/2$	$R = \frac{\rho}{4\pi L}\left(\log_e \frac{4L}{a} + \log_e \frac{4L}{s} - 2 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} - \cdots\right)$
└	Right-angle turn of wire, Length of arm L, depth $s/2$	$R = \frac{\rho}{4\pi L}\left(\log_e \frac{2L}{a} + \log_e \frac{2L}{s} - 0.2373 + 0.2146\frac{s}{L} + 0.1035\frac{s^2}{L^2} - 0.0424\frac{s^4}{L^4} - \cdots\right)$
⅄	Three-point star, Length of arm L, depth $s/2$	$R = \frac{\rho}{6\pi L}\left(\log_e \frac{2L}{a} + \log_e \frac{2L}{s} + 1.071 - 0.209\frac{s}{L} + 0.238\frac{s^2}{L^2} - 0.054\frac{s^4}{L^4} - \cdots\right)$
+	Four-point star, Length of arm L, depth $s/2$	$R = \frac{\rho}{8\pi L}\left(\log_e \frac{2L}{a} + \log_e \frac{2L}{s} + 2.912 - 1.071\frac{s}{L} + 0.645\frac{s^2}{L^2} - 0.145\frac{s^4}{L^4} - \cdots\right)$
✳	Six-point star, Length of arm L, depth $s/2$	$R = \frac{\rho}{12\pi L}\left(\log_e \frac{2L}{a} + \log_e \frac{2L}{s} + 6.851 - 3.128\frac{s}{L} + 1.758\frac{s^2}{L^2} - 0.490\frac{s^4}{L^4} - \cdots\right)$
✳	Eight-point star, Length of arm L, depth $s/2$	$R = \frac{\rho}{16\pi L}\left(\log_e \frac{2L}{a} + \log_e \frac{2L}{s} + 10.98 - 5.51\frac{s}{L} + 3.26\frac{s^2}{L^2} - 1.17\frac{s^4}{L^4} - \cdots\right)$
○	Ring of wire, Diameter of ring D, diameter of wire a, depth $s/2$	$R = \frac{\rho}{2\pi^2 D}\left(\log_e \frac{8D}{a} + \log_e \frac{4D}{s}\right)$
—	Buried horizontal strip, Length $2L$, section a by b, depth $s/2$, $b < a/8$	$R = \frac{\rho}{4\pi L}\left(\log_e \frac{4L}{a} + \frac{a^2 - \pi s b}{2(a+b)^2} + \log_e \frac{4L}{s} - 1 + \frac{s}{2L} - \frac{s^2}{16L^2} + \frac{s^4}{512L^4} - \cdots\right)$
●	Buried horizontal round plate, Radius a, depth $s/2$	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 - \frac{1}{12}\frac{a^2}{s^2} + \frac{1}{40}\frac{a^4}{s^4} - \cdots\right)$
	Buried vertical round plate, Radius a, depth $s/2$	$R = \frac{\rho}{8a} + \frac{\rho}{4\pi s}\left(1 + \frac{1}{24}\frac{a^2}{s^2} + \frac{3}{320}\frac{a^4}{s^4} - \cdots\right)$

*H. B. Dwight, Calculation of Resistance to Ground, *Electrical Engineering*, vol. 55, p. 1319, December 1936.

Table 13-2. *Resistivity of Different Soils*

Soil	Resistance,* ¾-in. × 5-ft rods			Resistivity, ohm-cm		
	Av	Min	Max	Av	Min	Max
FILLS (ASHES, CINDERS, BRINE WASTE)	14	3.5	41	2,370	590	7,000
CLAY, SHALE, GUMBO, LOAM	24	2	98	4,060	340	16,300
SAME—WITH VARYING PROPORTIONS OF SAND AND GRAVEL	93	6	800	15,800	1,020	135,000
GRAVEL, SAND, STONES, WITH LITTLE CLAY OR LOAM	554	35	2,700	94,000	59,000	458,000

*Bureau of Standards Technical Report 108.

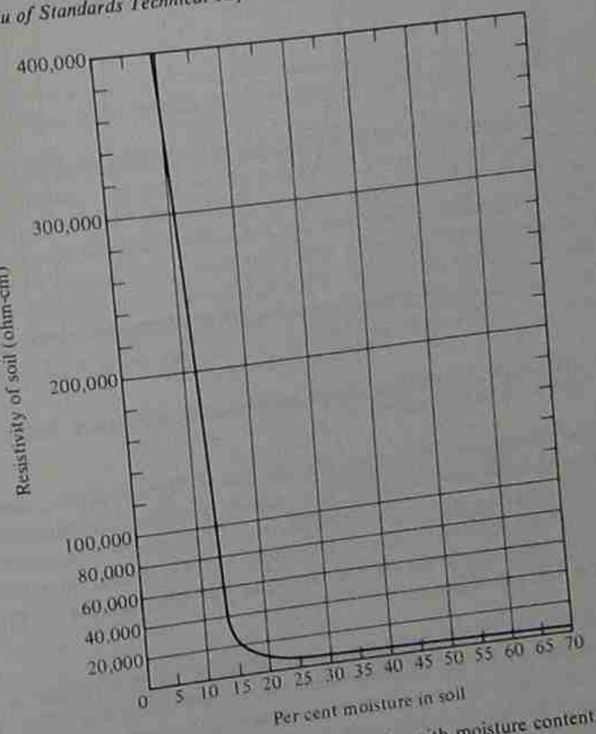


FIG. 13-2. The variation of soil resistivity with moisture content. Red clay soil.

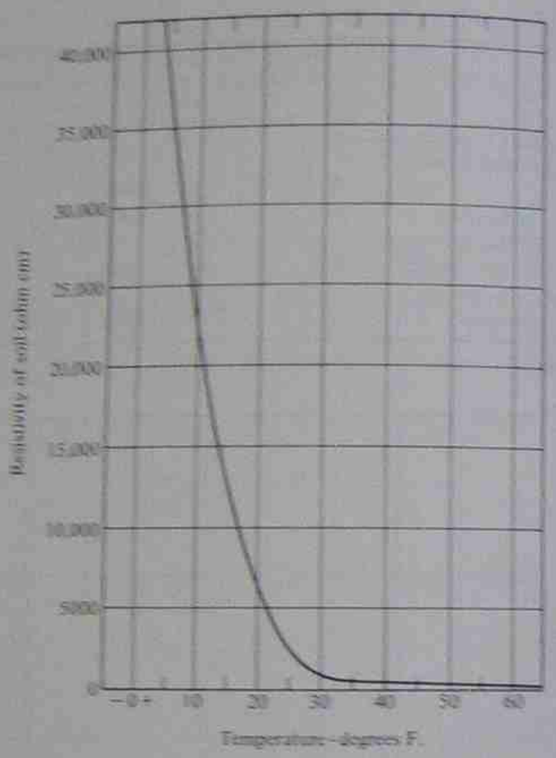


FIG. 13-3. The variation of soil resistivity with temperature. Red clay soil, 18.6% moisture.

soil may be underlayed with high-resistivity gravel. High-resistivity sand may be underlayed with low-resistivity clay. Loam or other low-resistivity soil may form a covering over high-resistivity rock. In some locations there are not only vertical variations in soil resistivity but horizontal variations, as well. This is particularly the case where land has been graded or filled, in preparation for construction.

b. Effect of Moisture. The resistivity of many soils is very strongly influenced by the moisture content, as shown by Fig. 13-2. With most soils, the more thoroughly it is saturated with moisture, the lower is its resistivity. The resistivity increases slowly as moisture content is decreased to about 15 percent. Below 15 percent the resistivity increases rapidly as the percent moisture is decreased. It may increase to 100 times its minimum value as moisture content is reduced to about 2 percent. At zero moisture content, most soils are almost perfect insulators. However, the behavior of soil with less than 2 percent moisture content is probably not of practical importance as it is seldom found except perhaps in a desert location.

c. Effect of Temperature. An example of the variation of soil resistivity with temperature is shown in Fig. 13-3. As may be noted, the resistivity of soil increases rather slowly as temperature drops to the freezing point (32°F). Below the freezing point the resistivity rises very rapidly with further decrease in temperature.

Since both temperature and moisture content strongly affect the value of the resistivity of soil, seasonal variations of resistivity are to be expected, particularly in those soil layers near the surface. A ground-electrode system buried more deeply within the ground is obviously more stable in characteristics.

13-5. HAZARDS ASSOCIATED WITH CURRENT FLOW TO GROUND

Whenever high-magnitude currents flow into the earth at ground electrodes, voltages appear that may be hazardous to personnel and to equipment in the near vicinity of the current-carrying ground electrode. These voltage hazards are illustrated by Fig. 13-4, which shows a hemispheric metal ground electrode A of radius r_a concentric with a hollow hemispheric electrode B, which is assumed to be of infinite radius. A generator G sends current I into the ground at electrode A, the current returning to the generator from electrode B. Suppose that a man standing on the surface of the ground at

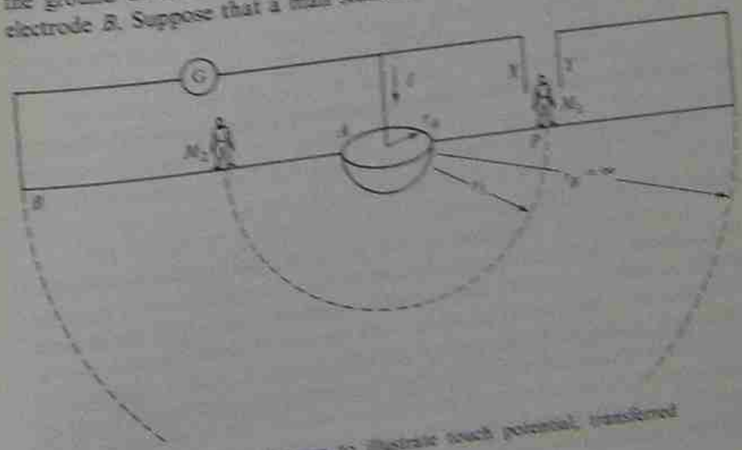


FIG. 13-4. A diagram to illustrate touch potential, transferred potential, and step potential.

P, distance r_1 from A, touches conductor X. The voltage to which he is subjected may be determined as the IR drop between electrode A and an imagined hemispheric surface of radius r_1. From Eq. (13-5) this is

$$V_{touch} = IR_{x1} = \frac{\rho I}{2\pi}\left(\frac{1}{r_A} - \frac{1}{r_1}\right) \tag{13-7}$$

This voltage is sometimes termed the *touch potential*. As may be seen, this voltage diminishes as r_1 decreases, reaching zero when r_1 is equal to r_A.

If while standing at point P, the man touches conductor Y, the voltage across his body is equal to the IR drop between the imagined electrode of radius r_1 and the electrode of radius infinity. Its value is expressed by

$$V_{trans} = IR_{1\infty} = \frac{\rho I}{2\pi}\left[\frac{1}{r_A} - \left(\frac{1}{r_A} - \frac{1}{r_1}\right)\right] = \frac{\rho I}{2\pi}\left(\frac{1}{r_1}\right) \tag{13-8}$$

This voltage is sometimes spoken of as the *transferred potential*. Its value is 0 if the point P is at great distance from electrode A. It reaches its maximum when the point P is on electrode A, its value then being equal to the value of the voltage supplied by the generator.

Next consider man M_2, who is walking on the surface of the ground and in his stride touches the ground at points one meter apart. One foot is at the distance r_1 from electrode A, while the other is at distance $r_1 + 1$. The voltage between his feet may be thought to be the IR drop between two hemispheric electrodes, one of radius r_1 and the other of radius $r_1 + 1$. This voltage, sometimes known as the *step potential*, is

$$V_{step} = \frac{\rho I}{2\pi}\left(\frac{1}{r_1} - \frac{1}{r_1 + 1}\right) = \frac{\rho I}{2\pi}\frac{1}{r_1(r_1 + 1)} \tag{13-9}$$

If r_1 is large compared with 1, the step potential is approximately

$$V_{step} \cong \frac{\rho I}{2\pi}\frac{1}{r_1^2} \tag{13-10}$$

where r_1 is greater than r_A.

The situations described in the preceding paragraphs have many similarities in practice. A man is subjected to touch potential if, while standing on the ground, he touches any metallic object that is tied to the ground electrode. This may occur if, while working out of doors, a man uses a power tool grounded to the station ground system. A man is subjected to the transferred potential if he is standing on a grounded object while handling a telephone wire which extends to a distant station. He is, of course, subjected to step potential as he walks any place toward or away from the ground electrode. Although the analysis here was made with a hemispheric electrode

assumed, a similar analysis made on a driven ground rod or other form of electrode will show the same basic hazards.

Many examples could be cited in which ground-electrode current flow causes stress on the insulation of operating power and communication equipment. Perhaps the most obvious is that which results from the voltage set up between equipment grounded at the station and a telephone line connected to another station some distance away.

13-6. A TWO-ELECTRODE GROUND SYSTEM

A study of a two-electrode ground system aids in showing the behavior characteristics of multipart ground-electrode systems in general. Refer to Fig. 13-5. Two hemispheric electrodes, A and B, of radius r_A and r_B are assumed buried flush with the surface of the earth separated by distance S. Current I_a flows into the earth at electrode A and current I_b flows into the earth at electrode B. The return current is from a very large hemispherical dish electrode, not shown.

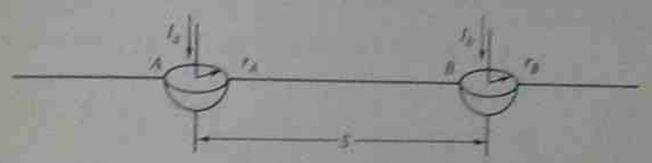


FIG. 13-5. Two hemispheric ground electrodes with radii r_A and r_B and spacing S.

Assume that the effects of the currents I_a and I_b may be linearly superimposed. This means that the current is assumed to flow radially from each electrode, unaffected by the presence of the other electrode. This is a good approximation provided that S is large compared to r_A and r_B. (If S has a value similar to r_A or r_B more advanced methods of analysis are demanded.)

The voltage on A (measured with respect to remote reference) due to I_a is given by Eq. (13-6) as

$$V_{Aa} = I_a\frac{\rho}{2\pi r_A} \tag{13-11}$$

The voltage on A due to the current I_b is the same as the transferred potential due to current I_b and is given by Eq. (13-8) as

$$V_{Ab} = I_b\frac{\rho}{2\pi S} \tag{13-12}$$

The voltage on A due to I_a and I_b is the sum of these voltages, or

$$V_a = I_a\frac{\rho}{2\pi r_a} + I_b\frac{\rho}{2\pi S} \tag{13-13}$$

Similarly, the voltage on B due to I_a and I_b is

$$V_b = I_a\frac{\rho}{2\pi S} + I_b\frac{\rho}{2\pi r_b} \tag{13-14}$$

Equations (13-13) and (13-14) may be regarded as the basic equations applying to this two-electrode system. As these are simultaneous equations in I_a, I_b, V_a, and V_b, it follows that if two of these four quantities are specified, the other two are uniquely determined.

Next consider the electric circuit shown in Fig. 13-6, in which the values

$$R_1 = \frac{\rho}{2\pi}\left(\frac{1}{r_a} - \frac{1}{S}\right) \qquad R_2 = \frac{\rho}{2\pi}\left(\frac{1}{r_b} - \frac{1}{S}\right)$$

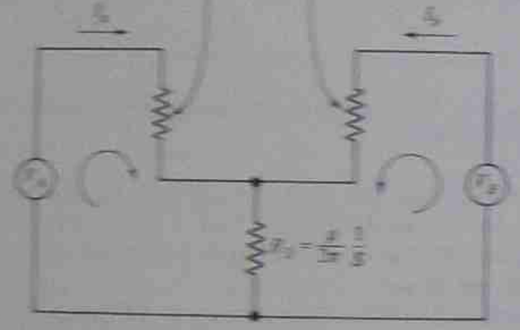
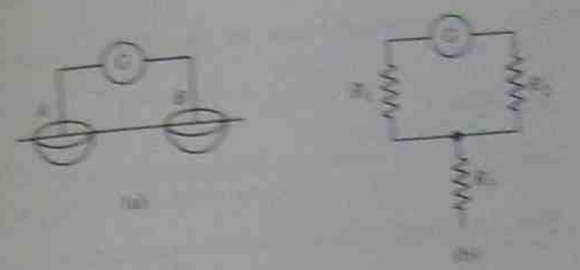


FIG. 13-6. The equivalent electric circuit of two ground electrodes.

of R_1, R_2, and R_3 are specified as shown. If Kirchhoff's voltage equations are written around the two meshes as indicated, simplification of the equations will reproduce Eqs. (13-13) and (13-14). Hence it may be concluded that the three resistances shown in this circuit are equivalent in electrical performance to the two-electrode ground system of Fig. 13-5. From this equivalent circuit diagram, it is possible to determine very quickly the value of resistance which would be measured if the two electrodes of Fig. 13-5 were put in series as shown in Fig. 13-7*a*. This condition is represented in the equivalent circuit shown in Fig. 13-7*b*. The resistance measured is

$$R_{series} = R_1 + R_2 = \frac{\rho}{2\pi}\left(\frac{1}{r_a} + \frac{1}{r_b} - \frac{2}{S}\right) \tag{13-15}$$



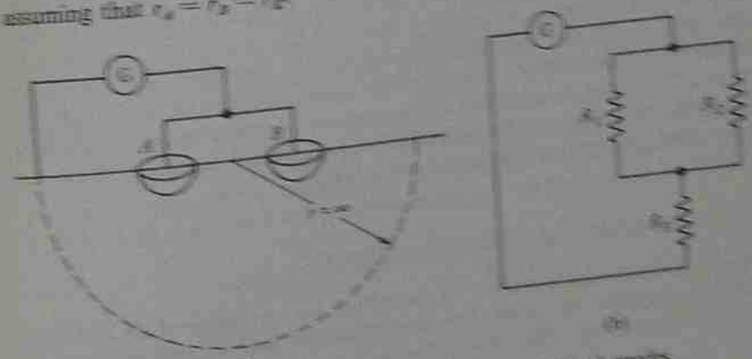
(a) (b)

FIG. 13-7. Two ground electrodes in series. (*a*) The electrodes. (*b*) The equivalent circuit.

Similarly, an analysis may be made of the ground resistance measured if the two electrodes of Fig. 13-5 are put in parallel, as shown in Fig. 13-8*a*. The equivalent circuit of this is shown in Fig. 13-8*b*. The combined resistance as determined from the equivalent circuit is given by

$$R = \frac{\rho}{2\pi}\left(\frac{1}{2r_a} + \frac{1}{2S}\right) \tag{13-16}$$

assuming that $r_a = r_b = r_c$.



(a) (b)

FIG. 13-8. Two ground electrodes in parallel. (*a*) The electrodes. (*b*) The equivalent circuit.

EXAMPLE 13-3. Consider two hemispheric electrodes, each of radius 25 centimeters, with a spacing 400 centimeters in soil of resistivity 8000 ohm centimeters. Calculate

a. R_1, R_2, and R_3.
b. the combined series equivalent resistance.
c. the combined parallel equivalent resistance.

Solution. a. The equivalent circuit of these two electrodes (Fig. 13-6) would have values

$$R_1 = R_2 = \frac{8000}{2\pi}\left(\frac{1}{55} - \frac{1}{400}\right)$$

$$= \frac{8000}{2\pi}(0.040 - 0.0025) = 47.7 \text{ ohms}$$

$$R_3 = \frac{8000}{2\pi}\frac{1}{400} = 3.2 \text{ ohms}$$

b. Then if the two electrodes were connected in series (Fig. 13-7), the resistance of the combination would be

$$R_{\text{series}} = R_1 + R_2 = 47.7 + 47.7 = 95.4 \text{ ohms}$$

c. If the two electrodes were connected in parallel to form a single ground connection (Fig. 13-8), the resistance of the combination would be

$$R = \frac{R_1}{2} + R_3 = 27.0 \text{ ohms}$$

Referring to Eqs. (13-15) and (13-16), it is seen that there are mutual influences between the two ground electrodes. In the case of the series connection, the resistance measured is less than the sum of the resistance of electrode A plus the resistance of electrode B, assuming each resistance measured independently. Only when the spacings are so far apart that the term $2/S$ becomes insignificant do they appear in simple series relationship. Similarly, the two electrodes in parallel behave as two independent electrodes only when the spacing between them is large.

13-7. MEASUREMENT OF GROUND RESISTANCE

Several methods are available for *measuring* the resistance of an installed ground electrode. Of these, the three-electrode method and the fall-of-potential method are the most common.

a. Three-Electrode Method. Consider a ground electrode A whose resistance is to be measured experimentally. This requires that two other electrodes, B and C, be (temporarily) buried in the ground (Fig. 13-9). The electrodes are shown as hemispheric electrodes. They might be driven ground rods or of other shape. The mathematics of the hemispheric electrodes has been presented and can be readily used here. It is necessary that the electrode spacings are large compared to their radii; otherwise errors are introduced. A bridge or other measuring circuit connected with one terminal

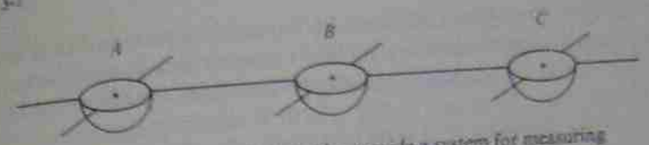


FIG. 13-9. Three ground electrodes provide a system for measuring ground electrode resistance.

on electrode A and one on electrode B measures R_x as

$$R_x = R_A + R_B \tag{13-17}$$

Similarly, R_y is measured between electrodes B and C, and R_z between electrodes C and A with the result

$$R_y = R_B + R_C \tag{13-18}$$

$$R_z = R_C + R_A \tag{13-19}$$

Solving these three equations simultaneously gives the value for R_A as

$$R_A = \frac{R_x + R_z - R_y}{2} \tag{13-20}$$

This method of measurement gives best results if the three resistors are of approximately the same resistance magnitude. If R_B or R_C is large compared to R_A, the calculated value of R_A is subject to considerable experimental error.

b. Fall-of-Potential Method. The resistance of a ground connection may also be measured by the *fall-of-potential* method presented in Fig. 13-10. Again A is the electrode under test whose radius is r_a. Current

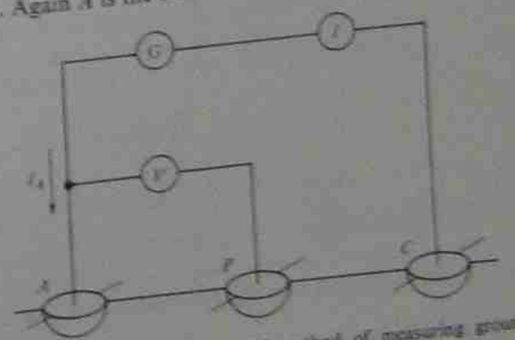


FIG. 13-10. The fall-of-potential method of measuring ground resistance.

from the generator G is sent into the earth through electrode A and returned from a current electrode C. The voltage V is measured between the electrode A and a potential electrode P. The three electrodes need *not* be in a straight line, as shown in Fig. 13-10. If all electrodes are very widely separated, the voltmeter V will measure substantially the same voltage as if connected from electrode A to a remote reference point. The resistance then is

$$R_A = \frac{V}{I} \tag{13-21}$$

In a practical situation, it is sometimes very difficult to provide physical separations that are large compared to the radius of the electrode under test. When measurements are made under these adverse conditions, the voltage of electrode A is determined not only by the current into A but also by the current flow field of electrode C. This behavior is similar to that shown by Eq. (13-13). Similarly, a voltage appears on point P due to the two current-flow fields. Therefore, P cannot be regarded as a reference point at infinity. Under such conditions, the measured value of resistance may be in error.

There are, however, certain electrode arrangements which (theory indicates) yield the correct value for the resistance of electrode A. One arrangement is shown in Fig. 13-11. With electrodes A and C located as shown, a correct reading of the resistance of electrode A is obtained with the electrode P at either X, Y, or Z. Considering the distance from A to C to be 100 percent, the point X is located 62 percent of the distance from A. The point Y is located 162 percent of the distance from A to C, the point Z is located 100 percent of the distance from A and 50 percent of the distance from C.

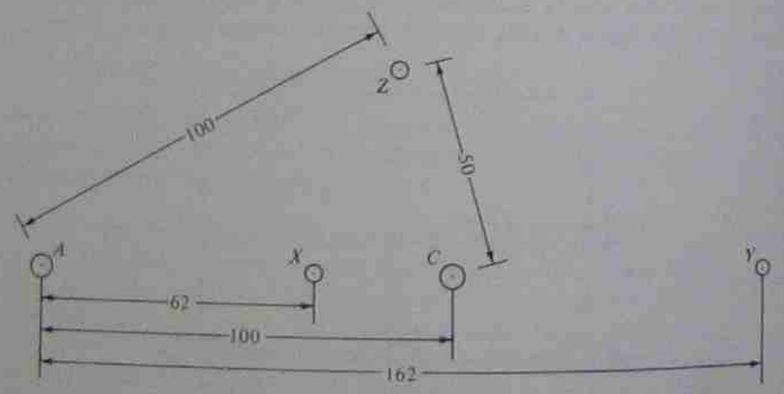


FIG. 13-11. Electrode arrangements which minimize error in the fall-of-potential method of measurement.

Although the measuring arrangement just described is theoretically correct for the assumption of uniform soil resistivity, it may be somewhat in error under the nonuniform conditions that always prevail.

c. Precautions in Measurements. Certain precautions are necessary in using either the three-electrode method or the fall-of-potential method in measuring ground resistance. The ground connection to be measured must be insulated from connections which may tie it to other grounds remotely located. For example, overhead ground wires of transmission lines sometimes are connected to station structures. The ground-wire connection at the structure should be removed or insulated. Care should be taken to make certain that all such connections are removed.

The leads that run from the measuring instruments to the three ground electrodes provide situations similar to those with which touch and transferred potentials were described in Section 13-5. In case a fault occurs on the power system of such nature as to cause high current flow through the ground under test, dangerous values of touch and transferred potential may be produced. A person making tests must protect himself against the possibility of a dangerous voltage appearing on his test leads.

13-8. MEASUREMENT OF SOIL RESISTIVITY

Soil resistivity may be measured by several different methods, two of which are described. As all the formulas for ground resistance given in Sec. 13-3 have, as a common factor, the resistivity of the soil, it is apparent that a knowledge of soil resistivity is helpful to the designer of a ground-electrode system to be installed at a particular location.

a. Four-Electrode Method of Measuring Resistivity. A commonly used method of measuring earth resistivity is described with reference to Fig. 13-12. Four electrodes, A, B, C, and D, are

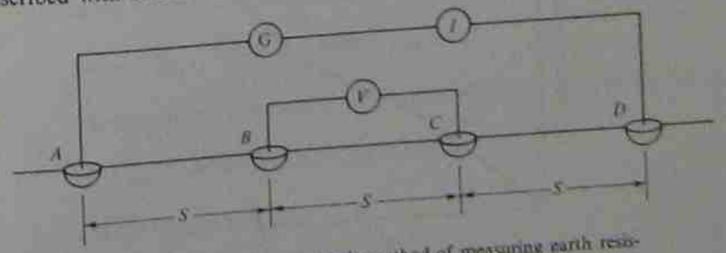


FIG. 13-12. The four-electrode method of measuring earth resistivity.

placed in the ground in a straight line with spacing S. In the diagram these electrodes are shown as being hemispheric in shape, although this is not a requirement. Short driven rods serve equally well and are more convenient to obtain and use. A current I is circulated through the ground between electrodes A and D. The voltage, V, between B and C is measured. Then

$$\rho = \frac{V}{I} 2\pi S \tag{13-22}$$

The spacing of the probes influences the depth of penetration of the principal part of the current between the electrodes A and D. For this reason, wide spacing S between the electrodes results in a measurement of the resistivity deep within the ground. It is sometimes assumed that the value of resistivity measured is approximately equal to the average value of the resistivity of the soil down to a depth S.

b. Driven-Ground-Rod Method. The resistivity of soil at varying depths may be determined quite accurately by driving a ground rod into the soil and making a measurement of its resistance, periodically, during the driving process. A curve is then plotted showing the rod conductance G plotted against *depth* L (Fig. 13-13). In Sec. 13-3 the formula for the resistance of a driven ground rod was given as

$$R = \frac{\rho}{2\pi L}\left(\log_e \frac{4L}{a} - 1\right) \tag{13-23}$$

This expression may be inverted to give the conductance of a ground rod:

$$G = L\frac{2\pi}{\rho}\frac{1}{\log_e (4L/a) - 1} \tag{13-24}$$

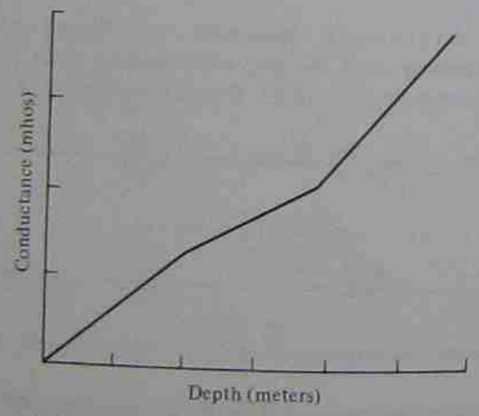


FIG. 13-13. Ground-rod conductance vs. depth.

Equation (13-24) shows the conductance of a driven rod to be the product of three terms, one is the length L, one is $2\pi/\rho$, and one is a logarithmic expression involving the ratio of rod length to rod radius. It may be observed that the term under the horizontal line is a very slowly changing function of L. For a rod of 1/2 inch radius, this term changes only from 4.2 to 6.5 as L is increased from 2 feet to 20 feet. If it is assumed to be constant, at a value 5.0, then an approximate expression for G is

$$G = \frac{2\pi L}{5\rho} \tag{13-25}$$

or

$$G = 0.4\pi L\sigma \tag{13-26}$$

where σ is the soil conductivity, the reciprocal of ρ.

Differentiating Eq. (13-26) with respect to L results in

$$\frac{dG}{dL} = 0.4\pi\sigma \tag{13-27}$$

or

$$\sigma = \frac{10}{4\pi}\frac{dG}{dL} \tag{13-28}$$

The value of σ derived from this relationship is the value applying to the soil at that depth for which dG/dL is calculated. L must be expressed in centimeters if σ is to be in mhos per centimeter. Then $\rho = 1/\sigma$ is in ohm-centimeters.

EXAMPLE 13-4. Suppose that a rod of $\frac{1}{2}$-inch radius is driven into the ground and resistance measurements are taken at various depths. At 8 feet (244 centimeters) the resistance is 500 ohms (0.0020 mho) and at 12 feet (366 centimeters) the resistance is 400 ohms (0.0025 mho). A plot of the conductance in this region is as shown in Fig. 13-14. The slope of the conductance line is

$$\text{slope} = \frac{\Delta G}{\Delta L} = \frac{0.0005}{122} = 0.0000041 \text{ mho/cm}$$

The conductivity in the region from 8 to 12 feet deep is then, by Eq. (13-28),

$$\sigma = \frac{10}{4\pi} \times 0.0000041 = 0.0000033 \text{ mho/cm}$$

and the resistivity is

$$\rho = \frac{1}{\sigma} = 304{,}000 \text{ ohm-cm}$$

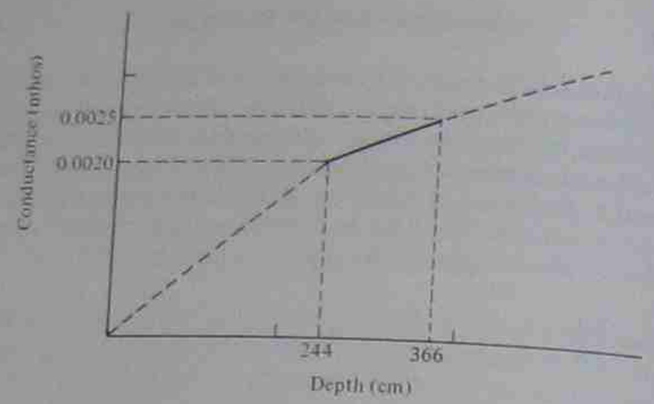


FIG. 13-14. An experimentally determined conductance-depth relationship of a driven ground rod.

In making ground-resistivity measurements near a ground electrode of an operating power system, safety precautions must be taken similar to those mentioned for the measurement of resistance in Sec. 13-7. In case of a heavy current flow through the power-system ground, voltages of dangerous magnitude may appear between the electrodes used for resistivity measurements.

In making measurements of resistance and resistivity it is necessary to *avoid* using direct current instruments. The conduction of current in the ground is by a process very similar to that of the conduction of the current in a liquid. With a unidirectional flow of current, a process known as polarization causes gas to accumulate near one of the electrodes, with an accompanying increase in the apparent resistance of that electrode. The use of alternating current for resistance and resistivity measurements entirely eliminates this effect. Self-contained ground-resistance measuring instruments are available which provide an alternating voltage source and the associated instrumentation.

13-9. LIMITATIONS ON GROUND-ELECTRODE DESIGN

In designing and constructing a ground-electrode system it may be hoped to meet certain specifications on the resistance of the finished system. From first considerations it might be thought that by putting enough electrode material in the earth, the ground resistance of the complete system could be made as low as desired. However, this is not the case if the land area for the construction of the electrode system is limited. This subject may be discussed more readily by referring to the conductance of the electrode system rather than its resistance. To attempt to reduce its resistance to a specified value is equivalent to attempting to raise its conductance to some value.

The limitations on the design of a ground-electrode system on a restricted area will be illustrated by reference to a system consisting of a number of driven ground rods. Suppose that a number of $\frac{3}{4}$-inch diameter, 10-foot rods are to be driven in a limited area to form a ground connection. The conductance of the system increases each time another rod is driven. However, the conductance of two rods is slightly less than twice the conductance of one rod, and as other rods are added the conductance increases but at a diminishing rate. Fig. 13-15 shows the ratio of the conductance of a group of rods to the conductance of one rod plotted against the number of rods. Separate curves are shown for different available ground surface areas. It may be noted that for an area of 500 square feet, 10 rods have about 4.7 times the conductance of a single rod. An infinite number of rods in that area would have a conductance only 4.9 times the conductance of one rod. This limitation may seem more reasonable when it is considered that an infinite number of 10-foot rods on the 500-square foot area would afford a ground electrode equivalent to that of a metal box 10 feet deep filling the entire 500 square foot area. This box might be compared with a hemispheric

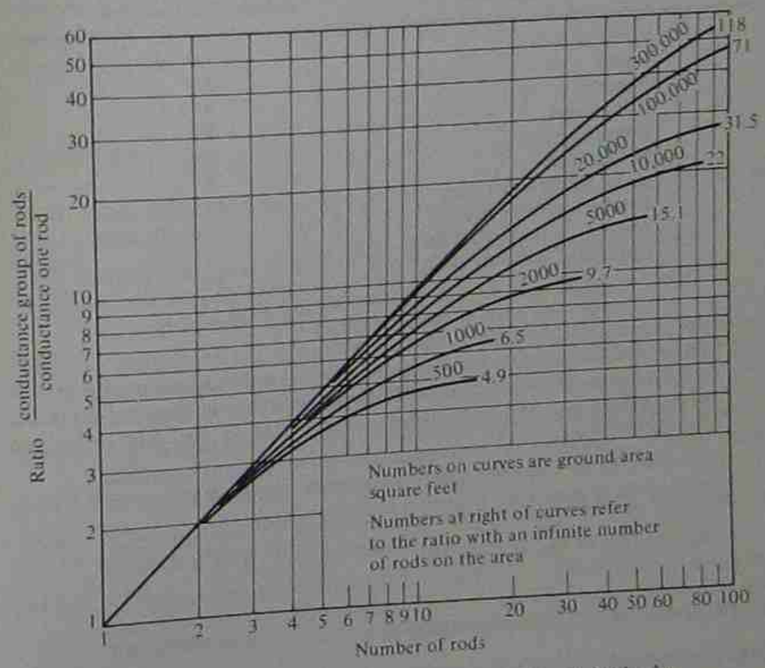


FIG. 13-15. Comparison of the conductance of many 3/4-in. by 10-ft ground rods spread over an area with the conductance of a single ground rod.

electrode of the same surface area, the resistance (or conductance) of which was discussed in Section 13-2.

In some cases, ground electrode systems are made of grids of buried horizontal wires. With such an arrangement, increasing the number of meshes in the grid increases its conductance. However, its conductance can never be increased beyond that of a buried plate of the same outside dimensions.

In some instances, a grid of buried horizontal wires is used in combination with driven ground rods. Table 13-3 shows a comparison of the conductance of different forms of ground-electrode systems, each restricted to a ground area 100 feet square. Attention must be given to the inherent limitations of the conductance of ground-electrode systems to avoid the expenditure of unnecessary time and materials in an effort to obtain a conductance that is, in fact, unattainable.

Table 13-3. *Comparison of the Conductance of a Single Ground Rod with the Conductance of Other Ground-Electrode Systems Land Area 100 feet by 100 feet*

Structure*	Relative Conductance
1 GROUND ROD	1.0
4 RODS	3.6
36 RODS	8.75
1-MESH GRID	7.0
4-MESH GRID	7.6
25-MESH GRID	8.7
PLATE, 100 by 100 ft	10.0
25-MESH GRID plus 36 rods	10.0
BOX, 100 by 100 ft, 20 ft deep	12.1
HEMISPHERE, diameter 100 ft	16.1

*Ground rods are 1-in. diameter by 20 ft deep
Grid wires are 1-in. diameter buried 1½ ft

EXAMPLE 13-5. Suppose that a 1-inch by 20-foot rod is driven into the ground and its resistance is measured as 250 ohms. Calculate the expected resistance of a 25-mesh grid of 1-inch-diameter wire buried 1½ feet deep on an area 100 by 100 feet.

Solution. Table 13-3 shows the conductance of such a grid to be 8.7 times that of the ground rod. Hence its resistance is

$$R_{grid} = \frac{R_{rod}}{8.7} = \frac{250}{8.7} = 29 \text{ ohms}$$

13-10. ANALYTICAL AND EXPERIMENTAL STUDIES OF ELECTRODES

Digital-computer methods are available for determining the resistance of a ground-electrode system of any configuration. The mathematical methods of analysis and the computer programming is beyond the scope of the present discussion. Practically all these methods of calculation are based on the assumption of uniform soil resistivity, a condition that is almost never found. For this reason the great precision of computer methods is of little help.

Ground-electrode-system designs may also be studied by means of scale models. The models may be constructed on a sheet of ¼-inch plywood, to support it at the surface of the water of a lake or swimming pool. The measurement of the resistance of the model is made in a fashion exactly like that described in Sec. 13-7 and Fig. 13-10.

Whenever a model is used it is necessary to determine the relations by which it is scaled. Consider the hemispheric electrode discussed in Section 13-2. Doubling the radius of such an electrode multiplies its volume by 8 and its surface area by 4. Reference to Eq. (13-6) shows that its resistance is divided by 2 or its conductance is doubled. Similarly, reference to the expression for the resistance of a driven ground rod Eq. (13-23) shows that if all dimensions of the rod are multiplied by 2, the conductance is doubled.

It may be shown that this form of relationship exists for all possible ground-electrode systems. If all the linear dimensions of the parts of a system are multiplied by the factor F, the conductance is multiplied by F. This relationship shows the simplicity of the study of electrode systems by means of scale models.

PROBLEMS

13-1. List, from your own observations, items of electrical equipment that are grounded.

13-2. Determine the resistance of a ¼-in. by 8-ft ground rod driven into
a. average clay soil.
b. high-resistivity sand.

13-3. Compare the resistance of a hemisphere electrode of diameter 50 cm with the resistance of a 50-cm-diameter ring of wire. The wire is 1 cm in diameter buried 20 cm deep. Specify the soil resistivity considered.

13-4. A ground-electrode system in red clay soil of 20 percent moisture content measures 35 ohms. What resistance might be expected if in a dry season, the moisture content dropped to 10 percent?

13-5. A ground-electrode system in clay soil measures 50 ohms when the temperature is 40°F. What resistance might be expected at 10°F?

13-6. A 25-cm-radius ground electrode is buried in soil of resistivity 8000 ohm-cm. A current of 500 amperes flows to ground through the electrode. A man is standing 6 meters from the electrode. Determine the voltage to which he will be subjected if he
a. touches a wire that connects to the electrode.
b. touches a wire that connects to a remote location.
c. in walking, touches the ground at two points 1 meter apart.

13-7. Three ground electrodes, *A*, *B*, and *C*, are widely spaced relative to their diameters. Resistances are measured by the three-electrode method with the following results:

A and *B*	370 ohms
B and *C*	750 ohms
C and *A*	420 ohms

Determine the resistance of each electrode.

13-8. Refer to Problem 13-7. Suppose that in making the *A* and *B* measurement, the value recorded was 5 percent too high. What then is the calculated resistance of electrode *A*? What percent error results?

13-9. The resistance of a ground-electrode system is made by the fall-of-potential method. The voltage of the source is 60 volts, the voltage between the subject electrode and the potential electrode is 21 volts, and the current is 5.1 amperes. What is the value of the ground resistance?

13-10. Ground resistivity is measured by the four-electrode method (Fig. 13-12), with electrodes spaced 12 feet apart. Observations show 32 volts and 0.15 amperes. Determine the soil resistivity in ohm-centimeters.

13-11. Refer to Problem 13-10. Suppose that electrodes *B* and *C* each had a resistance of 5000 ohms and the voltmeter had a resistance of 15,000 ohms. What correction in the results would be indicated? Is this same type of error possible in measuring resistance by the fall-of-potential method?

13-12. One $\frac{3}{4}$-in. by 10-foot ground rod has a measured ground resistance of 480 ohms. What will be the expected resistance of 20 rods spread over an area 50 by 100 feet?

13-13. Refer to Problem 13-12. What will be the expected resistance of a great number of rods spread over an area 100 by 100 feet?

13-14. Assume that the ground resistance is 2000 ohm-cms. Determine the resistance of

a. a 1-inch by 20-foot ground rod.
b. a 25-mesh grid with 36 rods, spread over an area 100 by 100 feet.
c. a hemisphere 100 feet in diameter.

13-15. A 20-foot, 1-inch-diameter rod is driven into the ground and resistance measurements taken as follows:

Depth, ft	Resistance, ohms
5	4000
10	2000
15	800
20	300

Determine the approximate soil resistivity at 17 feet.

chapter 14

Power Distribution

14-1. GENERAL

This chapter deals with the methods used in bringing electric power to the doorstep of the consumer, and with the various considerations and rules that the consumer must abide by in utilizing this power. This is what is meant by power distribution. Since distribution is that part of the power system which comes close to most people in their daily life, safety is the prime consideration, followed by reliability of service. Equipment ratings and layouts are thus regulated by various standards and codes, foremost among them being the National Electrical Code.

This book does not presume to be exhaustive on any topic. It is imperative that, in an actual distribution design or application, the reader consult the equipment manufacturers and the national and local codes in force. By their very nature the various codes and standards are terse since they are intended for the practitioner. It is hoped that this chapter will ease the reader's task as he delves into the codes.

In the general configuration bulk power is delivered by a high-voltage transmission line, say 240 kV, to a substation which steps the voltage down to a high-voltage distribution level, between 11 and 33 kV. From the high-voltage substation various lines branch out in the direction of a few large load concentrations, as shown in Fig. 14-1. Before reaching a large load concentration, the electric power is converted to a lower voltage (2 to 4 kV).

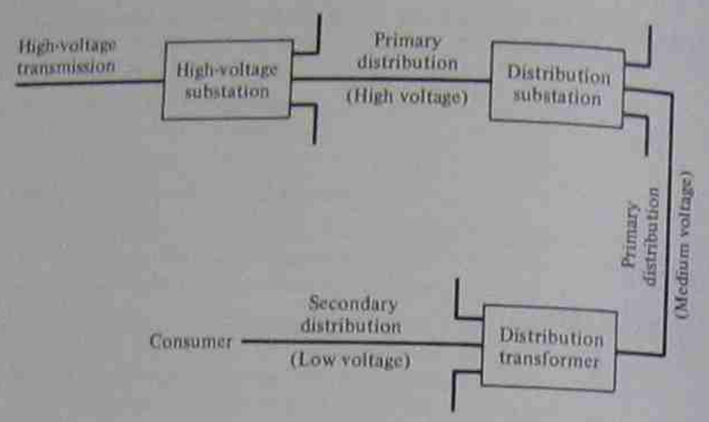


FIG. 14-1. The basic distribution system.

This is the primary distribution system. Various primary feeders then start out in the direction of load centers, each usually carrying a few hundred kilowatts a distance of up to 2 miles to transformer substations. The voltage is then stepped down to no more than 600 volts in what evolves as the secondary distribution system. Lines and cables not exceeding a few hundred feet in length then deliver power to the individual consumers.

The consumer, be it a residential house, apartment building, office building, or industrial plant, is connected to the distribution (secondary or street) transformer in the manner indicated in Fig. 14-2. The service equipment comprises the protective devices as well as the energy consumption meters. Large industrial plants consisting of many buildings spread over a wide area often have primary distribution lines running inside the plant itself, as in Fig. 14-3. The plant is then considered to be a conglomeration of load centers rather than a single load center. This scheme offers flexibility, efficiency, and reliability. The power is conveyed to the various load locations at the higher distribution voltage, resulting in greater economy of operation than if a single large substation is used at the plant entrance to reduce the voltage to secondary level. While a single large substation may be less expensive than a few smaller ones, the corresponding lower voltage cable system is costlier and less efficient than the higher-voltage one. Load-center power distribution is a means for decentralizing secondary distribution. The most common size is in the range 500 to 1500 kVA.

Load-center distribution is not suited to very small plants or buildings. In this case the secondary distribution system brings the voltage down to the appropriate level in one location of the plant or building, and from that point cables run to the various loads.

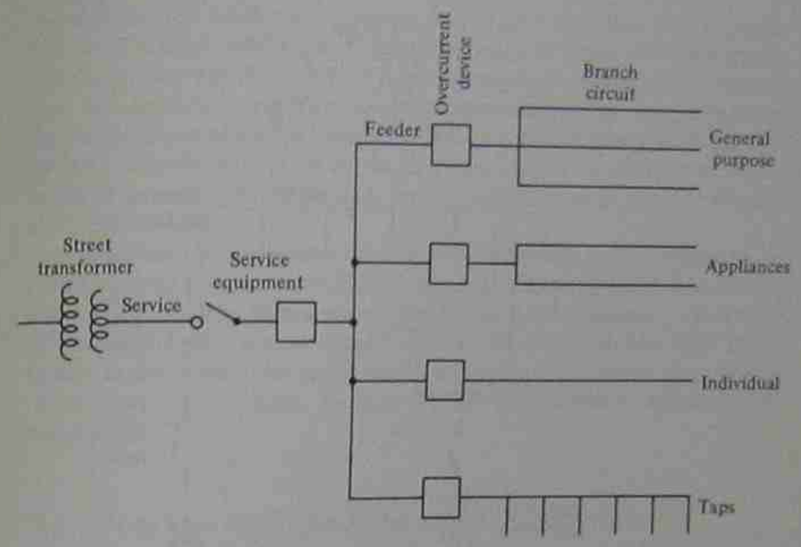


FIG. 14-2. Consumer connection to a distribution transformer.

Being located close to where power is consumed, load-center substations need short secondary feeders to connect them to their loads; the voltage drop in cables is thus lower than in the single large substation arrangement. For greater flexibility and reliability, more than one load-center substation may be located at the same point in the plant, and possibly be interconnected. Indeed, such substations do not have to satisfy all the load requirements at a given location. Moreover, it is not necessary to predict too far in the future the growth of the power consumption; new substations are added as the load grows and are sited where the load has actually grown.

The primary distribution system starts with the incoming utility line. There may sometimes be more than one line: two separate lines used alternately or simultaneously to feed separate parts of a plant; or two lines that may be paralleled, or that may be part of a loop. Whatever the case, it is important to know the nature of this line or lines and the utility equivalent circuit at the point of entry to the primary distribution system in order to be able to calculate short-circuit currents.

When the incoming line voltage exceeds 14 kV, the primary distribution substation is usually built outdoors with oil circuit breakers. For voltages below 14 kV the substations are built in or out of doors and the circuit breakers are normally of the metal-clad type. As for the transformers, they are usually connected in delta on the high-voltage side in order to have a stable voltage (the line voltage) across each primary winding, and connected

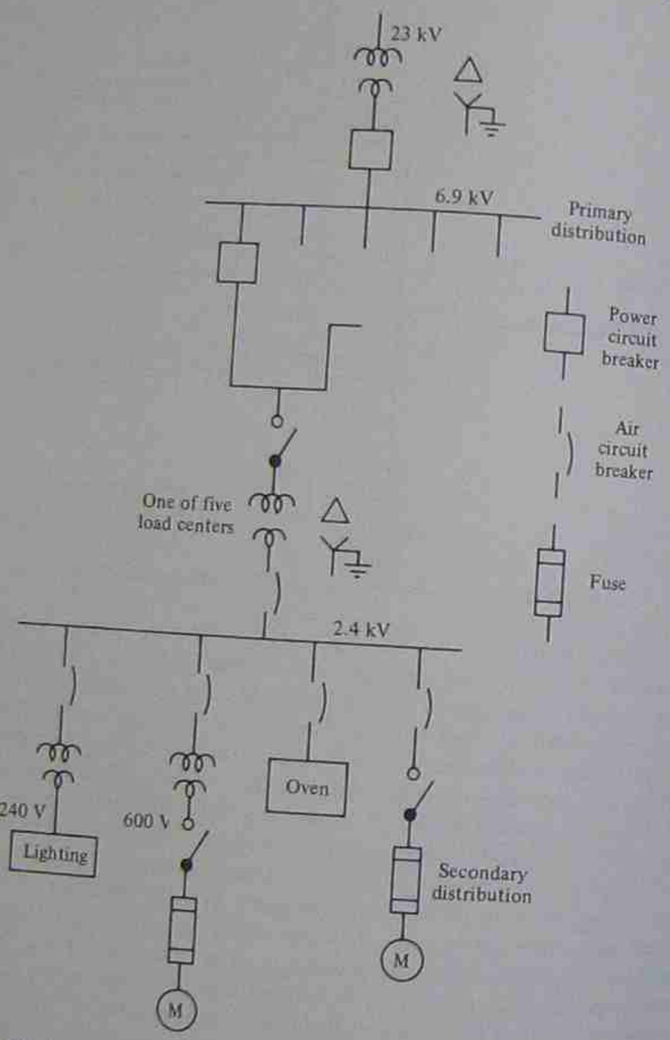


FIG. 14-3. Layout of the power distribution system in a large industrial plant.

in grounded wye on the secondary side in order to provide a ground to the low-voltage side.

The secondary distribution system starts from the load side of the secondary feeder protective device and ends at the load terminals. In order to limit the short-circuit current level in the secondary distribution system, the

transformer sizes feeding them should be properly evaluated. For example, the use of a single 1000-kVA transformer results in larger secondary short-circuit currents than if two 500-kVA transformers are installed. The reason is that, for the same transformer percent impedance, the per-unit impedance referred to a common kVA base for a 1000-kVA transformer is half that of a 500-kVA transformer. If small transformers cannot be used, some other means of increasing the impedance must be sought so as to restrict excessive short-circuit currents.

Reactors are sometimes employed in series with the transformers or cables in order to limit short-circuit currents. Their drawback is that they increase voltage drop during normal conditions, maybe excessively so during motor starting. It is always better to use a circuit breaker with high interrupting rating, even if the cost is somewhat higher than a lower interrupting rating breaker plus reactor. Besides, reactors are not purely inductive and lose power.

14-2. CONNECTION OF SECONDARY TO PRIMARY DISTRIBUTION

When many small unit substations are used instead of a single large substation, there exist many ways in which they can be connected to the primary distribution feeders and to each other. An important role played in this regard is that of an interrupter switch. An interrupter switch not only serves as a disconnecting means, but is also capable of interrupting currents at its rated voltage, not exceeding its continuous current rating. Thus, it cannot be used to open or make faulty lines, as it may explode and fatally injure its operator. When located on the primary side of a transformer, it is preferably used only for breaking the transformer magnetizing current. Ideally, a power breaker is used on the primary side, as shown in Fig. 14-4a. No particular precaution must be taken in opening or closing a breaker, but cost is a seriously restraining factor. When reenergizing a transformer in the system of Fig. 14-4b, it is very important that the feeder breaker be open before closing the interrupter switch to make sure that the latter would not make a faulty circuit.

There are many ways of connecting unit substations to the primary distribution system. In order of economy (and popularity) they are: radial, secondary pairing, secondary loop, primary pairing, and primary loop arrangements. The most widespread is, by far, the radial configuration.

A radial configuration exhibits no looping whatsoever. It provides a single direct path from the high-voltage feeder to the transformer to the load as shown in Fig. 14-5. It is safe, economical, simple to operate, and yet highly reliable due to the high reliability of the equipment. However, a failure at any point cuts off service to all points downstream from that point.

In the secondary pairing configuration pairs of load-center secondaries

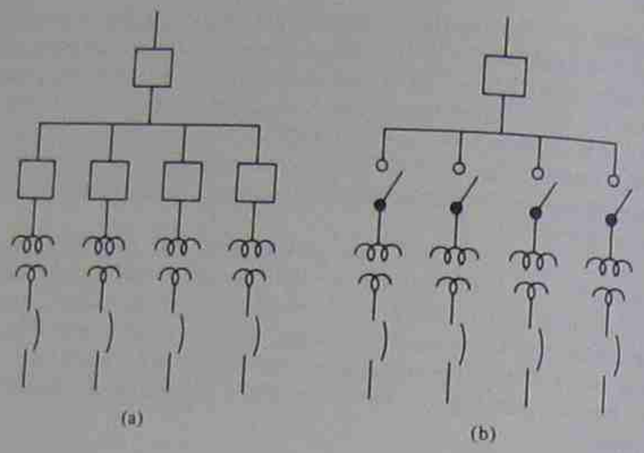


FIG. 14-4. Means of disconnecting a transformer. Solution at (a) is much more expensive, but safer, than solution at (b).

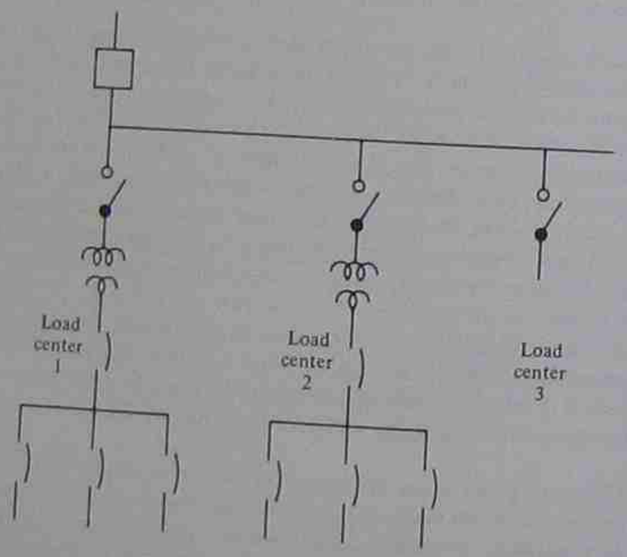


FIG. 14-5. Radial configuration.

are connected together either by cable if the substations are far from one another, or by circuit breaker especially if they are located in the same area (Fig. 14-6). A load may thus be supplied from one of two sides. This scheme provides greater flexibility than the radial one by allowing the removal of

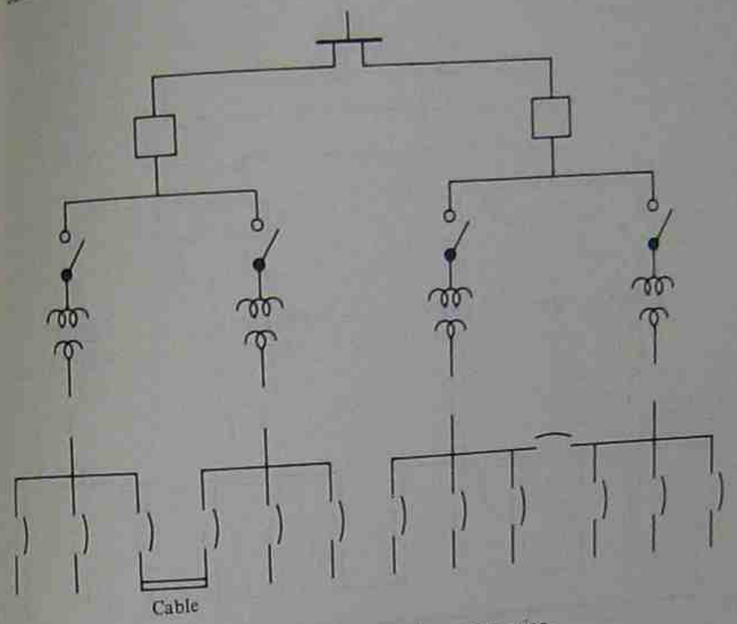


FIG. 14-6. Secondary pairing configuration.

certain pieces of equipment for repair or maintenance without interruption of service. However, there is the additional cost, not only of the equipment used in the tie, but of the augmented size of the transformer of each load-center substation which is now called upon to serve at least the essential part of the load of its partner. It is to be noted that the load-center pair does not operate in parallel; in normal operation the system is still radial.

In the secondary loop configuration all transformer secondaries are interconnected as depicted in Fig. 14-7. This arrangement is popular with utilities. In case of failure in a transformer branch, the primary feeder and the secondary circuit breakers would open, isolating the faulty region without interruption of service. The parallel operation of the transformers in this system offers the advantage of the overall load being shared by all the transformers, thus necessitating less reserve capacity than in the previous two systems. The drawback is that the equivalent circuit offers a reduced impedance to short-circuit currents, necessitating circuit breakers with higher interrupting rating. Besides, relaying is more difficult, several breakers having to be opened to clear a fault. A combined radial-secondary loop configuration is possible with the loop concept being applied locally to the circuits fed from every feeder.

Most plants opt for the secondary pairing rather than the secondary

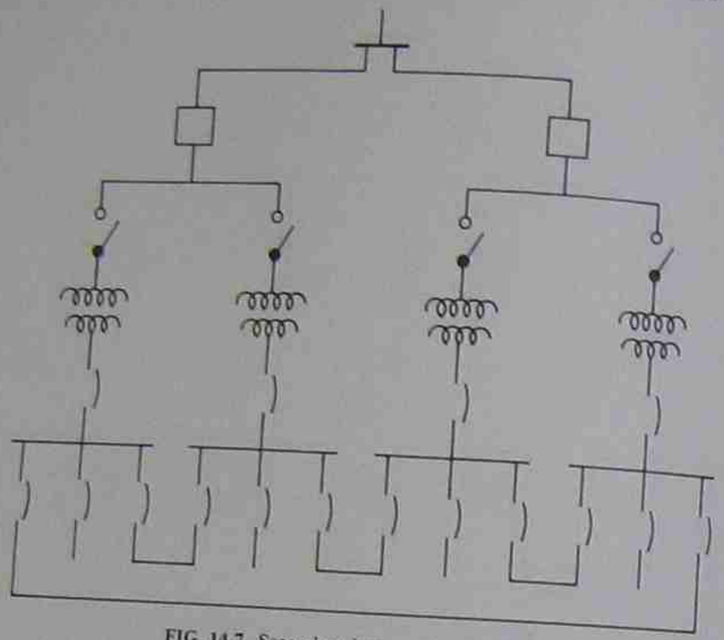


FIG. 14-7. Secondary loop configuration.

loop configuration because the former is less complex and less costly. The latter is, however, advantageous in cases where heavy loads shift during the day from one bus to another.

The primary pairing configuration is more reliable than the radial or the secondary pairing arrangements when underground cables supply the transformers, but it is more costly. While quite reliable, cables are more prone to breakdown than transformers. In order to reduce cost, circuit breakers *C*, *D*, *E*, and *F* in Fig. 14-8 are sometimes replaced by interrupting switches—at the expense of safety, though. Transfer from one primary feeder to the other must then be done with breakers *A* and *B* both open.

The primary loop configuration shown in Fig. 14-9 also provides service reliability against primary feeder breakdown. It is very costly, however, due to the many sectionalizing circuit breakers in the primary loop and associated problems of relaying selectivity. Should those breakers be replaced by switches in order to reduce cost, a very serious safety situation would ensue. In case of failure, a long sequence of switch openings and closings has to be carried out in a certain order which, if accidentally altered, may result in an interrupter switch making a faulty circuit. During the emergency of a failure the steps taken by the personnel must be as simple and as few as possible.

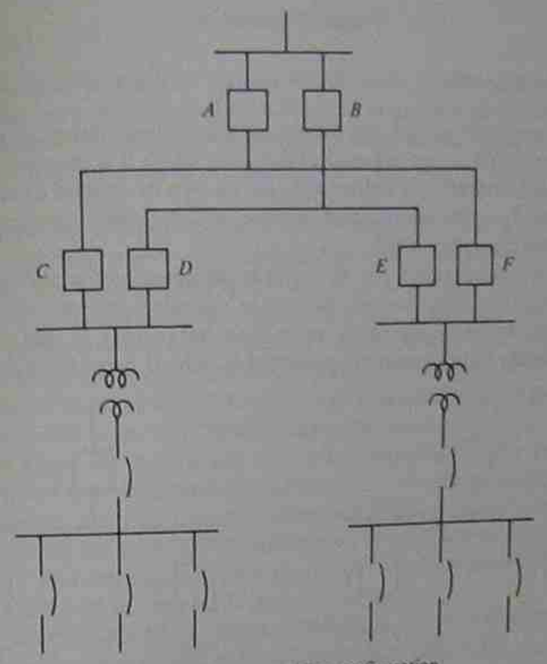


FIG. 14-8. Primary pairing configuration.

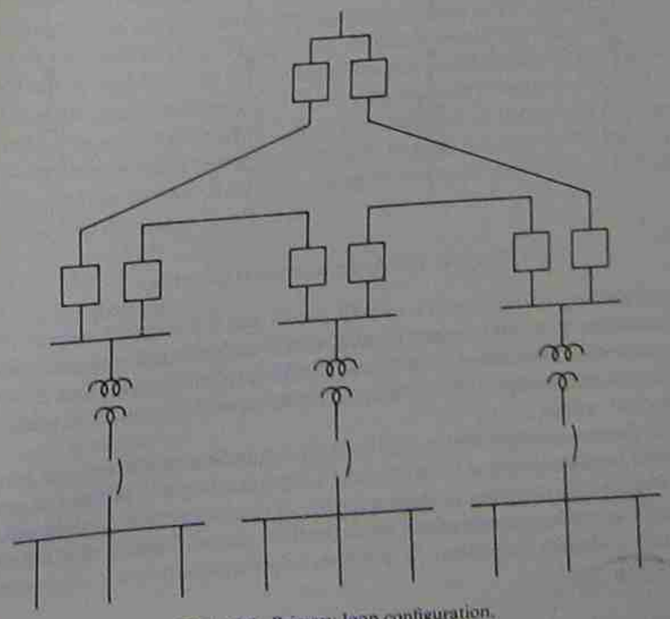


FIG. 14-9. Primary loop configuration.

14-3. TRANSFORMERS

A transformer is not a load, but simply an intermediate device. Its protection is therefore bound to depend on the circuits to which it is connected on both sides. It may be protected individually on its own or depend on the protection extended by the overcurrent devices of the circuits connected on its primary and secondary sides.

A transformer rated over 600 volts is protected on the primary side by fuses rated at no more than 150 percent of the rated primary current or by circuit breakers set to open at no more than 300 percent of that current. In Fig. 14-10*a* the transformers are protected by circuit breakers *B* and *C*. The

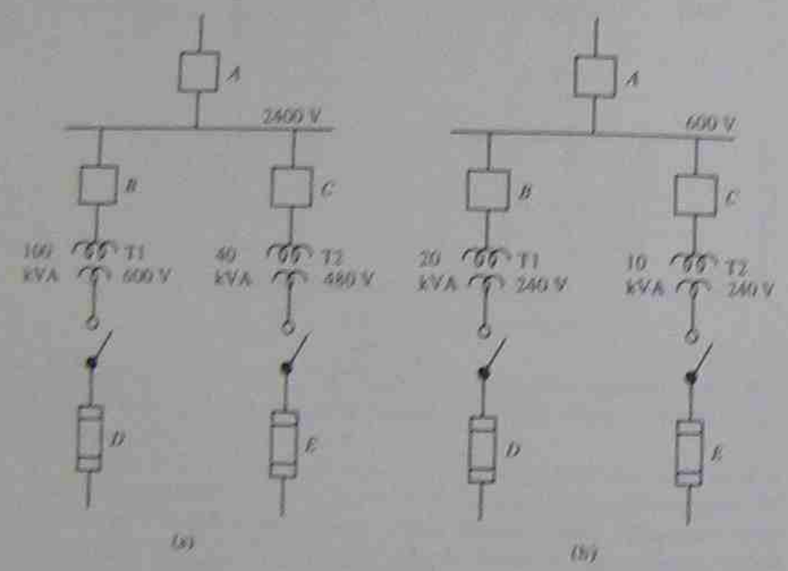


FIG. 14-10. Transformer overcurrent protection.

rated primary currents of T1 and T2 are 24 and 9.6 amperes, respectively. The settings of circuit breakers *B* and *C* should not exceed 72 and 29 amperes, respectively. If instead of circuit breakers there were fuses at *B* and *C*, their ratings should not exceed 36 and 14 amperes, respectively, or the next higher standard ratings.

Fuses or circuit breakers protecting a transformer 600 volts or below should be rated or set at no more than 125 percent of rated primary current. In Fig. 14-10*b* the rated primary currents of transformers T1 and T2 are 19 and 9.6 amperes, respectively. Circuit breakers (fuses) *B* and *C* should be set (rated) no higher than 24 or 12 amperes, respectively.

The question now arises: Can the transformers rely for their protection on the feeder protective device (*A* in Fig. 14-10) and the secondary circuit protective devices (*D* and *E* in Fig. 14-10)? In other words, could *B* and *C* be dispensed with in the presence of *A*, *D*, or *E*? The answer is conditionally affirmative.

Whatever the primary voltage, if the protective device at *A* provides the protection described above, the individual primary protection may be dispensed with. For example, in Fig. 14-10*a*, if *A* is a circuit breaker whose setting does not exceed 72 *A*, then *B* is not needed. This is also true if *A* is a fuse whose rating does not exceed 36 A. It is clearly unlikely that *A* would be set at 29 A, thus supplanting both *B* and *C* (the rated current of T1 alone is 24 A), unless the loads of T1 and T2 are of such a nature that the transformers are never expected to be fully loaded at the same time.

If *A* is a fuse, it can in no way replace *C*. Suppose *A* fails the test in that it is rated or set too high; then one turns attention to the secondary circuit devices *D* and *E*, provided the rating or setting at *A* is no more than double the limit imposed on *B* or *C*. The basic reason that a lower protection level is accepted is that transformers have proven to be quite reliable. Faults are more likely to occur in their loads than within them.

For transformers whose primary voltage is above 600 volts, if the secondary circuit device is rated or set at 250 percent or less of the transformer secondary rated current, then no individual protection is needed for the transformer. The limit is 125 percent for transformers whose primary voltage does not exceed 600 volts. Thus, in Fig. 14-10*a*, suppose the rating of fuse *A* is between 36 and 72 A, or the setting of breaker *A* is between 72 and 144 A. The rated secondary current of T1 is 96 A. Now, if the protective device at *D* is rated or set at no more than 240 A, then device *B* is not needed. In Fig. 14-10*b*, where the rated secondary current of T1 is 48 A, suppose that breaker *A* is set between 24 and 48 A. If the rating or setting of the device at *D* does not exceed 60 A, then *B* is not needed.

14-4. SWITCHING DEVICES

The switching devices used in a distribution system may be broadly classified as those used to disconnect a circuit with little or no current interrupting capability, and those that are expected to interrupt large currents due to overloads or faults.

Disconnecting switches are intended to isolate equipment from the power circuit. They are in general incapable of interrupting current, even under normal load conditions. They are usually provided with latches to prevent their forceful opening by the strong magnetic forces arising from short circuits. They should never be used to make or break a circuit.

Interrupter switches were introduced in Section 14-2. They are fundamentally disconnecting switches capable of interrupting normal load currents.

Thermal cutouts are heat-operated switches used to protect motors against overloads. They are not capable of clearing short circuits and must be used in conjunction with fuses or circuit breakers.

Fuses and *circuit breakers* were discussed in Chapter 9 in some detail. It is worth mentioning here that, for circuits below 600 volts, air circuit breakers are the most flexible and sturdy to use, but they are also the most expensive. They usually incorporate a tripping device with adjustable time setting. They are ordinarily used on main switchboards and wherever high-quality protection is desirable. On the other hand, molded-case circuit breakers are smaller in size, less sturdy, and less expensive than air breakers. Besides, they are not as adjustable. They are well suited for branch-circuit protection because of their small size and low cost. They operate very fast, often in the first cycle of a fault, and are not suited for coordinated operation.

Power circuit breakers are used to protect all sorts of equipment above 600 volts. They could be used for starting motors, but the repetitive nature of this duty sets serious limitations on this application; contactors are better suited for this purpose.

Fused switches consist of a combination interrupter switch and fuse mounted on the same base. They can be very fast, of high-interrupting capacity, and current-limiting. They find application in branch-circuit protection, especially where molded-case circuit breakers with suitable interrupting rating are not available. They are not used to protect main feeders because their very high speed precludes selectivity.

14-5. CONDUCTORS

Conductors used for wiring must be so selected as to assure safety and ease of identification. The selection of a conductor depends on the current that it is expected to carry, the insulation used, and the manner in which it is laid out in relation to other conductors.

The ampacity of a cable, i.e., its current-carrying ability, is restricted by the maximum temperature to which its insulation can be subjected without damage or deterioration. Cables, therefore, have temperature ratings. The difference between the temperature rating and the ambient temperature is the temperature rise that is permitted when current flows in the conductors. The greater the ability of a cable and its surroundings to dissipate heat, the larger the allowable current. Thus, the ampacity of cables isolated in air is higher than that of the same cables isolated in ducts. The crowding of conductors has the effect of concentrating the source of heat to a smaller area than if they

are spread out. The ampacity of three-conductor cables is therefore smaller than that of single-conductor cables. It is worthwhile to look at Tables A-10 and A-11 in the appendix and compare the current figures.

A cable ampacity is not proportional to the conductor cross section, as seen in the forementioned tables. This is explained in the following manner. If the conductor cross section is multiplied by k, its resistance is divided by k. For the same I^2R loss the square of the current is then k times larger; thus, the current is $\sqrt{k}$ times larger. But a larger cross section also means a larger diameter and a better heat dissipation capability for the same amount of heat generated. The ampacity is therefore expected to be more than just $\sqrt{k}$ times larger. For example, in Table A-10, a 500-MCM, insulated, single-conductor copper cable in air has an ampacity of 690 amperes. A 1000-MCM cable has double the cross section; its ampacity of 1060 amperes is larger than $690\sqrt{2}$ or 975 amperes, but certainly less than twice 690. Thus, two 500-MCM cables properly spaced and connected in parallel are capable of carrying more current than a single 1000-MCM cable. However, the parallel combination of two 500-MCM cables is bound to be more costly than a single 1000-MCM cable. A total installation cost should be considered before making a decision.

The selection of cables for a particular circuit is done not only on their ability to carry normal currents, but also on their capacity to handle short-circuit currents over specified periods of time. For example, if the short-circuit current is 50,000 A and the circuit breaker protecting the cable takes 0.2 second to interrupt the fault, the cable should be capable of carrying 50,000 A for at least 0.2 second without overheating to the point where its insulation is permanently damaged. Current-time curves are available to check the adequacy of a cable for a certain short-circuit duty.

When cables are connected in parallel, they must be identical in length, conducting and insulating material, cross section, and termination in order to ensure equal sharing of the load.

The ampacity of a cable is reduced as the ambient temperature rises. This is best illustrated with an example. No. 1 AWG single-conductor cable in air has an ampacity of 195 amperes (Table A-11) if its temperature rating is 75°C, for an ambient temperature of 30°C. In other words, if the cable carries no current, its temperature is 30°C; when it carries 195 amperes, its temperature rises to 75°C, which is the maximum temperature tolerated by the insulation of this cable. If the ambient temperature is 40°C, a current of 195 amperes raises the cable temperature above the allowable 75°C limit. The ampacity is then reduced by a derating (or correction) factor, say 0.85. The ampacity at 40°C then becomes 165 amperes. At 50°C let the derating factor be 0.75; the ampacity is then 145 amperes. Manufacturers normally provide tables of derating factor.

The ampacity is also reduced when more than three conductors share a raceway. The derating factor is 0.8 for 4 to 6 conductors, and 0.7 for 7 to 24 conductors.

In secondary distribution systems cables may be classified according to their use, mainly as:

1. *Service-entrance cables.* They connect the street main or transformer to the service equipment (circuit breaker, fused switch, or the like, and consumption meter) located at the entrance to the premises supplied.
2. *Feeder cables.* They connect the service equipment to the final branch-circuit overcurrent devices.
3. *Branch-circuit cables.* They connect the final overcurrent device protecting the circuit and the outlets or appliances. This is illustrated in Fig. 14-2.

a. Services. Service conductors are insulated or covered. They run overhead (service drops) or underground (laterals) and may be directly buried.

The number of service conductors entering a building is ordinarily decided by the utility. Normally, a single set of service conductors is used for currents up to 3000 amperes. A separate service may be provided for fire pumps and emergency electrical systems. Figure 14-11 illustrates some com-

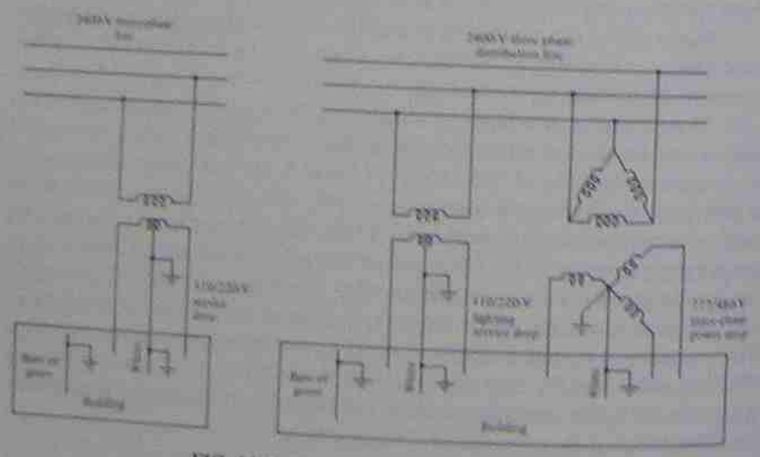


FIG. 14-11. Service entrance illustrations.

mon service entrances. Transformers are absent wherever the line voltage corresponds to the required service voltage.

Service-entrance conductors are not normally spliced. They are tapped, however, when supplying up to six disconnecting means located in the same space in a building, as in Fig. 14-12a, or when supplying any number of separate users, as in Fig. 14-12b. In the latter case, each user may have up to six disconnecting means as in Fig. 14-12a.

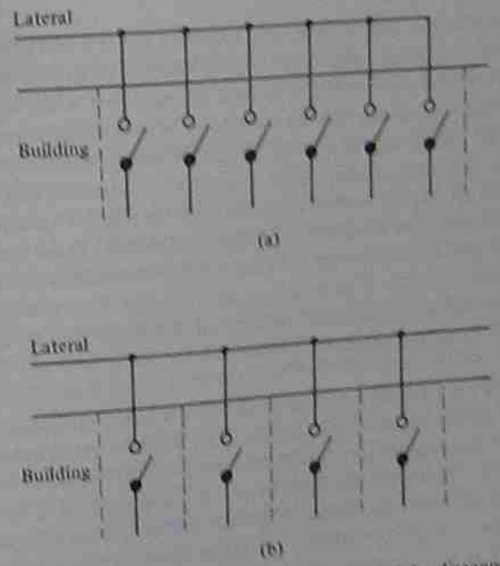


FIG. 14-12. Service-entrance tappings: (a) up to six for disconnecting means located in a common space of building; (b) any number of users in separate parts of building.

b. Feeders. The current that flows through a feeder depends on the capacity of the total load that it supplies. Since not all loads are expected to be on at the same time, the feeder current also depends on the demand factor. The latter is the ratio of the maximum load supplied at any time of the day to the total connected load. The demand factor cannot be known with certainty at the time the feeder is selected and must be estimated on the basis of surveys of similar existing installations.

In order to provide a margin of protection to the feeder, continuous loads (lasting at least 3 hours) should not exceed 80 percent of the feeder ampacity; this is equivalent to saying that the continuous load current should be multiplied by a factor of 1.25 when assessing feeder ampacity. Where a

mix of loads is supplied from the same feeder, the noncontinuous load current is added to 1.25 times the continuous load current.

Motors require particular attention as their characteristics and duties vary. At starting they draw currents considerably larger than rated, but they are unlikely to be started all together. For this reason branch-circuit or feeder conductors supplying a single motor are sized to carry at least 125 percent of the motor full-load current. Cables supplying more than one motor should be capable of carrying 125 percent of the largest motor full-load current, plus 100 percent that of the rest.

The full-load current of a motor depends on the duty to which it is subjected. The rest period following running allows the motor conductors to cool down. Thus, the shorter the time that the motor is used, the heavier its permissible load, i.e., the larger its current. For example, a motor may be rated 10 hp for continuous duty and 11 hp for intermittent duty consisting of 15 minutes of running followed by at least 15 minutes of rest. The cables feeding the motor should not be oversized for that larger intermittent duty since they have the same chance to cool off. For motors rated only for intermittent duty, cable ampacity may then have to be determined on less than 100 percent of motor current. For instance, for periodic duty the current to be considered for sizing cables is 85 percent of 5-minute motor current, and 90 percent of 15-minute rated motor current.

c. Branch Circuits. The rating of a branch circuit is defined by the rating or setting of the overcurrent device placed in it. The ampacity of branch-circuit conductors should not be inferior to the branch-circuit rating and certainly not less than the maximum load supplied. It is important to note at this point that the ampacity is not the only factor to consider in determining the size of a conductor. Voltage drop should also be borne in mind, limiting it to 3 percent on the branch circuit and 5 percent on the combination feeder-branch circuits.

The ampacity of tap conductors should be at least 40 percent of the branch-circuit rating. For example, the ampacity of taps on a 50-ampere branch circuit is at least 20 A. Receptacle ratings should in general not exceed the circuit rating.

Continuous loads must not exceed 80 percent of the branch-circuit rating. The aggregate of all fixed appliances, however, should not exceed 50 percent of that rating if their loads are supplied from the same branch circuit. Thus, on a 15-A branch circuit, a 12-A portable appliance may be connected. However, if other loads are expected on the circuit, fixed appliances are not permitted to draw more than 7.5 A. All these rules are intended to provide a reasonable margin of safety against improper or inadvertent overuse of the branch circuit by its users.

14-6. RACEWAYS

Cables may run isolated in air supported by insulators, stapled to boards, through holes in boards, or in raceways. A raceway is a general term denoting any channel used expressly for holding bare or insulated conductors. It may be metallic or of insulating material. The number of conductors in a raceway is limited by reason of heat dissipation and physical considerations such as the necessity of installing or withdrawing a conductor without damaging its insulation.

Raceways must not be shared by low-voltage conductors (not exceeding 600 volts) and high-voltage conductors (above 600 volts) for reasons of safety. Low-voltage conductors sharing a raceway must be of the same voltage class. Thus, low-voltage conductors of light and power systems may run in the same raceway provided all conductors are insulated for the highest voltage in that raceway.

Ducts used to carry dust, loose materials, steam, or flammable vapors may not be used as raceways. However, ducts used for environmental air (i.e., air breathed by people) may contain wiring systems enclosed in rigid metal conduits.

Raceways may come in the form of cable trays of various shapes. Cables normally run freely on horizontal trays but are fastened securely to sloping trays. If each phase or neutral of a circuit is made up of more than one single-conductor cable, groups of cables are formed such that each group consists of a single conductor per phase or neutral. This reduces mutual inductance between parallel conductors and concomittant current unbalance. Cables within a group are securely tied together to reduce their movement due to magnetic forces arising from fault currents (see Fig. 14-13). Large-

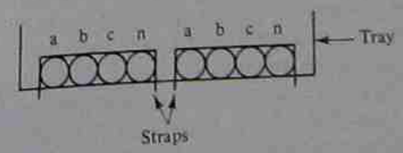


FIG. 14-13. Cross-sectional view of cables on a tray.

diameter cables are normally laid out side by side in a single row, while small-diameter cables (less than 1000 MCM) may be superposed. Manufactures usually provide guidelines for running cables on trays.

Feeders may take the form of bus bars instead of cables. This is particularly true where conductors have to run several floors up a building. Bus bars are available in modular form, housed in busways in standard lengths of up to 10 feet which can be simply bolted together, necessitating no splicing.

The bus bars, made of copper or aluminum, are individually insulated along their entire length with a layer of polyvinyl chloride and silver-plated at their contact surfaces. A busway cross section is illustrated in Fig. 14-14.

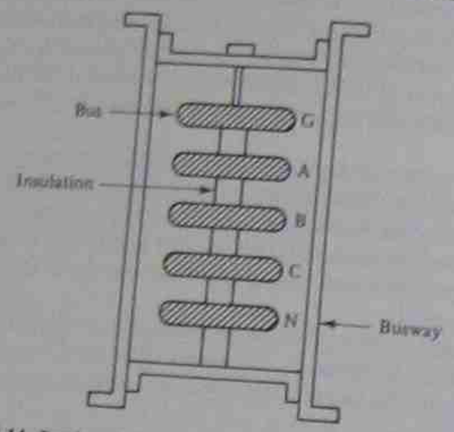


FIG. 14-14. Bus bars in busway. Ground bus bolted to housing.

Cable raceways may also be metal tubes of circular cross section called conduits. They are generally made up of several lengths, 0.5 to 6 inches in diameter, tied together with suitable couplings. Rigid conduits installed in concrete or in direct contact with the earth are protected against corrosion, and those located in wet locations are watertight. Flexible conduits are never used in wet locations, storage-battery rooms, underground, or embedded in concrete. Within a conduit cables may occupy between 30 and 50 percent of the conduit inside cross-sectional area, depending on the number and type of conductors. At any rate, conductors plus splices and taps should never occupy more than 75 percent of the conduit cross section at any point.

Surface raceways are allowed in dry locations and for low voltages (below 300 volts) (see Fig. 14-15). Underfloor raceways are those running beneath the surface of concrete or other flooring material. They are normally used to bring cables to office furniture or store displays.

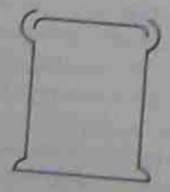


FIG. 14-15. Typical surface raceway.

Some cables come integrated with their raceways such as metal-clad cables. The latter are factory-assembled cables whose insulated conductors are enclosed in a flexible metallic enclosure. Type AC cables are branch-circuit or feeder cables with armor of flexible metal tape, containing a copper strip in direct contact with the armor along its entire length. The copper strip serves as ground conductor. These cables may be embedded in the plaster finish of masonry walls or may be run inside masonry blocks.

14-7. MOTORS

Motors are not part of the distribution system; they are loads, in essence users of the system. Nevertheless, they are discussed separately here because of their widespread use and their particular requirements.

The general configuration of a motor circuit is shown in Fig. 14-16. At times a motor may not be directly energized from the main power supply, but

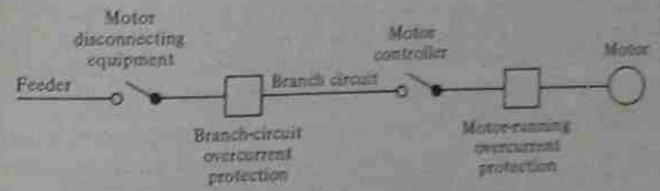


FIG. 14-16. General circuit configuration of a motor.

rather through power conversion equipment, for example through switched rectifiers in the case of dc motors, or frequency changers in the case of ac motors. If the power conversion equipment provides overcurrent protection to the motor, no separate overcurrent protection need be provided. Duplication of disconnecting means is not necessary either; the motor disconnecting equipment may be located at the input to the power converter.

Induction and synchronous motors usually draw, at starting, currents which are considerably larger than rated. If these starting currents last for short periods of time, the motors may be started directly across the line; otherwise, special means must be employed to limit the starting currents to acceptable levels. This usually involves reduction of the voltage applied to each armature phase. The armature may thus be started in wye connection and then run in delta. An autotransformer may be used to reduce the voltage at starting and progressively increase it to full value as the motor accelerates. Another approach is to construct the motor as a part-winding-start motor. The armature would then be made up of various parts, often two, connected in parallel. The impedance of each half is obviously higher than that of the

combination. Initially only one half of the winding is energized and, subsequently, the other half is connected. If each half is protected by a separate running overcurrent device, then each should have separate branch-circuit and ground-fault protection with trip currents no more than one half the value specified for the motor as a whole. Any such device with half the rating may be used for both winding halves if it does not hinder motor starting. At any rate, a time-delay fuse rating should not exceed 150 percent of the motor full-load current.

The purpose of the branch-circuit protection as separate from motor protection is that the conductors are sized to carry the starting current of the motor; their protective devices cannot protect the motor against running overloads. However, the branch-circuit protective device serves as backup protection against motor overloads. The motor overcurrent protection should trip at no more than 130 percent of the motor full-load current; the branch-circuit conductors must be rated to carry at least 125 percent of that current.

Fuses used for protecting motors of any kind against overload must be provided on each ungrounded conductor and, in the ac case, at least one fuse per phase. If overload protection is provided by circuit breakers, only one unit is required for a single-phase ac or dc motor, placed in an ungrounded conductor, and one per phase for a three-phase ac motor. This holds even for motor controllers if they incorporate the running overload protection. Illustrations are given in Fig. 14-17.

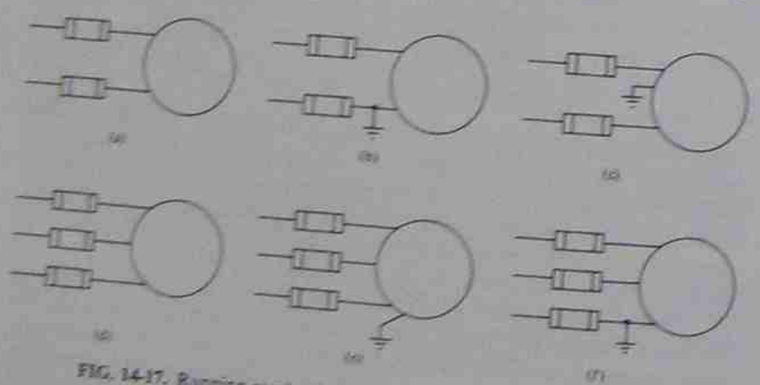


FIG. 14-17. Running overload protection of motors: (a) to (c) single-phase ac or dc; (d) to (f) three-phase ac; (d) ungrounded wye or delta; (e) grounded wye; (f) grounded delta.

Protection against short circuits for the motors, their controllers, and their branch-circuit conductors will now be discussed. The branch-circuit protective devices must obviously be capable of carrying the motor starting current. This sets a lower limit on the fuse rating, or setting in case of circuit

breakers. On the other hand, the rating or setting has an upper limit. For low-voltage applications ($\leq$600 V) this upper limit is determined by motor kind and size; short-circuit current values are not a determining factor. Thus, instantaneous-trip circuit breakers are not set above 700 percent of an ac motor full-load current, while the range for inverse-time breakers is 150 to 250 percent, depending on motor type and starting current. The range for non-time-delay fuses is 150 to 300 percent and for time-delay fuses 150 to 175 percent. Based on such considerations, the protective device rating may exceed the ampacity of the branch-circuit conductors. This does not imply that the conductors are not reasonably protected since, under a short-circuit fault on the conductors, the resulting current is so excessive as to open the circuit almost instantaneously.

For voltages above 600 volts coordinated protection must be provided to prevent damage to the motor, the controller, and the branch-circuit conductors. The latter must have an ampacity at least equal to the setting of the motor overload protective device. Circuit breakers must disconnect simultaneously all ungrounded conductors. Fuses must be placed in each ungrounded conductor and be used with some disconnecting means. The interrupting rating of breakers or fuses must be commensurate with the short-circuit currents.

The device protecting a feeder supplying several motors must clearly be rated or set higher than any of the devices protecting the corresponding branch circuits, but obviously not at the level of the sum of these protective devices ratings or settings. A reasonable rating or setting for feeder protection is the largest rating or setting of the motor branch-circuit protective devices, plus the full-load currents of the other motors and loads supplied from the same feeder.

A motor controller is any device used specifically to start and stop a motor. It could be a switch, circuit breaker, or any other means. It does not have to open all conductors to a motor unless it is also used as a disconnecting means. However, if it is connected to open a grounded conductor, it must simultaneously open all other conductors.

The disconnecting equipment shown in Fig. 14-16 must be capable of interrupting the supply to a motor in case of controller failure, except for motors larger than 100 hp. The disconnection must be done simultaneously on all ungrounded conductors.

Both controller and disconnecting means must have a horsepower rating at least equal to that of the motor. Motor-circuit switches rated in horsepower are available for that purpose. Besides, circuit breakers may be used. In general, the ampere rating of all disconnecting means must not be less than 115 percent of the motor circuit full-load current rating, including any other type of load supplied from the same circuit. A controller which may be operated with a handle and which satisfies all the requirements of a

disconnecting means may also be considered at the same time as the disconnecting means, thus permitting the omission of a separate device.

14-8. GROUNDING

Circuits are grounded in order to prevent high voltages from building up on the conductors, while equipment grounding aims at preventing enclosures from reaching voltages above ground. Grounding thus improves system protection and reliability and provides safety to people standing by.

Grounding every circuit, however, makes the system susceptible to excessive currents should a short circuit develop between a live conductor and ground. Thus, not all neutrals of wye-connected loads (especially large motors) should be grounded. Grounding should then be practiced selectively, especially on the primary distribution system, as shown in Fig. 14-18. In part (a), disconnection of motors M1 and M3 for maintenance or repair deprives the 2400-volt system of a ground. It is preferable to ground the system at the source, that is, at the transformer neutral in Fig. 14-18b.

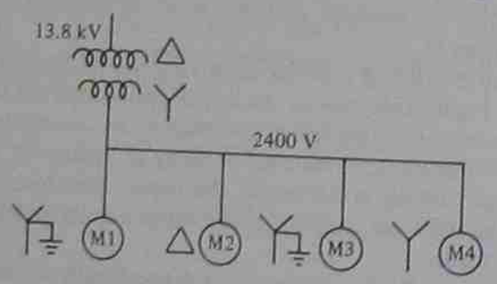


FIG. 14-18. Circuit grounding done selectively: (a) at a few motor neutrals (load); (b) at the transformer neutral (source).

In the secondary distribution system ($\leq$600 V) an insulated conductor of white color is used for circuit grounding, and of green color for equipment grounding. Uninsulated conductors are sometimes used for equipment grounding. Figure 14-11 illustrates the configuration of typical low-voltage secondary systems. Three-phase four-wire 480/277-volt systems are always grounded if the neutral is used as a circuit conductor. Single-phase three-wire 240/120-volt systems are grounded whenever the phase midpoint is used as a circuit conductor.

The source-grounding conductor shown in Fig. 14-11 is run to each service. The cross section of the grounded conductor should not be less than one-eighth that of the largest phase conductor in order to ensure a good conducting path if a live conductor gets shorted to ground. The equipment-grounding conductor (bare or green in Fig. 14-11) runs to the enclosures of the various equipments used on the premises in order to provide them with a good connection to ground. The mere standing of a piece of equipment on the floor does not mean that its enclosure is well grounded.

Metal enclosures, raceways, and fixed equipments are normally grounded. However, motors and generators well insulated from ground, and metal enclosures used to protect cables or equipments from physical damage, may be left ungrounded. Also, portable tools and home appliances, such as refrigerators and air conditioners, need not be grounded if constructed with double insulation.

Some ac circuits are required to be ungrounded as, for instance, in anesthesizing locations in hospitals. In fact, line isolation monitors are installed in such cases, capable of sounding warning signals.

High-voltage services (>1000 V) are not necessarily grounded, but they must be so if they supply portable equipment.

Metal underground water pipes are normally used for grounding. If their length is judged inadequate, they may be complemented by other means, such as a building metal frame or some underground pipe or tank.

PROBLEMS

14-1. A system has an equivalent reactance of 0.02 per unit, base of 1000 kVA. It may supply a composite load through either a single 1000-kVA transformer of 6% impedance, or two 500-kVA transformers of 5% impedance (each supplying separately roughly half the load). Determine the short-circuit current at the secondary bus of a transformer in both situations.

14-2. For the system of Problem 14-1 it is decided to use a single 1000-kVA transformer and a reactor to limit the short-circuit current to the value resulting from the use of two 500-kVA transformers. Find the per-unit impedance of such a reactor.

14-3. For the system of Problem 14-2 explain how reactors could be arranged to limit the voltage drop during normal conditions while providing the same limitation to the short-circuit current.

14-4. In the various distribution configurations shown in Figs. 14-5 to 14-9, which equipment can break down without interrupting service more than a few seconds?

14-5. In the various distribution configurations shown in Figs. 14-5 to 14-9, describe the steps taken in locating and isolating a fault.

14-6. For the system of Fig. 14-10a, let transformers T1 and T2 be rated 300 kVA and 100 kVA, respectively. *A* is a circuit breaker set at 480 A. *D* and *E* are fuses rated at 600 and 250 A, respectively. Determine:
a. the maximum rating of fuses at *B* and *C*.
b. the maximum setting of breakers at *B* and *C*.
c. whether it is possible to omit *B* or *C*.

14-7. Repeat Problem 14-6 for a circuit breaker at *A* set at 400 A.

14-8. For the system of Fig. 14-10b, let transformers T1 and T2 be rated 100 kVA and 80 kVA, respectively. *A* is a circuit breaker set at 300 A. *D* and *E* are fuses both rated at 250 A. Determine:
a. the maximum rating of fuses at *B* and *C*.
b. the maximum setting of breakers at *B* and *C*.
c. whether it is possible to omit *B* or *C*.

14-9. Repeat Problem 14-8 for a circuit breaker at *A* set at 220 A.

14-10. Refer to Table A-10 and compare the ampacities of 5-kV 250-MCM and 750-MCM single-conductor cables. Also compare the ampacities of single-conductor and three-conductor cables both of 250-MCM gage.

14-11. Determine the cable ampacities in the following situations:
a. Three single-conductor 5-kV 350-MCM cables sharing the same underground duct, earth temperature 20°C.
b. Same as (a) but with six conductors in the same duct.
c. Same as (a) but with an earth temperature of 30°C.

14-12. A 230-V feeder supplies an installed continuous load of 50 A and an installed noncontinuous load of 100 A. The demand factor of the continuous load is 80%, that of the noncontinuous load 60%. Determine the minimum feeder ampacity.

14-13. A 230-V feeder supplies two groups of motors. In the first group the sum of the full-load currents is 150 A, the largest motor full-load current is 20 A, the demand factor is 50%, and the peak current lasts 5 hours a day. In the second group the sum of the full-load currents is 100 A, the largest motor full-load current is 40 A, the demand factor is 80%, and the peak current lasts 1 hour a day. Determine the minimum feeder ampacity.

14-14. The rating of a fuse protecting a branch circuit is 40 A. Determine:
a. the rating of the branch circuit.
b. the minimum ampacity of tap conductors.

c. the maximum continuous current allowed.
d. the maximum current that may be drawn by fixed appliances.

14-15. A grounded-wye 440-V ac motor has a rated current of 50 A. Determine:
a. the maximum rating of time delay fuses to protect it against overloads.
b. the maximum trip current of circuit breakers used for current protection.
c. the minimum cable rating used to supply the motor.
d. the maximum setting of instantaneous-trip circuit breakers used for the branch circuit protection.

14-16. A feeder supplies three 440-V motors whose full-load currents are 50, 25, and 10 A. The branch circuits of these motors are protected by circuit breakers set at 150, 60, and 25 A, respectively. Determine a reasonable setting for the circuit breaker protecting the feeder.

appendix A

Tables For The Determination of Circuit Constants

Table A-1. *Resistivity and Temperature Coefficient of Conductor Materials*

Material	Resistivity (ρ) at 20°C Micro-ohm cm	Ohms cir mil per ft	Temp. Coefficient (α) at 20°C
ALUMINUM	2.83	17.0	0.0039
BRASS	6.4–8.4	38–51	0.002
BRONZE	13–18	78–108	0.0005
COPPER			
Hard drawn	1.77	10.62	0.00382
Annealed	1.72	10.37	0.00393
IRON	10	60	0.0050
SILVER	1.59	9.6	0.0038
SODIUM	4.3	26	0.0044
STEEL	12–88	72–530	0.001–0.005

Table A-2. *Characteristics of COPPER Conductors, Hard Drawn, 97.3 Percent*

Size of Conductor		Number of Strands	Diameter of Individual Strands Inches	Outside Diameter Inches	Breaking Strength Pounds	Weight Pounds per Mile	Approx. Current Carrying Capacity* Amps	Geometric Mean Radius at 60 Hz Feet
Circular Mils	A.W.G. or B. & S.							
1 000 000	----	37	0.1644	1.151	43 830	16 300	1 300	0.0368
900 000	----	37	0.1560	1.092	39 510	14 670	1 220	0.0349
800 000	----	37	0.1470	1.029	35 120	13 040	1 130	0.0329
750 000	----	37	0.1424	0.997	33 400	12 230	1 090	0.0319
700 000	----	37	0.1375	0.963	31 170	11 410	1 040	0.0308
600 000	----	37	0.1273	0.891	27 020	9 781	940	0.0285
500 000	----	37	0.1162	0.814	22 510	8 153	840	0.0260
500 000	----	19	0.1622	0.811	23 990	9 151	840	0.0259
450 000	----	19	0.1539	0.770	19 750	7 336	780	0.0247
400 000	----	19	0.1451	0.726	17 560	6 523	730	0.0229
350 000	----	19	0.1357	0.679	15 590	5 706	670	0.0214
350 000	----	12	0.1708	0.710	15 140	5 706	670	0.0225
300 000	----	19	0.1257	0.629	13 510	4 891	610	0.01987
300 000	----	12	0.1581	0.657	13 170	4 891	610	0.0208
250 000	----	19	0.1147	0.574	11 360	4 076	540	0.01813
250 000	----	12	0.1443	0.600	11 130	4 076	540	0.01902
211 600	4/0	19	0.1055	0.528	9 617	3 450	480	0.01668
211 600	4/0	12	0.1328	0.552	9 483	3 450	496	0.01750
211 600	4/0	7	0.1739	0.522	9 154	3 450	480	0.01579
167 800	3/0	12	0.1183	0.492	7 556	2 736	420	0.01559
167 800	3/0	7	0.1548	0.464	7 366	2 736	420	0.01464
133 100	2/0	7	0.1379	0.414	5 926	2 170	360	0.01292
105 000	1/0	7	0.1228	0.368	4 752	1 720	310	0.01113
83 690	1	7	0.1093	0.328	3 804	1 364	270	0.00992
83 690	1	3	0.1670	0.360	3 820	1 351	270	0.01016
66 370	2	7	0.0974	0.292	3 045	1 082	230	0.00883
66 370	2	3	0.1487	0.320	2 913	1 071	240	0.00903
66 370	2	1	.....	0.258	3 003	1 061	220	0.00836
52 630	3	7	0.0867	0.260	2 433	858	200	0.00787
52 630	3	3	0.1325	0.285	2 359	850	200	0.00805
52 630	3	1	.....	0.229	2 439	841	190	0.00745
41 740	4	3	0.1180	0.254	1 879	674	160	0.00717
41 740	4	1	.....	0.204	1 970	667	170	0.00663
33 100	5	3	0.1050	0.226	1 505	534	150	0.00638
33 100	5	1	.....	0.1819	1 591	529	140	0.00590
26 250	6	3	0.0935	0.201	1 205	424	130	0.00568
26 250	6	1	.....	0.1620	1 280	420	120	0.00526
20 820	7	3	.....	0.1443	1 050	333	110	0.00468
16 510	8	1	.....	0.1285	826	264	95	0.00417

*For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2 ft./sec.), frequency = 60 Hz

r_a Resistance Ohms per Mile per Conductor						X_a Inductive Reactance Ohms per mile per Conductor		X'_a Capacitive Reactance Megohm-miles per Conductor	
20°C (77°F.)			50°C (122°F.)						
4-in	25 Hz	60 Hz	4-in	25 Hz	60 Hz	25 Hz	60 Hz	25 Hz	60 Hz
0.0505	0.0505	0.0506	0.0646	0.0672	0.0685	0.333	0.400	0.0681	0.0901
0.0600	0.0600	0.0600	0.0741	0.0746	0.0753	0.339	0.406	0.0705	0.0914
0.0711	0.0705	0.0713	0.0856	0.0852	0.0847	0.344	0.413	0.0721	0.0924
0.0760	0.0807	0.0808	0.0903	0.0878	0.0858	0.348	0.417	0.0733	0.0941
0.0858	0.0861	0.0875	0.0954	0.0951	0.0960	0.353	0.422	0.0745	0.0954
0.0892	0.0897	0.1006	0.1064	0.1086	0.1095	0.355	0.423	0.0773	0.0977
0.1170	0.1188	0.1196	0.1288	0.1296	0.1301	0.359	0.443	0.0785	0.1004
0.1198	0.1188	0.1196	0.1288	0.1296	0.1300	0.371	0.445	0.0806	0.1005
0.1288	0.1318	0.1323	0.1402	0.1427	0.1440	0.376	0.451	0.1234	0.1020
0.1445	0.1477	0.1484	0.1585	0.1603	0.1619	0.382	0.458	0.1245	0.1038
0.1491	0.1484	0.1486	0.1928	0.1845	0.1845	0.389	0.466	0.1269	0.1058
0.1493	0.1484	0.1490	0.1928	0.1840	0.1845	0.384	0.460	0.1251	0.1044
0.1958	0.1961	0.1966	0.213	0.214	0.215	0.396	0.476	0.1296	0.1080
0.1950	0.1951	0.1966	0.213	0.214	0.215	0.392	0.470	0.1281	0.1068
0.234	0.235	0.236	0.256	0.257	0.257	0.466	0.497	0.1320	0.1098
0.234	0.235	0.236	0.256	0.257	0.257	0.461	0.481	0.1313	0.1094
0.234	0.277	0.278	0.305	0.369	0.305	0.414	0.497	0.1299	0.1131
0.276	0.277	0.278	0.305	0.307	0.305	0.409	0.492	0.1285	0.1119
0.276	0.277	0.278	0.305	0.305	0.305	0.439	0.550	0.1369	0.1136
0.349	0.349	0.359	0.381	0.382	0.382	0.451	0.555	0.1384	0.1155
0.349	0.349	0.356	0.381	0.382	0.382	0.451	0.518	0.1405	0.1173
0.446	0.449	0.449	0.481	0.481	0.481	0.443	0.522	0.1445	0.1205
0.455	0.455	0.505	0.486	0.487	0.487	0.454	0.546	0.1488	0.1240
0.699	0.699	0.699	0.756			0.467	0.560	0.1528	0.1254
0.692	0.692	0.692	0.959			0.464	0.507	0.1495	0.1246
0.881	0.882	0.882	0.964			0.478	0.524	0.1579	0.1308
0.873			0.955			0.476	0.511	0.1527	0.1283
0.864			0.845			0.464	0.581	0.1441	0.1245
1.113			1.206			0.490	0.598	0.1611	0.1343
1.385			1.204			0.488	0.585	0.1578	0.1315
1.896	Same as 6-c		1.192	Same as 6-c		0.494	0.595	0.1656	0.1380
1.388			1.018			0.499	0.599	0.1619	0.1349
1.916			1.893			0.507	0.609	0.1697	0.1415
1.908			1.914			0.511	0.613	0.1661	0.1384
1.173			1.895			0.519	0.622	0.1738	0.1449
2.33			2.41			0.523	0.628	0.1705	0.1419
2.34			2.39			0.531	0.639	0.1779	0.1483
2.73			2.61			0.542	0.651	0.1821	0.1517
2.41			2.40			0.554	0.665	0.1862	0.1552

Table 6-3. Characteristics of Aluminum Cable Steel Reinforced

Circular Mils or A.W.G. or Nom. Diam.	Aluminum			Steel		Cot. Inch Dia. Steel Inches	Copper Equiv. Used Circular Mils or A.W.G.	Size Nom. Strength Pounds	Weight Pounds per Mile	Geometric Mean Radius at 60 Cycles	Approx. Diameter Over All Inches
	Strands	Layers	Strand Dia. Inches	Strands	Strand Dia. Inches						
795 000	54	3	0.1716	19	0.1030	1.545	1 000 000	30 000	3 277	0.0328	1.293
715 500	54	3	0.1672	19	0.1004	1.506	900 000	27 000	3 205	0.0320	1.263
666 600	54	3	0.1628	19	0.0977	1.465	840 000	25 200	2 988	0.0313	1.232
636 000	54	3	0.1601	19	0.0961	1.441	800 000	24 000	2 858	0.0309	1.213
605 000	54	3	0.1558	19	0.0935	1.402	760 000	22 800	2 717	0.0303	1.192
556 500	54	3	0.1486	19	0.0892	1.338	700 000	21 000	2 502	0.0294	1.152
1 113 000	54	4	0.1456	19	0.0963	1.310	1 400 000	42 000	4 486	0.0324	1.440
1 033 500	54	4	0.1564	19	0.1284	12.46	1 300 000	39 000	4 166	0.0318	1.400
954 000	54	4	0.1520	19	0.1229	1.196	1 200 000	36 000	3 845	0.0312	1.358
900 000	54	4	0.1481	19	0.1203	1.152	1 130 000	33 900	3 625	0.0307	1.326
874 500	54	4	0.1470	19	0.1189	1.146	1 100 000	33 000	3 525	0.0305	1.312
795 000	54	4	0.1414	19	0.1144	1.095	1 000 000	30 000	3 205	0.0296	1.263
795 000	30	3	0.1749	7	0.1360	1.358	500 000	25 000	2 778	0.0278	1.293
715 500	30	3	0.1658	7	0.1289	1.248	450 000	22 500	2 500	0.0270	1.164
666 600	30	3	0.1599	7	0.1243	1.204	420 000	21 000	2 333	0.0265	1.085
636 000	30	3	0.1559	7	0.1212	1.173	400 000	20 000	2 222	0.0261	1.035
605 000	30	3	0.1519	7	0.1180	1.142	380 000	19 000	2 111	0.0257	0.984
556 500	30	3	0.1444	7	0.1122	1.086	350 000	17 500	1 944	0.0250	0.906
666 600	54	3	0.1511	19	0.0906	1.358	420 000	21 000	2 333	0.0265	1.085
636 000	54	3	0.1485	19	0.0891	1.335	400 000	20 000	2 222	0.0261	1.035
605 000	54	3	0.1446	19	0.0868	1.301	380 000	19 000	2 111	0.0257	0.984
556 500	54	3	0.1384	19	0.0830	1.245	350 000	17 500	1 944	0.0250	0.906
605 000	26	3	0.1525	7	0.1186	1.142	380 000	19 000	2 111	0.0257	0.984
556 500	26	3	0.1463	7	0.1138	1.086	350 000	17 500	1 944	0.0250	0.906
556 500	30	3	0.1362	7	0.1060	0.953	350 000	17 500	1 944	0.0250	0.906
500 000	30	3	0.1291	7	0.1004	0.904	314 500	15 700	1 746	0.0241	0.814
477 000	26	3	0.1355	7	0.1054	0.853	300 000	15 000	1 667	0.0237	0.776
477 000	30	3	0.1260	7	0.0981	0.792	250 000	12 500	1 389	0.0229	0.679
397 500	26	3	0.1236	7	0.1031	0.894	250 000	12 500	1 389	0.0229	0.679
397 500	30	3	0.1151	7	0.0895	0.723	6/0	10 000	1 111	0.0220	0.604
336 400	26	2	0.1128	7	0.0941	0.761	4/0	8 000	889	0.0211	0.539
336 400	30	2	0.1059	7	0.0901	0.682	266 800	6 660	740	0.0202	0.479
300 000	30	2	0.1014	7	0.0850	0.642	266 800	6 660	740	0.0202	0.479
266 800	26	2	0.1003	7	0.0788	0.602	3/0	5 000	556	0.0193	0.428
266 800	6	1	0.2109	7	0.0703	0.602	2/0	4 000	445	0.0184	0.381
4/0	6	1	0.1878	7	0.0878	0.535	1/0	3 160	351	0.0174	0.339
3/0	6	1	0.1672	7	0.0672	0.447	1	2 500	278	0.0164	0.302
2/0	6	1	0.1490	7	0.0595	0.398	2	1 990	221	0.0155	0.269
1/0	6	1	0.1327	7	0.0737	0.355	3	1 580	176	0.0146	0.239
1	6	1	0.1182	7	0.1182		4	1 250	139	0.0138	0.213
1	6	1	0.1051	7	0.0701	0.316	5	1 000	111	0.0130	0.190
2	6	1	0.0934	7	0.1299	0.223	6	790	88	0.0122	0.169
3	6	1	0.0833	7	0.0977	0.281	7	630	70	0.0115	0.150
4	6	1	0.0742	7	0.0834	0.250	8	500	55	0.0108	0.134
5	6	1	0.0661	7	0.0743	0.223	9	400	44	0.0102	0.119
6	6	1	0.0590	7	0.0661	0.198	10	310	35	0.0095	0.106

*Based on copper 97 percent, aluminum 61 percent conductivity.

†For conductor at 75°C., air at 25°C., wind 1.4 miles per hour (2.3 km), frequency = 60 Hz.

‡"Current Approx. 75% Capacity" is 75% of the "Approx. Current Carrying Capacity in Amps." and is approximately the current which will produce 50°C. conductor temp. (25°C. rise) with 25°C. air temp., wind 1.4 miles per hour.

x_a Resistance Ohms per Mile per Conductor						x_d Inductive Reactance Ohms per Mile per Conductor		x'_a Capacitive Reactance Megohm-miles per Conductor	
25°C (77°F) Small Currents			50°C (122°F) Current Approx. 75% Capacity‡						
d-c	50 Hz	60 Hz	d-c	50 Hz	60 Hz	50 Hz	60 Hz	50 Hz	60 Hz
0.0587	0.0590	0.0591	0.0660	0.0675	0.0684	0.299	0.359	0.0977	0.0814
0.0618	0.0624	0.0622	0.0680	0.0710	0.0720	0.302	0.362	0.0986	0.0821
0.0632	0.0655	0.0656	0.0718	0.0749	0.0760	0.304	0.365	0.0996	0.0830
0.0691	0.0694	0.0695	0.0761	0.0793	0.0803	0.307	0.369	0.1006	0.0838
0.0734	0.0733	0.0734	0.0808	0.0840	0.0851	0.310	0.372	0.1016	0.0847
0.0781	0.0786	0.0784	0.0862	0.0894	0.0906	0.314	0.376	0.1028	0.0857
0.0839	0.0843	0.0844	0.0924	0.0957	0.0969	0.317	0.380	0.1040	0.0867
0.0903	0.0907	0.0909	0.0994	0.1025	0.1034	0.321	0.385	0.1053	0.0878
0.0979	0.0981	0.0982	0.1079	0.1160	0.1128	0.325	0.390	0.1068	0.0890
0.104	0.104	0.104	0.1145	0.1175	0.1185	0.328	0.393	0.1078	0.0898
0.107	0.107	0.108	0.1178	0.1218	0.1228	0.329	0.395	0.1083	0.0898
0.117	0.118	0.119	0.1288	0.1328	0.1378	0.334	0.401	0.1100	0.0903
0.117	0.117	0.117	0.1288	0.1288	0.1288	0.332	0.399	0.1095	0.0917
0.117	0.117	0.117	0.1288	0.1288	0.1288	0.327	0.393	0.1085	0.0912
0.133	0.133	0.132	0.1442	0.1472	0.1482	0.339	0.407	0.1119	0.0934
0.133	0.133	0.133	0.1442	0.1442	0.1442	0.337	0.405	0.1114	0.0932
0.133	0.133	0.133	0.1442	0.1442	0.1442	0.333	0.399	0.1104	0.0928
0.140	0.141	0.141	0.1541	0.1591	0.1601	0.343	0.412	0.1132	0.0920
0.147	0.148	0.148	0.1618	0.1678	0.1688	0.345	0.414	0.1140	0.0943
0.147	0.147	0.147	0.1618	0.1618	0.1614	0.344	0.412	0.1135	0.0939
0.147	0.147	0.147	0.1618	0.1618	0.1618	0.339	0.406	0.1125	0.0946
0.154	0.155	0.155	0.1692	0.1755	0.1775	0.348	0.417	0.1149	0.0937
0.124	0.154	0.154	0.1706	0.1720	0.1720	0.346	0.415	0.1149	0.0957
0.168	0.168	0.168	0.1849	0.1839	0.1859	0.350	0.420	0.1144	0.0951
0.168	0.168	0.168	0.1849	0.1859	0.1859	0.346	0.415	0.1159	0.0965
0.187	0.193	0.187	0.206			0.351	0.421	0.1149	0.0957
0.196	0.196	0.196	0.216			0.358	0.430	0.1167	0.0973
0.196	0.196	0.196	0.216			0.353	0.424	0.1186	0.0988
0.215	Same as d-c		0.259	Same as d-c		0.367	0.441	0.1176	0.0980
0.215			0.259			0.362	0.433	0.1219	0.1013
0.278			0.306			0.376	0.451	0.1208	0.1006
0.278			0.306			0.371	0.445	0.1248	0.1039
0.311			0.342			0.382	0.458	0.1238	0.1032
0.311			0.342			0.377	0.452	0.1269	0.1057
0.350			0.385			0.387	0.465	0.1258	0.1049
								0.1289	0.1074

						Single Layer Conductors					
						Small Currents		Current Approx. 75% Capacity‡			
						50 Hz	60 Hz	50 Hz	60 Hz		
0.351	0.351	0.352	0.386	0.510	0.552	0.388	0.466	0.504	0.605	0.1294	0.1079
0.441	0.444	0.445	0.485	0.567	0.592	0.437	0.524	0.484	0.581	0.1336	0.1113
0.556	0.559	0.560	0.612	0.697	0.723	0.450	0.540	0.517	0.621	0.1477	0.1147
0.702	0.704	0.706	0.771	0.866	0.895	0.462	0.562	0.534	0.641	0.1418	0.1182
0.885	0.887	0.888	0.974	1.08	1.12	0.473	0.568	0.547	0.656	0.1460	0.1216
1.12	1.12	1.12	1.23	1.34	1.38	0.483	0.580	0.554	0.665	0.1500	0.1250
1.41	1.41	1.41	1.55	1.66	1.69	0.493	0.592	0.554	0.665	0.1542	0.1285
1.41	1.41	1.41	1.55	1.62	1.65	0.493	0.592	0.535	0.642	0.1532	0.1276
1.78	1.78	1.78	1.95	2.04	2.07	0.503	0.604	0.551	0.661	0.1583	0.1320
2.24	2.24	2.24	2.47	2.54	2.57	0.514	0.611	0.549	0.659	0.1627	0.1355
2.24	2.24	2.24	2.47	2.53	2.55	0.515	0.618	0.545	0.655	0.1615	0.1346
2.82	2.82	2.82	3.10	3.16	3.18	0.525	0.630	0.557	0.665	0.1656	0.1388
3.56	3.56	3.56	3.92	3.97	3.98	0.536	0.643	0.561	0.673	0.1708	0.1423

Table A-4. *Inductive Reactance Spacing Factor (x_d) Ohms per Mile, per Conductor*

Feet	SEPARATION Inches 0	1	2	3	4	5	6	7	8	9	10	11
0	—	−0.2513	−0.1812	−0.1402	−0.1133	−0.0941	−0.0795	−0.0681	−0.0591	−0.0514	−0.0447	−0.0386
1	0	0.0000	0.0156	0.0226	0.0291	0.0352	0.0410	0.0465	0.0516	0.0564	0.0611	0.0654
2	0.0695	0.0742	0.0782	0.0820	0.0857	0.0892	0.0926	0.0960	0.0992	0.1023	0.1053	0.1082
3	0.1111	0.1139	0.1165	0.1192	0.1217	0.1242	0.1267	0.1290	0.1314	0.1336	0.1359	0.1380
4	0.1402	0.1423	0.1443	0.1463	0.1483	0.1502	0.1521	0.1539	0.1557	0.1575	0.1593	0.1610
5	0.1627	0.1644	0.1660	0.1677	0.1692	0.1708	0.1724	0.1739	0.1754	0.1769	0.1783	0.1797
6	0.1812	0.1825	0.1839	0.1851	0.1866	0.1879	0.1892	0.1905	0.1918	0.1931	0.1943	0.1955
7	0.1967	0.1979	0.1991	0.2003	0.2014	0.2026	0.2037	0.2048	0.2059	0.2070	0.2081	0.2092
8	0.2102											
9	0.2223											
10	0.2328											
11	0.2428											
12	0.2513											
13	0.2593											
14	0.2668											
15	0.2738											
16	0.2803											
17	0.2864											
18	0.2922											
19	0.2977											
20	0.3029											
21	0.3078											
22	0.3125											
23	0.3170											
24	0.3213											
25	0.3254											
26	0.3294											
27	0.3332											
28	0.3369											
29	0.3404											
30	0.3439											
31	0.3472											
32	0.3504											
33	0.3535											
34	0.3565											
35	0.3595											
36	0.3623											
37	0.3651											
38	0.3678											
39	0.3704											
40	0.3730											
41	0.3755											
42	0.3779											
43	0.3803											
44	0.3826											
45	0.3849											
46	0.3871											
47	0.3893											
48	0.3914											
49	0.3935											

60 Hertz

x_d at 60 cycles
$x_d = 0.2328 \log_{10} \frac{d}{r}$
d = separation, feet.

Feet	SEPARATION Inches 0	1	2	3	4	5	6	7	8	9	10	11
0	—	−0.3013	−0.2174	−0.1682	−0.1333	−0.1062	−0.0841	−0.0654	−0.0492	−0.0349	−0.0223	−0.0106
1	0	0.0000	0.0187	0.0271	0.0349	0.0423	0.0492	0.0558	0.0620	0.0678	0.0735	0.0785
2	0.0841	0.0891	0.0938	0.0984	0.1028	0.1071	0.1113	0.1152	0.1195	0.1237	0.1264	0.1299
3	0.1333	0.1366	0.1399	0.1430	0.1461	0.1491	0.1520	0.1549	0.1577	0.1604	0.1631	0.1657
4	0.1682	0.1707	0.1732	0.1756	0.1779	0.1802	0.1825	0.1847	0.1869	0.1891	0.1912	0.1933
5	0.1953	0.1973	0.1993	0.2012	0.2031	0.2050	0.2069	0.2087	0.2105	0.2123	0.2140	0.2157
6	0.2174	0.2191	0.2207	0.2224	0.2240	0.2256	0.2271	0.2287	0.2302	0.2317	0.2332	0.2347
7	0.2362	0.2376	0.2390	0.2404	0.2418	0.2431	0.2445	0.2458	0.2472	0.2485	0.2498	0.2511
8	0.2523											
9	0.2666											
10	0.2794											
11	0.2910											
12	0.3015											
13	0.3113											
14	0.3202											
15	0.3286											
16	0.3364											
17	0.3438											
18	0.3507											
19	0.3573											
20	0.3635											
21	0.3694											
22	0.3751											
23	0.3805											
24	0.3856											
25	0.3906											
26	0.3953											
27	0.3998											
28	0.4043											
29	0.4086											
30	0.4127											
31	0.4167											
32	0.4205											
33	0.4243											
34	0.4279											
35	0.4314											
36	0.4348											
37	0.4382											
38	0.4414											
39	0.4445											
40	0.4478											
41	0.4506											
42	0.4535											
43	0.4564											
44	0.4593											
45	0.4619											
46	0.4646											
47	0.4672											
48	0.4697											
49	0.4722											

x_d at 50 cycles
$x_d = 0.2794 \log_{10} \frac{d}{r}$
d = separation, feet.

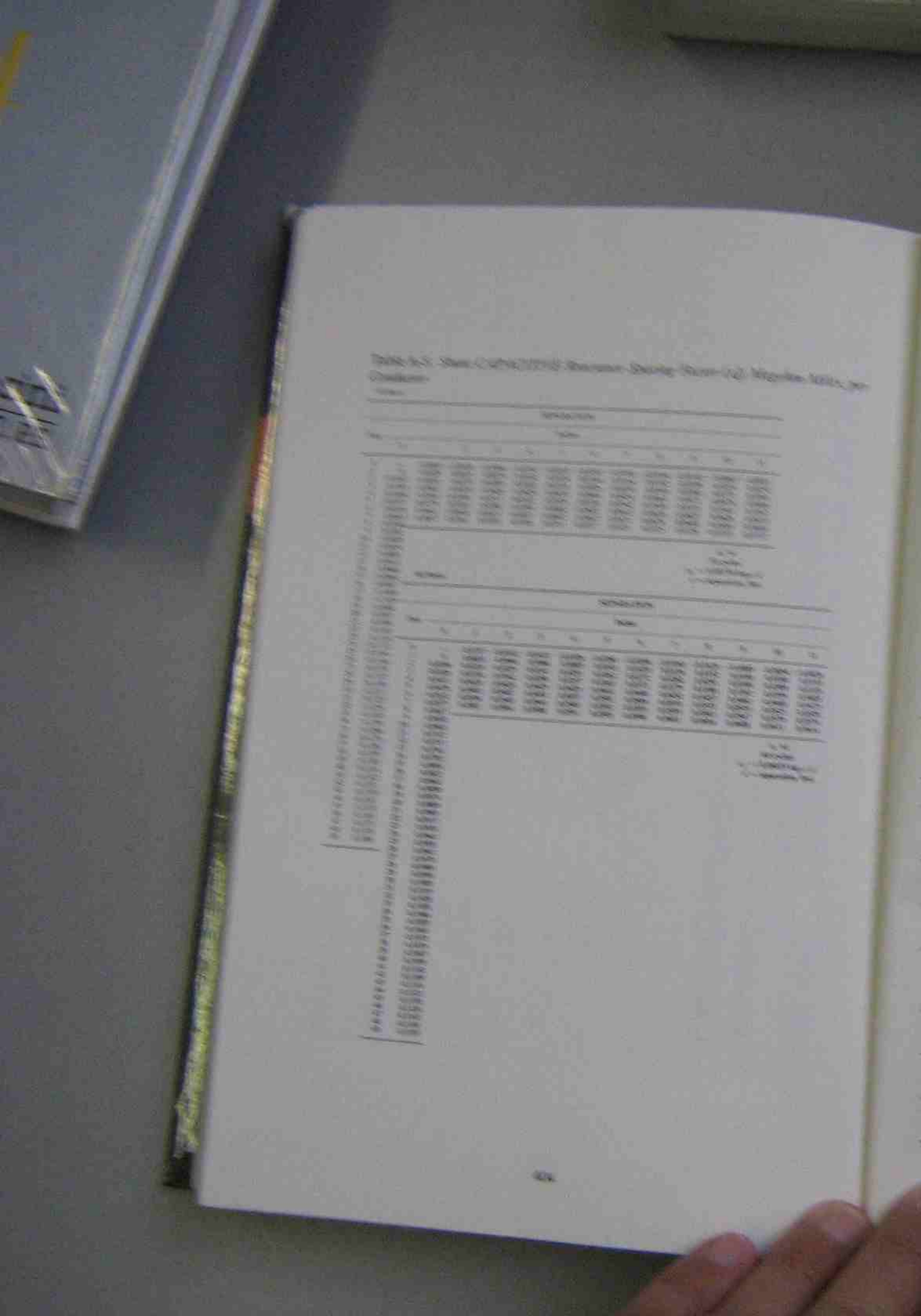


Table A-8. *Transformer Reactance, Percent*

Distribution transformers kV	3 to 500 kVA %
2.5	1.2–5.0
15	1.2–5.0
25	4.0–5.5
69	6.0–6.5

Station transformers kV	500–5000 kVA %
2.5	5.5
15	5.5
34.5	6.0– 6.5
69	7.0– 7.5
138	8.0–10.5
230	9.0–11.0

Station Transformers kV	Above 30000 kVA %	
	A*	B*
34.5	5.0– 8.5	8.7–14
69	6.0–10	10 –16
138	6.6–13	10 –20
230	7.5–16	13 –27
345	8.5–18	14 –30
500	9 –21	15 –34
725	11 –22	23 –35

*A—Oil-immersed self-cooled, and forced air cooled.
*B—Oil immersed, forced oil cooled with water cooler.

The higher values of impedance are associated with the higher kVA rating in the voltage class.

Transformer resistance is usually well below 1 percent.

Table A-9. Rotating Machine Reactances for Short-Circuit Calculation

Type of Rotating Machine	Positive Sequence Reactances for Calculating: Interrupting Duty (per Unit)	Positive Sequence Reactances for Calculating: Momentary Duty (per Unit)
All turbogenerators, all hydrogenerators with amortisseur windings, and all condensers	$1.0X''_d$	$1.0X''_d$
Hydrogenerators without amortisseur windings	$0.75X''_d$	$0.75X'_d$
All synchronous motors	$1.5X''_d$	$1.0X''_d$
Induction motors		
Above 1000 hp at 1800 r/min or less	$1.5X''_d$	$1.0X''_d$
Above 250 hp at 3600 r/min		
From 50 to 1000 hp at 1800 r/min or less	$3.0X''_d$	$1.2X''_d$
From 50 to 250 hp at 3600 r/min		
Neglect all three-phase induction motors below 50 hp and all single-phase motors		

ANSI/IEEE C37.5–1979, Calculation of Fault Current for Application of AC High-Voltage Circuit Breakers Rated on a Total Current Basis, © 1979 by The Institute of Electrical And Electronics Engineers, Inc.

Table A-10. *Approximate Ampacities of Insulated Copper Cables According to Layout**

Conductor Size, AWG (MCM)	Isolated In Air: 1-Conductor amps	Isolated In Air: 3-Conductor amps	In Underground Ducts: 3 1-Conductors amps	In Underground Ducts: 1 3-Conductor amps
6	110	80	85	75
4	145	105	110	100
2	190	140	145	135
1	225	160	170	155
1/0	260	185	195	175
2/0	300	210	220	200
3/0	340	250	250	230
4/0	400	280	290	260
250	440	320	320	290
350	550	390	380	350
500	680	480	460	430
750	880	610	560	530
1000	1060	700	640	600

* Based on conductor temperature of 90°C, ambient air temperature of 40°C, and ambient earth temperature of 20°C.

Table A-11. *Approximate Ampacities of Insulated Copper Cables According to Temperature**

Conductor Size, AWG (MCM)	Temperature Rating of Cable†						
	60°C		75°C		90°C		Bare Conductors
	A	B	A	B	A	B	
6	55	80	65	95	70	100	100
4	70	105	85	125	90	135	130
2	95	140	115	170	120	180	175
1	110	165	130	195	140	210	200
1/0	125	195	150	230	155	240	230
2/0	145	220	175	260	185	280	270
3/0	165	260	200	310	210	330	320
4/0	195	300	230	360	230	380	370
250	210	340	255	400	270	420	410
350	260	420	310	500	320	530	510
500	320	510	380	620	400	660	630
750	400	650	470	780	500	840	810
1000	450	780	540	930	580	1000	960

* Based on ambient temperature of 30°C.

† Column A is for three conductors or less in raceway or cable, or buried directly in earth. Column B is for a single conductor in air.

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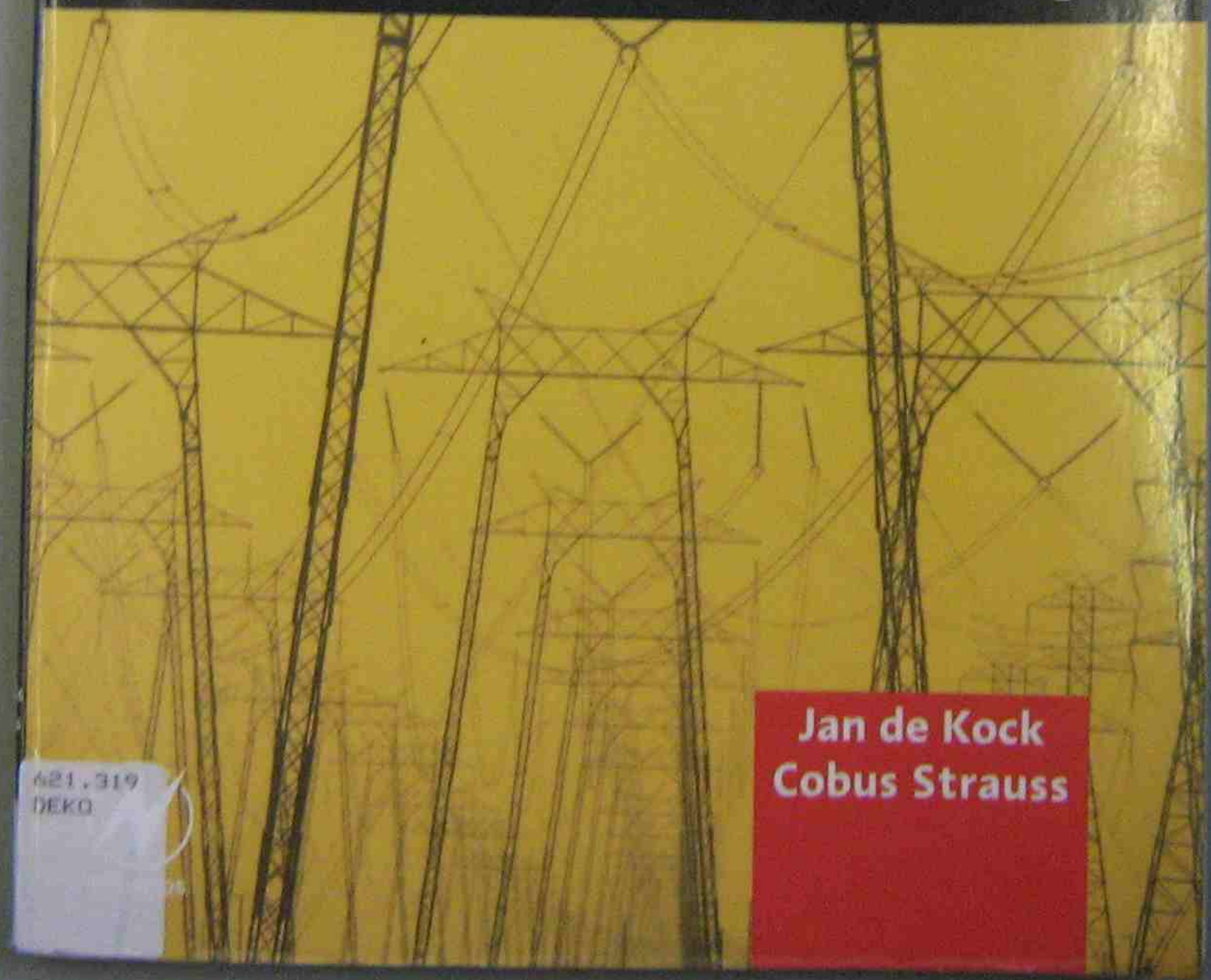
Practical

Power Distribution for Industry



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BASICS

electric power transmission

Anthony J. Pansini and Kenneth D. Smalling

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1

General Concepts

Like air, water, and food, electrical energy has become an integral part of our daily personal and business lives. It is so taken for granted that little thought is given to the process that produces and delivers this energy to where it is used. It is a unique process among industries; practically all that is produced is used instantly in the quantities required for light, actions, or communication, and is not stored in warehouses or on shelves.

Similar to other businesses, means must be provided to bring the product to the consumer—in this case, from the generating plant to the consumer's premises. In most business processes, provision is made for the delivery of the product in bulk and for its retail distribution. In an electrical power system, the bulk delivery is referred to as the *transmission system*, while the retail delivery is known as the *distribution system* (see Fig. 1-1).

Some people are unaware that an electric utility is a business enterprise, whether or not the industry has been deregulated in their state. Where the industry is regulated, the price charged for its product is not entirely under its control, but is fixed at various levels by regulatory bodies. This often leads to a public perception that an electric utility monopoly is guaranteed a profit no matter what. In fact, it is not guaranteed a profit. A limit is set on how much profit can be made under proficient management. The fact remains that utilities must pay for materials, labor, and capital they require and pay taxes just like any other business.

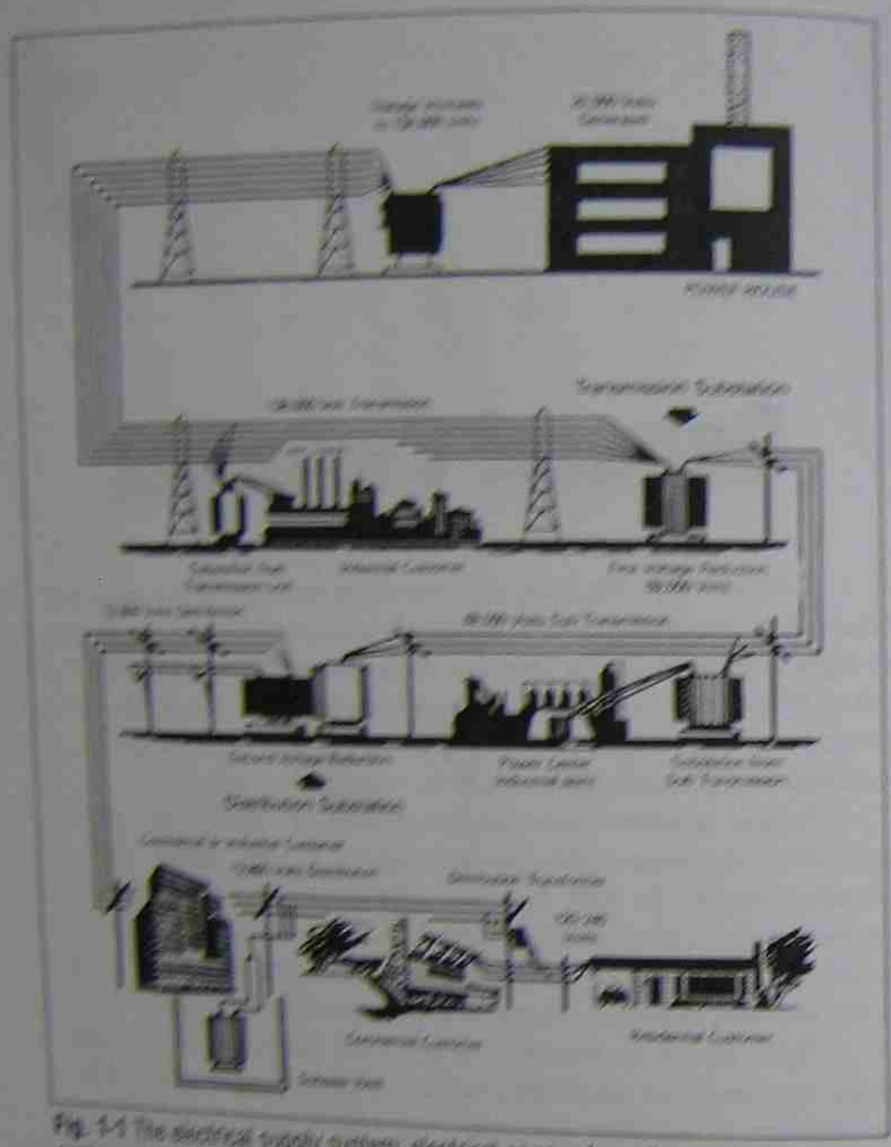

Fig. 1-1 The electrical supply system: electrical service from the generation to the customer

In obtaining these commodities, utilities must compete for them at prices generally dictated by the marketplace, while the prices charged for their electrical energy product are limited by regulatory agencies. In addition, electrical utilities must abide by regulatory standards for reliability of delivery and for the quality of the voltage at which the energy is delivered.

The Transmission System

Transmission systems carry the bulk supply to load centers from generating plants. These plants are generally located in outlying areas because of their environmental impact and need for large amounts of water for cooling purposes. A factory or generating plant is rarely situated at or near a population or load center. Generally, high voltages and great capacity are essential for the transmission system.

Transmission lines also provide interconnections for the transfer of electrical power between two or more utilities for economic and emergency purposes. Such interconnections of utilities are referred to as pools or grids and sometimes more formally as integrated systems.

From wholesale centers or transmission substations, means are provided to distribute the electricity to regional load and population centers where a demand for the product exists. These means constitute the distribution system.

The principal purpose of a transmission system, then, is to carry bulk quantities of electrical energy to or between convenient points. At these points, the electrical energy may be subdivided for eventual delivery to one or more distribution systems. A synthesis of definitions accepted by the Federal Energy Regulatory Commission and various state utility commissions follows:

> A transmission system includes all land, conversion structures, and equipment at a primary source of supply; lines, switching, and conversion stations between a generating or receiving point and the entrance to a distribution center or wholesale point; and all lines and equipment whose primary purpose is to augment, integrate or tie together sources of power supply.

The FERC also emphasizes the significance of transmission systems in a survey:

> The strategic importance of transmission is much greater than is indicated by the 20% average share in the overall cost of electricity. (The 20% average would pertain to transmission no matter who "owns" it.) Adequate interconnections, where

economically justified, provide the keys to large-scale generating units, to major savings in capacity because of load diversity, and the most efficient utilization of existing generating capacity. In short, interconnection is the coordinating medium that makes possible the most efficient use of facilities in any area or region.

In Figure 1-1, note that the generator produces electricity at a pressure of 20,000 volts. This pressure is raised, by means of an apparatus known as a transformer, to a value of 138,000 volts or higher for the long transmission journey. This electric power is conducted over 138,000-volt (138-kV) transmission lines to substations located in important centers of population or electrical loads in the territory served.

When the electric power reaches the substations, its pressure is reduced or stepped down (also by a transformer) to 69 kV. It is then transmitted in smaller quantities to other substations in the local load areas. (In some cases, it might be stepped down to 13.8 kV for direct distribution to local areas.) Transmission circuits of such voltages may consist of open wires on poles in outlying zones (along highways, for example) where this type of construction is practical. Or it may consist instead of cables installed in ducts underground or buried directly in the ground in more densely populated areas.

While the transmission line system shown in Figure 1-1 is simple, many transmission line installations can provide for an interchange of power between two or more neighboring utility companies to their mutual advantage. Such lines permit one utility to purchase power from another when it is economically advantageous to do so. A utility might also purchase power produced elsewhere during periods of emergency when its own generating units may be out of service for repair or maintenance. Such interconnecting grids between utility companies may be very complex (see Fig. 1-2).

Wheeling of Power

The traditional concept of transmission interconnections between adjacent utility systems to exchange emergency power, economic generation, and capacity sales has changed under deregulation of the power industry. These transmission systems may now transfer energy and power requirements between any supplier and a consumer. Suppliers may be electric utility systems (sometimes geographically remote from the ultimate customer),

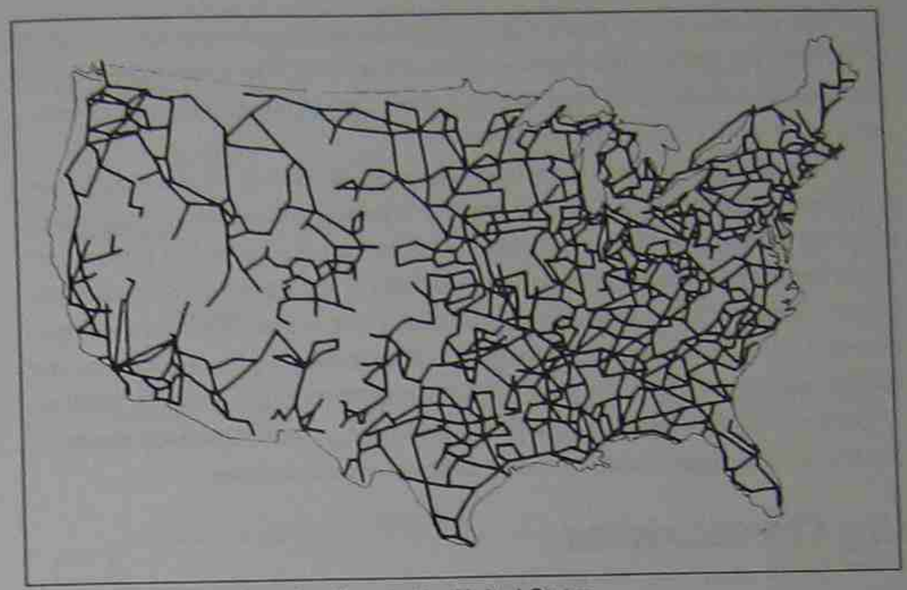

Fig. 1-2 Major transmission lines in the United States

independent power producers, or marketing firms (similar to stockbrokers).

The basic concept remains the same: using transmission to wheel power from the supply to the consumer with appropriate compensation for the use of the lines. However, the marketing aspect has been influenced by competition, open access to transmission, deregulation, and restructuring of utility corporations.

In the United States, deregulation was initiated through the federal Energy and Policy Act of 1992 (EPACT), introducing competition to the interstate and intrastate electric energy markets. In April 1996, the FERC issued Order 888, which eased the restrictions on transmission utilities. This was accomplished by opening access to transmission lines and separating the functions of generation and transmission for wholesale wheeling. Further development of competition in the electric energy market is now embodied in specific programs established by state regulatory authorities.

The wheeling of power under both normal and emergency conditions must still be planned and operated in such a manner as to provide reliable electric service. This requires adhering to generating reserve criteria and the operating capacity of the transmission system, particularly when the emergency operating capability limits are used. Notice of contingencies can range

from several minutes or more (such as an operating generator unit coming off the line for some reason) to fractions of a second. The latter might occur when a transmission line trips under a short circuit condition—either temporarily or until repairs can be completed.

Wheeling of power on an interconnected system, with the emergence of competition in the supply of electric energy to consumers, has made planning and operating transmission systems a very complex procedure. There are more unknowns relating to quantity and timing than ever before. System operators must now cope with many more transactions on their system and have to coordinate with new entities called regional independent system operators (ISOs). Another complicating factor is the growing number of independent power producers (IPPs) and energy market brokers developing and managing contracts between supplier and consumer.

Line Characteristics

Before discussing the physical and electrical characteristics of transmission lines, it may be well to consider an analogy between electric transmission systems and water systems.

Water/Current Analogy

The flow of electricity can be compared to the flow of water. Whereas water flows in a pipe, electric current is made to flow through conductors or wires (see Fig. 1-3). To move a definite amount of water from point to point in a given amount of time, a large-diameter pipe and low pressure may be employed to force it through. Alternately, a small-diameter pipe could be used with high pressure applied to the water. If the higher pressure is used, the pipe must have thicker walls to withstand the pressure.

The same rules apply to the transmission of electric current. In this case, the diameter of the pipe corresponds to the diameter of the wire, and the thickness of the pipe walls corresponds to the thickness of the insulation around the wire. (For more detailed information, refer to appendix C, "Basic Electricity.")

Voltage and Load-Carrying Capability

Transmission lines are designed to transport large amounts of electricity—usually expressed in ratings by kVA (1,000 volt-amperes) or MVA (1 million volt-amperes)—over relatively long distances. Transmission systems are

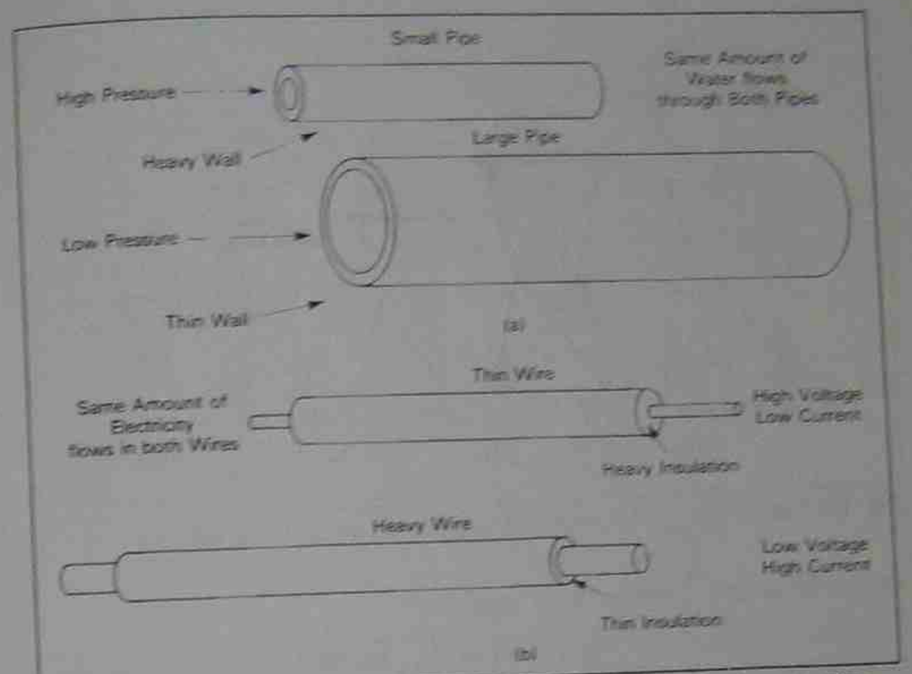

Fig. 1-3 Water/current flow analogy: **(a)** comparison of water flow through different size pipes **(b)** comparison of current flow in different size wires

generally designed so that remaining lines pick up the load when a transmission circuit is interrupted. Normal line ratings are used under normal operating conditions. Emergency line ratings exceed normal ratings and become the design limit on the basis of known contingency conditions resulting from system load flow studies.

Transmission lines may carry less than 10 MVA to hundreds of MVA up to many hundreds of miles. When the *power factor* is known (refer to appendix C), the lines can also be rated in kW (kilowatts) or MW (megawatts) of electric power. The electrical pressures, or voltages, at which these lines operate may range from a few thousand volts to values of more than 765 kV, with experimental lines operating up to 1,500 kV. In general, the larger the amount of power to be carried, and the greater the distance to be traversed, the higher the voltage at which the transmission line is designed to operate (see Fig. 1-4).

Historically, standard transmission voltages have been approximate multiples of a base of 115 volts (see Table 1-1). Transmission lines strung

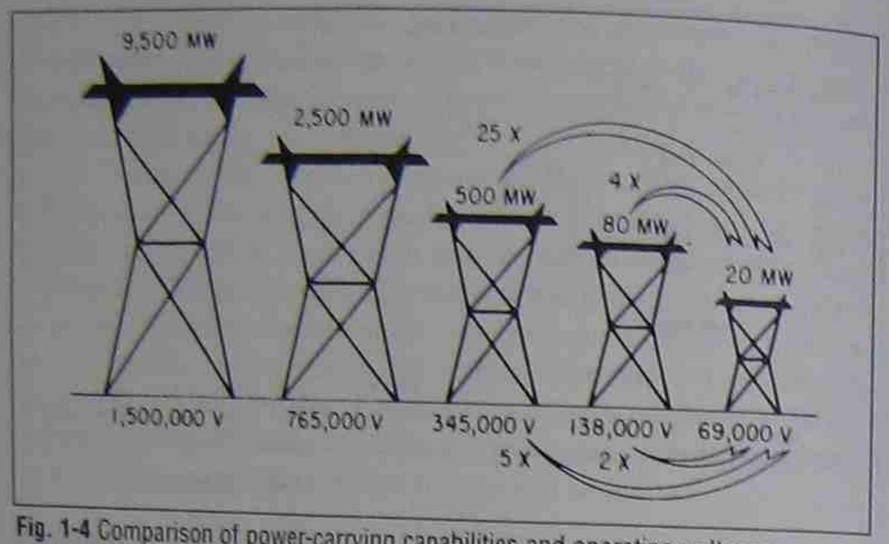

Fig. 1-4 Comparison of power-carrying capabilities and operating voltages

Table 1-1 Standard Transmission Voltages

13,800	23,000	34,500	46,000	69,000	115,000	138,000
230,000	354,000	500,000	765,000	1,000,000	1,500,000	

between substations and local or regional center are sometimes called *sub-transmission lines*. They generally operate at 69 kV or less. Lines operating at 500 kV or more are generally referred to as extra-high-voltage (EHV) lines.

Cost Considerations

Transmission facilities are costly, whether overhead or underground. The investment required, as a percentage of total utility plant, may be as much as 20%. (Again, that 20% is an average.) This is not only because of the requirement to move ever-larger amounts of power over considerable distances, but also because of the greater attention being given to appearance and effect on environment.

Transmission structures have been specifically designed for appearance, employing gracefully shaped and colored structures pleasing to the eye and blending with the surroundings (see Fig. 1-5). The color of insulators has generally been brown, but changes to light blue and gray standards have been made. These colors are less obtrusive against sky backgrounds and are aesthetically more acceptable.

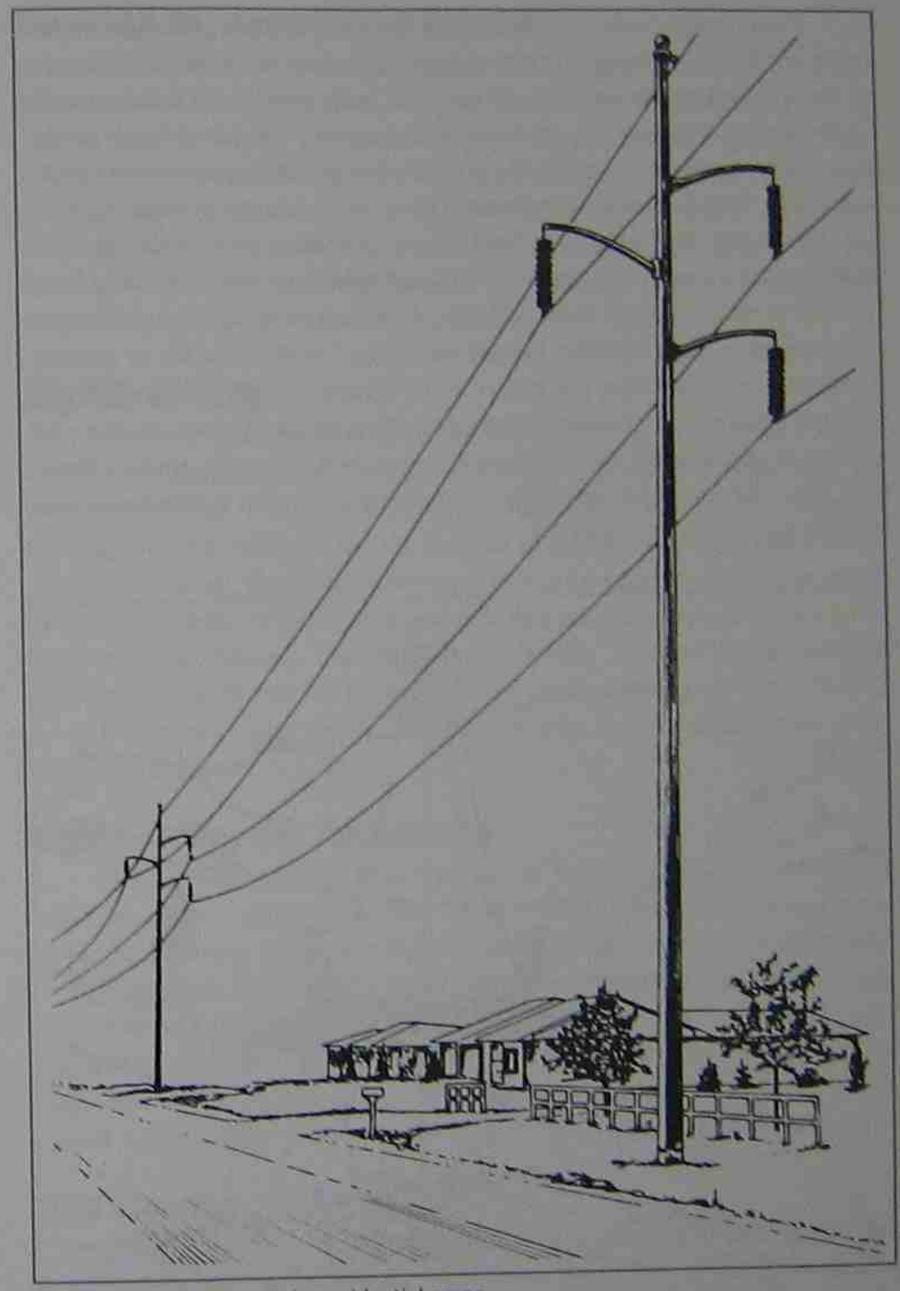

Fig. 1-5 Pole structures in residential areas

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Transmission costs are affected by the costs of rights-of-way and the higher quality of construction needed in congested areas. Transmissions costs are also affected by the need for stronger ties both within and between utilities because of reliability requirements introduced by the use of larger generating units and underground cable systems. Transmission requirements may be reduced, however, when generating plants are in or near the load centers.

Data collected by the Federal Power Commission indicate costs for underground transmission lines in rural and suburban areas may vary from 10 to 30 times as much as overhead lines. Costs vary depending on the types of construction (duct or direct burial) and cables (solid insulation or hollow) employed. In urban areas, the ratio may be greater. In other places, because of rough ground, inaccessible terrain, and other special situations, this cost may be as much as 50 times greater (see Fig. 1-6). It would appear, therefore, that overhead lines may continue to predominate in transmission systems for some time to come.

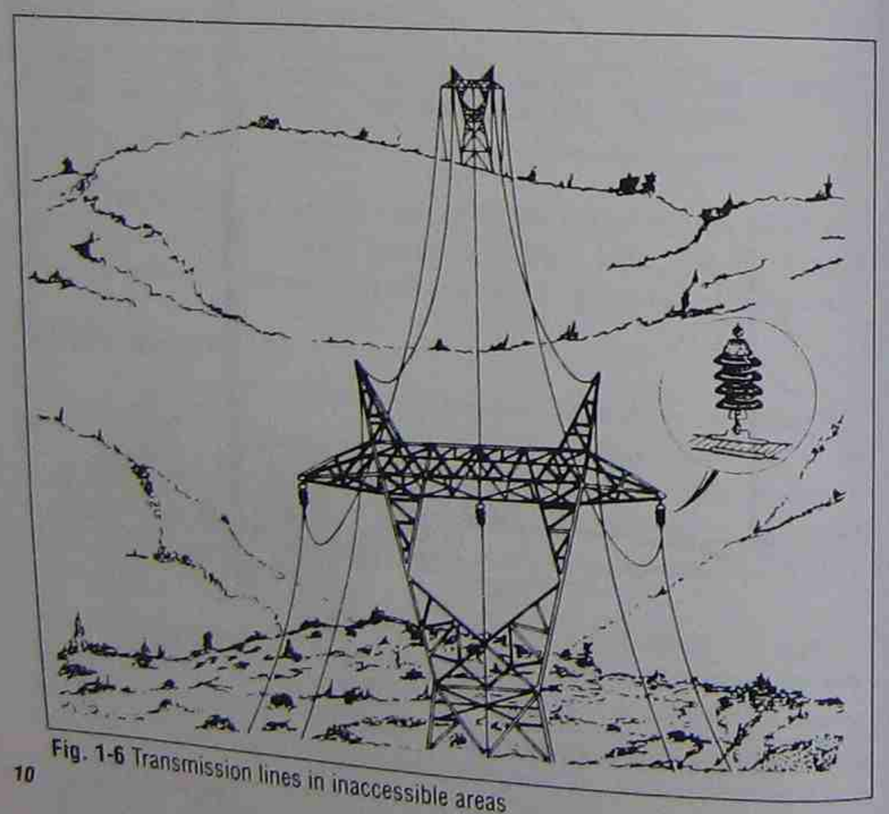


Fig. 1-6 Transmission lines in inaccessible areas

Overhead Vs. Underground Repairs

While overhead lines are exposed to the hazards of vandalism and weather, particularly lightning, ice, and wind, faults are usually relatively easy to find and repair. The reverse is generally true of underground lines. While relatively free from harmful exposure, when faults do occur, they are relatively hard (and time-consuming) to find and repair. Highly specialized skills are required for both their installation and repair. The addition of new lines or substations in an underground transmission system presents difficulties not usually met in overhead systems.

Rights-of-Way

Overhead transmission lines are admirably suited to open country areas where rights-of-way of ample width and reasonably straight lines are available (see Fig. 1-7). The straight-line route, with few angles, decreases the length of line required and the amount of guying or special construction necessary. Further, these rights-of-way are usually easier to acquire, whether by purchase, lease, or other arrangement. Appearance may not always be of paramount importance. Transmission line heights required by national and local safety code clearances for the voltage ranges involved and the economics of long spans make such overhead installations very adaptable to open, cross-country areas.

Rights-of-Way and Appearance

If transmission lines must be built in densely populated urban and suburban areas, rights-of-way may be restricted to relatively narrow areas along the streets or in alleys in the rear of buildings. Construction is usually limited to single (rather high) poles with span lengths of one city block or less. Unusual attention must be given to appearance, tree conditions, guying, and other factors that may be detrimental to good public relations. This may also include limited access in which materials may have to be transported by hand as well as agreements limiting work to off-schedule hours.

Tree Clearing

Often the rights-of-way require clearing of trees, brush, and other growth, and must be maintained sufficiently clear so that subsequent growth will not affect operation of the lines. The engineer will designate all danger trees, which may be removed or topped at the option of the contractor.

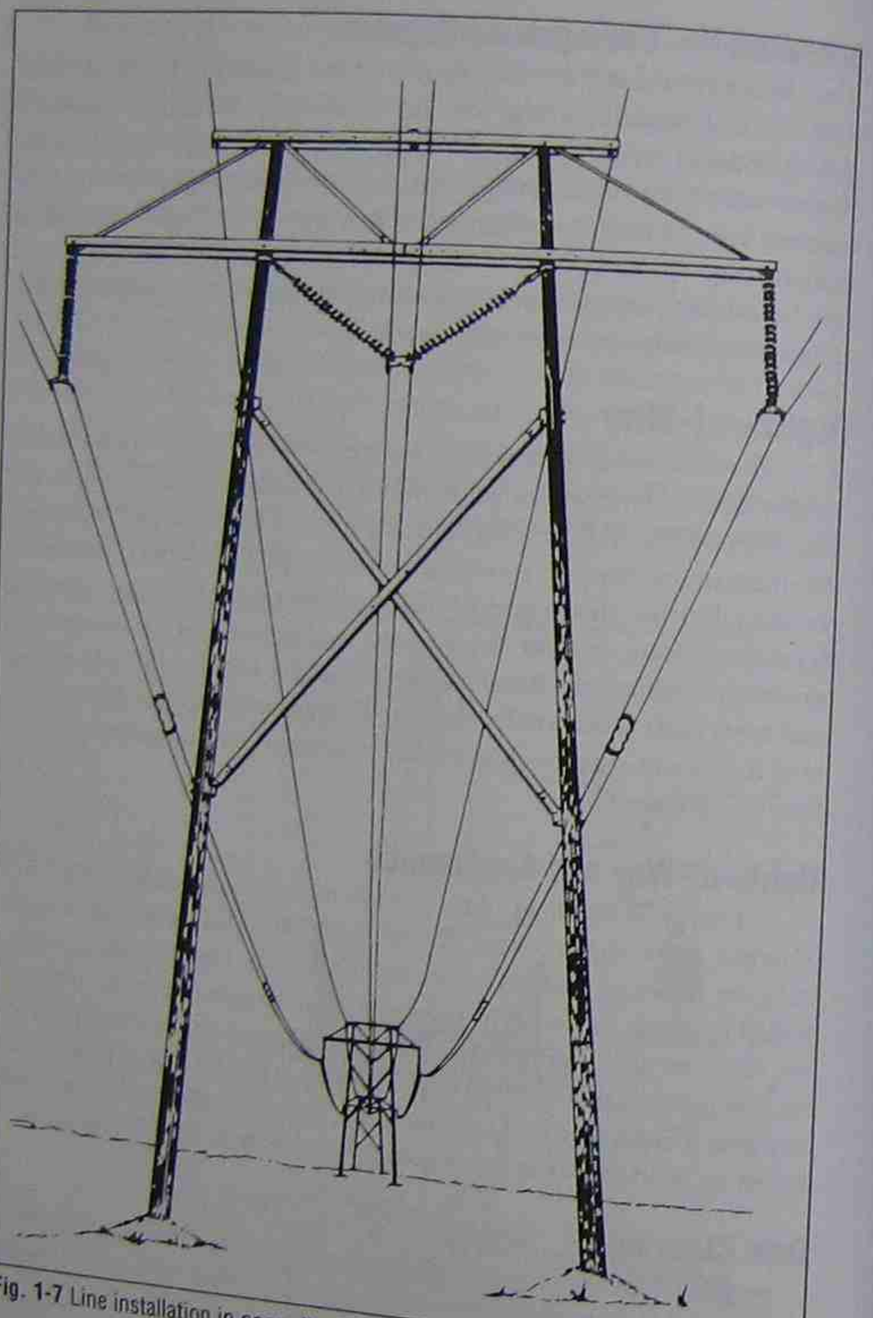


Fig. 1-7 Line installation in open, flat terrain

In approximately level terrain, trees that would reach within five feet of a point underneath the outside conductor in falling are examples of danger timber. In wooded areas, the right-of-way is cleared back far enough so that trees falling will not fall into the line. Trees may be topped gradually so that so-called danger timber will not inflict damage to the lines (see Fig. 1-8).

Access roads must also be provided not only for construction, but for future patrols, inspections, repairs, and maintenance of the lines. Portions of the right-of-way must be cut so stumps will not prevent the passage of tractors and trucks along the right-of-way.

Rough Terrain

In some instances, such as where lines traverse heavily forested, rough terrain, helicopters may be used to deliver materials. Such deliveries often include preassembled tower structures, as well transporting personnel to the job sites for both construction and maintenance purposes (see Fig. 1-9).

Railroad Rights-of-Way

The installation of transmission lines along railroad rights-of-way would appear to provide a logical and desirable location for such lines (see Fig. 1-10). Often, however, these rights-of-way may also contain communication circuits that may suffer electrical interference from the high voltages of the transmission lines. Care must be exercised during work on such lines

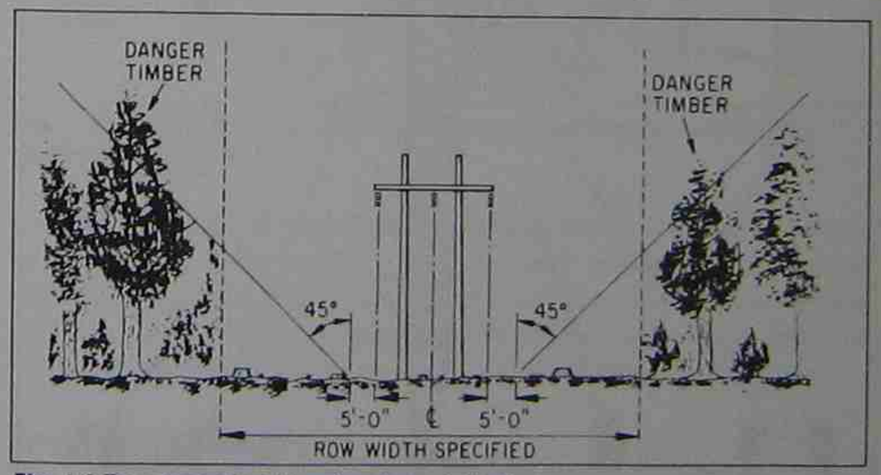


Fig. 1-8 Tree removal and topping along right-of-way

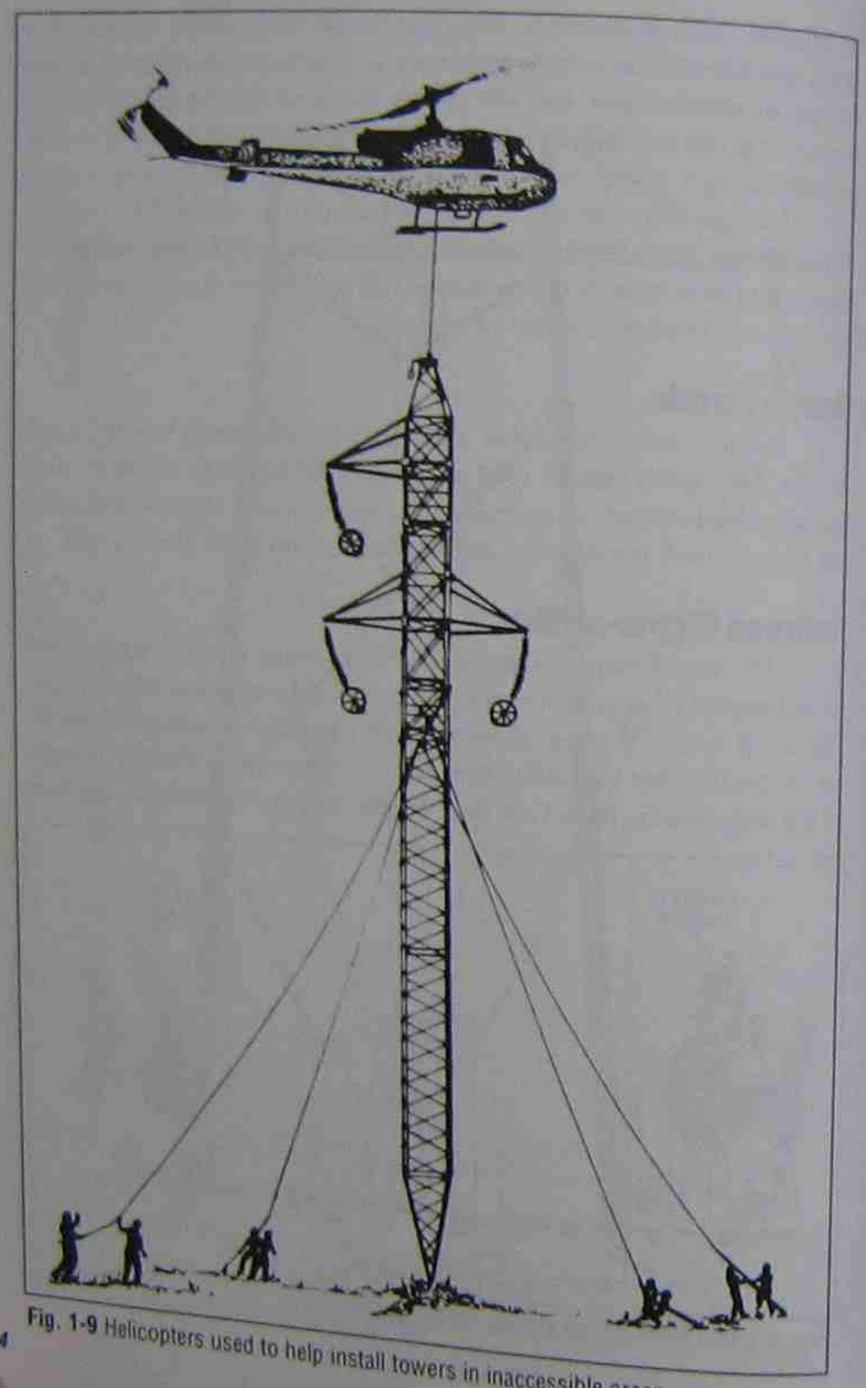


Fig. 1-9 Helicopters used to help install towers in inaccessible areas

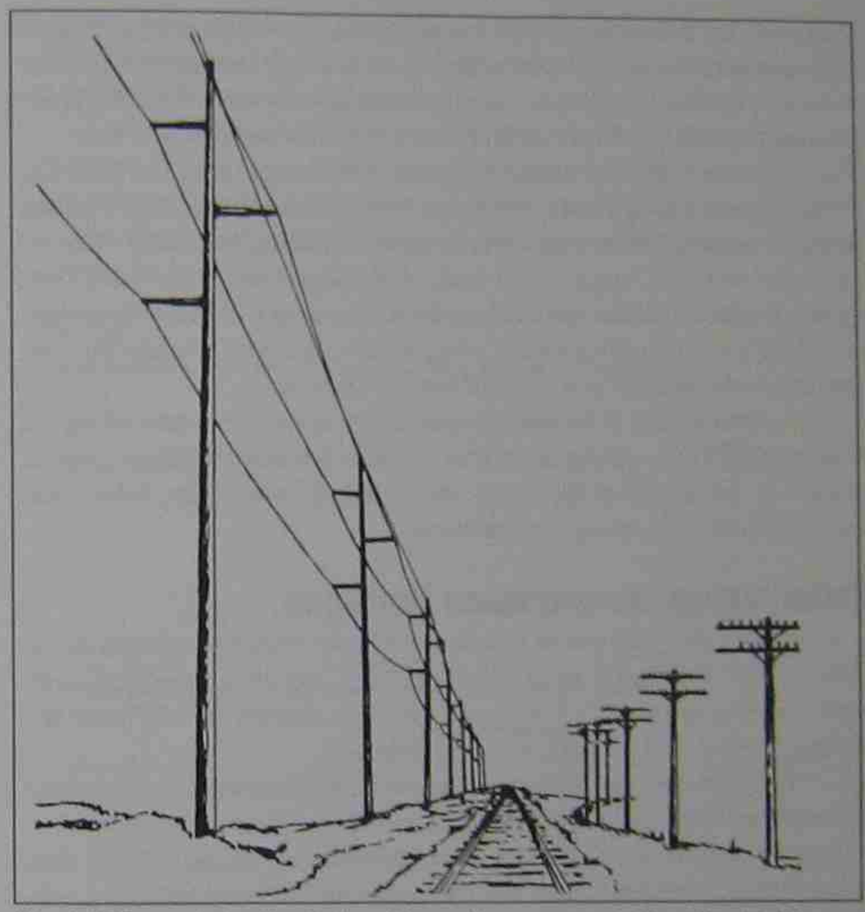


Fig. 1-10 Transmission line (left) and low-voltage communications line (right) along railroad right-of-way

to insure the safety of personnel from passing trains. This may sometimes cause protracted and expensive delays in work schedules. Despite these drawbacks, railroad rights-of-way provide excellent routes for transmission lines. This is especially true since the railroad usually serves population or industrial centers that also constitute electric load centers.

Increasing Capacity

Overhead transmission lines more readily lend themselves to increased capacity because of system load growth than underground lines. Their

capability may be increased by raising the operating voltage or by adding or replacing conductors. With the difficulty in securing construction permits because of environmental constraints and occasionally adverse public opinion, uprating existing lines is often much easier than building new lines.

Capacity additions to underground transmission lines are generally limited by initial design and installation. New techniques have improved the ability to uprate. These techniques include circulating insulating fluids in pipe-type cables or replacing the cable with larger conductors using new, thinner insulations at the same voltage level. Replacing the cable with a higher level of insulation to operate at a higher voltage is also possible with the new materials available as a result of industry research.

Another means of increasing capability is to apply real-time ratings to both overhead and underground lines. This is described in more detail in chapter 6. Such technology makes use of actual known data rather than assumptions in calculating the line rating.

Determining Transmission Voltages

Earlier, the relationship between conductor sizes and voltages in the transmission of electrical power was explained, including an analogy with water-carrying systems. This principle is basic in considering the choice of a voltage (or pressure) for a transmission system.

There are two general ways of transmitting electricity: overhead and underground. Both can use a variety of conductors. These include copper or aluminum conductors, aluminum conductors steel reinforced (ACSR), and, in some cases, steel conductors. But the insulation in the first instance is usually air except at the supports (towers, poles, or other structures), where it may be porcelain, glass, or other material. In underground transmission, the conductor is usually insulated with oil-impregnated paper, or a special type of plastic material.

In overhead construction, the cost of the copper or aluminum conductors as compared to the insulation is relatively high. It is therefore desirable, when transmitting large amounts of electric power, to resort to the higher electrical pressures or voltages, thereby employing thinner, less-expensive conductors that are easier to handle. Low voltages require heavy conductors that are costly, bulky, and expensive to install.

There is a limit, however, to how high the voltage and how thin the conductors can be. In overhead construction there is the problem of

supports—poles, structures, and towers. If the conductor is too thin, it will not be able to support itself mechanically, and the cost of additional supports and insulators becomes inordinately high.

Underground construction faces the same economic limitations, and in this case, the expense of insulation. An underground cable must be thoroughly insulated and sheathed from corrosion. The greater the overall size of the cable, the more sheathing becomes necessary and more difficulty is experienced in its handling (see Fig. 1-11).

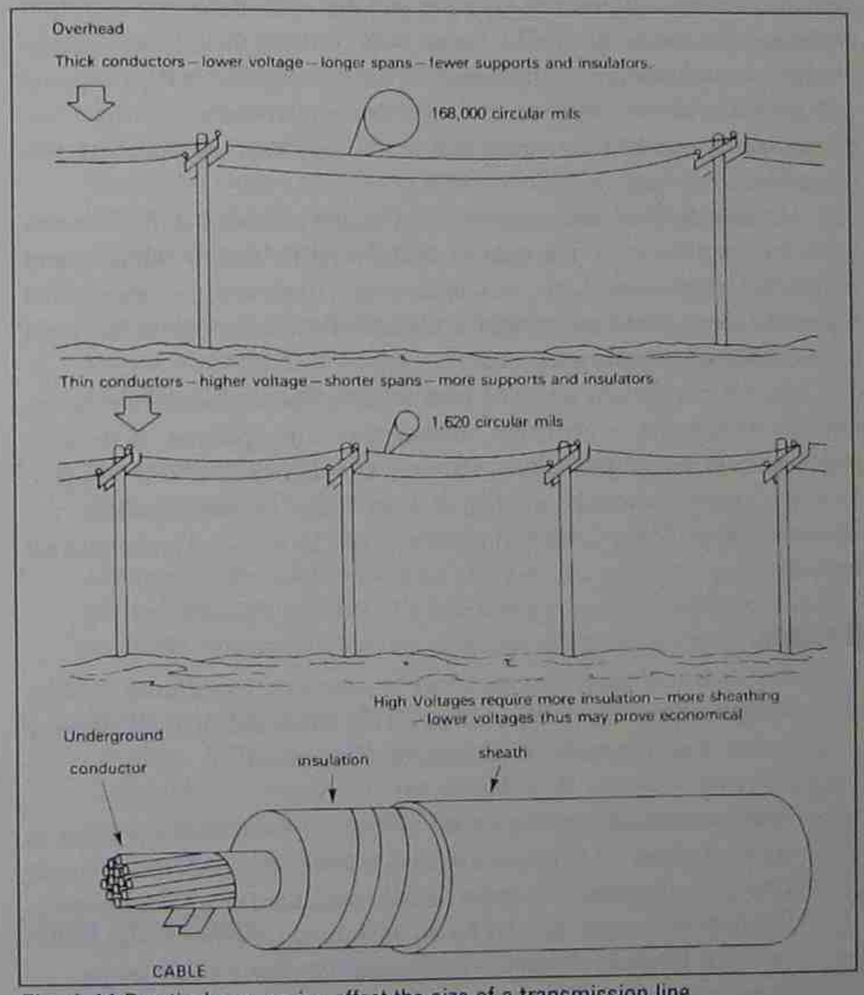


Fig. 1-11 Practical economics affect the size of a transmission line

Determining transmission voltages is a matter that requires careful study. Engineers "cost out" the systems, employing several generally standard voltages (and standard materials and equipment). For example, they might calculate the annual costs for each of the following systems: 69 kV, 138 kV, and 230 kV. Approximate costs of conductors and necessary equipment, insulators, supports, rights-of-way, labor costs, and associated expenses involved in construction and installation are carefully evaluated.

The annual carrying charges are calculated, to which are added the estimated annual maintenance expenses and the value of the losses for each of the systems under study. The lowest sum of these annual costs usually determines the selection of the voltage. The lowest overall annual expense will generally be found to occur when the annual carrying charges are approximately equal to the annual cost of the electrical losses incurred; this is known as Kelvin's Law.

In making these determinations, the future increased demand is also taken into consideration. The increase over a period of time is estimated and is included in the study. Again, economic studies determine the extent of the future time period to be considered, at the end of which facilities would need to be reinforced or replaced.

In the calculations involved in arriving at the selection of the transmission voltage, the construction, maintenance, and operation of the projected facilities are subject to the overriding considerations of safety. In general, the utility standards are higher than those recommended by the National Electric Safety Code and those imposed by local and governmental regulations.

Review

- The system of supplying electricity to a community includes facilities for production (generating plants), for wholesale or bulk delivery (transmission), and for local retailing (distribution).

- Transmission circuits may consist of open wires on towers or poles in outlying zones, or of cables installed in ducts underground or buried directly in the ground in more densely populated areas. Transmission line installations can provide for an interchange of power between two or more neighboring utility companies to their mutual advantage. Power may also be "wheeled" to non-adjacent companies via the facilities of the intervening companies. Such interconnections between utility companies are often referred to as a grid or pool.

- Transmission lines transport relatively large amounts of electric power over relatively long distances. Power may range from less than 10,000 kW and a few miles to more than 3 million kW and many hundreds of miles. The voltages at which these lines operate range from a few thousand volts to more than 765 kV.

- The voltage of a transmission line is usually determined by economics. Higher voltages are generally desirable since smaller, less-expensive conductors may be used. However, for overhead lines, the mechanical strength of the conductor may limit the span length, requiring a greater number of poles, insulators, etc. The annual costs of several standard voltage lines are evaluated; the lowest annual cost usually determines the selection of voltage.

- Transmission lines between substations and local or regional load centers are sometimes called *subtransmission lines*. They generally operate at voltages of 138 kV volts or less.

- Lines operating at 500 kV or more are generally referred to as extra-high-voltage (EHV) lines.

- Overhead transmission lines are more suited to open country areas, where rights-of-way of ample width and reasonably straight lines are available. Appearance also is not always of paramount importance.

- While overhead lines are exposed to the hazards of vandalism and weather, faults are usually relatively easy to find and repair. Conversely, underground lines are relatively free from harmful exposure. However, the faults that do occur are relatively hard (and time-consuming) to find and repair.

Study Questions

1. What is the function of transmission lines or systems?
2. What factors influence the voltage selected for a transmission line?

3. How does the load-carrying capability of a transmission line relate to the voltage at which the line operates?
4. What are some typical standard voltages of transmission lines?
5. What are subtransmission lines? At what voltages do they operate?
6. How do generating plants affect the transmission system?
7. What are the advantages of overhead-constructed transmission lines?
8. What are the disadvantages of overhead-constructed transmission lines?
9. What are the advantages of underground-constructed transmission lines?
10. What are the disadvantages of underground-constructed transmission lines?

2

Overhead Construction

The several elements constituting an overhead transmission line, together with pertinent information concerning their purpose, characteristics, and methods of handling, are covered in this chapter.

Poles and Towers

Structures for supporting the overhead conductors are broadly classified as poles (see Fig. 2–1 and Fig. 2–2) or towers (see Fig. 2-3 and Fig. 2–4).

Single pole supports may be spaced a few feet apart or more than 100 feet (ft) apart. They may be made of natural wood: southern yellow pine, western red cedar, douglas fir, larch, and other species, reflecting the availability of suitable timber in the several geographic areas of the country. They can also be made of imported wallaba where extra strength is required. These may be chemically treated, round-shaped tapered poles or square-shaped poles. Poles may also be of hollow, tapered, tubular design, made of steel or aluminum. They may also be built up of flat metal members, latticed together into a variety of cross sections, from squares to duodecagons (12-sided).

Wood poles are set directly in the ground. Metal poles may be embedded directly in earth or concrete, or secured to bolts embedded in a concrete

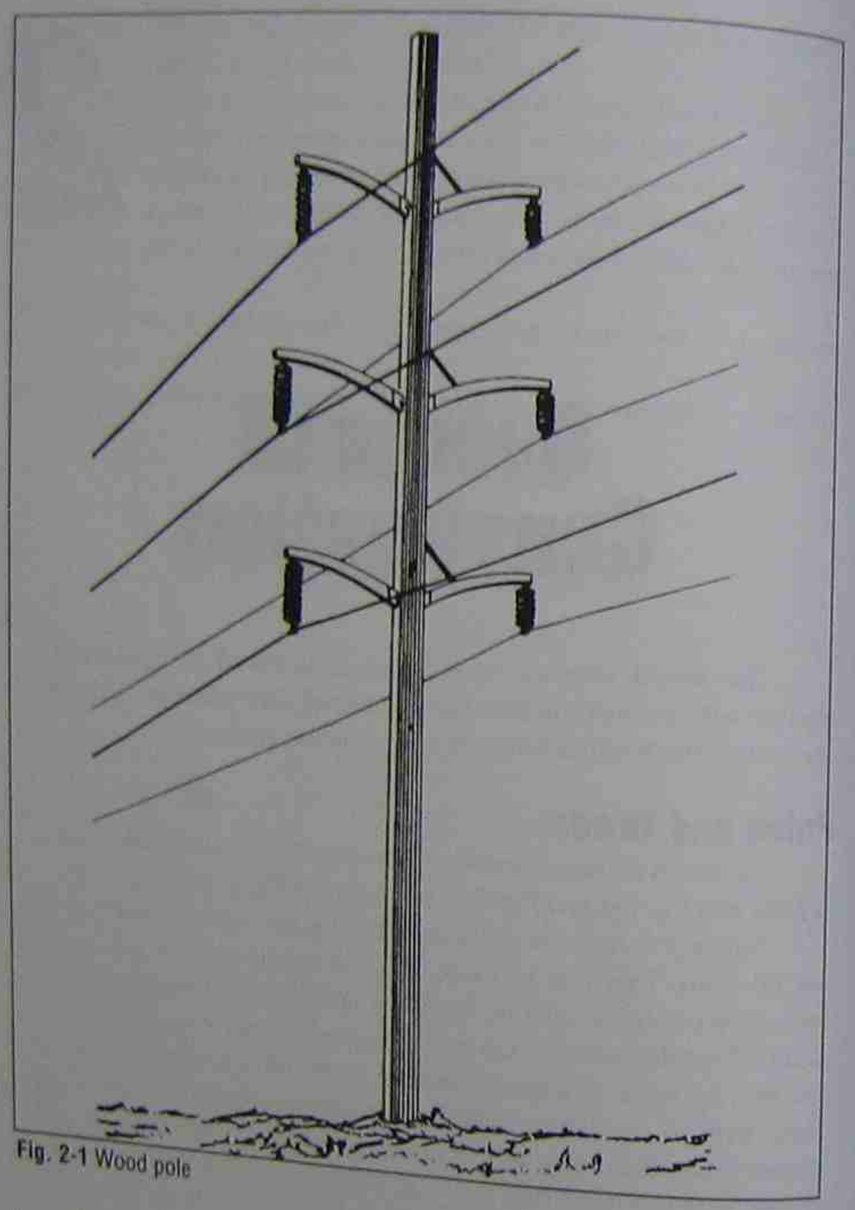


Fig. 2-1 Wood pole

base. Wood and metal poles may be combined as members of a structure into A-frames, H-frames, and sometimes into V- or Y-type transmission line supports capable of carrying longer spans.

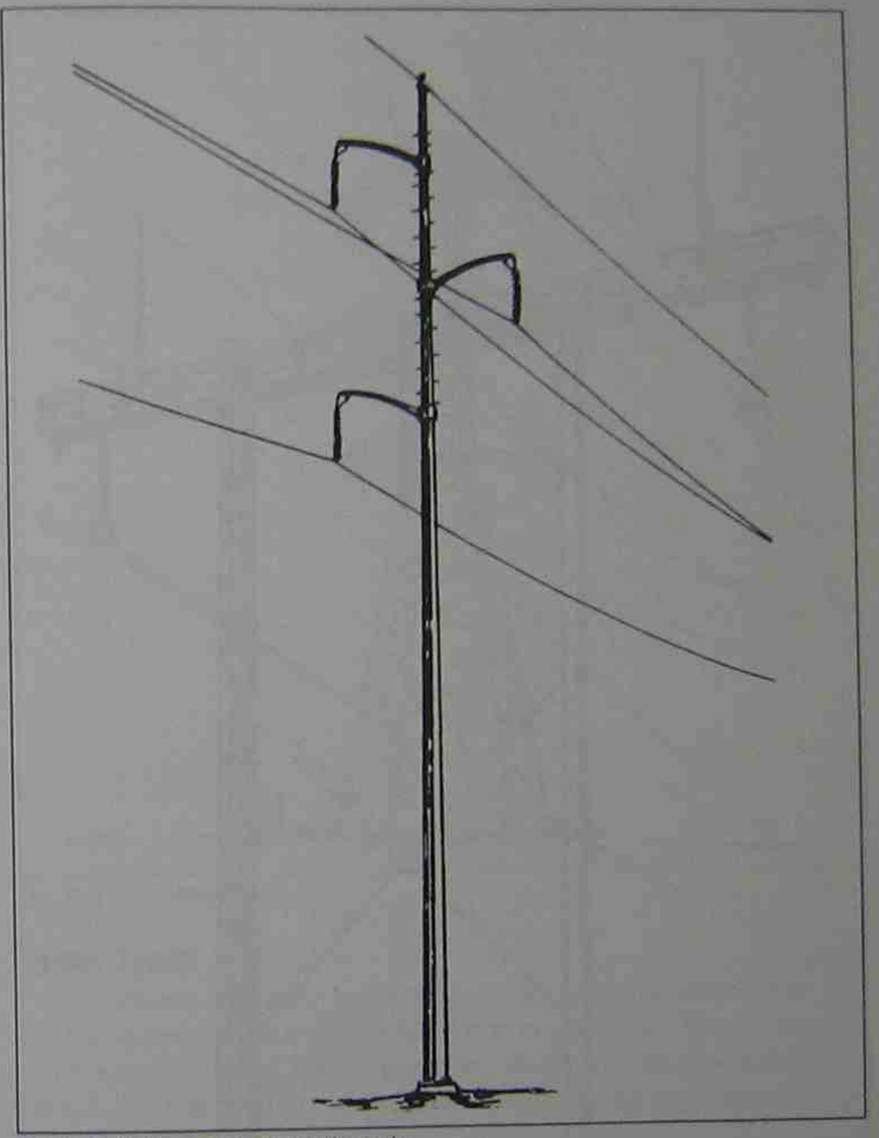


Fig. 2–2 Hollow, tapered, tubular pole

Reinforced concrete, hollow, round, or square poles have long life, structural strength, freedom from weathering, good appearance, and low maintenance costs. They are, however, relatively expensive in first cost and extremely heavy, making their handling difficult.

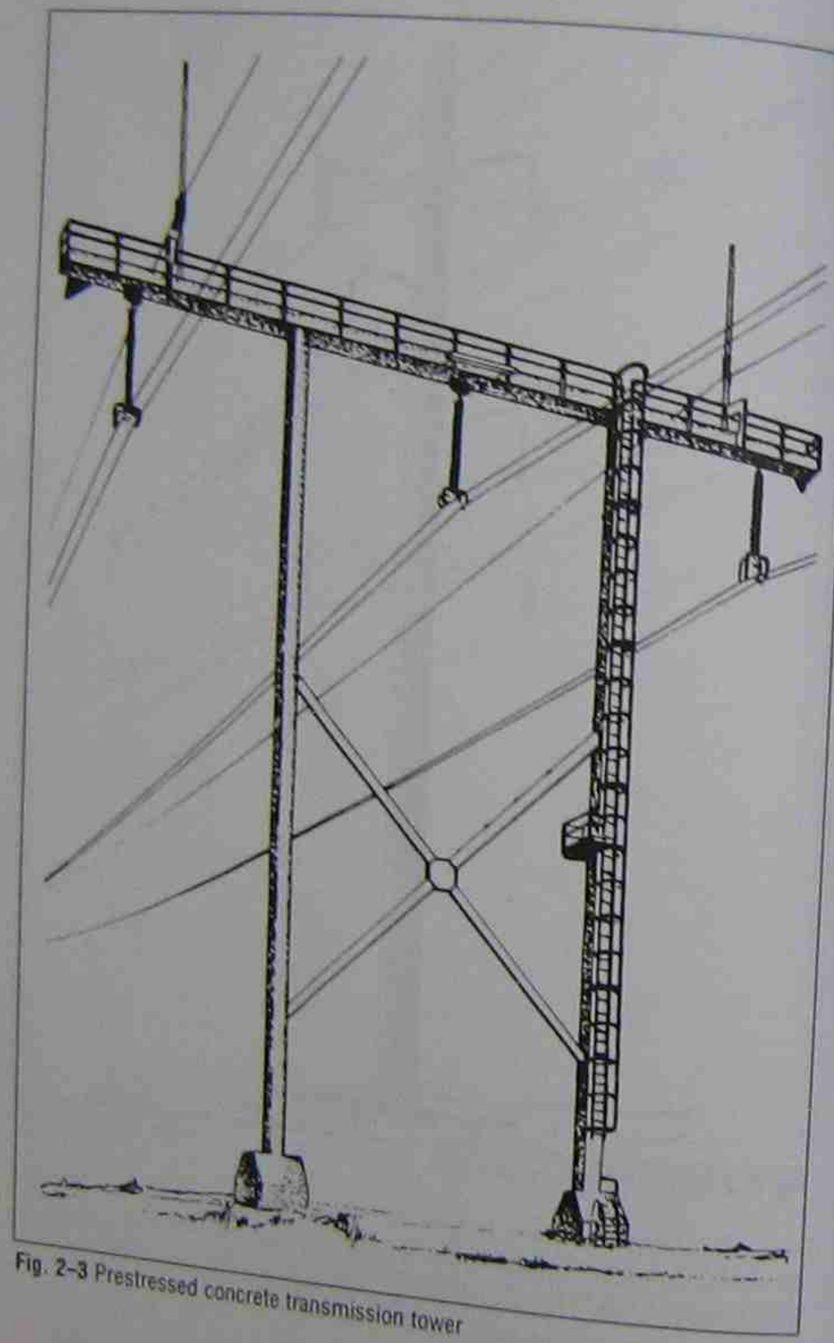


Fig. 2–3 Prestressed concrete transmission tower

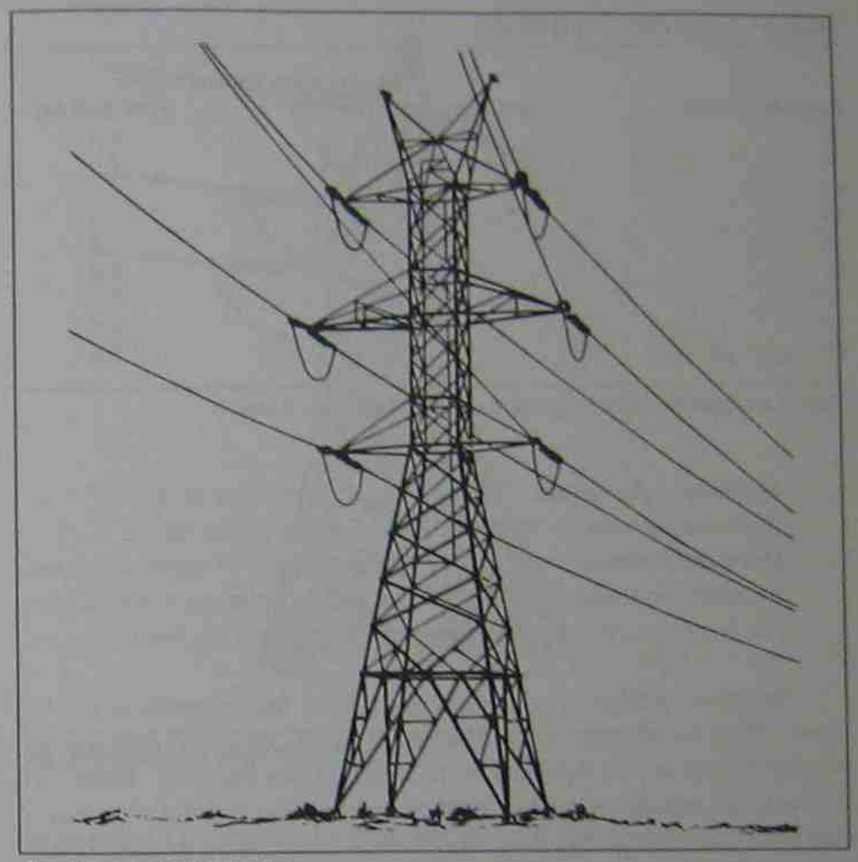


Fig. 2–4 Steel lattice tower

Tower Types

Common long-span construction consists of structures suitably latticed or braced and made of galvanized steel or aluminum. They are mounted on wide rectangular bases and sometimes are referred to as towers (see Table 2-1). Their footings may be of reinforced concrete or grillages made of assembled steel beams. There are several types of towers.

- **Tangent towers.** The conductors supported are essentially a straight line
- **Small-angle towers.** The conductors supported change direction slightly, perhaps 5°–10°

Table 2-1 Typical Pole Setting Depths

Pole Length (ft)	Approximate Setting Depth All Solid Rock (ft)	Firm Soil (ft)*
35	4.5	6.0
40	5.0	6.0
45	5.5	6.5
50	6.0	7.0
55	6.0	7.5
60	6.5	8.0
65	7.0	8.5
70	7.0	9.0
75	7.0	9.5

*Based on approximately 10 percent of pole length plus 2 feet.

- **Medium-angle towers.** These have support changes of 20°–30°
- **Heavy-angle towers.** These accommodate sharper turns
- **Dead-end towers.** They support the entire pull of conductors that terminate on them and are located at anchor points in a line, at certain angles in the line, or at points of take-off from the line

Structures may be of self-supporting latticed (tower) construction or guyed. These latter may be modified **A**, **H**, **V**, **Y**, or guyed-mast types, designed to give certain flexibility to the structure (see Fig. 2–4). Towers or structures are usually referred to by type, voltage, and number of circuits, such as: H-frame, tangent, 138-kV, and double-circuit tower. In many cases, the transmission line will contain two or more types of supporting structures.

Guy Wires and Anchors

Guy wires (guys) and anchors are installed where lines terminate (referred to as dead-ends), at angles, on long spans where pole strength may be exceeded, and at points of excessive unbalanced conductor tension. Guying for line protection is installed at various points in the line to limit damage should storms or other violent action cause the line to fail in somewhat of a domino fashion.

While practically all wood or metal pole transmission structures have guy and anchor installations associated with them, occasionally, some self-sustaining towers may also require their installation. One example is at 90° turns in the line (see Figs. 2-5, 2–6, 2–7, and 2–8). Both guy wires and

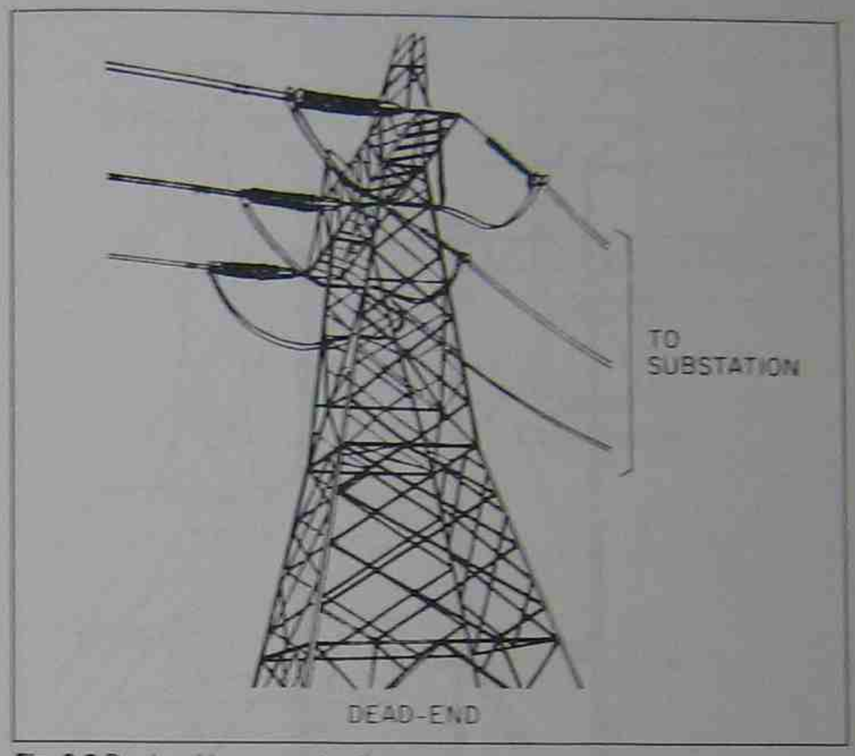


Fig. 2-5 Dead-end tower construction

anchors used in transmission lines are generally heavier than those for distribution lines.

Distribution Underbuild

In some instances, transmission poles may also carry distribution circuits, generally in a lower position on the pole. Design of such common lines requires extreme care to protect the distribution lines from the effects of the higher voltage lines and to provide safe working conditions for the workers. Additional guying may be necessary to compensate for the effect of such underbuild on transmission structures (see Fig. 2-9).

Design Factors

The choice of supporting structures is influenced by many factors that, considered together, result in the greatest economy. The voltage of the

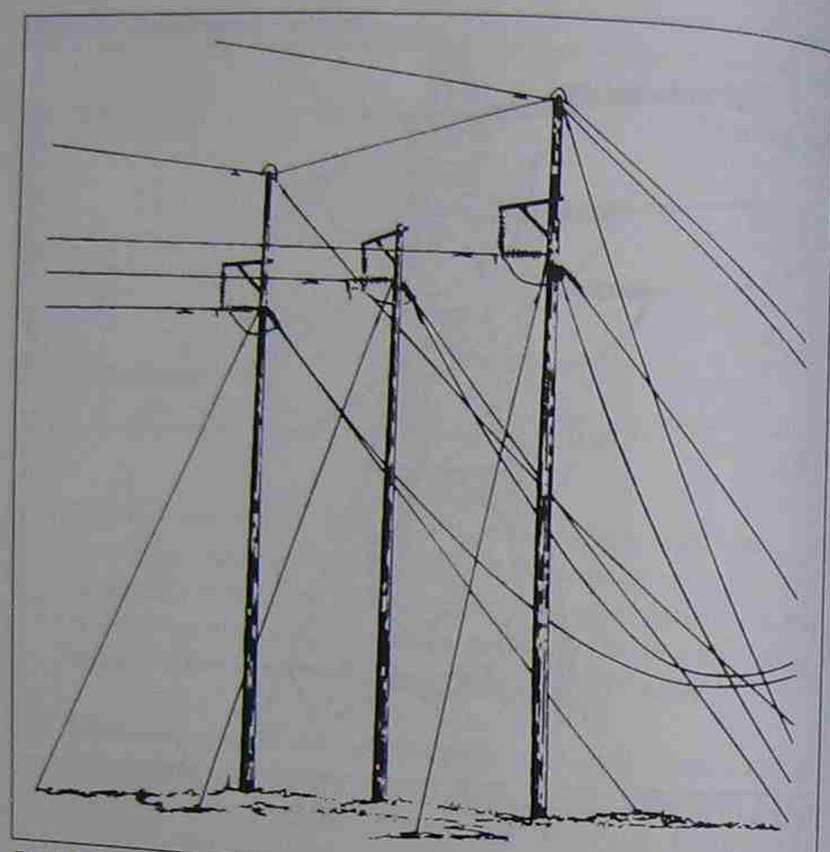


Fig. 2-6 Guyed structures

line or lines to be carried, both present and future, determine the spacing of the conductors and the length of the string of insulators required. This may be subject to modification to provide proper space and conditions for the workers. Span length in turn is affected by the clearances required for safety (see Table 2-2).

These minimums are usually specified by the National Electric Safety Code (NESC), whose provisions are established and revised periodically by the Institute of Electrical and Electronics Engineers (IEEE). They generally reflect the latest practices; reference should therefore be made to the latest code revision. They are also influenced by local ordinances, and by the allowable difference in sags of the conductors under summer and winter conditions.

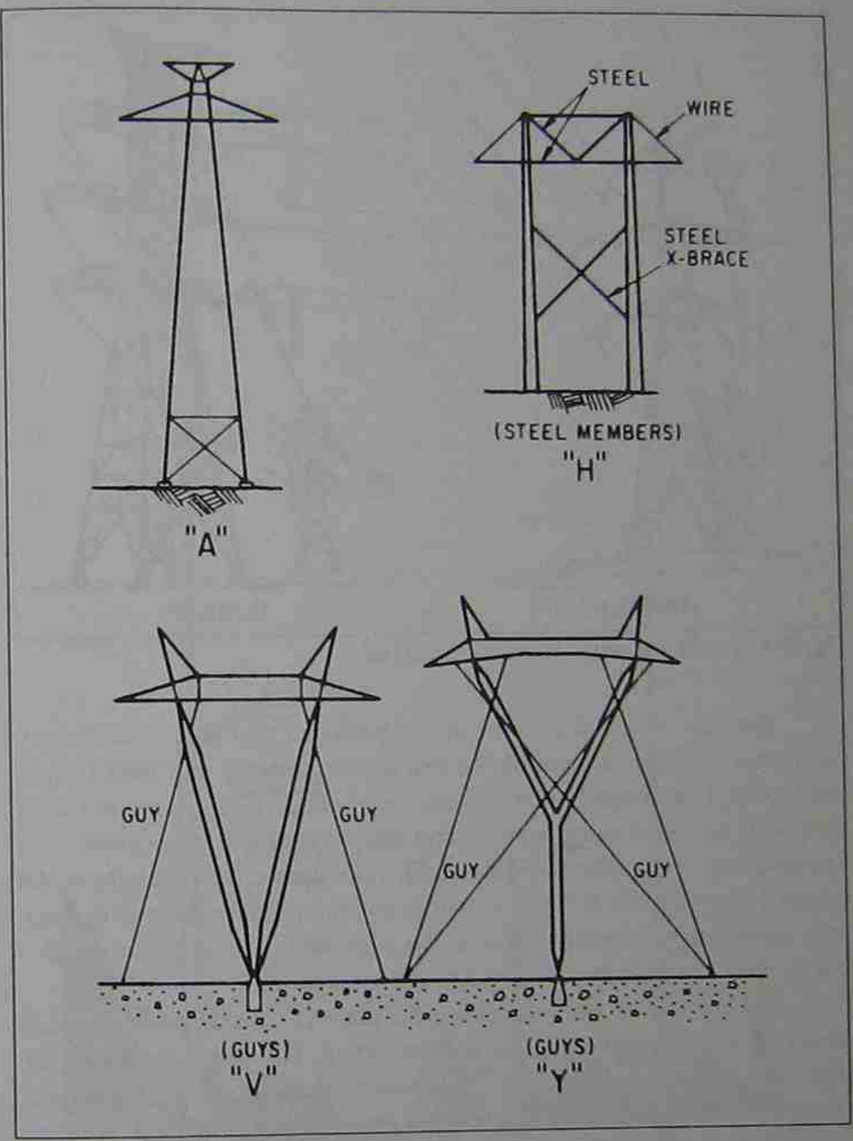


Fig. 2-7 Wood and metal pole constructions

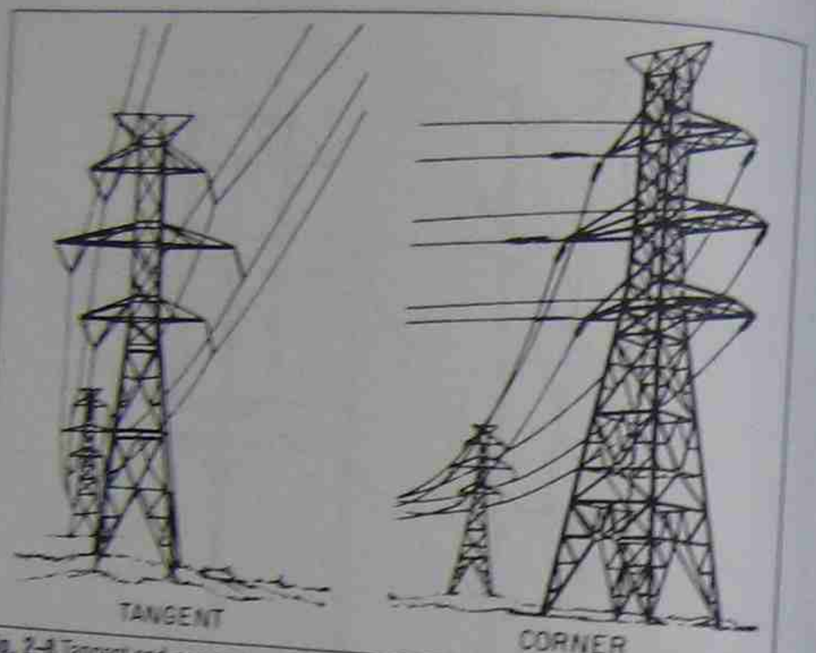


Fig. 2-8 Tangent and corner tower constructions

The size, type, and material of the conductor also affect span length. Aluminum conductors generally have a greater summer sags than copper conductors. Consequently, they require higher supports to achieve the same minimum clearance above ground and also to keep the conductors from swinging into each other (see Table 2-3). Appearance, the character of the terrain (whether plain or hilly), climactic conditions, the nature of the soil, and transportation facilities have to be evaluated. The structure itself—wood, metal, or concrete—is also a determining factor.

The first cost of such supports is not the only consideration; the costs of operation and maintenance are also important. The longer the spans, the fewer will be the number of points of support. There will also be fewer insulators necessary requiring possible replacement, fewer structures requiring painting, and fewer poles requiring replacement. All of these factors may vary with the time of installation, location, local conditions, prevailing regulations, and with plans for the future. (For example, there might be an addition of a second line several years after the initial installation.) However, the final decision is usually the result of many judgments and compromises.

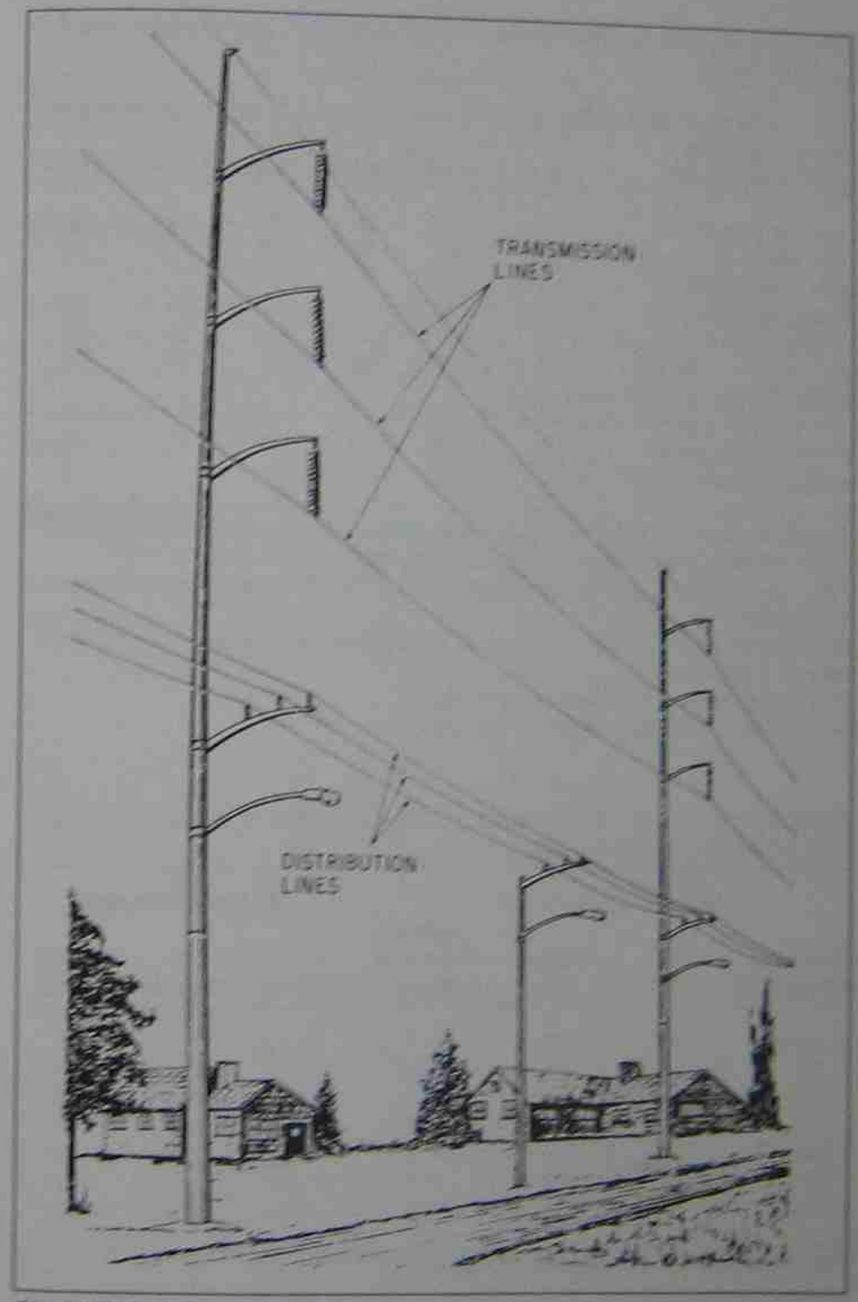


Fig. 2-9 Distribution underbuild

Table 2-2 Recommended Minimum Vertical Clearance of Conductors (in ft) Above Ground or Rails

(120°F, No Wind, Final Sag. Conductor Design Tension 50% of Ultimate Strength) Nature of ground or rails underneath	34.5 kV	46 kV	69 kV	115 kV	138 kV	161 kV
Track rails of railroads	32	32	33	35	35	36
Public streets & highways	25	25	26	28	28	29
Areas accessible to pedestrians only	19	19	20	22	23	24
Cultivated fields†	20	20	21	23	24	25
Along roads in rural districts	22	22	23	25	26	27
Natures of wires crossed over						
Communication lines	8	8	9	11	11	12
Supply lines up to 50,000 volts*	6	6	7	9	9	9

Sag should allow one foot greater clearance than shown above. Conductors smaller than 1/0 ACSR may require additional clearance.
†The NESC does not specify the clearances that should be maintained across cultivated fields.
Local conditions and regulations may call for deviations from these recommended minimum clearances.
*For lower conductor at its initial unload sag.
Always refer to the latest edition of the Code.

Table 2-3 Clearances in Any Direction from Line Conductors to Supports and Guy Wires Attached to the Same Support

	Suspension Insulators			Minimum Clearance		
Rated Line Voltage (kV)	No. Units*	Weight (lb)	Normal Clearance to Support	NESC	To Support	To Guy Wires
34.5	3	38	1' 7"	0' 10"	1' 0"	1' 5"
46	3	38	1' 7"	1' 1"	1' 0"	1' 9"
69	4	48	2' 1"	1' 6"	1' 3"	2' 7"
115	7	78	3' 6"	2' 6"	2' 2"	4' 1"
138	8	88	4' 2"	3' 0"	2' 9"	4' 10"
161	10	108	5' 0"	3' 6"	3' 6"	5' 7"
230	12-14	138	6' 10"	4' 11"	5' 0"	7' 11"

* For average conditions tangent structure.

Computers can be used to make these calculations, varying each and every factor as desired. Further, they can do this in the time that engineers previously calculated by hand only a few choices, using only a few important variables. In general, the calculated results will depend on the estimates of cost, depreciation allowances, and power to be transmitted.

Cross-arms

Cross-arms for towers are generally of galvanized steel or aluminum; wood is used for pole and A- or H-frame construction. Laminated wood cross-arms and arms made of epoxy synthetics have also been used (see Fig. 2-10). Since these materials are insulators, the number of insulators in a string may be reduced. The other advantages are better appearance and better working conditions because of the completely insulated arm.

Conductors

The size, type, and material of conductors are affected by the amount of power desired to be transported and the distance it is to be transported. Both factors largely influence the voltage at which the line is to operate.

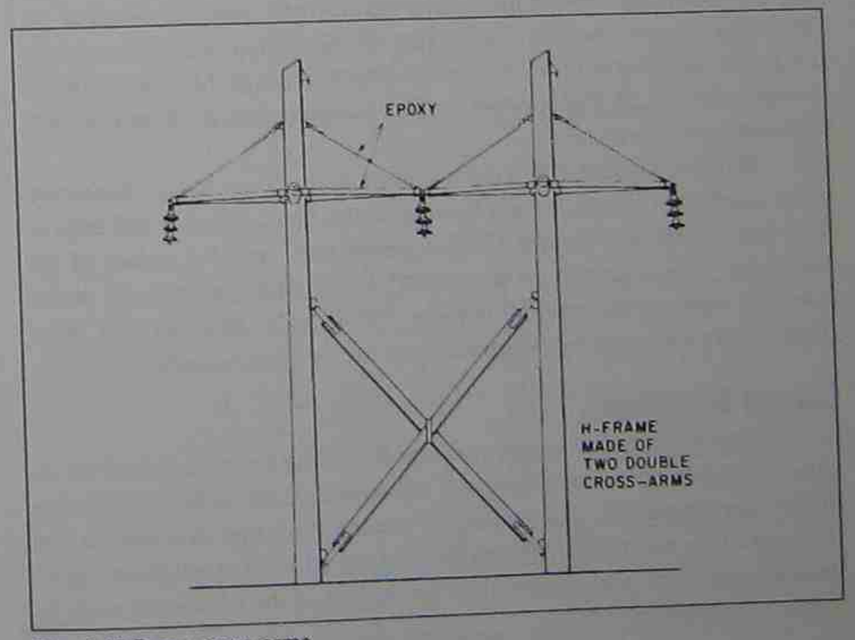


Fig. 2-10 Epoxy cross-arms

Theoretical considerations indicate that the most economic conductor will be the one whose annual carrying charges equal the annual cost of power losses in the conductor. (Annual carrying charges include interest on investment, operation and maintenance costs, taxes, and insurance.)

However, the drop in voltage and the heating of the line may be excessive. In such cases, the economy of the smaller conductor line may have to give way to one with larger conductors. This may be necessary in order to produce tolerable voltage losses and heating conditions (see Fig. 2-11).

The size of conductor may have to meet mechanical considerations and electrical losses because of the phenomenon known as "skin effect" and corona (explained later in this chapter). Too thin a conductor may require additional supports due to its lack of mechanical strength. On the other hand, large conductors are difficult to handle and may impose larger-than-desirable strains on insulators. One remedy is to subdivide the circuits into two or more circuits, which may add other advantages in reliability.

Self-inductance and Skin Effect

When a conductor carries an alternating current, it produces around itself a magnetic field whose intensity varies with the changing values of the alternating current (see Fig. 2-12). This changing magnetic field cuts the conductor, inducing within it voltages that tend to retard the flow of current normally flowing in the conductor. This phenomenon is known as self-inductance or self-reactance.

Within a conductor, this effect is more pronounced toward the center of the conductor. Hence, current flowing within that conductor will tend to flow more easily (and consequently in greater part) near the surface of the conductor. This is known as "skin effect" and is more pronounced as the operating voltages increase. Where the conductor is stranded, the outer strands carry more current per strand than do the inner strands.

Corona Discharge

When a conductor carries a voltage exceeding a certain critical value, a halo-like glow, known as a "corona," will appear on the surface of the conductor (see Fig. 2-13). The amount of corona discharge depends on the diameter of the conductor, the condition of the adjacent atmosphere, other nearby conductors, and condition of the surface of the conductor, such as dirt or roughness.

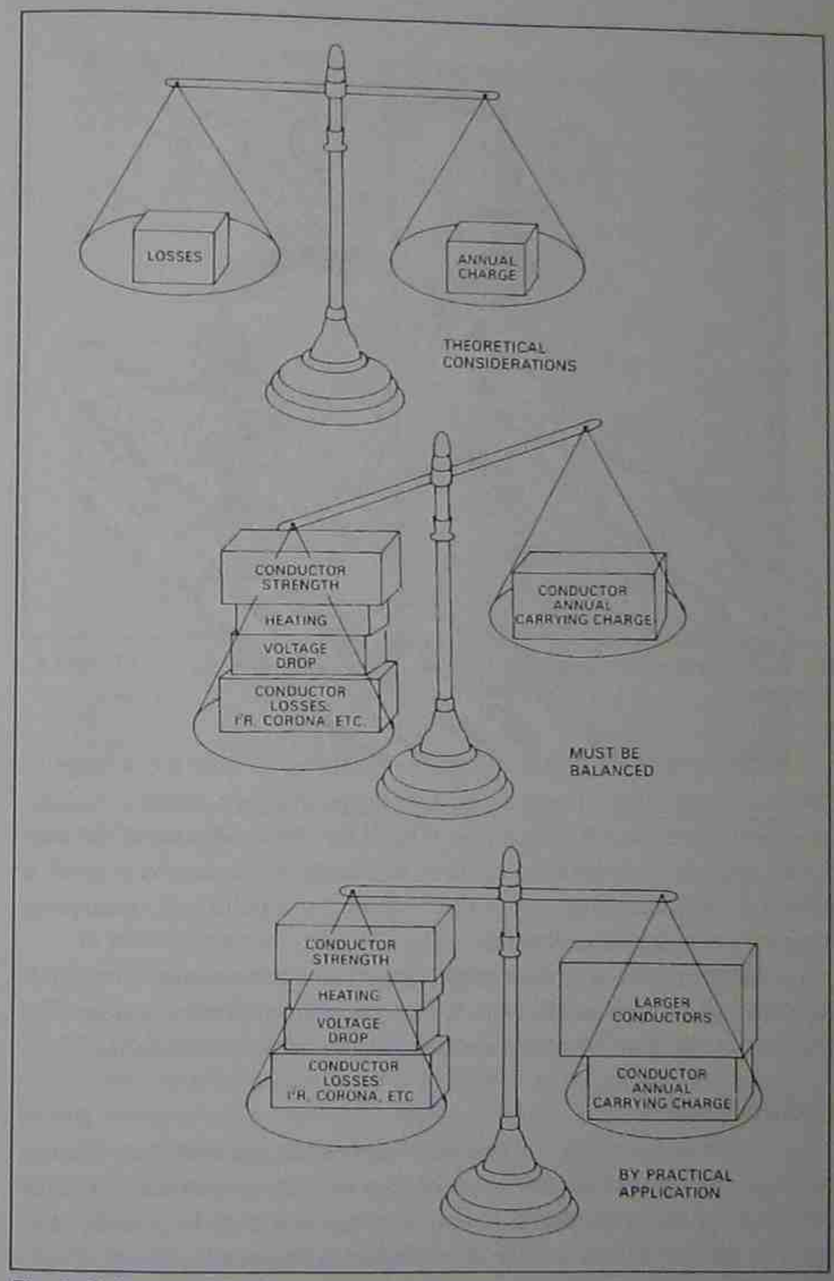


Fig. 2-11 Steps in selecting the right conductors

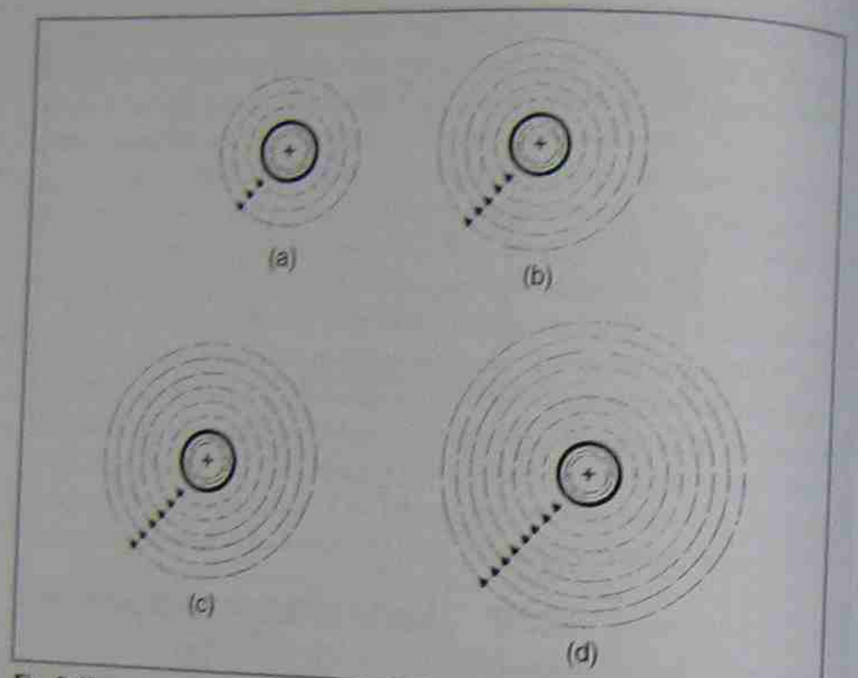


Fig. 2-12 Magnetic field expanding (a, b, c, d) and contracting (d, c, b, a) about a conductor

The luminous effect of the corona discharge is from a discharge of electrical energy from the conductor into the atmosphere, where it is dissipated and represents a loss of power (I^2R). If the distance between this conductor and other nearby conductors or structures is comparatively small, a sparkover may occur, triggering a short circuit at this point with consequent interruption or damage to the line.

Corona discharge and skin effect may cause interference on communication circuits that parallel the transmission lines. Further, corona discharge may also interfere with local radio and television broadcasting.

Hollow Conductors

To lessen the impact of skin effect and corona, expanded conductors having hollow or partially hollow cores have been developed. Such conductors eliminate the center part of the conductor, which is not fully used in carrying current because of the skin effect. Further, because a conductor of larger outside diameter results, the tendency for corona to appear is decreased.

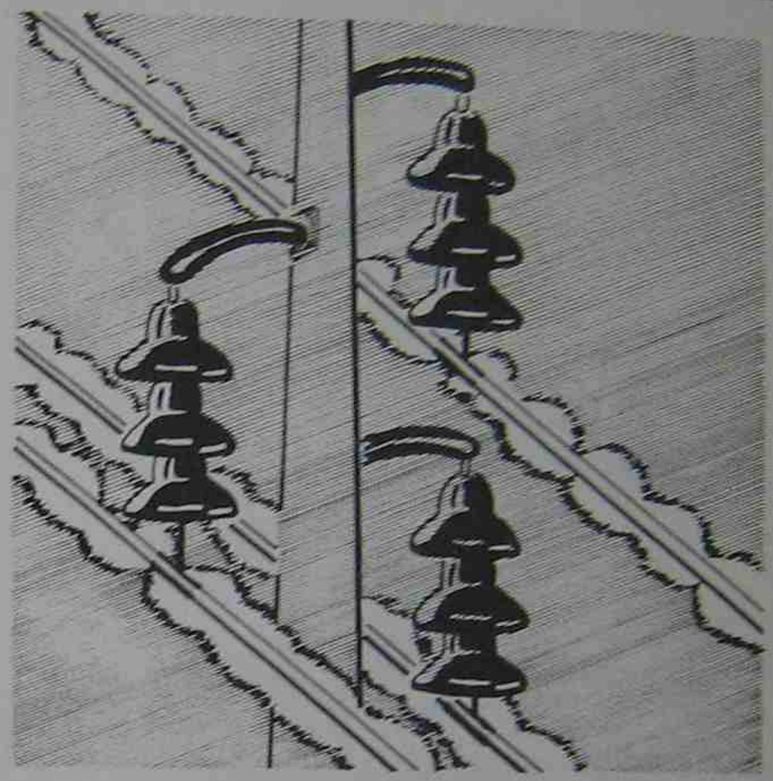


Fig. 2-13 Corona effect

A wire or conductor in which electricity may be flowing is surrounded not only by a magnetic field, but also by an electrostatic field. Electrostatic fields generally form in uniform patterns around a straight conductor and are also conductors of electricity. These patterns tend to become concentrated at points where the conductor is bent or at its edges or ends; the conducting tendency is also increased at these points.

Since corona discharge tends to appear at points where the electrostatic fields around a conductor are concentrated, sharp bends, corners, and points should be avoided. Corners or bends should be made gradual and smooth. Corona discharges may be greater, and actually observed, during

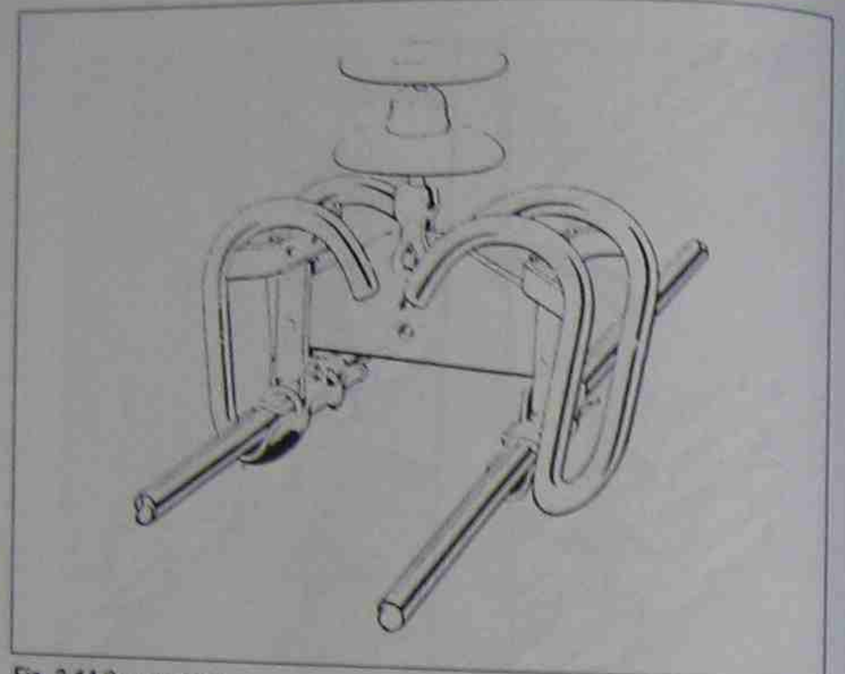


Fig. 2-14 Corona shield

period of rain. The raindrops accumulating on a conductor essentially change its shape; the clinging drops create relatively sharp pips on the conductor, encouraging the formation of corona at these points.

Corona Shields

To prevent corona flashover damage to insulators, particularly during inclement weather, shields (see Fig. 2-14) or rings (see Fig. 2-15) are provided at both the conductor and the supporting end of the insulators. This furnishes a path for the flashover away from the surface of the insulators. The insulators are thereby protected from the shattering effect of the current that flows during the flashover.

Conductor Materials

Conductors can be made from various types of materials (see Fig. 2-16). High conductivity (lesser resistance to the flow of electricity), great strength, and elasticity favor hard-drawn copper for use as a conductor.

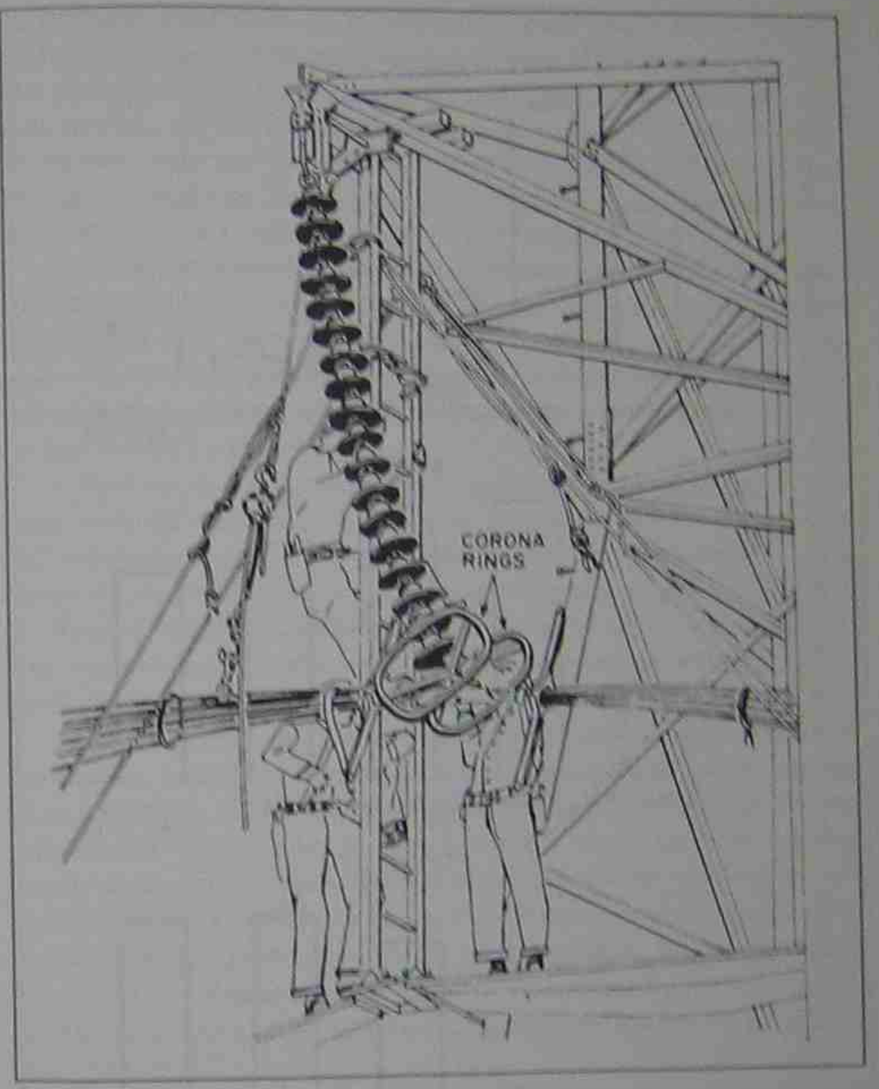


Fig. 2-15 Corona rings

However, aluminum has an advantage because of the requirement for a large diameter to avoid corona. This, together with price advantages, makes it almost universally used in high-voltage transmission lines.

The lower conductivity of aluminum, about 60% that of copper, results in a conductor having a diameter of 1.26 times that of a copper

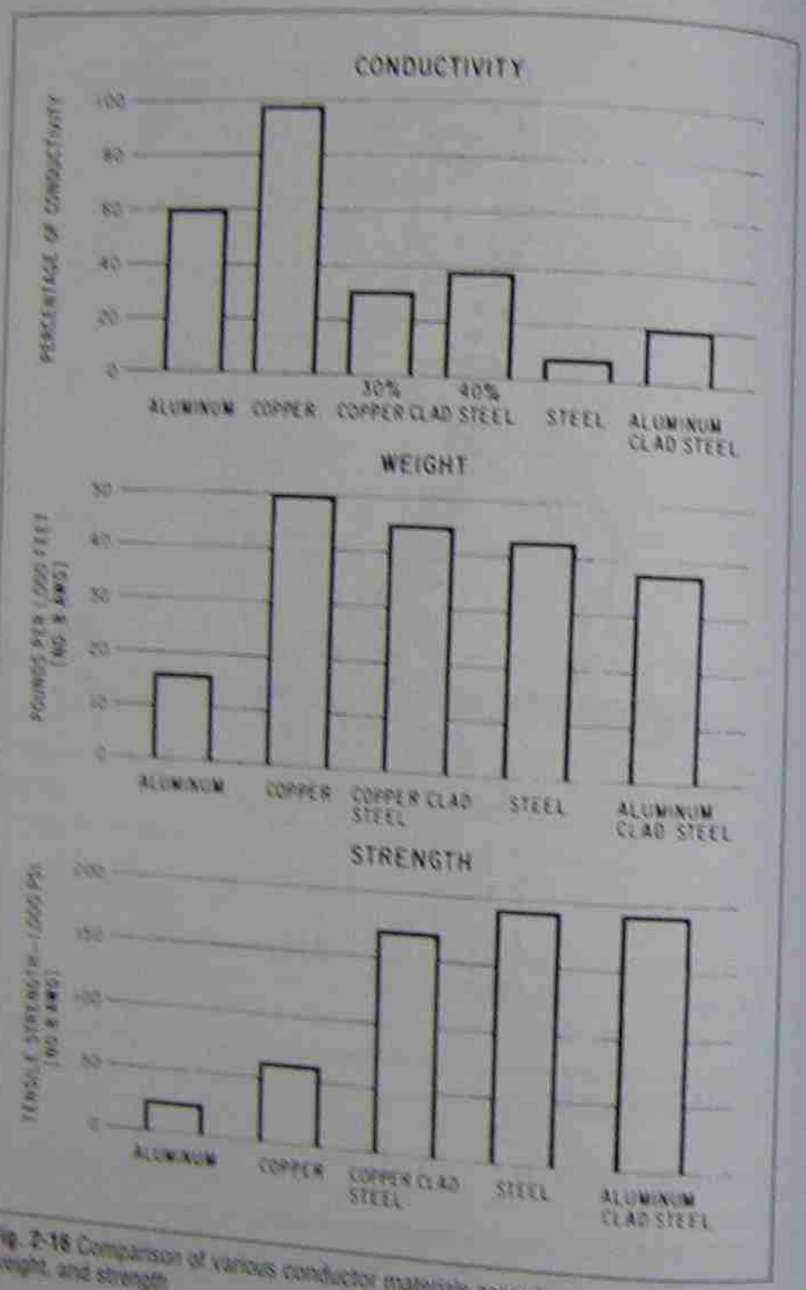


Fig. 2-16 Comparison of various conductor materials according to conductivity, weight, and strength.

conductor of equal resistance. In addition, its lower weight makes it somewhat easier to handle. However, the lower strength of aluminum, about 70% that of copper, makes it less suitable for long spans. To overcome this, aluminum cable, steel reinforced (ACSR) was developed. In this type of cable, aluminum conductors are wrapped around a steel cable that provides the strength necessary for longer spans. Later designs have replaced the inner steel cable with one made of a high-strength aluminum alloy.

For shorter lines designed to carry smaller amounts of power, conductors made of copper-clad steel and aluminum-clad steel provide mechanical strength. They also furnish the relatively large diameters needed to mitigate skin and corona effects. For higher capacities, several of these clad wires may be used as a core, around which copper or aluminum strands may be laid to form a reinforced conductor.

Steel conductors are occasionally used for extra-long spans, such as river crossings, where very high mechanical strengths may be required. The self-inductance is greater because of the magnetic properties of steel. As a result, the skin effect may be great enough to require a larger cross section for the steel conductor than for equivalent copper or aluminum conductors. The larger diameter serves to increase the value of critical voltage at which corona forms.

To minimize corona effects, the overall diameters of ACSR (and other) conductors have been expanded by introducing intermediate suitable fibrous material. Corona effects are also minimized by forming air pockets between the outer aluminum strands and the inner steel core. Another means of minimizing corona losses is to replace the one conductor with a "bundle" of two, three, or four conductors. These are held in place by spacers and separated from each other by suitable distances up to about 18 in. Less expensive conductors may be used with this construction, though greater ice and wind loads may be experienced, and greater sag for a given span may result.

Conductors for high-voltage transmission lines are handled very carefully to keep them from scraping on the ground during installation. Often special tension-stringing equipment is used that eliminates scratches or sharp edges on the conductor, which may cause corona discharges. Aluminum is more subject to chemical attack and corrosion from substances found on the ground and in the atmosphere than is copper.

Natural Hazards

Overhead transmission lines are exposed to attacks by the forces of nature. These include not only rain, which affects the corona discharge on conductors, but also wind and ice loading of conductors. Provision must therefore be made in the design of supporting structures for the effects of ice, wind, lightning, and other ravages of nature.

Aeolian Vibrations

Overhead conductors of transmission lines in areas where span lengths are relatively long (usually in open country) are subject to vibrations and movement produced by wind.

One type, known as aeolian vibrations (see Fig. 2-17), is a regular high-frequency oscillation caused by the eddies behind a conductor

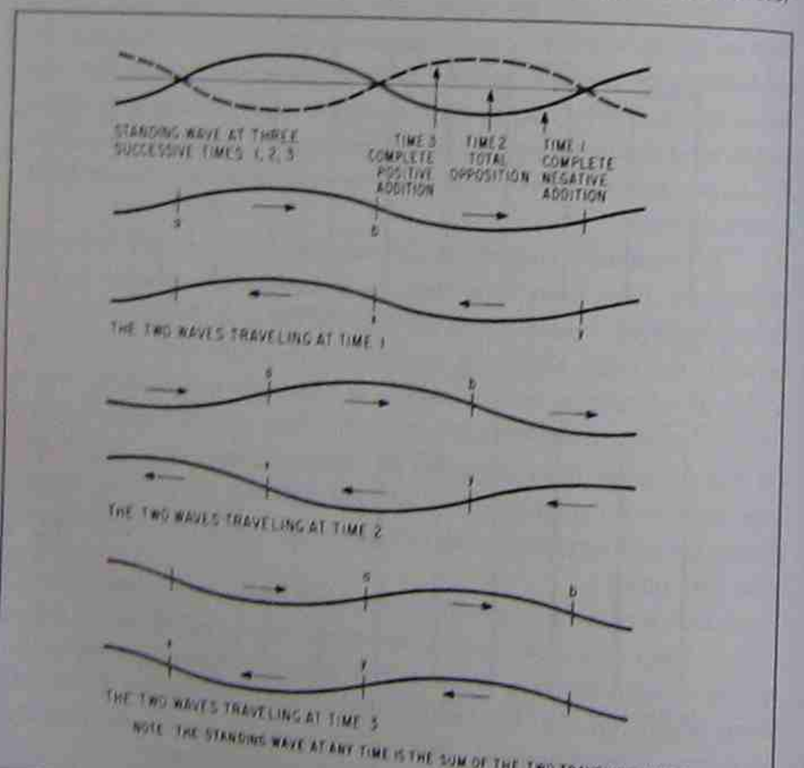


Fig. 2-17 Standing waves on a conductor because of aeolian vibrations

produced by wind. The frequency of vibration depends on the size of the conductor and wind velocity. To lessen the effect of these vibrations, dampers (masses of metal) are installed on the conductors at node points (see Fig. 2-18).

Generally, true node points are impossible to be determined because of the varying factors producing the vibrations. However, the dampers usually are located near the towers at points calculated to give as much dampening as is practical. Armor rods are also installed in aluminum conductors at the insulator clamps to reduce the wearing effect of the vibrations in such conductors.

A self-damping conductor is designed to reduce the aeolian vibration effect. This self-damping effect is achieved by making the shapes of the conductor strands different. The outer strands are trapezoidal, while the inner ones are round (see Fig. 2-19). Relatively large clearances between these conductors permit motion to take place within the conductor layers, which tends to break up the vibration of the conductor caused by wind blowing against and around it. With this conductor design, appropriate splicing and terminating materials and procedures are necessary.

Galloping or Dancing Conductors

Another type of vibration, much more severe, is known as "galloping" or "dancing" conductors. The cause for this occurrence is not always known. However, ice forming on the conductors during freezing rain or sleet storms may sometimes assume the approximate shape of an airfoil. Wind blowing against it may cause the conductor to be lifted appreciably until it reaches a

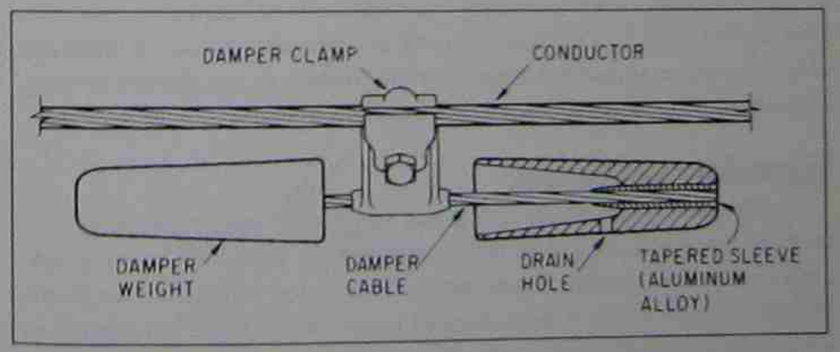


Fig. 2-18 Dampers on a conductor

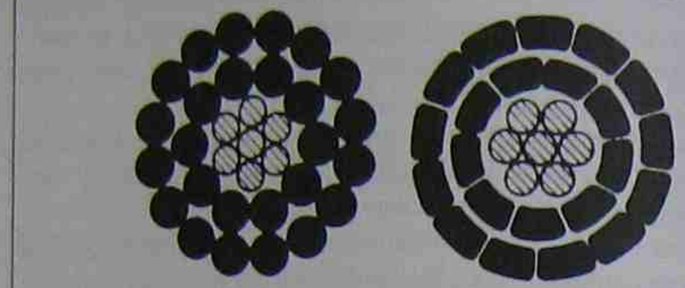


Fig. 2-19 Conventional ACSR (**a**) and the self-damping conductor (SDC)(**b**)

point where the conductor falls or is blown downward. Such a condition imposes extremely severe strains on both conductors and supporting structures and may cause them to fail.

Further, the increased sag of the conductors because of the ice load coupled with the nonrhythmic swaying may cause them to whip together. This could result in flashovers and short circuits, which may trip the circuits or burn down the conductors. Little can be done to correct this condition, which is fortunately rare, except to attempt to melt the ice from the conductors. This is sometimes done by overloading a circuit deliberately, either by transferring loads from other circuits or by connecting a "phantom" load to it (see glossary for definitions of these terms). Such overloads cause the conductors to heat and thus melt away the ice.

This practice of overloading has been successful in many instances, though sometimes uneven heating and dissipation of heat cause only portions of the conductors to become free of ice. If the circuits can be taken out of service, this is sometimes done, and the conductors are allowed to whip together with no danger of short-circuit and burndown.

Connectors and Splices

Mechanical connectors are almost universally used in splicing conductors. These may sometimes consist of sleeves or yokes that hold the conductors together by bolts. Sometimes the ends of the conductors are inserted into a sleeve, which is then crimped hydraulically. These are referred to as compression connectors.

These latter often have the indentations filled with solder, and the whole splice is polished so that the tendency for corona to form about the splice is reduced. For ACSR conductors, two sleeves are used, an inner steel sleeve fitting over the steel core only, and an outer sleeve of aluminum fitting over the entire conductor (see Fig. 2-20). For aluminum reinforced aluminum conductors, only one overall outer sleeve is used. Mechanical or hydraulic compressors are used to create the indentations on both the steel and aluminum sleeves that grip the conductors. Such indentations are

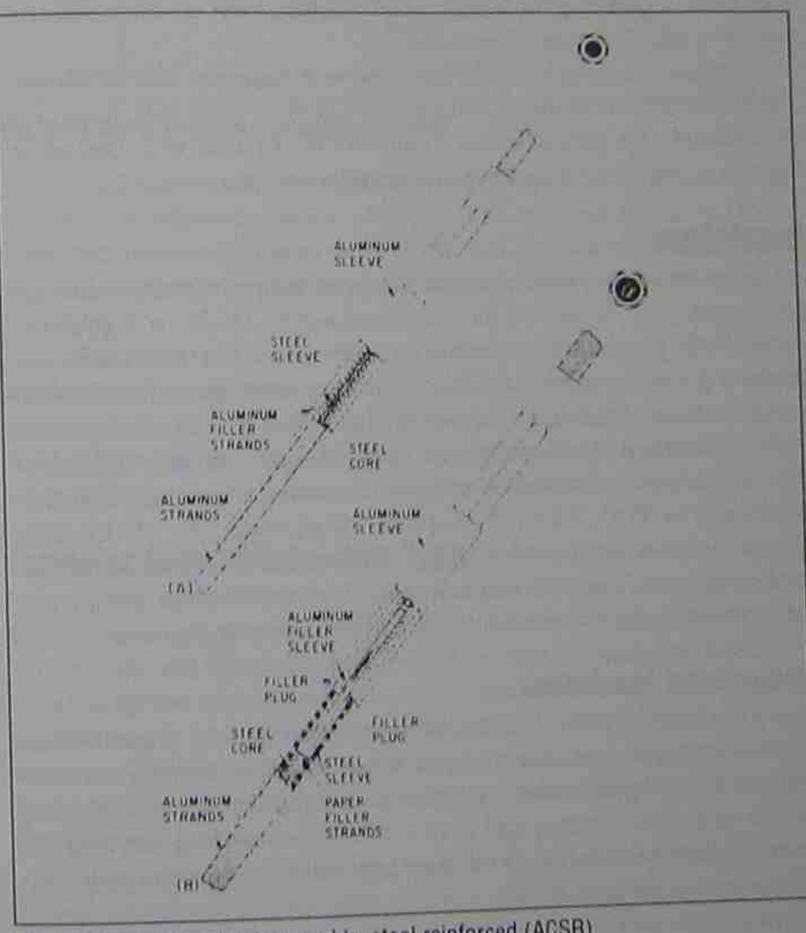


Fig. 2-20 Joint for aluminum cable, steel reinforced (ACSR)

usually started at the center of sleeve and proceed toward each end; the length of the sleeve may increase during compression.

Heat Detection

Splices or connections in the conductor are often sources of trouble if improperly made or oxidized. A loose connection or broken strands may create hot spots in the line, which may cause failure. Usually, these are difficult to discover. A bolometer (a device used for measuring heat at a distance) can be equipped with a television camera and mounted on a truck or aircraft. Used in patrolling the line, it can successfully ferret out these potential sources of trouble before failure occurs.

Infrared imaging has been advanced as a diagnostic tool for corona and heat detection. However, while coronas produce some heat, it may not be detectable by infrared when compared to the heat of a conductor. Coronas usually are detected as static on radio receivers.

Insulators

Insulators used for transmission lines are both of the suspension and pin or post types. In general, for tower lines and A-, H-, V-, or Y- (wood or metal) frame construction, standard insulator discs 10 in. in diameter and spaced 5-1/4 in. apart are used. The number required depends on the voltage of the line. Standards adopted by the Edison Electric Institute and National Electrical Manufacturers Association specify minimum numbers of discs in a string for certain line voltages. For instance, some disc specifications are: 4 for 69 kV, 7 for 138 kV, 12 for 230 kV, and 19 for 345 kV. Extra discs are added to provide safety factors. They are also used to allow for contamination and damage and to compensate for the effect of altitude and metal structures (as compared to wood) on insulation requirements.

Suspension Insulators

The higher the voltage, the more insulation value is needed. Transmission lines operate at high voltages, such as 69 kV, for example. At these voltages the pin-type insulator becomes bulky and cumbersome. Besides, the pin that must hold it would have to be inordinately long and large. To meet the problem of insulators for these high voltages, the suspension insulator is used (see Fig. 2-21).

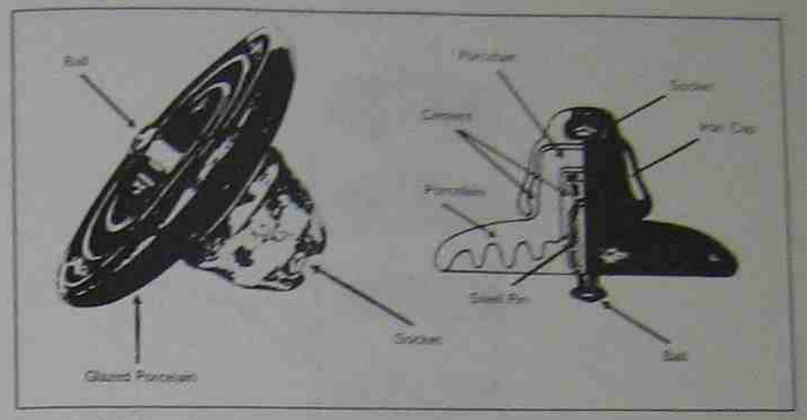


Fig. 2-21 Ball-and-socket suspension insulator

The suspension insulator hangs from the cross-arm, as opposed to the pin insulator, which sits on top of it. The line conductor is attached to its lower end. Because there is no pin problem, any distance between the cross-arm and the conductor may be obtained just by adding more insulators to the "string."

The entire unit of suspension insulators is called a string. How many insulators this string consists of depends on the voltage, prevailing weather conditions, the type of transmission construction, and the size of insulator used. It is important to note that in a string of suspension insulators, one or more insulators can be replaced without replacing the whole string.

Insulator Assemblies—Disc Type

Disc insulators are usually made of porcelain and designed so the porcelain is in compression (see Fig. 2-22). Though they may be made in various sizes and shapes for specific purposes, the standard type disc mentioned above has received wide acceptance. Glass and some synthetic (epoxy, polymer) types are also in use. (See Appendix H, "Porcelain vs. Polymer Insulation". Where additional mechanical strength is required, as in very long spans, two or more strings of insulators may be paralleled to provide the additional strength.

The string of insulators may support a conductor vertically from a cross-arm or structure. Alternately, it may support a conductor horizontally (a string each direction) where strains are unusually great, as at turning

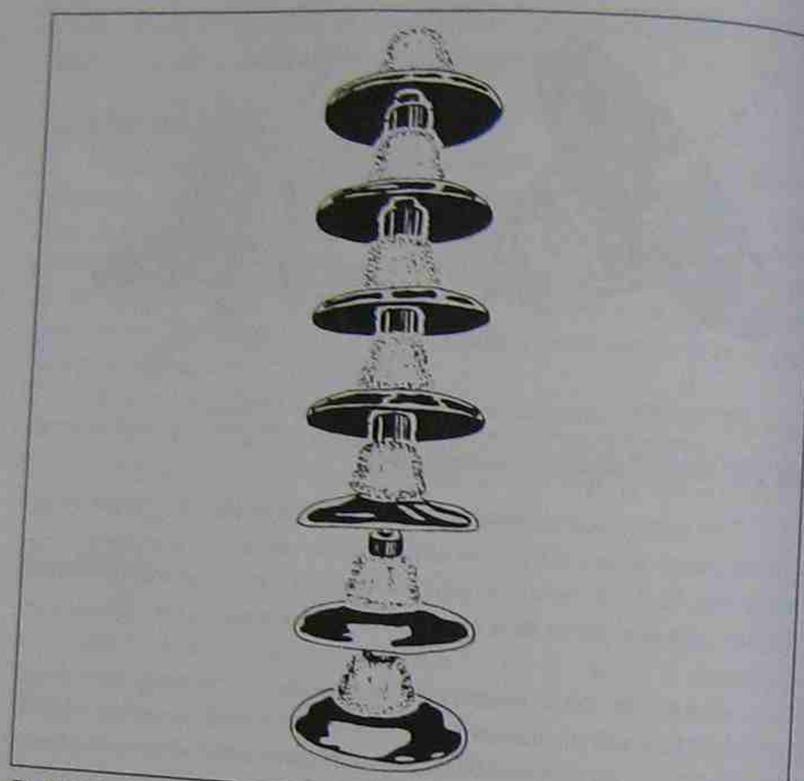


Fig. 2-22 Typical string suspension insulator

points in the line (see Fig. 2-23). (Insulator strings can also be used in line applications with no strain as shown in Fig. 2–24.)

"Strain" or "dead-end" insulator strings are also used on a long line to divide it into several sections. Consequently, under unusual conditions such as storms, if a conductor fails, damage will be restricted to a small section. The unbalance caused by such a conductor failure may affect adjacent spans in a domino-like effect. The installation of these dead-end strings prevents the entire line from being affected.

Pin and Post Insulators

Pin insulators (see Fig. 2-25 and Fig. 2–26) and post insulators (see Fig. 2-27 and Fig. 2–28) are generally confined to transmission lines of lower

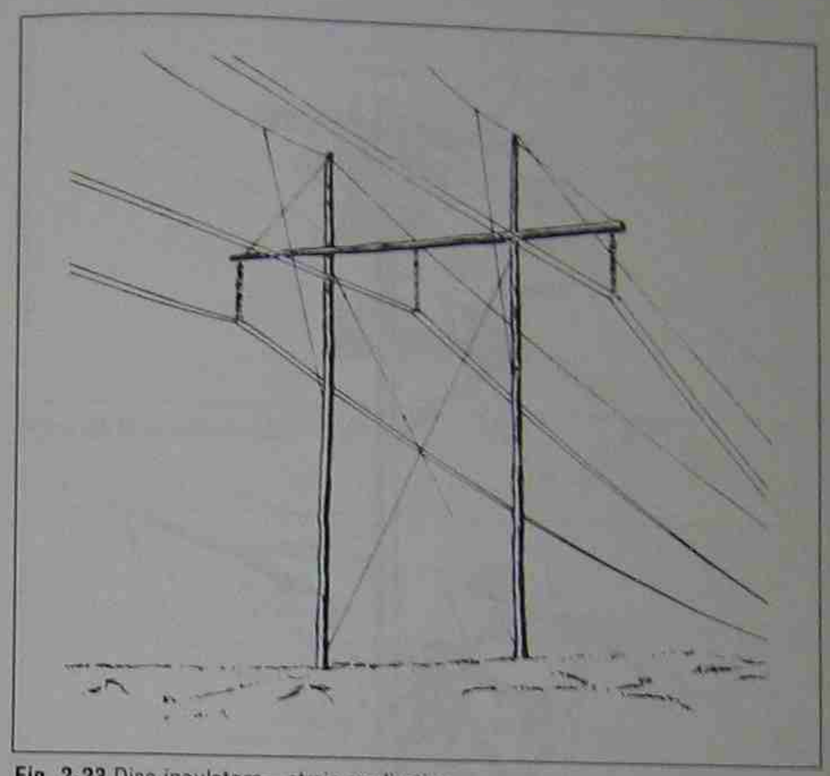


Fig. 2-23 Disc insulators—strain application

voltages, usually up to 69 kV. These may be mounted on cross-arms where, since the conductor is mounted on the top of such insulators, the pole height can be reduced by that amount. Post-type insulators may be mounted horizontally on poles in a so-called "armless" construction, which has the advantages of better appearance and narrower right-of-way requirements.

Combinations of string insulators and horizontally mounted posts or insulated struts are used to control the position of the conductor, especially at angles in the line. Two strings of insulators, mounted from a cross-arm in a V position, are also used to hold a conductor in place away from towers or wood frame construction. These are referred to as V-strings (see Fig. 2-29 and Fig. 2–30).

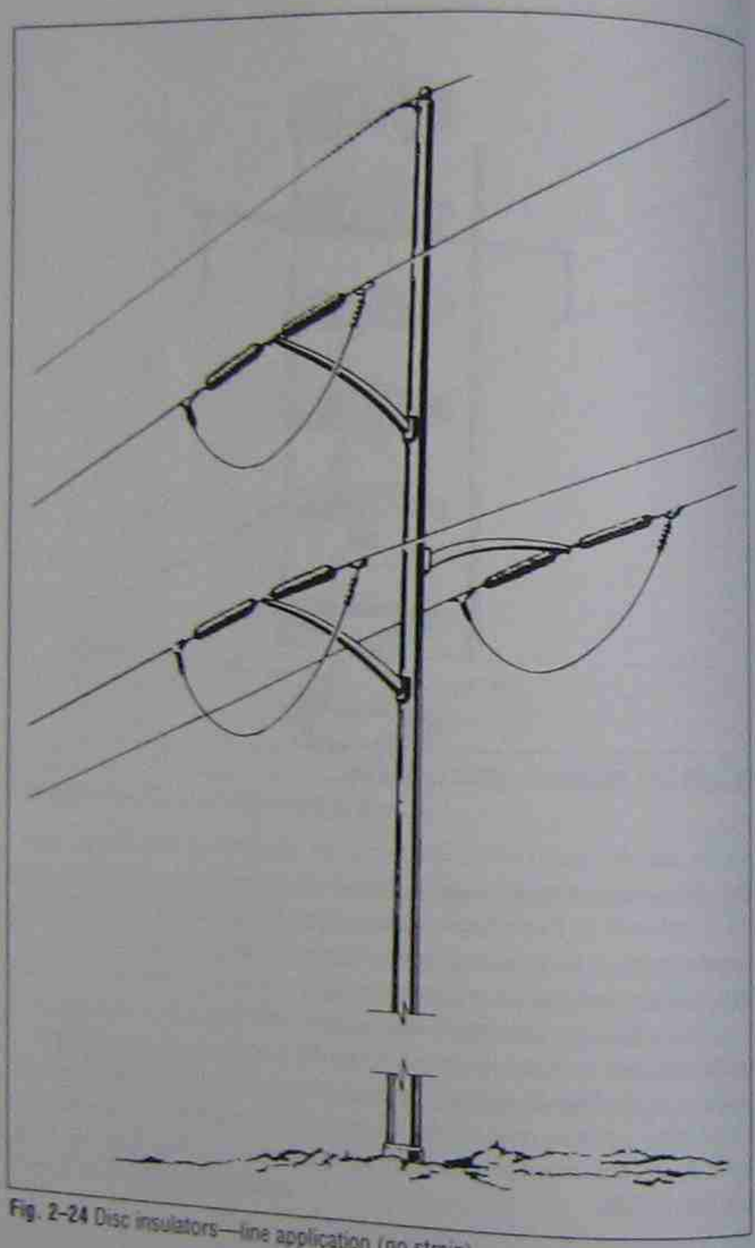


Fig. 2-24 Disc insulators—line application (no strain)

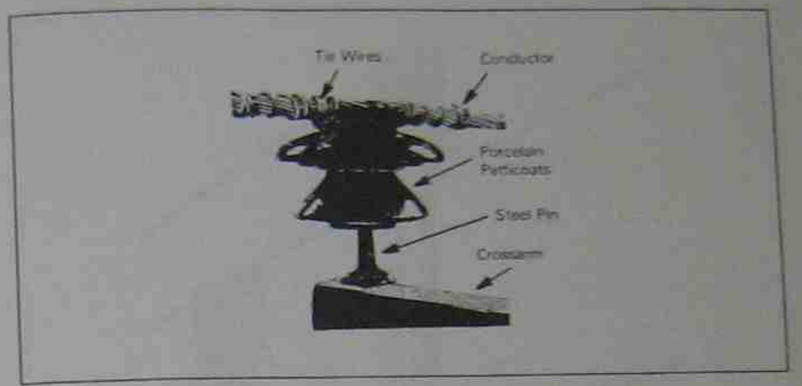


Fig. 2-25 Mounted pin-type insulator

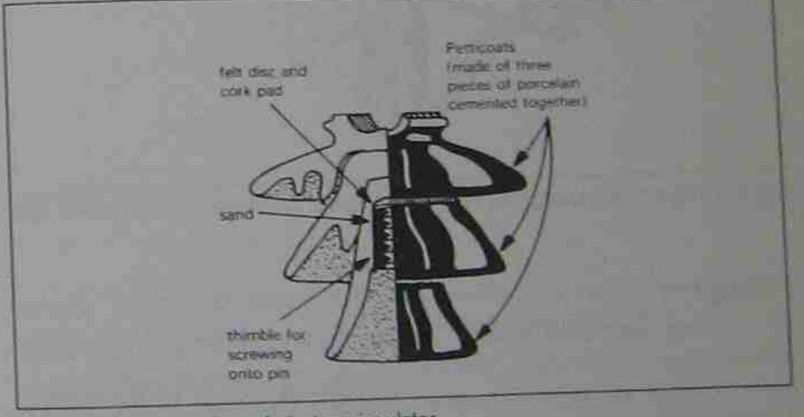


Fig. 2-26 Cutaway view of pin-type insulator

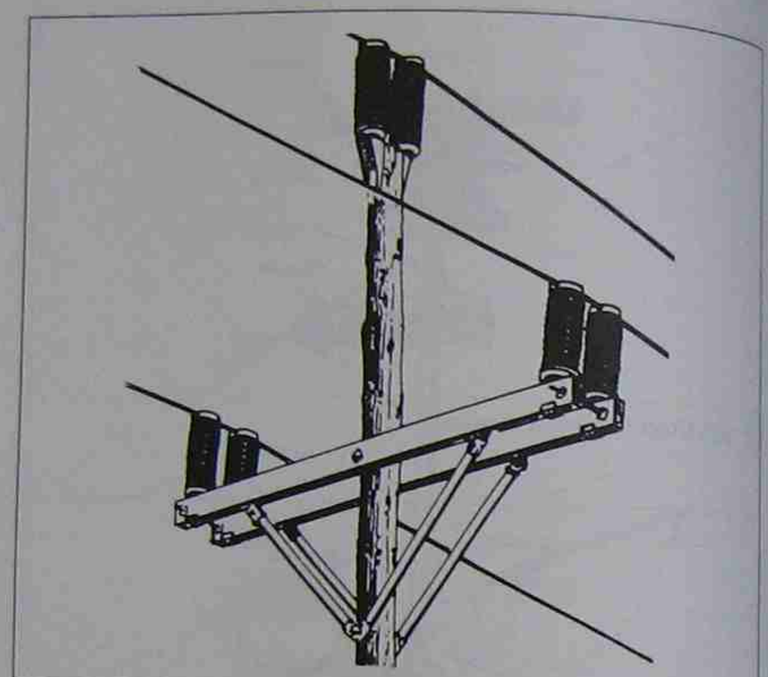


Fig. 2-27 Post-type insulators using cross-arms

Fittings

Fittings associated with the insulators are made of galvanized steel, malleable iron, or aluminum. The first two are used where strength requirements are high, the last for corrosion resistance and lessened corona effect because of the greater smoothness that can be attained. Aluminum-coated steel fittings are also available.

Lightning

When lightning strikes at or near a transmission line, voltages are created in those lines greater than those at which the line normally operates. These "induced" voltages may be destructive if allowed to flashover to other lines or structures. Means are provided to "bleed" off these surges harmlessly. Arcing rings, mounted at one or both ends of the insulator string, permit the high-voltage surge to flashover between the ring and the structure or

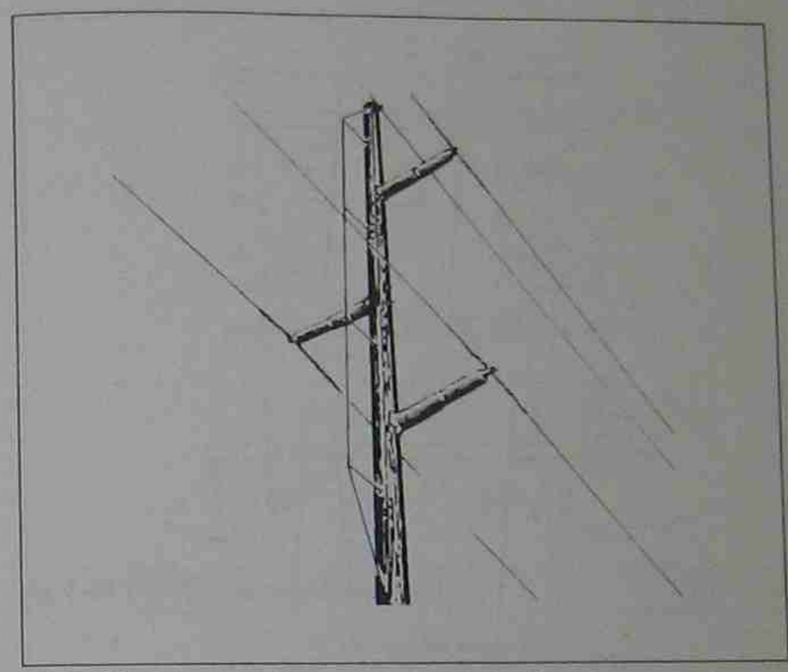


Fig. 2–28 Post-type insulators using armless construction

between these rings, away from the porcelain insulators. The energy is passed over to the ground, where it is dissipated (see Fig. 2-31).

Lightning or Surge Arresters

Lightning or surge arresters, usually a series of air gaps or special semiconducting materials, also are used to drain away the voltage surges. These are generally placed at the terminals of the lines to protect transformers, circuit breakers, and other equipment (at the substation). They also may be placed along the lines at strategic locations.

The elementary lightning arrester (see Fig. 2-32) consists of an air gap (horn air gap) in series with a resistive element. The overload voltage surge causes a spark that jumps across the air gap, passes through the resistive element (silicon-carbide, for example). The resistive element is usually a

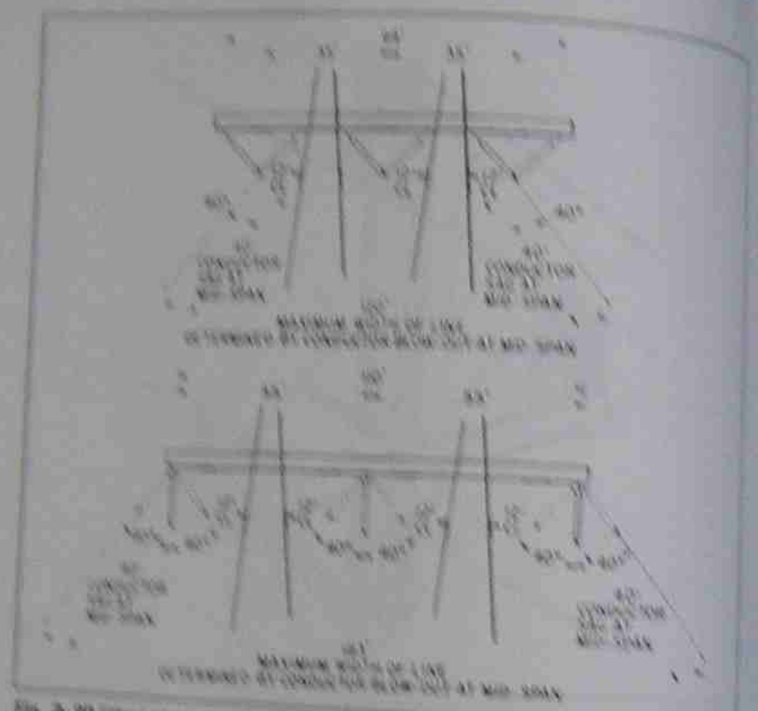


Fig. 2-29 Effect of v-string insulator configuration on the right-of-way requirement

material that allows a low-resistance path for the high-voltage surge, but presents a high resistance to the flow of line energy.

There are many different types of arresters, but they all have one principle in common. There is always an air gap in series with a resistive element. Whatever the resistive (or valve) element is made of, it must act as a conductor for high-energy surges and also as an insulator toward the line voltage. In other words, the lightning or surge arrester leads off only the surge energy. Afterwards, there is no chance of the oncoming line voltage being led into the ground.

The valve element in a resistor arrester (see Fig. 2-33) consists of ceramic-like discs that act as conductors under high-voltage surges and present a high resistance to the line energy. In the arrester shown in Figure 2-34, the lightning current passes through a series of bypass gaps to the main gap

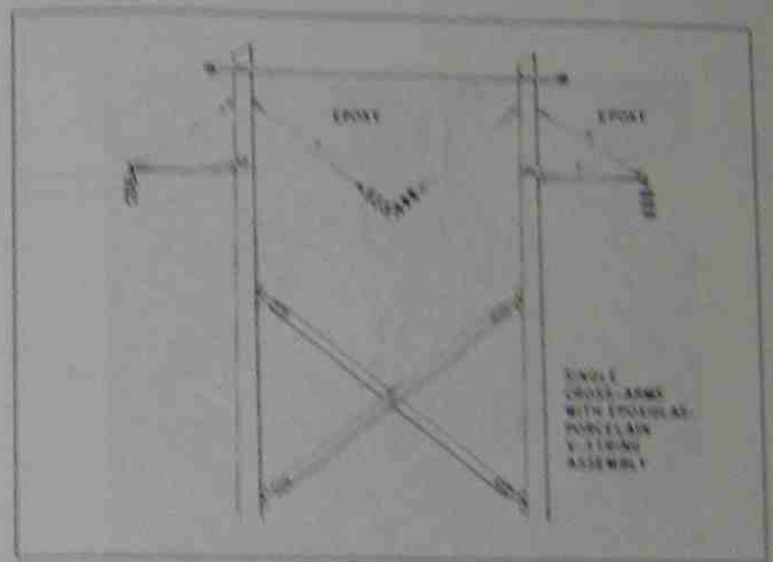


Fig. 2-30 V-string insulators and insulated struts

and an element to ground. If the line energy attempts to follow the lightning energy, that line energy is made to flow through a series of coils that create a magnetic field. The magnetic field is strong enough to extinguish the arc of the lightning discharge (see Fig. 2-33). This extinguishing action is so rapid that it takes place in less than 1/2 cycle of the line energy.

Shield or Ground Wires

Shielding these lines by means of a wire above them, which is directly connected to ground, is another form of protection from lightning. These wires will drain off the voltage surges from direct or nearby strikes of lightning (see Fig. 2-36). Further, they cause the air adjacent to the lines to be drained of static electricity that sometimes serves to "attract" lightning discharges. This acts much the same as the ordinary lightning rod and may be thought of as a continuous lightning rod, protecting the lines.

One or more wires may be mounted on the structures supporting the transmission line (see Fig. 2-37), depending on the type of structure and number of circuits. It has been found that the installation of the overhead

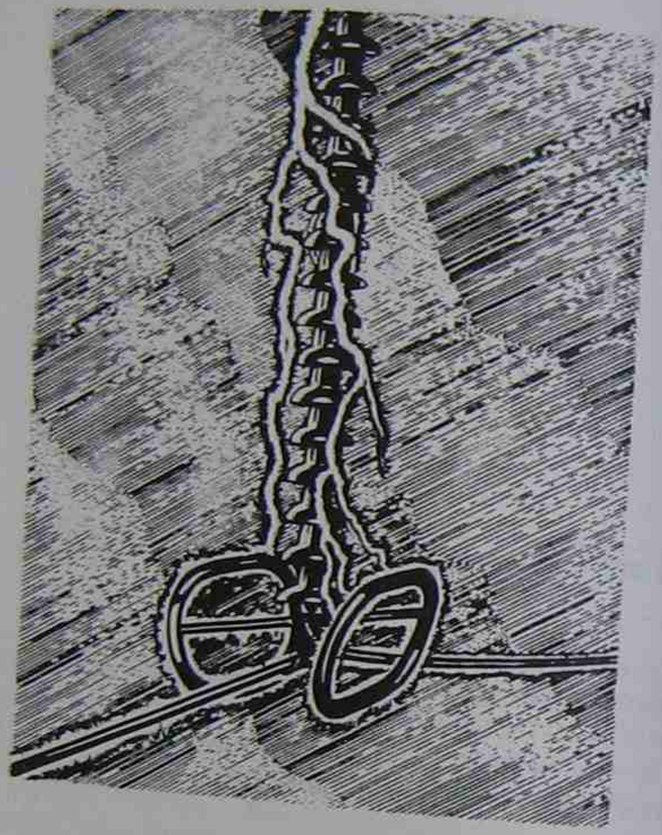


Fig. 2–31 Arcing rings on the insulator

shield wires (at an angle of 30° or less from vertical) covering the lines generally results in the greatest protection of these lines. Wire for this purpose is generally of galvanized steel of small diameter. However, copper-clad steel is sometimes used to reduce electrical resistance while maintaining mechanical strength.

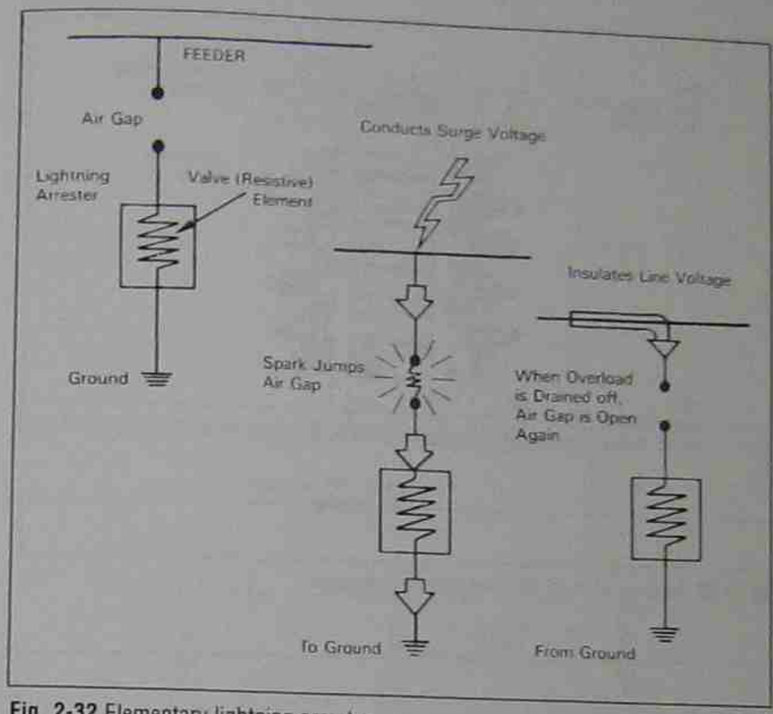


Fig. 2-32 Elementary lightning arrester

Counterpoise

To help this system drain off the lightning discharges, its resistance to the ground is kept low. This is further improved by burying rods or wire radially around the bases of the towers or supports, or burying a wire between them. This is known as a "counterpoise" (see Fig. 2-38), and its function is to dissipate the discharge over a larger area of ground, thereby lessening the resistance to the flow of these discharges. It is desirable, therefore, for the tower footing resistance to be made as low as possible; a value of 5 ohms (Ω) or lower is generally sought. The question now arises as to how the value of tower footing resistance is measured and how it may be reduced.

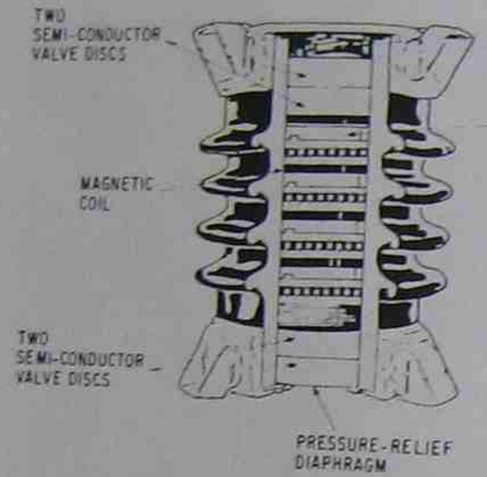


Fig. 2-33 Cutaway view of resistor lightning arrester

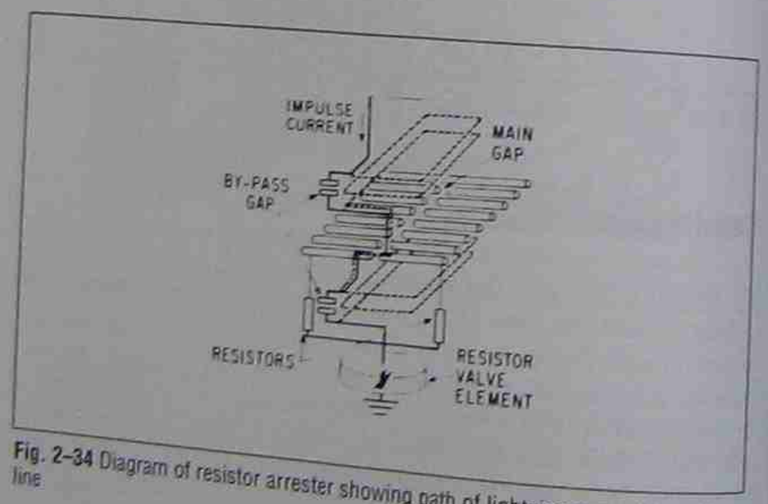


Fig. 2–34 Diagram of resistor arrester showing path of lightning current in solid line

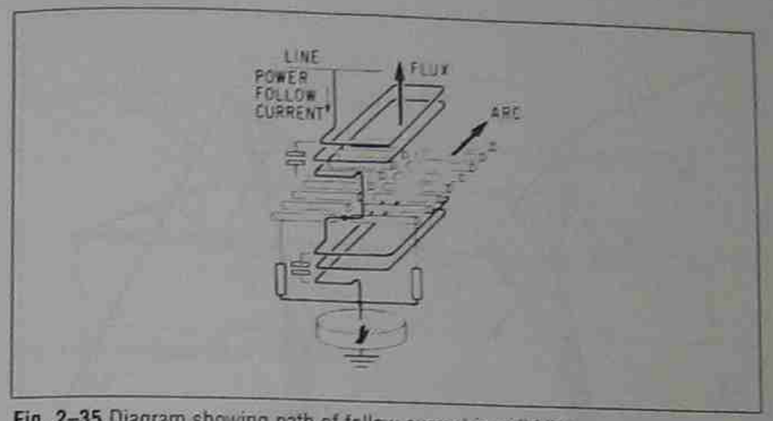


Fig. 2–35 Diagram showing path of follow current in solid line

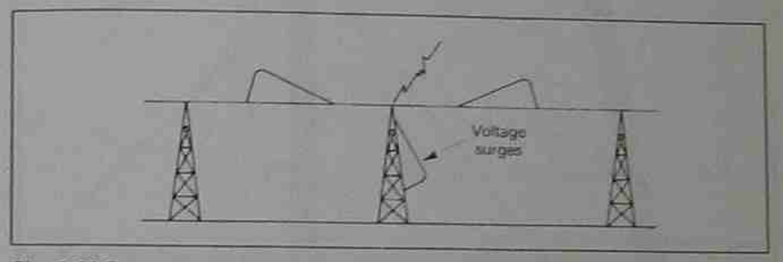


Fig. 2-36 Transmission-line ground wire struck by lightning

Methods of Measurement

There are three general methods used to measure the ohmic resistance from the tower to earth.

Fall of Potential Method

In Figure 2–39, a known current, measured by the ammeter, flows in the ground between the tower and electrode B. The voltage drop, or fall of potential, between the tower and electrode A is measured with a voltmeter. The tower footing resistance (R_t) is then determined by the relation:

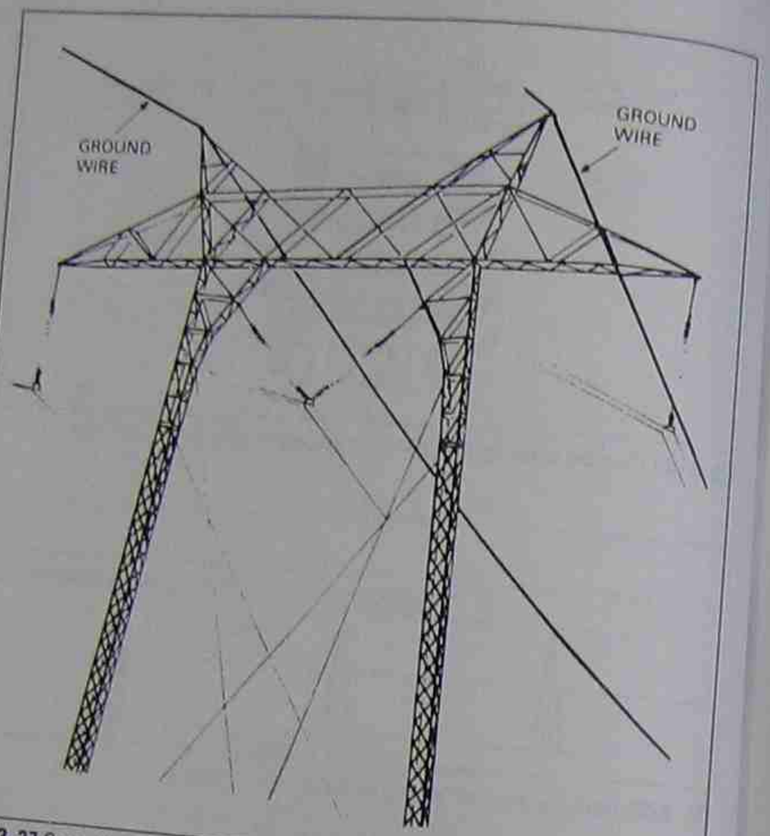


Fig. 2–37 Ground wires

$$\text{Footing Resistance } (R_f) = \frac{\text{Fall of potential}}{\text{Known current}}$$

The electrodes should be located sufficiently apart to avoid proximity effect on each other.

Three-Point Method

In Figure 2-40, three different resistance measurements are obtained: R_x in series with resistance of electrode R; R_x in series with the resistance of

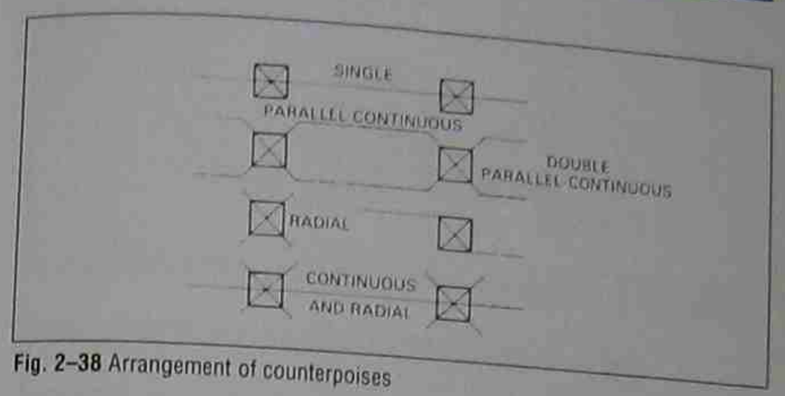


Fig. 2–38 Arrangement of counterpoises

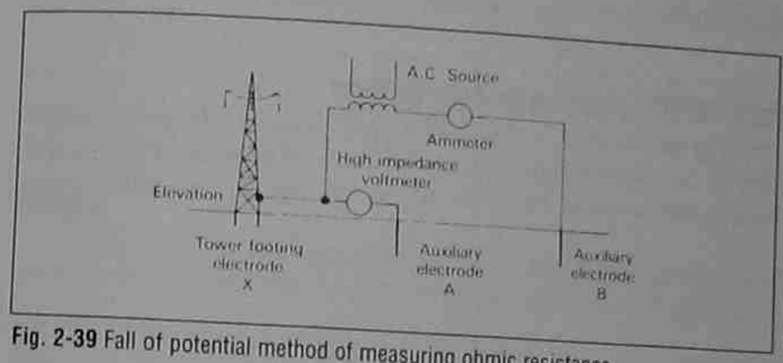


Fig. 2-39 Fall of potential method of measuring ohmic resistance

electrode R_B; and R_x in series with R_B. Three measurements are taken, each one in turn, by using the voltmeter-ammeter method of measuring resistance. The footing resistance (R_x) is then computed from the equation:

$$R_x = \frac{(R_x + R_x) + (R_x + R_B) - (R_x + R_B)}{2}$$

The electrode should have resistances of the same order of magnitude as that of the tower footing.

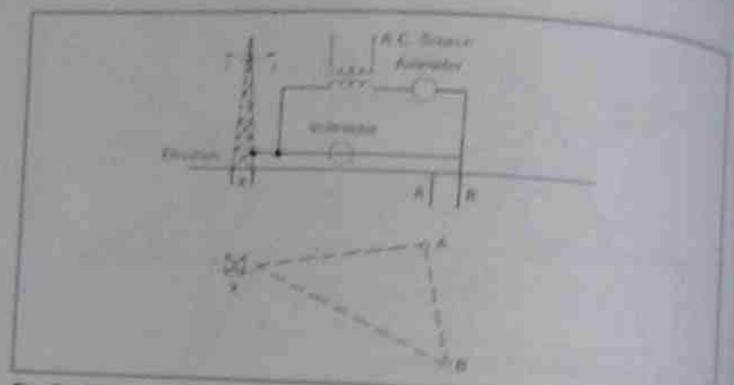


Fig. 2–40 Three-point method of measuring ohmic resistance

Ratio or Wheatstone Bridge Method

In Figure 2–41, $R_x + R_a$ is first measured with the Wheatstone bridge. (This is a laboratory measuring device based on a comparison of current and resistance ratios used to determine unknown quantities of resistance.) Then:

R_x is to $(R_x + R_a)$ as R_s is to $(R_s + R_a)$

or

$$\frac{R_x}{(R_x + R_a)} = \frac{R_s}{(R_s + R_a)}$$

but

$$R_x + R_s = R_s + R_a$$

and

$$R_x = R_s$$

$$R_a = \frac{R_s(R_s + R_a)}{(R_s + R_s)}$$

or

$$R_s = \frac{(R_s + R_a)\,R_s}{(R_s + R_a)}$$

It should be realized that the resistance of an earth connection varies with many factors such as moisture, temperature, depth and diameter of electrodes, season of the year, and earth composition.

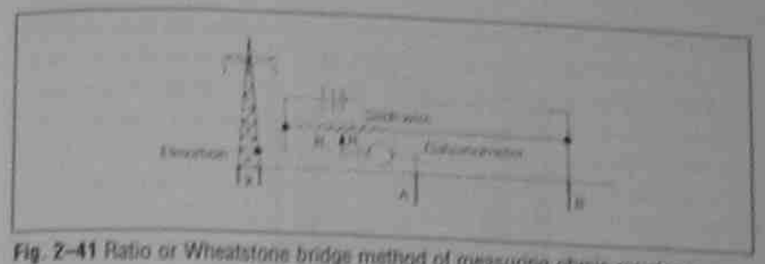


Fig. 2–41 Ratio or Wheatstone bridge method of measuring ohmic resistance

Methods of Reducing Tower Footing Resistance

Resistance of tower footings may be reduced by: installing additional conductor paths in the counterpoise; driving additional ground rods and connecting them to the counterpoise; or a combination of both.

In some regions, it is fairly easy to obtain tower-footing resistances of 5 Ω or less. In other regions, it may be more difficult. Soil resistivity is the most important factor in determining the resistance of tower footings. Some typical values are shown in Table 2–4.

Surges

Similar "surges" will occur in transmission lines from switching operations or from intermittent temporary short circuits. The first are created

Table 2–4 Typical Values of Soil Resistivity*

Soil	Resistivity Range
Clay, moist	14–30
Swampy ground	10–100
Humus and loam	30–50
Sand below ground water level	60–130
Sandstone	120–70,000
Broken stone mixed with loam	200–350
Limestone	200–4,000
Dry earth	1,000–4,000
Dense rock	5,000–10,000
Chemically pure water	250,000
Tap water	1,000–12,000
Rain water	800
Sea water	0.01–1.0
Polluted river water	1–5

*In ohms per cubic meter.

when a switch or circuit breaker is opened on interconnected lines, and the surge is created much as in a water system when a valve is suddenly closed. The latter may be caused by tree limbs, kites, or other foreign objects making temporary contacts. Rapid relaying is sometimes provided, which takes the lines out of service before damage to them or other equipment can occur.

As soon as the transient disturbance is removed, service is restored to them by automatic reclosing devices called "reclosers." Figure 2-42 is an oscillogram showing a typical example of a recloser operation. Notice that the first time it opens and closes, the action is instantaneous, requiring only 1.6 cycles. The second time the action is delayed to 2 cycles, the third time to 6, and the fourth time to 5-1/2 cycles. Then the recloser locks itself open, and a worker must correct the fault and manually close the mechanism.

The timing mechanism (see Fig. 2-43) that can effect this sort of action is a hydraulic system utilizing transformer oil as retarding fluid. With this device, the second, third, and fourth openings of the recloser can be set to any desired time span. To adjust the second and third openings, the time plate must be positioned. To designate whether the lockout should occur after two, three, or four operations, the cotter pin must be placed in the proper hole. To select the number of fast operations (one, two, or three), the roll pin must be positioned. If it is desirable to have all four operations be instantaneous, the timing plate must be removed.

Maintenance

When such disturbances occur, it is usually customary to patrol the line to look for places of fault. Flashover marks, pitted conductors, chipped

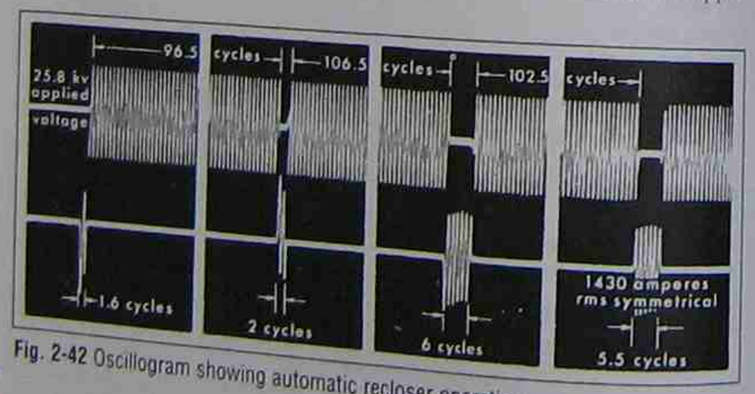


Fig. 2-42 Oscillogram showing automatic recloser operation

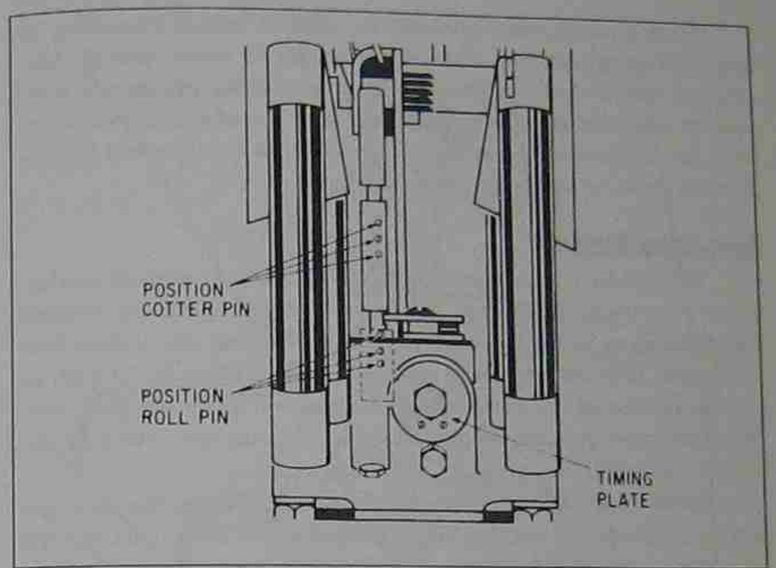


Fig. 2–43 Timing mechanism for oil circuit recloser, illustrating components for sequence adjustment

or stripped insulators, and fallen overhead ground or shield wires may be found. Maintenance and replacement of damaged units usually follow to prevent these relatively minor incidents from developing into major sources of trouble. Helicopters and aircraft have been used, as well as patrols by foot, horseback, and car.

Live-line Operation

Insulators, conductors, and other items may be handled while energized with live-line (hot stick) or bare-hand methods. Ingenious tools, mounted on the end of wood sticks, are used in live-line maintenance. The wood acts as insulation. The worker fastens the stick to a conductor, after first disconnecting it from the insulator or insulators. Lashing the stick to the pole or tower keeps the energized conductor a safe distance away while insulators are changed, structure repairs are made, or ground shield conductors are reinstalled.

More sophisticated procedures are used to replace connectors, to wrap reinforcing rods around pitted conductors or broken strands. Care must be taken to see that workers always have sufficient insulation or space between them and energized parts of the line. For additional mechanical safety, conductors and other energized items are usually supported by one or more hot sticks, or by a hot stick and insulating rope.

Bare-hand Method

Methods have been developed to allow workers to work on conductors or other energized items as long as the platforms or buckets in which they are standing are insulated (see Fig. 2-44). Work may also be done from a dolly that rides on the conductor that is being worked on. In such an instance, no attempt is made to insulate the worker from the energized item. The worker now becomes energized together with the item. However, the support (or dolly) is insulated.

Extreme caution is necessary in this method. The insulated platform or bucket insulates the workers from a live conductor and ground, but will not protect them when working on two or more live conductors between which high voltages may exist. Although known as "bare-hand" method, workers usually wear noninsulating work gloves.

Review

- Structures for supporting overhead conductors are broadly classified as poles and towers. They may be made of natural wood: southern yellow pine, western red cedar, Douglas fir, larch, and other species. They may be chemically treated, round, tapered poles, or laminated, round or square poles (two or more layers of wood are glued together).

- Poles may also be of hollow, tapered, tubular design, made of steel or aluminum, or built up of flat metal members, latticed together, into a variety of cross sections. Reinforced concrete poles are used in special cases.

- Poles may be combined in A-frames, H-frames, and sometimes into V- or Y-type transmission structures.

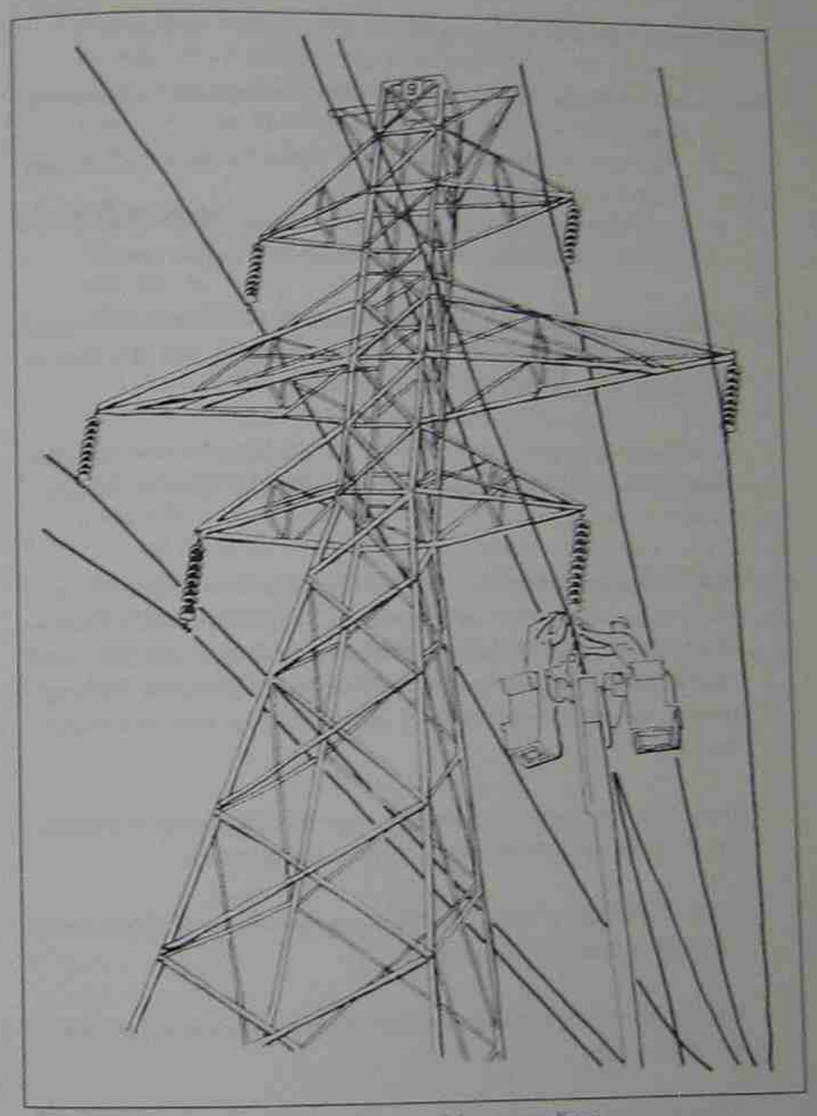


Fig. 2-44 Workers in insulated buckets repairing power lines

- Towers may be of several types:

  1. A tangent tower, on which the conductor supported is essentially a straight line
  2. A light-angle tower, on which the conductor supported changes direction slightly, perhaps 5° or 10°
  3. A medium-angle tower, with support changes of 20° to 30°
  4. A heavy-angle tower, which accommodates sharper turns

- Generally, guys and anchors should be installed on dead-ends, angles, long spans where pole strength may be exceeded, and at points of excessive unbalanced conductor tension.

- The choice of supporting structures for transmission lines is influenced by many factors, which, considered together, result in the greatest economy.

- Both skin effect and corona discharge may cause interference on communication circuits that may parallel the transmission lines. Corona discharge may also cause interference to local radio and television broadcasting. To lessen the effects of skin effect and corona discharge, hollow expanded conductors and corona rings are used in transmission lines.

- Cross-arms for towers are generally of galvanized steel or aluminum; wood is used for pole and A- or H-frame construction.

- In the ACSR type of cable, aluminum conductors are wrapped about a steel cable that provides strength.

- Insulators used for transmission lines are both of the suspension and pin or post types.

- Long overhead conductors of transmission lines are subject to aeolian vibrations and galloping (or dancing) conductors.

- Arcing rings and lightning arresters protect transmission lines from damage caused by lightning. Shielding the lines by means of a wire above them, which is directly connected to ground, is another form of protection from lightning. Lower tower footing resistance is important.

Study Questions

1. What are transmission line supports usually called? Of what material may they be made?
2. What type of transmission structures can be made of wood or metal poles?
3. Into what types may towers be classified?
4. Where are the guys and anchors generally installed?
5. What factors influence the choice of supporting structures?
6. What is meant by "skin effect"? What is corona discharge? How may these effects be minimized?
7. Of what materials are overhead transmission conductors made?
8. What types of insulators are used on transmission lines? What are the advantages of each?
9. How do the forces of nature affect overhead transmission lines?
10. How are overhead transmission lines protected from lightning?

3

Underground Construction

General Concepts

Underground transmission lines have some advantage of freedom from above ground weather and traffic problems, and thus experience fewer interruptions than overhead lines. However, there are a variety of failures that do affect underground cables. Interruptions underground may last from a few days to several weeks while the fault is located, the cable exposed, and repairs made under necessarily very exacting conditions.

This repair time compares unfavorably to that of outages on overhead lines, where fault location and repair are generally short-lived. Significant economic problems develop, therefore, because underground systems require that more facilities be available to attain the same level of reliability as that of the overhead systems. Underground transmission facilities are many times more costly than overhead ones. Consequently, they are feasible only in special locations, such as metropolitan centers, where towers on high poles in congested areas would be completely unacceptable.

Underground transmission cables may be laid directly in the ground in open fields or under suburban and rural roads (see Fig. 3–1). They may be drawn into ducts or installed in pipes in more or less densely populated urban and suburban areas (see Fig. 3–2). They can also be installed in troughs in special cases, such as under bridge structures or in tunnels

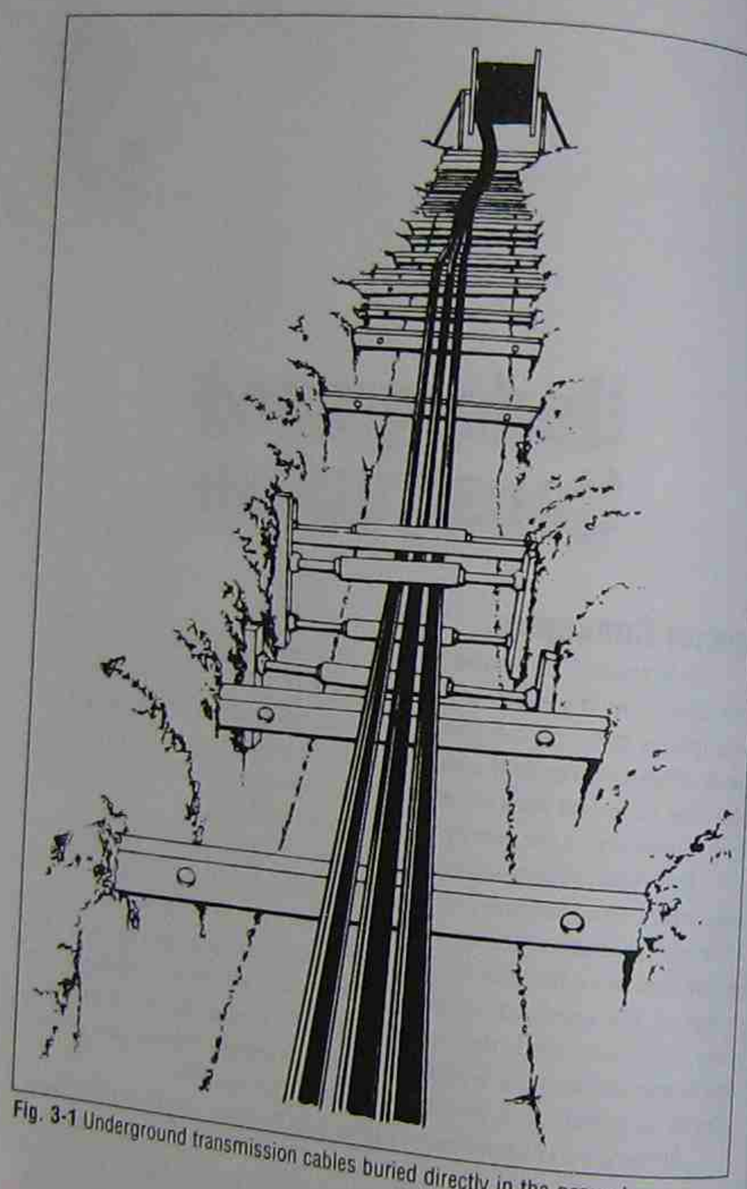


Fig. 3-1 Underground transmission cables buried directly in the ground

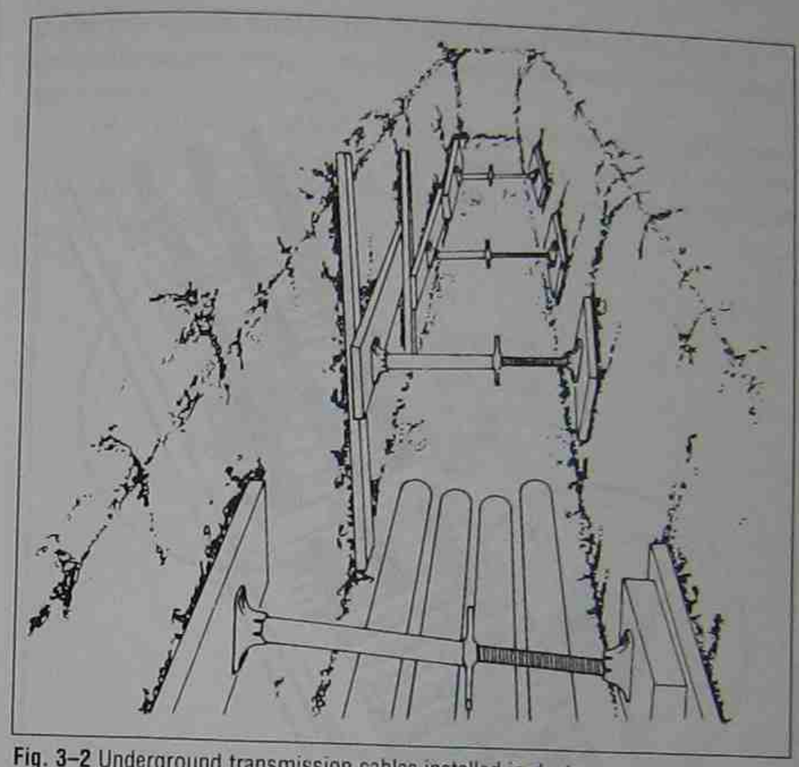


Fig. 3–2 Underground transmission cables installed in ducts

(see Fig. 3-3). The method of installation depends on the voltage and kind of cable, and the area in which it is installed.

Cables

Tracking

High-voltage cables present particular problems, since the conductors of the cables are subjected to thermal expansion and contraction from the loading and unloading of current during daily or other periodic cycles. They initiate motion with respect to the insulation, which tends to cause voids or pockets to form in the insulation. A void between the conductor and the insulation, or between the insulation and the grounded sheath, may also be

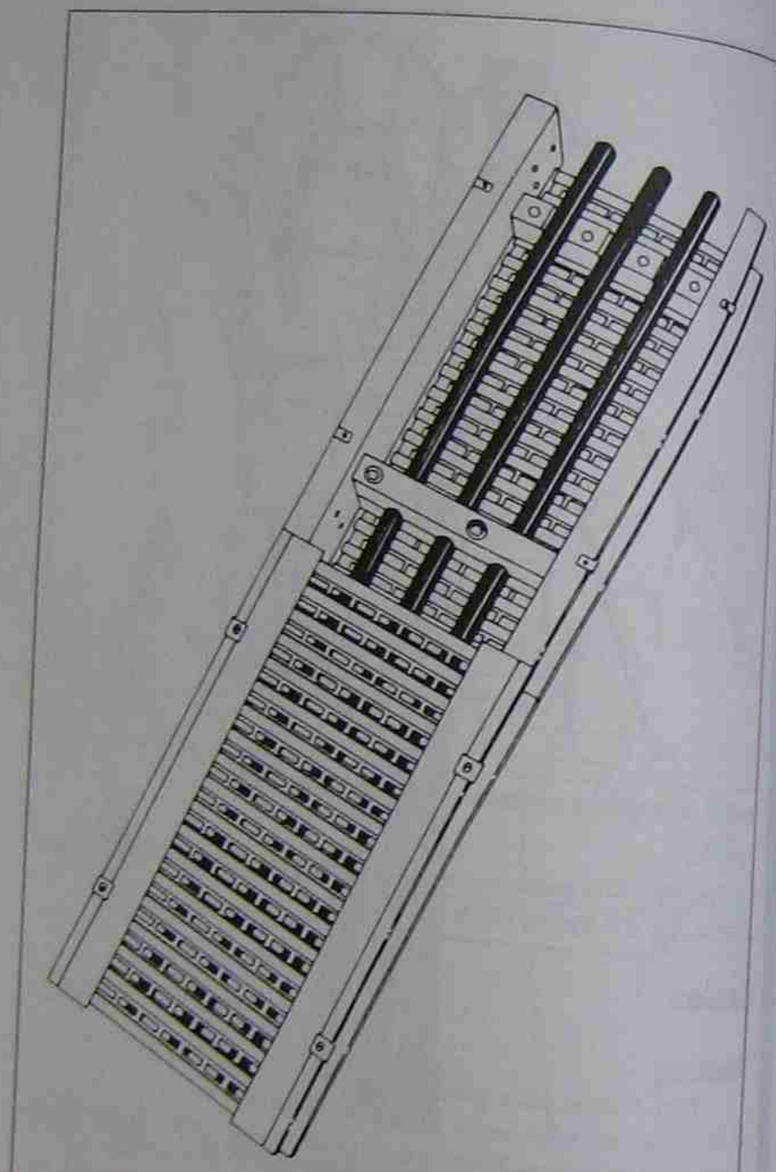


Fig. 3–3 Underground transmission cables installed in troughs

formed due to other factors. These include faulty manufacture, bending too sharply during installation, or thermal expansion and contraction because of load cycling (see Fig. 3-4a).

Such minute air pockets, under the electrostatic forces of the energized conductor, tend to ionize, that is, become conductors of electricity. This ionization of minute particles within the void causes corona discharge.

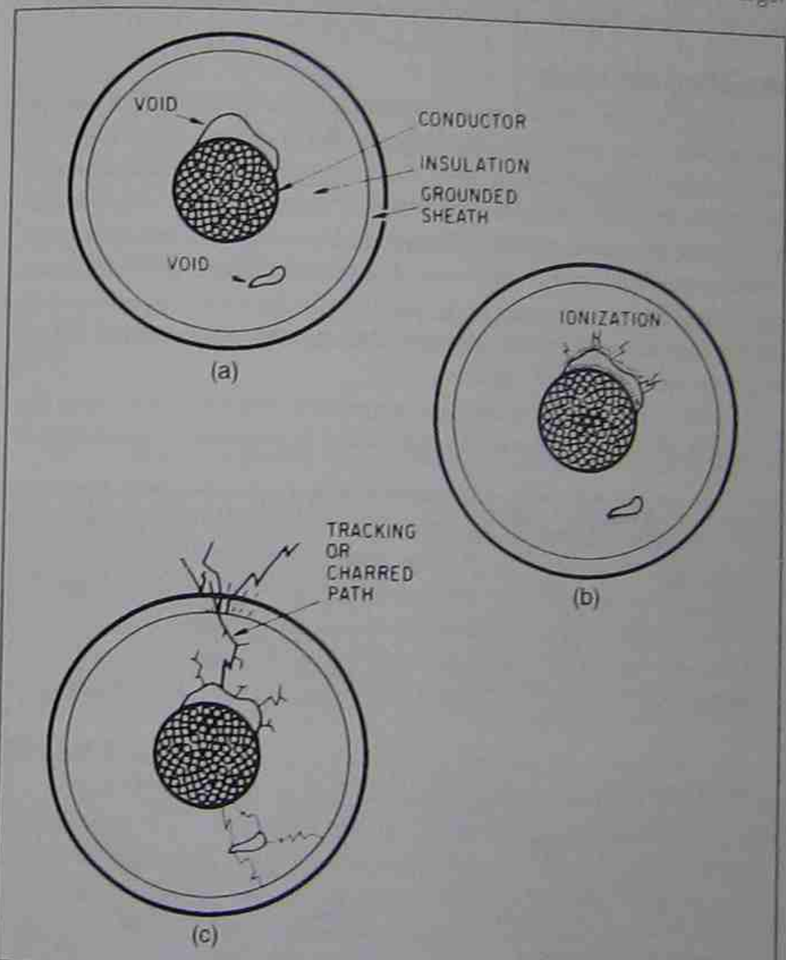


Fig. 3-4 Tracking in a cable: (**a**) void between the conductor and the insulation; (**b**) corona discharge; (**c**) cable failure

The corona discharge results in minute scorching and carbonizing of adjacent insulation. This is the beginning of "tracking" and the creation of ozone that damages the insulating value of most compounds (see Fig. 3-4b). When enough air pockets form, a tracking or charred path occurs where the insulation breaks down. Ultimately, the insulation is bridged with a carbonized track that is conductive, and the cable fails (see Fig. 3-4c). Some high-voltage cables for underground transmission systems are shown in Figure 3-5.

Insulating Materials

Insulation for cables has largely been oil-impregnated paper, though more recent cables employ plastic materials. Some cables consist merely of paper wrapped around one or more conductors, enclosed within a protective sheath. In others, the insulation wrapped around the conductors is subject to oil or gas under pressure. The gas used is usually nitrogen, but sulfur hexafluoride (SF_6) has also been used. Theoretically, when such voids occur in the insulation, the oil or gas under pressure fills the void and prevents ionization, tracking, and failure. Figure 3-6 shows the most suitable voltage ranges for paper-insulated cables.

Historically, fluid-impregnated paper-tape insulation has been the workhorse of high-voltage transmission cables. Its excellent properties result

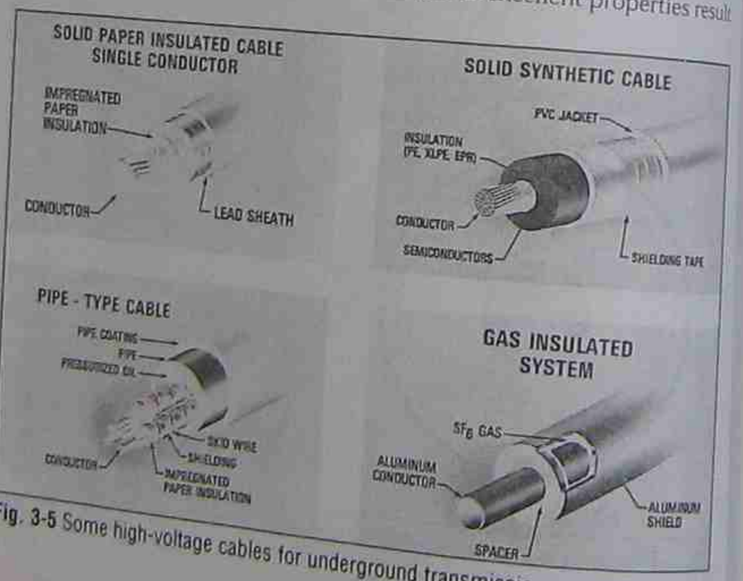


Fig. 3-5 Some high-voltage cables for underground transmission systems

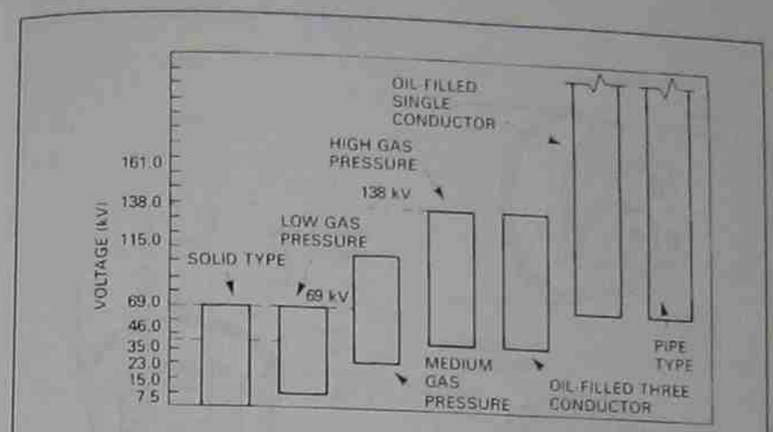


Figure 3.4 Recommended voltage ranges for various types of paper insulated power cables

Fig. 3-6 Recommended voltage ranges for various types of paper-insulated power cables

in very reliable underground transmission operation. In the mid-1980s, a new, laminated polypropylene and paper-tape (PPP) insulation was made commercially available. It featured properties that improved on those of paper insulation—thinner insulation walls, lower dielectric loss, and higher impulse level strength. PPP-insulated cables have higher capacity ratings than all paper cables. For example, a 1.5 thousand circular mills (mcm) copper conductor paper cable would be rated at 490 MVA, compared to PPP rated at 570 MVA, which is about 15% more.

Hollow Cables

In "hollow" cables, the oil or gas passage is located within the conductor or cable (see Fig. 3–7). In "pipe" cables, the oil or gas surrounds the conductors (see Fig. 3-8). Special accessories and auxiliary equipment to handle the oil or gas are needed with these latter cables. A comparison of power transmission capacity between gas- and oil-impregnated insulated cables is shown in Figure 3-9.

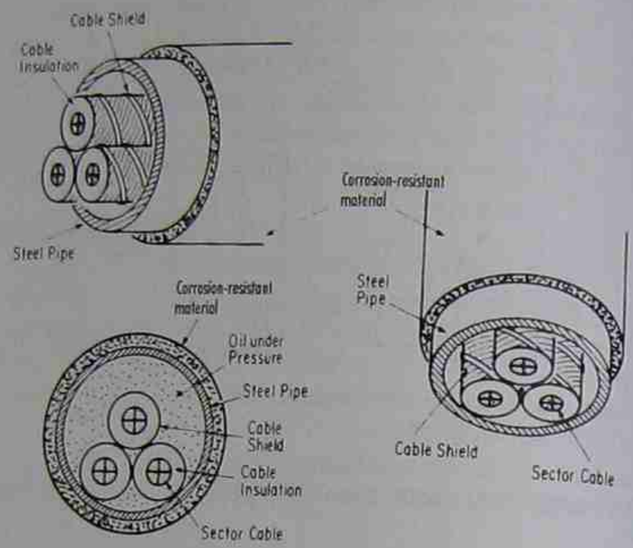


Fig. 3-7 Typical oil-filled cables (*courtesy of Edison Electric Institute*)

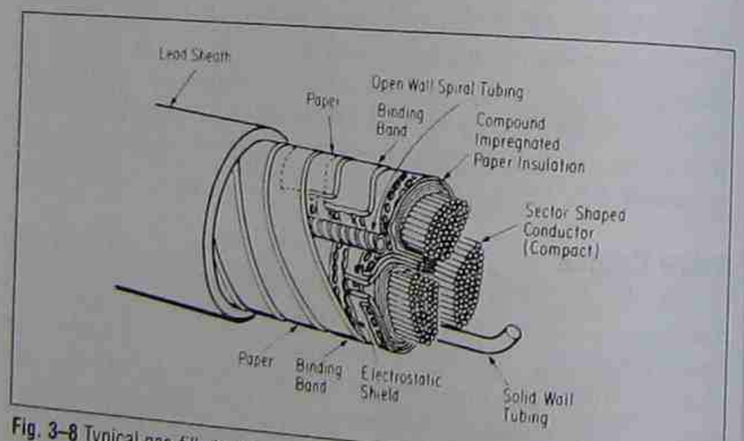


Fig. 3–8 Typical gas-filled cables (*courtesy of Edison Electric Institute*)

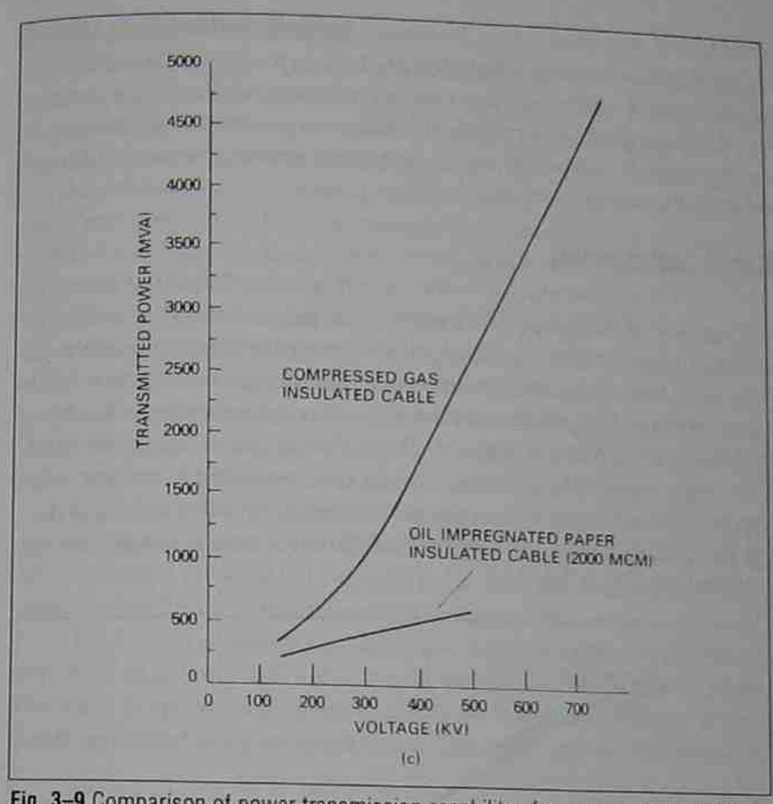


Fig. 3–9 Comparison of power transmission capability of compressed gas, insulated cable, and oil-impregnated paper insulated cable (*courtesy of Edison Electric Institute*)

Solid Insulation Cables

Solid insulated cables were formerly restricted to voltages of about 46 kV. However, with improved methods of manufacture and use of plastics, such as polyethylene-polypropylene, solid cables of 69 kV and 138 kV have been built and put into operation.

Pipe Coverings

Hollow cables have been used in circuits operating from 69 kV to 350 kV. These installations require extraordinary care, since the pipe interior

must be free of contamination. Evacuation before the introduction of the oil or gas therefore requires a high degree of vacuum and cleanliness. Special coverings on the pipe are used to avoid corrosion, electrolysis, and other damage to the pipe. Obviously such installations, while varying with type of construction, the nature of the ground, road surface, transportation, and other facilities, are extremely expensive.

Cable Installation

Care should be exercised when installing cables by pulling them in a duct or pipe. This is especially necessary in the case of gas- and oil-type cables. The stresses set up in the cables during the operation may cause damage to the conductors, the insulation, and the gas or oil paths. Outer armor wires, usually spiraled about a cable, may tighten about a cable so as to damage the insulation and cut off the flow of gas or oil in the cable. Thousands of feet of gas and oil cables may be pulled in at one time. Dynamometers, instruments for measuring tension, are often employed during the pulling process to ascertain that allowable pulling stresses are not exceeded (see Fig. 3-10).

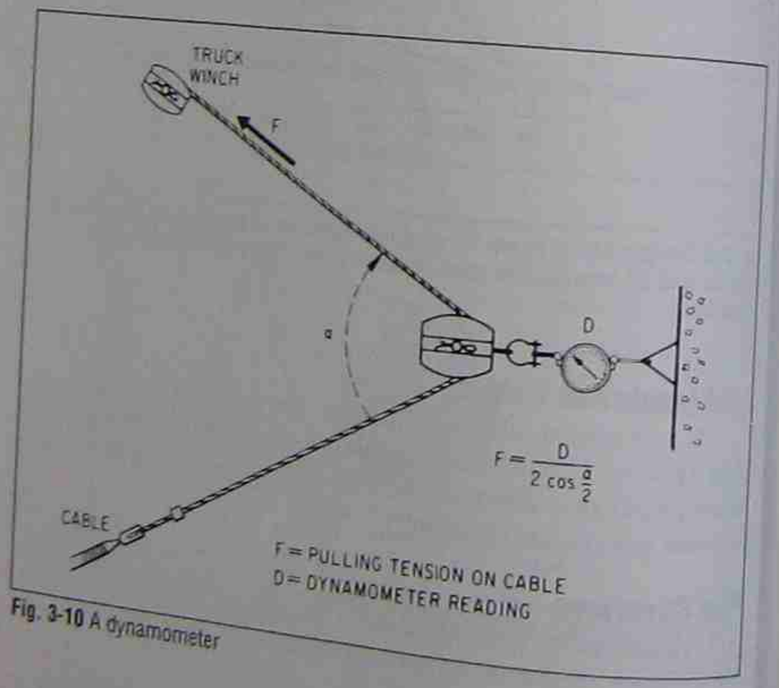


Fig. 3-10 A dynamometer

Repair of Oil-filled Cables

While solid cables require relatively little maintenance and are comparatively easy to replace or repair, oil- and gas-filled cables present much greater difficulties. Oil or gas leaks occasionally occur, and these must be found and repaired, generally without deenergizing the cable. At some point, oil-filled cables have to be replaced, whether because of failure, inadequacy, public improvement, or for other reasons. When this occurs, it is necessary to seal off the flow of oil on both sides of the section on which work is to be performed.

The flow of oil is sealed off by freezing an oil slug from the outside of the cable or pipe by pouring liquid nitrogen around it until there is assurance the oil flow is stopped. These low temperatures are maintained by encasing the cable or pipe in ice and continued dripping of liquid nitrogen. The cable or pipe may then be cut, cables replaced, repaired, or rerouted, and in the case of pipe cables, the pipe assembly welded together again.

Care is taken to reestablish the protective covering. Before reenergization, it is necessary not only to replace the oil in the affected section, but to ascertain that all of the oil in the system is free from air, moisture, and other contaminants. This is a time-consuming and expensive process.

Figure 3-11 illustrates how freezing is employed. The method shown consists of an approximate 2-ft-long split lead sleeve with two stand pipes. The sleeve is opened sufficiently to pass round the cable. The gap is then closed and sealed along its length with solder. The ends are then sealed to

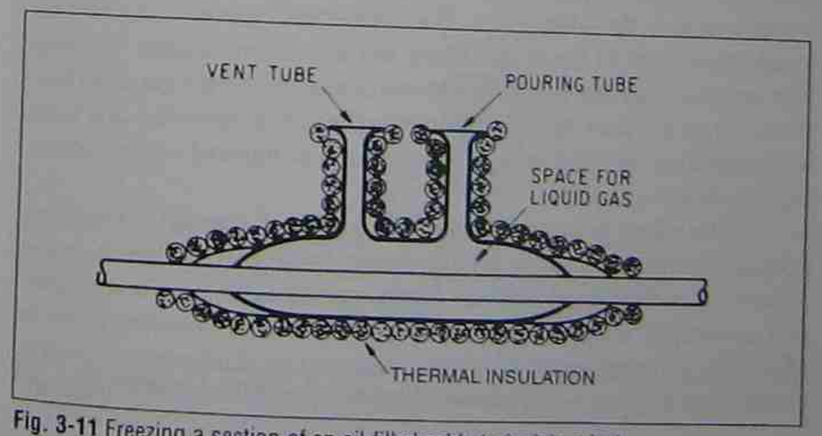


Fig. 3-11 Freezing a section of an oil-filled cable to isolate a leak

the cable jacket by the application of rubber tapes and reinforcing tapes (such as hessian). The whole of the sleeve and the stand pipes are then insulated thermally either in tape or rope form.

Liquid nitrogen is poured into the freezing sleeve, via a funnel, to one of the stand pipes; the other acts as a vent for the exhaust of the nitrogen vapor. Experience has shown that the time required to provide a solid blockage in a cable of approximately 2-1/2 in. outer diameter is 30 minutes. For cables up to approximately 4 in. in diameter, 1 hour is needed.

Repair of Gas-filled Cables

Repair of gas-filled cables generally follows the same procedure as for oil-filled cables except for one important difference. There is no oil to be frozen to stop the flow of oil out of the cable while it or a joint is being repaired. In gas cables, the gas is allowed to escape freely from between two stop joints and replaced with clean, dry gas when work is completed. Gas is fed at one of the stop joints and allowed to flow out at the stop joint on the other side of the repair. Gas is allowed to flow out for a brief period to ascertain no air or moisture remains in the cable before sealing at both stop joints.

Joints

In long installations, it is obvious that a gas or oil leak in either the hollow or pipe cable systems could lead to a long and costly decontamination process. To restrict the possibility of widespread contamination, such systems are usually sectionalized through the insertion of stop joints and semistop joints in the cable system. The number and types of such joints are usually dependent on the length of the line and its importance. The stop joint provides a physical barrier to both the conductor and the gas or oil flow system. These are used on long transmission lines and permit the line to be sectionalized so that the cables may be repaired or replaced without affecting the entire length of line.

The semistop joint allows the conductor to pass through but imposes a physical barrier to the gas or oil-flow system (see Fig. 3-12). Hence, in the event of a leak that would allow air or other contaminant to enter the cable, only a relatively small section of the line between the semistop joints is affected. In repairing gas-filled cables, the gas in one of the sections is completely replaced, and no operation similar to the oil freezing is required.

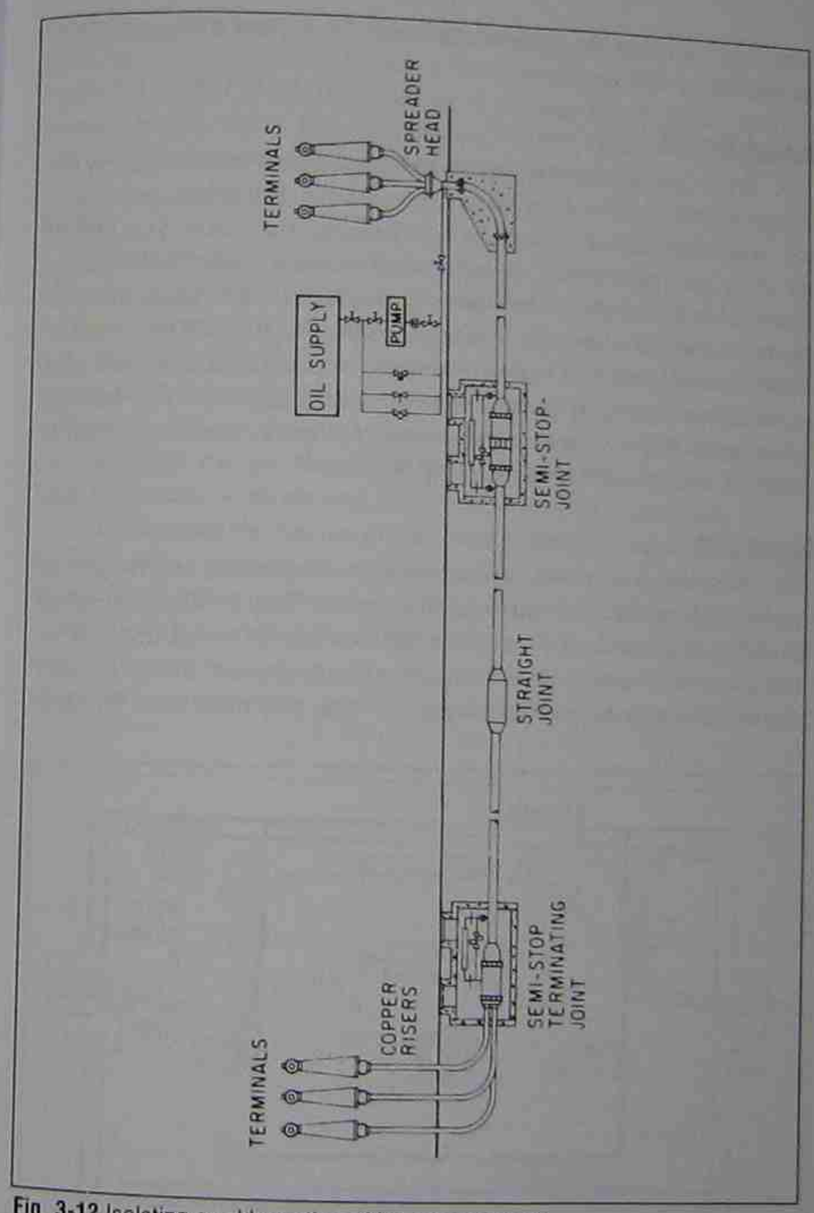


Fig. 3-12 Isolating a cable section with a semistop joint

Hence, both the time for repair and decontamination and the cost for such an incident are held down.

Direct Burial

When lead-sheathed or steel-armored cables are laid directly in the ground, precautions should be taken to prevent their being damaged. Stones and other rough material should be kept away from the cable. It is important to dig the trench deeply enough to keep plows or diggers from damaging the cable. It also should be wide enough to enable soft, sandy fill to be packed around the cable to prevent bruises and cuts. This will also improve heat dissipation, described later in this chapter. A plank or other marker may be placed horizontally in the trench on top of the cable to act as a warning to workers. It will also serve to protect the cable in the event the ground is disturbed after the cable is laid (see Fig. 3-13).

Manholes

Manholes may or may not be provided, depending on the area of installation, length of cable runs, and other factors. They are usually required for pulling-in purposes and for splices both for original installation and for repair or replacement. Their dimensions and arrangement should be such that the cables are not bent too sharply. However, they must allow for cable

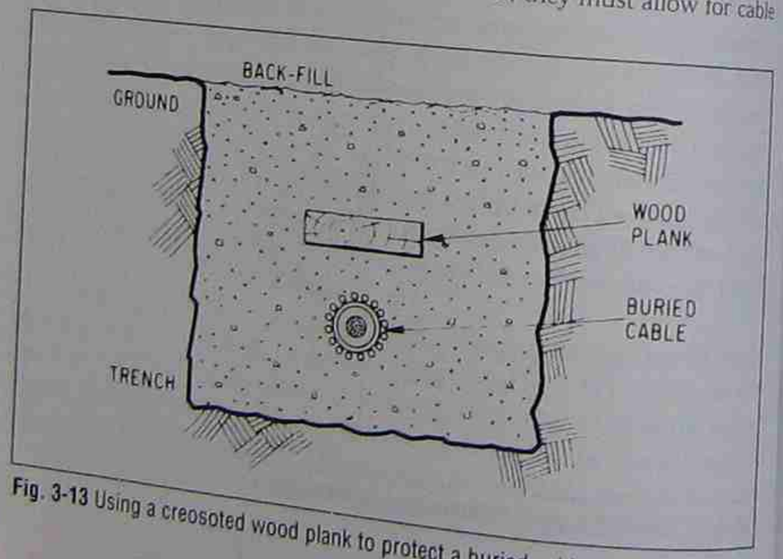


Fig. 3-13 Using a creosoted wood plank to protect a buried cable

movement under load or temperature differences so as not to put undue stress on the splice. Typically, for a 3-in. diameter cable, as shown in Figure 3-14, offset length (L) would be 66 in., joint length, 30 in., and the manhole length, 162 in. In many instances, manholes have been eliminated, and the entire installation is buried in the ground.

Soils

Underground cables—whether directly buried (see Fig. 3-13) or encased in a steel pipe (see Fig. 3-15)—are directly affected in capacity rating by the thermal characteristic of the surrounding soil. Thermal resistivity is the measure of the ability of the soil to conduct heat away from the cable source and be dissipated. Even soils with poor resistivity characteristics, such as dry clay, can achieve acceptable levels of resistivity if the moisture content is high enough. Moisture in the earth tends to move away from the cable heat source to an ambient point some distance from the cable.

If the moisture does not migrate back towards the cable fast enough, the earth surrounding the cable will dry out and become a poor thermal conductor. If the drying out continues, a hot spot can develop through "thermal runaway," with the probability of cable failure. This can be prevented if the load on the cable is reduced or the thermal properties of the soils are improved by proper application of a better backfill, such as thermal sand.

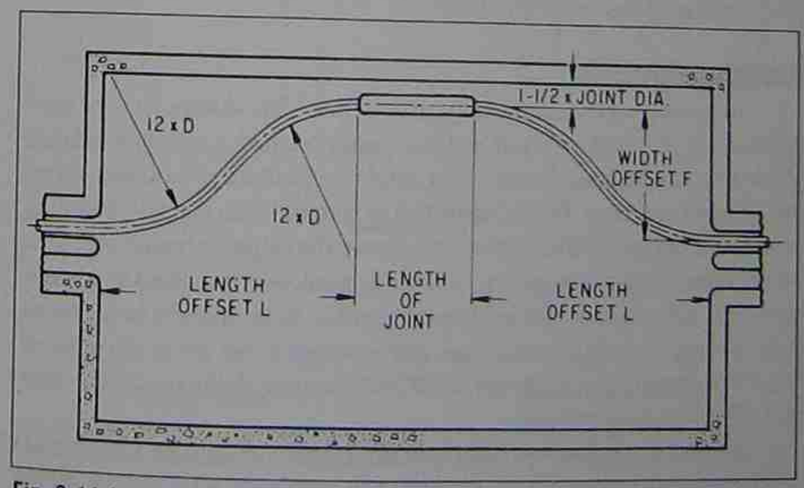


Fig. 3-14 A typical manhole

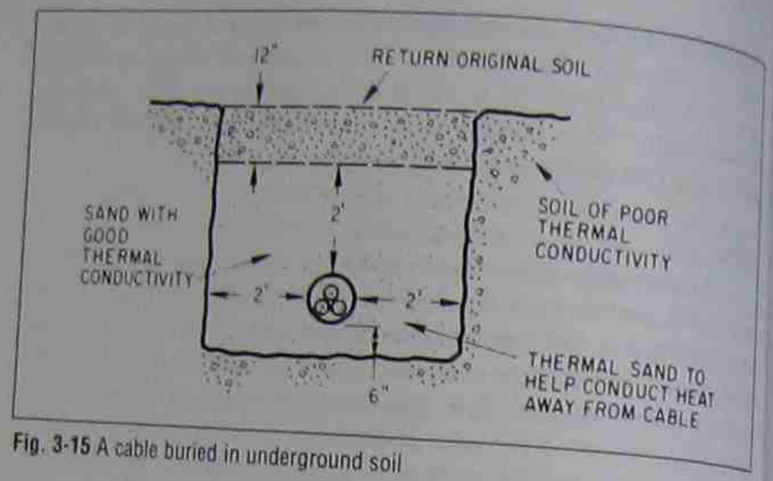


Fig. 3-15 A cable buried in underground soil

Splices

In splicing such cables, precautions similar to those used with overhead splices are taken. These include filling in the indentations on compression-type connectors and smoothing the surfaces to reduce or eliminate corona effects. The conductors are usually of stranded copper, though they may be of aluminum. Hollow conductors lend themselves to reducing skin effect, similar to overhead conductors.

Charging Currents

In underground transmission systems, the high voltage and the configuration of the conductor and metallic sheath produce a capacitor effect, a phenomenon somewhat similar to the condition of clouds in thunderstorms that produce lightning. This is intensified as voltage levels increase, resulting in so-called charging currents that may exceed the cable thermal limits. This occurs if the length of the cable is sufficiently great, which makes the amount of current necessary to "charge" the cable rather large, thereby reducing its load-carrying capability. In instances where voltage levels are in the order of 345 kV or greater, total depletion of the load-carrying ability may occur after only 30 miles of transmission.

Corrective equipment, called a shunt reactor, is available to compensate for this energy loss, but at extremely high cost. This cost must be added to the high cost of underground cable, the cost of splicing (which requires

special skills), and other costs associated with underground installations. Figure 3-16 illustrates the charging current phenomenon. For a more technical explanation, refer to appendix C, "Basic Electricity."

Review

- Underground transmission cables may be: (1) placed directly in the ground using armored cables; (2) drawn into ducts or installed in pipes; or (3) installed in troughs in special cases. Insulation for cables has largely been oil-impregnated paper, though more recent cables employ plastic materials.

- In "hollow" cables, the oil or gas passage is located within the conductor or cable; in "pipe" cables, the oil or gas surrounds the conductors.

- Dynamometers are often employed while pulling cables to assure that allowable pulling stresses are not exceeded.

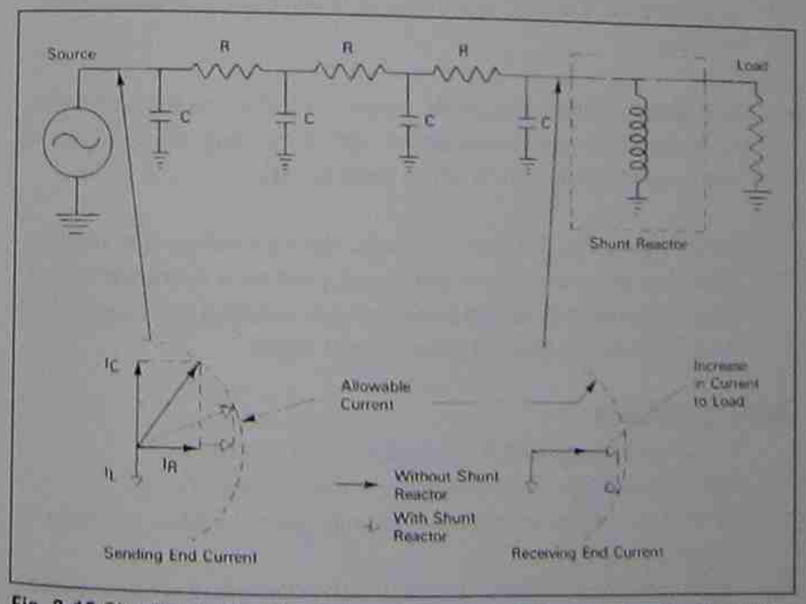


Fig. 3-16 Simplified cable circuit shows how power delivered to load is affected by a shunt reactor; in the absence of shunt reactors, this power decreases to zero at some critical length

- Solid cables require relatively little maintenance and are comparatively easy to replace or repair, while oil- and gas-filled cables present much greater difficulties. Where oil-filled cables have to be replaced it is necessary to seal off the flow of oil on both sides of the section on which work is to be performed.

- Stop joints are used in long installations to sectionalize the cable system to facilitate repair.

- Manholes are often required for pulling-in purposes and for splices both for original installation and for repair or replacement.

- Underground cables, whether of the types buried directly in the ground or pipe types, are installed at depths below the frost line, usually 24 in. deep or deeper. The soils in which they are buried must provide adequate heat dissipation to prevent overheating and failure of the cables. If hot spots occur, that particular area may be replaced with earth or "thermal" sands having better heat-dissipating characteristics.

- In splicing underground cables, precautions of filling in the indentations on compression connectors and smoothing the surfaces to reduce or eliminate corona effects must be taken.

- In underground transmission systems, the high voltage and the configuration of the conductor and sheath produce a condenser action. This is intensified as voltage levels increase, resulting in "charging currents" that may exceed the cable thermal limits.

Study Questions

1. How may underground transmission cables be installed?
2. What do underground transmission cables consist of?
3. What may happen to insulation in underground cables, especially at higher voltages?
4. What may the insulation of underground transmission cables consist of?

5. What is the difference between a "hollow" cable and a "pipe" cable?
6. What are stop joints and semistop joints? Where are they used?
7. How are sections of oil-filled cables replaced or repaired?
8. What is the function of manholes? What determines their design?
9. What effect does the surrounding soil have on buried cables?
10. What precaution should be taken when splicing two conductors?

4

Substations

Substation Functions and Types

Substations serve as sources of an energy supply for the local areas of distribution in which they are located. Their main functions are to receive energy transmitted at high voltage from the generating stations, reduce the voltage to a value appropriate for local use, and to provide facilities for switching (see Fig. 4-1).

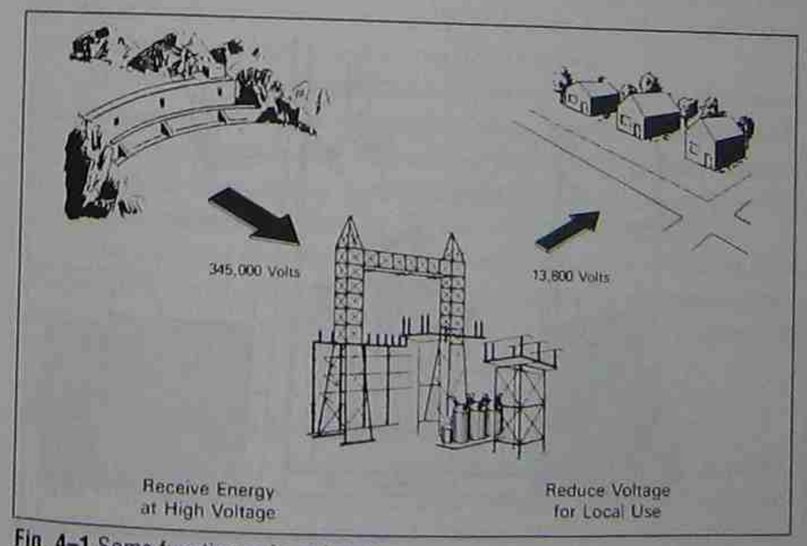


Fig. 4–1 Some functions of a substation

Substations have some additional functions. They provide points where safety devices may be installed to disconnect circuits or equipment in the event of trouble. Voltage on the outgoing distribution feeders can be regulated at a substation. In addition, a substation is a convenient place to make measurements to check the operation of various parts of the system.

There are substations that are simply switching stations, where different connections can be made between various transmission lines.

Some substations are entirely enclosed in buildings; others are built entirely in the open (see Fig. 4-2). In this latter type, the equipment is usually enclosed by a fence. Other substations have step-down transformers,

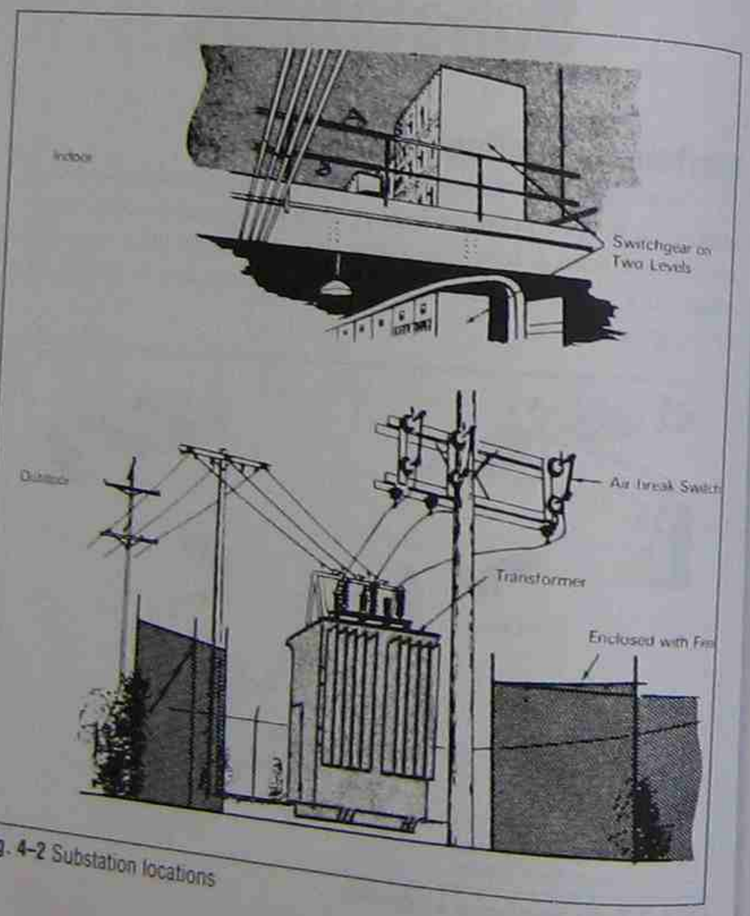


Fig. 4-2 Substation locations

high-voltage switches, circuit breakers and lightning arresters located just outside the substation building. The substation building houses the relaying and metering facilities.

Factors Influencing Location

Sites for distribution substations are generally selected so that the stations will be as near as possible to the load center of the areas they are intended to serve. Sites for transmission substations are selected using the following criteria:

- Terminal points of interconnections
- Transitions between overhead and underground transmission
- Key points of transmission interfaces for transfer of power between areas
- Critical service reliability locations of the transmission system

Typical Features of a Transmission Substation

Transmission substations usually have several incoming and outgoing transmission lines connected to bus arrangements through very high-speed circuit breakers. Bulk power distribution in various directions is the principal purpose but may be accompanied by distribution stepdown transformers and circuit breakers to serve local loads. Stepdown of a high-transmission voltage to a subtransmission system may also be present.

Usually these stations are operated automatically, with control communication routed back to an operating center. Such centers not only tell operators the condition of the stations, but enable them to operate equipment remotely. These control communication circuits may be utility-owned wires, public telephone circuits, or radio or microwave links.

The design of the substation arrangement should permit taking lines or equipment out of service for maintenance or operating purposes without affecting service continuity. A typical substation arrangement is shown in Figure 4-3, using standard symbols for equipment.

Automatic Versus Manual Operation

Substations may have an operator in attendance part or all of the day, or they may be entirely unattended. In unattended substations, all equipment functions automatically, or may be operated by remote control from an

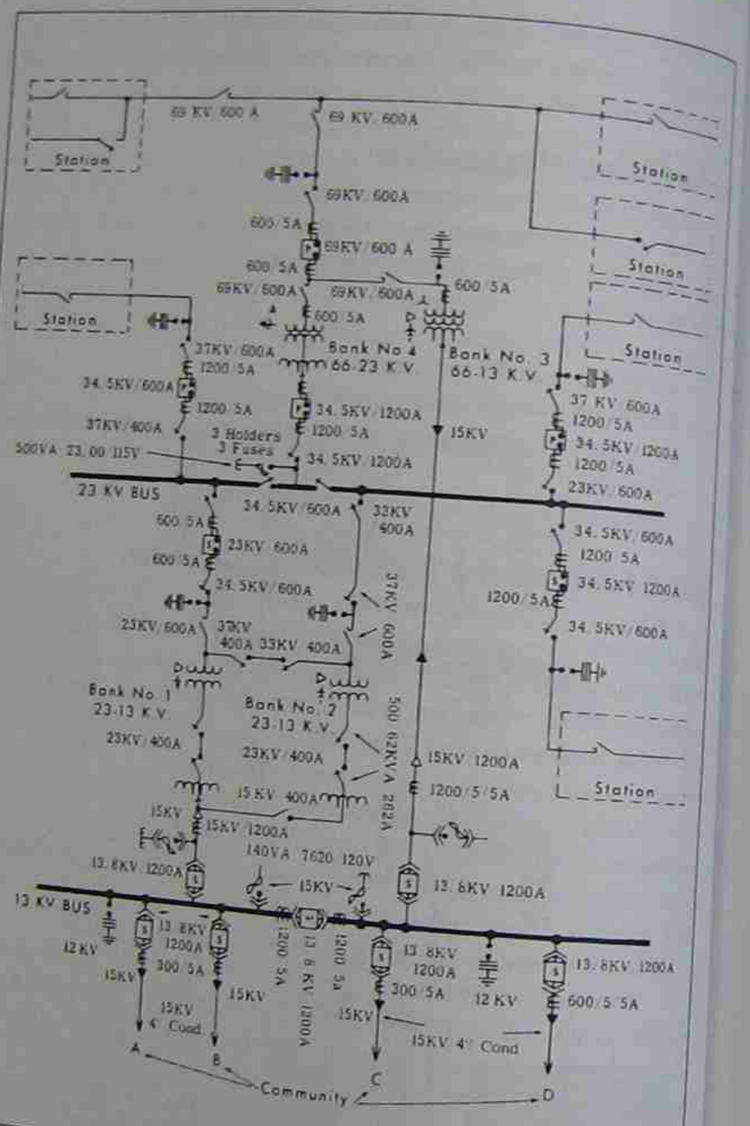


Fig. 4–3 Typical arrangement of a substation

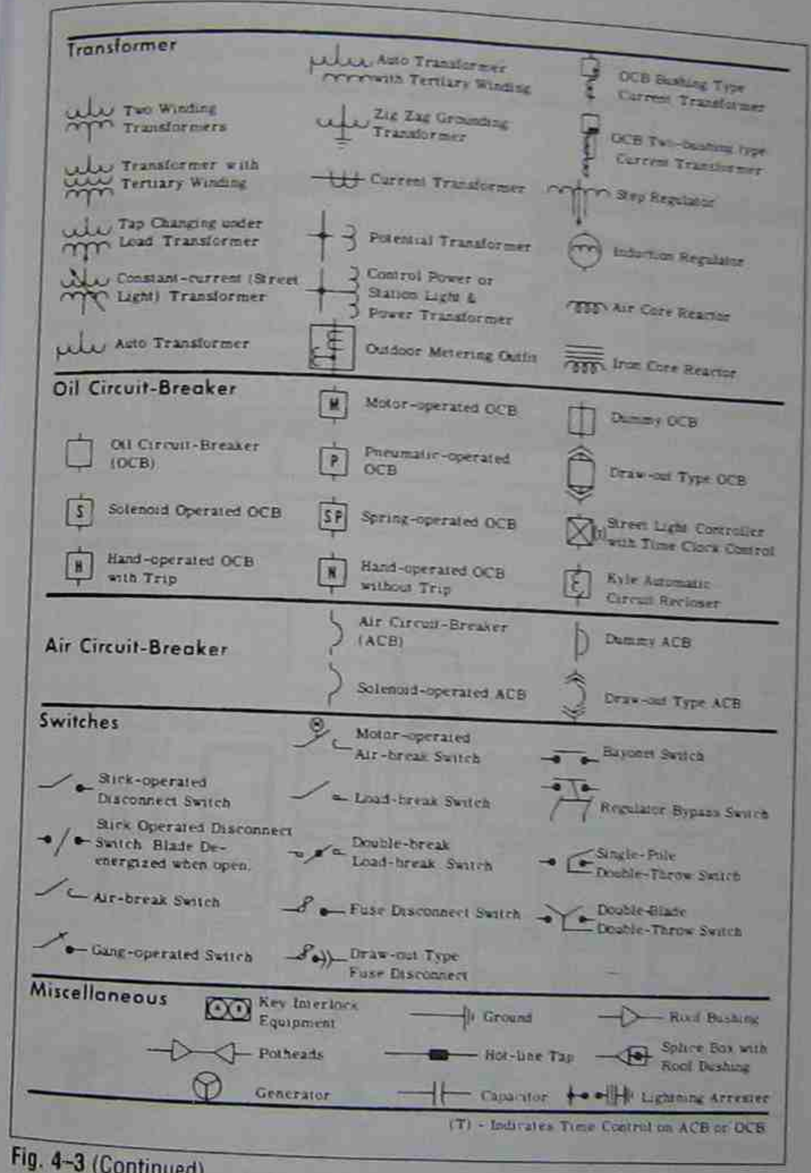


Fig. 4–3 (Continued)

attended substation, or from a control center (see Fig. 4-4). In some unattended substations, the equipment function is monitored and will give an alarm at a remote station when a "roving operator" needs to be dispatched to operate that station.

Substation Equipment—The Transformer

When a transmission substation is a multipurpose station, the voltage of the incoming supply is changed to that of the subtransmission or distribution feeders by means of a transformer.

Fundamentally, a transformer consists of two or more windings placed on a common iron core (see Fig. 4-5). All transformers have a primary winding and one or more secondary windings. The core of a transformer is made of laminated iron and magnetically links the coils of insulated wire that are

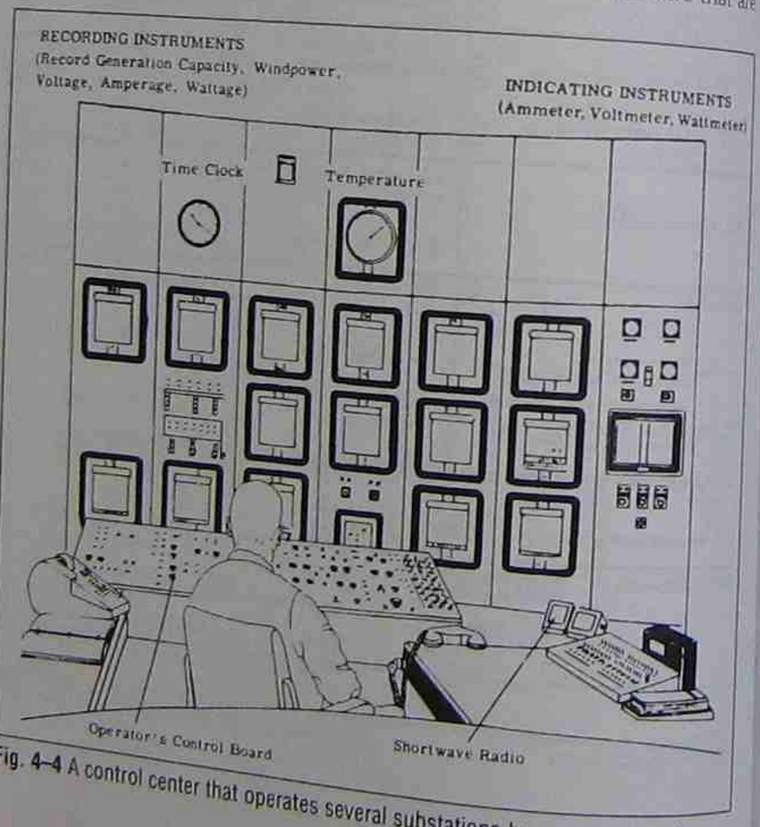


Fig. 4–4 A control center that operates several substations by remote control

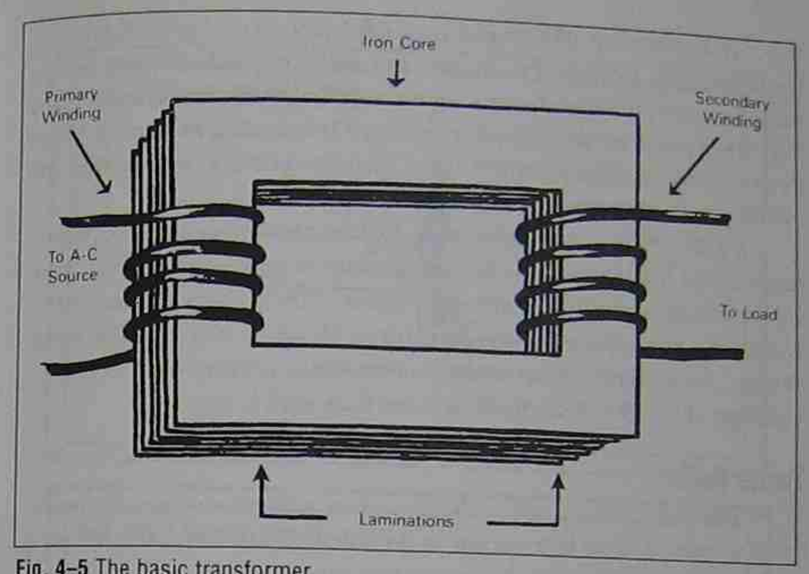


Fig. 4–5 The basic transformer

wound around it. There is no electrical connection between the primary and the secondary windings; the coupling between them is through magnetic fields. This is why transformers are sometimes used for no other purpose than to isolate one circuit from another electrically. When this is done, the transformer used for this purpose is called an "isolating" transformer.

The winding that is connected to the source of power is called the primary, and the winding connected to the load is called the secondary. The essential function of the conventional power transformer is to transfer power from the primary to the secondary with a minimum of losses. As we shall see, in the process of transferring energy from primary to secondary, the voltage delivered to the load may be made higher or lower than the primary voltage.

Step-up and Step-down Transformers

Transformers are wound to be as close to 100% efficient as possible. That is, all the power in the primary (as much as possible) is transferred to the secondary. This is done by selecting the proper core material, winding the primary and secondary close to each other, and following a number of other careful design specifications.

Thus, assuming 100% transformer efficiency, we can then assume that the relationship between the primary and secondary voltages will be the same as the relationship between their turns. If the secondary has more turns than the primary, we say that the transformer is operating as step-up transformer. If the secondary has less turns than the primary, we say that the transformer is operating as a step-down transformer.

Figure 4-6 is a representation of an autotransformer together with a conventional transformer. The autotransformer is somewhat different from the conventional transformer in that a portion of the primary and secondary is common, or makes use of the same turns. However, like all other transformers, the autotransformer does have the basic primary and secondary windings, although not physically isolated from each other.

Turns Ratio

Whether a transformer is of a step-up or step-down type, the power in the primary is equal to the power in the secondary (see Fig. 4-7). Thus, if the load draws 1,000 watts, the product of voltage and current in the primary is also equal to 1,000 watts. Another important principle is the fact that the primary and secondary voltages are in the same ratio as their turns. If the

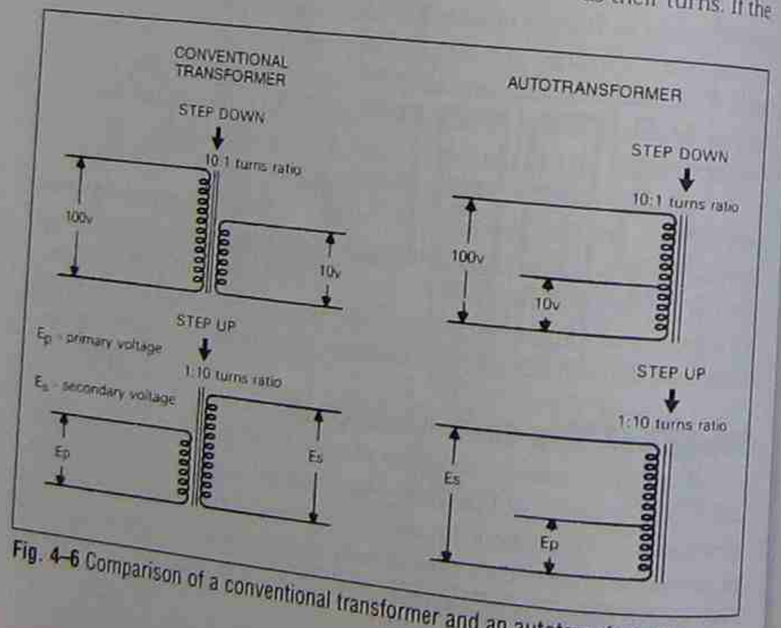


Fig. 4–6 Comparison of a conventional transformer and an autotransformer

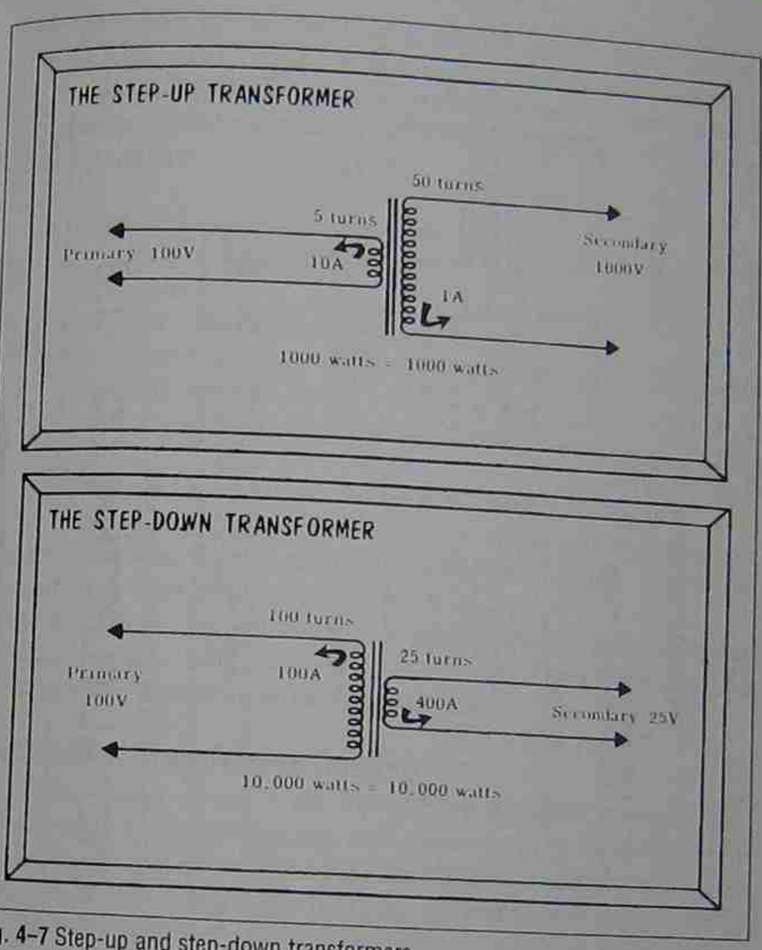


Fig. 4–7 Step-up and step-down transformers

secondary has twice the turns of the primary, the secondary voltage will be twice as great as that of the primary.

Transformer Rating

The nameplate on a transformer gives all the pertinent information required for the proper operation and maintenance of the unit (see Fig. 4-8). The capacity of a transformer (or any other piece of electrical equipment) is limited by the permissible temperature rise during operation. The heat gen-

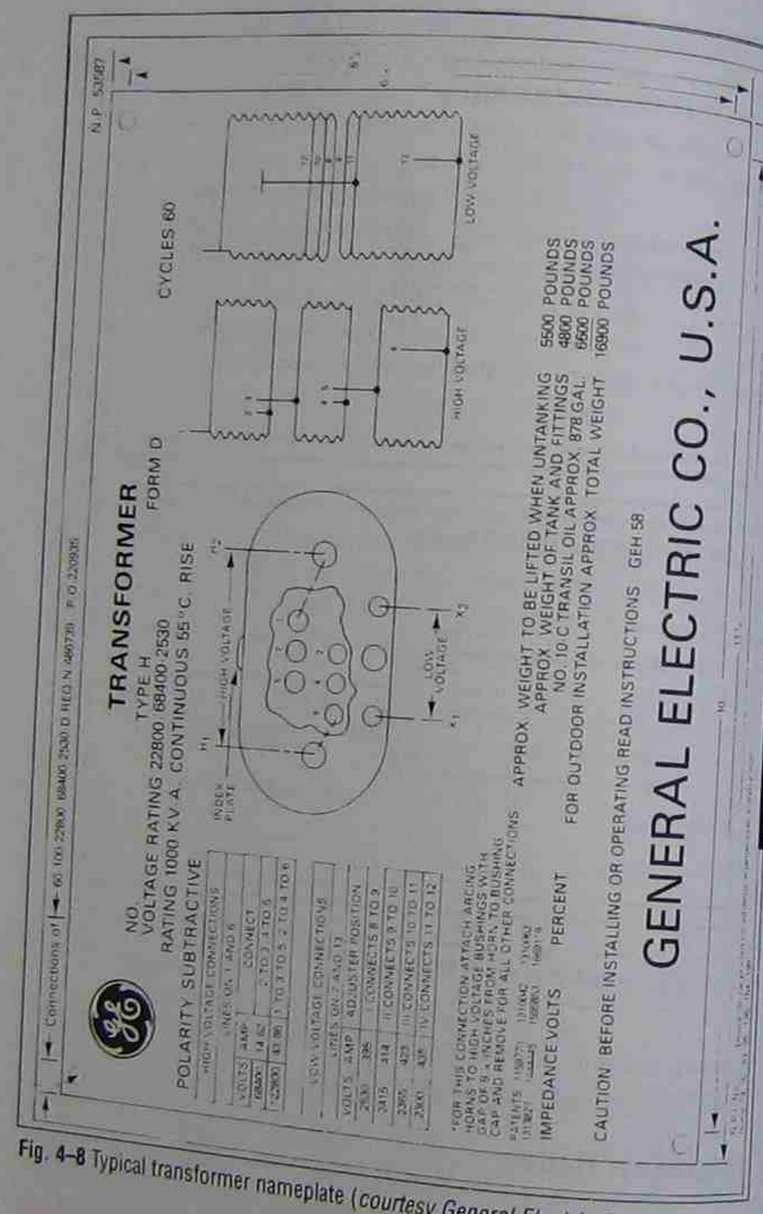


Fig. 4–8 Typical transformer nameplate (*courtesy General Electric Company*)

erated in a transformer is determined by both the current and the voltage. Of more importance is the kilovolt-ampere (kVA) rating of the transformer. This indicates the maximum power on which the transformer is designed to operate under normal conditions. Other information generally given on the nameplate includes:

- The phase (single-phase, three-phase, etc.)
- The primary and secondary voltages
- The frequency
- The permitted temperature increase
- The cooling requirements (includes the number of gallons of fluid that the cooling tank may hold)
- Percent impedance (full load voltage drop)

Primary and secondary currents may be stated at full load.

Depending upon the type of transformer and its special applications, there may be other types of identifications for various gauges, temperature indication, pressure, drains, and various valves.

The transformer consists primarily of a primary and a secondary winding; however, there are many other points to take into consideration when selecting a transformer for a particular use.

Methods of Transformer Cooling

The wasted energy in the form of heat generated in transformers because of unpreventable iron and copper losses must be carried away. This is necessary to prevent excessive rise of temperature and injury to the insulation around the conductors. The cooling method used must be capable of maintaining a sufficiently low average temperature. It must also be capable of preventing an excessive rise in any portion of the transformer, and the formation of hot spots. This is accomplished, for example, by submerging the core and coils of the transformer in oil, and allowing free circulation for the oil (see Fig. 4–9).

Since oil may be a fire hazard, inert fluids, known as askarels, are sometimes used in place of the oil. These special fluids may be harmful to personnel handling them as well as to the varnishes generally applied to the

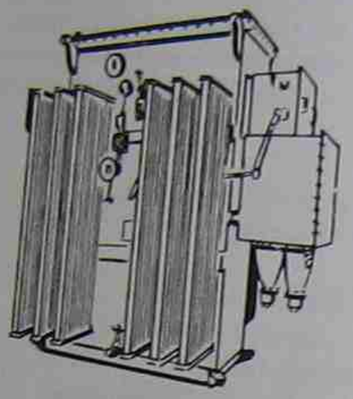


Fig. 4–9 Oil-cooled transformer

insulation of the coils. Extreme care should be exercised in handling to prevent contact with eyes or open cuts and wounds.

Some of the oils and askarels in use have been found to contain polychlorinated biphenyl (PCB), considered a teratogen. Steps have been taken to eliminate the hazard by replacing these oils and askarels with safer oils and other coolants. It also requires disposal of these materials as "regulated hazardous wastes" under the federal Toxic Substances Control Act (TSCA). In some instances this is accomplished by replacing existing transformers. In other instances, the contaminating fluid may be drained at the site. The transformer is flushed several times with special contaminant-absorbing fluids that draw the PCB from the transformer core and parts. The drained fluids are then replaced with PCB-free oil or other fluids.

In clean, dry, indoor locations, an open, dry-type air-cooled unit can be used. For outdoor (and indoor) use, a sealed, dry unit can be employed (see Fig. 4-10).

Some transformers (fluid filled or dry) are cooled by other means. These include forced air or air blast, a combination of forced oil and forced air, and in some special applications, water cooling.

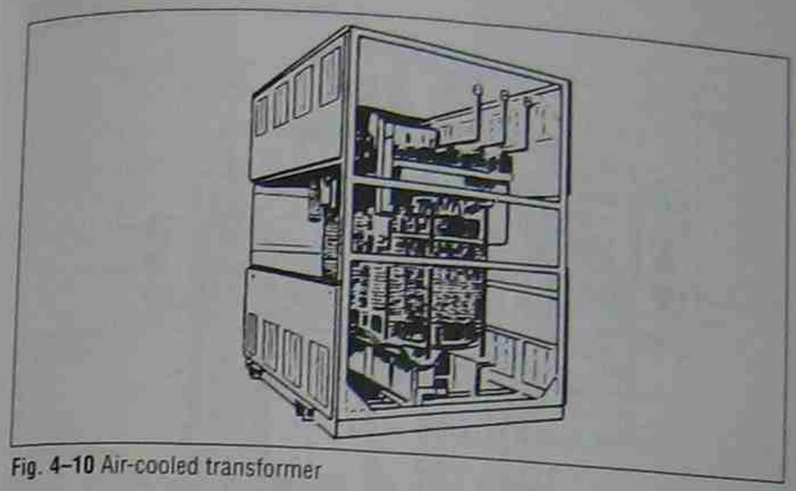


Fig. 4–10 Air-cooled transformer

Related Substation Equipment

Busbars

Busbar (or bus, for short) is a term used for a main bar or conductor carrying an electric current to which many connections may be made.

Buses are merely convenient means of connecting switches and other equipment into various arrangements. The usual arrangement of connections in most substations permits working on almost any piece of equipment without interruption to incoming or outgoing feeders.

Some of the arrangements provide two buses to which the incoming or outgoing feeders and the principal equipment may be connected. One bus is usually called the "main" bus and the other the "auxiliary" or "transfer" bus. The main bus may have a more elaborate system of instruments, relays, etc. associated with it. The switches that permit feeders or equipment to be connected to one bus or the other are usually called "selector" or "transfer" switches. As shown in Figure 4-11, busbars comes in a variety of sizes and shapes.

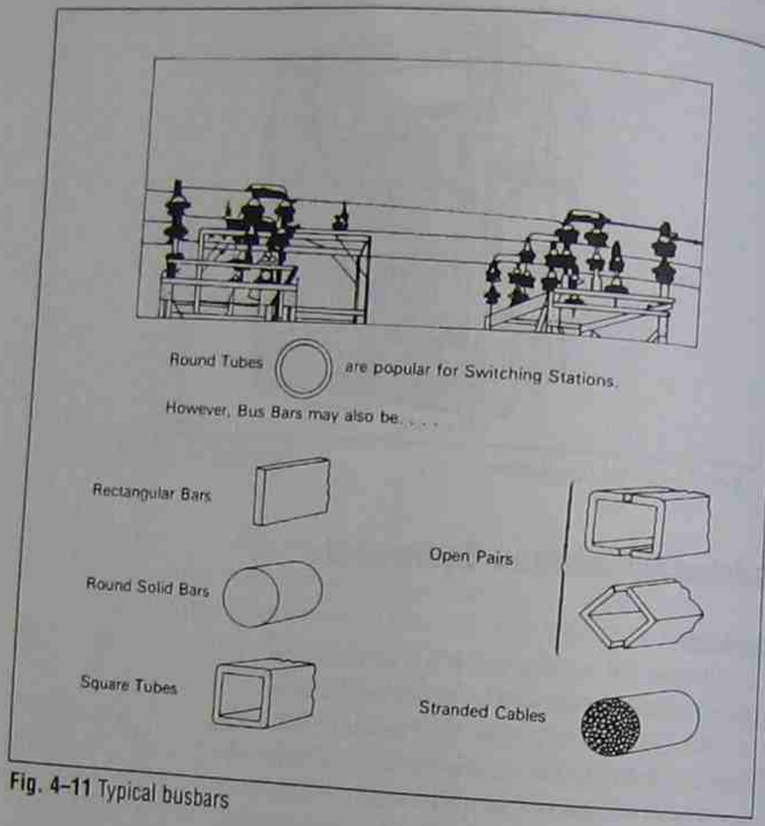


Fig. 4–11 Typical busbars

Regulators

A regulator is really a transformer with a variable ratio (see Fig. 4-12). When the outgoing voltage becomes too high or too low for any reason, the apparatus automatically adjusts the ratio of transformation to bring the voltage back to the predetermined value. The adjustment in ratio is accomplished by tapping the windings, varying the ratio by connecting to the several taps. The unit is filled with oil and is cooled much in the same manner as a transformer. A panel mounted in front of the regulator contains the relays and the other equipment that control the operation of the regulator.

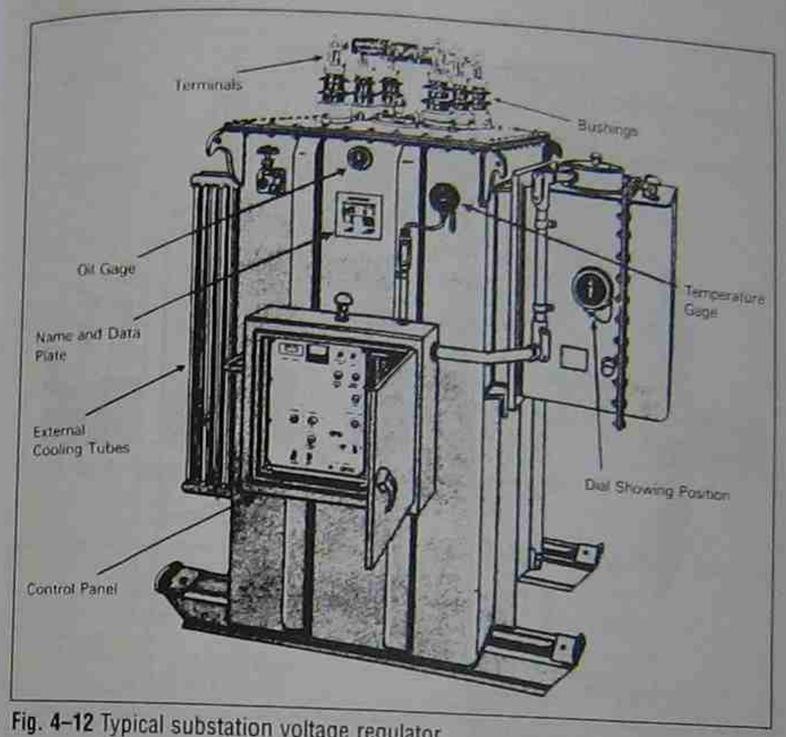


Fig. 4–12 Typical substation voltage regulator

Circuit Breakers

In past years, oil circuit breakers (see Fig. 4-13) were used to interrupt load or "fault" current by making or breaking electrical contact. The oil served to quench the arc as the contacts opened. Transmission breakers are designed to operate very fast as compared to distribution circuit breakers. Usually, transmission circuit breakers operate automatically through relay protection arrangements, or manually by remote control from a nearby control panel in the substation. They can also be operated from a remote location by communication with a power control center.

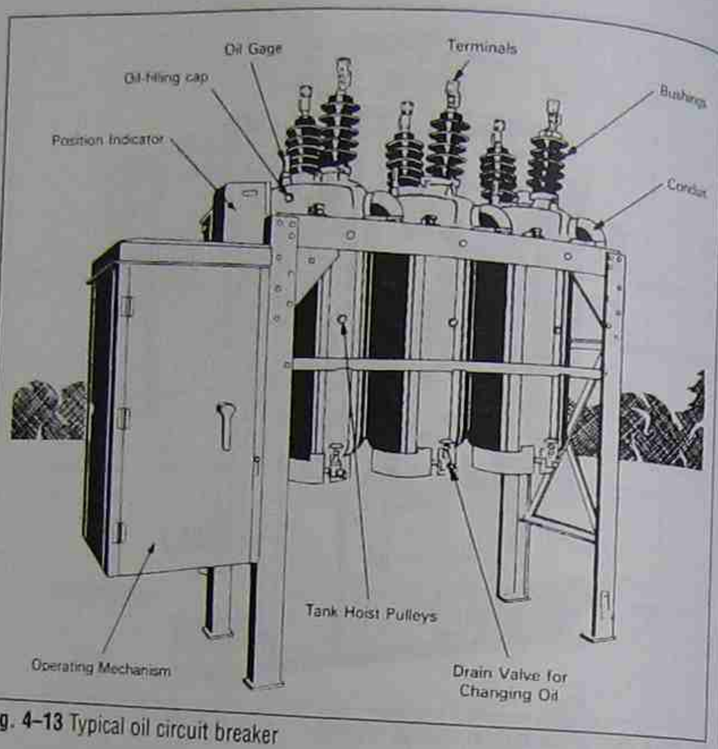


Fig. 4–13 Typical oil circuit breaker

Air Break and Disconnect Switches

Some switches are mounted on an outdoor steel structure called a rack (see Fig. 4-14 and Fig. 4-15), while others may be mounted indoors on the switchboard panels. They are usually installed on both sides of a piece of equipment to deenergize it effectively for maintenance.

Instrument Transformers

When values of current or voltage are large, or when it is desired to insulate the meter or relay from the circuit in which they are to operate, an instrument transformer is used.

In measuring current of high value, a current transformer (CT) is used (see Fig. 4-16). The ratio of transformation reduces the high-current circuit, which in this case is the primary of the transformer, to a smaller current in the secondary connected to the ammeter or relay.

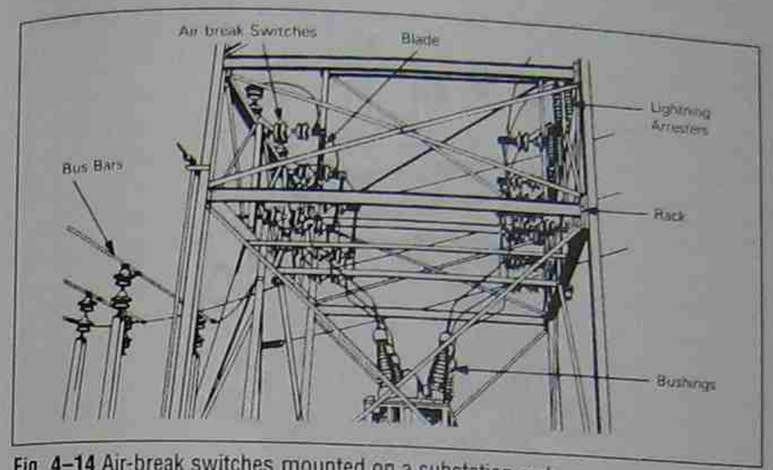


Fig. 4–14 Air-break switches mounted on a substation rack

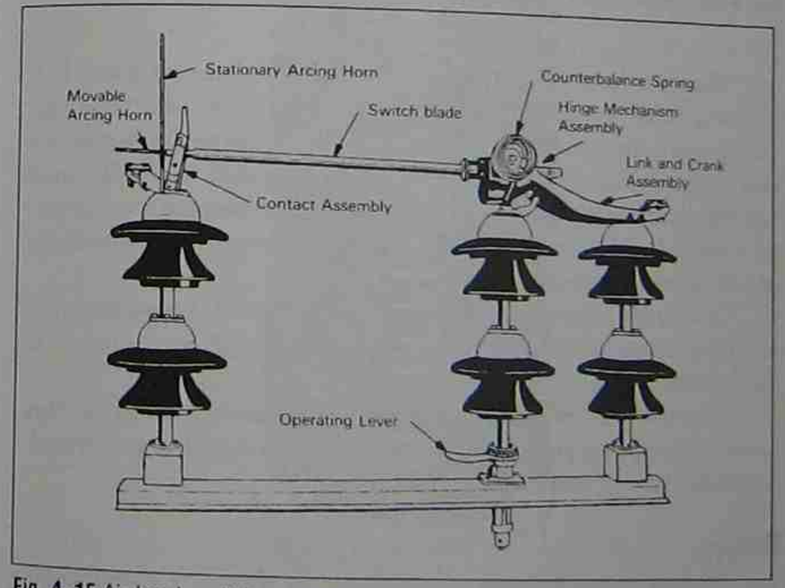


Fig. 4–15 Air-break switch assembly

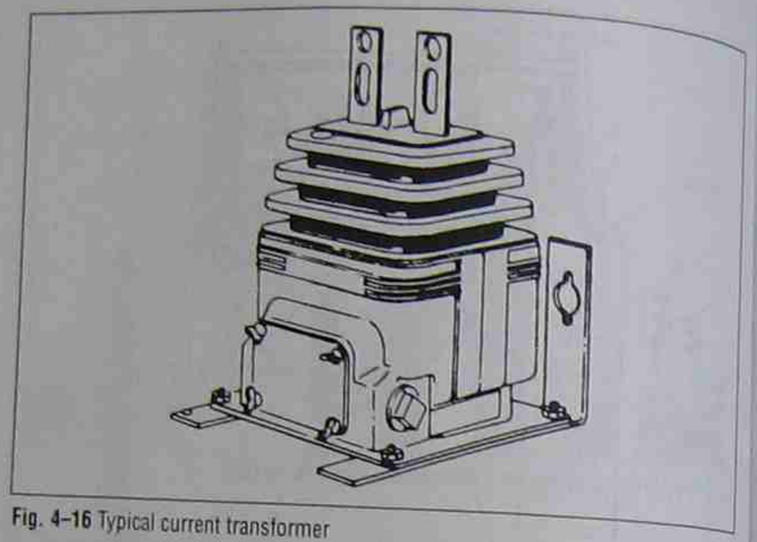


Fig. 4–16 Typical current transformer

Because of the high turn ratio of the current transformer, a very high (and very unsafe) voltage may exist at the secondary terminals with the high voltage side energized and the secondary open at the terminals. As soon as a load (instruments or relays) is connected to the terminals the voltage drops very rapidly. For safety reasons the terminals should always be short-circuited when no loads are connected. Loads are first connected before the short-circuiting device is removed.

Similarly, a potential transformer (PT) (see Fig. 4-17) has a fixed ratio of primary to secondary voltage. The secondary terminals are connected to the voltmeter or relay circuit.

Instrument transformers differ from power transformers in that they are of small capacity and are designed to maintain a higher degree of accuracy under varying load conditions.

Relays

A relay is a low-powered device used to activate a high-powered device. In a transmission or distribution system, it is the job of relays to give the tripping commands to the right circuit breakers.

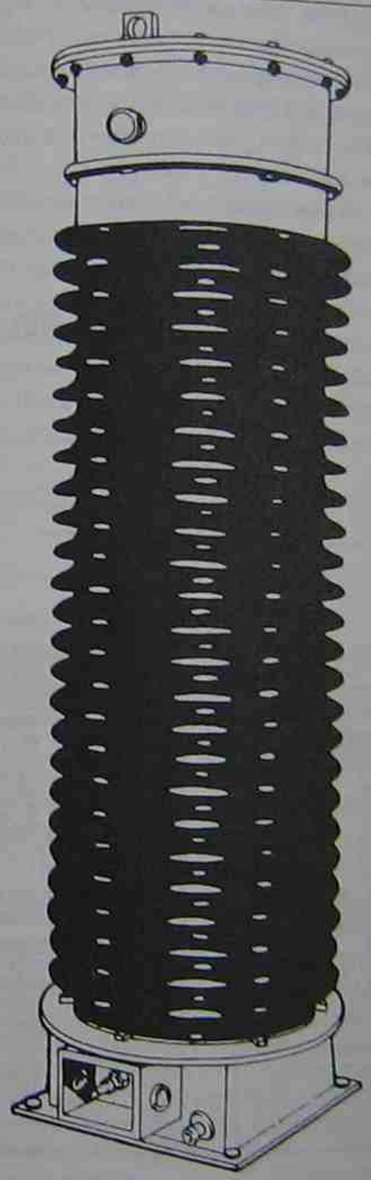


Fig. 4–17 Typical potential transformer

The protection of the lines and equipment is of paramount importance and is usually accomplished by the opening of circuit breakers automatically actuated by relays. In general, it is more important to provide protection for the components of a transmission system than on a distribution system. Greater blocks of load may be affected and resultant damage to lines and equipment may be more costly.

Relays are used to protect the feeders and the equipment from damage in the event of fault. In effect, these relays are measuring instruments, but equipped with auxiliary contacts that operate when the quantities flowing through them exceed or go below some predetermined value (see Fig. 4-18). When these contacts operate, they in turn actuate mechanisms that usually operate switches or circuit breakers, or in the case of the regulator, operate the motor to restore voltage to the desired level.

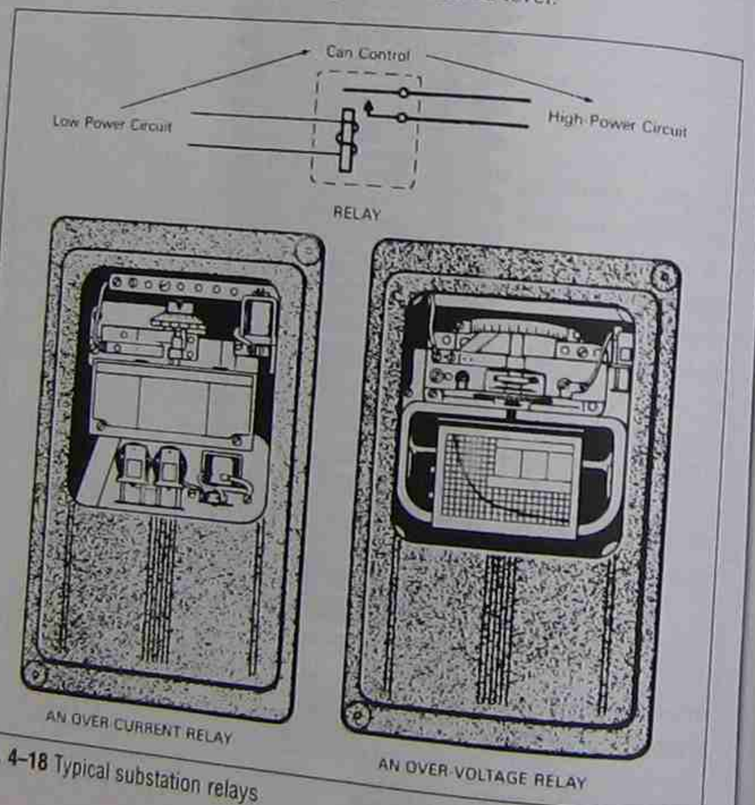


Fig. 4–18 Typical substation relays

With the solid-state electronic technology currently available and associated computer development, the relay-protection system has become more flexible, reliable, and adaptive to changing conditions than was possible with electromechanical relays. System Control and Data Acquisition (SCADA) systems, coupled with improved relay technology and computer information processing, are valuable tools to utilities. They provide system operators with the ability to control and coordinate the complex power systems while adjusting to competition transactions, open access to transmission, and the growth of independent power producers.

Bus Protection Differential Relaying

In providing protection against faults or buses, current supplied to the bus is measured against current flowing from it (see Fig. 4-19). These should be equal (with slight tolerances). When a fault develops on such a bus, this balance is disturbed, and a relay will operate, usually clearing both incoming and outgoing feeds from the bus. This is known as differential relaying.

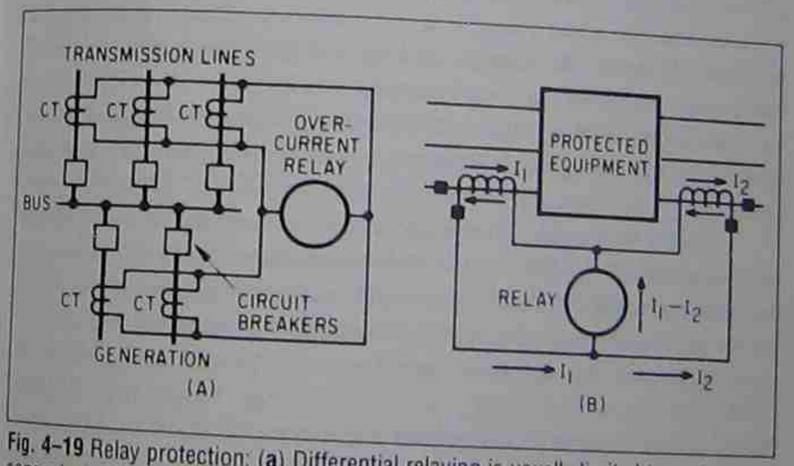


Fig. 4–19 Relay protection: (**a**) Differential relaying is usually limited to equipment concentrated in one area due to the large numbers of control wires between sensing devices or current transformers; (**b**) A difference in current on either side of the protected equipment, due to a fault in the protected equipment, will be detected by current transformers and will pass through the relay actuating coil ($I_1 - I_2$). When $I_1 = I_2$, no current passes through the relay.

Transmission Line Protection

Relay Protection

When a fault occurs on a transmission line, from whatever cause, it is imperative that the line be deenergized quickly for safety reasons. This is accomplished by the opening of circuit breakers at each of its terminals which are actuated by relays. The relays contain a movable element that is actuated by the current flowing through it. The movable element makes or breaks one or more sets of contacts. These, in turn, activate the mechanisms that operate the circuit breakers.

The minimum value of the current that actuates the relays is predetermined for the basic overcurrent relay. When an additional element is added that will actuate the relay when the direction of current flow is opposite to the normal flow, the relay is termed a directional relay. When the movable element is actuated by a difference in the value of the current flowing into the protected line or equipment and that away from it, the relay is called a differential relay. Refinements in the applications of the currents flowing in the relay result in relays sensitive to other features of line and equipment operation. These are discussed more fully in a companion book, *Electrical Transformers and Power Equipment* (Pansini, 1988).

Applications of such protective relays are shown in Figure 4-20 for typical lines emanating from a generating station supplying one or more substations.

When a fault occurs on a transmission line near one of its terminals, the greater part of the fault current will flow through the circuit breaker of the nearest terminal. This will cause the circuit breaker to operate first, making the other end supply the fault current until the circuit breaker farthest from the fault operates somewhat later. The relatively much longer period in which fault current flows may cause severe damage. Hence, it is desirable that the circuit breakers at both ends of a faulted transmission line be opened simultaneously. This is especially true in the case of rather long transmission lines.

Pilot Protection

The simultaneous opening of circuit breakers at the terminals of transmission lines may be accomplished by means of a communication link between the circuit breakers involved.

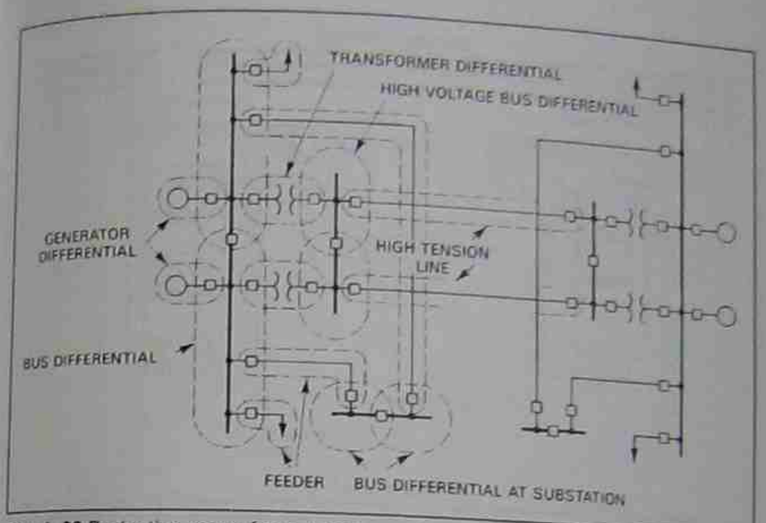


Fig. 4–20 Protective zones for generators and outgoing high-voltage transmission lines (*courtesy Westinghouse Electric Company*)

This link may consist of physically separate pilot wires. Two schemes employing overcurrent relays at each end are shown in Figure 4-21a and Figure 4–21b. A scheme employing differential relays at one end is shown in Figure 4-21c. All of these employ three to six pilot wires. One scheme employing only two pilot wires, polyphase directional relays at each end, and a direct current source is shown in Figure 4-21d.

Another more popular method requiring only two pilot wires employs an AC source and special relays. These combine the currents in each of the current transformers into a single-phase voltage that is compared to a similar quantity from the opposite end of the line. A simplified circuit is shown in Figure 4-22.

Often pilot wires are leased, adding to the cost of such systems. Moreover, for positive and effective operation, the systems have a practical limit, usually about 10 miles. For longer lines, carrier pilot relaying and microwave relaying systems are employed.

Carrier Pilot Relaying

In this type of protection, the pilot wires are replaced by the transmission line conductors themselves, with a high-frequency current (50–200

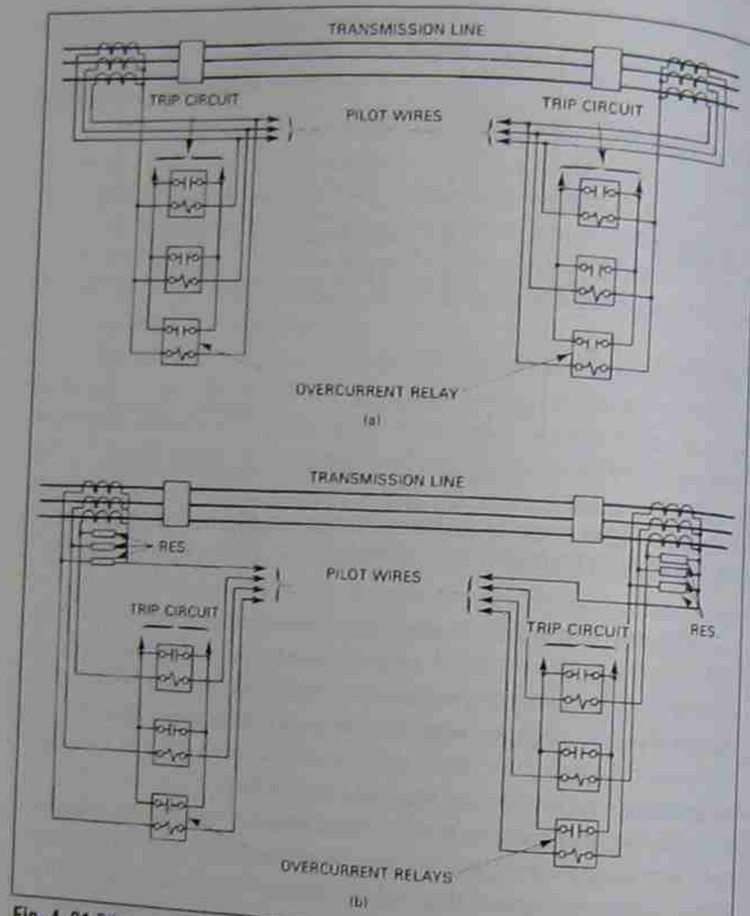


Fig. 4–21 Pilot wire schematic: (**a**) circulating-current pilot wire schematic with load currents and through fault currents circulating over pilot wires; (**b**) balanced-voltage pilot-wire schematic with load currents and through fault currents, producing equal opposing voltages at line terminals; (*courtesy Westinghouse Electric Company*)

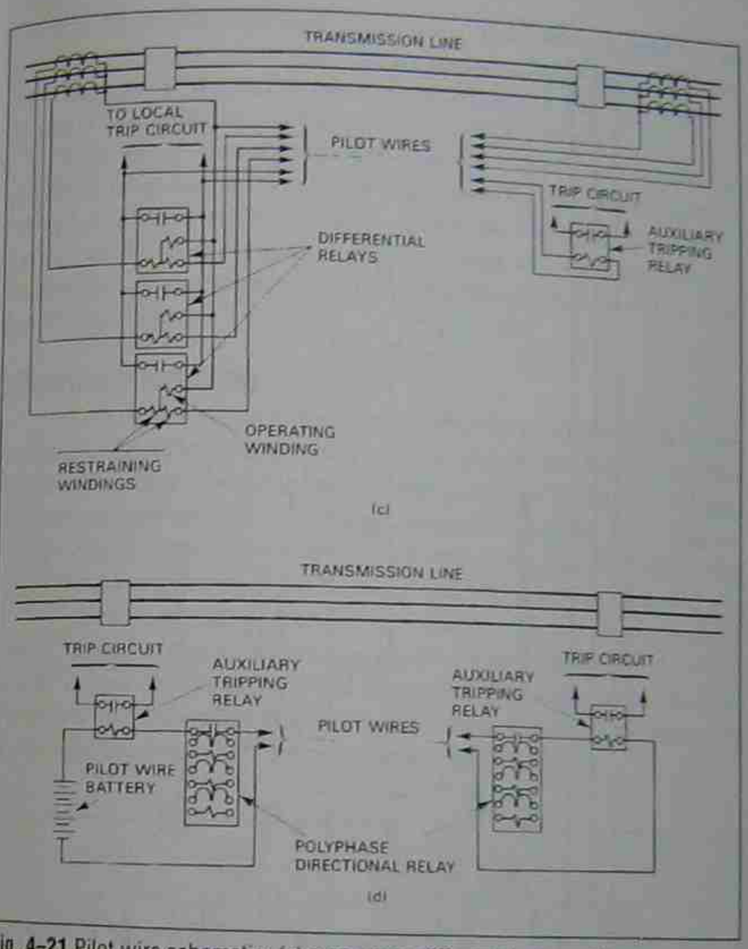


Fig. 4–21 Pilot wire schematic: (**c**) percentage differential relays pilot-wire schematic; (**d**) directional comparison pilot wire schematic using DC over a pair of wires (connections a–c omitted for simplicity)(*courtesy Westinghouse Electric Company*)

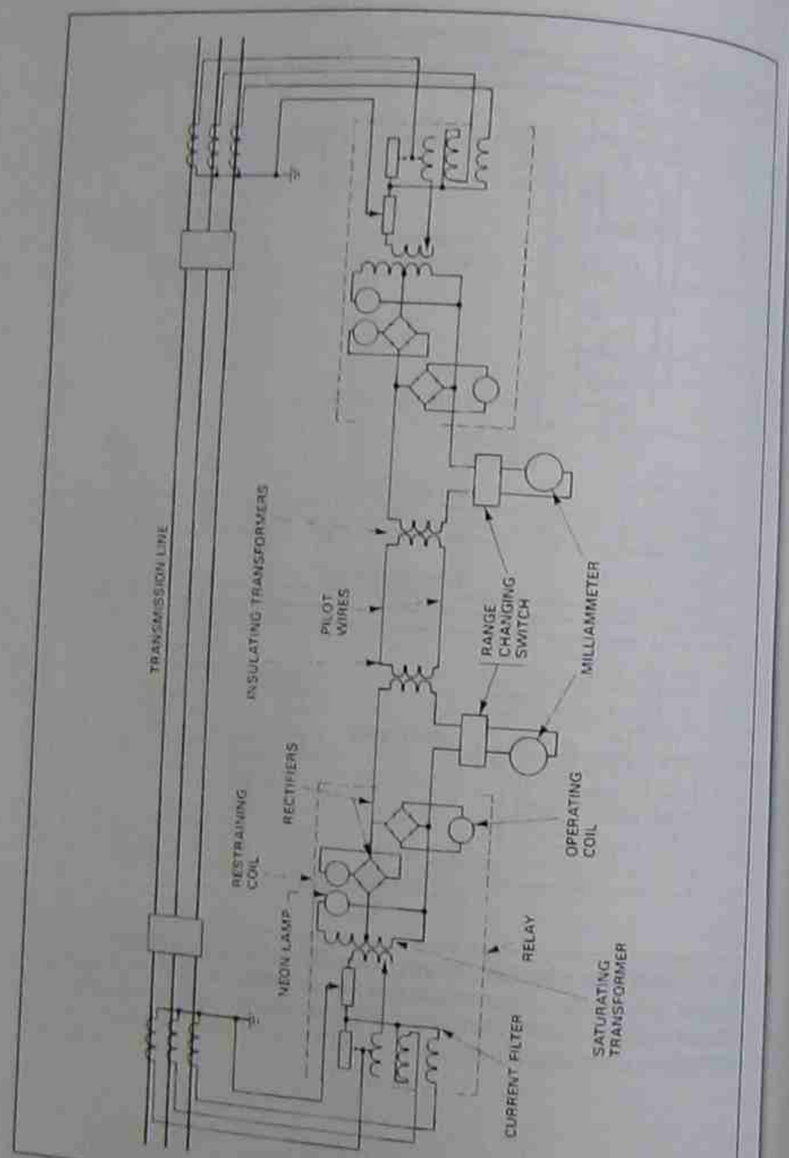


Fig. 4–22 Alternating current pilot wire schematic using special relays (*courtesy Westinghouse Electric Company*)

kilocycles per second) superimposed on them. A simplified diagram and an installation at one end of the terminals are shown in Figure 4-23 and Figure 4-24, respectively. The carrier signal normally operates the relays in such a manner as to keep the circuit breakers in a closed position.

When the transmission line is faulted, the carrier signal is interrupted, and the relays operate to open the circuit breakers. The system functions positively and effectively for several hundred miles. The carrier channel may also be used for other purposes; e.g., telemetering and supervisory controls that operate on coded impulses, for telephone communication, and for other unrelated business.

Microwave Relaying

In microwave relaying, the pilot systems are transmitted over microwave radio channels. This system is not subjected to line faults, and it may also accommodate several other separate functions. Because the transmissions are affected by line-of-sight limitations, several units may be required for long and tortuous lines. The intermediate units receive their signals and retransmit them to the next unit (referred to as *relay stations*).

Generally, the pilot schemes operate to keep the circuit breakers closed. When the line is faulted, the signals are interrupted, and the relays operate to open the circuit breakers. Similarly, if the pilot systems, including carrier and microwave systems, fail for any reason, the circuit breakers open to deenergize the lines and the transmission system "fail-safe."

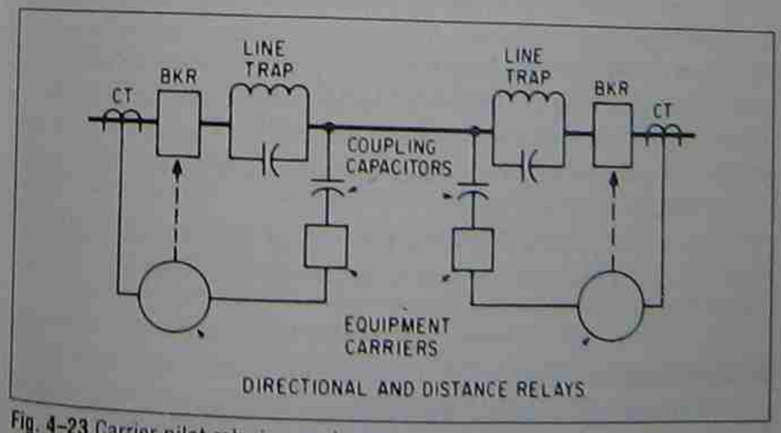


Fig. 4–23 Carrier pilot relaying equipment

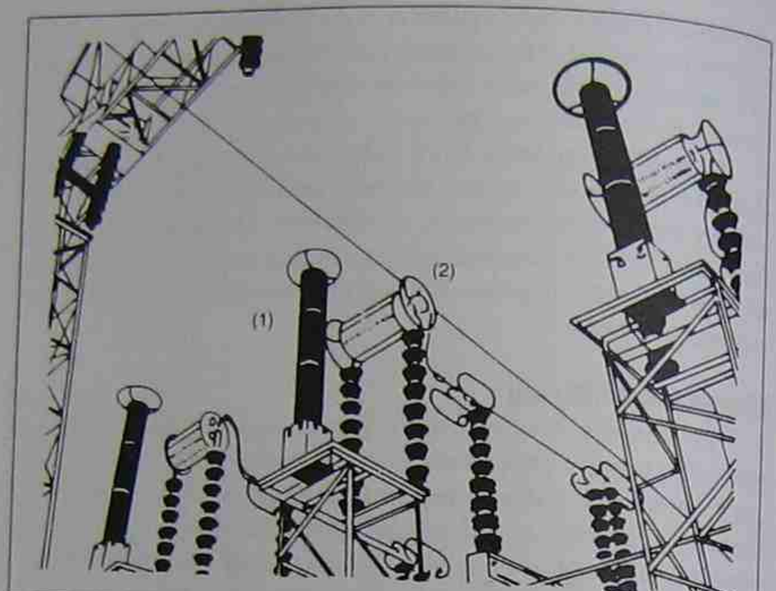


Fig. 4–24 Installation of the coupling capacitor (**1**) and the line trap (**2**) on a 345-kV transmission line

Ground Relay

Other schemes measure the flow of so-called ground current. In a transmission line, the currents flowing in each of the conductors are usually fairly well balanced in magnitude. The return or ground conductor carries little or no current. By measuring this directly, or by measuring each conductor and determining the difference, this ground current can be made to actuate relays when it exceeds certain predetermined values. Other more sophisticated schemes are sometimes used, but generally they employ one or more of the described basic ideas.

Figure 4-25 shows a relay using ground fault detection and illustrates the ability of this protection scheme to discriminate between load current and fault current.

Voltage Surges

Voltage surges can occur from lightning, switching, or fault conditions. Whatever the source, it is necessary to consider the effects not only on

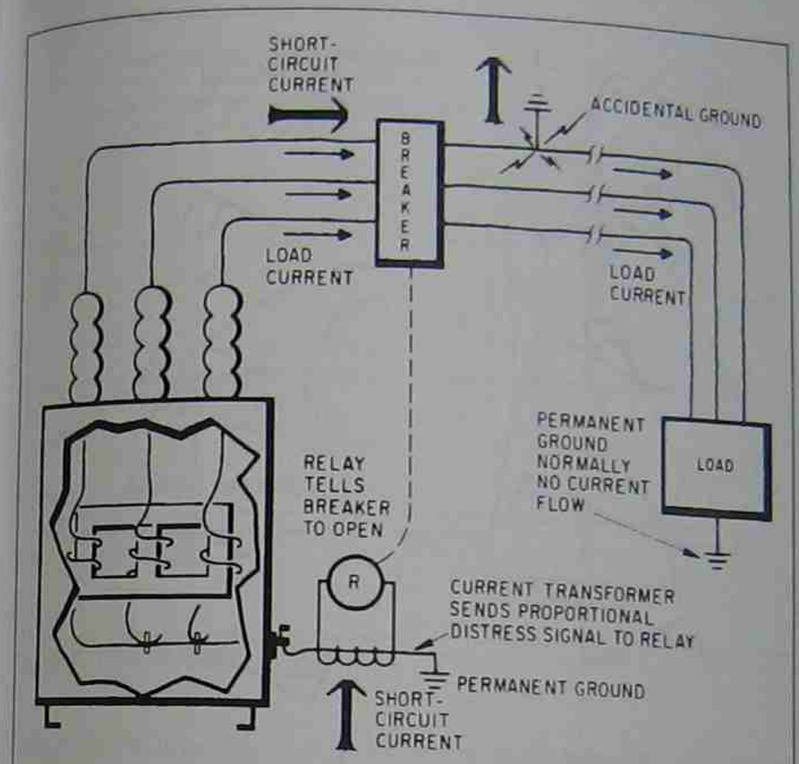


Fig. 4–25 Ground relaying

the transmission lines themselves, but also on the equipment that may be connected to them. These include switches, circuit breakers, transformers, generators, buses, regulators, and any other device that may be connected to them. Generally, these are situated at generating stations and substations. Much of this equipment is similar to and operates in the same manner as that found in distribution substations; however, several are of greater importance for the transmission system.

Figure 4-26 is a graphical representation of a traveling wave on a transmission line showing two of several possibilities of voltage surges occurring at points of discontinuity. (These could be an open switch, a transformer bank, or change of overhead to underground.) In (A), the characteristics of the point of discontinuity are such that the reflected wave is superimposed in

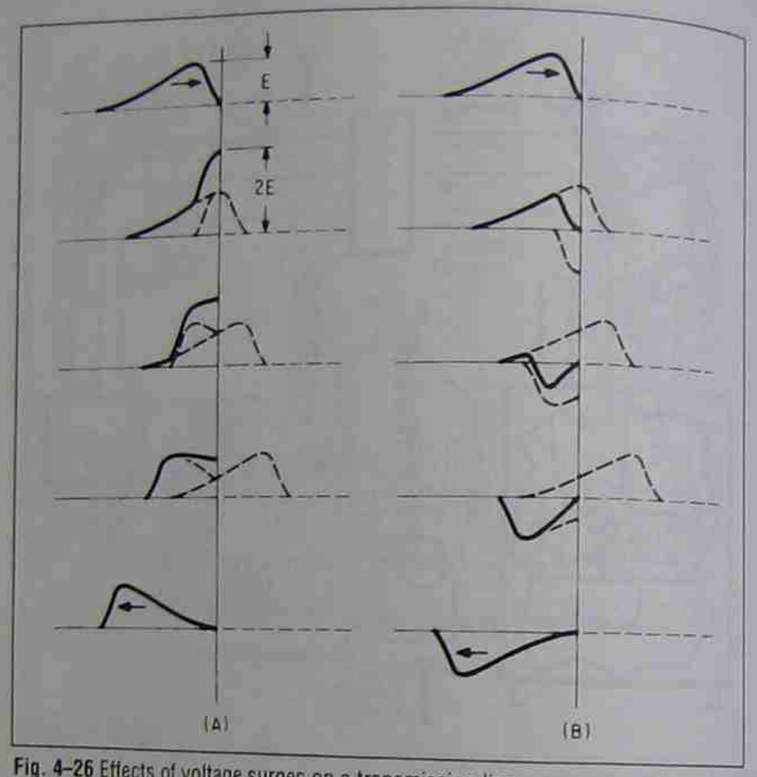


Fig. 4–26 Effects of voltage surges on a transmission line

the original surge voltage wave. The crest voltage is double the original value at the point of discontinuity. In (B), the characteristics of the point of discontinuity are such that the reflected wave is subtracted from the original wave.

Basic Insulation Level (BIL)

Since the operating voltages in a transmission system are relatively high, special attention is given to the insulation associated with the several parts of the system. This is true both in the lines as well as in the stations. The insulation here has to withstand not only the normally applied operating voltages, but the surge voltages explained later (see Fig. 4-27). Since

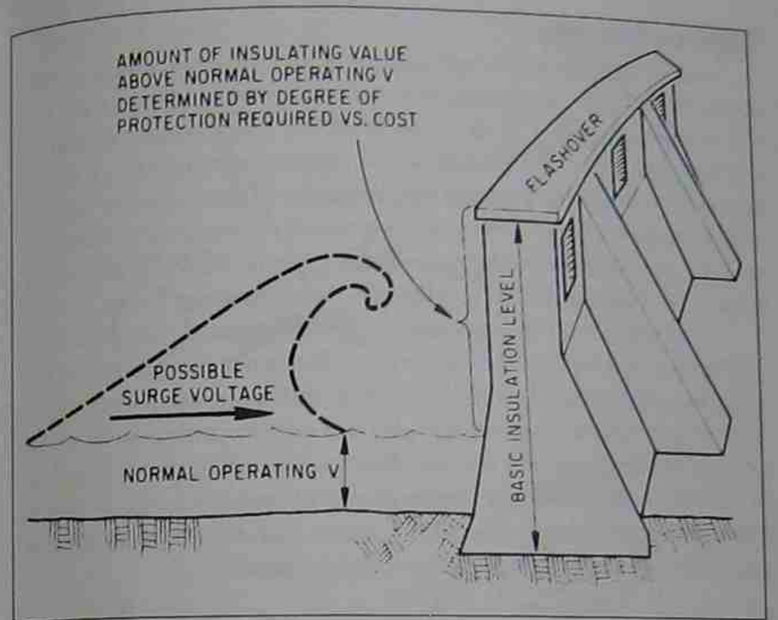


Fig. 4–27 The basic insulation level (BIL)

such insulation is expensive, it is desirable not to "overinsulate" any portion of the system unnecessarily. Hence, the insulation of the several components of the entire system must be coordinated, and a level of insulation to be provided decided upon.

Levels of insulation that will safely sustain the surge voltages, known as basic insulation levels (BIL), have been set up for electrical apparatuses, such as transformers, circuit breakers, and switches. These designated minimum levels may be from 2–3-1/2 times the normal operating voltage, depending on the degree of reliability desired. The minimum insulation level should prevail under wet conditions, and in general, should be the same for line insulation as for apparatus insulation.

At some point, usually at the bushing, the insulation value is made deliberately at the lowest value. This is arranged so that if a failure occurs, it will occur at a point that is readily accessible for repair or replacement.

Short-Circuit Duty

Again, because of the high voltages employed, when a fault or short circuit occurs on a transmission line, the amount of current that will flow will be inordinately great. This current flows not only through the transmission line conductors, but through all the apparatuses connected to it. This high-magnitude current produces magnetic fields of great intensity with corresponding great forces. These forces tend to pull conductors apart and damage lines and equipment. Hence, equipment, particularly circuit breakers, must be built rugged enough to withstand these disruptive forces.

The measure of the ruggedness of the equipment is referred to as the interrupting capacity or "short-circuit duty." It is generally expressed in kVA (thousand volt amperes) or mVA (million volt amperes). Hence, circuit breakers and other equipment are rated not only for their normal voltage and current carrying ability, but also their so-called short-circuit duty (e.g., 69 kV, 500 A, 500 mVA). As transmission grids become larger, with more generation interconnected, the fault currents and associated short-circuit duty become larger, making equipment more expensive.

Stability

When faults occur on a transmission grid supplied by two or more generators (see Fig. 4-28), the current flow to the fault will be proportioned to the distance (electrically) of the several generators. Thus, the generator closest to the fault will supply the greatest share (see Fig. 4-28a). As these heavy currents are imposed on the several generators, it will cause them to slow down, but not equally. Again, the one supplying the greatest share of current will slow down the most.

Consequently, these generators will no longer operate "in step." The one that slowed down least will attempt now to supply the other generators connected to the grid, which are now "bucking" it. This will cause it to slow down, and the process reverses. A rocking back and forth effect between generators will ensue. The generators then act very much as if they are connected together mechanically through a spring (see Fig. 4-28b).

If the fault is removed in time, this rocking effect will subside and the generators will snap back into step. If not, the effect will increase progressively until the current supplied by some generator exceeds its protective relay setting, and it will be disconnected from the grid. If the fault persists,

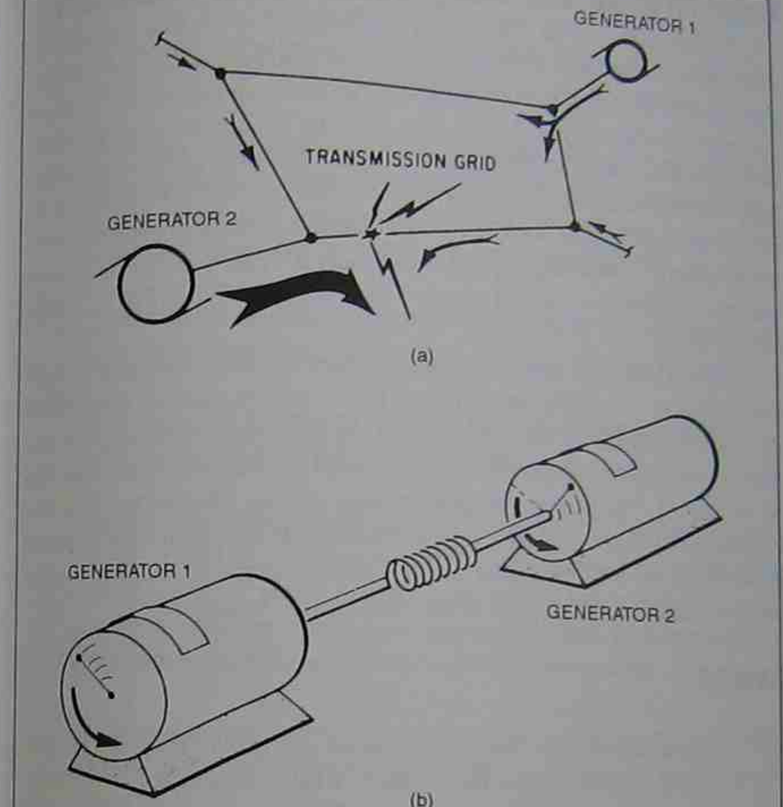


Fig. 4–28 Effects of faults on a transmission line connected to more than one generator. (**a**) Short circuit in a transmission grid. Generator 2 supplies a major portion of the short circuit current. This causes Generator 2 to slow down. (**b**) Generator 1 tries to assist. The effect is similar to a spring construction between generators, tending to keep them in step.

similar effects will cascade to other generators until all the units are disconnected, and a "blackout" results. This effect is generally referred to as a lack of stability or an unstable condition. Settings on protective relays and devices are designed to switch out the faulted section of the system as rapidly as possible, restoring the rest of the system to normal.

Cogeneration and Independent Power Producers

Large industrial or commercial consumers may sell their excess energy to utility companies. This can occur if the industrial or commercial consumer has an excess of steam energy that can be converted into electricity, or can generate electricity and has excess capacity. In addition to cogeneration installations, the independent power producer (IPP) has become an increasingly significant factor to the transmission system. The IPP constructs an electric generating station apart from the stations owned and operated by the utility system. Generating capacity from sources other than investor-owned and government systems has grown from 19,237 MW in 1970 to 55,188 MW in 1992.

This supply of power is accomplished by interconnecting the IPP installation to the utility transmission lines, usually through a substation installation. They must not only provide the necessary equipment and protective devices, but must coordinate them with the utility to which they may be connected. The power they put out may also be wheeled to other consumers or utilities. In any case, this portion of their operation must be placed under the control of the utility or pool system operator. Such installations may be considered as another of the transmission substations.

Review

- Substations receive energy transmitted at high voltage from the generating stations, reduce the voltage to a value appropriate for local use, and provide facilities for switching. They also provide points where safety devices may be installed to disconnect circuits or equipment in the event of trouble.

- Substations are generally located so that they will be as near as possible to the load center of the areas that they are intended to serve. Availability of land, cost, local zoning laws, future load growth, and taxes are some of the many factors that must be considered.

- Substations usually have two or more incoming supply transmission lines for reliability. Many of these stations are operated automatically with control circuitry connected back to an operating center.

Substations may have an operator in attendance part or all of the day, or they may be entirely unattended. In some unattended substations, the equipment function is monitored remotely. If an alarm is signaled, a "roving operator" will be dispatched to operate that station.

- The voltage of the incoming supply is changed to that of the outgoing subtransmission of distribution feeders by means of a transformer. The nameplate on a transformer gives all the pertinent information required for the proper operation and maintenance of the unit.

- A busbar is a main bar, or conductor, carrying an electric current to which many connections are made.

- A regulator is a transformer with a variable ratio that maintains a transmission voltage at the specified level.

- Circuit breakers allow interrupting a circuit while current is flowing through it. Oil circuit breakers are the most common, but another type, called an air circuit breaker, puts out the arc by a blast of compressed air. Another type has its contacts enclosed in a vacuum or a gas, which tends to keep the arc from maintaining itself.

- Instrument transformers are used to measure large currents or voltages and to insulate a meter or relay from the circuit in which they are to operate.

- Relays provide protection for the components of a transmission system by providing tripping commands to the circuit breaker or breakers in an overloaded circuit.

- Differential relaying provides protection against faults on buses by comparing current supplied to the bus with current flowing from the bus. The currents should be approximately equal. A fault on a bus creates an imbalance that triggers a relay to clear both incoming and outgoing feeds from the bus.

- In carrier relaying, input and output currents are measured at both ends of a line. A pilot wire, microwave transmission, or other means are used to transmit these quantities to relays at both ends to clear the lines in trouble. Sometimes, the conductors themselves are used to transmit these signals.

- In ground relaying, ground current that is produced when the current flowing in the conductors is unequal can be made to actuate relays when it exceeds certain predetermined values.

- Basic insulation level (BIL) is the level of insulation that will safely sustain surge voltages. BIL must be considered when selecting devices such as transformers, circuit breakers, and switches. Minimum levels designed may be from 2–3-1/2 times the normal operating voltage, depending on the degree of reliability desired.

Study Questions

1. What is the function of a transmission substation? What other purposes may it serve?
2. What are some features of transmission substations?
3. What important factor influences the location of a transmission substation? What other factors are also considered?
4. What pieces of equipment may be found in a transmission substation?
5. What is the function of a substation transformer? Of a regulator?
6. What is the function of a circuit breaker? What types are there? How are they rated? Show a typical rating.
7. Why is it more important to provide protection for components of a transmission system than for a distribution system? How is this accomplished?
8. What are the functions of air-break switches and disconnects?
9. What is a relay? Describe three relay applications in transmission systems.
10. What is meant by the BIL of a piece of equipment?

5

Extra-High Voltage and Direct-Current Transmission

Increased Demand and Challenges

Increases in transmission voltages are due to many factors, but principally are the result of the need to provide ever-greater amounts of power over the same rights-of-way. This need for higher transmission voltages increases with increases in the cost of land (and its clearing) and decreased land availability. As power systems continue to be interconnected to provide greater economy and service reliability, that need becomes more imperative.

While such an increase in the voltage of a transmission line appears simple, it creates problems involving insulation, lightning protection, switching, and losses. Equipment such as circuit breakers, transformers, surge arresters, reactors and capacitors, towers and supports, and conductors (along with most other items of material) are affected. Corona losses, skin effect, and the effects of moisture, dirt, smog, and salt on insulators must be considered with other factors.

Audible noise problems, as well as problems with radio, television, and other communications, also tend to increase with overhead higher voltage transmission lines. Questions also are raised as to the effect of such

high-voltage lines on human, animal, and plant life. These concerns apply as well to the effect on structures, vehicles, and other organic and nonorganic objects located or operating in their vicinity.

Undergrounding high-voltage transmission lines proves technically feasible but economically unfeasible, except in a few instances. (For example, this might be used for very short distances within such cities as New York.)

Direct-current (DC) transmission for long overhead or short underground or underwater distances is generally limited to intersystem ties of 250–1,500 MW capacities.

Operations

The capacity of transmission lines may be limited so that its outage or nonavailability will not inordinately affect the operation of the associated system or grid. This compares to the effect of having a large generator out of service. Further, for overhead lines that constitute the overwhelmingly majority of such lines, the maximum achievable transmission line loading is limited by the right-of-way available. It is evident, therefore, that environmental concerns (including beautification) and the desire for low-cost power are not easily reconciled.

Relationship of Line Capability and Voltage

For a given conductor, that is, a conductor with a fixed electrical resistance, the amount of electricity or current that may be carried by it economically is limited by one of two things. These are:

1. The permissible voltage drop or loss of electric pressure
2. The power loss that represents the heat dissipated from the line

Both must be considered in relation to either the transmission line voltage or total power transmitted. For example, permissible voltage drop may be 10% of the transmission line voltage, or permissible power loss may be 10% of the total power transmitted. Expressed in the form of an equation:

$$\text{transmitted power} = \text{current} \times \text{voltage}$$

or

$$P = I \times E_{ln}$$

where

P is the transmitted power
I is the current
E_{ln} is the line voltage

Then, if the voltage of a line is doubled, the current that will flow for the same power supply will be only half the original current.

Voltage drop and power loss may be expressed as follows:

$$E_{drop} = IR \text{ and } P_{loss} = I^2R$$

where

I is the current
R is the resistance of the conductor
E_{drop} is the voltage drop or voltage loss
P_{loss} is the power loss in the transmission line

With half the current flow, the voltage drop or loss is also halved, and the power loss, with only half the current flow, will be only one quarter the original loss. Conversely, if the power loss can be maintained at its original proportional part, the transmitted power can be quadrupled. The voltage then can be doubled, and the amount of current sent through the same conductor can also be doubled. The power that this conductor now is capable of carrying, represented algebraically (as compared to the original), is:

$$P(\text{orig.}) = I(\text{orig.}) \times E(\text{orig.})$$

$$P(\text{new}) = 2I(\text{orig.}) \times 2E(\text{orig.}) = 4P(\text{orig.})$$

Hence, doubling the voltage of a line will increase its capability 4 times.

Extra-High Voltage

Many economic factors have contributed to the development of higher voltage transmission lines. Basically, the power that a line will carry increases as the square of its voltage increase. If the voltage is doubled, the power capacity is increased 4 times. More specifically, a 345-kV line will carry 9 times the power of a 115-kV line even though the voltage is only 3 times as high. A 765-kV line has 25 times the power capability of a 138-kV line.

When all the factors are considered, the 765-kV line is capable of carrying 4–6 times as much power as a 345-kV line over comparable distances. Put another way, the cost per megawatt of power transmitted is reduced considerably when a higher voltage is used. Tower lines and equipment are very large in size (see Fig. 5-1).

Cost Comparisons

In selecting the voltage of a transmission line, it is essential that the incremental differences in costs of all the other associated equipment be

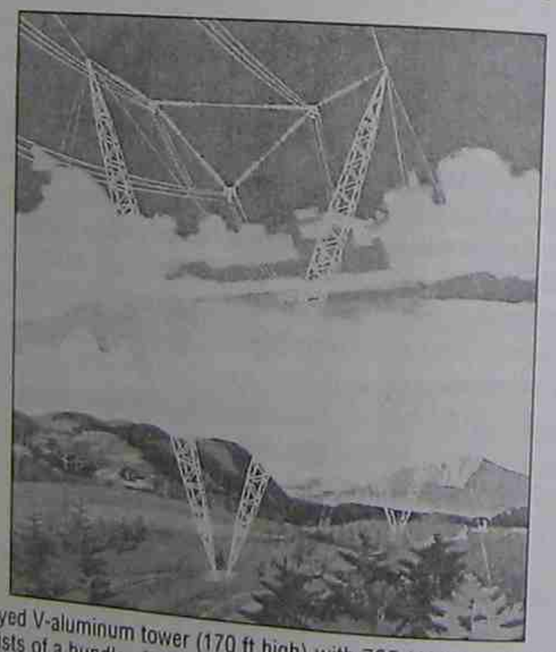


Fig. 5–1 Guyed V-aluminum tower (170 ft high) with 765-kV line; each phase conductor consists of a bundle of four substrands (*courtesy Ohio Brass Company, a subsidiary of Henry Hubbell*)

taken into consideration. These include circuit breakers, transformers, switchgear, lightning protection, structures, buildings, rights-of-way, various control equipment, and measuring devices.

Cost consideration should include annual carrying charges (annual losses of energy from all sources). These are influenced by the different voltages under consideration and must be taken into account. Results should, however, be tempered with practical considerations, such as the availability of skilled workers and potential access problems. It is very important to consider environmental protection, the appearance of the line, and the effect it might have on the community.

Comparisons can be made of costs with alternating-current (AC) systems of similar voltages and load-carrying abilities. While costs of terminals and other associated equipment are essentially the same, line costs can be substantially lower (see Table 5-1).

Mine-Mouth Generation

The use of extra-high voltages makes practical mine-mouth generation (see Fig. 5-2). Here, instead of transporting coal to the generating plant, it is cheaper to generate the power right at the mine and then transport the power by transmission line. Similarly, other remote sources of power, as hydroelectric plants, are made practically available to major consumer centers. Because of insulating material limitations, voltages produced by generators are restricted to about 20 kV. The AC output, however, is readily

Table 5-1 Economic Comparisons for Extra-High Voltage Transmission (in percent)

Equipment for AC Transmissions	450 kV	765 kV	1,000 kV
Circuit breakers/unit	100	200	400
Autotransformers/kVA	100	125	150
Reactors/kVAR	100	120	140
Series Capacitors/kVAR	100	110	120
Line/mile	100	150	210
Equipment for DC Transmission		**±375 kV**	**±900 kV**
Terminals, including rectifiers/kW		200	220
Line/mile*		50	200

*Compared to AC figures.

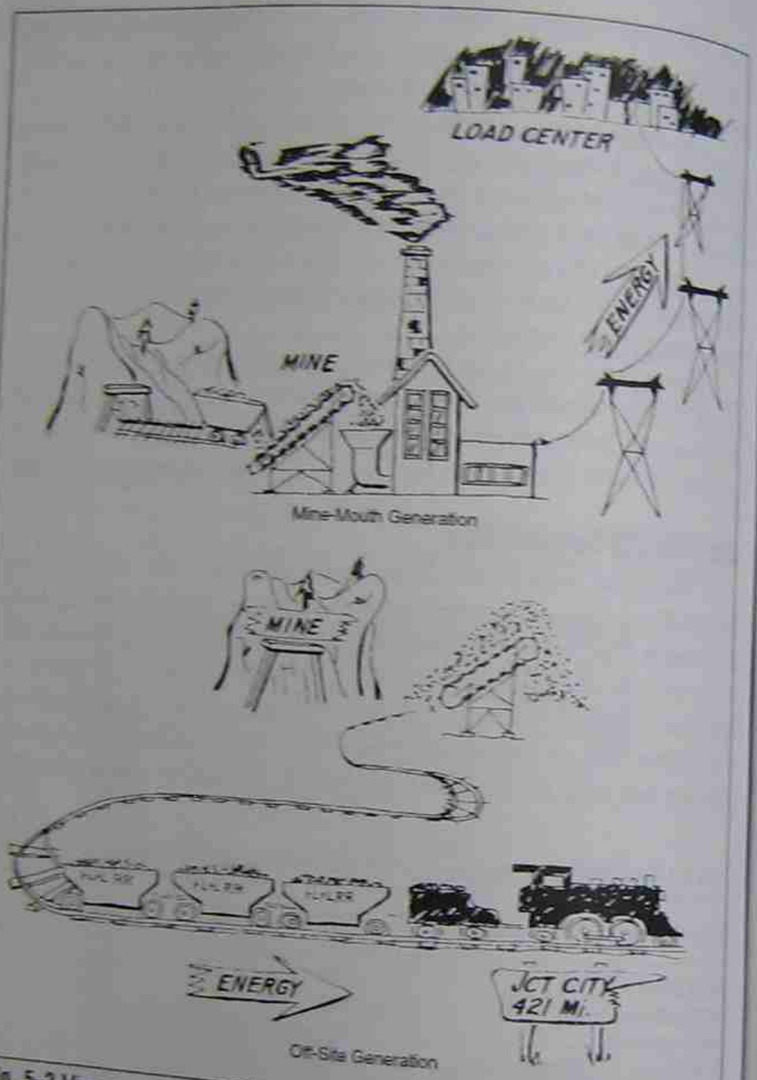


Fig. 5–2 Mine-mouth power generation (power generated at the mine) vs. transportation of coal to generate electricity elsewhere

changed by means of transformers, so the generated voltages are easily stepped up to transmission voltages.

Equipment

Circuit Breakers

Circuit breakers are becoming more complex. Because the higher voltages tend to have longer arcs that persist for longer periods of time during the disconnecting phase of their operation, greater attention is paid to the insulating arc-quenching medium. Use of sulphur hexafluoride (SF_6) gas under pressure has solved the problem of arcing, at the same time providing insulation qualities that are roughly 100 times better than oil. The pressure applied to the gas, however, aggravates the possibility of leakage.

The sudden interruption of current at these high voltages creates voltage surges greater in magnitude than line voltages. These surges not only are applied to the breaker conductors, but travel out along the lines until they dissipate or are bled to ground through surge arresters. The effect of this phenomenon is to require greater insulation to be specified at critical points in the breaker, the lines, and in other equipment that may be connected to them. The interrupting duty of such breakers becomes greater as values of voltage and current become larger, requiring much greater mechanical reinforcement of the component parts. The size of the breaker may be inordinately large.

Transformers, Reactors, Capacitors

Similar problems of higher voltages, surges, and mechanical stresses imposed on component parts apply to these pieces of equipment as to circuit breakers (detailed in previous section). Structural reinforcement of coils, cores, and supports are necessary to withstand the extraordinarily high currents that may flow when faults or short circuits occur anywhere on the line. As no arcs are to be quenched, oil or askarels are satisfactory for insulation purposes. Because of possible voltage surges causing flashover, bushings may be proportionately larger than those for lower voltage equipment.

Lightning or Surge Protection

Voltage surges caused by lightning or switching are more apt to result in flashover across insulator strings and to the tower or support structure. They involve problems of clearances and insulator swing geometrics.

Lightning striking at or near an overhead transmission line creates surges of voltage that travel along the line. This action is the same for all

overhead lines exposed to lightning. Extra-high-voltage transmission lines differ in that the line current that flows in the flashover tends to be much greater because of the greater line voltage. Obviously, this greater current imposes greater stresses on the equipment through which it may flow with possible damage to the equipment. This is especially true of the circuit breakers called upon to interrupt such currents.

Not only are a greater number of lightning or surge arresters installed along the line, but greater effort is made to reduce ground resistances to enable the surge voltage to be dissipated as quickly as possible.

While the voltage surges caused by switching may not be as great as those caused by lightning, the same general conditions result as those described, and the solutions are the same. To aid in reducing damaging flashovers, extra insulators may be added to the strings than would normally be required. The longer string of insulators allows the conductor attached to it to have a greater radius in its sway. This calls for greater clearances of the conductor from the tower or supporting structure. Furthermore, the string must be carefully placed so that the swinging conductor will not make contact with adjacent conductors.

For the principle of operation of surge arresters, the several types, and their application, refer to chapter 2, "Overhead Construction."

Underground Transmission

The capacitance or condenser effect of high-voltage cable absorbs energy and limits the amount of useful energy as well as the distance over which it may be transmitted. To reduce this capacitance effect, compressed gas (sulphur hexafluoride) at 50 pounds per square inch pressure is employed as insulation in extra-high-voltage cables. While satisfactory for this purpose, it introduces problems of maintenance (leakage and repairs). Nevertheless, this form of insulation can withstand the great stresses of high voltages under varying temperature and current loading conditions.

Superconductors

Liquified gas—such as nitrogen circulating within the conductors to maintain extremely low (cryogenic) temperatures—makes possible conductors having very low resistance. For example, if aluminum is cooled to the temperature of liquid nitrogen (-320°F), its electrical resistance is approximately 1/10 the value at normal temperatures. (Its mechanical properties

change at such low temperatures.) However, necessary refrigeration and associated equipment to maintain the liquidity of the gas for the continuous removal of heat requires special manufacture and use of certain materials, resulting in an extremely costly installation.

Certain comparatively rare metals, such as Niobium, if cooled to temperatures approaching that of liquid helium (-425°F), lose all resistance to the flow of direct current. Such cables are termed superconductors, as compared to the cryogenic cable mentioned. The difference is in the temperatures and materials employed. Economically, such cables could become practical, offering the possibility of substantial reduction in cost in the high-power capability range (5,000 mVA and greater).

DC Transmission

Comparison of AC and DC

In a circuit, the maximum voltage permissible is fixed by its insulation. In DC systems, the maximum voltage is applied throughout the entire time the flow of electricity takes place. In AC systems, the maximum voltage is applied only a portion of the time. If the values are averaged (from 0 to maximum and back to 0), it would be found that this average value is 70.7% of the peak value (see Fig. 5-3). Hence, the capacity of a two-wire AC system is limited to only 70.7% that of a two-wire DC system having the same insulation and the same conductor size. This must be considered in order that the insulating value of the insulation not be exceeded.

DC Transmission Features

Many benefits can be realized by using DC for high-voltage transmission. In AC circuits, the effective voltage is 70.7% of the peak value the line carries; in DC circuits, the effective and peak values are one and the same. Hence, for a particular voltage rating, the DC circuit requires only 70.7% of the insulation required by the AC circuit. Conversely, with the same size cables and the same insulators, a DC line can carry about 40% more power. Further, the conductors are not subject to skin effect, although corona discharge continues to be a problem.

Since the circuits are not subject to alternating magnetic fields, no inductance within a conductor or between conductors is generated (except at the moments of energization and deenergization). Hence, voltage and

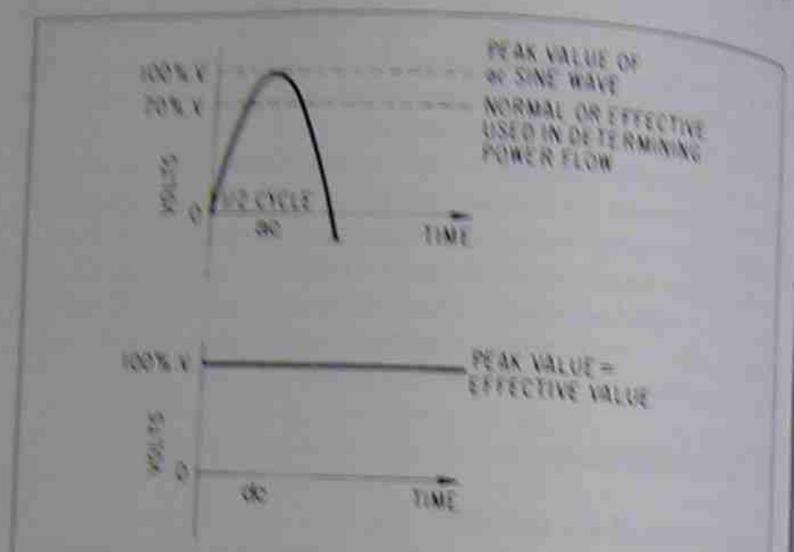


Fig. 5-3 AC vs. DC power transmission. In AC, the peak voltage must be used in calculating the insulation required from conductor to grounded supporting structure. This value is higher than the effective value of the DC system shown at the bottom. The DC system utilizes the maximum voltage to ground to transmit power.

energy losses are reduced. Further, as will be described later, fewer conductors are employed in a DC circuit as compared to an AC circuit. Generally two or three are used in DC as compared to four in AC. In some cases where "ground" is used as a return circuit (such as a body of water), only one DC conductor may be used.

Advantages

High-voltage DC permits the use of higher effective voltages for a given number of insulators in a string and a given length of flashover distance between the conductors and supporting structures. Leakage and corona losses are thereby decreased.

Since there is no alternating magnetic field around the conductor (except at the time of energizing and deenergizing), there are no inductive or capacitive effects. In AC systems, these often require corrective measures. The power factor is unity, a fact that alone accounts for considerable reduction of transmission losses. This is especially important in underground

cable systems. Similarly, the lack of a moving magnetic field reduces the stresses on circuit breakers, reducing their interrupting duty requirements.

Another important advantage of DC transmission is the ability to interconnect separate transmission systems (of the same voltage) without the necessity of first synchronizing them (see Fig. 5-4). This essentially eliminates the stability problems associated with interconnected AC transmission systems.

DC lines may consist of few conductors (use of only one or two conductors compared to three or more for AC systems). Consequently, tower and supporting structure requirements as well as those for rights-of-way are relatively less and are reflected in lower line construction and maintenance costs.

In addition, DC cable circuits have some special advantages over AC. For long cable circuits, DC has a lower investment cost because fewer individual cables are needed. DC does not have the problems of high amounts of reactive power that are produced in an AC cable. Also, DC cables have lower losses than equivalent AC cables (in long AC cables, shunt reactors are usually required to counter the capacitance effect of the cable itself).

Disadvantages

It is generally uneconomical to tap DC lines, and tapping is generally avoided. Line tapping requires conversion to AC before lower (or higher) voltages can be transformed to desired values. If the desired voltage is DC, conversion from AC back to DC is also required (see Fig. 5-5).

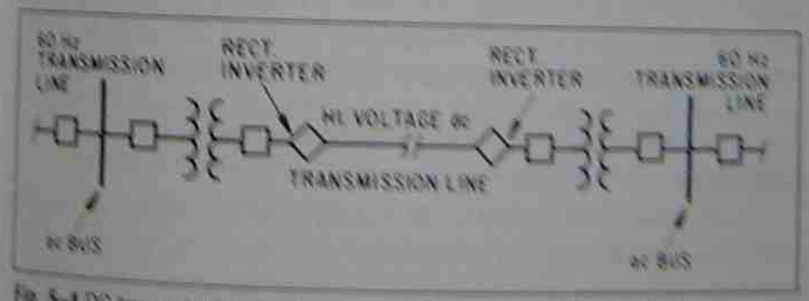


Fig. 5-4 DC transmission used over very long distances. The two AC buses may be hundreds of miles apart and do not have to be synchronized, or in phase, to permit power to flow between systems.

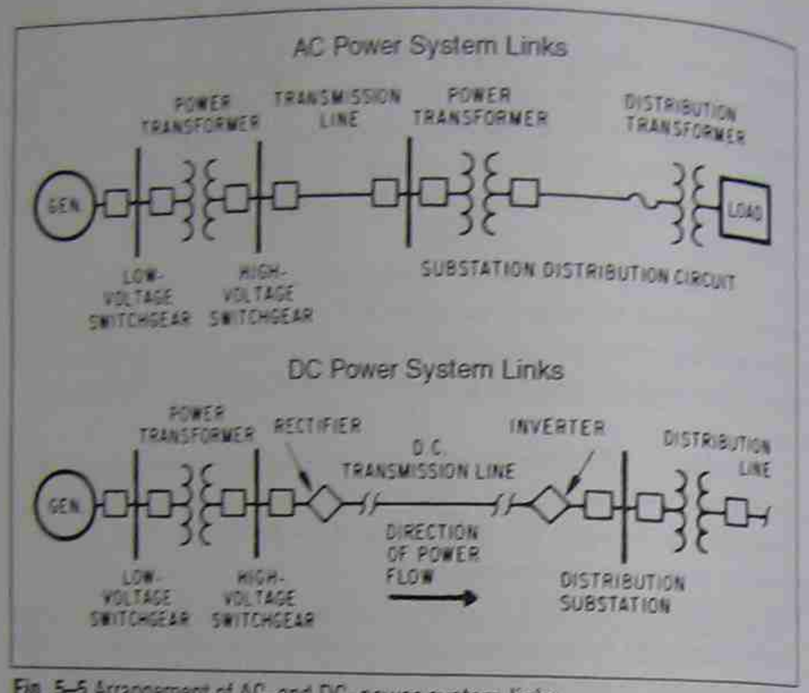


Fig. 5–5 Arrangement of AC–and DC–power system links

Changing Voltage—DC Systems

To raise or lower voltages in a DC system, it is necessary to go through the same procedure described for tapping of such circuits. Costly terminal equipment is necessary to convert power to AC at transmission and distribution substations to incorporate DC lines. Further, there are challenges associated with tapping DC lines or changing values of DC voltages. It has not yet proven feasible to control power flow and protect the circuit in the same fashion as a tap-off or change in voltage of an AC circuit.

Rectifiers

Conversion of AC power to DC power (and vice versa) is accomplished through rectifiers. For the amounts of power to be transmitted in such extra-high-voltage lines, mercury arc rectifiers, sometimes referred to as mercury valves, are used. The number employed depends on the amount of power to be converted.

Mercury arc rectifier installations are usually large and require periodic maintenance. Moreover, the stability of the arc is subject to momentary dips in the incoming source that may cause the arc to be extinguished, necessitating restart. Later installations employ solid-state rectifiers, sometimes referred to as thyristor valves, replacing the mercury arc converters. While these, too, are costly, they require little or no maintenance.

In short, high-voltage DC is suitable almost exclusively for transmission of large blocks of power over long distances in point-to-point transmission. The cost for DC lines is less than for AC lines. However, there are costs associated with the converter stations necessary for the conversion of AC to DC for transmission and then back to AC transmission for short lines. Economically, a break-even point in costs for high-voltage DC compared to extra-high-voltage AC appears to be at line lengths of about 400–500 miles. At this point DC appears economically feasible. As for underground cable circuits, this break-even point appears to be about 40–60 miles.

History

The earliest transmission lines were short, low-voltage, low-power, DC runs, confined to European countries. They consisted of a series circuit, known as the Thury system (see Fig. 5-6). Here a number of DC generators were connected in series to develop the high voltage of the transmission line, carrying a constant value of current.

At the receiving end were a number of motors connected in series, located at one or more substations, with the current flowing in each one having the same value. These motors, in turn, drove DC generators whose output served low-voltage DC distribution requirements. Variations in load, which necessitated changes in the voltage to vary with the load, were taken care of by short circuiting one or more generators as well as motors at the substations.

The vast increase in demands for electricity, especially with the advent of World War I, were met by the rapidly developing and expanding conventional AC systems, employing the transformer (with no moving parts). Thury systems were finally supplanted by conventional AC systems, although the last ones persisted until the early 1930s.

DC transmission is emerging as a transmission tool for large-capacity links over long distances, particularly for interconnections of dissimilar

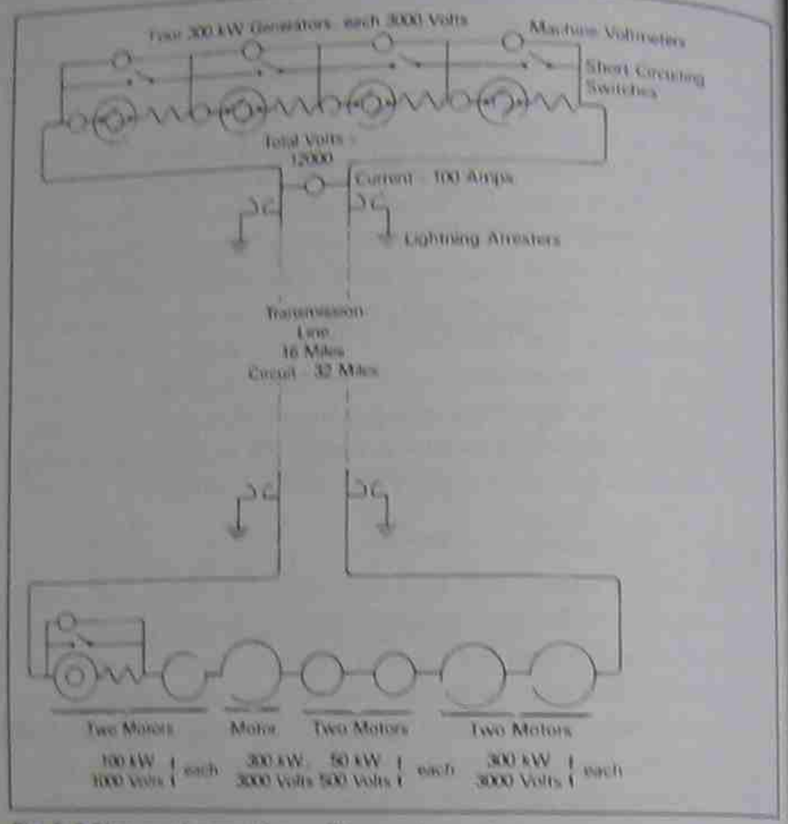


Fig. 5–6 Diagram of connections—Thury series system

areas. India, for example, has a 1,500-MW, 500-mile link. There also is a 2,000-MW link between eastern Canada and northeastern United States. Thyrister converter stations and new insulation material for cable circuits are making DC transmission links possible both in the United States and overseas. It is expected that by 2005, the total capacity of DC links will exceed 14,000 MW.

Review

- Extra-high-voltage (EHV) transmission often permits transmitting large blocks of power more economically than lower voltage transmission.

effective voltage of an AC system is only 70.7% of the maximum voltage of the AC sine wave.

- EHV transmission is ideal for "mine-mouth" power generation; the power-generating station is located right at a coal mine. This eliminates having to transport the coal to a generating station miles away.

- Load-carrying ability of transmission lines varies as the square of the operating voltages; doubling the line voltage results in quadrupling the line capacity.

- EHV transmission lines have serious effects on the design and construction of related equipment, such as circuit breakers, transformers, reactors, capacitors, lightning or surge arresters, conductors, towers and supporting structures, etc.

- EHV lines are subject to insulator flashovers and can subject equipment to large mechanical stresses.

- Flashovers caused by lightning or switching may result in greater flow of follow current that may cause greater fault current to flow, imposing greater stresses in equipment.

- Liquified gases at extremely low temperatures (in the −400° F range) circulate within conductors, causing their resistances to approach 0. These are often referred to as cryogenic cables and superconductors.

- The major advantages of DC transmission over AC transmission are:

  1. Higher power capability for the same size conductor and insulation
  2. Elimination of skin effect and inductances (loads are delivered at essentially unity power factor)
  3. Fewer conductors required for transmission

- The major disadvantage of DC transmission is the difficulty in stepping voltages up and down, requiring expensive equipment, including rectifiers.

Study Questions

1. What is meant by extra-high-voltage transmission?
2. What is the relationship between line voltage and capability?
3. What are three main considerations in selecting the type and voltage of a transmission line?
4. What are the advantages of EHV transmission?
5. What are the disadvantages of EHV transmission?
6. What is meant by "mine-mouth" generation? Where is it used?
7. What are the advantages of DC transmission compared to AC transmission?
8. What are some of its disadvantages?
9. What are superconductors? What are their advantages? What are some of their disadvantages?
10. How might AC and DC systems be interconnected?

6

Dynamic Capabilities

Conventional procedures used to calculate current-carrying capabilities of transmission-class overhead and underground lines depend on complex formulas and on conservative assumptions of conditions under which lines are operated. In transmission lines, normal ratings may not be as limiting a factor as the emergency ratings. Transmission systems are usually designed to carry the load even when one or more lines are out of service under a contingency condition, or during the loss of a generating unit or interconnection.

Transmission-line capability and reliability have also become increasingly important because few new transmission lines have been built in the United States since the 1970s. As shown by Table 6-1, bulk transmission line additions (220 kV and above) declined by more than 60% from 1975 to 1990. Even with this trend, economic and environmental restraints in the electric utility industry dictate that planners and operators make better use of existing system facilities.

Table 6–1 Average bulk transmission lines added (in the United States)

5-Year Period Ending	Avg. Net Miles Increase/Year (for 5-Year Period)
1975	6,467
1980	4,767
1985	4,051
1990	2,269

Source: EEI historical statistics

An Emerging Technology

Conservative assumptions in calculating circuit ratings include conductor temperature, ambient temperature, wind speed, subsurface conditions (soil characteristics and moisture content), historical load data, and insulation and conductor condition in service. Many operators and planners use these calculations for certain periods of the year (often summer and winter). The result is lines being underutilized or overloaded when actual conditions fall short of or exceed assumed conditions.

The challenge, then, is to measure actual operating conditions, automate the data-gathering, and integrate the information with accepted rating calculations. This can be used to produce "real-time" capability ratings (compared to "book" ratings) on a timely basis. In this way, technicians can operate the system safely and with full utilization of its capability (see Fig. 6-1).

Dynamic Rating Systems

History of Dynamic Rating Systems

In the early 1970s, L. Fink recognized the potential benefits of real-time knowledge of the actual data of a transmission circuit's thermal state. He recommended the creation of real-time monitoring and computer programs for establishing circuit capability. In the late 1970s, the Cable Monitoring and Rating System (CMARS) was developed through Department of Energy sponsorship. M. Davis made a similar approach for overhead lines.

In 1975, Underground Systems Incorporated (USi) was formed to supply real-time capability system components and technical evaluation for a CMARS demonstration project on cable circuits owned by Public Service and Gas in New Jersey. It was the first real-time transmission monitoring and rating system ever installed and produced valuable information before it was taken out of service when the demonstration period ended.

In the mid-1980s, a commercial, real-time monitoring and dynamic rating system for transmission cables, UPRATE™, was developed by USi. It was first installed on the Boston Edison system followed by installations at Long Island Lighting Company, PSE & G, Consolidated Edison of New York, and the New York Power Authority (see Figs. 6-2 and 6-3). The real-time systems were augmented by systems for overhead transmission lines and substation transformers in the late 1980s.

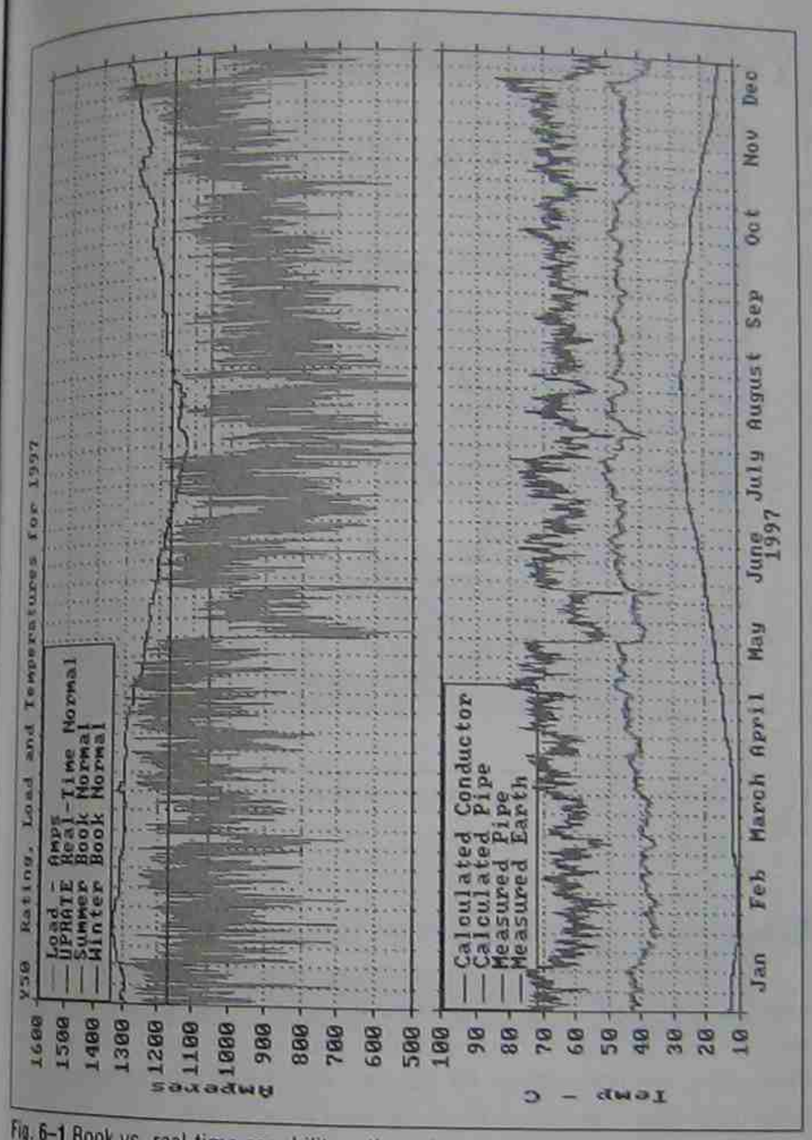


Fig. 6–1 Book vs. real-time capability ratings (*courtesy USi*)

Y50 345 kV Intertie - UPRATE® System

LILCO Operations Center

Fig. 9-2 System operator console (arrow points to real-time monitor) (courtesy LIPA)

Dynamic Rating System Design Requirements

Real-time dynamic ratings must be accurate for all load, environmental, and equipment operation conditions. This is essential to ensure that cable and equipment are not overloaded and helps to build confidence in those using real-time ratings for normal or emergency conditions. It also helps those who plan system reinforcements or additions.

Three elements are required to ensure the accuracy of real-time ratings modeling, measurement, and parameter identification. These elements are common for all of the equipment in the power delivery system including overhead transmission lines, underground transmission lines and substation equipment.

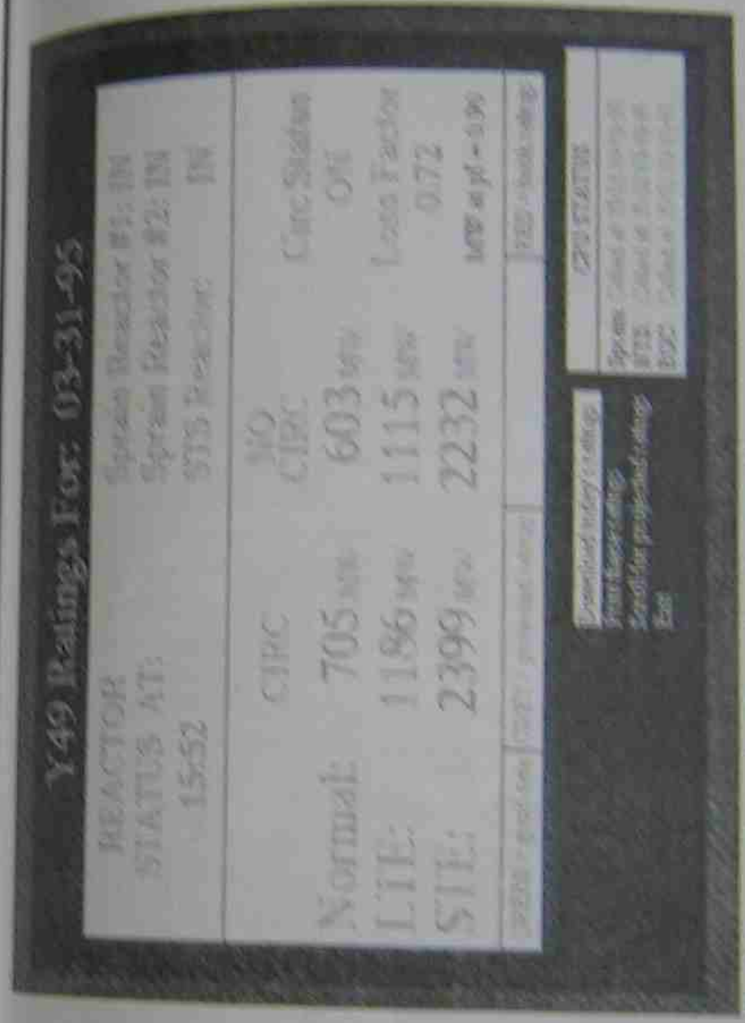


Fig. 9-3 Screen display of real-time ratings (courtesy LIPA)

An accurate dynamic thermal model of the equipment that operates in real-time is the basis of an accurate rating system. The thermal model must correctly describe the equipment's thermal performance, both during normal function and during emergency situations. For example, thermal models for transmission lines track problems arising from heat transfer in pipe-type cables or from sag clearances on overhead lines. They provide temperature and rating information in the event of an operational problem. The model must allow quantification of the actual equipment capacity and, in addition, operational condition and environmental parameters critical to the stability of the equipment.

Second, equipment must be installed to measure key parameters on a real-time, continuous basis. Parameters that drive the model, such as load, temperature, wind speed, etc., and the operational status of equipment must be measured. They are needed to identify the thermal characteristics of the equipment that relate to its thermal response (see Figs. 6-4, 6-5, and 6-6).

Third, parameter identification algorithms must be used continually to evaluate and update key, uncertain thermal parameters. For all power delivery components there are key parameters that are "uncertain" in that they can and do change. However, they can have a significant effect on the temperature and ratings of the equipment. For example, in underground transmission cables, these parameters include earth resistivity and earth ambient temperature. For overhead lines the uncertain variable is wind.

Benefits/Typical Performance

All of these dynamic rating systems provide a variety of benefits. These include rating increases, improved safety in the use of ratings, identification of environmental problems, and equipment diagnostic information that can reduce the incidence of future failures. Dynamic ratings systems can yield enormous operational savings when real-time ratings score higher than book ratings. This allows use of economic generation within the system.

Open-access transmission and marketing of power make more effective use of interconnections to limit serious system problems involving possibility of blackouts (loss of service to large areas). In some emergency situations, if the system operator follows book ratings, he may have to interrupt load or lose the entire network. With real-time capability, he finds that capacity limits are usually higher than the book ratings, particularly for emergency ratings. Consequently, he may not be forced into a situation in

Fig. 6–4 Installation of sensor donut on OH 230-kV line (*courtesy USi*)

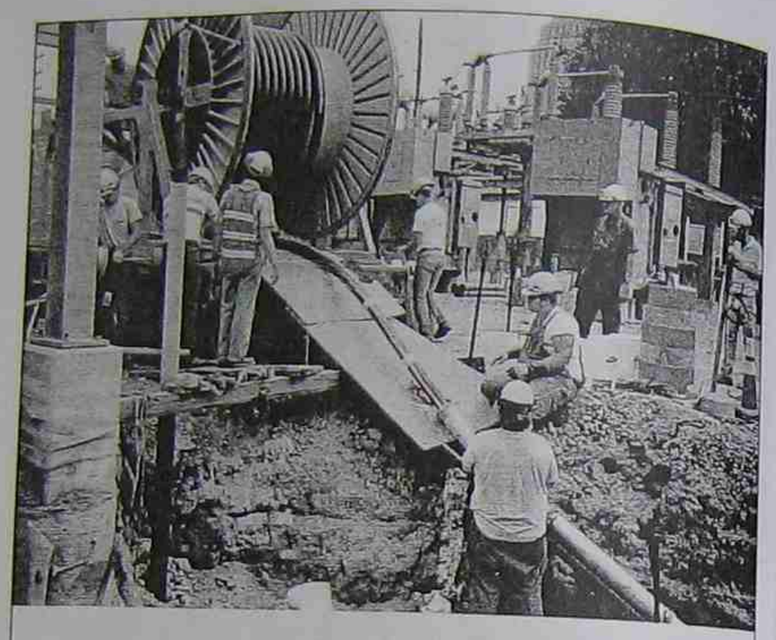


Fig. 6–5 Installation of thermocouples on a new 138-kV cable (*courtesy USi*)

which he must either drop load or lose an entire area. System planners may find they do not need to reinforce a transmission line or construct a new one to avoid exceeding the book rating of a transmission component.

Actual commercial use of dynamic rating systems, such as USi's Uprate™, has resulted in useful data concerning underground cable and overhead transmission lines.

Underground Cable

Dynamic ratings on cable systems typically boost short-time emergency cable ratings 40–110% and normal ratings 15–25% compared to book ratings. Transmission capacity is not only increased but made safer, because the system ratings are based on actual cable component temperatures and earth thermal conditions.

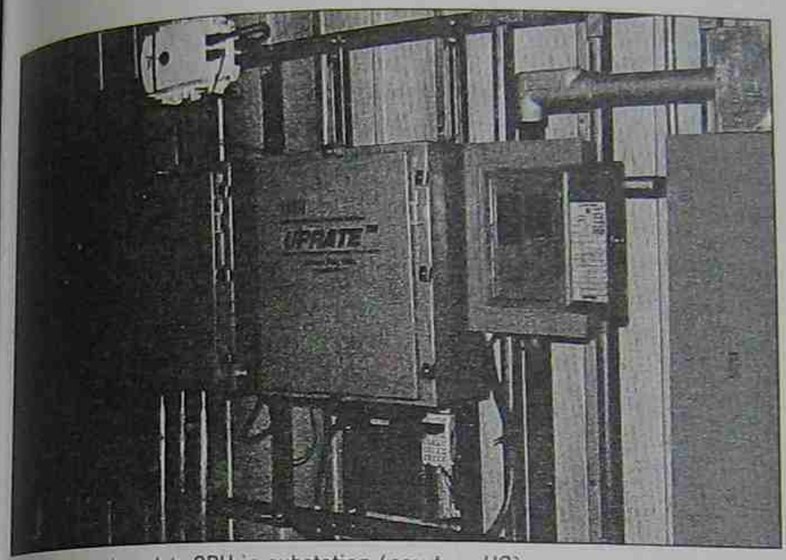


Fig. 6–6 Real-time data CPU in substation (*courtesy USi*)

For example, cases have occurred in which the utility book rating was based on an assumed earth *rho* (measurement of soil thermal resistance) of 60, when in fact the earth rho at the monitored cross section was more than 100. Alerting engineering/operations to take corrective action may well have averted an expensive cable failure from the heat effect on the insulation.

Overhead Transmission Lines

Actual utility data show dynamic ratings usually exceed book ratings 70–90% of the time for well-defined periods of the day. Further, due to typical wind conditions during midday, they often exceed the book ratings during the hottest time of the day when load requirements are greatest. During periods when winds are lighter than expected and dynamic ratings are lower than book ratings, the dynamic ratings are more accurate to maintain safe conductor temperatures for sag and clearance requirements.

Integrated Power Delivery Data and Dynamic Rating Systems

Real-time monitoring and dynamic rating systems for power delivery components can be integrated to provide real-time circuit ratings for all of

the load-carrying equipment on a circuit or segment of the system. To determine this circuit rating, the ratings of each component must be established and the lowest rating selected in real time. This becomes the circuit rating. This lowest-rated component can then either be replaced, reinforced, or investigated for means of increasing the rating.

System-wide implementation of real-time monitoring and dynamic rating for power delivery allows users to easily access the data for a variety of uses. (Data are made available through a power delivery applications server.) These uses include rating and temperature information for system planning and engineering and diagnostic status for maintenance and substations operations. It also provides real-time dynamic ratings for system operations and power pool/ISO organizations in the format required.

From an economic standpoint, utility studies have shown that deferred installations and economic dispatch improvements can pay back investments on dynamic systems in less than a year. They can provide additional generation revenue for future power delivery marketing and power generation conditions prevalent in today's competitive energy business.

Appendix **A**

Environmental Considerations

Many environmental considerations are taken into account in the planning, design, construction, maintenance, and operation of transmission lines and associated substations. A few examples follow to illustrate the scope and magnitude of such considerations.

Safety

Overall, perhaps the prime considerations are the measures taken to protect people from injury. In addition to maintaining certain minimum clearances of hazardous objects from the general public, there are other important measures. These include:

- Barriers, fences, and walls around potentially dangerous areas
- Locks on doors, gates, operating handles, and other accesses to facilities and equipment
- Interlocks on critical equipment and devices to prevent incorrect operation and accidental energization and deenergization of facilities that could endanger workers and the public
- Grounding of fences, towers, and other metallic structures accessible to the general public that could be accidentally energized

- Smoke and fire alarms to warn the public of impending possible danger
- Measuring devices installed throughout a region to monitor pollutants of the surrounding atmosphere

Aesthetics

Transmission lines are routed to avoid areas of particular interest. Such areas might include:

- National monuments or regional parks
- Areas of population density or recreational importance
- Areas where people congregate for special events
- Playgrounds
- Buildings and other structures of historical interest
- Areas for the preservation of the integrity of national resources as ecological preserves, including animal sanctuaries and forest reserves

Much attention has been directed toward making transmission lines and associated substations less obtrusive and more pleasing (or less displeasing) to observers. Poles and support structures have been gracefully designed to blend with their surroundings (see Figs. A–1, A–2, A–3, and A–4). Similar treatment is applied to insulators and equipment mounted on the structures. For lower voltage lines (up to 69 kV), lines are constructed without cross-arms to improve appearances (see chap. 1).

Rights-of-way are cleared of unsightly growth, and landscaping is provided in some areas; in other areas, flowers and other plants are used to create pleasant garden effects. Substations are landscaped to conceal or beautify the enclosures of equipment (see Figs. A–5 and A–6). In some instances, the station is contained within structures made to conform and blend in with the neighborhood (see Fig. A–7).

When other means have proven impractical, lines are placed underground for short distances through the areas affected, including cable ads and exits from substations.

Pollution

Sight is not the only sense to which attention is paid. Steps are taken to eliminate or abate disagreeable sounds. Acoustic barriers are installed.

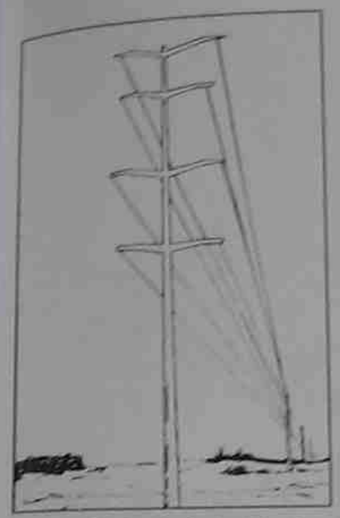


Fig. A–1 Single-shaft, double-circuit, 345-kV line (*courtesy FL Industries, MN*)

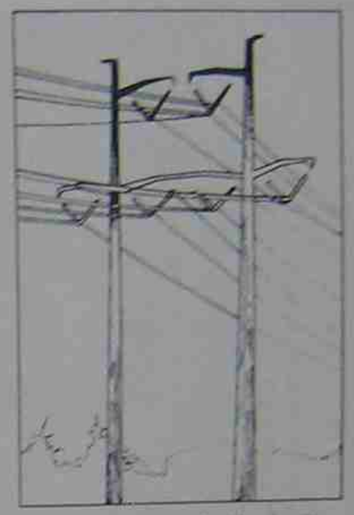


Fig. A–2 H-frame, double-circuit, 500-kV line (*courtesy FL Industries, MN*)

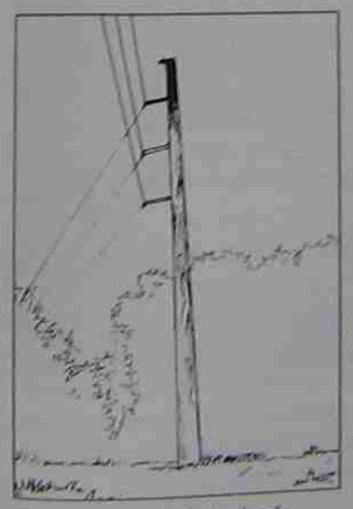


Fig. A–3 Light-duty steel pole (*courtesy FL Industries, MN*)

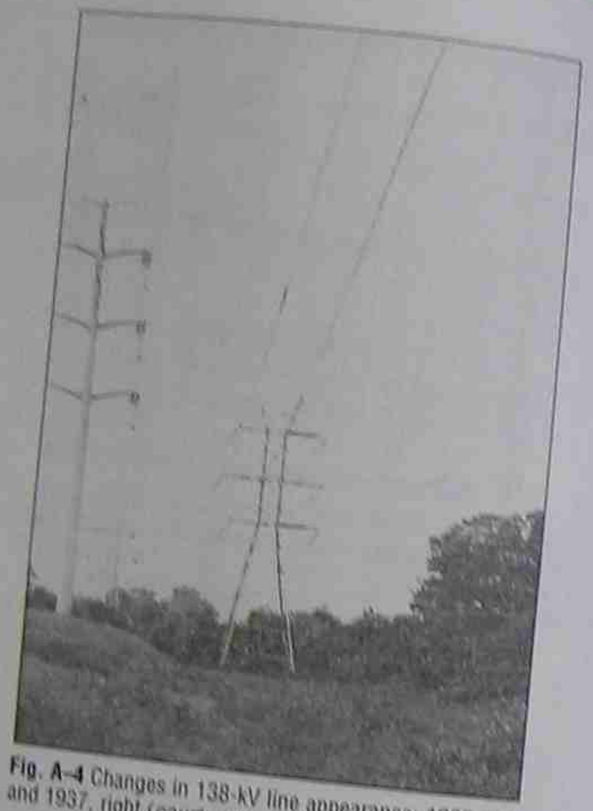


Fig. A–4 Changes in 138-kV line appearance: 1987, left, and 1937, right (*courtesy Long Island Lighting Company*)

generally at substations, to keep annoying sounds confined within limited areas. In some instances, devices producing sound frequencies to cancel those produced by energized equipment are installed to lessen this form of nuisance.

There is a possibility of pollution of surface and subsurface water sources from oil spills from electrical equipment (transformers, circuit breakers, etc.). Dams and barriers are carefully designed and constructed around such equipment to prevent this from occurring.

Ecology

The preservation of wildlife refuges and sanctuaries, including endangered species, by the rerouting of facilities has been discussed previously.

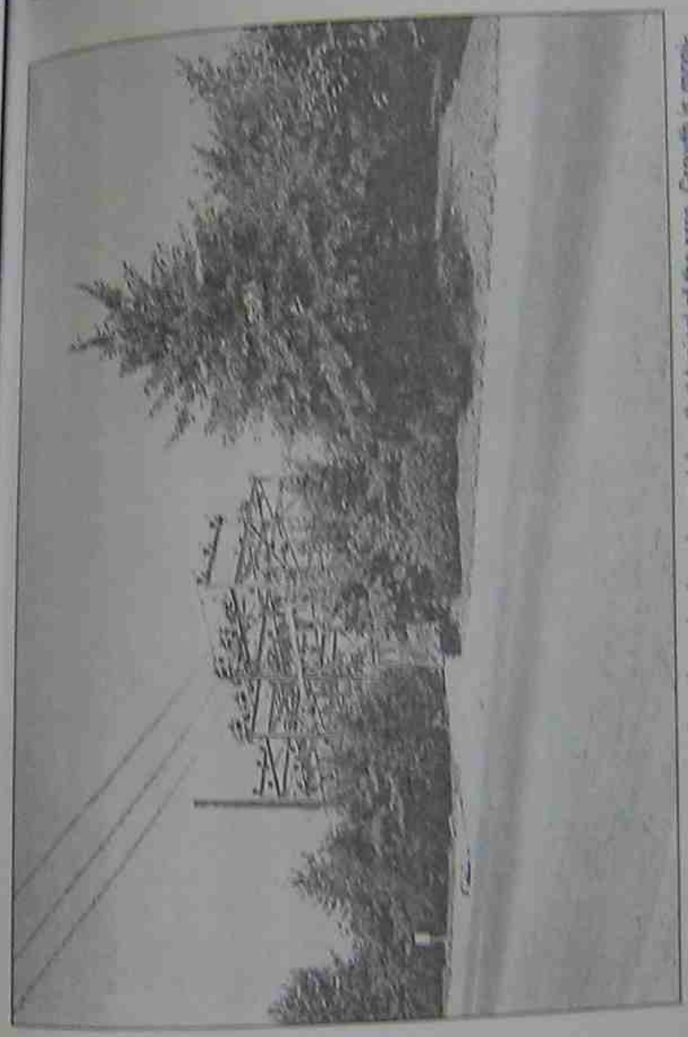


Fig. A–5 Green Acres substation. Heavy landscaping matches that typical of the area. Growth is monitored to maintain appearance, whereas trees that pose a threat to structures from view as much as possible. (*courtesy Long Island Lighting Company*)

Fig. A–6 Atlantic Beach substation. Low-profile substation has fencing and shrubs typical of the neighborhood. Structures are painted in colors defining their type and function, with special emphasis on hazardous areas. Major equipment is colored to be as inconspicuous as possible. *(courtesy Long Island Lighting Company)*

Fig. A–7 Seaport substation in Manhattan. Walls around equipment are made to look like other industrial buildings in the area. *(courtesy Consolidated Edison Company)*

Other provisions are made to protect some wildlife from self-destruction (as well as to prevent interruption of service). These include shields placed on the lower parts of poles, towers, and other structures to keep such animals from contact with energized conductors. Similar guards are installed on equipment bushings to serve the same purpose.

In some instances, usually where ospreys, eagles, and other birds with large wingspans exist, nests are mounted on separate structures a short distance away from the transmission lines. These are meant to keep such birds from nesting on or in the line structures, where they may come in contact with energized conductors.

Hazardous Materials

Hazardous materials usually are avoided; where they may exist still, steps are taken to eliminate them. Where insulating oils and askarels contain polychlorinated biphenyl (PCB), steps are taken to replace the fluids (where necessary the entire equipment itself), or clarify them. (PCB is considered a teratogen.) Again: Disposal falls under "regulated hazardous waste," per the federal Toxic Substance Control Act (TSCA).

Similarly, where there is asbestos insulation or noise barriers that contain asbestos, steps are taken to remove this material or replace it with other nonhazardous materials (see chap. 4).

Electromagnetic Radiation

In the case of higher voltage transmission lines, research continues on the effect of their strong magnetic fields on human, animal, and plant life in their vicinity. As is known, a voltage is induced in a conductor cut by a magnetic field, its magnitude in part depending on the strength of the magnetic field. People, animals, and plants constitute conductors of sorts. They have voltages induced in them that cause currents to flow within them as "eddy" currents, as well as between them and the ground or other objects with which they may come in contact.

The effect these currents have on the biological system, and especially on the nervous system, appears to be minimal or nonexistent, although the length of time of such exposure may play an important part. Meanwhile, tentative standards are being drawn calling for minimum widths of rights-of-way in accordance with the voltage of the transmission lines. For example, some states have legislated a minimum right-of-way width of 350 ft—or 171

meters (m). Additional width is provided to maintain a maximum magnetic field strength of 1.6 kV/m from conductor to the area or structure in its vicinity applied to the shortest distance between them.

These observations apply to both AC and DC lines. Magnetic fields produced by the former alternate in direction according to the frequency of the circuit. This constant to-and-fro motion produces alternating current on whatever bodies that are cut by the magnetic fields. In DC transmission, the magnetic fields produced are stationary (except when first energized and again when deenergized). However, objects in motion in their vicinity cut the magnetic field, producing a direct current within them.

Tentative "wire codes" have been established by some utilities that correlate the number of wires and their diameters and voltages to specific "safe" distances from vulnerable objects. Wire codes are modified by other factors. These include pollution effects on the lines, population density in the vicinity of the line, traffic in the area, the shielding effect of other structures, and other factors that may influence possible current flow.

* * *

These are only a few of the measures taken to improve and maintain the quality of the environment that may be influenced by transmission lines. They are an indication, however, of the scale and scope of the considerations taken into account that affect transmission lines from the planning stages to their final construction and operation.

Appendix **B**

Guide for Uprating Transmission Structures For Higher Operating Voltages

Transmission lines can have their capacities uprated to accommodate increased loading to utilize existing rights-of-way. This may be accomplished by installing larger conductors on existing structures, increasing operating voltages, or both. In general, uprating existing lines creates fewer environmental, economic, and public relations problems than obtaining rights-of-way for new facilities. In such uprating, however, reconstruction and replacement of structures as well as revisions and beautification of existing rights-of-way may be necessary.

The guide details the handling of all of the elements in the transmission line to be uprated. It lends itself admirably to working out the details for obtaining and preparing rights-of-way as well as those associated with the construction of a new transmission line.

Standards and methods employed are those of the Rural Electrification Administration (REA) of the U.S. Department of Agriculture, to whom thanks are due for extending this courtesy. While the standards and methods

...ECEs may differ in some details from those of other public and private electric utilities, due, first, to inherent characteristics of the utility industry. They should also differ for the purposes indicated. This is especially appropriate when it is considered that important ECE activities include the planning, engineering, construction, maintenance, and operation of high-voltage, large-capacity, and long-mile-country transmission lines.

Additional information, specifications, and other material may be secured from ECE offices.

Case Study: 69-kV to 115-kV Line Uprating

Introduction

This analysis provides a brief summary of a 69-kV to 115-kV uprating case study. The original 69-kV line was constructed to the standard ECE T-1 single-pole structure (see Fig. 9-1). The uprated 115-kV line structure was constructed on the T3-115E structure (see Fig. 9-2).

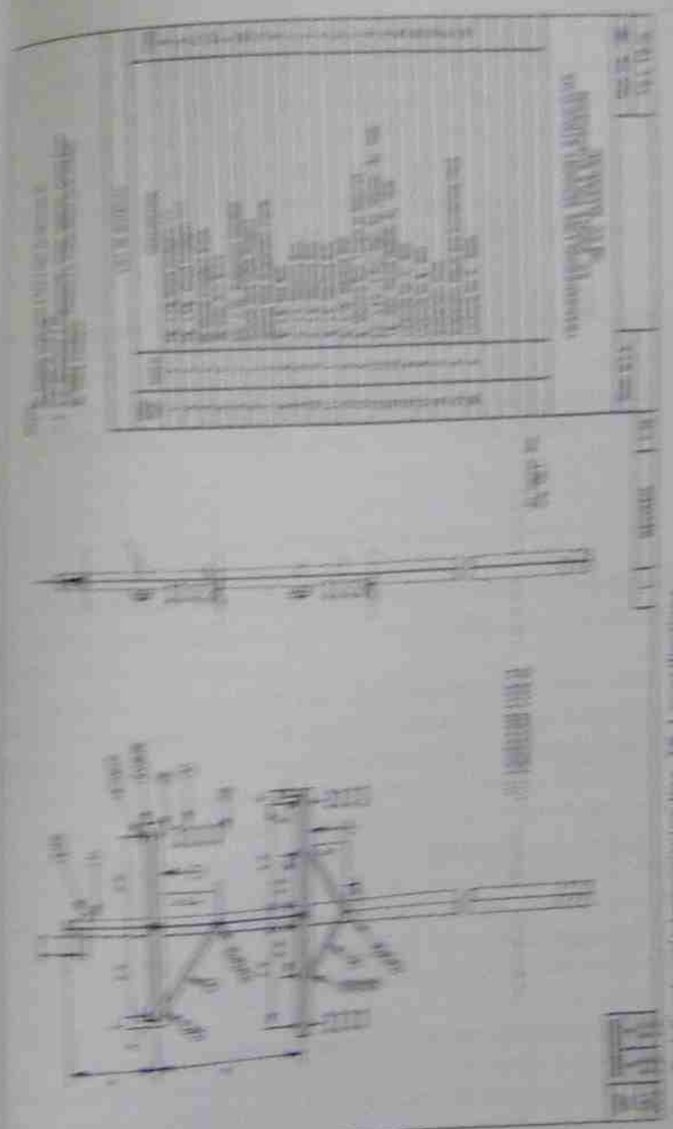
Analysis

The original 69-kV line was designed and constructed in 1951–1952 under the safety guidelines of the ninth edition of the National Electrical Safety Code (NESC) and the then-existing ECE "Transmission Line Design Criteria." The uprated 115-kV line was designed in 1970 in accordance with the 1977 edition of the NESC, the 1972 ECE Bulletin 62-1, and July 1970 "Top Mast" ECE Bulletin 62-1 vertical clearance requirements.

A comparison of the original and uprated design criteria is provided in Table 9-1.

Table 9-1 Original vs. Uprated Design Criteria

Design Item	Original Design	Uprated Design
Conductor	#1/0 ACSR 6/1	#1/0 ACSR 6/1, ACSR
Shield wire	3/8" H.S. Steel	3/8" H.S. Steel
Loading	3/8" ice 0.4# Wind @ 0°F	3/8" ice 0.4# Wind @ 0°F
Aerial span	350 ft	350 ft
Voltage	69 kV	115 kV
Basic span	300 ft (2)	300 ft (2) 6/6/6 (2) 1 span



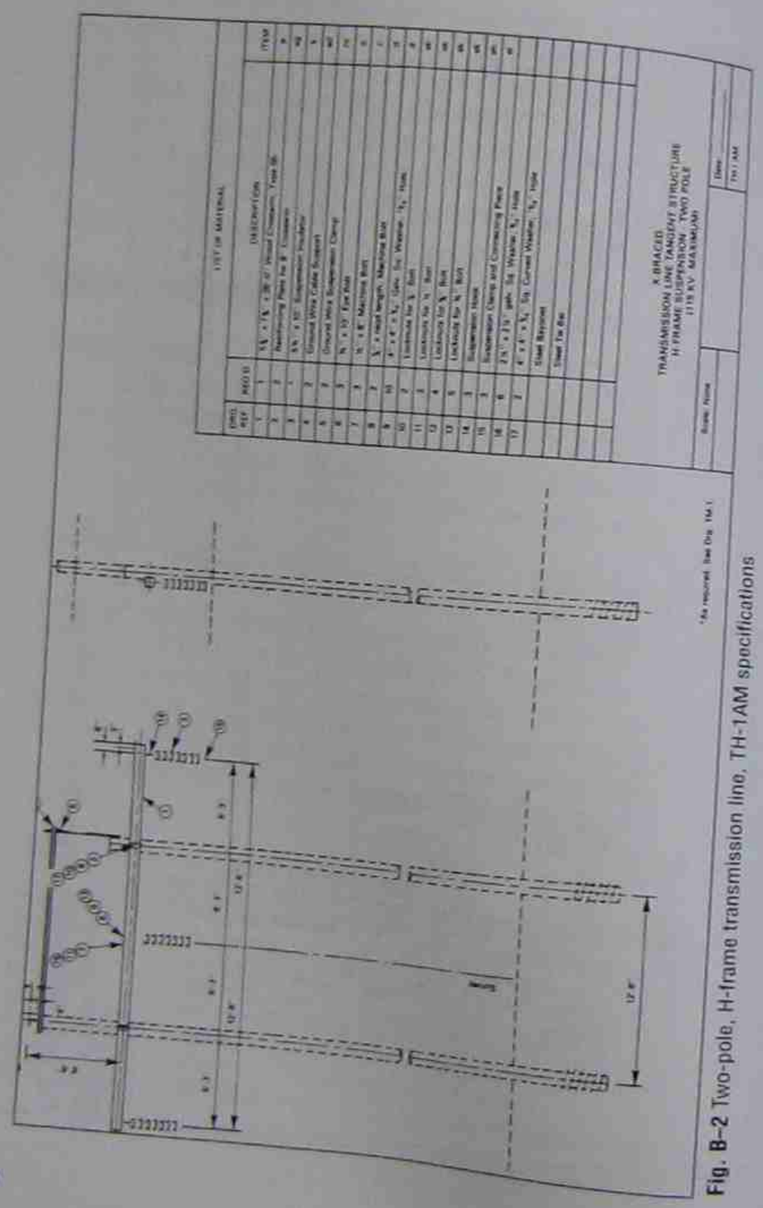


Fig. B–2 Two-pole, H-frame transmission line, TH-1AM specifications.

The original 69-kV line had a design ruling span of 500 ft as compared with an actual ruling span of 380 ft based on structure locations. A check of several contemporary line projects revealed a similar practice.

Summation of moments at the groundline because of wind and ice loads revealed that the larger 477 mcm 26/7 conductor and two 3/8" H.S. steel shield wires could be installed on the uprated TH-1AM tangent structure. This would provide a 4.0 safety factor under NESC heavy-loading criteria. The maximum allowable sums of adjacent spans for several typical structure heights are given in Table B–2.

Table B–2 Maximum Sums of Adjacent Spans, TH-1AM Structures of Several Heights

TH-1AM Structure Height (ft)	Class	Maximum Sum of Adjacent Spans (Safety factor = 4.0)
50	3	1,151 ft
55	3	1,136 ft
60	3	1,129 ft

The single cross-arm (Type 55) of the TH-1AM structure has a maximum vertical span limitation of 822 ft under NESC heavy-loading conditions and a 4.0 safety factor.

The allowable sum of adjacent spans and the vertical span allowed by the cross-arm strength permitted existing poles and pole locations to be used in spotting all tangent structures in the uprated line. Additional span lengths could have been attained by installing X-braces or using an assembled cross-arm. The span lengths in the existing line, however, allowed the use of the unbraced, single-piece cross-arm structure as described.

As a general rule, standard REA angle and dead-end structures were called for at line angles and dead-end points in the uprated line. No attempt was made to redesign or uprate existing 69-kV structure configurations. This rule was employed to assure ample strength and electrical clearances at these critical line locations.

The galloping ellipse patterns were calculated and plotted for the longest individual span in the line (590 ft). The single loop method of analysis was used and less than 10% overlap was detected. Therefore, the structure spacing, wire sags, and maximum span length were concluded to be satisfactory.

Inspection/Survey

A vital part of the design procedure in a line uprating is a thorough inspection of the existing line. A competent inspection crew should be assigned to foot patrol and inspect the entire line length. The inspection crew should use copies of the existing line plan and profile drawings. They should perform many checks including the following:

- Verify the elevation of the elevation profile
- Verify the height and groundline circumference of each existing structure
- Verify the height and survey station of each utility crossing
- Report the location and extent of any right-of-way encroachment (house, barn, mobile home, radio/TV antenna, etc.)
- Verify survey station of all highway/road/railroad crossings
- Report any land-use changes (original pastureland now under cultivation, pivot irrigation now installed, etc.)
- Report any terrain changes (excavations, landfills, stock tanks, terraces, etc.)
- Report any structures requiring line maintenance (ground or internal rot, damaged pole, etc.)

Line conversion or voltage uprating may warrant a complete new line survey. If the existing transit and level data are relatively recent (less than 10 years old) and the line route is not in a developing urban area, the existing survey information may be adequate. It must, however, be verified thoroughly by the foot patrol inspection noted above.

An important point to recognize in line uprating is the fact that the centerline of the uprated structure may not be the same centerline of the original structure. The original centerline of the TS-1 structure coincided with the original survey centerline. However, the centerline of the uprated TH-1AM structure was offset 1.91 m (6 ft 3 in.) from the original survey centerline. Because of the flatness of the terrain passed through in this study, the offset did not create a real problem. However, a similar offset through heavily wooded or side-sloping terrain might have been prohibitive.

Right-of-Way

The original TS-1 single pole 69-kV transmission line required only 15.24 m (50 ft) of right-of-way—7.62 m (25 ft) either side of the centerline. The uprated TH-1AM two-pole 115-kV line requires a minimum of 22.8 m (75 ft) of permanent right-of-way. This is based on 9.14 m (30 ft) from one side to the original centerline plus 12.19 m (40 ft) on the other side to allow for centerline and conductor offset, blow-out, and electrical clearance.

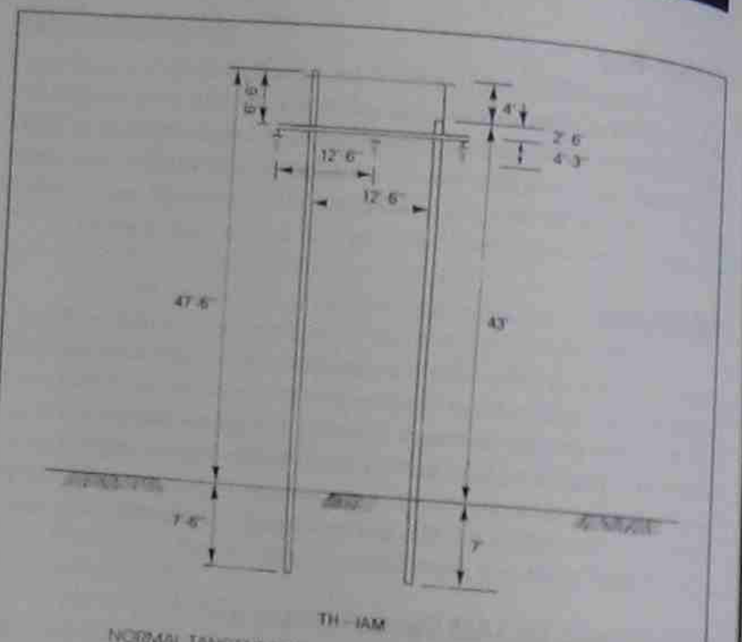
Notification

A "notice of intent to construct" is usually required by local regulatory agencies. This type of notification should be given even if it is not required by statute. Information concerning line route, structure configuration, wire size, minimum ground clearances, operating voltage, etc. should be sent to appropriate agencies. These include local utilities, highway departments, county officials, pipeline companies, rural water cooperatives, the Federal Aviation Administration, or other groups that may have facilities in the area or be affected by the new construction.

Design Data: TH-1AM Uprated Line

Design summary data for the TH-1AM uprated line and structure are given in Figures B–3 , B–4, B–5 , and B–6, and pages following. One of the main advantages of using the TH-1AM configuration is that it allows an increased ground clearance of 1.68 m (5 ft 6 in.) over the ground clearance allowed by the original TS-1 structure. This provided enough additional ground clearance to allow use of larger conductors as well as voltage upgrading. An additional 0.46 m (1 ft 6 in.) of ground clearance could be provided by raising the cross-arm to within 0.3048 m (1 ft 0 in.) of the pole top of the original structure.

The lightning shield angle of the TH-1AM structure is approximately 28° to the outside phases.



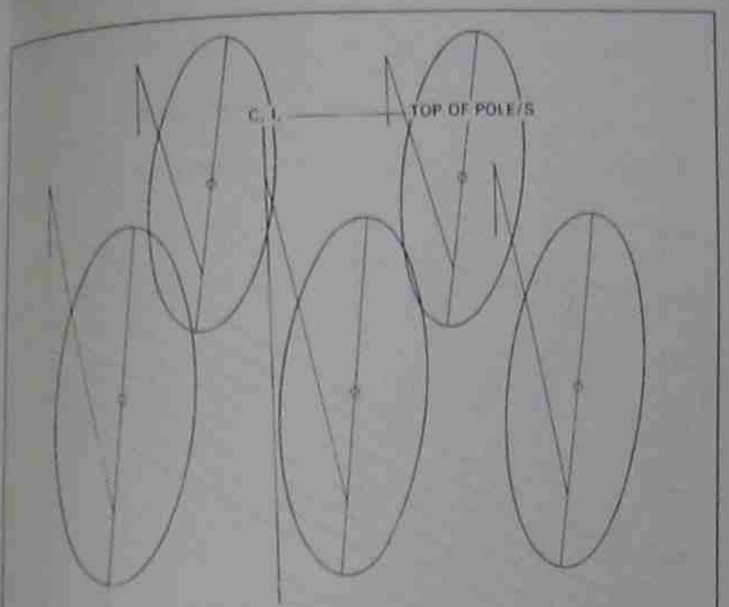
TH–1AM

NORMAL TANGENT SPAN ON LEVEL GROUND

STRUCTURE TYPE MODIFIED H-FRAME
POLE 50' CLASS 3
CONDUCTOR 477 26/7 ACSR HAWK

HEIGHT OF LOWEST COND ABOVE GROUND	=	36.25
GROUND CLEARANCE + 1 FT	-	25.00
SAG IN LEVEL GROUND SPAN	=	11.25
SAG IN 380 FT RULING SPAN @ MAX TEMP FINAL	=	8.15
SPAN = SQUARE ROOT OF (11.25 × 380 × 380 ÷ 8.15)		446.46 FT

Fig. B–3 TH-1AM specifications (tangent span on level ground)



FOR SPAN LENGTH OF 500 FEET
SINGLE LOOP LISSAJOUS ELLIPSE PATTERN
STRUCTURE MODIFIED H-FRAME

DATA TABLE FOR WIRE CODEWORD ⅜" H.S. STEEL

ANGLE 15.672537 AND ANGLE + ANGLE/2 = 23.508806 DEGREES
A + E = 12.197964 FEET
MAGNITUDE OF MAJOR AXIS 16.247455 FEET
MAGNITUDE OF MINOR AXIS 6.498982 FEET
B = 3.049491 FEET

POINT OF ATTACHMENT = -3.25 DOWN AND 6.75 FROM CENTER LINE
POINT OF ATTACHMENT = -3.25 DOWN AND -6.75 FROM CENTER LINE

DATA TABLE FOR WIRE CODEWORD HAWK

ANGLE 11.652755 AND ANGLE + ANGLE/2 = 17.479133 DEGREES
A + E 18.851455 FEET
MAGNITUDE OF MAJOR AXIS 19.652519 FEET
MAGNITUDE OF MINOR AXIS 7.861008 FEET
B 3.730504 FEET

POINT OF ATTACHMENT 2.75 DOWN AND 12.5 FROM CENTER LINE
POINT OF ATTACHMENT 2.75 DOWN AND 0 FROM CENTER LINE
POINT OF ATTACHMENT 2.75 DOWN AND -12.5 FROM CENTER LINE

Fig. B–4 TH-1AM wire specifications

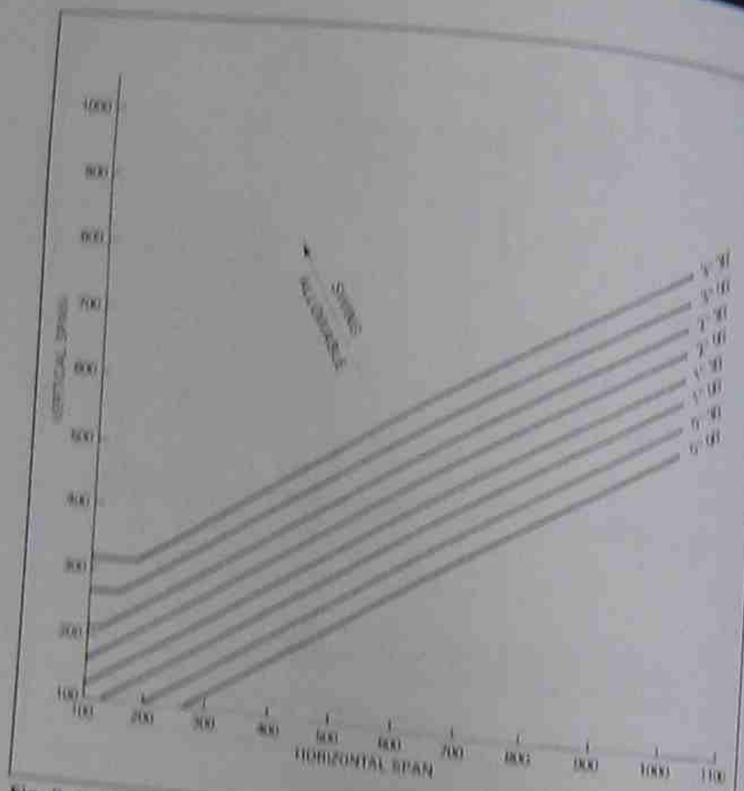
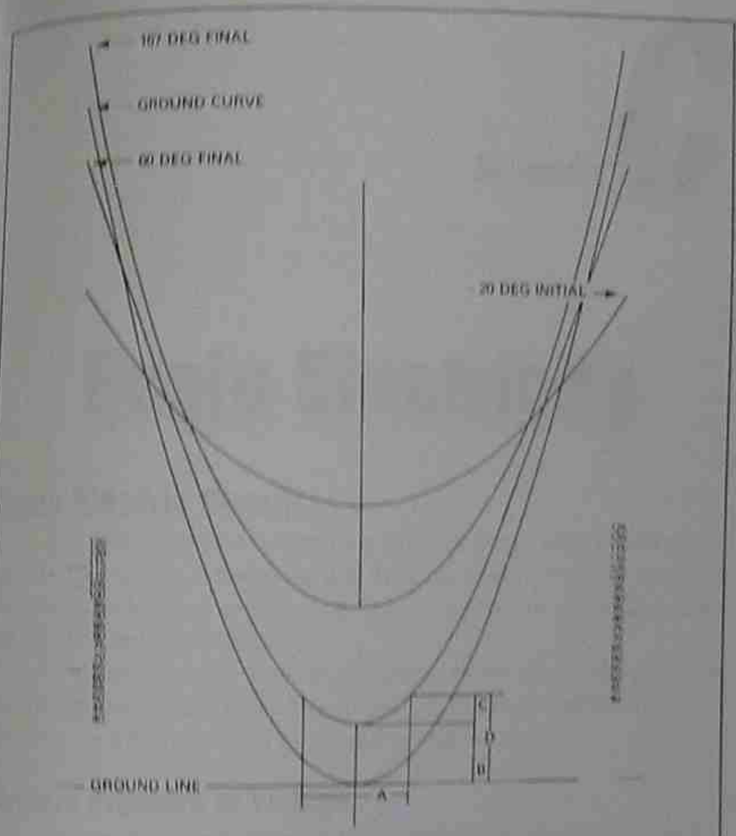


Fig. B-5 Allowable swing for TH-1AM design



MODIFIED H-FRAME

477 26/7 ACSR HAWK 380 FT RULING SPAN 115.00 KV HEAVY LOADING ZONE 50/3 POLE MODIFIED H-FRAME STRUCTURE MAXIMUM DESIGN TENSION 5819 LBS (29 9511.0 DEG INITIAL TENSION = 4080 LBS (21 00)11 ULTIMATE STRENGTH 19430 LBS

A - LEVEL GROUND SPAN =	446.5
B - GROUND CLEARANCE =	25
C - SAG IN LG SPAN	11.25
D - HT ABOVE GR OF LOWEST COND =	36.25
E - DIST FROM POLE TOP TO COND =	6.75

SAG TEMPLATE SCALE 40/400

Fig. B-6 Sag template for TH-1AM design

Appendix C

Basic Electricity

Basic Electric Circuit

The basic circuit for transmitting electrical energy must consist of two paths or conductors, one sending and the other a return, together forming a continuous path or a closed circuit for the electric current to flow. This holds for both DC and AC systems.

The conductors or wires in an electric circuit can be thought of as electrical pipes through which flow a stream of electrons, constituting a flow of electricity (refer to chap. 1 for a water analogy).

Electric Pressure or Voltage

For the electrons to stream through the wires, an electrical pressure is necessary. This pressure can be created by a generator that may be likened to a pump. The electrical pressure is expressed in volts (named in honor of the Italian physicist Alessandro Volta).

Current or Amperage

Electric current is the rate of flow of electrons in a circuit. Similar to the flow of water measured in gallons or liters per second, the number of electrons passing a reference point in 1 second determines the current strength. This is expressed in amperes (named after the French physicist André-Marie Ampère). Scientific measurement has determined that 6.29 billion electrons passing in 1 second make up 1 ampere.

Resistance

Just as water flowing in a pipe is resisted by friction between the water and the pipe, electrons encounter resistance to their flow in conductors. A fixed volume of water encounters less resistance to its flow in a large diameter pipe than in one of small diameter. This is also true for electric current: a fixed value of electric current will encounter less resistance in a large diameter conductor than in one of small diameter. The electrical resistance is expressed in ohms (after Georg Simon Ohm, the German physicist).

Ohm's Law

In any electrical circuit, the three factors of pressure, current, and resistance are interrelated.

In a circuit, the current flow will vary directly with the pressure applied, and inversely with the resistance of the circuit. This can be expressed as:

$$\text{Current in amperes} = \frac{\text{Pressure in volts}}{\text{Resistance in ohms}}$$

This is known as Ohm's Law. Expressed with variables, the law becomes:

$$I = \frac{E}{R}$$

where

I is the intensity of the current in amperes
E is the pressure in volts
R is the resistance in ohms

If any two quantities are known, the third may be found by applying this equation.

Types of Circuits

There are two basic types of electric circuits: the series circuit and the multiple or parallel circuit; other types are a combination of the two.

Series Circuit

In a series circuit, all the parts making up the circuit are connected in succession, so that the current through all of the parts is the same.

The circuit shown in Figure C-1 contains four resistances connected in series with the same current through each of them. Assume an electrical pressure or voltage of 120 volts (V) is applied across the terminals of the circuit and a current of 6 amperes (A) flows through the circuit. Then, by Ohm's Law, the total resistance of the circuit will be found to be 20 ohms (Ω); that is:

$$I = \frac{E}{R} \text{ or } 6 = \frac{120}{R}; \text{ solving for } R = \frac{120}{6} = 20 \text{ ohms}$$

Voltages measured across each of the four resistances (R_1, R_2, R_3, and R_4) shown are found to be:

$$E_1 = 18 \text{ V}; E_2 = 30 \text{ V}; E_3 = 48 \text{ V}; E_4 = 24 \text{ V}$$

Applying Ohm's Law to each part of the circuit, the resistance values can be found:

$$I = \frac{E}{R} \text{ from which } R = \frac{E}{I}$$

Hence

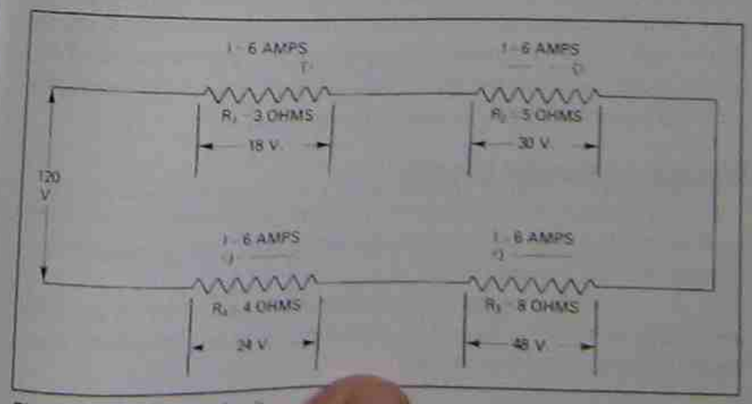


Fig. C-1 Simple series circuit

$$R_1 = \frac{18}{6} = 3 \text{ ohms} \quad R_2 = \frac{30}{6} = 5 \text{ ohms}$$

$$R_3 = \frac{48}{6} = 8 \text{ ohms} \quad R_4 = \frac{24}{6} = 4 \text{ ohms}$$

We can check these values. The sum of the four voltages across each of the resistance (the drop in pressure as the current flows in the resistance) will be:

$$E_1 + E_2 + E_3 + E_4 = E$$

or

$$18 \text{ V} + 30 \text{ V} + 48 \text{ V} + 24 \text{ V} = 120 \text{ V}$$

The sum of the separate resistances is equal to the total resistance:

or $$R_1 + R_2 + R_3 + R_4 = R$$

$$3 \text{ ohms} + 5 \text{ ohms} + 8 \text{ ohms} + 4 \text{ ohms} = 20 \text{ ohms}$$

Note that there is a drop in voltage through each resistance. From Ohm's Law, this drop will be the product of the current and resistance, that is $E = IR$, and is usually referred to as the IR drop. Note also that the voltage drop in each part is proportional to its resistance and that the sum of all the voltage drops is equal to the applied voltage. (Resistance of the connecting wires has been neglected for purposes of illustration.)

Multiple or Parallel Circuits

In a multiple or parallel circuit, all of the components are connected so as to receive full line voltage, and the current that flows in each component depends on its resistance.

If the same four resistances are connected in parallel across the same line voltage, as shown in Figure C-2, applying Ohm's Law, the currents flowing in each resistance have the following values:

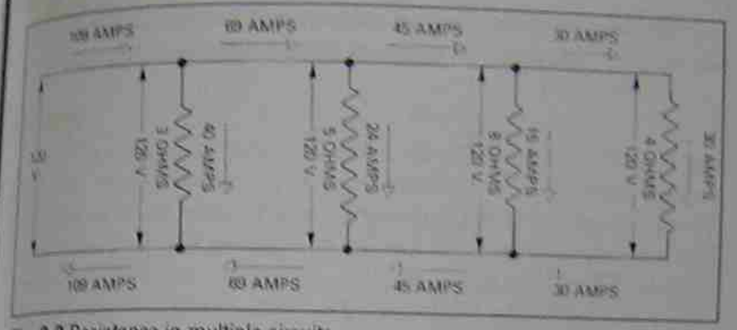


Fig. C-2 Resistance in multiple circuits

Since

$$R_1 = 3 \text{ ohms}, I_1 = \frac{E}{R_1} = \frac{120}{3} = 40 \text{ amperes}$$

$$R_2 = 5 \text{ ohms}, I_2 = \frac{E}{R_2} = \frac{120}{5} = 24 \text{ amperes}$$

$$R_3 = 8 \text{ ohms}, I_3 = \frac{E}{R_3} = \frac{120}{8} = 15 \text{ amperes}$$

$$R_4 = 4 \text{ ohms}, I_4 = \frac{E}{R_4} = \frac{120}{4} = 30 \text{ amperes}$$

The total current will be:

$$I_1 + I_2 + I_3 + I_4 = I$$

or

$$40 \text{ amperes} + 24 \text{ amperes} + 15 \text{ amperes} + 30 \text{ amperes} = 109 \text{ amperes}$$

The resistance of the entire circuit, applying Ohm's Law, will be:

$$R = \frac{E}{I} = \frac{120}{109} = 1.101 \text{ ohms}$$

Another way of obtaining the same result is to add the reciprocals of each resistance and taking the reciprocal of the sum of the reciprocals.

$$\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} = R$$

$$\frac{1}{3} + \frac{1}{5} + \frac{1}{8} + \frac{1}{4} = \frac{1}{R}$$

$$0.333 + 0.200 + 0.125 + 0.250 = 0.908$$

$$R = \frac{1}{0.908} = 1.101 \text{ ohms}$$

Note that the resultant resistance is always less than the smallest of the component resistances. Each additional resistance connected in parallel adds an additional path for the current to flow; as the conducting paths are increased, the total resistance is lowered.

Series-Parallel Circuit

An example of resistances connected in series-parallel is shown in Figure C-3. To obtain the total resistance of this circuit, the resultant resistance of each of the parallel groups is first determined, then added to the resistances in series. The same process applies to any number and kind of groups of resistances.

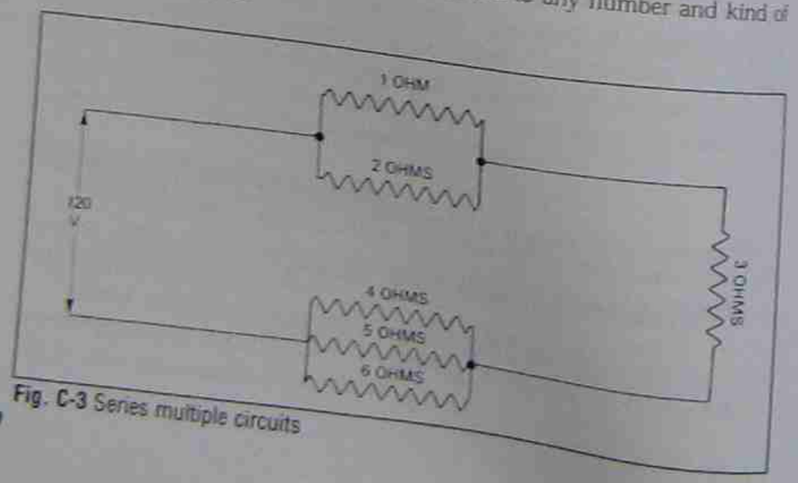


Fig. C-3 Series multiple circuits

Exercise C.1: Find the voltages across each of the resistances, the currents flowing in them, and the total resistance of the circuit.

Power

When electricity flows through a resistance, electrical energy is consumed in that resistance. The *rate* of consumption of electrical energy is known as electrical power. The unit of electrical power is called the watt (W) (after James Watt, the developer of the steam engine). The watt is too small for practical purposes, and the kilowatt (kW—equal to 1,000 W) is most frequently used.

Power is the *rate* of doing work. Electrically, this depends on the electrical pressure applied and the current flowing in a device, represented as a resistance. Hence:

$$\text{Power (W)} = \text{Pressure (V)} \times \text{Current (A)}$$

By experiment, it is found that 746 W of electrical power are equivalent to 1 horsepower (hp) of mechanical power.

Energy

Since power is the rate of expending energy, then energy expended will be the product of power and the time it is applied:

$$\text{Energy} = \text{Power} \times \text{Time}$$

Time may be expressed in any unit: seconds, minutes, hours, days, etc. The common unit is the hour (hr); hence:

$$\text{Energy} = \text{Power (kW)} \times \text{Time (hr)}$$

The most commonly used unit of electrical energy is the kilowatt-hour (kWh).

Heat Loss

When power flowing in a circuit does not produce useful work, that is, where the electrical energy is not converted to some mechanical work, it is converted into heat. This heat is dissipated into the surrounding atmosphere,

Owing to the electrical resistance encountered, a loss be likened to the loss encountered by traffic and represents a loss. This may be determined by applying Ohms Law:

P

Power (W) = Voltage × Current, or W = E × I

and

Voltage = Current × Resistance, or E = IR

then

Power (W) = Voltage (E) × Current (I)
W = (R × I)
W = I²R

This represents the rate of energy loss given off as heat, actual energy loss multiplies this value by the time it is dependant and is measured in watt-hours.

Note that if the current (I) flowing in a resistance (conductor) is doubled, the heat loss is not doubled, but quadrupled.

In overcoming power loss two basic concepts, two factors must be considered:

1. The voltage (dE) drop in the line must not be so great that insufficient electrical pressure or voltage will reach at the receiving end.
2. The power (I²R) loss in the line must not be so great that when means of supplying power may prove most economical. (The energies would be set up a generating plant at or near the receiving end and transport that there.)

Inductance

There is a basic relationship between electricity and magnetism. As electric current flowing in a conductor will produce a magnetic field around it. A conductor cutting the magnetic field will have an electric voltage

induced in it, and a current will flow if the conductor is part of a circuit. In either case, the magnitude of the voltage produced depends on the length of the conductor cutting the field. It also depends on the speed at which the conductor cuts the magnetic field, and the density of the magnetic field.

An AC carrying conductor will have a magnetic field around it that produces its characteristics as the current in the conductor alternates with a frequency. The magnetic field builds up to a maximum in one direction, around as it builds up to a maximum in the opposite direction, and again around as it, completing one cycle. (Frequency is the number of such cycles or cycles, occurring in 1 second.)

Self-Inductance

The alternating magnetic field around the conductor will cut the conductor, inducing in it a voltage distinct from that causing the original current to flow. This induced voltage will also produce a current flow, as it too, affects the original current. This, in turn, affects the magnetic field around the conductor, thus affecting the entire relationship that finally stabilizes at some point.

The currents flowing in the conductor, the original and induced, are not in step, or "in phase." In other words, the rising and falling of their cycles do not coincide. These relationship may be shown as Figure C-8, the two voltage waves will be displaced a quarter cycle from each other. Actually of course, only the one resultant voltage exists in the conductor.

The current values, however, still reach their maximum and 0 values as they did originally. The net effect of the reactive in the conductor is to cause the current to "lag" behind the voltage, as illustrated in Figure C-8c. It will be noted that now the current and voltages do not act together throughout the cycle. Only some portion of the current will act in conjunction with the voltage. The power produced then will be the product of the voltage and current values at any particular point and not the product of the voltage and current values acting together, or "in phase." The ratio of the true quantity to the latter is known as the "power factor."

Mutual Inductance

The same reaction may be caused by the magnetic fields of adjacent conductors and, since both conductors affect each other, it is called "mutual inductance" (see Fig. C-9).

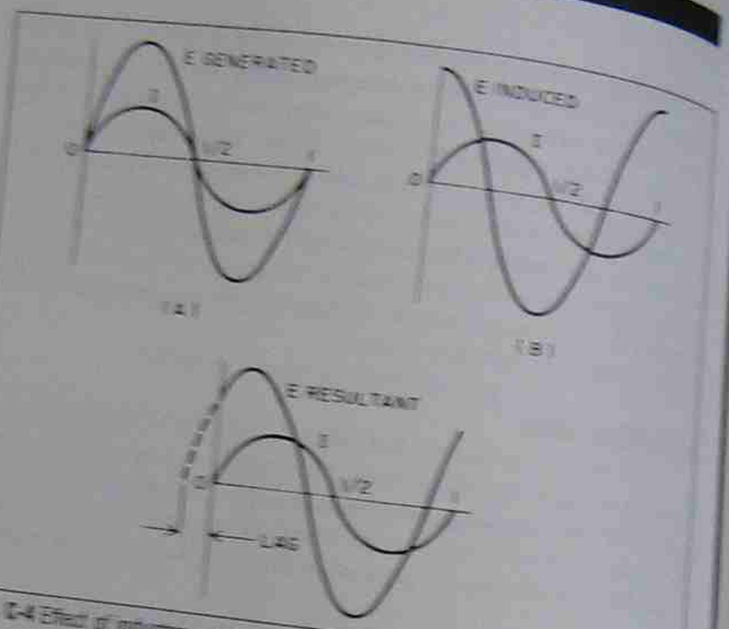


Fig. C-4 Effect of inductance on voltage and current in a conductor (not to scale)

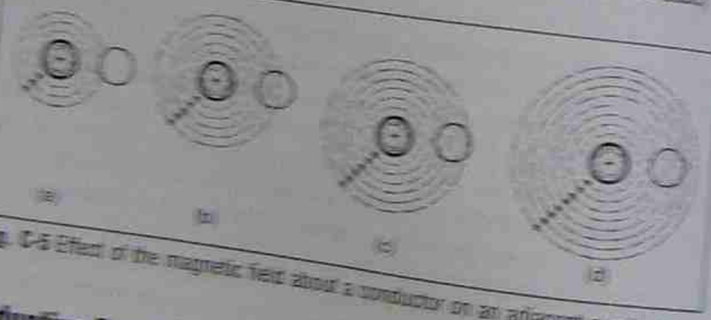


Fig. C-5 Effect of the magnetic field about a conductor on an adjacent conductor

Inductive Reactance

The effect of this inductance is to act as an obstruction to the flow of current in a circuit, similar to, but greatly different than, the effect of resistance. Such an obstruction is known as the "reactance" of the circuit and is also expressed in ohms. (To avoid confusion, the letter *R* is used to denote resistance and *X*_L to denote reactance due to inductance.)

Ohm's Law can also be used to find the current flow in an inductive circuit, assuming the circuit has no resistance. Hence:

$$I = \frac{E}{X_L}$$

Note, however, that when only inductance obstructs the flow of electricity, the current wave "lags" the voltage wave by a quarter cycle (see fig. C-4b).

Resistance and Inductance

We can apply Ohm's Law to each of two circuits, one containing resistance only, the other inductive reactance only. Assuming a voltage of 120 V is applied to each, respectively, an obstruction equivalent to 2 Ω, then:

$$I = \frac{E}{R} = \frac{120}{2} = 60 \text{ amperes} \qquad I_L = \frac{E}{X_L} = \frac{120}{2} = 60 \text{ amperes}$$

Now assume a circuit that has a combination of both resistance and inductive reactance, with the same values indicated above. With a voltage of 120 V applied, the current will be found to be 42.6 A. By Ohm's Law:

$$R = \frac{120}{42.6} = 2.82 \text{ ohms}$$

The resultant obstruction to the flow of electricity is greater than either the resistance or the inductive reactance (each 2 Ω) but is not equal to the arithmetic sum (4 Ω). By analysis, it will be found that the resultant obstruction may be found by obtaining the square root of the sum of the squared values of resistance and inductive reactance:

$$Z = \sqrt{R^2 + X_L^2} \quad \text{or} \quad \sqrt{2^2 + 2} = \sqrt{8} = 2.83 \text{ ohms}$$

where

Z is the resultant obstruction (referred to as "impedance" to differentiate it from its component resistance and inductive reactance)

From Figure C-6b it will be noted that when resistance is combined

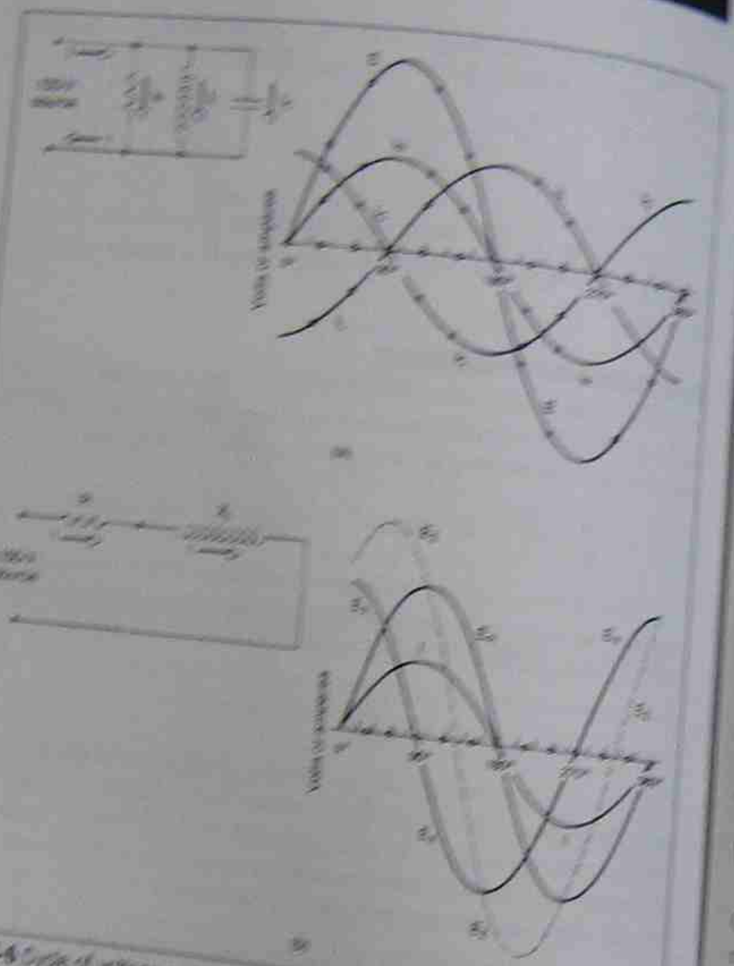


Fig. C-6 Cycle of voltage and current values: (a) resistance, inductance, and capacitance in parallel; (b) resistance and inductance in series

with inductance, the current lags the voltage wave less than when the circuit consisted only inductance. As more resistance is added, the current and voltage waves will closely approach each other.

Capacitance

There is another reaction that occurs in AC-carrying conductors that is not due to the magnetic fields around them. This is an electrostatic effect that takes place between conductors. During one-half cycle of the alternation, there will be a scarcity of electrons in a conductor (with reference to a fixed point), and it will tend to attract electrons from an adjacent conductor. During the next half cycle, a reverse action takes place—an excess of electrons in the conductor, and a tendency for electrons to flow to the adjacent conductor. Thus a to-and-fro, or alternating, circulation of electrons is set up in the second conductor; that is, an AC is set up in the second conductor.

If both conductors carry AC, they will react on each other as described above. The amount of this reaction is called "capacitance" and will depend on the areas of the conductors exposed to each other. The distance and kind of insulating material between them and the number of electrons involved depend on the voltage or current in the conductor.

Similar to inductance, capacitance will set up a distinct current in the conductor that will be displaced by a quarter cycle from the normal line current. In this case, however, the current will "lead" the voltage wave by a quarter cycle (see Fig. C-7).

Such obstruction of the capacitance or capacitor to the flow of electricity in a conductor is referred to as capacitive reactance and is also measured in ohms. Capacitive reactance is denoted by the letters X_c to distinguish it from other quantities.

Water Analogy of a Capacitor

A water analogy can be used in the discussion of capacitors (see Fig. C-8). As the pump moves to the right, water flows in the top pipe to the cylinder at the right. The flexible diaphragm in the cylinder will move to the right (as shown), transmitting its motion to the water to its right during the motion of the pump. In the leftward motion of the pump, the reverse action takes place. The net result is that an alternating flow of water is set up in both the pipes, without a direct connection between the water in the lower pipe and that in the upper pipe.

In the process, because of the flexibility of the diaphragm, the current of water will tend to arrive at the undisturbed diaphragm before the pump completes its stroke in one direction. This may be observed by the relative positions of the driving motor on the left and the water in the pipes driving a

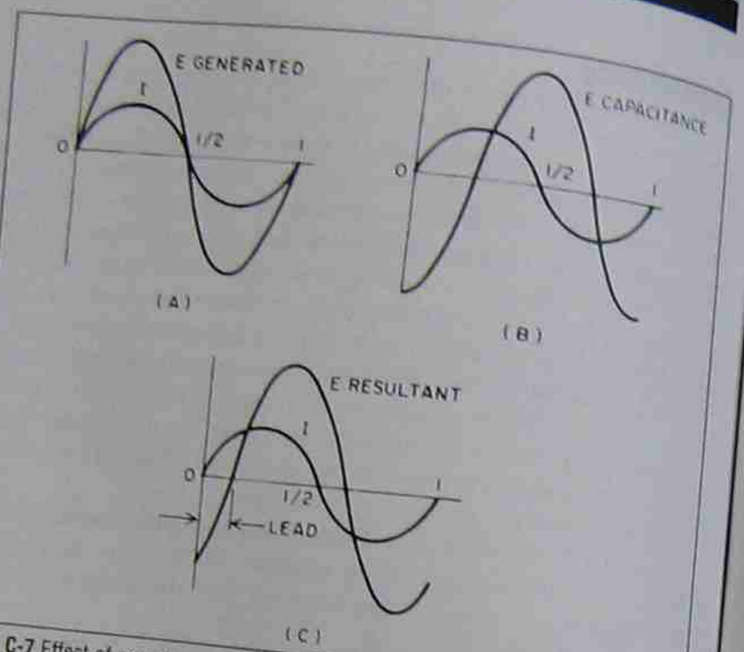


Fig. C-7 Effect of capacitance on voltage and current in a conductor (not to scale)

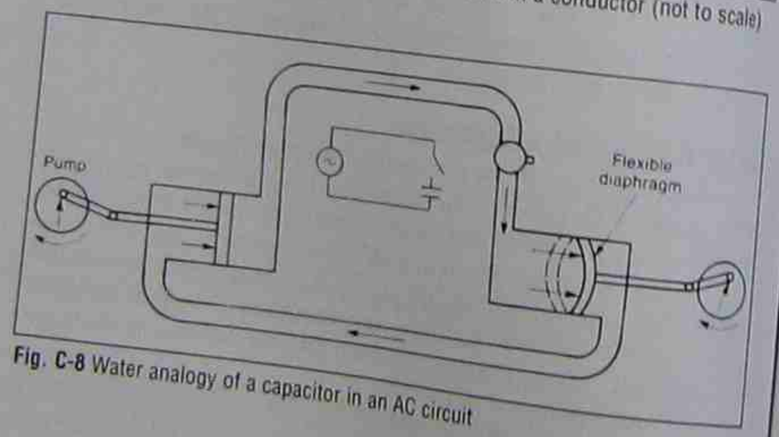


Fig. C-8 Water analogy of a capacitor in an AC circuit

water motor. The current flow may be said to "lead," or act ahead of, the pressure being applied by the pump at the left. The mechanical stresses on the diaphragm, alternately compression on one side and elongation on the other, correspond to the electrostatic stresses on the dielectric in the capacitor.

Resistance and Capacitance

The same phenomenon as existed in an inductive circuit exists in the capacitive circuit, except that the obstructive effects are in opposition (180° apart). In a circuit containing both resistance and capacitance, the resulting obstruction is obtained in the same manner as for resistance and inductance. That is:

$$Z = \sqrt{R^2 + X_c^2}$$

In this case, the more resistance added, the closer the voltage and current waves will approach each other.

Impedance

The total obstruction to the flow of current in a circuit may be caused by resistance, inductance, and capacitance. The effects of inductance and capacitance are generally referred to as reactance. Hence, the combined effect of resistance and reactance is called the "impedance" of the circuit and, as already noted, is designated by the letter Z. For AC circuits, therefore, Ohm's Law becomes:

$$I = \frac{E}{Z}$$

Resistance, Inductance, and Capacitance

As mentioned earlier, the effects of inductance and capacitance are in direct opposition to each other. Hence, the net reactance will be the difference between the inductive reactance and capacitive reactance, that is:

$$X = X_L - X_C$$

The resultant impedance of a circuit containing resistance and reactance will then be:

$$Z = \sqrt{R^2 + X^2}$$

Or substituting:

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

The current flowing in the circuit will be calculated by Ohm's Law:

$$I = \frac{E}{Z} = \frac{E}{\sqrt{R^2 + (X_L - X_C)^2}}$$

Resonance

It is evident that if $X_L = X_C$, the only quantity left will be R, the resistance. When this condition occurs, the circuit is said to be in "resonance."

The relative value of resistance, inductance, and capacitance of a circuit will determine the relative position of the current wave with respect to the voltage wave.

Power in AC Circuits

As mentioned earlier, power is the rate at which electrical energy is transformed into heat or mechanical energy and is equal to the product of the voltage and current. In an AC circuit, the change of energy at any moment is the product of voltage and current at that instant. Power values for circuits having only resistance, only inductance, and only capacitance are shown in Figure C-9. Note that real power is produced only in the resistance circuit. In the inductance and capacitance circuits, the net result of the power curves is 0. In other words, the areas under the curves above the axis are exactly equal to those below the axis.

In both the inductance and capacitance circuits, electric energy is stored in the magnetic and electrostatic fields during the time the current is increasing. The energy is returned back to the circuits when the current is decreasing.

Power Factor

As indicated earlier, the product of voltage and current does not indicate the true power flow in the circuit. Such a product is termed "apparent

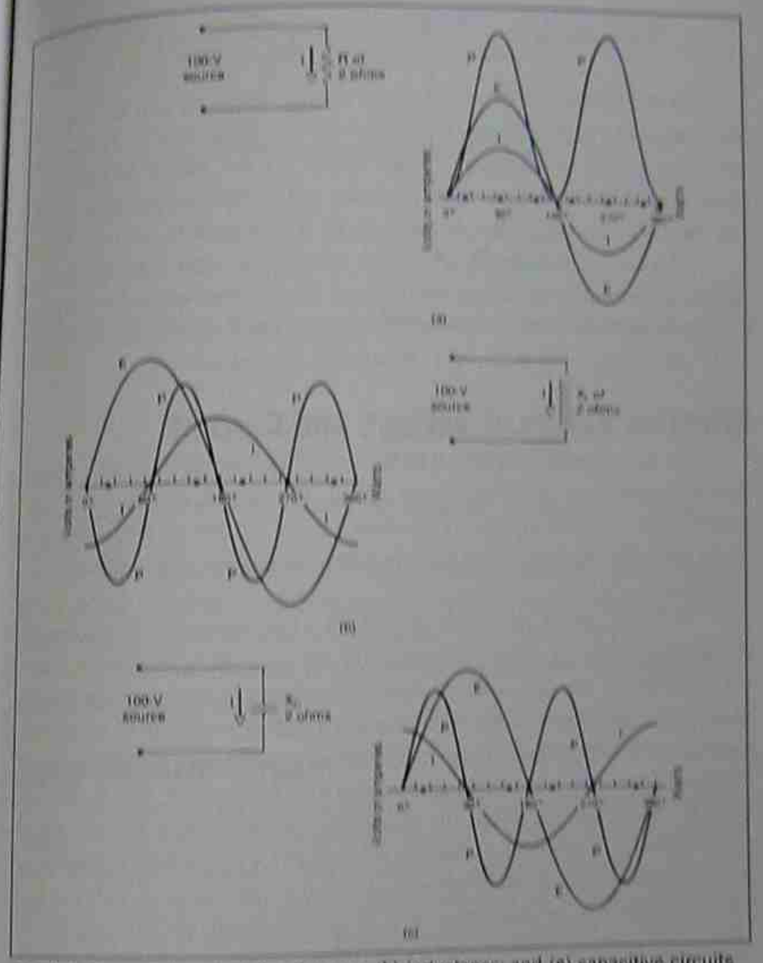


Fig. C-9 Power values in (a) resistance; (b) inductance; and (c) capacitive circuits

power" and is expressed in volt-amperes, or kilovolt-amperes (kVA), instead of watts or kilowatts (kW). To calculate the true or real power, the apparent power is multiplied by a factor called the "power factor."

The power factor of a circuit is the ratio between the true and the apparent power and is usually expressed as a decimal or percent.

$$\text{Power Factor} = \frac{\text{True power}}{\text{Apparent power}} = \frac{\text{Watts}}{\text{Volt-amperes}} = \frac{\text{kW}}{\text{kVA}}$$

In the resistance circuit, all of the energy delivered to it is converted into heat or mechanical energy. Consequently, the true power and the apparent power are the same, and the power factor is 1 (or 100%). In the inductance or capacitance circuit, the true power is 0, while the apparent power may have a value. The power factor for both, however, is 0, or 0%.

In a circuit containing resistance, inductance, and capacitance, the real power and apparent power are unequal. Thus the power factor will have a value somewhere between 0 and 100%, depending on the relative values of the resistance, inductance, and capacitance components.

Effective Values of Voltage and Current

As mentioned earlier, when an electric current flows through a circuit, heat is generated or produced in the circuit. The rate at which heat is produced in the circuit is equal to I^2R; where I is the current in amperes and R is the resistance in ohms. This heating effect takes place when either AC or DC flows.

In an AC circuit, the rate at which heat is being generated is constantly changing because the current is constantly changing. In a DC circuit, when a current flows, the rate at which heat is developed is constant (for a fixed value of current) because the direct current remains constant in value. For example, the alternating current that reaches a maximum value of 100 A would not have the same heating effect as a direct current of 100 A. To produce the same heating effect, the alternating current would have to be of such value that it reaches a maximum value of 141.4 A. Such a current varying according to a sine wave between 0 A and a maximum of 141.4 A has the same effective heating value as a direct (constant) current of 100 A. Hence, its "effective" value is said to be 100 A.

The same effective value is used for voltages. Thus an alternating (sine wave) voltage varying between 0 V and 141.4 V is said to have an "effective" value of 100 V.

Both alternating currents and voltages are usually expressed in terms of effective values. The ratio between the effective and maximum values is illustrated in Figure C-10. This ratio can be expressed in either of two ways:

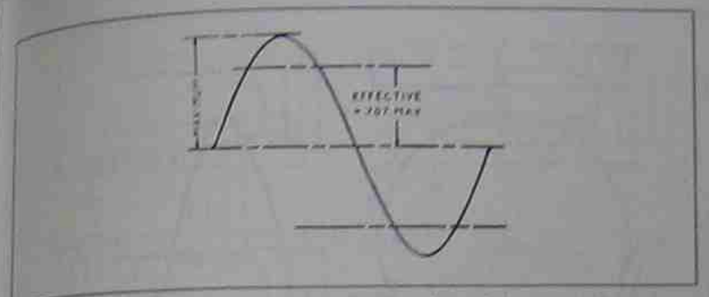


Fig. C-10 Ratio between maximum and effective values of sine wave voltage or current

$$\frac{\text{Effective value}}{\text{Maximum value}} = \frac{0.707 \times \text{Maximum value}}{1.414 \times \text{Effective value}}$$

Thus, if one value is known, the other can be easily determined.

The maximum value is an instantaneous value. Any other instantaneous values for other instants during the cycle can be determined by scaling off values from the curve of a sine wave.

AC instruments, such as ammeters and voltmeters, are calibrated to indicate effective values.

Basic Electric Circuit

The basic circuit for transmitting electrical energy consists of two paths or conductors, one sending and the other returning. This holds for both AC and DC systems. In DC systems, the voltage applied is continuous, and the current flows in one direction continuously. In AC systems the voltage applied rises from 0 to a maximum and drops back to 0. It then reverses its direction and goes through the same variations. A graph of this pattern is called a "sine wave" (see Fig. C-11). Current flows back and forth in a push-pull fashion with each half of the cycle doing productive work.

In the United States, systems operate at 60 cycles per second; that is, there are 60 of these push-pull flows each second. In other parts of the world, many systems operate at 50 cycles per second.

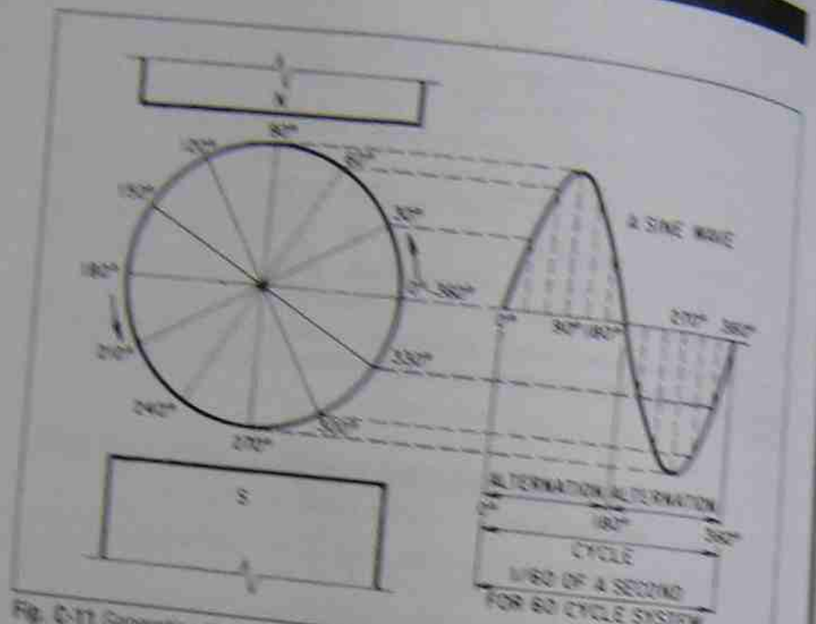


Fig. C-11 Generating the sine wave

Ground Neutral

One such two-wire circuit (see Fig. C-12), whether AC or DC, can carry a certain prescribed amount of power. For safety reasons, usually one conductor—the return—is grounded, that is, connected to earth. The voltage applied, then, can be specified as so many volts above or from ground.

If more transmitted power is desired, a second similar circuit can be added. In the latter circuit, the voltage applied can be in the reverse direction of the first, that is, so many volts below ground. If the first voltage applied is labeled positive, then the second can be labeled negative. It will be noted that both circuits have one conductor grounded; hence, these two ground, or return, conductors can be connected together. It will further be observed that the current in one return circuit opposes that of the other circuit. The common return—or neutral—conductor will now carry only the difference in magnitude of these two currents. The neutral conductor, therefore, need not be as large as either of the main conductors, resulting in economy.

Further, if both circuits carried exactly equal currents, the current in the neutral would be 0, and the neutral conductor could be eliminated,

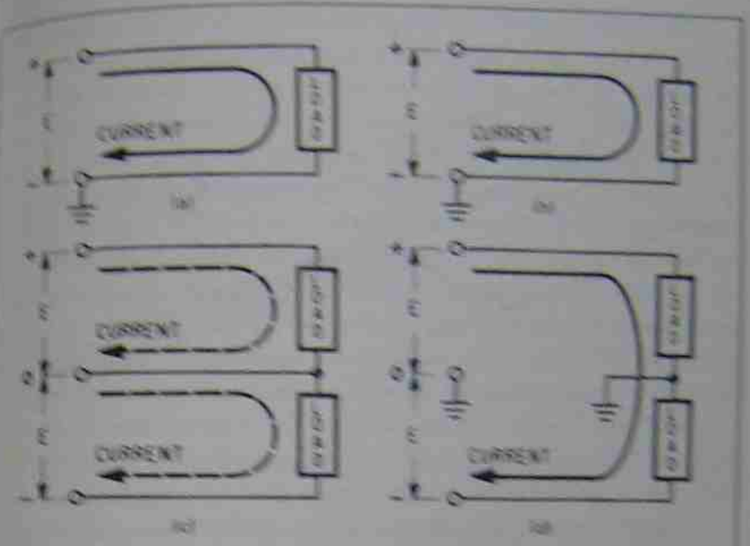


Fig. C-12 Effects of ground/neutral connections. (a) a schematic two-wire DC transmission line where E is voltage from the line to the supporting structure; (b) schematic DC transmission line using earth return; (c) three-wire DC system where current is cancelled in the center leg; (d) schematic ± E DC grounded transmission line with twice the current flow capacity of (a) and same insulation and conductor size

resulting in further economy. The voltage difference between both main conductors will now be double that for one. However, since each conductor carries insulation for its original voltage, the insulators existing between both conductors will be sufficient to sustain the double voltage.

Polyphase Systems

For AC systems, the power supplied can be delivered over more than two circuits, as described. These are known as polyphase (or multiphase) circuits. In a single-phase circuit, only one phase or set of voltages of sine-wave form is applied to the circuit and only one phase of sine-wave current flows in the circuit. In polyphase circuits, two or more phases or sets of sine-wave voltages are applied to the different portions of the circuits. A corresponding number of sine-wave currents will flow in these portions of the circuits.

The different systems of the polyphase circuits are usually called by 'phase.' Studies indicate an economic and practical arrangement is to have this number to three, and this is referred to as a three-phase circuit. Practically all AC transmission systems are three phase and have three current carrying conductors. The phases are usually labeled to identify them as the "A" phase, "B" phase, and "C" phase. The voltages applied to the separate phases of the circuit are correspondingly referred to as the "A-phase voltage" the "B phase voltage," etc. The phase currents are similarly identified.

In a three phase circuit, the alternating pulses of electricity are displaced one from another by 120°, that is, one complete cycle is considered to represent 360°. Then, if the voltage in one conductor (A) starts at zero, its voltage in a second conductor (B) with reference to the first will begin its cycle 120° later. That in the third conductor (C), with reference to the first will begin 240° later (see Fig. C-13). The fundamental principles of the flow of AC are the same whether applied to single phase or polyphase circuits.

The voltages for polyphase systems are supplied from polyphase (usually) generators, each phase of voltage generated in a separate coil (or coils connected in parallel). The separate coils are arranged for connection in different ways to form the polyphase system. Two commonly used methods of connecting the coils of three phase generators to supply three phase transmission systems are shown in Figure C-14. One method employs the 'delta' connection, the other the "wye" or "star" connection.

Delta and Wye Connections

The voltages between the terminals or conductors of the two types of three phase systems are shown in Figure C-14. Note the voltages between the terminals are the same for both systems. In the delta system, the full line (full) voltage is imposed on the coils of the generator or motors whose coils are also connected in delta and that may be connected to the delta system. In the wye system, the voltage imposed on these coils is only 0.866 that of the delta system.

The common connection of the three phases in the wye system may be connected to a neutral or fourth conductor, or may be left as is to "float." The neutral wire may also be the fourth wire that carries the unbalance of the three such three phase circuits. In some cases, it is also connected to or serves as the neutral conductor for distribution circuits that may be installed on the same supporting structures.

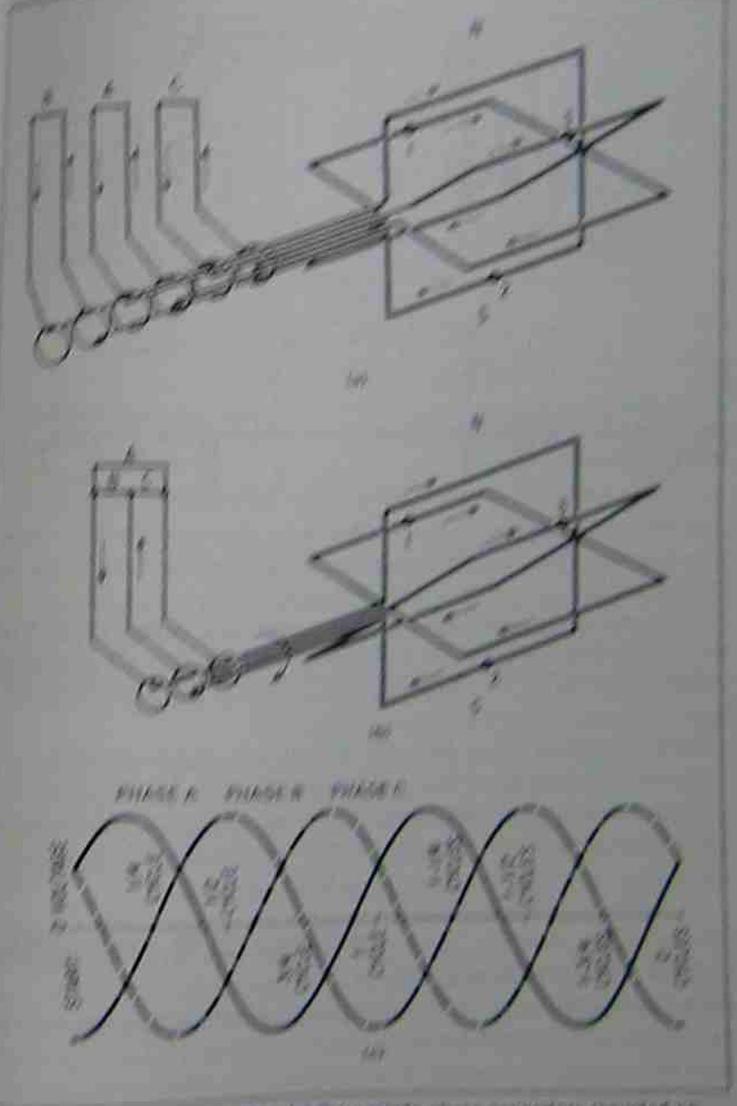


Fig. C-13 Three-phase generator. (a) three single phase generators mounted on the same shaft. (b) a three phase generator. (c) curves showing voltages in a three phase generator

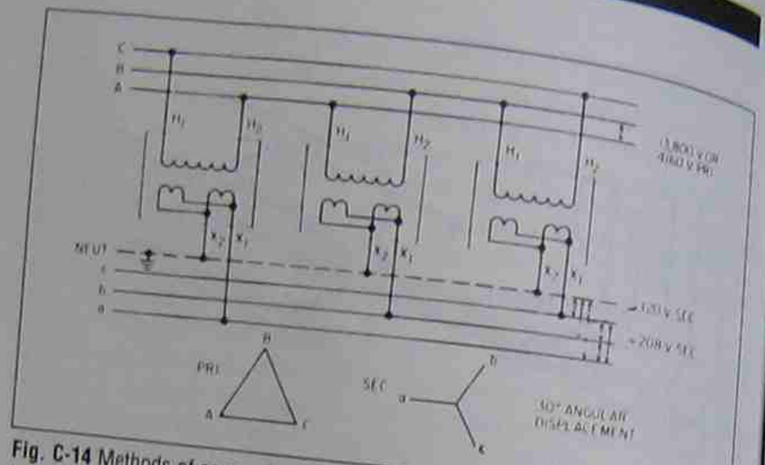


Fig. C-14 Methods of connection of generator (or motor) coils for three-phase systems

The coils connected in the delta system are subjected to higher voltages than coils in the wye system. As there is no ground connection, one or more grounds (faults) on only one phase will not affect the operation of the system. A second ground on another phase constitutes a short circuit.

In the wye system, while the coils have a lower voltage imposed on them, if the system is grounded, a ground (or fault) on any one phase constitutes a short circuit. This may cause the circuit to be deenergized with outages to consumers supplied from the circuit.

If the system is not grounded, a ground (or fault) will establish a "common" grounded point, not symmetrical to the circuit's three phases. The voltages on each phase become distorted. The voltage on the grounded phase may be lower than its nominal values, possibly causing damage from overvoltage to consumers supplied from those two phases.

Considering the supply of power to a motor or engine, DC provides a continuous and even flow, making for a smooth effort. With AC, or push-pull, the flow will build to a maximum and then subside (Fig. C-15). If all the power is supplied in one circuit or one phase, the resulting effort will be very rough. If it can be supplied in three parts or three phases, each one-third in magnitude but applied three times in a given time, the result is less rough. This is similar to hammering home a nail with one big blow, as opposed to using three blows, each one-third in magnitude; the effect is smoother.

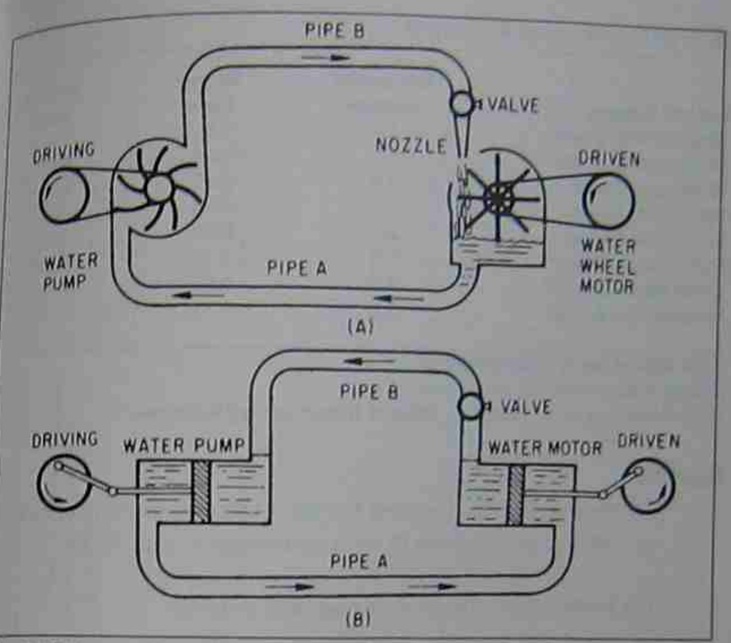


Fig. C-15 The need for using three-phase power: (**a**) smooth flow in one direction analogous to DC power flow; (**b**) reciprocating motion analogous to AC single-phase power flow (More cylinders would be analogous to three-phase power flow.)

Another analogy may be that of a large-bore, two-cylinder engine compared to a small-bore, six-cylinder engine in an automobile. The power of both engines is the same, but the latter drives more smoothly than the former. Hence, three-phase power transmission is usually specified in AC systems.

Comparison of AC Systems

Comparisons of the various AC systems assuming the same (balanced) load, the same voltage between conductors, and the same conductor size are shown in Table C-1 and Table C–2. Using a single-phase, two-wire circuit as a basis for comparison, the relative amount of conductor, power loss, and voltage drop for the different types are shown.

Table C-1 Comparison of AC Systems

Type of System	Conductor Amount	Power Loss	Voltage Drop
Single-phase, 2-wire	1.0	1.0	1.0
Single-phase, 3-wire	1.5	0.25	0.25
Two-phase, 3-wire	1.5	0.50	0.50
Two-phase, 4-wire	2.0	0.50	0.50
Two-phase, 5-wire	2.5	0.50	0.50
Three-phase, 3-wire*	1.5	0.167	0.86
Three-phase, 3-wire**	1.5	0.50	0.167
Three-phase, 4-wire*	2.0	0.167	0.50
			0.167

*Wye voltage same as single-phase
**Delta voltage same as single-phase
More detail is given in Table C-2, Table of Transmission Efficiencies

Review

- Electrical pressure is measured in volts. Current is given in ampere resistance in ohms, power in watts, and energy in watt-hours.
- The relationship between these quantities is useful:

$$\text{Ohm's Law: (Current amperes)} = \frac{\text{Pressure (volts)}}{\text{Resistance (ohms)}}$$

$$\text{Power (watts)} = \text{Pressure (volts)} \times \text{Current (amperes)}$$

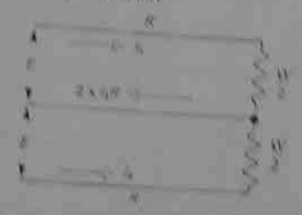
$$\text{Energy (watt-hours)} = \text{Power (watts)} \times \text{Time (hours)}$$

- Electricity requires a complete circuit to flow. The two kinds of circuits are the series circuit and the multiple or parallel circuit. The series-parallel circuit is a combination of the two.
- In a series circuit, the same current flows in each of the components. In a multiple circuit, the voltage across each of the components is the same.
- Power is the rate of expending energy. Energy is the expenditure of power over a period of time.

Table C-2 Transmission Efficiencies

Table C-2 Transmission Efficiencies (continued)

4. Two-Phase, 3-wire



$I_L = \sim I_1$

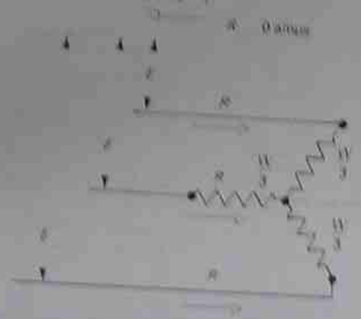
$I_1^2 = 2R + (\sqrt{2}I_1)^2R$
$= I_1^2(2R + 2R)$
$= 4I_1^2R$
$\therefore I_1^2 = I_1^2R$
$= \sim(2I_1^2R)$

$I_1R = \sqrt{2}I_1R$
$= I_1R + 1.41\ I_1R$
$= 2.42\ I_1R$
$= 2.42I_1^2R$
$= 1.21 \times I_1R$
$=$ approx $\sim(2I_1^2R)$

5. Two-Phase, 5-wire

Since loads are balanced, no current will flow in the fifth or neutral wire. Hence, current, power loss, and voltage drop will be the same as for the Two-Phase, 4-wire system; refer to item 3 above.

6. Three-Phase, 3-wire – Δ



$I_L = \frac{I_1}{\sqrt{3}}$

$I_L^2 \times R \times 3$
$= \left(\frac{I_1}{\sqrt{3}}\right)^2 \times R \times 3$
$= \frac{1}{3} I_1^2R$
or $\frac{1}{6}(2I_1^2R)$

$I_L \times R = \frac{I_1}{\sqrt{3}}R$
$= \frac{1}{3}(2I_1R)$

Table C-2 Transmission Efficiencies (continued)

Type of Circuit	Current in Conductor	Power Loss (I^2R) in Conductor	Voltage Drop (IR)
7. Three-Phase, 3-wire	$I = \frac{I_1}{\sqrt{3}}$	$I_L^2 \times R \times 3$ $= \left(\frac{1}{\sqrt{3}}\right)^2 \times R \times 3$ $= I_1^2R$ or $\sim(2I_1^2R)$	$I_L \times R = \frac{I_1}{\sqrt{3}}R$ $= \frac{1}{3\sqrt{3}}(2I_1R)$ *
8. Three-Phase, 4-wire – Y	Since loads are balanced, no current will flow in the fourth or neutral wire. Hence, current, power loss, and voltage drop will be the same as for Three-Phase, 3-wire – Y system; refer to item 6.		

*Based on fixed, balanced loads at power factor of 1.0 and same wire size.

*For comparison, this value should be multiplied by $\sqrt{3}$ because line to neutral voltage in this case is only $\frac{1}{\sqrt{3}}$ of E assumed in case 1. Therefore, comparative voltage drop $= \sim(2I_1R)$

- Current in a wire produces heat and a loss or drop in voltage.

- Inductance is the obstruction to the flow of current in an AC circuit caused by magnetic lines of force cutting it. These lines of force may be produced by the current flowing in the conductor itself, or by an adjacent conductor. The first is called self-inductance, the latter mutual inductance. They are expressed in ohms.

- Capacitance is the obstruction to the flow of current in an AC circuit caused by electrostatic fields set up by adjacent conductors, it is expressed in ohms.

- Inductance and capacitance in an AC circuit cause the current and voltage to be displaced from each other and not to act together when producing power.

- Impedance is the net result of the action of resistance, inductance, and capacitance in an AC circuit; it is expressed in ohms. Ohm's Law for AC becomes:

$$\text{Current (amperes)} = \frac{\text{Pressure (volts)}}{\text{Impedance (ohms)}}$$

$$\text{Power (watts)} = \text{Pressure (volts)} \times \text{Current (amperes)} \times \text{Power factor (percent)}$$

- Power factor is the ratio of real power to apparent power; it is expressed in percent.

- The effective value of an AC sine-wave voltage or current is 70.7% of the maximum value of the sine wave and is equal to the effective value of DC voltage or current values.

- The basic circuit (either DC or AC) consists of two wires, a sending one and a return.

- In an AC circuit, power may be delivered over two or three circuits or phases whose voltages are displaced electrically by 120° for three-phase circuits.

Study Questions

1. What are the units of electrical pressure, current, and resistance?
2. Express the relationship between the three quantities in a simple electric circuit. What name is given to this relationship?
3. What are the two basic types of electric circuits? How do they differ?
4. What is the difference between power and energy?
5. What two factors must be considered in transmitting power a great distance?
6. How may a voltage be induced in a conductor? On what factors does the magnitude of the induced voltage depend?
7. What is meant by inductance? What is meant by capacitance? What effect do they have on the relationship between voltage and current in a circuit?
8. What is meant by impedance? How is Ohm's Law affected by alternating currents? What is meant by resonance?
9. What is meant by power factor in an AC system? How is it expressed?
10. What is meant by a single-phase circuit? By a polyphase circuit? What are the advantages and disadvantages of each?

Appendix **D**

Electrical Power Glossary

Accuracy. The extent to which a given measurement agrees with a standard defined value. For revenue metering, public service authorities require stringent, very high degrees of accuracy in watt-hour and demand meters. These include pre-installation testing and calibration as well as periodic testing, which may be done on a sampling basis for electric utilities. Remote meter reading devices must also meet both the utility standard and public service authority standards for accuracy.

ACSR. Aluminum cable, steel reinforced.

Adjustment clauses. A clause or series of clauses in a rate schedule (tariff) that permits a utility to charge for changes in fuel costs, temperature deviations from normal, cost of purchased power, ratchet demands, etc.

Allocation. The procedural step in a cost of service study whereby joint costs are allocated among consumer classes based on demand, energy or some other cost-related feature of service.

Allowable costs. Expenses that are allowed as operating costs chargeable to the consumers; certain other costs are chargeable to the stockholders or other owners.

Ammeter. An instrument to measure current flow, usually indicating in amperes. Where current is measured in milliamperes (1/1,000 of an ampere), the instrument may be called a milliammeter.

Ampere (amp). The unit of measurement of electric current. It is proportional to the quantity of electrons flowing through a conductor past a given point in 1 second. It is the unit current produced in a circuit by 1 volt acting across a resistance of 1 ohm.

ASE cable. A variant of SE cable in which a flat, steel strip is inserted between the neutral conductor and the outside braid for greater mechanical strength.

Automatic meter reading. A method of reading a meter (watt-hour, demand, gas, water, or any other type of meter), preparing and conditioning the data, and transmitting the accumulated information from the meter location back to a central data accumulation device. This central collection device in most cases is some form of computer. The communication link may be radio, telephone line, power line carrier, cablevision, or any combination thereof.

Average annual electric bill. Annual electric revenue from a class of service divided by the average number of such consumers for the 12-month period.

Average cost. A method of determining the cost of providing service to the various consumer classes. Average cost-of-service figures may be used in setting rates. Average costs are total costs divided by the number of units produced. This method, while distinguishing costs between different consumer classes, fails to recognize that not all kilowatts and kilowatt-hours are produced at the same cost within one consumer class. Seasonal, time-of-day, and marginal cost-based rates more accurately reflect the true costs of producing each kilowatt or kilowatt-hour.

Avoided costs. The costs an electric utility would otherwise incur to generate power if it did not purchase power from another source.

Basic reference standards. Those standards with which the value of electrical units are maintained in a laboratory and which serve as the starting point of the chain of sequential measurements carried out in the laboratory.

Bolometer. A device used for measuring heat at a distance, used to patrol electrical lines and locate hot spots before failure occurs.

Bottom-connected meter. A meter having a bottom-connection terminal assembly. Also referred to as an A-base meter.

Capability. In general, the maximum load in amperes, kW, or kVA that a system or a component of a system can carry without exceeding its design limits. They are usually defined as being normal or emergency limits. Normal limits are those that can meet expected conditions in the normal operation of the system without damage to the facility or without incurring a significant loss of expected life of the item. Emergency capability is some level above the normal limit that takes into account specific conditions of ambient temperature, preceding loading, and a calculated loss of life of the equipment.

Capacitance. That property of an electric circuit that allows storage of energy and exists whenever two conductors are in close proximity but separated by an insulation or dielectric material. When direct voltage is impressed on the conductors, a current flows momentarily while energy is being stored in the dielectric material. It stops when electrical equilibrium is reached. With an alternating voltage between the conductors, the capacitive energy is transferred to and from the dielectric material, resulting in an alternating current flow in the circuit.

Central station. Control equipment, typically a computer system, which can communicate with metering and load-control devices. The equipment may also interpret and process data, accept data from other sources, and prepare reports or consumer bills.

Class designation. The maximum of the watt-hour meter load range in amperes.

Connection charge. An amount to be paid by the consumer in a lump sum, or in installments, for connecting a consumer's facilities to the electric system.

Constant kilowatt hour. Pertaining to a meter (register constant, dial constant): the multiplier applied to the register reading to obtain kilowatt-hours.

Corona discharge. A luminous effect from the discharge of electrical energy on the surface of a conductor. Corona discharge occurs when the conductor carries voltage exceeding a critical value.

Creep. For mechanical meters, a continuous motion of the rotor of the meter with normal operating voltage applied and the load terminals open-circuited. For electronic meters, a continuous accumulation of data in a consumption register when no power is being consumed.

Demand. The rate at which electric energy is delivered to or by a system, part of a system, or a piece of equipment. It is expressed in kilowatts, kilovolt-amperes, or other suitable unit at a given instant or averaged over any designated period of time. The primary source of demand is the power-consuming equipment and devices of consumers.

Demand charge. That portion of the charge for electric service based on the peak load furnished within a time period according to the established tariff.

Demand constant. Pertaining to pulse receivers, the value of the measured quantity for each received pulse, divided by the demand interval, expressed in kilowatts per pulse, kilovars per pulse, or other suitable units. The demand interval must be expressed in parts of an hour such as 1/4 for a 15-minute interval or 1-1/2 for a 5-minute interval.

Demand interval. The period of time during which the electric energy flow is averaged in determining demand, such as 60 minutes, 30 minutes, 15 minutes, or instantaneously.

Demand meter. A metering device that indicates or records the demand and/or the maximum demand, or both. Since demand involves both an electrical factor and a time factor, mechanisms responsive to each of these factors are required, as well as an indicating or recording mechanism. These mechanisms may be either separate from or structurally combined with one another. An alternative mode would be to have a computer interpret and calculate the desired demand.

Demand register. A mechanism (for use with an integrating electricity meter) that indicates maximum demand and also registers energy (or other integrated quantity).

Demand side management (DSM). The broad term for electric load management applying to utility actions, programs, and designs for the purpose of lowering system peaks and reducing energy consumption by the consumer as well as the utility system. There are direct actions and controls by the utility that result in immediate results to lower peaks and reduce energy requirements. There are also indirect (passive) programs requiring the cooperation and participation by the consumer to achieve similar results.

Detent. A device installed in a meter to prevent reverse rotation.

Dial-out capability. The ability of a meter to initiate communications with a central station, usually using telephone lines.

Disk constant. See watt-hour constant.

Disk position indicator. Also known as a "caterpillar," it is an indicator on the display of a solid state register that simulates rotation of a disk at a rate proportional to power.

Diversity. That characteristic of a variety of electric loads whereby individual maximum demands usually occur at different times. This permits design of capability to meet a demand reduced from the sum of all the individual peak demands.

Dump energy. Energy generated that cannot be stored or conserved when such energy is beyond the immediate use in a system. This energy is usually bid out to neighboring systems at a price less than the cost to produce it.

Electromagnet. A magnet in which the magnetic field is produced by an electric current. A common form of electromagnet is a coil of wire wound on a laminated iron core, such as the voltage coil of a watt-hour meter stator.

Embedded coil. A coil in close proximity to, and nested within, a current loop of a meter to measure the strength of a magnetic field and develop a voltage proportional to the flow of current.

Encoder. A device that converts a meter reading into a form suitable for communicating to a remote central location or to a portable recording device or remote dial.

Energy charge. That portion of the charge for electric service based on the energy (kWh) consumed by the consumer.

Energy conservation. The strategy of a utility leading to programs for the reduction of electric energy consumption by the consumer. This includes rebates and/or low-cost financing assistance for the consumer to install or replace appliances, lighting, and motors with more efficient ones. It also includes using higher grades of insulation to reduce heat loss in cool weather and to reduce heat absorption in warm weather. Utilities will often furnish information and technical assistance at no cost to the consumer, but it is the consumer who will make the decision to increase his capital cost to reduce his energy costs. In addition to reducing energy consumption, conservation also lowers the peak loads.

Functional accounts. Groupings of plant and expense accounts according to the specific function in the electric system, sometimes referred to as the Uniform System of Accounts. For instance, there would be an account number such as 13804 or some other specific number for the capital value of all the meters a utility owns.

Gear ratio. The number of revolutions of the rotating element of a meter for one revolution of the first dial pointer.

Grounding conductor. A conductor used to connect any equipment device or wiring system with a grounding electrode or ground system.

Incentive rate. Some form of reduced rate generally designed to provide an incentive for targeted consumers to remain in the service territory or to lure other businesses to the territory, usually offered for a fixed period of time. Time-of-day rates are in some sense an incentive rate to the consumer to time his load use so as to minimize his energy or demand use during peak load periods.

Inductance. That property of an electric circuit that opposes any change of current direction through the circuit. In a direct current circuit, where current does not change in direction, there is no inductive effect. In alternating current (AC) circuits, the current is constantly changing direction, so the inductive effect is appreciable. Changing current produces changing flux, which, in turn, produces induced voltage. The induced voltage opposes the change in applied voltage, hence the opposition to the change in current. Since the current changes more rapidly with increasing frequency, the inductive effect also changes with frequency.

Instrument transformer. A transformer that reproduces in its secondary circuit, in a definite and known proportion, the voltage or current of its primary circuit, with the phase relationship substantially preserved.

IPP. Independent power producer.

ISO. Independent system operator.

K_c. *See* **KYZ output constant.**

K_h. *See* **watt-hour constant.**

K_m. *See* **mass memory constant.**

kVA. One thousand volt-amperes.

kW. One thousand watts.

kWh. One thousand watt-hours.

KYZ output constant (K_z). The pulse constant for the KYZ outputs of a solid state meter, programmable in unit-hours per pulse.

Lagging current. An alternating current that, in each half cycle, reaches its maximum value a fraction of a cycle later than the maximum value of the voltage that produces it.

Leading current. An alternating current that, in each half cycle, reaches its maximum value a fraction of a cycle sooner than the maximum value of the voltage that produces it.

Load compensation. That portion of the design of a watt-hour meter that provides good performance and accuracy over a wide range of loads. In modern, self-contained meters, this load range extends from load currents under 10% of the rated meter test amperes to 667% of the test amperes for class 200 meters.

Load control. A direct action by the utility to shift load off-peak, either by a programmed computer command or by manual implementation of remote control. Voltage reduction and cycling of motor and appliance loads and water/house heating are examples of load control.

Load curve. A curve on a chart showing energy, power, or amperes plotted against time of occurrence to show the varying magnitude of a load during the period covered.

Load factor. The ratio of the average load in kilowatts (kW) supplied during a designated period to the peak or maximum load in kW occurring in that period. Load factor, in percent, also may be derived by multiplying the kilowatt-hours in the period by 100 and dividing by the product of the maximum demand in kW and the number of hours in the period.

Load forecast. A predicted demand or energy amount expected during a period of time or at a specific instant in time. Load forecasts may be short-term for operating purposes, long-term for system planning purposes, or any range in between. Forecasts may be of total system or regional load, or of areas of the system such as served by a substation or distribution circuit. They might also be of consumer loads (especially in the case of transmission consumers), or appliance/device loads, including street lighting.

Load research. Generally refers to a utility activity designed and carried out to determine consumer load characteristics. The results of load research activities are not only used in rate analysis and development but also to determine the electric design parameters, both for the system and the components of the system.

Load shape control. *See* **load shifting.**

Load shifting. Reducing the system peaks by curtailing load directly or by a rate structure that motivates the consumer to move some of his energy requirements from peak load hours to off-peak usage. Filling the dips in the load curve improves the system load factor and makes more use of lower cost energy produced by base load units or off-peak purchased power.

Load survey. The measurement of the electrical characteristics of a consumer or segment of the electric system. This is usually done by portable special load monitoring instruments installed either on the consumer premises or on some part of the electric supply system to measure demand, energy usage, amperes, voltages, and/or power factor. An alternative to special field instrumentation would be to transmit consumer data back to a central location and develop the required information through computer programs.

Loss compensation. A means for correcting the reading of a meter when the metering point and point of service are physically separated, resulting in measurable losses. These losses include I^2R losses in conductors and transformers, and iron core losses. These losses may be added to, or subtracted from, the meter registration.

Loss factor. The ratio of the average loss in kilowatts during a designated period to the peak, or maximum loss of kilowatts occurring in that period.

Losses. The general term applied to energy (kilowatt-hours) and power (kilowatts) lost in the operation of an electric system. Losses occur principally as energy transformations from kilowatt-hours to waste heat in electrical conductors and equipment or devices.

Mass memory constant (K_m). The value, in unit quantities, of one increment (pulse period) of stored serial data. For example, K_m = 2,500 W-hr/pulse.

Maximum demand. The demand usually determined by an integrating demand meter or by the integration of a load curve. It is the summation of the continuously varying instantaneous demands during a specified time interval. With the computer technology available, the integration of demand can also be accomplished through automatic meter readings transmitted from the consumer meter back to a central location. This makes it possible not to have a demand meter or register at the location of usage.

Memory. Electronic devices that store instructions and data. Volatile memories can be written to, and read from, repeatedly. Random-access memories (RAM) require uninterrupted power to retain their contents. Read only memories (ROMs) are programmed once, may only be read (but can be read repeatedly), and do not require constant power to retain their contents. ROMs are typically used to store firmware in dedicated systems.

Ohm. The practical unit of electrical resistance. It is the resistance that allows 1 ampere to flow when the impressed electrical pressure is 1 volt.

On-peak demand register. A register that will record the total energy used and, in addition, will register maximum demand during on-peak periods. The control of the demand recording is with a solenoid-operated demand gear train that may be actuated from a local device or from a device located remotely.

Percent registration. Percent registration of a meter is the ratio of the actual registration of the meter to the true value of the quantity measured in a given time, expressed as a percentage. Percent registration is also sometimes referred to as the accuracy of the meter.

Phantom load. A device that supplies the various load currents for meter testing, used in a portable form for field testing. The power source is usually the service voltage, which is transformed to a low value. The load currents are obtained by suitable resistors switched in series with the isolated low-voltage secondary and output terminals. The same principle is used in most meter test boards.

Phase angle. The phase angle or phase difference between a sinusoidal voltage and a sinusoidal current is defined as the number of electrical degrees between the beginning of the cycle of voltage and the beginning of the cycle of current.

Photoelectric meter. Also known as a counter, this device is used in the shop testing of meters to compare the revolutions of a watt-hour meter standard with a meter under test. The device receives pulses from a photoelectric pickup, which is actuated by the anticreep holes in the meter disk (or the black spots on the disk). These pulses are used to control the standard meter revolutions on an accuracy indicator by means of various relay and electronic circuits.

Power factor (PF). The ratio of real power (kW) to apparent power (kVA) at any given point and time in an electrical circuit. Generally it is expressed as a percentage ratio. Resistance-type loads, such as incandescent lamps or electric resistance heating, are characterized as 100% PF loads. Electric motor loads in refrigerators and air conditioners are around 80% PF or lower.

Primary/transmission metering. When consumer loads reach a magnitude such that they will benefit from higher service voltage rates, the revenue will be metered by special metering installations called primary metering. This means the consumer is served at a distribution voltage of 4,000 volts (V) or higher (usually 13,000 V) or by a transmission line, usually operating

at 69,000 V or higher. In these cases, the consumer furnishes his own step-down transformers and high-voltage service equipment. The utilities use potential transformers (PTs) and current transformers (CTs) to reduce both potential and current to levels for which the meter is designed.

Pulse device. For electric metering, it is the functional unit for initiating, transmitting, retransmitting, or receiving electric pulses, representing finite quantities, such as energy. Normally pulses are transmitted from some form of electric meter to a receiver unit.

Pulse initiator. Any device, mechanical or electrical, used with a meter to initiate pulses, the number of which is proportional to the quantity being measured. It may include an external amplifier or auxiliary relay or both.

Q-hour meter. An electricity meter that measures the quantity being obtained by lagging the applied voltage to a watt-hour meter by 60°, or for electronic meters by delaying the digitized voltage samples by a time equivalent to 60° (electrical).

Rate base. The value established by a regulatory authority, upon which a utility is permitted to earn a specified rate of return. Generally this represents the amount of property used and useful in servicing of consumers.

Reactance. The measurement of opposition to the current flow in an electric circuit caused by the circuit properties of inductance and capacitance, normally measured in ohms.

Reactive power. The portion of apparent power that does no work. It is commercially measured in kilovars (volt-amperes reactive). Reactive power must be supplied to most types of magnetic equipment, such as motors. It is supplied by generators or by electrostatic equipment known as capacitors.

Real power. The energy or work-producing part of apparent power; the rate of supply of energy, measured commercially in kilowatts. The product of real power and length of time is energy, measured by watt-hour meters and expressed in kilowatt hours (kWh).

Register constant. The number by which the register reading is multiplied to obtain kilowatt-hours. The register constant on a particular meter is directly proportional to the register ratio, so any change in ratio will change the register content.

Register freeze. The function of a meter or register to make a copy of its data, and perhaps reset its demand, at a pre-programmed time after a certain event (such as demand reset) or upon receipt of an external signal. It is also known as self-read, auto-read, or data copy.

Register ratio. The number of revolutions of the gear meshing with the worm or pinion on the rotating element for one revolution of the first dial pointer.

Registration. The registration of the meter is equal to the product of the register reading and the register constant. The registration during a given period of time is equal to the product of the register constant and the difference between the register readings at the beginning and the end of the period.

SE cable. Service entrance cable usually consists of at least two conductors with appropriate insulation, laid together and covered with a jacket material about which is wrapped a stranded, bare neutral conductor. An outer covering over the neutral conductor is a flame-retarding and waterproof braid. (*See also* **ASE cable**.)

Service entrance conductors. For an overhead service, that portion of the service conductors that connects the service drop to the service equipment. The service entrance for an underground service is that portion of the service conductors between a terminal box (external or internal) and the service equipment. In the absence of a terminal box, the service entrance runs from the point of entrance into the building to the service equipment junction.

Skin effect. The tendency of current flowing within a conductor to flow more easily (and in greater part) near the surface of the conductor in an AC circuit.

Socket. Also known as a trough, it is the mounting device consisting of jaws, connectors, and enclosure for socket-type meters. A mounting device may be either a single socket or a trough. The socket may have a cast or formed enclosure, the trough an assembled enclosure which may be extended to accommodate more than one mounting unit, as may be encountered in multiple occupancy buildings.

Stator. The unit that provides the driving torque in a watt-hour meter. It contains a voltage coil, one or more current coils, and the necessary steel to establish the required magnetic paths.

Submetering. The metering of individual loads within a building or subdivisions of property (such as a trailer park) for billing purposes by the owner. For that application, usually there is one master meter by the utility for billing the owner and the sub-meters are used by the owner to charge tenants for energy used.

Temperature compensation. In reference to a watt-hour meter, refers to the factors included in the design and construction of a meter that make it perform with good accuracy in a wide range of temperatures. In modern electric meters this may range from –20° F to 140° F. In a gas meter installation, this temperature compensation may also mean the factor applied to compensate for the difference in temperature between inside metering and outside metering.

Three-rate watt-hour meter. A watt-hour meter with three sets of registers. It is constructed so that the off-peak energy will be recorded on one set of dials, and the on-peak energy for two different on-peak periods will be recorded on the other two sets of dials. The control of the recording system is by an internal switch or remote control system. In the event of a power failure, carryover for an internal time switch can be accomplished by battery or spring storage.

Time division multiplication. An electronic measuring technique that produces an output signal proportional to two inputs, for example, voltage and current. The width or duration of the output signal is proportional

to one of the input quantities; the height is proportional to the other. The area of the signal is then proportional to the product of the two inputs.

Time-of-day rates. A rate strategy enacted by the utility to influence the consumer to change his load pattern and shift loads to off-peak hours by charging a higher rate for usage during peak hours and lower rates for off-peak hours.

Time-of-use metering. A metering method that records consumption and demand during selected periods of time. This allows consumption and demand (in some cases for commercial loads or very large houses) to be billed at different rates established in the utility tariff.

Transducer. A solid-state electronic device to receive energy from one system and supply energy, of either the same or different kind, to another system. This occurs in such a manner that the desired characteristics of the energy input appear at the output. For instance, it may take an AC voltage frequency or magnitude from a suitable interface and transmit it to a reading device or control relay.

Trough. *See* **socket.**

Two-rate watt-hour meter. A watt-hour meter with two registers or sets of dials, constructed so that the off-peak energy will be recorded on one set of dials and the on-peak energy on the other set. The control of the recording system is by an internal switch or external remote control signal. In the event of a power failure, carryover for an internal time switch can be accomplished by battery or spring storage.

V. *See* **volt.**

VA. *See* **volt-ampere.**

Var-hour meter. An electricity meter that measures and registers the integral, with respect to time, of the reactive power of the circuit in which it is connected. The unit in which this integral is measured is usually the kilovar-hour. This is most often used to obtain power factors.

Volt. The unit of electromotive force or electric pressure. It is the electromotive force that, if steadily applied to a circuit having a resistance of 1 ohm, will produce a current of 1 ampere; abbreviated V.

Voltage control. A utility's actions to reduce peak load, either on a planned basis or in an emergency situation in which generation or tie capacity is not available to meet the demand. A signal from a system operator to a remote device at substations automatically reduces the outgoing primary voltage and results in a temporary immediate load reduction.

Voltage of a circuit. The electric pressure of a circuit or system measured in volts. It is generally a nominal rating based on the maximum normal effective difference of potential between any two conductors of a circuit. In a typical house service and meter, this nominal voltage of 120 volts (V) can fluctuate between 117 V and 124 V due to consumer load variations.

Volt-ampere. The basic unit of apparent power. The volt-amperes (VA) of an electric circuit is the mathematical product of the volts and amperes of the circuit. The practical unit of apparent power is the kilovolt-ampere (kVA), which is 1,000 volt-amperes. An average residential service may have an apparent power of 5–10 kVA compared to a primary distribution circuit capability of 8,000 kVA and a transmission circuit capability of 100,000–700,000 kVA.

Watt. The electrical unit of real power or rate of doing work. The rate of energy transfer flowing due to an electrical pressure of 1 volt at unity power factor. One watt is equivalent to approximately 1/746 horsepower, or 1 joule per second. An average size incandescent light bulb uses 75 watts.

Watt-hour. The total amount of energy used in 1 hour by a device that requires 1 watt of power for continuous operation. Electric energy is commonly sold by the kilowatt-hour (kWh; 1,000 watt-hours).

Watt-hour constant (K_h). For an electromechanical meter, the number of watt-hours represented by one revolution of the disk. It is determined by the design of the meter and not normally changed; also called the disk

constant. For a solid state meter (K_h or K): the number of watt-hours represented by one increment (pulse period) of serial data. Example: K_h or $K = 1.8$ watt-hours/pulse.

Watt-hour meter. An electricity meter that measures and registers the integral, with respect to time, of the active power (often referred to as real power) of the circuit in which it is connected. This power integral is the energy delivered to the circuit over which the integration extends, and the unit measured is usually the kilowatt-hour. This is the most frequently used revenue meter device on an electric utility system found in residences, commercial establishments, and industrial plants.

Wheeling charge. An amount paid by a consumer or utility for transporting power over electric lines owned by others. This can be in the form of an energy charge, demand charge, capacity charge, or a combination of these.

Appendix E

Electric Utility Ownership and Operation

Electric utilities can be classified by size, type of operation, ownership, and territory served. While there are no typical or usual organizations in the climate of competition and corporate "re-engineering" evident in the past few years, there are some generalizations that can be made. It should also be remembered that an electric utility may also be in the natural gas business or other commercial endeavors.

Utility Organization

There are broad general function splits between support services and actual operations in the medium-to-large size utilities that may not be found in smaller utilities (see Table E–1). If a utility is large enough, divisions of functions and areas may be established that then report back to a central management group or authority.

Table E–1 Utility Support Services and Operations

Support Services	Operations
legal	generation
finance	system operation
accounting	line construction
public relations	line maintenance
human resources	distribution operation
purchasing	major construction
computer services	emergency (storm) restoration
transportation	
engineering and survey	
load research and rates	

Services Found in Either Category

system planning
meters
meter reading
stores
distribution engineering
mapping
general shops
consumer facility engineering

Utility Classification—Ownership

1. Investor-owned or private utilities can be found in all sizes and in all areas of the United States. These utilities are owned by stockholders who expect a return on their investment. Such utility corporations are not guaranteed a profit but do have a maximum return on their investment set by a public authority who determines the rate tariffs charged to consumers. These utilities pay both income taxes and property taxes. The largest investor-owned utility in Texas is Texas Utilities Company, Dallas, with a summer peak load of 18,000 MW (1990) serving a population of 5,000,000.

2. A second classification of ownership is the Rural Electric Membership Corporation (REMC) set up by the Federal Rural Electrification Administration (REA). These were originally set up to bring electric energy to the more rural areas of the country but now also serve fair-sized towns. They frequently will have the designation "cooperative"

or "association" associated with their geographic name. One of the largest in Texas is the Pedernales Electric Cooperative, Johnson City, with a summer system peak load of 537 MW (1993) and 81,000 consumers.

3. A third class of ownership consists of the municipal utilities, which are usually owned by the political area served. As of this writing, they do not pay taxes as investor-owned utilities do and frequently enjoy lower cost of financing because of their public ownership and ability to raise money through taxes on their constituents. Most municipals are small in size, although some urban "munis" are large in scale, such as the Austin Electric Utility Department with a summer peak load of 1,483 MW (1990) and 265,000 consumers.

4. The fourth class of ownership consists of federal, state, and district systems. These are similar to "munis" in that they pay no taxes and have very low rates of financing. They tend to cover large geographic areas and are generally wholesalers to other electric utilities. Well-known examples are the Tennessee Valley Authority (TVA), Bonneville Power Authority (BPA), and the New York Power Authority (NYPA). A state-owned Texas example is the Lower Colorado River Authority, operating out of Austin with a net peak load of 2,257 MW in 1997.

5. Overlaying the individual utilities are operating entities known as "power pools" that coordinate interchange of power between individual companies and between other power pools. Regional groups of power pools are often organized as coordinating councils, such as the Middle Atlantic Coordinating Council (MACC). These regional councils, as well as the individual power pools, establish area transmission and generation plans, operating standards, and pricing of energy. There is also environmental involvement through committees made up of representatives of the individual companies.

Appendix **F**

The Electric Utility System

The typical electric utility system is comprised of generation, transmission, substation, and distribution components. They are operated together to supply electrical energy to consumers at any given time and in any given amount of energy required (see Fig. F–1).

Generation

Generation consists of the electrical energy producing or manufacturing facilities owned by the utility company and those facilities owned by others that are connected to the electric utility system. The latter may be in the form of refuse recovery plants, cogeneration, or separately owned generating plants. A utility may also own all or part of a generating plant located remotely from its own territory.

Generating facilities are usually designated as either base load generation or peaking generation. Base load generation units are generally the most economical energy-producing units that are run to supply a major portion of the system load for most of the time. Peaking generation units are ones that are run to make up the difference between base load and the maximum loads either during daily load cycles or seasonally.

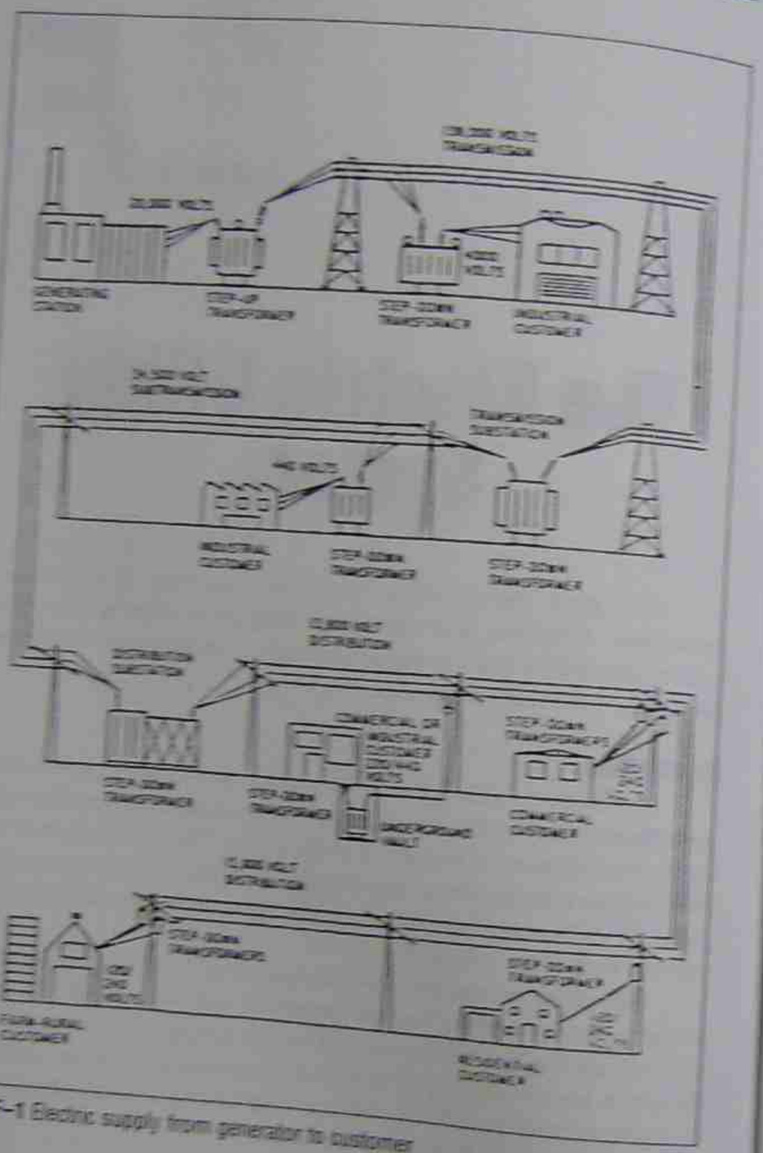


Fig. F-1 Electric supply from generator to customer

Transmission

The transmission part of the electric system moves the power from generating plants and interconnections with other utilities to load centers throughout the utility territory. Transmission lines operate at voltages up to 765,000 volts (V) AC and may be overhead on structures or underground, and in some special cases, under water.

Substations

At load centers in the utility territory, the transmission voltage is reduced (stepped down) to a primary distribution voltage or in some cases to a subtransmission voltage. This allows power to be brought to consumers in the local area by the primary distribution system.

Primary distribution

From the substation, power is distributed to the local area over primary voltage distribution lines operating at voltages from 4,000 V to as many as 45,000 V. The most frequently used primary voltage is 13,000 V. As in the case of transmission, distribution lines may be overhead or underground, but it is much more frequently used underground than in transmission systems. This is particularly true in urban areas and high load density locations, such as shopping centers or industrial parks.

Distribution transformers

A distribution transformer is used to reduce the primary voltage to a utilization voltage that consumers can use within their premises. Residential consumers are usually served at 240/120 V. Appliances such as large air conditioners, electric ranges, and pumps utilize 240 V, while lighting, TVs, and computers use 120 V. Commercial and industrial consumers use higher utilization voltages (up to 480 V).

Appendix **G**

Meter Reading

Most utility revenue meter reading is done manually by going to a consumer location, reading the meter, recording it in some fashion, and returning the data to a central location. Some (a relatively small portion) meters are read by automatic devices that transmit data back to a central control, recording, and processing unit.

Meter Routes

A block of meters is set up for a meter reader to be able to cover in a normal working day in a relatively small geographic area. These vary greatly with the characteristics of the area; in rural, mountainous, desert, or farm areas, the meters will have considerable distance between them compared to a suburban housing development of single-family homes, condos, or townhouses. Urban apartments, shopping centers, and other high-density locations also affect the meter route.

Billing Cycles

A common practice is to read meters every other month and estimate the bill in between using the consumer use characteristic. Commercial and industrial meters are usually read every month because of their high energy use and demands, and because they usually represent a small percentage of the total meters on a system. Utilities have also made available to residential consumers a budget payment plan, so they pay an estimated average fixed

amount each month until the end of the budget period. At the end of the period the actual cost is reconciled with the total of the budget payments.

Estimated Reading

An estimated reading can be made by using the historical meter reading information, generally contained in computer files. This can be done for the different seasons and adjusted for any trend indicated by load additions or reductions from improving consumer energy efficiencies.

Hard-to-Read Meters

Inside meter locations present the most common impediment to physically reading a meter, because it depends on someone being there to let the meter reader in. This can be costly to make an actual read if several visits are needed or special appointments have to be set up to get an actual reading. There may be, in some cases, a public service requirement to have an actual read within a certain time period. Some utilities utilize a remote meter dial mounted outside the house, which is connected to the inside meter register. Other "hard-to-reads" are caused by physical obstructions and animals. The possible danger of physical harm to a meter reader inherent in some urban situations also comes under the hard-to-read category.

Cut-Ons and Cut-Offs

When ownership or tenant of a premise changes, the utility may remove the meter or discontinue the service temporarily to show the change in consumer accounts. Cut-ons are more usual for new construction, while a cut-off can also be caused by nonpayment of the bill or theft of service. The latter requires a physical action in the field to actually change the service status by removing the meter or disconnecting the service wires at the pole and/or to read and inspect the meter.

Theft of Service

A residential meter can sometimes be removed and reinserted so that the register runs in reverse, or the meter removed and a jumper installed for a period of time to reduce the actual registration of energy used. To prevent this, most utilities use a meter seal having a unique registered number that is broken if the meter is removed for any reason. If an unauthorized meter

removal is made, this would be detected by the meter reader or some other operating person. Programmed computer checks can also be made to show extraordinary-normal estimated usage and trigger an investigation. In remote automatic meter reading systems, the theft of service attempt would be detected at the time it occurs.

Appendix H

Insulation: Porcelain vs Polymer

For many years, porcelain for insulation purposes on lines and equipment has exercised a virtual monopoly. It was perhaps inevitable that plastics1 successful as insulation for conductors since the early 1950s, should supplant porcelain as insulation for other applications in the electric power field.

The positive properties of porcelain are chiefly its high insulation value and its great strength under compression. Its negative features are its weight (low strength to weight ratio) and its tendency to fragmentation under stress. Much of the strength of a porcelain insulator is consumed in supporting its own weight. (Figs. H-1a and b)

In contrast, the so-called polymer not only has equally high insulation value, but acceptable strength under both compression and tension. It also has better water and sleet shedding properties, hence handles contamination more effectively, and is less prone to damage or destruction from vandalism. It is very much lighter in weight than porcelain (better strength to weight ratio), therefore more easily handled. (Figs H-2; Table H-1)

Economically, costs of porcelain and polymer materials are very competitive, but the handling factors very much favor the polymer.

Polymer insulation is generally associated with a mechanically

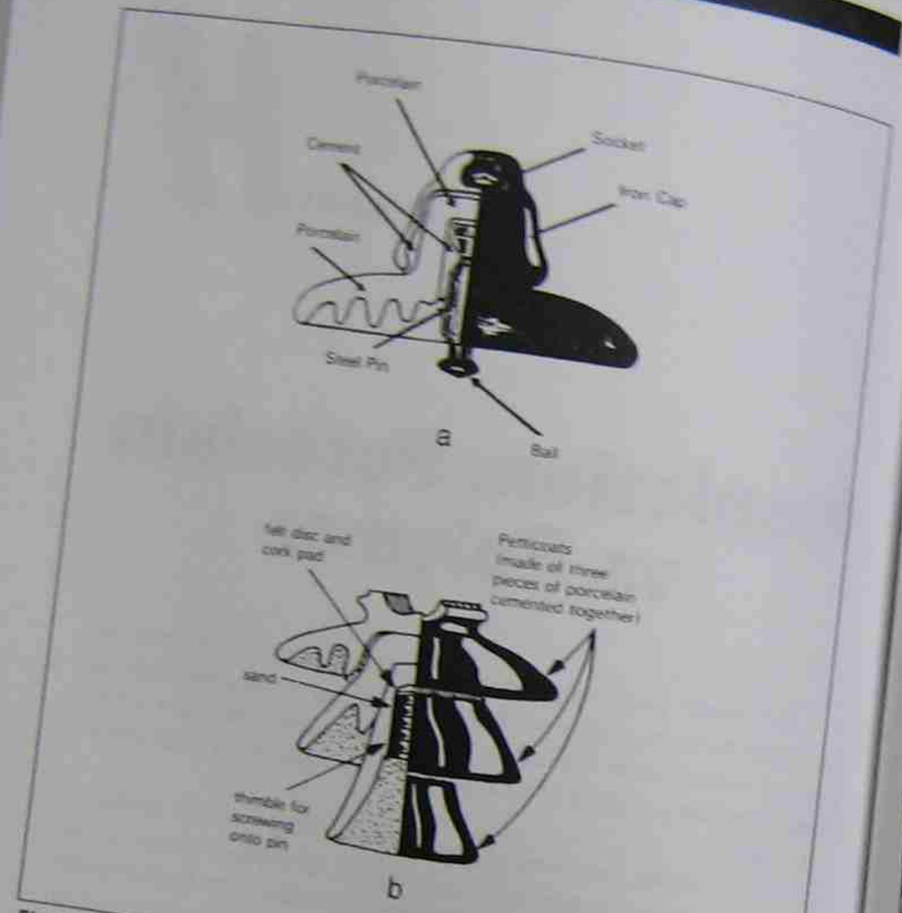


Fig H-1a Ball and socket type suspension insulator. **b** Pin type insulator

stronger insulation, such as high strength fiberglass. The fiberglass insulation serves as an internal structure around which the polymer insulation is attached, usually in the form (and function) of petticoats (sometimes also referred to as bands, watersheddersr but for comparison purposes, however, here only the term petticoat will be used). The insulation value of the polymer petticoats is equal to or greater than that of the fiberglass to which it is attached.

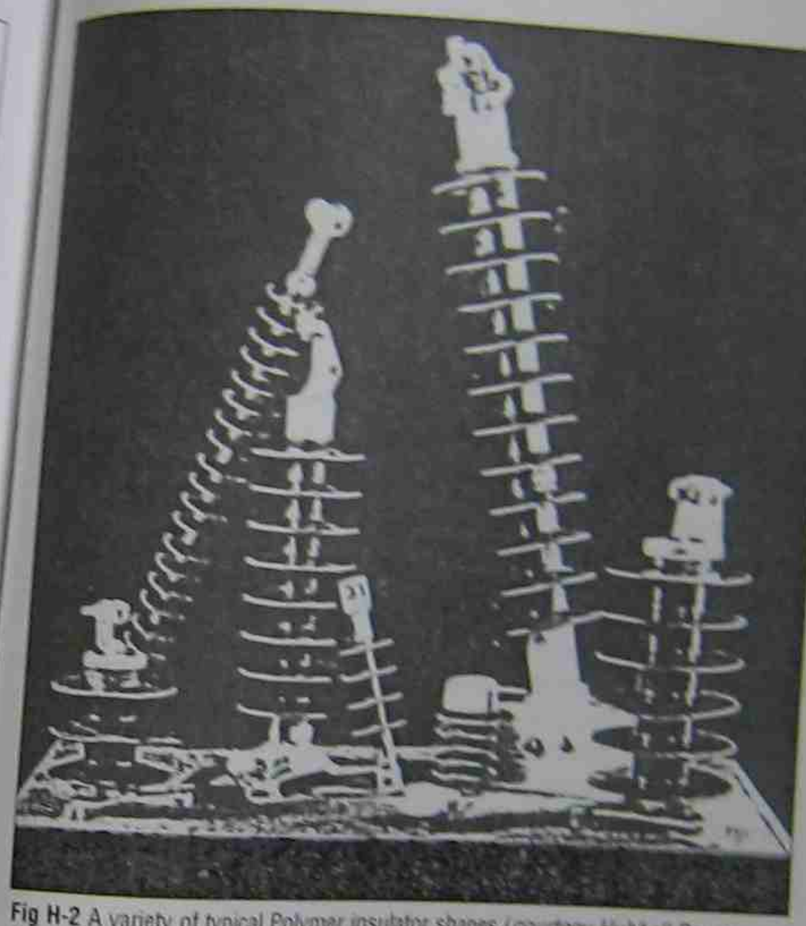


Fig H-2 A variety of typical Polymer insulator shapes (*courtesy Hubbell Power Systems*)

The internal fiberglass structure may take the form of a rod (or shaft), a tube, cylinder, or other shape. It has a high comparable compression strength as a solid and its tensile strength, equally high, is further improved by stranding and aligning around a fiber center. The polymer petticoats are installed around the fiberglass insulation and sealed to prevent moisture or contamination from entering between the petticoats and fiberglass Figure H-3. The metal fittings at either end are crimped directly to the fiberglass.

developing a high percentage of the inherent strength of the fiberglass. It should be noted that fiberglass with an elastometric (plastic) covering has been used for insulation purposes since the early 1920s.

Table H-1 Polymer Insulation Weight Advantage

Product	Type	Voltage (kV)	Porcelain Weight (lbs)	Polymer Weight (lbs)	Percent Weight Reduction
Insulator	Distribution	15	9.5	2.4	74.7
Arrester	Distribution	15	6.0	3.8	36.7
Post Insulator	Transmission	69	82.5	27.2	67.0
Suspension	Transmission	138	119.0	8.0	93.2
Intermediate	Substation	69	124.0	28.0	77.4
Arrester					
Station	Substation	138	280.0	98.9	64.7
Arrester					

Source: Hubbell Power Systems

The polymer petticoats serve the same function as the petticoats associated with porcelain insulators, that of providing a greater path for electric leakage between the energized conductors (terminals, buses, etc.) and the supporting structures. In inclement weather, this involves the shedding of rain water or sleet as readily as possible to maintain as much as possible the electric resistance between the energized element and the supporting structure, so that the leakage of electrical current between these two points be kept as low as possible to prevent flashover and possible damage or destruction of the insulator. Tables H-2a & b.

Table H-2a Polymer Improvement Over Porcelain

Voltage kV	Watts Loss Reduction* (watts per insulator string) Relative Humidity 30%	50%	70%	90%	100%
69	0.6	0.8	0.9	1.0	4.0
138	1.0	2.4	4.5	7.2	8.0
230	1.0	2.5	5.7	14.0	29.0
345	2.5	4.2	8.5	15.0	30.0
500	2.8	7.8	11.5	33.0	56.0

*Power loss measurements under dynamic humidity conditions on I-strings
Source: Hubbell Power Systems

Table H-2b Polymer Distribution Arrester Leakage Distance Advantage

MCOV	Standard Porcelain Leakage Distance (in)	Standard Porcelain Height (inches)	Special Porcelain Leakage Distance (in)	Special Porcelain Height (inches)	Standard Polymer Leakage Distance (in)	Standard Polymer Height (inches)
8.4	9.0	9.4	18.3	15.9	15.4	5.5
15.3	18.3	15.9	22.0	20.0	26.0	8.5
22.0	22.0	20.0	29.0	28.9	52.0	17.2

Source: Hubbell Power Systems

When the insulator becomes wet, and especially in a contaminated environment, leakage currents begin to flow on the surface; if the current becomes high enough, an external flashover takes place. The rate at which the insulation dries is critical. The relationship between the outer petticoat diameter and the core is known as the form factor. The leakage current generates heat (12R) on the surface of the insulator (eddy currents). In addition to the effects of the leakage current, the rate at which the petticoat insulation will dry depends on a number of factors. Starting with its contamination before becoming wet, the temperature and humidity of the atmosphere and wind velocity following the cessation of the inclement weather. In areas where extreme contamination may occur (such as some industrial areas or proximity to ocean salt spray), the polymer petticoats may be alternated in different sizes, Figure H-4, to obtain greater distance between the outer edges of the petticoats across which flashover might occur. When dry, the leakage current (approximately) ceases and the line voltage is supported across dry petticoats, preventing flashover of the insulator. It is obviously

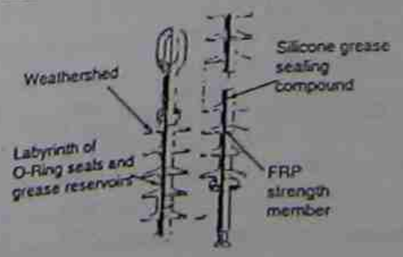


Fig H-3 Polymer insulator—showing fiberglass rod insulation and sealing (*courtesy Hubbell Power Systems*)

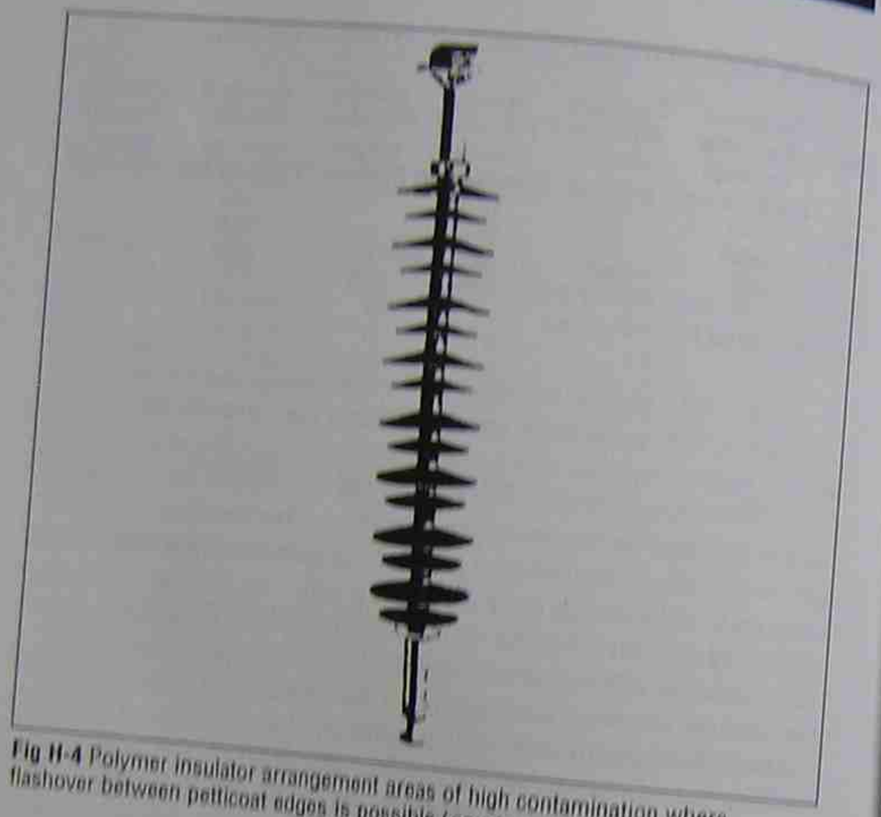


Fig H-4 Polymer insulator arrangement areas of high contamination where flashover between petticoat edges is possible (*courtesy Hubbell Power Systems*)

Impractical to design and manufacture comparable porcelain insulators as thin as polymers and having the same form factor. (Table H-3)

Table H-3 Comparison of Contamination Performance of Polymer verses Porcelain Housed Intermediate Class Arresters

MCOV (kV)	Housing Material	Housing Leakage Distance (in)	Max. Current (mA crest)	Max. Disc. Temp. (°C)	5	10	15	20
57	Polymer	81	<1	<38	35	42	44	44
66	Porcelain	54	68	>163	–	–	–	–
84	Polymer	109	<1	<38	50	52	60	60
98	Porcelain	122.4	18	<82	143	160	175	185

Source: Hubbell Power Systems

In addition, in porcelain insulators, the active insulating segment is usually small and, when subjected to lightning or surge voltage stresses, may be punctured. In subsequent similar circumstances, it may breakdown completely, not only causing flashover between the energized element and the supporting structure, but may explode causing porcelain fragmentation in the process; the one-piece fiber glass insulator will not experience puncture.

The polymer suitable for high voltage application consists of these materials:

1. Ethylene Propylene Monomer (EPM)
2. Ethylene Propylene Diene Monomer (EPDM)
3. Silicone Rubber (SR)

Both EPM and EPDM, jointly referred to as EP, are known for their inherent resistance to tracking and corrosion, and for their physical properties. SR offers good contamination performance and resistance to Ultra Violet (UV) sun rays. The result of combining these is a product that achieves the water repellent feature (hydrophobic) of silicone and the electromechanical advantages of EP rubber.

Different polymer materials may be combined to produce a polymer with special properties; for example, a silicone EPDM is highly resistant to industrial type pollution and ocean salt.

The advantageous strength to weight ratio of polymer as compared to porcelain makes possible lighter structures and overall costs as well as permitting more compact designs, resulting in narrower right-of-way requirements and smaller station layouts. The reduction in handling, shipping, packaging, storage, preparation and assembly, all with less breakage, are obvious—these, in addition to the superior electromechanical performance.

Fiberglass insulation with its polymer petticoats is supplanting porcelain in bushings associated with transformers, voltage regulators, capacitors, switchgear, circuit-breakers, bus supports, instrument transformers, lightning or surge arresters, and other applications. The metallic rod or conductor inside the bushing body may be inserted in a fiberglass tube and sealed to prevent moisture or contamination entering between the conductor and the fiberglass tube around which the polymer petticoats are attached. More often, the fiberglass insulation is molded around the conductor, and the polymer petticoats attached in a similar fashion as in insulators. (Fig H-5)

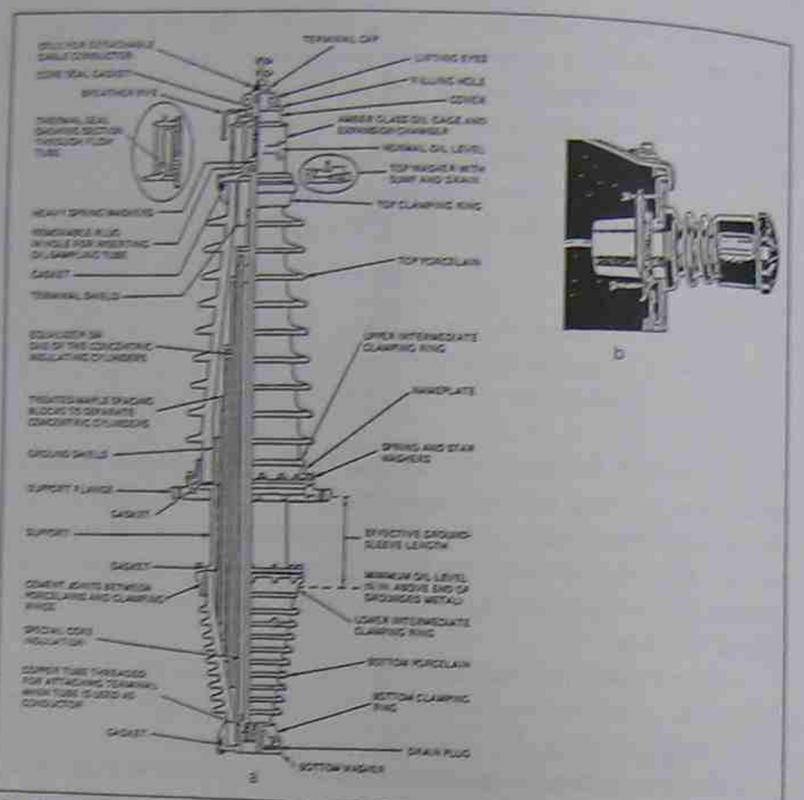


Fig H-5 Typical porcelain bushings that may be replaced with polymers. **a**. Typical oil-filled bushing for 69 kV transformer. **b**. Sidewall mounted bushing

Lightning or surge arrester elements are enclosed in an insulated casing. Under severe operating conditions, or as a result of multiple operations, the pressure generated within the casing may rise to the point where pressure relief ratings are exceeded. The arrester then may fail, with or without external flashover. Figure H-6 exploding and violently expelling fragments of the casing as well as the internal components, causing possible injury to personnel and damage to surrounding structures. The action represents a race between pressures building up within the casing and an arcing or flashover outside the casing. The length of the casing of the arrester limits its ability to vent safely. The use of polymer insulation for the casing permits

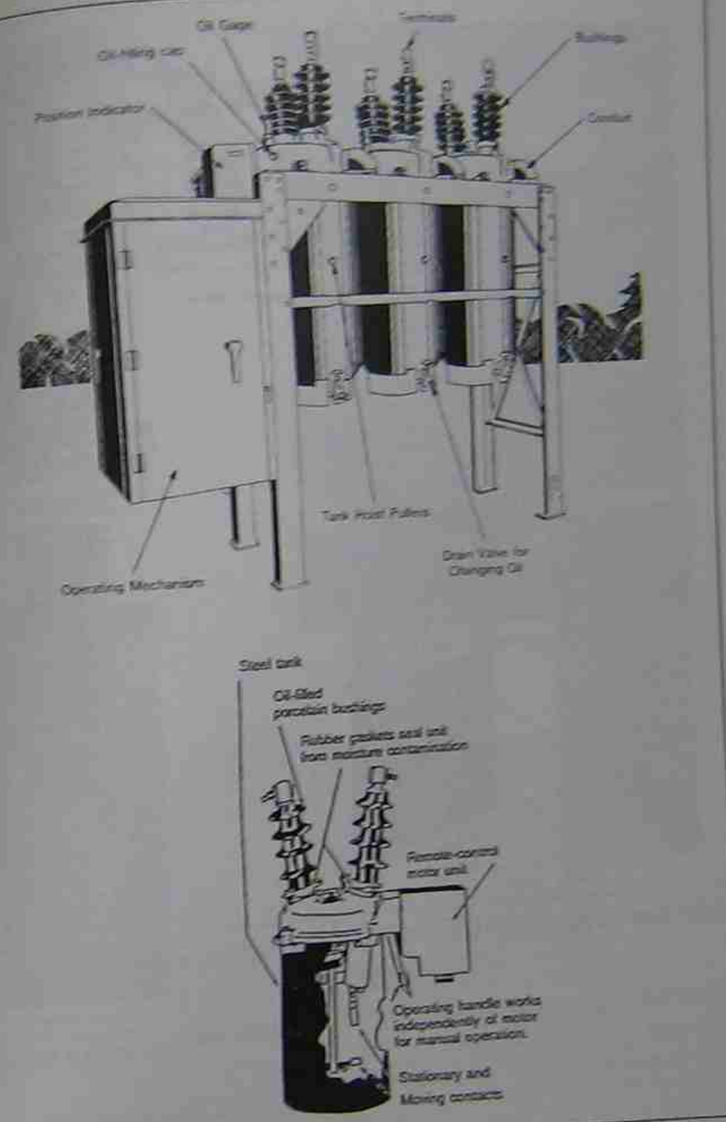
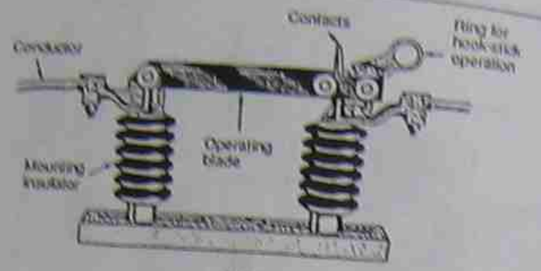


Fig H-5 Con't Bushings that may be replaced with polymers



A disconnect switch.

A Primary Capacitor

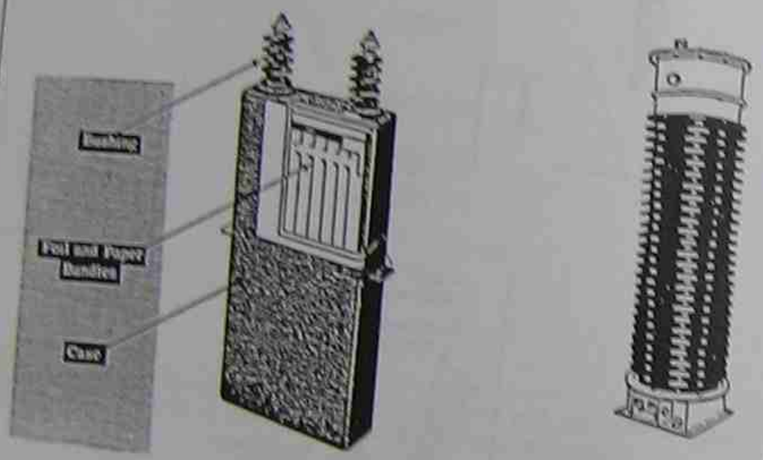


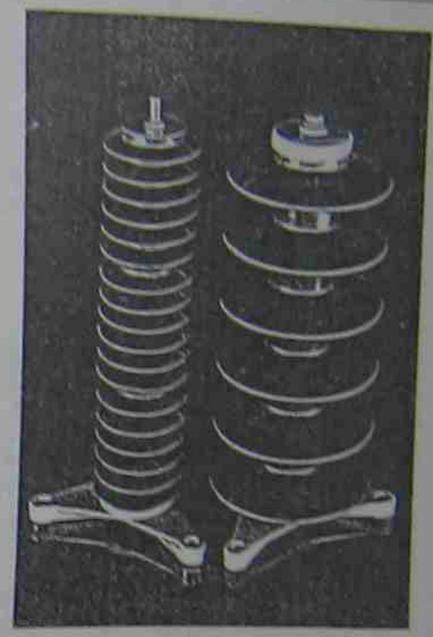
Fig H-5 Con't More porcelain bushings that may be replaced with polymers

puncturing to occur, without the fragmentation that may accompany breakdown and failure of porcelain

Summarizing, the advantages of polymers over porcelain include:

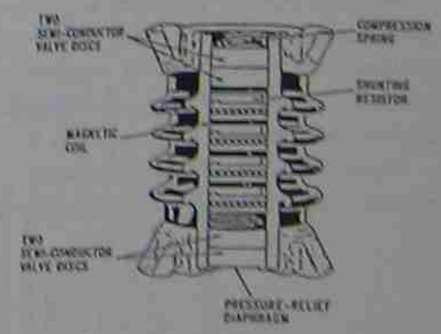
- Polymer insulation offers benefits in shedding rain water or sleet, particularly in contaminated environments.

Photographs show the pressure relief capability of surge arresters.



Polymer Insulated Arresters Station Type

Polymer insulated Intermediate Type Arrester



Cross-section of Porcelain Cased Arrester

Fig H-6 Polymer and porcelain cased arresters

- Polymer products weigh significantly less than their porcelain counterparts, particularly line insulators, resulting in cost savings in structures construction and installation costs. Table H-4.

- Polymer insulators and surge arresters are resistant to damage resulting from installation and to damage from vandalism. The lack of flying fragments when a polymer insulator is shot deprives the vandal from his satisfaction with a spectacular event and should discourage insulators as convenient targets.

- Polymer arresters allow for multiple operations (such as may result from station circuit reclosings), without violently failing.

- Polymer insulators permit increased conductor (and static wire) line tensions, resulting in lower construction designs by permitting longer spans, fewer towers or lower tower heights.

- Polymer one-piece insulators, lacking the flexibility of porcelain strings and the firm attachment of the conductor it supports are said to produce a tendency to dampen galloping lines.

Although polymer insulation has become increasingly utilized over the past several decades, there are literally millions of porcelain insulated installations in this country alone; economics does not permit their whole replacement. Advantage is taken of maintenance and reconstruction of such facilities to make the change to polymers.

Much of the data and illustrations are courtesy of Hubbell Power systems, and is herewith duly acknowledged with thanks.

Table H-4 Example - 10 Miles, 345 kV, 250 Strings of Insulators

Porcelain - 4,500 bells, 52-3, 13.5 lbs. ea., total 60,750 lbs. 750 crates at 3.1 cu. ft. = 2,325 cu. ft.
Polymer - 250 units, 14.4 lbs. ea., total 3,600 lbs. 5 crates at 75 cu. ft. = 375 cu. ft. Insulator cost = $51,750

	Savings	
1. Storage space at receiving point (3 mos.) porcelain - 580 sq. ft.; polymer - 100 sq. ft.	480 sq. ft.	$60.00
2. Off-load, reload at receiving point porcelain - 10 man-hrs.; polymer - 2 man-hrs.	8 man-hrs.	$120.00
3. Breakage - off-loading, storage, reloading porcelain - 1 percent; polymer - 0	1 percent	$517.50
4. Truck - receiving point to tower sites (5 miles) porcelain - 1.00/cwt.; polymer .50/cwt.	$589.50	$589.50
5. Off-load at tower site porcelain - 5 man-hrs.; polymer - 1 man-hr.	4 man-hrs.	$60.00
6. Unpack at tower site porcelain - 50 crates/hour, 25 man-hrs.; polymer - 50 insulators/hr, 5 man-hrs	20 man-hrs	$300.00
7. Breakage - off-loading through string assembly & cleaning porcelain - 1 percent; polymer - 0	1 percent	$517.50
8. Assemble strings, attach blocks porcelain - 40 man-hrs.; polymer - 8 man-hrs	32 man-hrs.	$480.00
9. Clean insulators porcelain - 10 min./string; polymer - 3 min./string	29 man-hrs.	$435.00
10. Lift string into place (2 men) porcelain - 5 min./string; polymer - 2 min./string	25 man-hrs	$375.00
11. Install & connect to tower (2 men) porcelain - 5 min./string; polymer - 2 min./string	25 man-hrs	$375.00
12. Breakage - lifting & installation porcelain - 0.5 percent; polymer - 0	0.5 percent	$258.75
13. Cleanup packaging materials at jobsite porcelain - 6 man-hrs.; polymer - 1.5 man-hrs	4.5 man-hrs	67.50

Source: Hubbell Power Systems

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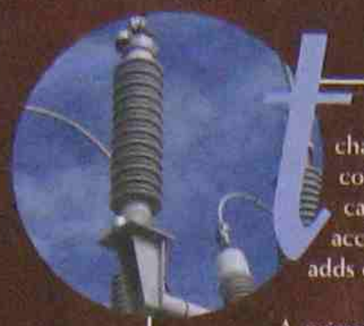

The electric utility industry is coping with significant changes brought on by deregulation, industry restructuring, consumer choice, and increasing costs of new generation capacity. The advent of independent power producers and access to transmission systems owned and operated by utilities adds complexity to these issues.

A primary concern is matching consumer loads with capacity to supply energy in an economical and reliable manner. In recent years, net generating capacity has declined 40% while energy consumption has increased by more than 50%. Without new generating capacity being added to match load growth, other means have to be developed to reduce peak demands in order to maintain an adequate ratio between capacity and demand.

An important technology to facilitate this is electric load management—managing consumer loads, and ultimately system loads, by various strategies and techniques. This book provides a general knowledge of demand control and energy conservation generically referred to as electric load management.

about the authors

Anthony J. Pansini brings more than 50 years of engineering and management experience to this book. His areas of expertise include planning, design, construction, maintenance, and operation of electric transmission and distribution systems. He spent 15 years in leadership roles with Consolidated Edison of New York and 31 years with Long Island Lighting Company before becoming a highly respected consultant. A licensed professional engineer, Pansini holds several patents, has instructed courses for industry and academia, and has authored numerous articles and books including: Basics of Electric Motors, 2nd Edition, Power Transmission and Distribution, and Guide to Electrical Power Distribution Systems, 5th Edition.

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PREFACE

This book provides an annotated vocabulary of some terms frequently used in discussions of electric power systems. Technical papers and general-interest papers in many instances use terms and acronyms that are unfamiliar to many engineers and to others interested in power system matters. The terms chosen for this vocabulary are those that may be encountered but are not fully discussed in the usual four-year undergraduate course in electrical engineering, and that in all likelihood are unfamiliar to those who have little experience in power systems. Each term is discussed from the viewpoint of providing an understanding of its meaning and usage, and some idea of how it fits into the general framework of power system analysis, planning, design, and operation. Following the discussion of each term is a list of appropriate references with pertinent quotations from each. It is not the intent of this book to provide rigorous mathematical analyses of electric system matters, but to inform intelligent readers.

The vocabulary is intended to be of interest to senior students in electrical engineering, to graduates just beginning a career in electric power system work, to lawyers and economists whose work is related to electric power systems, and to others who wish to learn something about the systems that provide electric power for use by the general public. I have avoided, as much as possible, the use of mathematical expressions in the discussions and have attempted to explain the meaning, in plain English, of the terms in the vocabulary. (It appears appropriate to quote here a statement by F. L. Lawton in his discussion of a paper that appeared in AIEE Power Apparatus and Systems, No. 8, Oct. 1953: "The paper would have been improved significantly by a brief statement in English, rather than mathematical symbols, outlining the incremental fuel cost of thermal plant, incremental transmission loss of thermal plant, incremental water rates at hydro plants, and related factors. Some such section, entitled perhaps "The Fundamental Problem" would have the advantage of developing the thinking of those studying the paper rather than being faced with complex equations and symbols at the outset.") My intent

is neither to replace nor compete with existing electrical engineering dictionaries, but to supplement them with respect to the use of some terminology.

An electric system (or "the" electric system) is a complex entity. Those not closely associated with electric power systems may not be fully aware of the degree of complexity. To use the remark made by former Supreme Court Chief Justice Earl Warren in a different context, the electric power system has "an iceberg quality, containing beneath [the] surface simplicity, submerged complexities."[1] This book is intended to reveal some of the "submerged complexities" associated with power systems.

The author would appreciate comments and constructive criticism from readers.

[1]*Storm Center—The Supreme Court In American Politics*, David M. O'Brien (New York: Norton, 1986), chap. 4, pp. 163, 164 from *Flast v. Cohen*, 392 U.S. 83, 94–95 [1968]

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Oxford University Press, permission to use specified material from the book *Electrical Circuits and Systems, An Introduction for Engineers and Physical Scientists*, by A. M. Howatson, Oxford University Press, 1996.

Introduction

The purpose of this book is to widen the perspective of a newly-graduated electrical engineer and to enlighten others who have an interest in electric power systems by defining and discussing some of the relevant terminology, and enlarging upon methods and important activities that relate to power system engineering. A four-year degree in electrical engineering provides knowledge of system principles and some practices, but much more should be known by a power system engineer. To broaden the knowledge of those entering the power system field, this book provides a short vocabulary, of terms that may not be covered in detail by courses devoted to principles, and amplifies the definitions by discussion of their application and meaning. This book will be of use to graduates in electrical power system engineering who are just beginning their working careers, lawyers practicing before governmental agencies that regulate electric utilities, economists involved in electric utility studies, and members of the general public who want to gain some understanding of electric utilities.

General Discussion of Electric Power Systems

Power system planning, analysis, and operation embrace several interrelated studies, among them:

- generating capacity needed for meeting customer demands (type, magnitude, location, cost, fuel supply, timing of installation), adequacy of generating capacity for foreseen needs and reserve capacity for contingencies.

- matching of transmission facilities to generating capacity and projected loads, with provision for contingencies, selection of transmission voltages, routing of lines, carrying capacity of lines, location and design of substations.

- forecasts of future demands and energy requirements for system-wide needs and for differing growth rates of subareas of the system.

- economic operation of generators and other system facilities.

- the use of statistical data for evaluating the performance of systems and components.

- the benefits and problems associated with interconnections among utilities.

In order to properly fulfill his (or her) responsibilities, a power system engineer must have sound knowledge of electrical and mechanical theory and practice related to the design, construction, and

operation of electric power plants, electric transmission facilities, and electric distribution equipment. The engineer must also be conversant with the theory and techniques of the mathematics relevant to the planning and operation of electric systems. An additional requirement is knowledge of utility practices (and their rationales) with regard to transfers of energy among systems under normal and emergency conditions. These practices involve not only the operational methods used to effect the transfers but also the financial aspects of the purchases and sales of power and energy: costs, losses, and conditions of sale. In addition, the complete power system engineer should have a solid foundation in engineering economics: the time value of money, annuities, comparison of various methods of financing large-scale purchases of equipment, methods of comparing costs when equipment components have different lifespans, tax considerations, and related financial matters.

A power system engineer should be capable of directing the preparation and compilation (and presenting in useful form) of data regarding the performance of electric systems and facilities in normal and abnormal situations. He (or she) is also responsible for using appropriate mathematical and statistical methods to analyze power system data for the purpose of improving future system operations with respect to safety, cost, and reliability.

Among the major studies undertaken in power system analysis are the following, which are generally referred to as "system studies:"

1. Power Flow (also referred to as "load flow")
2. Short Circuit ("fault") studies
3. Stability (maintenance of synchronous operation)
4. Generating Capacity Requirements
5. Load Forecasting (Demand and Energy)
6. Economic Dispatch and Unit Commitment

The purposes of these system studies are to a large extent complementary, and their databases overlap. Each study is interlinked with the others; as a group they provide an overall view, necessary for adequate planning and operation, of the system "dimensions." Some of the terminology used in these studies and in other relevant analyses is defined and discussed in the vocabulary that follows. In evaluating all the following analyses and discussions the readers should remember that they are usually based on simplified models of the circuits and devices studied. Actual conditions may differ from those assumed in an analysis, and therefore actual results may differ from those calculated and expected.

The Vocabulary of Electric Power Systems

with quotations from selected references

Aeolian Vibration

(Also see *Galloping* and *Stockbridge Damper*)

Vibration of the conductors of a transmission line, in a direction transverse to the conductor length, caused by action of the wind, is termed "Aeolian Vibration." The magnitude and frequency of the vibration is a function of wind direction and speed; conductor size, shape, stiffness, and material; conductor tension; proximity of other conductors; temperature. Generally the magnitude of the vibration is small; large-magnitude vibration is discussed under the heading of "*Galloping.*" Aeolian vibration, if excessive, may cause eventual breakage of a conductor due to fatigue of materials. Aeolian vibration is reduced by devices known as "Dampers" (See "*Stockbridge Damper*"), which are attached to the conductors near the supporting structures.

Auxiliary Power System

(Also see *Station Service Equipment*)

The "Auxiliary Power System" of a generating unit consists of all the machinery, devices and circuits specifically associated with that unit, required to make the unit function. These items are used solely for one unit; they are not used in the operation of any other generating unit in the power plant. Each generating unit has its own "Auxiliary Power System." Additional elements of the power plant, also necessary for the operation of any unit, are associated with the power plant as a whole, not with a specific unit; these elements com-

prise the "Station Service System," also called the "House Service System." Different types of generating units require different types of auxiliary power systems and station service systems.

1. Fossil Fuel Steam-Generating Units

For convenience, a fossil fuel steam-generating unit may be considered a system composed of several subsystems: the fuel system, the combustion air-flow system, the working fluid system, the condense cooling system, and the electrical output system. Each of these requires certain devices to make it function properly. The aggregate of these devices comprises the "Auxiliary Power System" for a specific unit.

a) The fuel system supplies the fuel that is mixed with air in the furnace and burned, to provide the heat needed to convert the working fluid to vapor or steam and provide the energy to rotate the turbine-generator. The fuel may be coal, oil, natural gas, or some other combustible material. About 50 percent of the energy generated by U.S. power plants comes from coal.

Power plants that burn coal may receive deliveries by barge, railroad train, or truck. Most coal is delivered by barge or train or both. The delivered coal, after being unloaded, is stored in the "coal pile" or "coal yard:" it is pushed to and fro by bulldozers to form a rectangular, flat-topped pile. The coal stored in the pile is usually sufficient for some two to four months of use. Each utility has its own standard for the amount of coal storage required for reliable operation of its power plants. For use in the power plant, the coal is "reclaimed" by being pushed by bulldozers onto an inclined endless conveyor belt that raises the coal to a high level in the power plant structure, where it is transferred to a horizontal conveyor belt. This belt moves the coal to several vertical storage bins and dumps it in. Magnetic and other devices are located on the belts for the purpose of removing extraneous material that may have found its way into the coal as it moved from the mine to the power plant site. All the machinery and equipment for moving the coal from the delivery point to the storage bins are part of the power plant's "Station Auxiliary System, ", not the Unit Auxiliary Systems, because they are required for the operation of any unit, not being associated only with a specific unit. Devices, circuits and systems associated only with a specific unit are part of that unit's Auxiliary Power System.

Coal storage bins are associated with specific units. From a storage bin, the coal falls through a chute into a mechanism known as a "Coal Feeder," which acts as a valve to feed the coal into a "Pulverizer" (also known as a "Coal Mill"). The Pulverizer grinds the coal to a fine powder. The powdered coal is drawn from the pulverizer by a large exhaust fan ("Pulverizer Exhauster") and is then blown through the furnace nozzle (burner) into the furnace, where it mixes with the air forced into the furnace by the air-flow system, and is burned. Steam units require several groups of coal storage bin-pulverizer-exhauster arrangements. The number required is determined by the size of the unit and the utility's experience with these items of machinery and their reliability; the number must be sufficient to provide spare capacity for feeding coal to the furnace if one or more bin-pulverizer-exhauster trains breaks down or is taken out of service for maintenance. Each bin-pulverizer-exhauster group serves several burners.

At the point of combustion (the burner tip), in the furnace, the fuel supply system and the combustion airflow system merge and become the gaseous stream of "Products of Combustion" (Flue Gases). The walls of the furnace are largely tubes containing the working fluid, generally water. The stream of hot gases flows around and over these tubes transferring to the fluid the heat of combustion, converting the fluid to steam. The flue gases then flow over additional arrangements of tubing, some containing water entering the boiler-furnace wall tubing and some containing steam, which now becomes "superheated". Eventually the flue gases exit through the chimney stack to the atmosphere. Prior to entering the stack the Flue Gases flow through various devices that conserve the energy of the fuel by transferring heat to the incoming combustion air. The flue gases also pass through devices that remove, (to the extent possible), particulate matter and noxious gases resulting from combustion of the coal.

If the plant is fueled by oil, the oil is delivered by pipeline; a storage tank usually is installed to level out pulsations in the oil flow and to provide a relatively minor amount of oil storage for temporary pipeline interruptions. Heaters may be installed for heating the heavy oil and promoting its flow, through pumps, from the tank or pipeline. If the fuel is gas, a storage tank is provided, to level out pulsations in flow and provide for temporary interruptions in the gas delivery pipeline.

Furnace boiler nozzles may allow the simultaneous burning of coal and oil or coal and gas. Nozzles are also available, (but not commonly used), to allow the simultaneous combustion of coal, oil, and gas.

Heavy ash resulting from the combustion of fuel drops to the bottom of the furnace and is transported by the ash-handling equipment to a "Settling Pond" where it is cooled and then disposed of. Particulate matter resulting from the combustion process ("Fly Ash") is removed from the flue gas stream by mechanical structures and by electrical means. The electrical device for removing the fly ash is the Electrostatic Precipitator, an arrangement of rods and plates suspended in the flue gas stream and charged electrostatically. The charge attracts the particles in the stream and causes them to adhere to the rods. Periodically the rods are shaken by mechanical devices, the particles drop off and then are collected and disposed of.

The major items of the Unit Auxiliary Power System in the fuel cycle are the Coal Feeder, Pulverizer, Pulverizer Exhauster, Ash Handling Pumps, and Electrostatic Precipitator.

b) The air-flow system provides air for combustion of the fuel in the furnace and carries the heat generated in the furnace across and around tubes in which the working fluid is contained. From the point of combustion the air and fuel systems are merged into the "flue gas" stream, which transfers the energy of the burning fuel to the fluid system and eventually exits to the atmosphere through the "stack" (chimney). The flow of the incoming air, and the flue gas flow to the stack, is maintained by convection (the hot flue gas rises through the stack, because its density is less than that of the surrounding atmospheric air) and by fans that force air into the furnace, aiding the convection effect.

The combustion of coal (and to a lesser extent the combustion of oil), results in an accumulation of soot on the tubes in some areas of the boiler structure. The use of gas as a fuel causes only minimal accumulation of soot. Soot coating the tubes reduces the transfer of heat from the flue gases to the water and steam inside the tubes, reducing the efficiency of the boiler. To remedy this, "Soot Blowers" are installed at several levels in the boiler structure. A soot blower is a long tube that can be extended into the boiler for a short time and then be retracted. When the tube is inside the boiler it delivers a stream of high- pressure air or steam against the boiler tubes, to cleanse them of soot deposits.

The major items of electrical equipment in the airflow system are the Forced Draft Fan, the Induced Draft Fan, and the electrically operated dampers, which control the flow of air through the furnace and boiler structure.

c) The working fluid in the usual steam generator is water, which is converted to steam in the furnace-boiler tubes. The steam is further heated in the "superheater" tubes, then passes through the turbine, where it gives up part of its energy by making the turbine-generator rotate. Leaving the turbine, the steam enters the "Condenser," where it is cooled and converted to water, which is pumped back into the furnace-boiler tubing. Some of the steam that enters the turbine does not pass completely through it but is diverted ("bled") from the main flow to move through "Feedwater Heaters" and give up some its energy to preheat the feedwater entering the boiler. A feedwater heater is a "Heat Exchanger" in the form of an assembly of tubes within an airtight shell; the incoming steam bled from the turbine flows over the tubes and transfers part of its heat content to the boiler feedwater inside the tubes. A turbine may have several "bleed" points; these are associated with a series of feedwater heaters. The steam from each bleed point condenses in each feedwater heater as its energy is transferred to the boiler feedwater; the condensed steam is collected by appropriate piping and is added to the boiler feedwater stream.

d) The condenser is a "Heat Exchanger," similar in concept to the Feedwater Heaters described but much larger and different in detail. Steam leaving the turbine exhaust piping flows over the tubes, which are cooled by "Circulating Water" taken from a source at approximately atmospheric temperature. The relatively cold water in the tubes causes condensation of the hot steam flowing over the tubes. The condensed steam is forced back into the boiler tubes by the "boiler feedwater pumps." The boiler water and the circulating water (cooling water) do not mix. The cooling water is taken from a source, which may be a lake, river, pond, or "Cooling Tower" by the "Circulating Water Pumps," which force it into the condenser tubes and out the "Discharge Canal" back to the source. The cooling water as it moves from the source is filtered through a "Trash Rack" or "Circulating Water Screen" to prevent debris and plant life (and fish, if the water source is an ocean, lake, or river) from entering the condenser tubing. The circulating water is usually treated by

means of chlorine or other chemicals to prevent the growth of algae and other deposits in the intake canal, condenser tubing, and discharge canal.

e) The electric output system consists of the generator, which is attached to and rotates with the turbine; bus work and cables that conduct the generator output to a transformer (Generator Transformer); mechanisms and devices to provide direct current that establishes a magnetic field through which the generator windings rotate; devices and circuitry to control the magnitude and phase angle of the generator voltage; and equipment to control the substance used for cooling the generator windings; the coolant may be hydrogen, water, or air. Generators in modern fossil-fuel steam plants are cooled by hydrogen or by water. The rotor may be cooled by one medium and the stator by another.

Power supply for the unit auxiliaries is usually provided by a transformer, connected to the generator output terminals so that the auxiliaries may be kept in operation when the generator is disconnected from the system. Power for starting the generator and its auxiliaries from a "cold" condition is provided by a transformer fed from the system; after operating conditions have been reached the auxiliaries are switched over to the generator transformer supply.

References on Auxiliary Power Systems

1. "Considerations in the Design of the Station Auxiliary System at the Encina Generating Station," T. H. Jacobsen, J. F. Sinnott, Paper No. 52-274, AIEE Power Apparatus and Systems, No. 3, Dec. 1952, pp. 983-985. © 1952 IEEE.

"To assure continuity of operation and protection of equipment, the auxiliary system warrants the same degree of consideration in the selection of operational features and protective relays as the main units themselves.

"Power Supply: Normally Unit Number 1 will carry its own auxiliaries through the transformer bank [7,500/9375 kva 13,800/2400 volt 3-phase transformer] connected to the generator leads."

There are two starting transformers, each 5,000/6,250 kva 138,000/2400 volt 3-phase, connected in parallel to the 138-kv out-

door switching station bus; these can carry the full load of the station auxiliary bus of unit 1 and the starting load of the station auxiliary bus of a second similar future unit.

2. "Auxiliary Power Systems for Steam-Electric Generating Stations," A. G. Mellor, R. A. Schmidt, Jr., Paper No. 52-286, AIEE Power Apparatus and Systems, No. 3, Dec. 1952, pp. 986-990. © 1952 IEEE.

"Conclusions: 5. The use of grounded auxiliary power systems reduces the probability of multiple outages and the resulting loss of all auxiliary power."

"Auxiliary power requirements: . . . as steam pressure increases, the boiler feed pump power becomes a larger proportion of the total auxiliary power and the size of individual boiler feed pump motors may present a problem in system design to provide adequate voltage during motor starting . . . an upper limit of 3,000-pound-per-square-inch throttle pressure has been assumed in estimating power requirements." [Fig. 1 of the paper shows what appears to be a linear relationship between auxiliary power as percent of maximum generator output and throttle steam pressure in psi. For non-reheat units the auxiliary power ranges from about 4.5 percent at 600 psi to about 8.4 percent at 3000 psi; for reheat units the auxiliary power ranges from 4 percent at 600 psi to about 7.3 percent at 3000 psi.]

"Auxiliary System Arrangements: . . . it has become almost universal practice to use the unit system with the output of the generator going directly through a step-up transformer to a high-voltage bus. This arrangement does not provide for any switching at generator voltage and so there is no generator bus to provide a source of auxiliary power. It has become general practice in most stations to obtain the normal auxiliary power supply from transformers directly connected to the generator leads. This provides a reliable source of auxiliary power at the efficiency of the main generating unit and also provides continuity of auxiliary power in case the unit is tripped off the high-voltage bus due to a system disturbance."

"Grounding of Auxiliary Power Systems: In a grounded system a single phase-to-ground fault forces the immediate outage of the faulty feeder. An ungrounded system does not have this requirement. However if the faulty feeder is not removed, the resulting transient