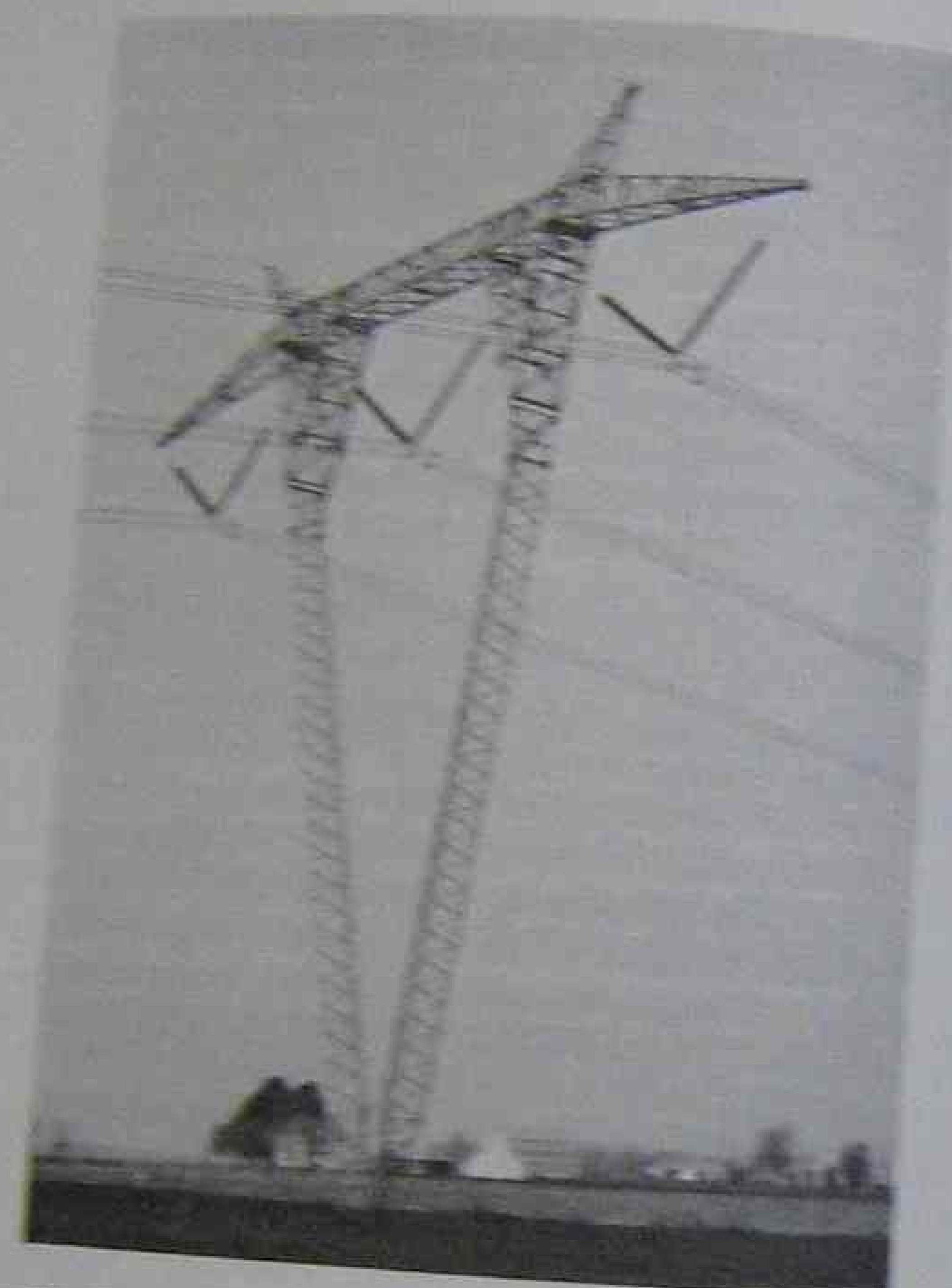


FIG. 12-21. A 765-kV transmission line showing the ground wires, bundle conductors, and V-string insulators.

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 20 by 20 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 center conductor is 0.8 cm and that of the outer conductor is 2.1 cm.

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.

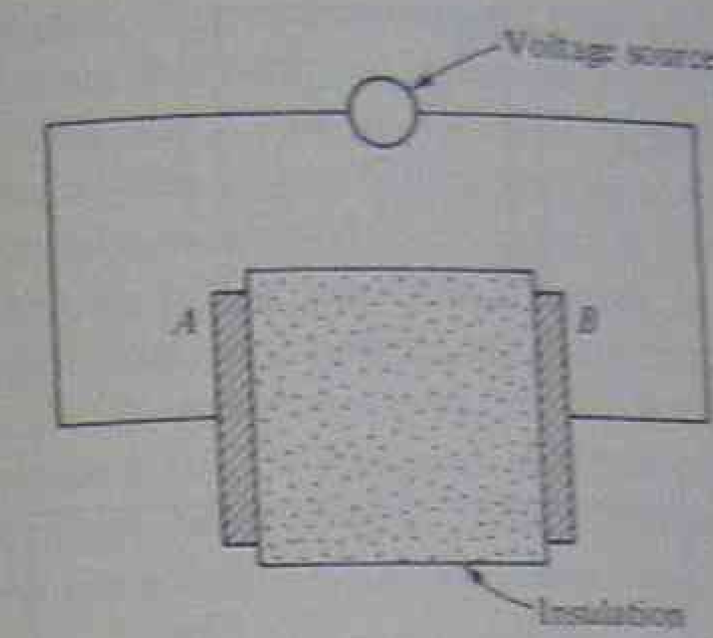


FIG. 12-1. Insulation under electrical stress between two metal electrodes.

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.

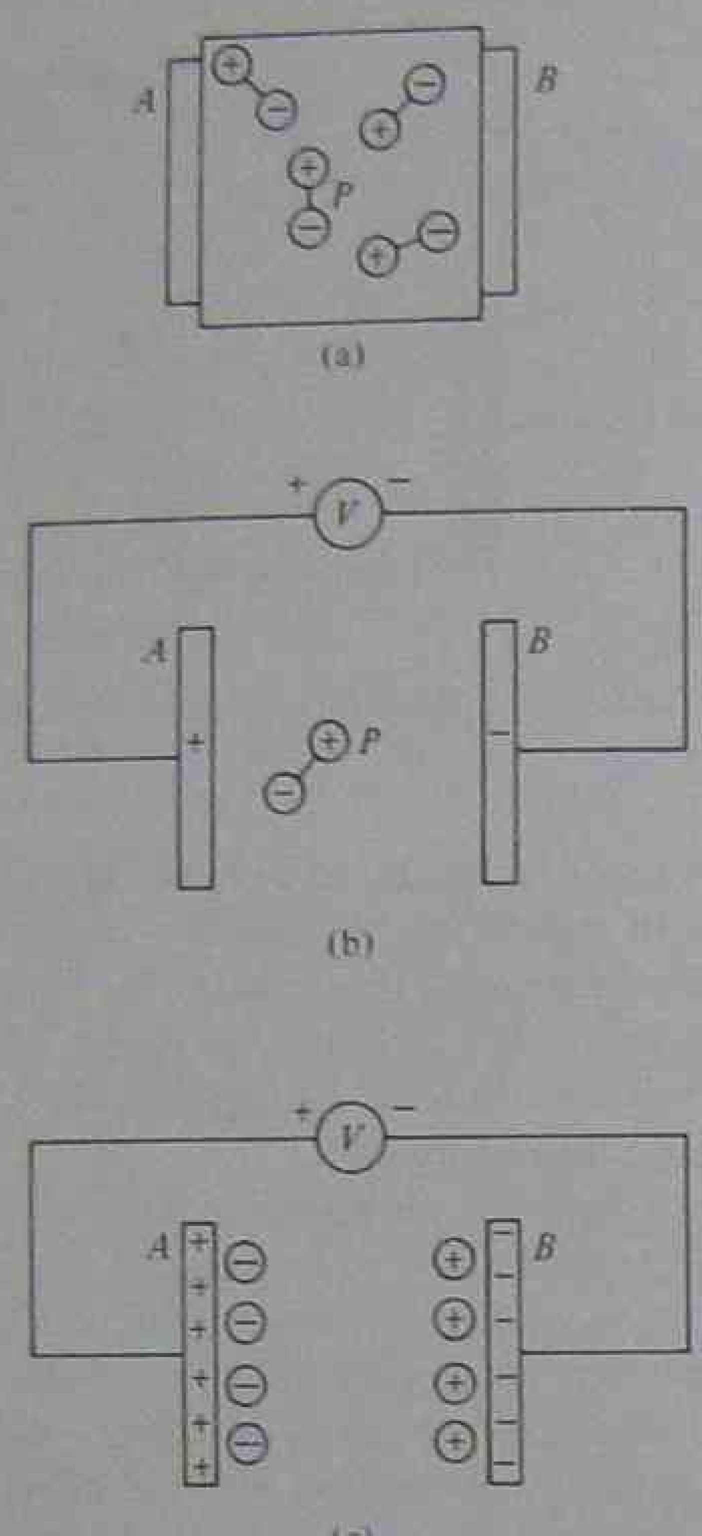


FIG. 12-2. The effect of electrical stress of insulation. (a) Some polar molecules under normal conditions. (b) The polar molecule P changes position under stress. (c) The charge layers adjacent to the electrodes.

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

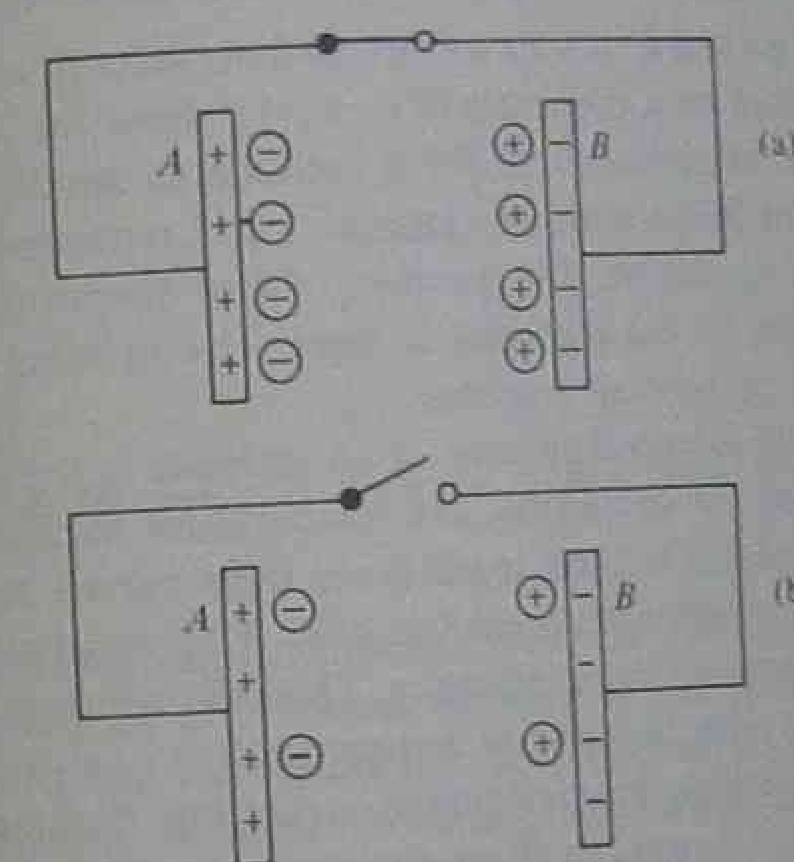


FIG. 12-3. Charge conditions in a capacitor that has been energized. (a) Immediately after being short-circuited. (b) After the short circuit is removed.

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

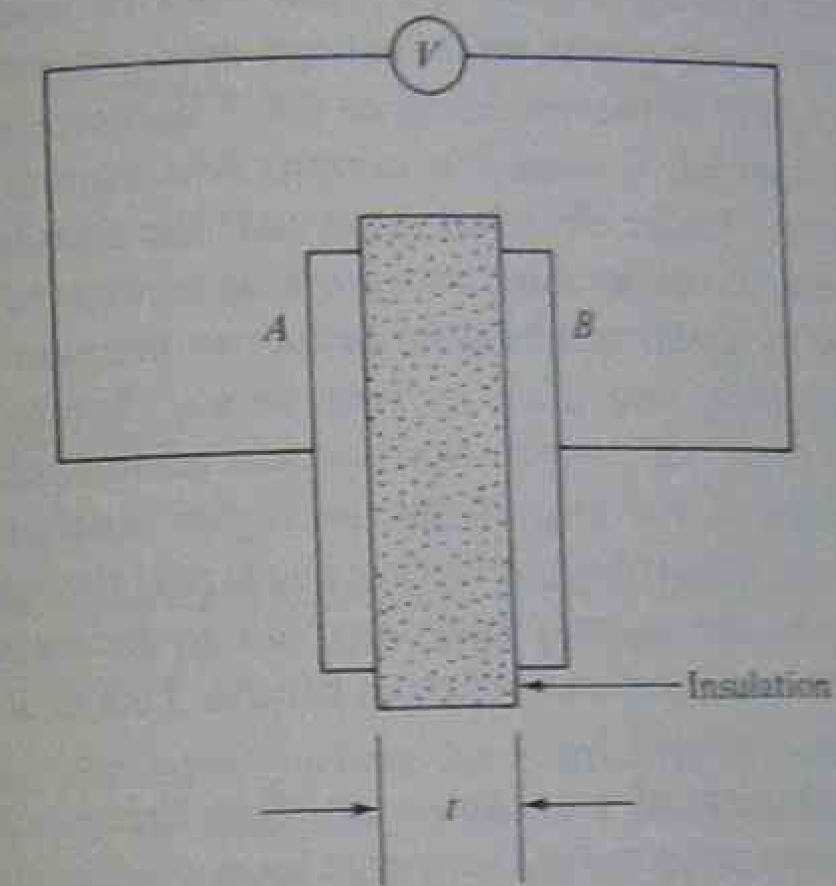


FIG. 12-4. Insulation of thickness t being stressed by applied voltage V.

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.

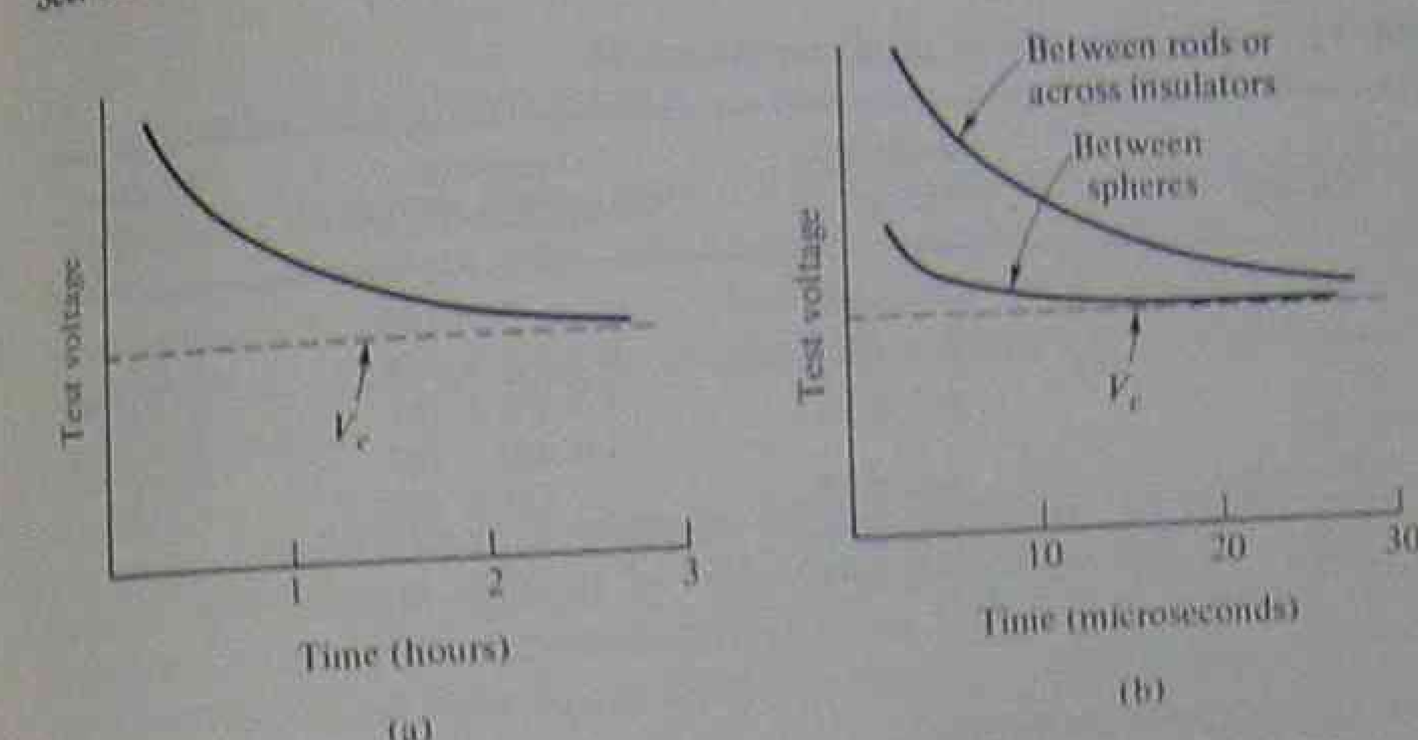


FIG. 12-5. Volt-time characteristics of insulation breakdown. (a) Solid insulation. (b) Air between spheres and between rods.

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}	$0.5\text{–}3.0 \times 10^6$	5.4–9.9
MICA	2×10^{17}	$3.5\text{–}7.0 \times 10^6$	2.5–6.6
PAPER		$1.0\text{–}4.0 \times 10^5$	2.0–2.6
PORCELAIN	3×10^{14}	1.0×10^5	5.7–6.3
RUBBER	1×10^{18}		2.0–3.5
COPPER	1.6×10^{-8}		

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.

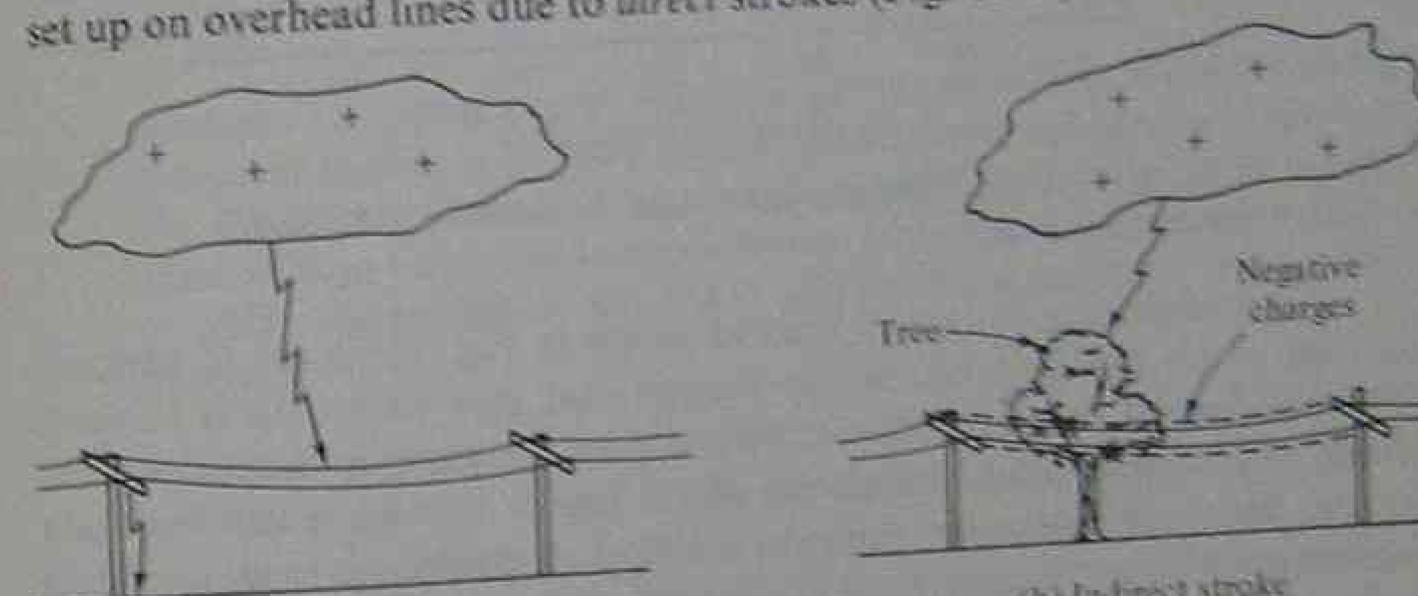
Similar statements could be made regarding other equipment, such as generators, instrument transformers, and circuit breakers. An arbitrary increase in insulation strength results in increased costs of associated parts and, in many instances, less satisfactory operating characteristics.

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.

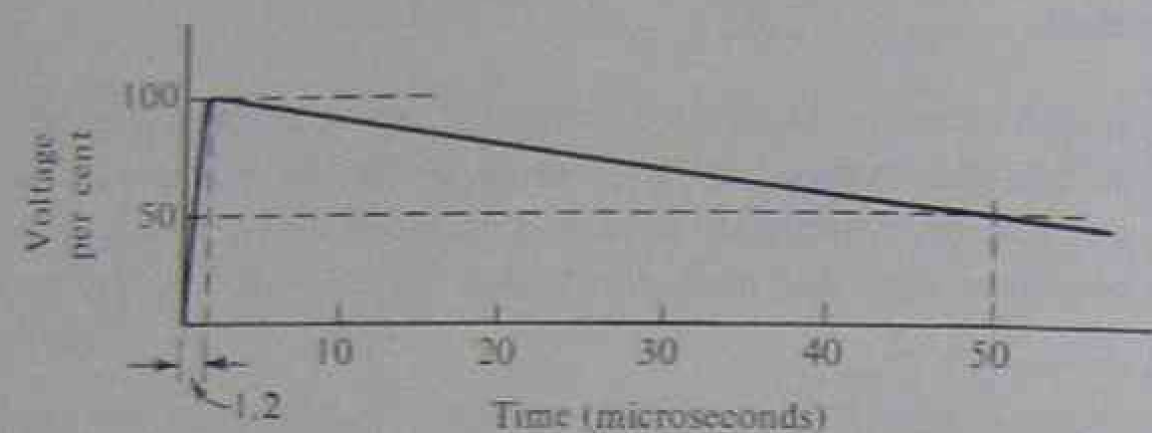


FIG. 12-7. A 1.2×50 test wave used to simulate a lightning-produced voltage.

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

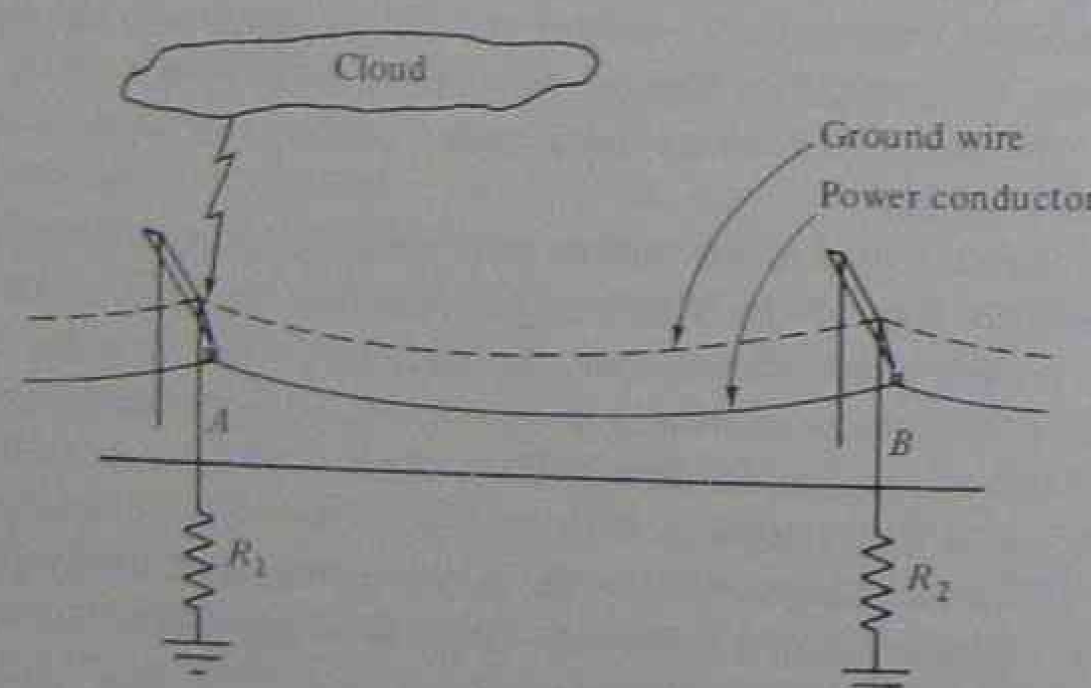


FIG. 12-8. A lightning stroke to a transmission line with overhead ground wire.

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

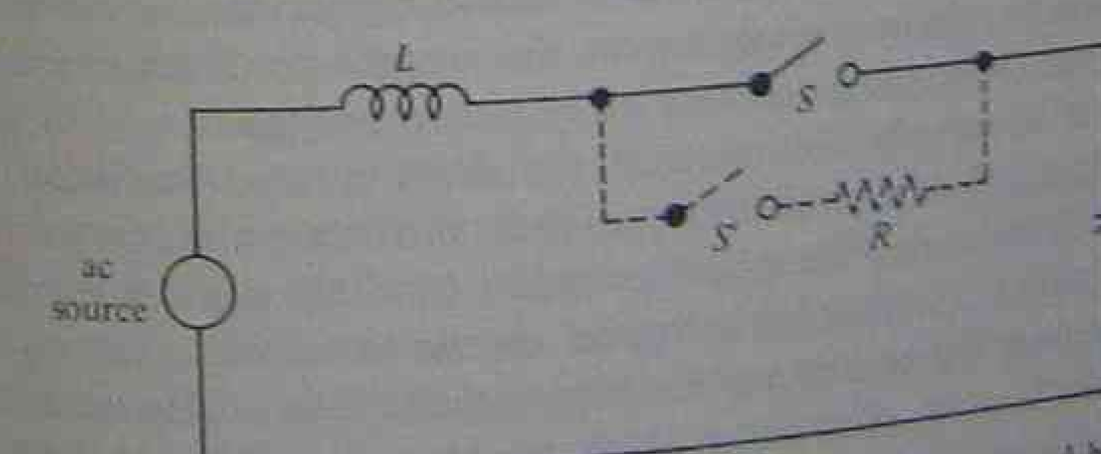


FIG. 12-9. A circuit in which overvoltages may be produced by switching.

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

$$f = \frac{1}{2\pi\sqrt{LC}}$$ (12-[illegible])

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.

6. 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 second-

ary 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

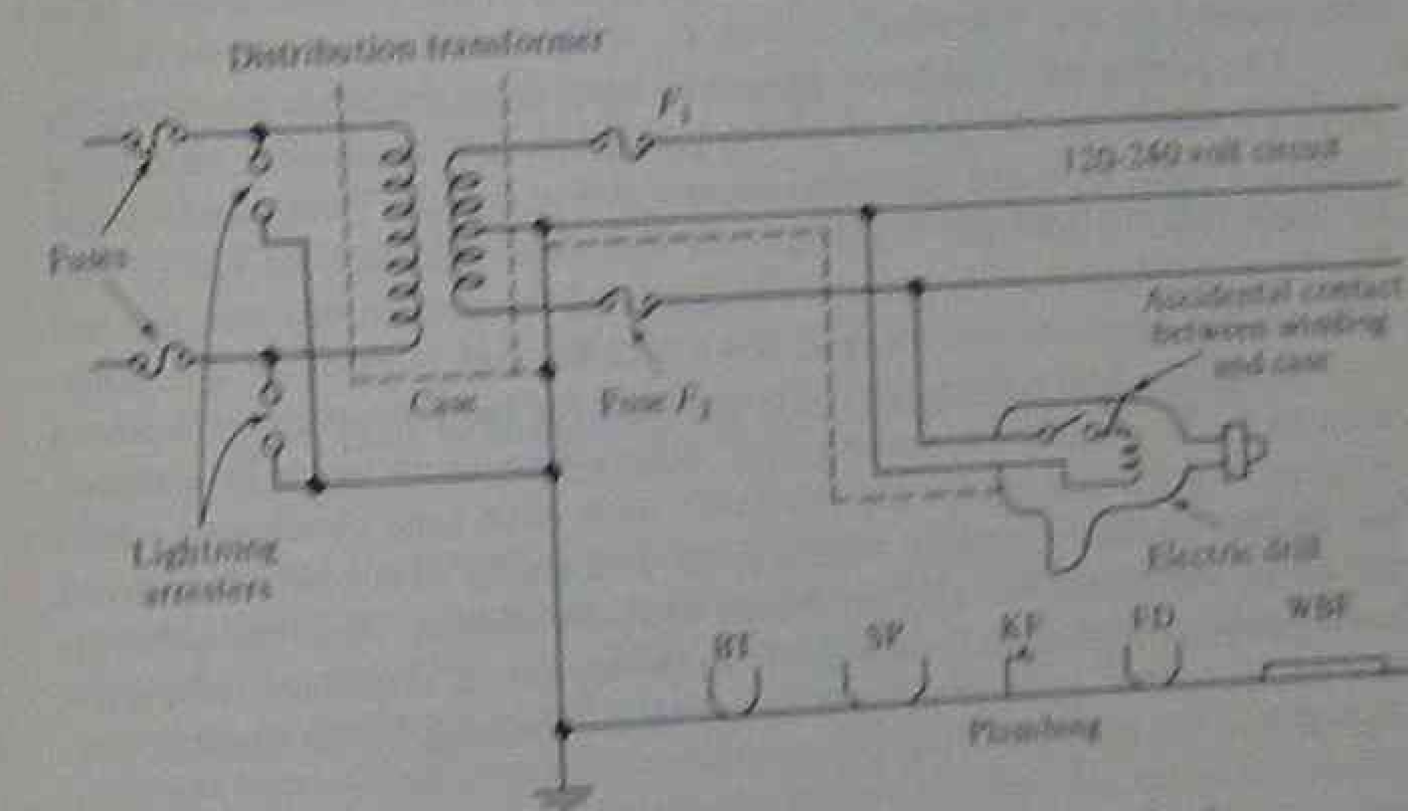


FIG. 12-10. A typical residential distribution circuit showing equipment which is directly connected to the circuit neutral.
BT Bathtub
SP Swimming Pool
KF Kitchen Faucet
FD Furnace Duct
WBF Wet Basement Floor.

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 [illegible]ic 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.

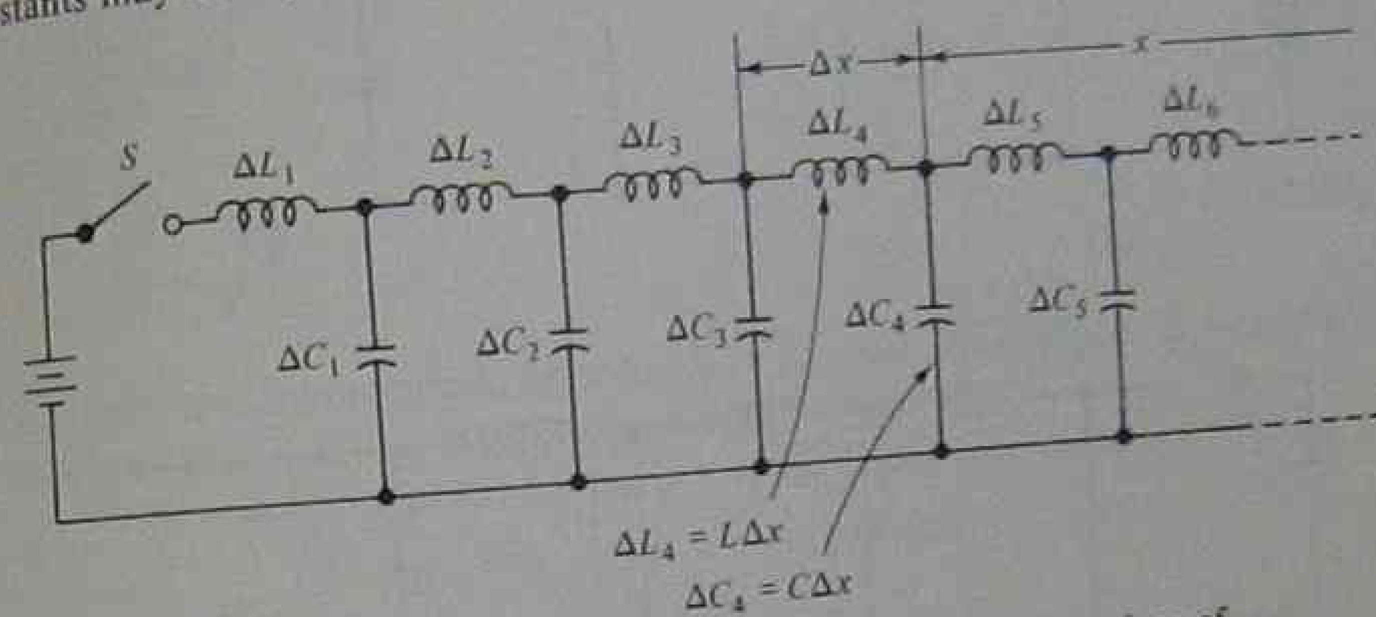


FIG. 12-11. A transmission line shown as incremental sections of inductance and capacitance.

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:

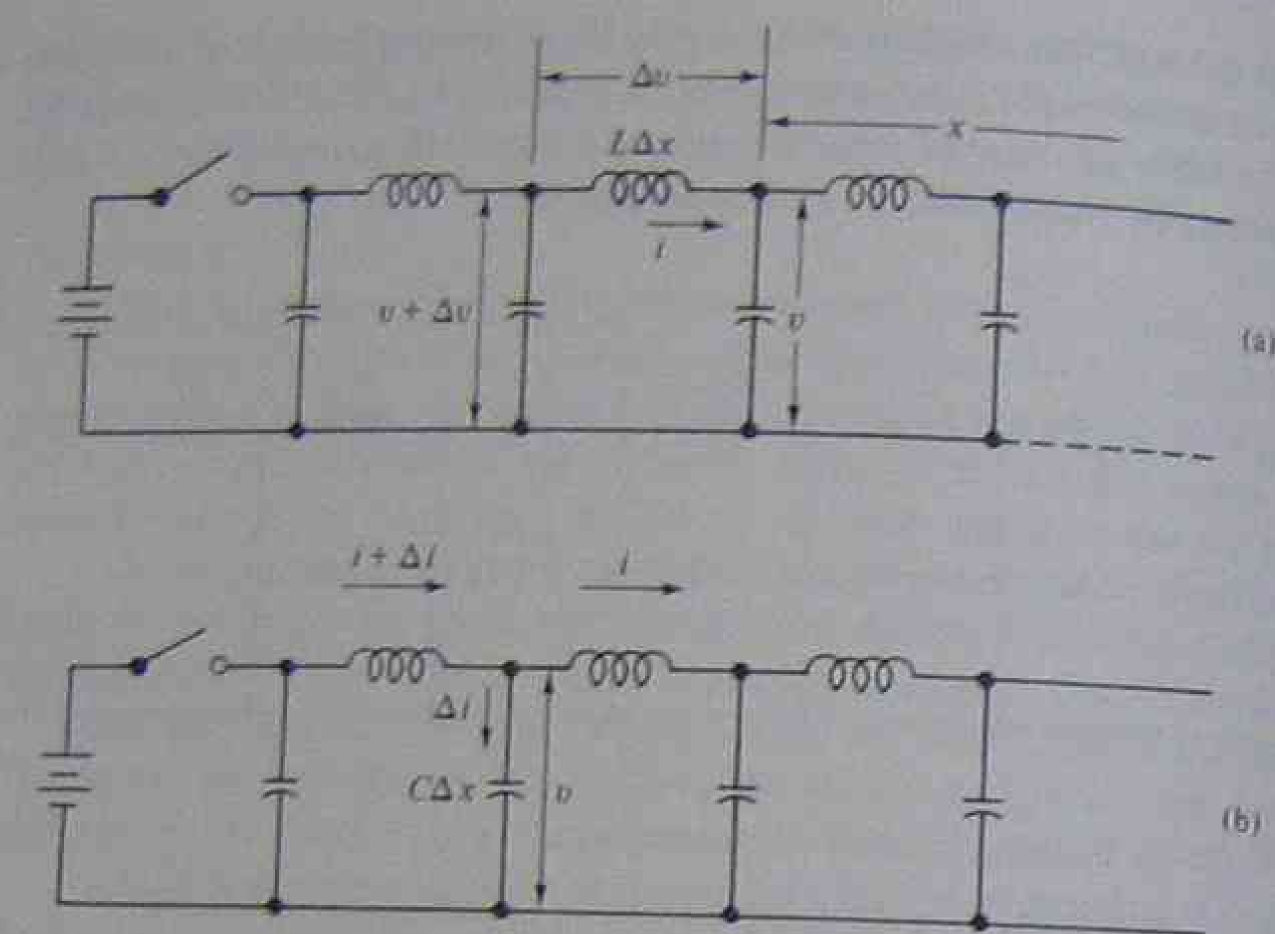


FIG. 12-12. An incremental section of a line. (a) Voltage conditions. (b) Current conditions.

$$\frac{\partial v}{\partial x} = L\frac{\partial i}{\partial t} \tag{12-6}$$

$$\frac{\partial i}{\partial x} = C\frac{\partial v}{\partial t} \tag{12-7}$$

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

$$W_L = \tfrac{1}{2} L i^2$$

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

$$W = \tfrac{1}{2}Li^2 + \tfrac{1}{2}Li^2$$
$$= Li^2 \tag{12-13}$$

Similarly,

$$W = Cv^2 \tag{12-14}$$

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

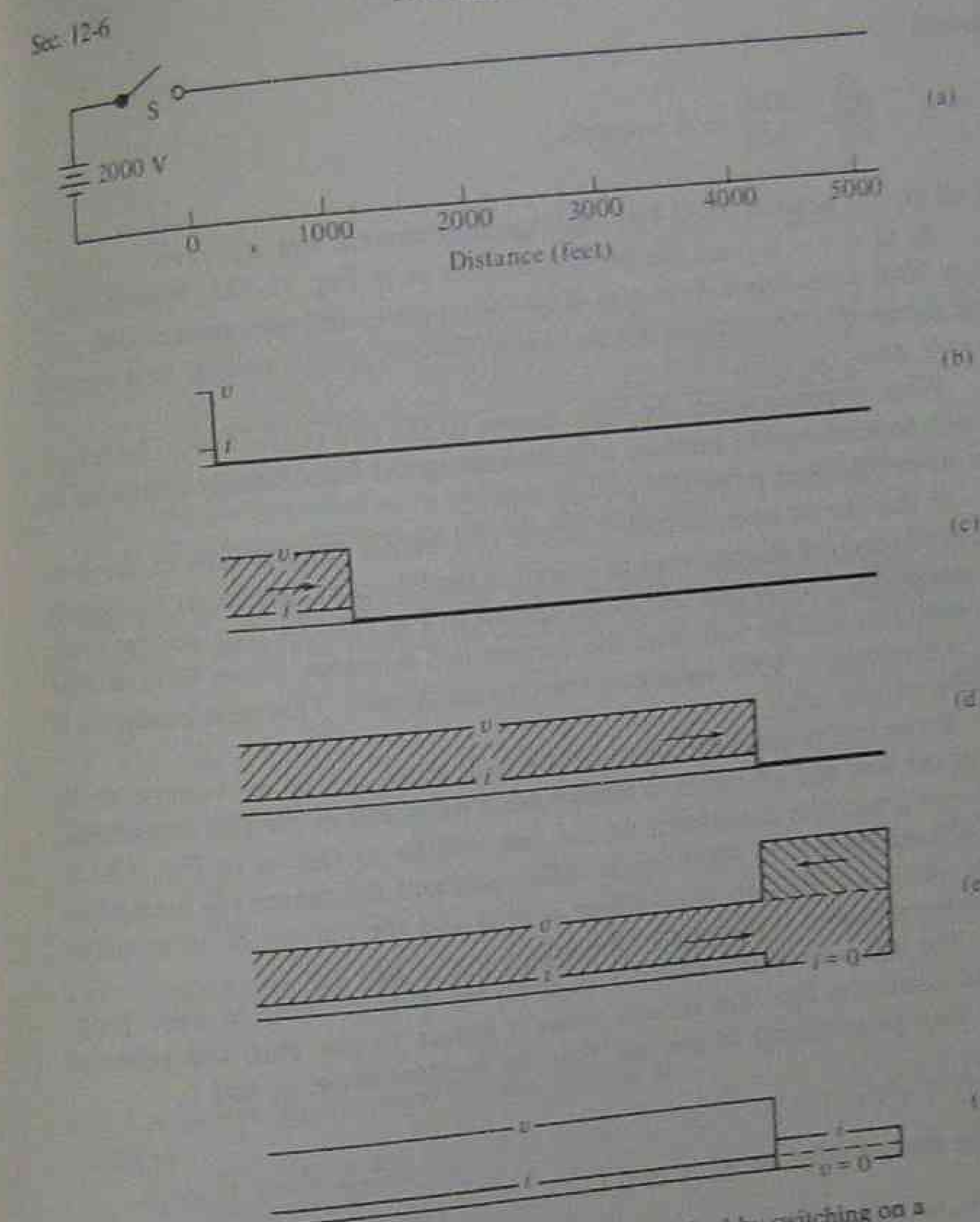


FIG. 12-13. A transmission line being energized by switching on a constant voltage source. (a) The circuit arrangement. (b) Voltage and current conditions at $t = 0+$. (c) Voltage and current conditions at $t = 1$ μsec. (d) Voltage and current conditions at $t = 4$ μsec. (e) Voltage and current conditions, 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 $t = 4$ μsec 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 $t = 6$ μ 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.

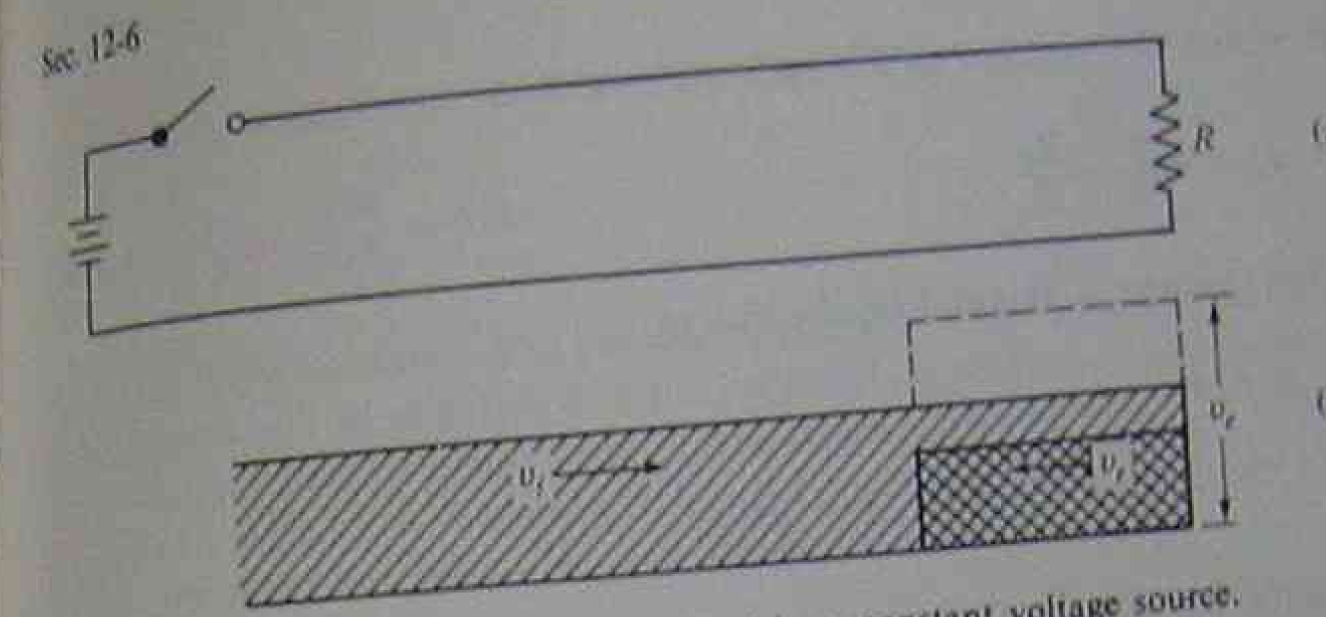


FIG. 12-14. A line being energized by a constant voltage source. The line is terminated by a resistor R. (a) The circuit arrangement. (b) Voltage conditions on the line after reflection.

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

$$\begin{aligned} v_e &= v_i + v_r \\ &= 2v_i \frac{R}{R + Z_C} = 2v_i \frac{1}{1 + Z_C/R} \end{aligned} \tag{12-23}$$

This equation has the form of the expression for the voltage across R in the circuit of Fig. 12-15.

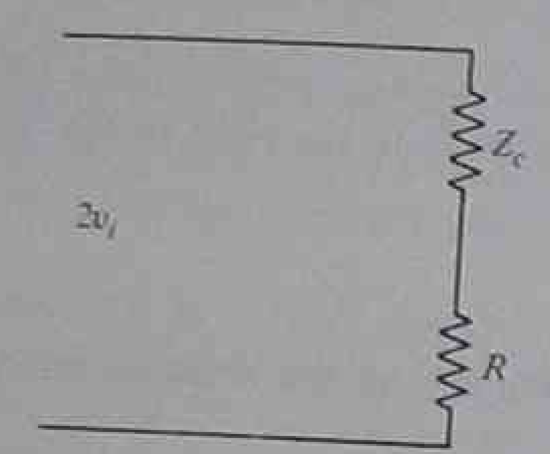


FIG. 12-15. The circuit equivalent of a line terminated in a resistor.

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),

$$\begin{aligned} v_r &= v_i \frac{R - Z}{R + Z} = 2000 \frac{600 - 400}{600 + 400} \\ &= 400 \text{ V} \end{aligned}$$

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

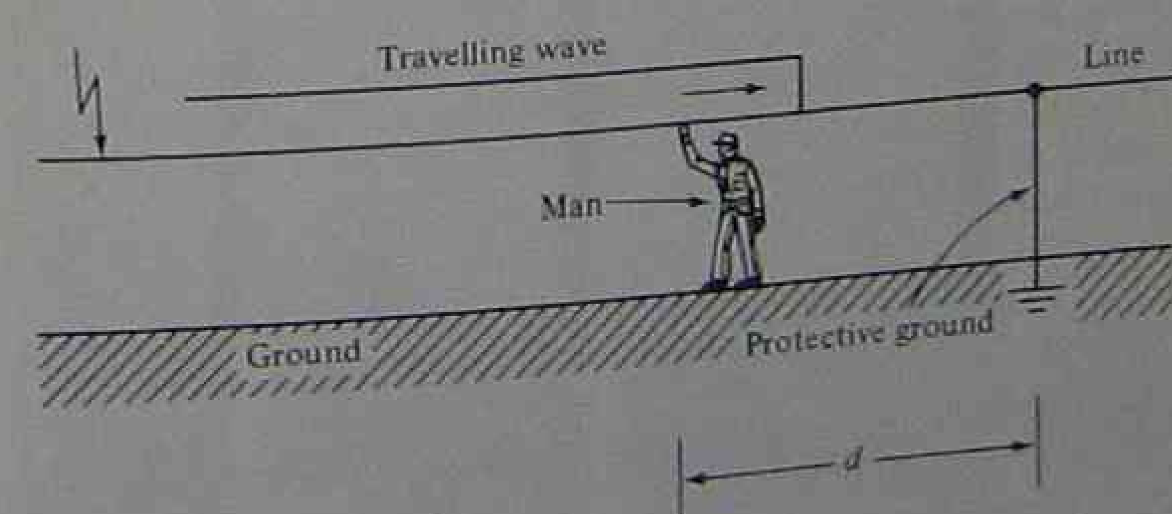


FIG. 12-16. A man working on a line between his protective grounds and the source of a traveling wave.

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

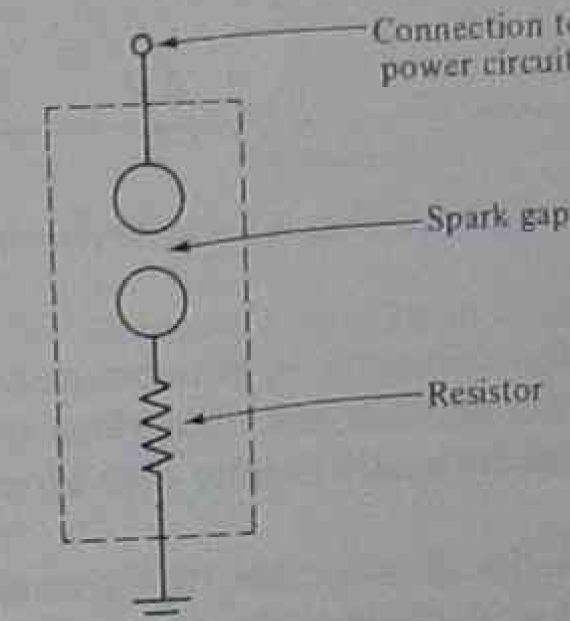


FIG. 12-18. A basic lightning arrester.

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

$$v_a = 2v_i \frac{1}{1 + Z_c/R} \tag{12-23}$$

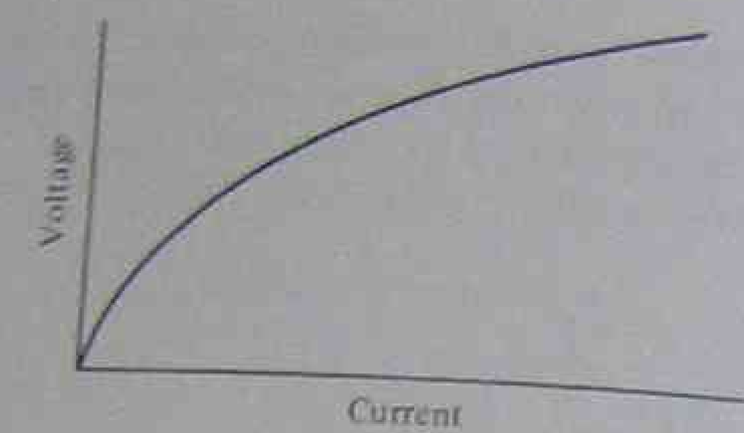


FIG. 12-19. The volt-ampere relationship in the non-linear resistor of an arrester.

It may be noted that as R is decreased, v_a becomes a smaller fraction of v_i. 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-

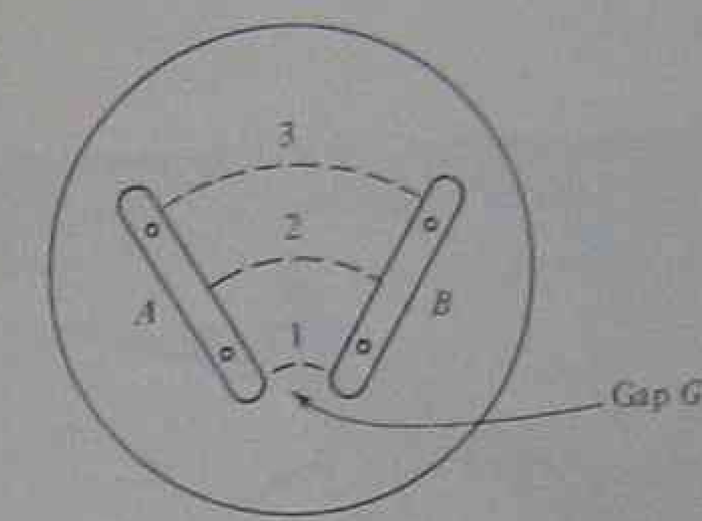


FIG. 12-20. The confined spark-gap of a lightning arrester.

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*.