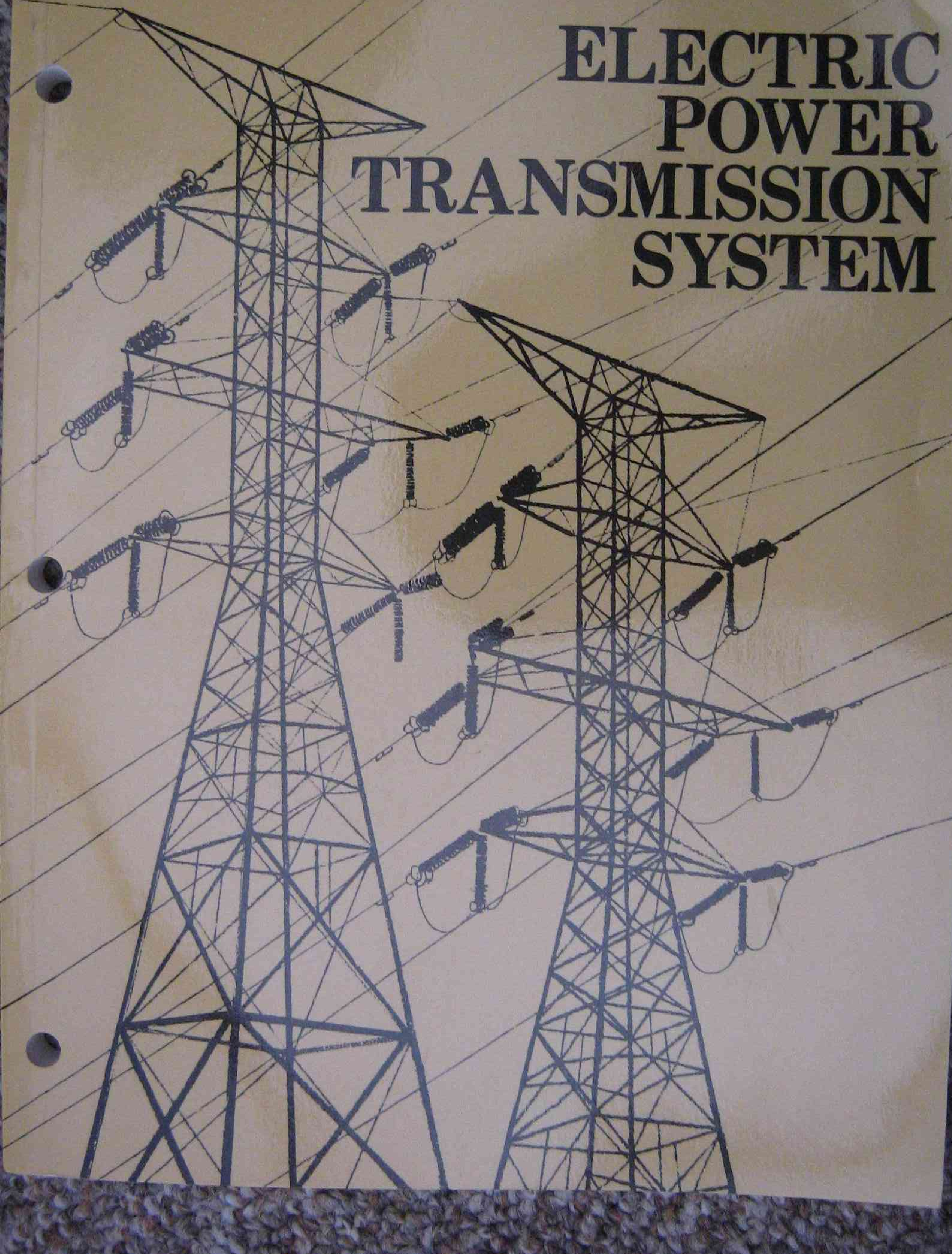
ELECTRIC POWER TRANSMISSION SYSTEM



Electric Power Transmission System

240/415 V – 50 Hz

by

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and

the Staff of

Lab-Volt

Lab-Volt®

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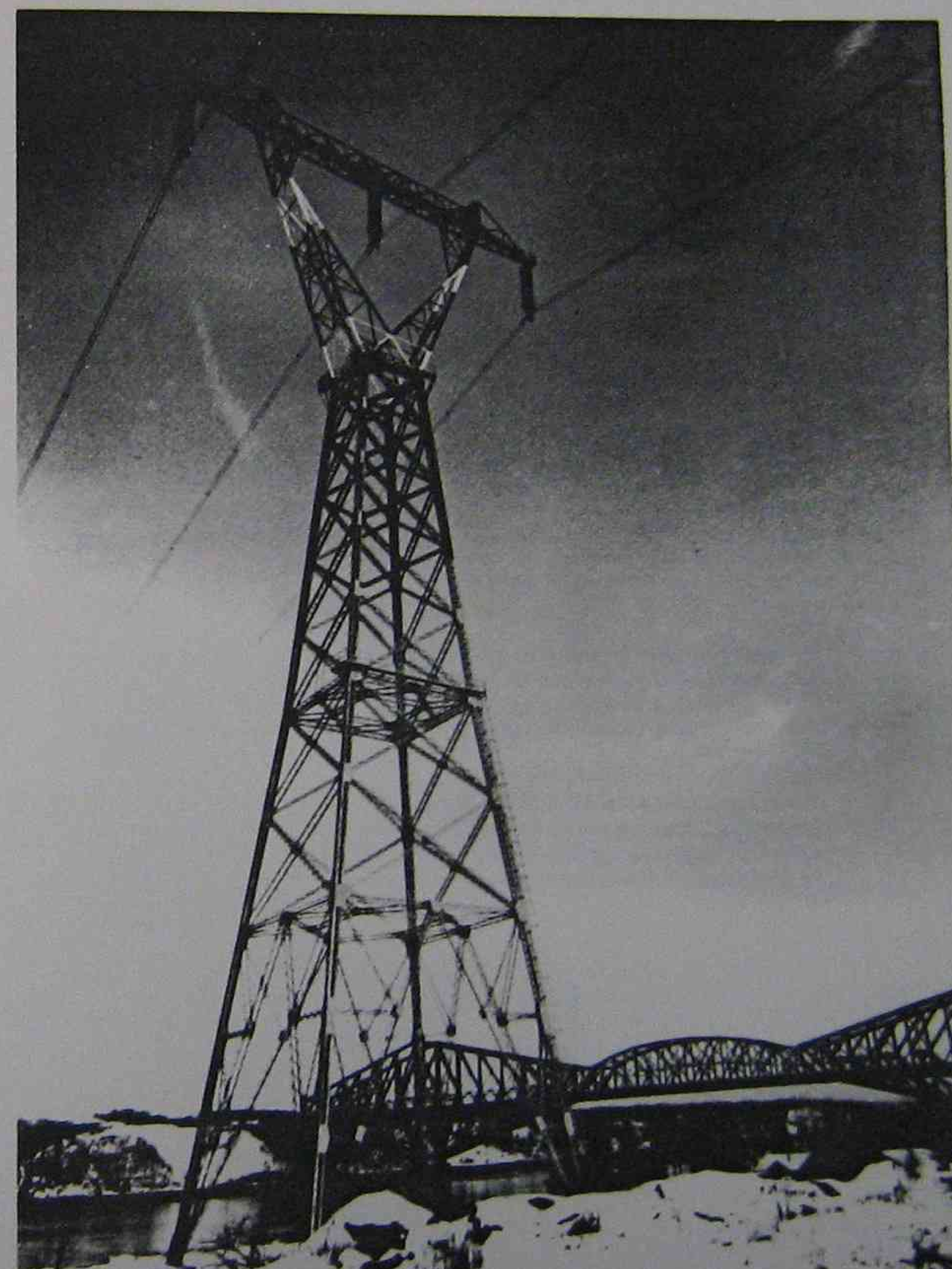


Foreword

Industrialized and developing countries of the world are more and more orienting their energy needs towards an electric power economy. Enormous generating capacity will have to be installed to meet the needs of industry, commerce and residential homes. But the power plants that generate electricity must be linked to the user by means of an adequate transmission and distribution system. Just as vital as the shaft between the engine and the wheels of a car, an electric transmission line is essential between the power station and its ultimate load.

This manual on Electric Power Transmission Systems explains by hands-on experiments the principles of generation, transmission, and utilization of electric power. Particular emphasis has been devoted to developing a practical understanding of the transmission line link – a subject which is usually taught in a strictly theoretical way.

The experiments show how changes in the source, the load, and the transmission line affect the overall performance of the system. In particular, they illustrate the meaning of real and reactive power, how the voltage at the end of a line can be lowered or raised, how power can be forced to flow over one line instead of another, how generators can be synchronized and how a system behaves when subjected to disturbances. The tests relating to switching transients, sudden overloads and momentary short-circuits dramatically demonstrate the mechanical swing of generator poles and the concurrent surges of power over the transmission line. More than any amount of theory could show, these experiments convey the meaning of power stability and the limits to power flow.

Economical, low-power, and safe electric alternators, motors, capacitors, reactors, resistors, meters, transformers, and transmission lines are employed. Despite their small size, these electric machines and devices are designed to act in exactly the same way under steady-state and transient conditions, as their larger counter parts in industry.

This practical, hands-on course is presented in a way that is readily understandable by anyone who has a knowledge of electricity at the technical school. (Such training can be provided by the Lab-Volt Electric Power Technology learning system which employs modular laboratory equipment entirely compatible with the Electric Power Transmission System.)

Real and Reactive Power Flow

Owing to varying practices and different points of view in the power industry as regards the meaning and interpretation of power flow, w believe that a few remarks on the subject will be helpful. First, we shall discuss the flow of real power.

Real Power

Consider the zero-center-scale megawatt-meter shown in Figure 1, calibrated 0-100 MW on either side of the zero marker. This instrument is connected into a power line to measure the *value* and the *direction* of real power which flows in the line. If no power flows, the pointer will indicate zero as in Figure 1.

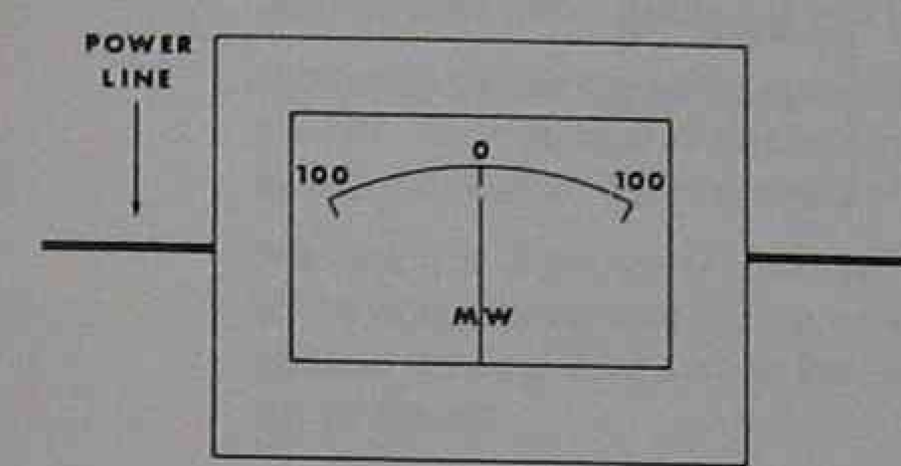


Figure 1.

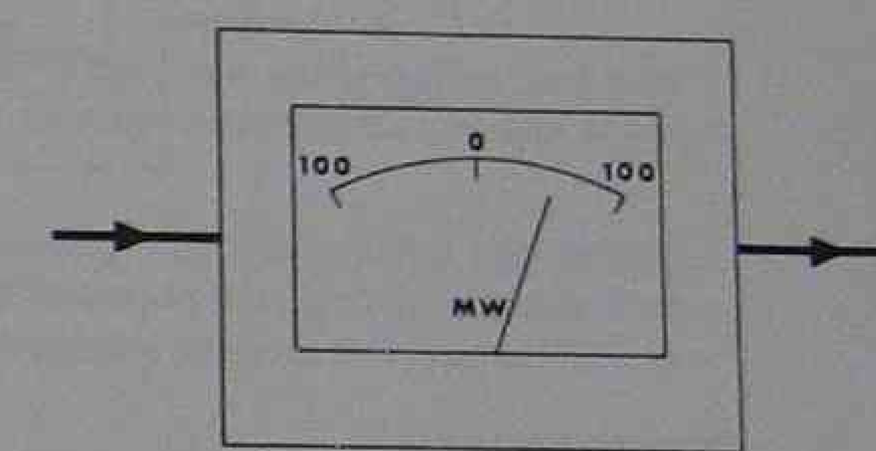


Figure 2.

If power in the line flows from left to right, the pointer will be deflected to the right as shown in Figure 2. Conversely, if power flows from right to left, the pointer will be deflected to the left as shown in Figure 3. Thus, if the MW-meter were connected between a generator and a resistive load, as shown in Figure 4, the meter would correctly show that power is flowing from the generator to the load.

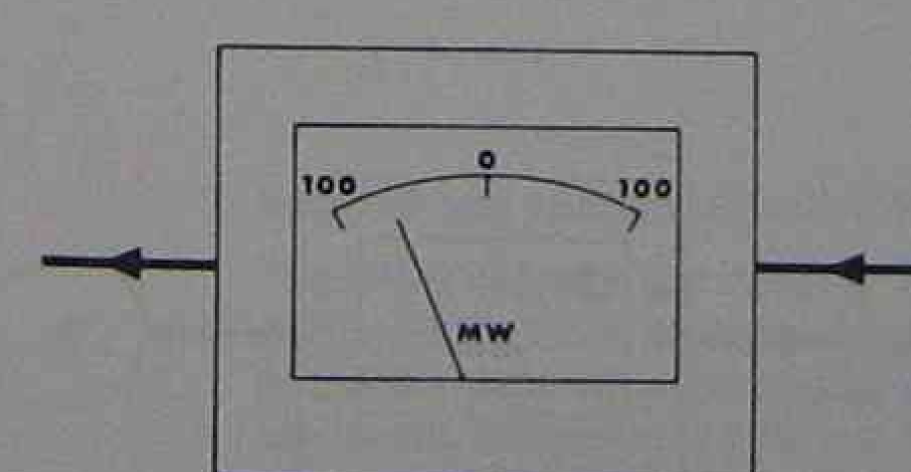


Figure 3.

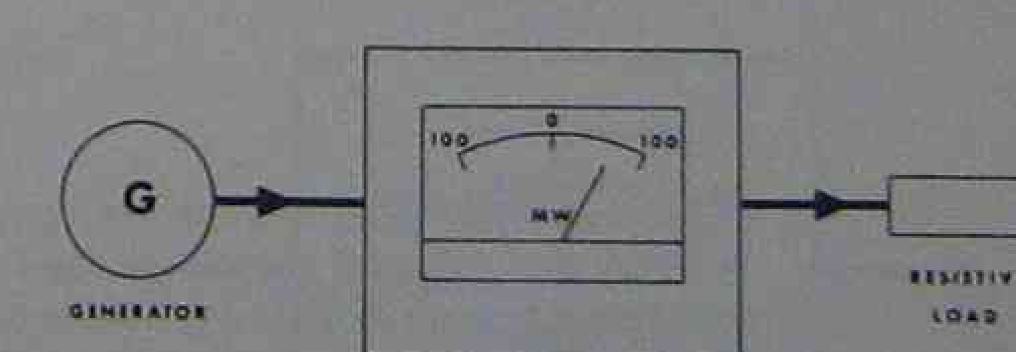


Figure 4.

"Power In" and "Power Out"

The terms "power in" and "power out" used in some supply authorities can readily be understood by referring to Figure 4. In this figure it may be said that the meter indicates "power out" of the generator or, if we wish, "power in" to the load. As a further illustration, Figure 5 shows a situation where there is "power out" of B (a substation say) or, equally correct, "power in" to A (a factory, say).

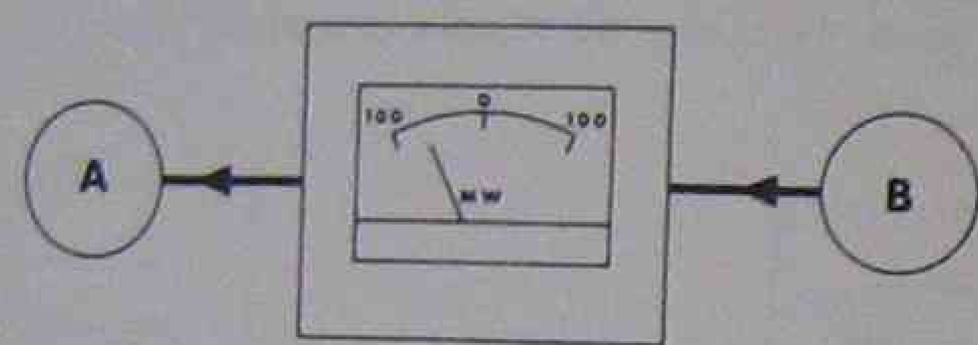


Figure 5.

Reactive Power

The same terminology can be applied to meters which measure reactive power, such as the megavarmeter of Figure 6.

If the pointer deflects to right (Figure 7) this indicates that reactive power is flowing from left to right, that is, from A to B. If we wish, we could say there is reactive "power out" of A or reactive "power in" to B. Just as a resistor "absorbs" real power, a coil or magnet "absorbs" reactive power. In AC circuits reactive power is needed to create a magnetic field. If a MVAR-meter is connected between a generator and a coil, its pointer will deflect to the right as shown in Figure 8. Some people would say there is reactive "power out" of the generator which is the same as saying there is reactive "power in" to the coil.

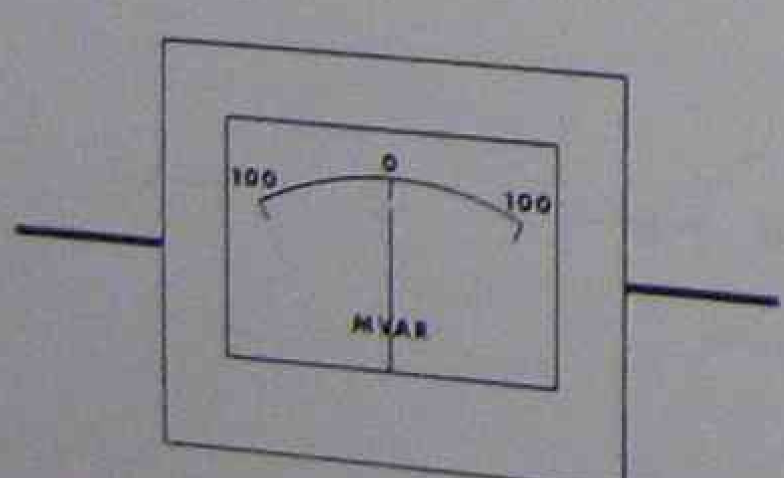


Figure 6.

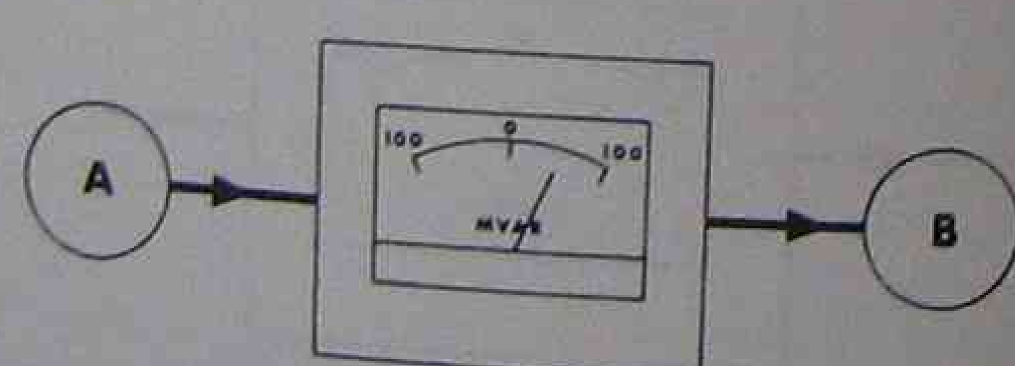


Figure 7.

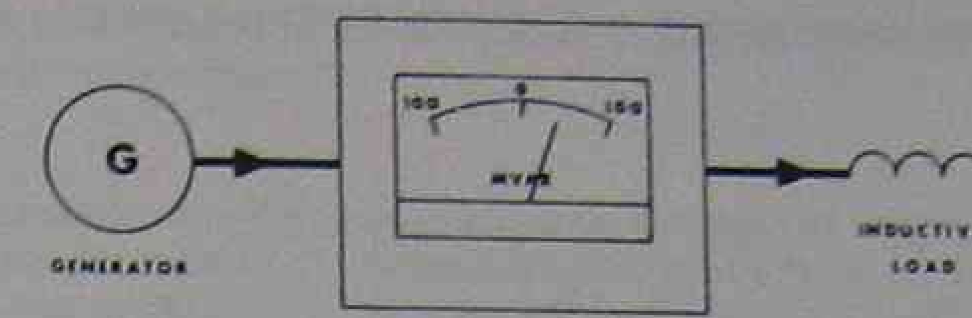


Figure 8.

Meters with Zero Marker at the Left

Instead of having the zero marker in the center of the scale, some meters have it on the left. The *direction* of power flow is then found by observing the position of the switch associated with the meter.

For example, if the meter gives an upscale reading when the switch S (Figure 9) is at the right, then power (active or reactive) is flowing to the right. Conversely, if an upscale reading results when the switch is towards the left (Figure 10) power is flowing to the left.

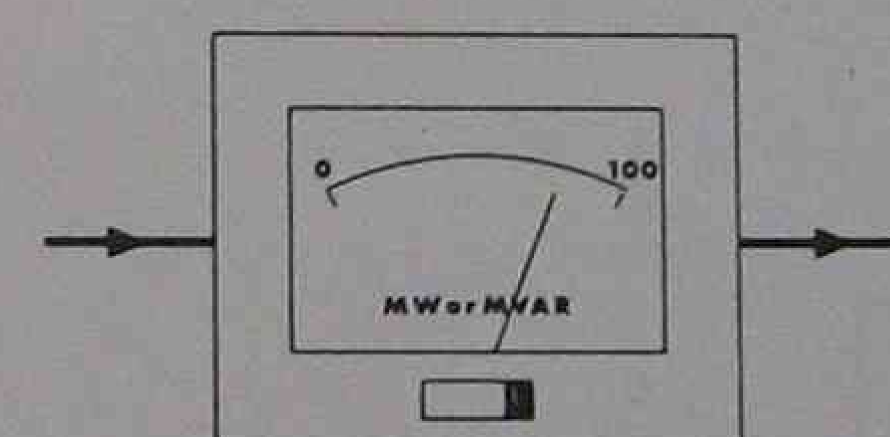


Figure 9.

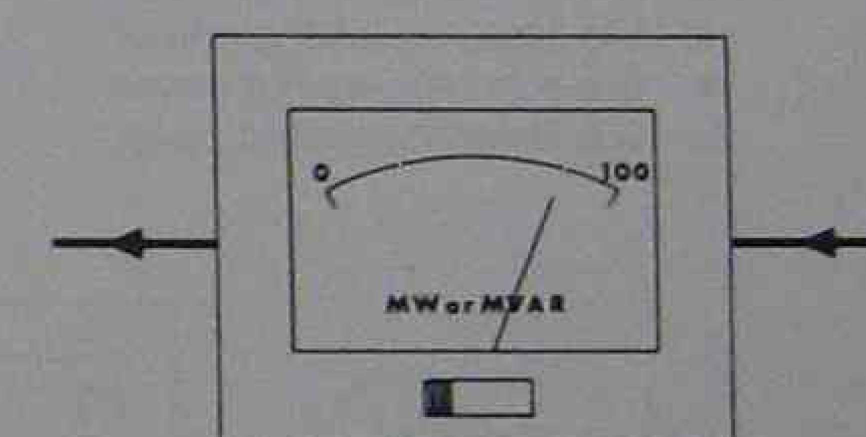


Figure 10.

Lagging and Leading Reactive Power

The terms "lagging" and "leading" reactive power are still widely used and require some explanation in the light of what has been said so far. "Lagging" and "leading" power are really two ways of looking at the same thing. Just as we can equally well say for two linemen on a pole that one is "above" or the other is "below" so we can equally well say that power may be "leading" or "lagging". To understand this we must state two facts:

1. Leading power can be considered as the exact opposite of lagging power, as regards the *direction* of reactive power flow.
2. The reactive power measured by VAR-meters is "lagging" reactive power.

People who use the terms "lagging" and "leading" interpret Figures 11 and 12 as follows:

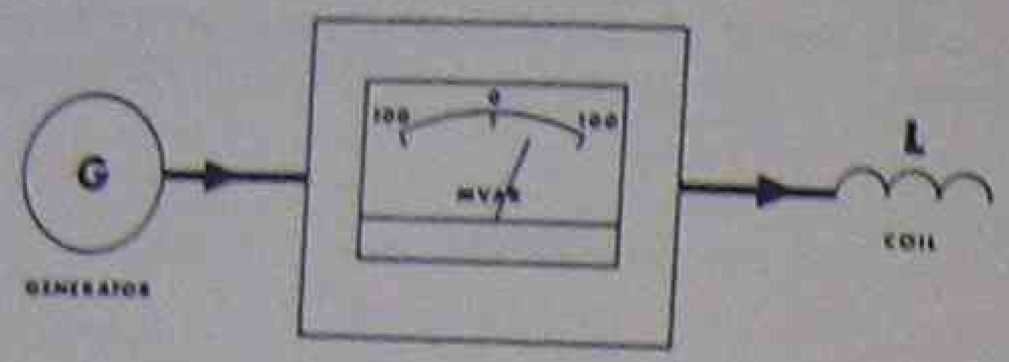


Figure 11.

Note: *Arrows show the direction of "lagging" power flow. All the following statements referring to Figure 11 are correct.*

a. Lagging power is flowing from G to L.
b. Leading power if flowing from L to G*.
c. L is absorbing lagging power.
d. L is supplying leading power*.
e. G is supplying lagging power.
f. G is absorbing leading power*.

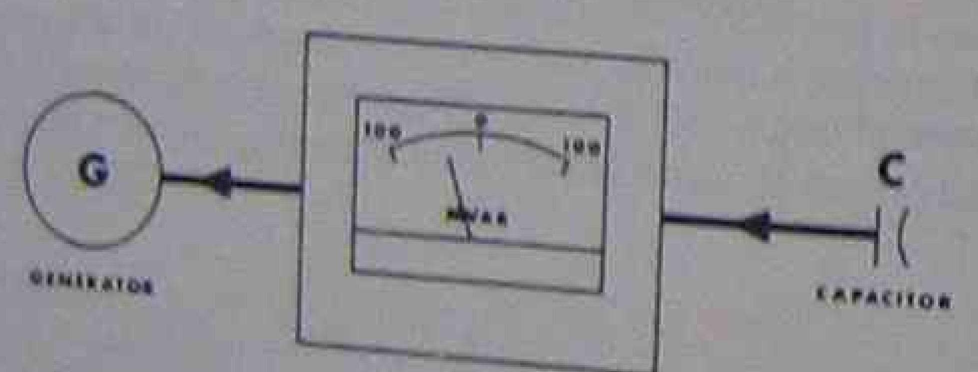


Figure 12.

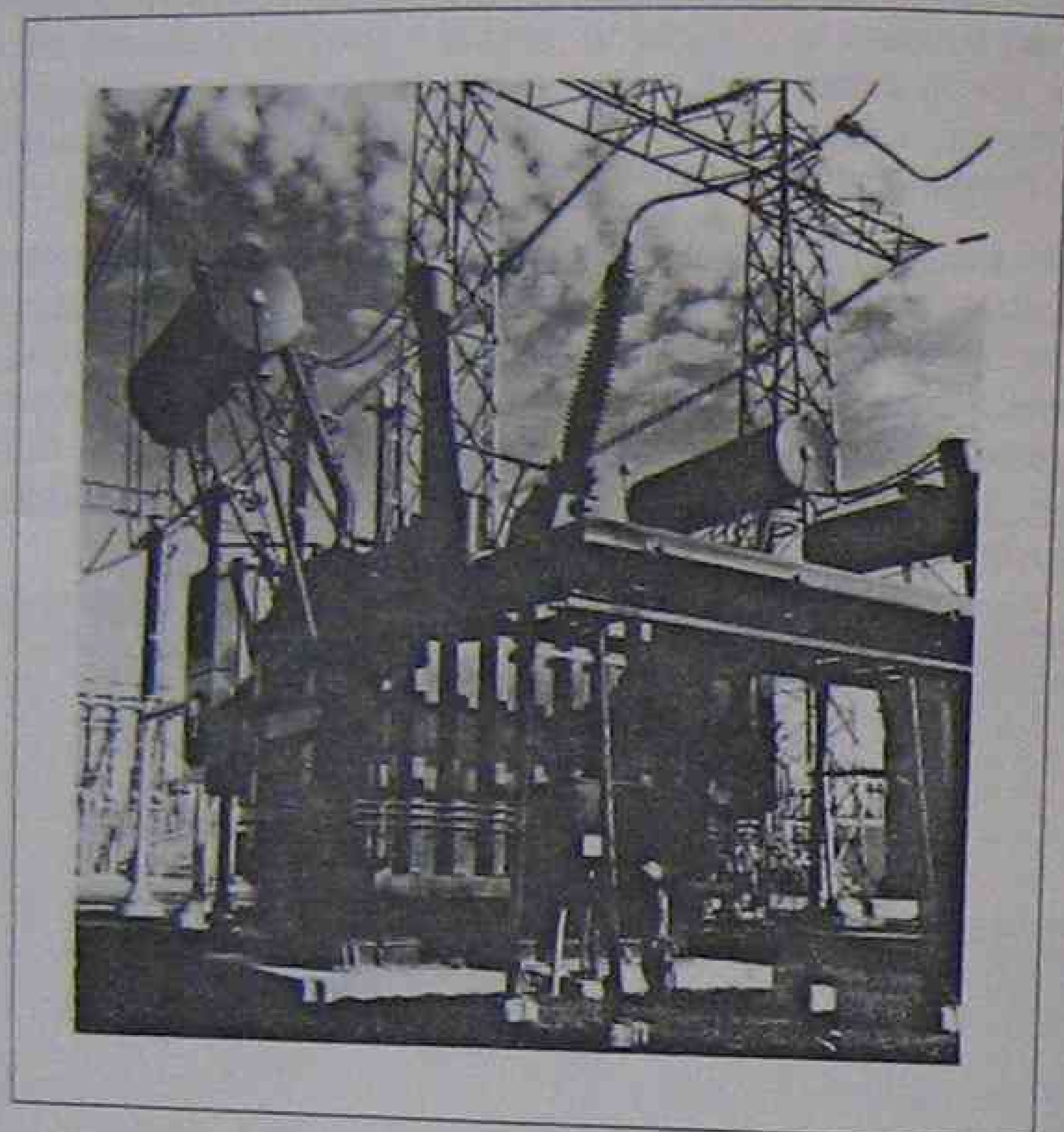
Note: *Arrows show the direction of "lagging" power flow. All the following statements referring to Figure 12 are correct.*

a. Lagging power is flowing from C to G.
b. Leading power if flowing from G to C*.
c. G is absorbing lagging power.
d. G is supplying leading power*.
e. C is supplying lagging power.
f. C is absorbing leading power*.

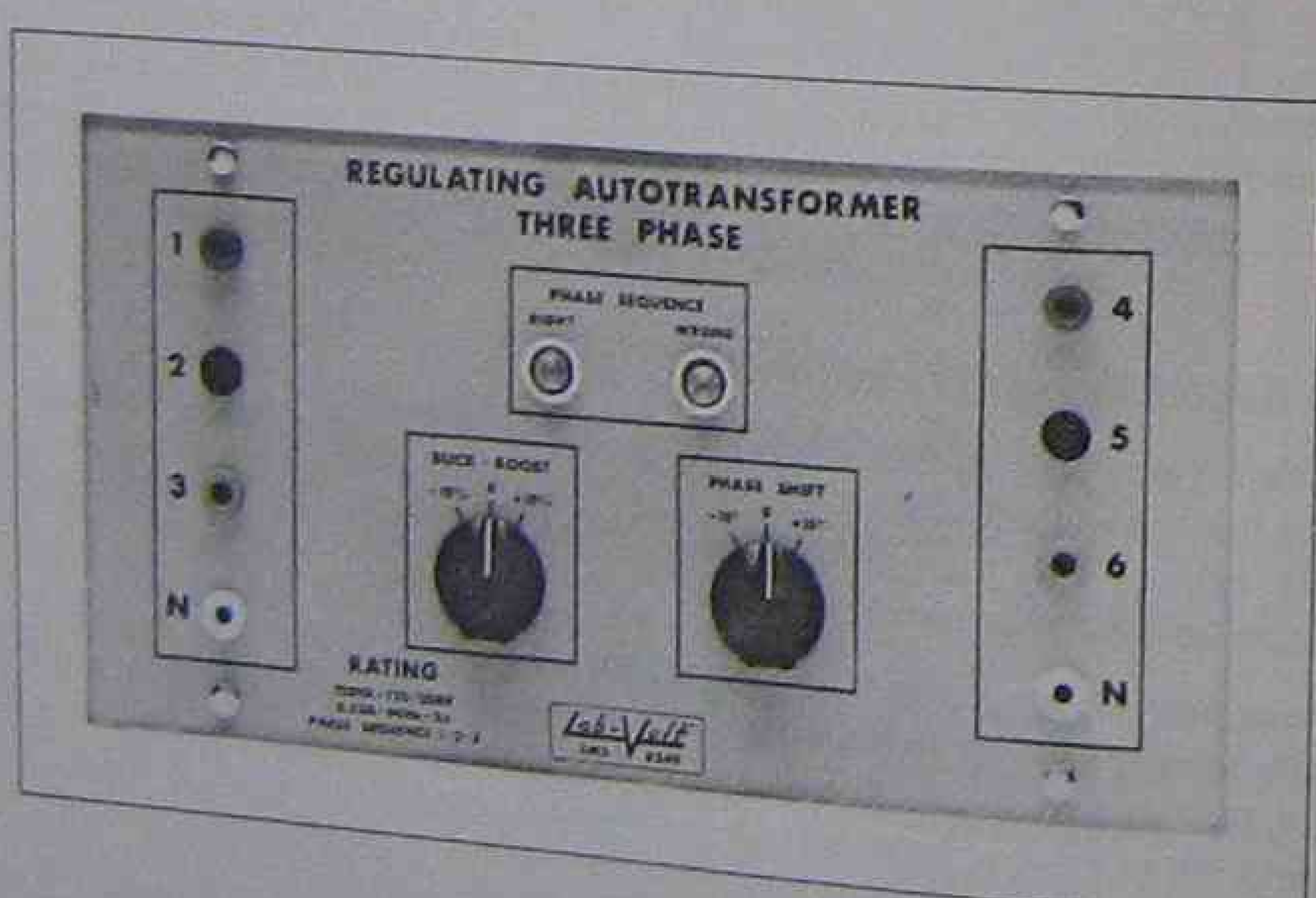
* **Note:** *Although statements b, d and f are theoretically correct this terminology is seldom, if ever, used in the power industry.*

Owing to the confusion which can arise when speaking of "lagging" and "leading" reactive power, the Institute of Electrical and Electronics Engineers (IEEE)* has recommended that only one term be used, namely "reactive power". By virtue of the IEEE definition, "reactive power" means "lagging" power.

* Reference: Electrical Transmission and distribution Reference Book, Page 291, 202, Westinghouse Electric Corporation, East Pittsburgh, Pensylvania.

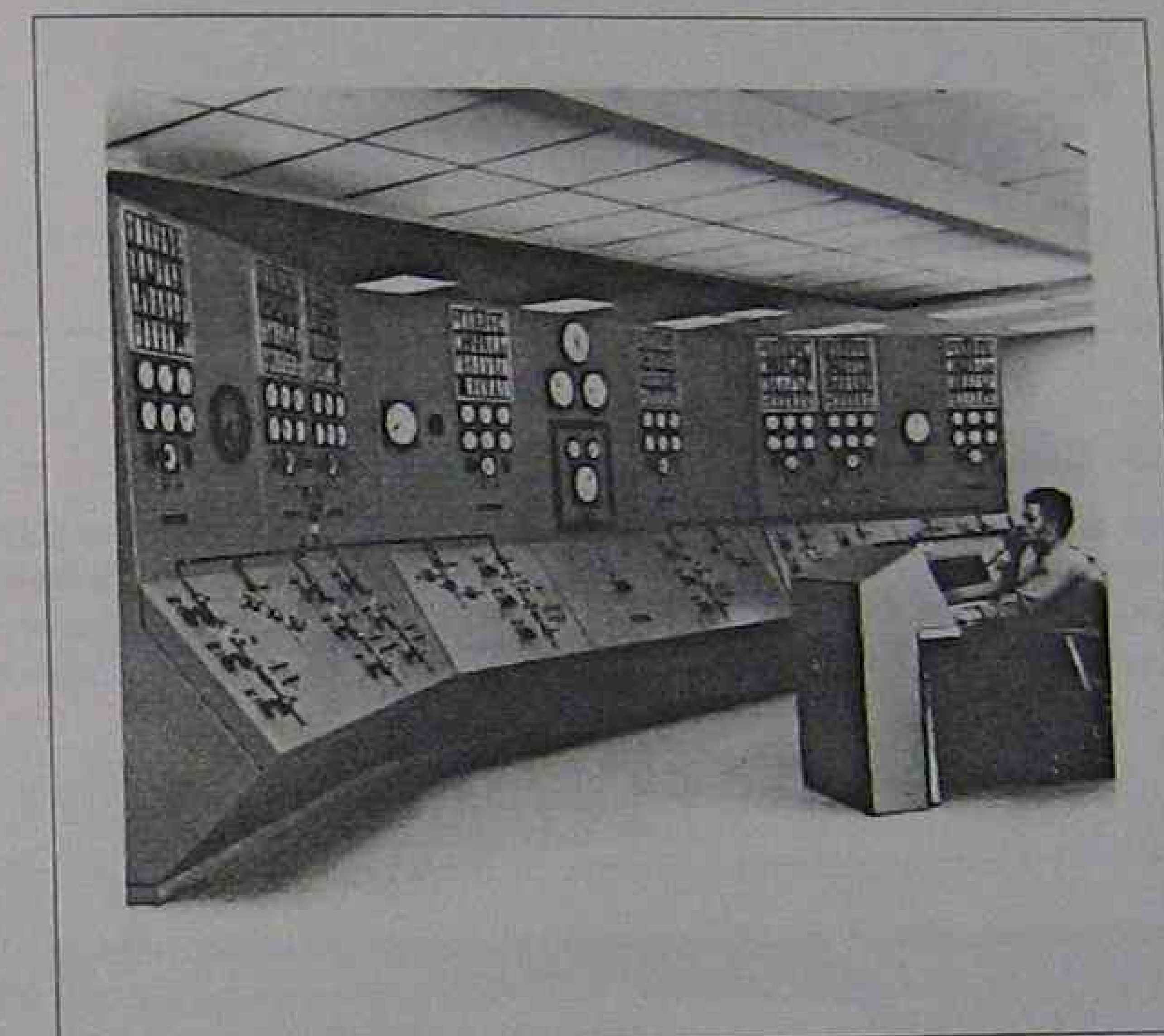


This large single-phase transformer dwarfs the station maintenance operator who inspects it.



Real and Reactive Power and the Wattmeter/Varmeter

A large industry or city absorbs a lot of electric power. Most of it is used to develop mechanical power (motors), to produce heat (toasters and radiators), to produce light (fluorescent lamps) or to produce chemical changes (electroplating and aluminum production). This kind of power is called real or active power and is measured in watts, kilowatts or megawatts.

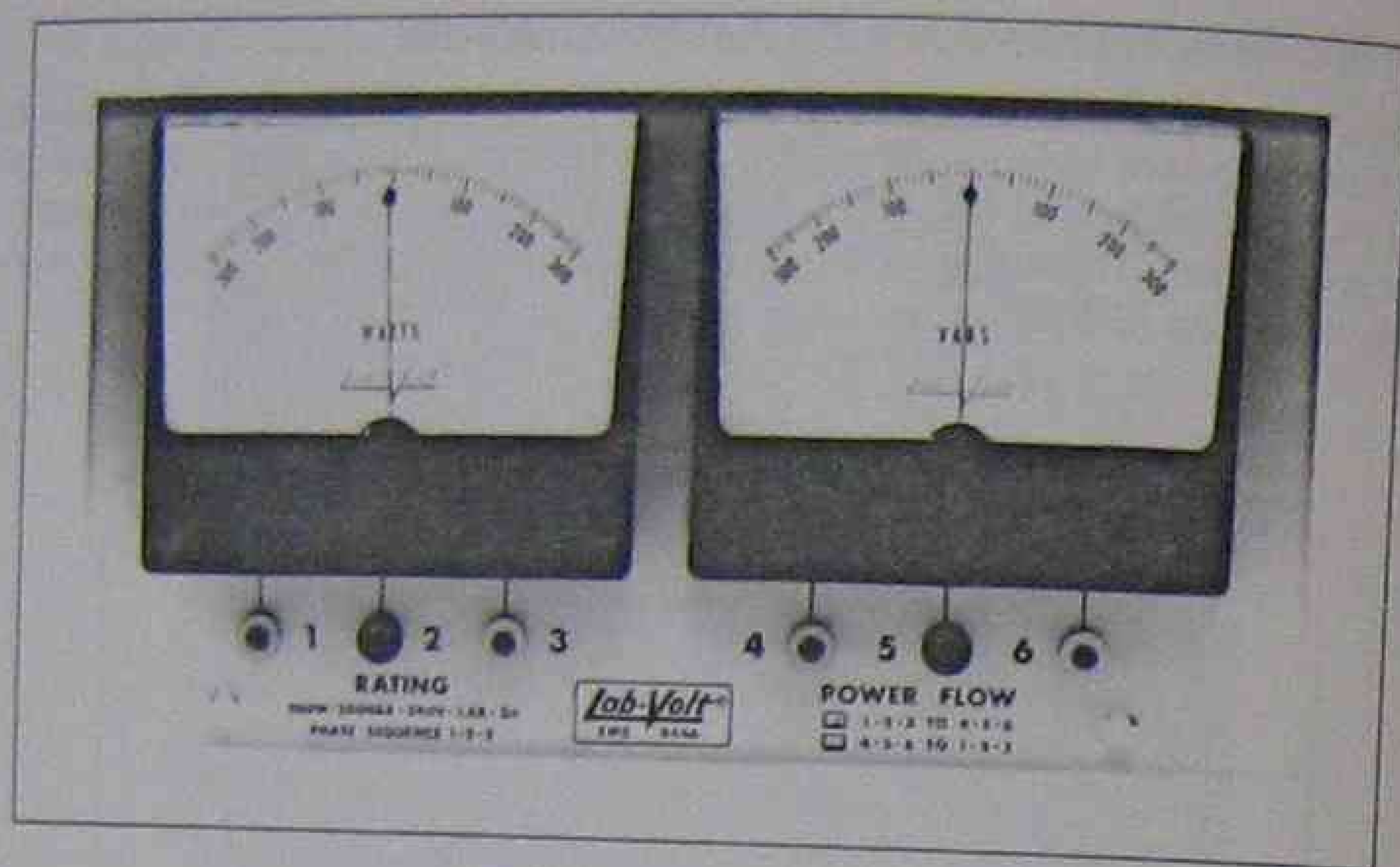


Wattmeters and Varmeters are widely used in this control room of Manicouagan Power Station No. 2.

However, another kind of power is needed to create the AC magnetic field in motors, transformers, relays and magnets. This is the so-called reactive power, measured in vars, kilovars or megavars.

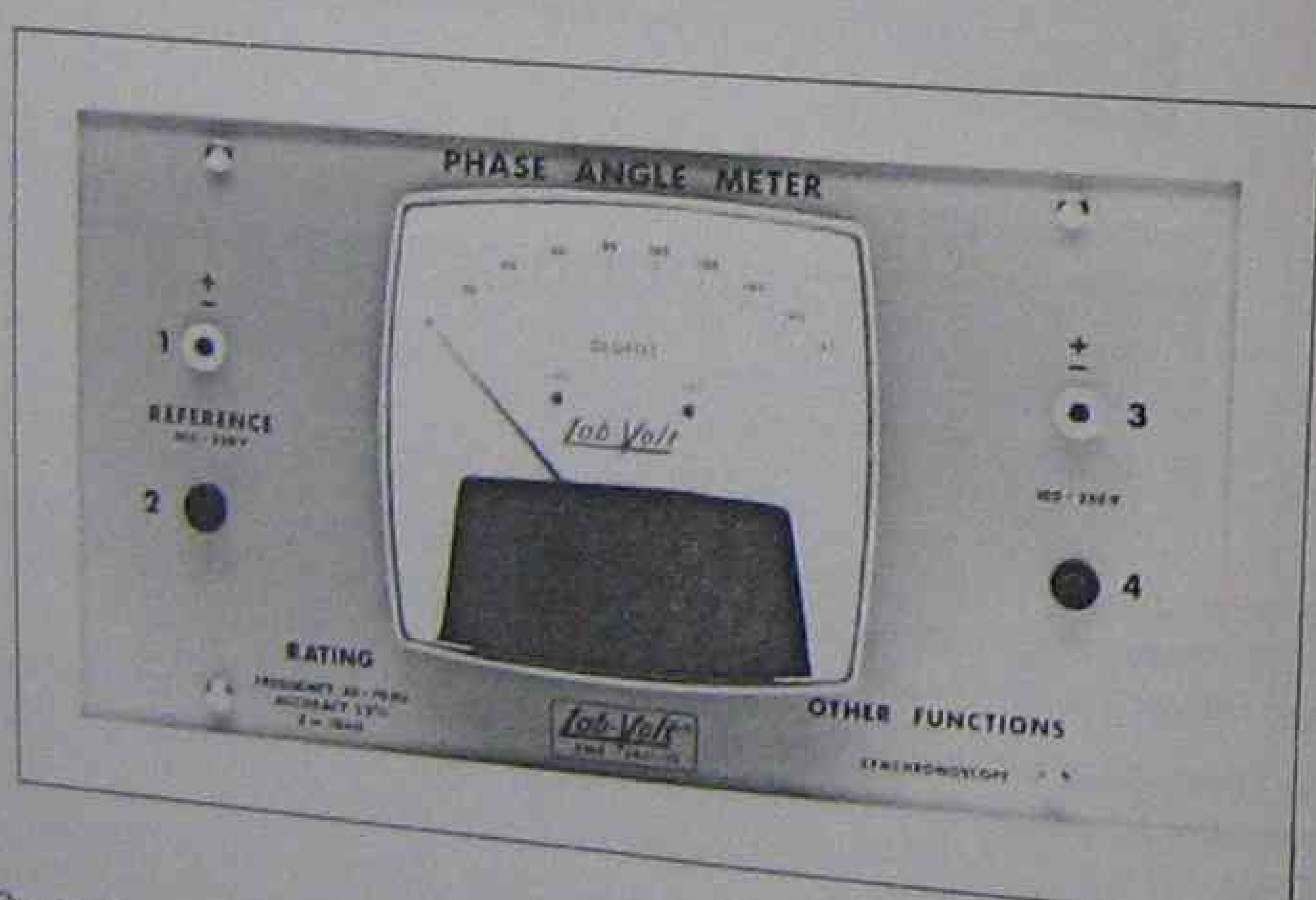
The Three-Phase Wattmeter/Varmeter enables us to measure the real and reactive power which flows in a balanced three-phase circuit as well as the direction in which it flows.

Controlling the flow of electric power is important to electric power companies because it influences not only the revenue but also the electrical stability of the power system.



The Phase Meter

The phase angle between the sender and receiver of a transmission line plays a crucial role in the amount of real power which the line will carry. The Phase Meter is particularly useful in this regard. It is used to measure the phase angle between the voltages of a transmission line or, for that matter, between any two voltages of a circuit.

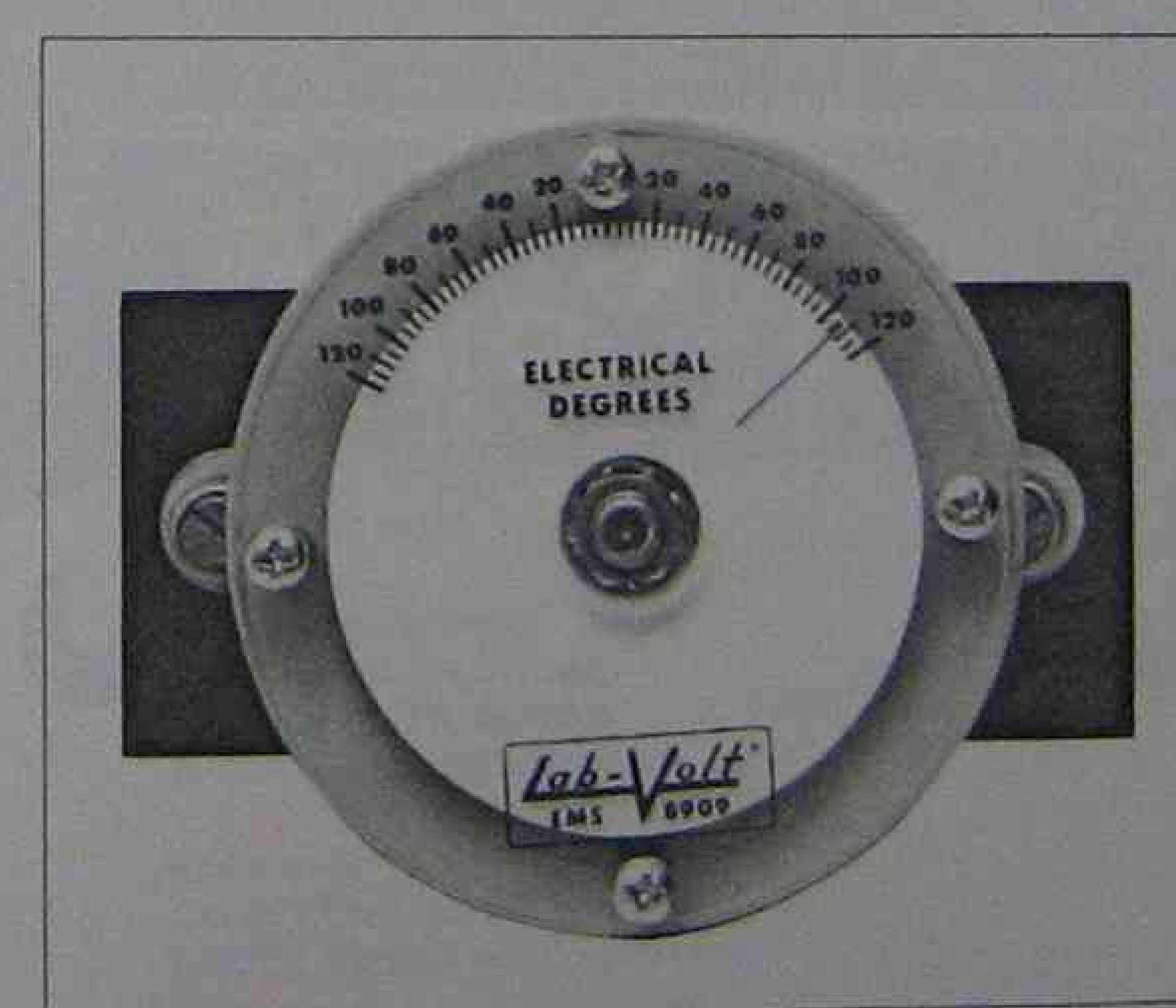


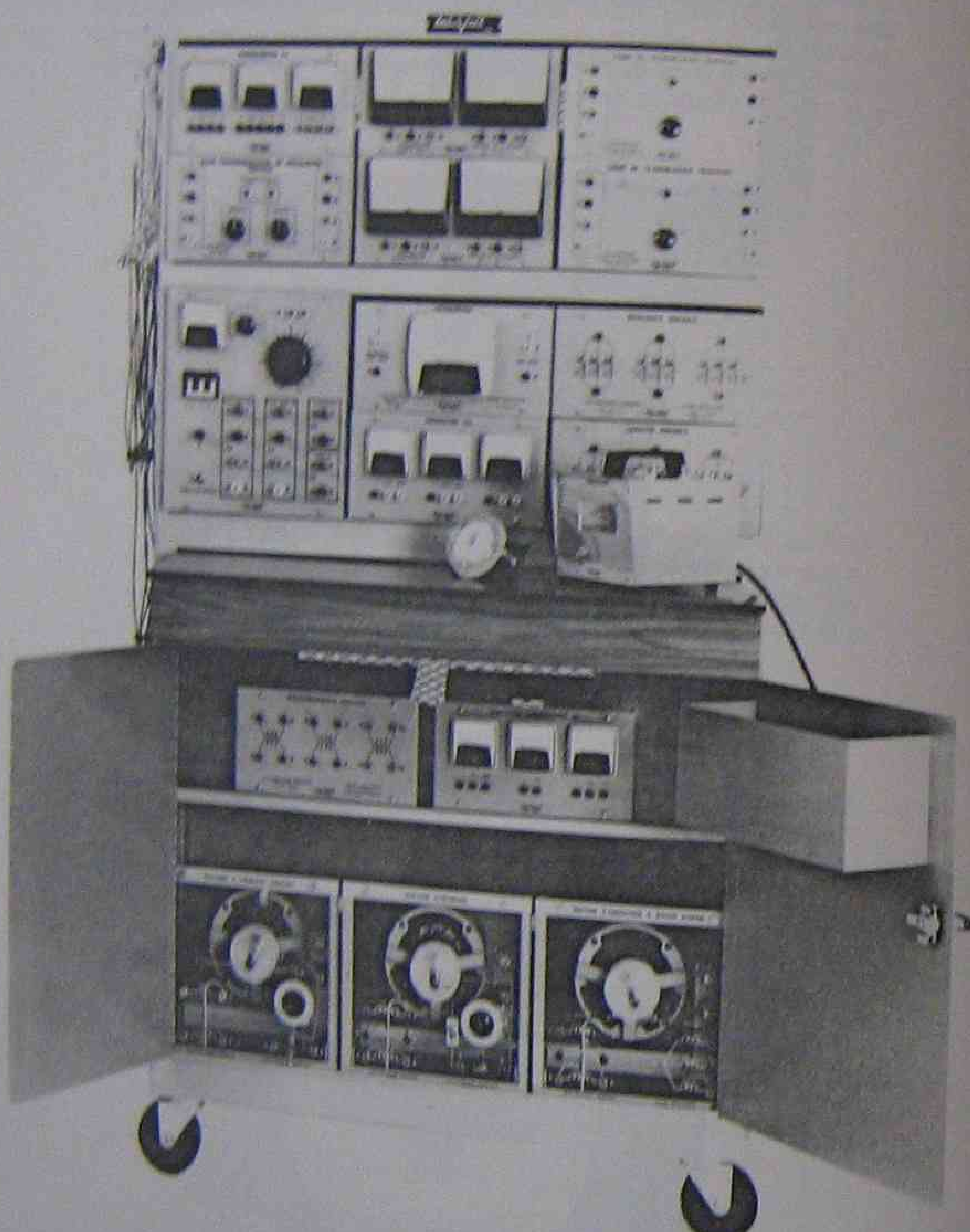
The meter can also be used as a synchroscope when a Three-Phase Synchronous Motor/Generator has to be synchronized with an existing power system.

The Stroboscope and the Phase-Shift Indicator

The behavior of generators and synchronous motors under variable load conditions, and particularly under system disturbances, can be witnessed by means of the Stroboscope. The shift in position of the rotor poles under increased load and the oscillatory swing under transient conditions enable one to understand why sudden load changes should be avoided.

Used in connection with the Phase-Shift Indicator, the strobe light can be used to make accurate measurements of rotor pole shift in electrical degrees.

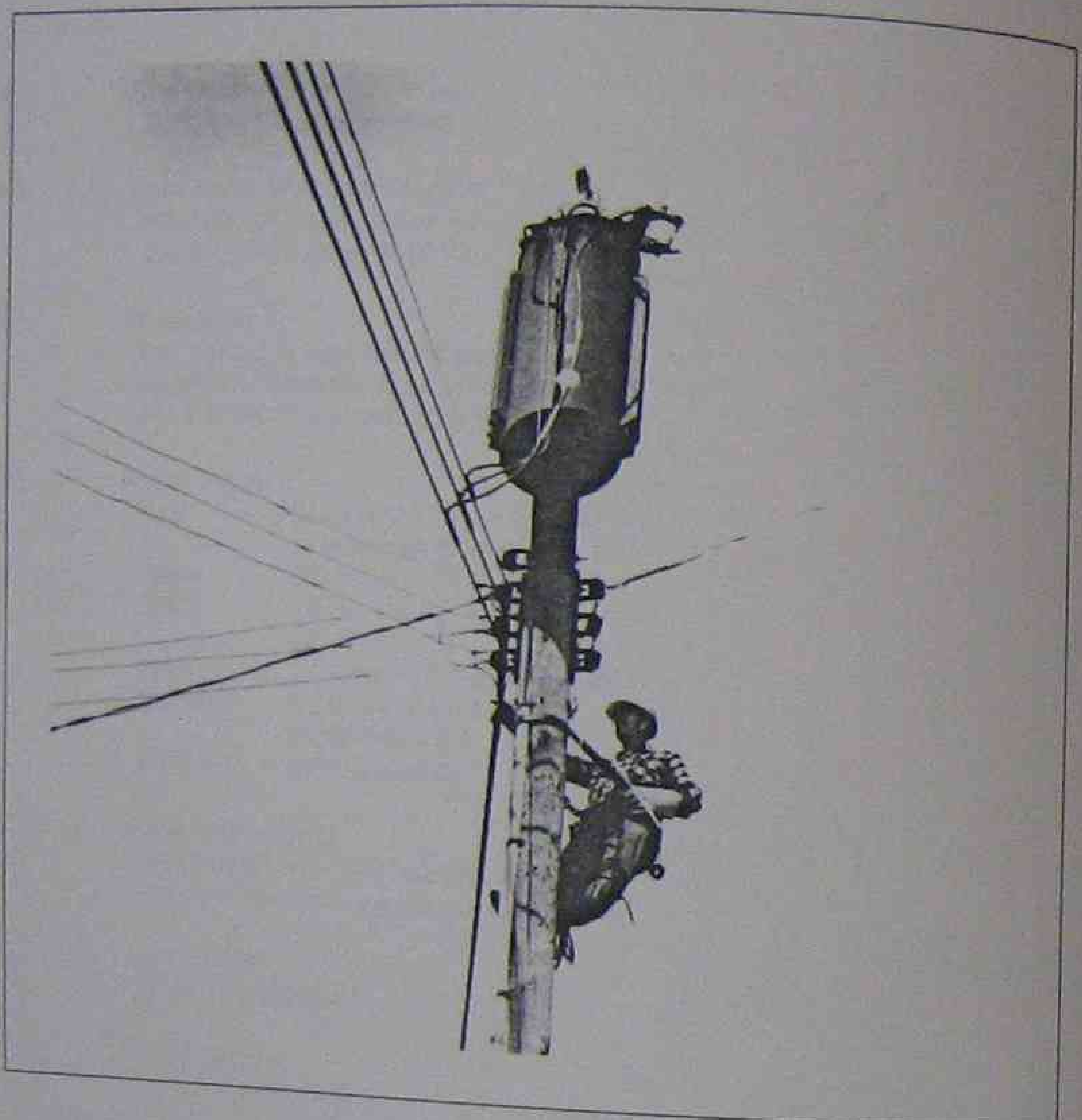




List of Required Equipment

MODEL	DESCRIPTION	QUANTITY
8110	Mobile Workstation	1
8211	DC Motor/Generator 175 W, 1500 r/min, 240 V dc motor 120 W, 1500 r/min, 240 V dc generator	 1 1
8221	Four-Pole Squirrel-Cage Induction Motor 175 W, 1345 r/min, 240/415 V, 3 phase	1
8231	Three-Phase Wound-Rotor Induction Motor 175 W, 1315 r/min, 240/415 V, 3 phase	1
8241	Three-Phase Synchronous Motor/Generator 175 W, 1500 r/min, 240/415 V, 3 phase motor 120 VA, 1500 r/min, 240/415 V, 3 phase generator	1
8311	Resistive Load Loading capacity 0 to 252 W in 12 W steps, three separate sections, 5% accuracy, 1 phase/3 phase/dc	1
8321	Inductive Load Loading Capacity 0 to 252 var in 12 var steps, three separate sections, 5% accuracy, 1 phase/3 phase at 50 Hz	1
8329	Three-Phase Transmission Line Impedance 0, 200, 400, 600 Ω 0,17 A, 3 phase at 50 Hz	2
8331	Capacitive Load Loading Capacity 0 to 252 var in 12 var steps, three separate sections, 5% accuracy, 1 phase/3 phase, 50 Hz	1
8348	Three-Phase Transformer – Ratio 1:1 42 VA, 415/415 V, 0,1 A 1 phase, 50 Hz, 3 units	1
8349	Three-Phase Regulating Autotransformer 120 VA, 240/415 V, 3 phase at 50 Hz Buck-Boost +15%, 0, −15% Phase Shift +15°, 0, −15°	1
8412	DC Voltmeter/Ammeter 0-300 mA dc, 2% accuracy 0-1,5/3 A dc, 2% accuracy 0-40/400 V dc, 2% accuracy	1
8425	AC Ammeter 0-0,25/1,5/5 A ac, 2% accuracy 0-0,25/1,5/5/15 A ac, 2% accuracy	1

8426	AC Voltmeter 0-250/500 V ac, 2% accuracy	1
8446	Three-Phase Wattmeter/Varmeter 300-0-300 W, 300-0-300 var 450 V, 0,8 A, 3 phase at 50 Hz	2
8451	Phase Meter 0 to 180° lag or lead, isolated inputs, impedance: reference 30 kΩ, incoming 20 kΩ, 200 V to 450 V, 1 phase, 40 to 60 Hz	1
8821	Power Supply input – 240/415 V – 10 A – 3 phase (4 wires plus ground) output (fixed) – 240/415 V – 10 A – 3 phase 240 V – 10 A – 1 phase 240 V dc – 1 A output (variable) – 0-240/415 V – 3 A – 3 phase 0-240 V – 3 A – 1 phase 0-240 V dc – 5 A Voltmeter – 0-500 V ac/V dc	1
8909	Phase-Shift Indicator Synchronous motor pole-shift indicator 0 to ±120 electrical degrees, adjustable zero	1
8915	Inertia Wheel Inertia = 0,026 kg·m²	1
8922	Stroboscope: Trigger Frequency (f) Int.: 50 Hz Ext.: 1000 Hz max Trigger Voltage 20-450 V rms Maximum Flash Rate 50 Hz Ext. Trigger Input Z_i 30 kΩ Flash occurs when rising trigger voltage passes through zero Power requirements: 0,125 A, 240 V, 50 Hz, 1 phase	1
8942	Timing Belt	1
9128	Connection Leads 40 stack-up banana plug patch cords 15 A continuous operation	1
13486-0A	Student Manual	1



Safety and the Power Supply

OBJECTIVE

- To learn the simple rules of safety.
- To learn how to use the ac/dc power supply.

DISCUSSION

TO ALL STUDENTS AND TEACHERS

Everyone should know the location of the FIRST AID supply in your shop or laboratory. Insist that every cut or bruise receives immediate attention, regardless of how minor it seems to be. Notify your instructor about every accident. He will know what to do.

If the student follows the instructions and observe the proper precautions, there are no serious hazards or dangers in the Electro Mechanical Systems of learning. Students should be aware that many people receive fatal shocks every year from the ordinary 240 V electricity found at home.

A thorough safety program is a "must" for anyone working with electricity. Electricity can be dangerous and even fatal to those who do not understand and practice the simple rules of SAFETY. There are many fatal accidents involving electricity by well-trained technicians who either through over-confidence or carelessness, violate the basic rules of personal SAFETY. The first rule of personal safety is always:

THINK FIRST!

This rule applies to all other industrial workers as well as to electrical workers. Develop good habits of workmanship. Learn to use tools correctly and safely. Always study the job at hand and think through your procedures, your methods, and the applications of tools, instruments and machines before acting. Never permit yourself to be distracted from your work and never distract another worker engaged in hazardous work. Don't indulge in practical jokes! Jokes can be fun, but not near moving machinery or electricity. There are generally three kinds of accidents which appear all to frequently among electrical students and technicians. These are: electric shock, burns, and mechanical injury. Your knowing and studying about them and observing simple rules will make you a safe person to work with. You could personally be saved from painful and expensive experiences – you might be saved to live to a rewarding retirement age.

ELECTRIC SHOCK

What about electric shocks? Are they fatal? The physiological effects of electric currents can generally be predicted by the chart shown in Figure 1-1.

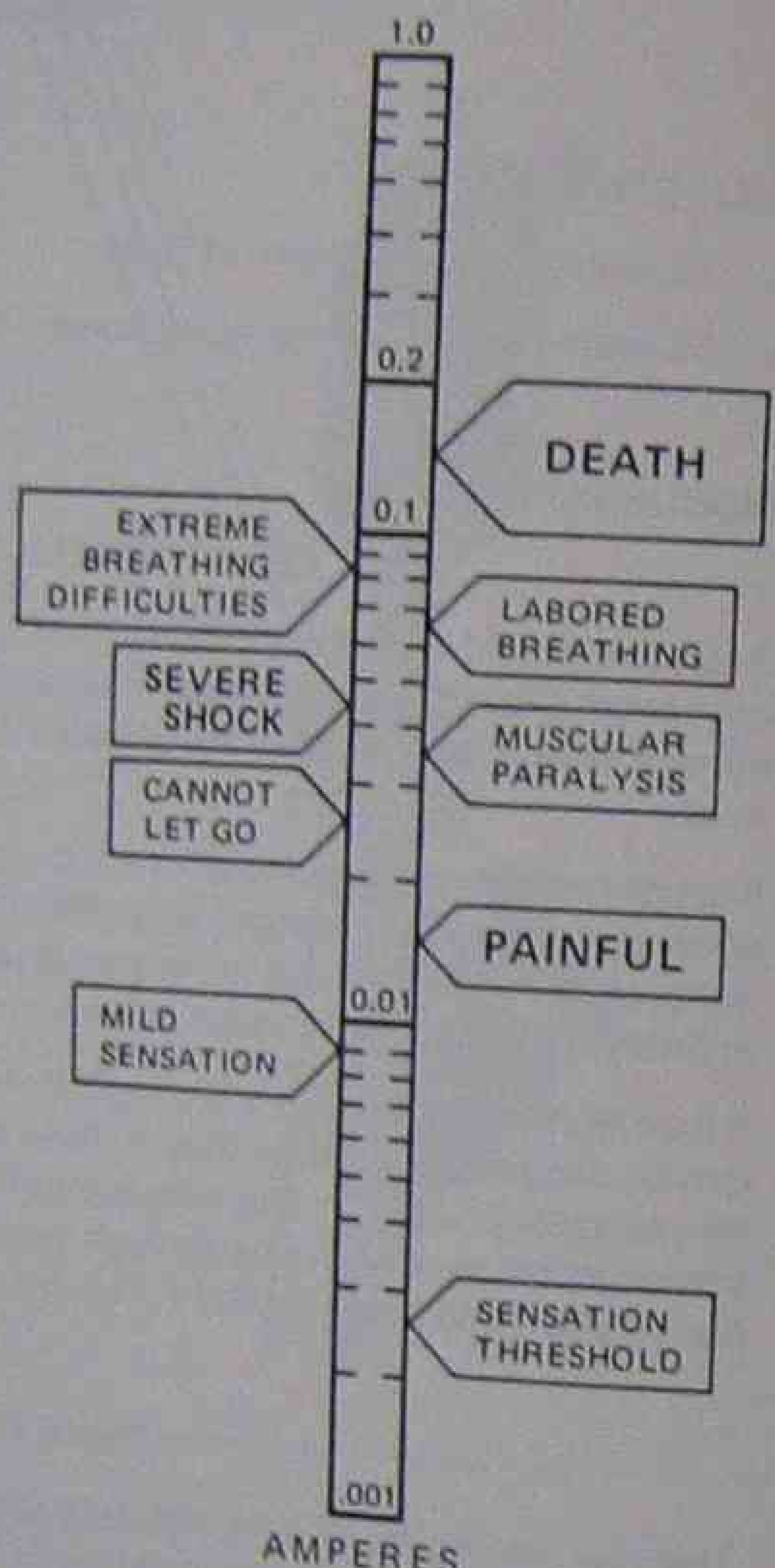


Figure 1-1.

Notice that it is the current that does the damage. Although currents above 100 mA or only one tenth of an ampere can be fatal, a person who has experienced currents in excess of 200 mA may live to see another day if given immediate treatment. Currents below 100 mA can be serious and painful. A safe rule: **Do not place yourself in a position to get any kind of a shock.**

What about VOLTAGE?

Current depends upon voltage and resistance. Let's measure your resistance. Using your ohmmeter, measure your body resistance between these points:

From right to left hand ______ Ω (resistance)

From hand to foot ______ Ω (resistance)

Now wet your fingers and repeat the measurements:

From right to left hand ______ Ω (resistance)

From hand to foot ______ Ω (resistance)

The actual resistance varies, of course, depending upon the points of contact and, as you have discovered, the condition of your skin, and the contact area. Notice how your resistance varies as you squeeze the probes more or less tightly. Skin resistance may vary between 250 Ω for wet skin and large contact area, to 500 000 Ω for dry skin. Considering the resistance of your body previously measured, and 100 mA as a fatal current, what voltages might prove fatal for you to contact.

Use the formula: Volts = 0,1 × ohms

Contact between two hands (dry): ______ V

Contact between one hand and one foot (dry): ______ V

Contact between two hands (wet): ______ V

Contact between one hand and foot (wet): ______ V

DO NOT ATTEMPT TO PROVE THIS!

Eight rules for safe practice and to avoid electric shocks:

1. Be sure of the conditions of the equipment and the dangers present **before** working on a piece of equipment. Many sportsmen are killed by supposedly unloaded guns; many technicians are killed by supposedly "dead" circuits.
2. **Never** rely on safety devices such as fuses, relays and interlock systems to protect you. They may not be working and may fail to protect when most needed.
3. **Never** remove the earth connection prong of a three wire input plug. This could eliminates an important safety grounding feature of the equipment making it a potential shock hazard.
4. **Do not work on a cluttered bench.** A disorganized mess of connecting leads, components and tools only leads to careless thinking, short circuits, shocks and accidents. Develop habits of systemized and organized work procedures.
5. **Do not work on wet floors.** Your contact resistance to ground is substantially reduced by moist environment. Work on a rubber mat or an insulated floor.
6. **Don't work alone.** It's just good sense to have someone around to shut off the power, to give artificial respiration and to call a doctor.
7. **Never talk to anyone while working.** Don't let yourself be distracted. Also, *don't talk to anyone*, if he is working on dangerous equipment. Don't be cause of an accident.
8. **Always move slowly** when working around electrical circuits. Violent and rapid movements lead to accidental shocks and short circuits.

BURNS

Accidents caused by burns, although usually not fatal, can be painfully serious. The dissipation of electrical energy produces heat.

Four rules for safe practice and to avoid burns:

1. *Resistors can get very hot*, especially those that carry high currents. Watch those five and ten watt resistors. They will burn the skin off your fingers. Stay away from them until they cool off.
2. *Be on guard for all capacitors which may still retain a charge.* Not only can you get a dangerous and sometimes fatal shock, you may also get a burn from an electrical discharge. If the rated voltage of electrolytic capacitors is exceeded or their polarities reversed they may get very hot and may actually burst.
3. *Watch that hot soldering iron or gun.* Don't place it on the bench where your arm might accidentally hit it. Never store it away while still hot. Some innocent unsuspecting student may pick it up.
4. **Hot solder** *can be particularly uncomfortable in contact with your skin.* Wait for soldered joints to cool. When de-soldering joints, don't shake hot solder off so that you or your neighbor might get some in the eyes, clothes, or body.

MECHANICAL INJURIES

This third class of safety rules applies to all students who work with tools and machinery. It is a major concern of the technician and the safety lessons are found in the correct use of tools. Five rules for safe practice and to avoid mechanical injury:

1. Metal corners and sharp edges on chassis and panels can cut and scratch. File them smooth.
2. Improper selection of the tool for the job can result in equipment damage and personal injury.
3. Use proper eye protection when grinding, chipping or working with hot metals which might splatter.
4. Protect your hands and clothes when working with battery acids, etchants, and finishing fluids. They are destructive!
5. If you don't know – **ASK YOUR INSTRUCTOR.**

THE POWER SUPPLY

The Power Supply provides all of the necessary ac/dc power, both fixed and variable, single phase and three-phase, to perform all of the Laboratory Experiments presented in this manual.

The module must be connected to a three-phase, 240/415 V, four wire (with fifth wire earth) system. Power is brought in through a five pin, twist-lock connector located at the rear of the module. An input power cable with mating connector is provided for this purpose.

The power supply furnishes the following outputs:

1. Fixed 240/415 V, 3-phase power is brought out to four terminals, labeled 1, 2, 3 and N. Fixed 415 V 3-phase may be obtained from terminals 1, 2 and 3. Fixed

415 V ac may be obtained between terminals 1 and 2, 2 and 3 or 1 and 3. Fixed 240 V ac may be obtained between any one of the 1, 2 or 3 terminals and the N terminal. The current rating of this supply is 10 A per phase.

2. Variable 240/415 V, 3-phase power is brought out to four terminals, labeled 4, 5, 6 and N. Variable 3-phase, 0-415 V may be obtained from terminals 4, 5 and 6. Variable 0-415 V ac may be obtained between terminals 4 and 5, 5 and 6 or 4 and 6. Variable 0-240 V ac may be obtained between any one of the 4, 5 or 6 terminals and the N terminal. The current rating of this supply is 3 A per phase.
3. Fixed 240 V dc is brought out to terminals labeled 8 and N. The current rating of this supply is 1 A.
4. Variable 0-240 V dc is brought out to terminals labeled 7 and N. The current rating of this supply is 5 A.

The full current rating of the various outputs cannot be used simultaneously. If more than one output is used at a time, reduced current must be drawn. The neutral N terminals are all connected together and joined to the neutral wire of the ac power line. All power is removed from the outputs when the on-off breaker is in the off position (breaker handle down).

CAUTION

Power is still available behind the module face with the breaker off! Never remove the Power Supply from the console without first removing the input power cable from the rear of the module.

The variable ac and dc outputs are controlled by the single control knob on the front of the module. The built-in voltmeter will indicate all the variable ac and the variable and fixed dc output voltages according to the position of the voltmeter selector switch. The power supply is fully protected against overload or short circuit. Besides the main 10 A 3-phase on-off circuit breaker on the front panel, all of the outputs have their own circuit breakers. They can be reset by a common button located on the front panel.

The rated current output may be exceeded considerably for short periods of time without harming the supply or tripping the breakers. This feature is particularly useful in the study of dc motors under overload or starting conditions where currents of up to 100 A may be drawn.

All of the power sources may be used simultaneously providing that the total current drawn does not exceed the 10 A per phase input breaker rating. Your Power Supply, if handled properly, will provide years of reliable operation and will present no danger to you.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
AC Voltmeter	8426
Power Supply	8821
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power should be turned off after completing each individual measurement.

☐ 1. Examine the construction of the Power Supply. On the front panel of the module, identify the following:

a) The three-pole circuit breaker on-off switch.

b) The three lamps indicating the operation of each phase.

c) The ac/dc voltmeter.

d) The ac/dc voltmeter selector switch.

e) The variable output control knob.

f) The fixed 240/415 V output terminals (labeled 1, 2, 3 and N).

g) The variable 0-240/415 V output terminals (labeled 4, 5, 6 and N).

h) The fixed dc output terminals (labeled 8 and N).

i) The variable dc output terminals (labeled 7 and N).

j) The common reset button.

k) The ground terminal (green).

☐ 2. State the ac or dc voltage and the rated current available from each of the following terminals:

a) Terminals 1 and N = ______ V ___ ______ A

b) Terminals 2 and N = ______ V ___ ______ A

c) Terminals 3 and N = ______ V ___ ______ A

d) Terminals 4 and N = ______ V ___ ______ A

e) Terminals 5 and N = ______ V ___ ______ A

f) Terminals 6 and N = ______ V ___ ______ A

g) Terminals 7 and N = ______ V ___ ______ A

h) Terminals 8 and N = ______ V ___ ______ A

Safety and the Power Supply

i) Terminals 1, 2 and 3 = ______ V ___ ______ A

j) Terminals 4, 5 and 6 = ______ V ___ ______ A

k) The receptacle = ______ V ___ ______ A

☐ 3. Examine the interior construction of the Power Supply. Identify the following items:

a) The 3-phase variable autotransformer.

b) The filter capacitors.

c) The thermal-magnetic circuit breakers.

d) The solid state rectifier diodes.

e) The diode heat sinks.

f) The five-pin twist-lock connector.

☐ 4. Insert the Power Supply into the console. Make sure that the on-off switch is in the off position and that the output control knob is turned fully counterclockwise for minimum output. Insert the power cable, through the clearance hole in the rear of the console, into the twist-lock module connector. Connect the other end of the power cable into a source of 3-phase 240/415 V.

☐ 5. a) Set the voltmeter selector switch to its 7-N position and turn the Power Supply on by placing the on-off breaker switch in its "up" position.

b) Turn the control knob of the 3-phase autotransformer and note that the dc voltage increases. Measure and record the minimum and maximum dc output voltage as indicated by the built-in voltmeter.

$V\ dc_{minimum}$ = ______ V $V\ dc_{maximum}$ = ______ V

c) Return the voltage to zero by turning the control knob to its full ccw position.

☐ 6. a) Place the voltmeter selector switch into its 4-N position.

b) Turn the control knob and note that the ac voltage increases. Measure and record the minimum and maximum ac output voltage as indicated by the built-in voltmeter.

$V\ dc_{minimum}$ = ______ V $V\ dc_{maximum}$ = ______ V

c) Return the voltage to zero by turning the control knob to its full ccw position.

☐ 7. What other ac voltages are affected by turning the control knob?

Terminals _______ and _______ = _______ V ac

Terminals _______ and _______ = _______ V ac

Terminals _______ and _______ and _______ = _______ V ac

☐ 8. For each of the following conditions:

a) Connect the 500 V ac meter across the terminals specified.

b) Turn on the Power Supply.

c) Measure and record the voltage.

Terminals 1 and 2 = _______ V ac

Terminals 2 and 3 = _______ V ac

Terminals 3 and 1 = _______ V ac

Terminals 1 and N = _______ V ac

Terminals 2 and N = _______ V ac

Terminals 3 and N = _______ V ac

d) Turn off the Power Supply.

e) Are any of these voltages affected by turning the control knob?

☐ Yes ☐ No

☐ 9. a) Set the voltmeter selector switch to its 8-N position.

b) Turn on the Power Supply.

c) Measure and record the voltage.

Terminals 8 and N = _______ V dc

d) Is this voltage affected by turning the control knob?

☐ Yes ☐ No

e) Turn off the Power Supply.

☐ 10. For each of the following positions of the voltmeter selector switch:

a) Turn on the Power Supply and rotate the control knob to its full cw position.

b) Measure and record the voltage.

Terminals 4 and 5 = _______ V ac

Terminals 5 and 6 = _______ V ac

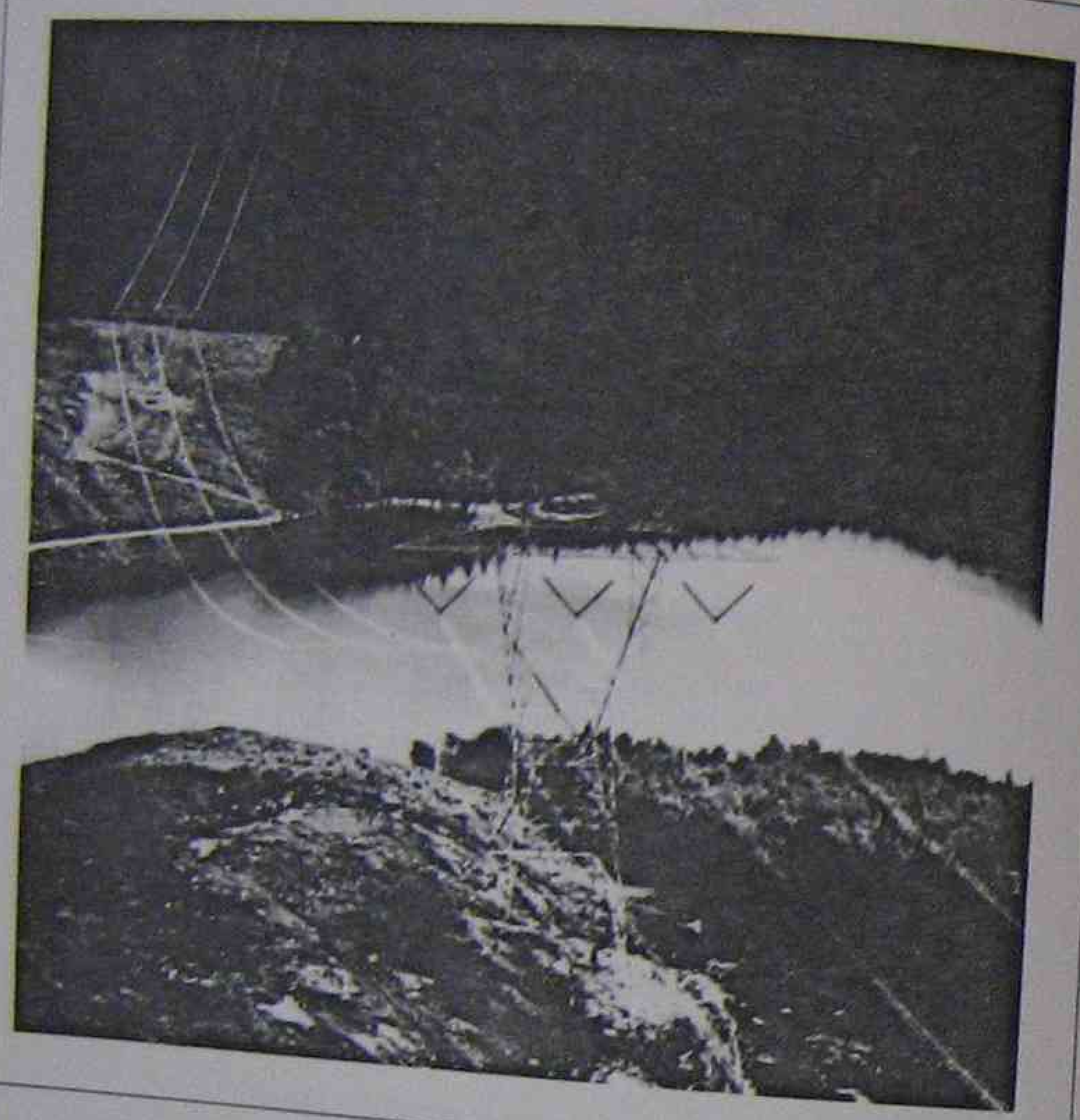
Terminals 6 and 4 = _______ V ac

Terminals 4 and N = _______ V ac

Terminals 5 and N = _______ V ac

Terminals 6 and N = _______ V ac

c) Return the voltage to zero and turn off the Power Supply.



This three-phase 735 kV transmission line easily spans the Saguenay River, Quebec (Canada).

Phase Sequence

OBJECTIVE

- To determine the phase sequence of a three-phase source.

DISCUSSION

The phase sequence of a three-phase source is the time order in which its three line voltages succeed each other, that is, the order in which they attain their maximum positive values. A knowledge of phase sequence is important when other three-phase lines are to be connected in parallel or when the direction of rotation of large motors must be known in advance. Phase sequence is also important in many three-phase metering devices such as sequence relays and varmeters. If the phase sequence is not checked, the readings may be quite different from what they should be.

Phase sequence is usually indicated on bus bars by a color code of some kind, or it may be found by using a phase sequence indicator, commercially available. In the absence of such a device, the phase sequence can be found by connecting in star two equal resistors and a capacitor to the three terminals of the power source as shown in Figure 2-1. The voltages across the two resistors will be found to be unequal and the phase sequence is in the order, (high voltage) – (low voltage) – (capacitor). For example, if the voltages across the resistors are 20 V and 80 V as shown in Figure 2-1, the phase sequence is B-A-C. The voltages succeed each other in the sequence B-A-C-B-A-C; hence the sequence B-A-C is the same as the sequence A-C-B or the sequence C-B-A.

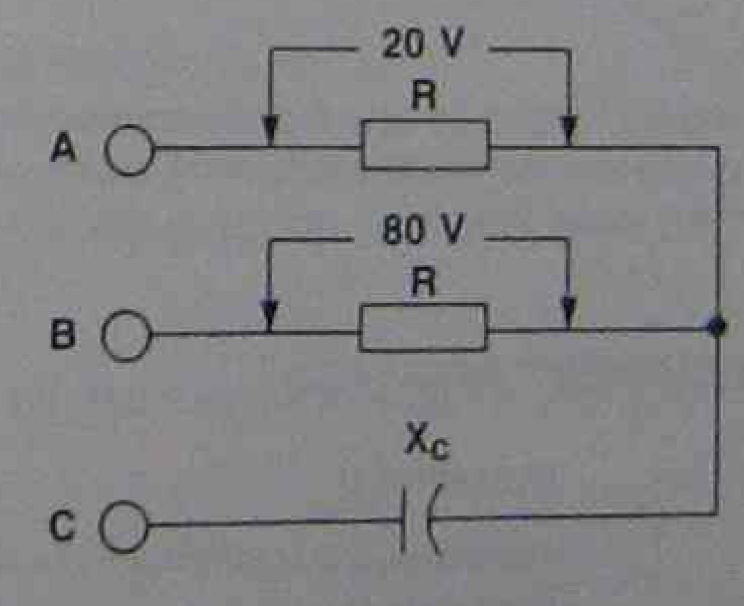


Figure 2-1.

The phase sequence of a three-phase line can be changed by interchanging any two conductors. On small power set-ups this is an easy task, but on large transmission lines and heavy bus bars, such a conductor change is a major, costly, job. For this reason the desired phase sequence on large power installations is thought out well in advance.

Multiple Outlets

In some installations (such as in a laboratory) a number of receptacles may be fed from a common bus. These receptacles may have terminals marked, say, 1-2-3 and, following the procedures we have just outlined, the phase sequences can everywhere be established in the order 1-2-3. Figure 2-2 shows how three receptacles P, Q, R may be connected in this way to the main bus, whose phase sequence is in the order A-B-C. The phase sequence of each receptacle is in the order 1-2-3 but is is obvious that if terminal 1 of receptacle P is connected to terminal 1 of receptacle R a short-circuit will result. In other words, correct phase sequence is not a guarantee that similarly-marked terminals may be connected together.

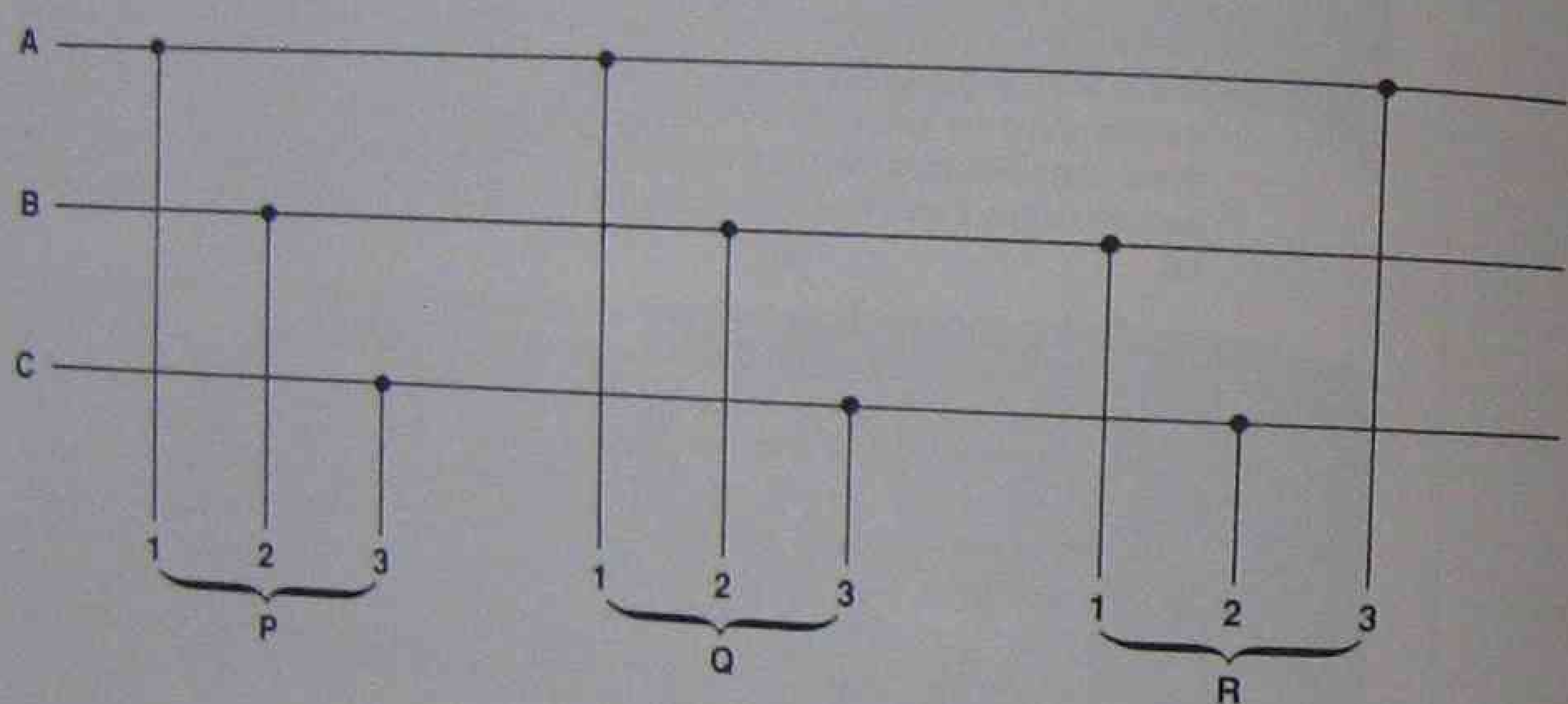


Figure 2-2.

The only way to be sure that the connections are identical for various receptacles is to measure the voltage between similarly-marked terminals. If the voltage is zero in every case, the phase sequence *and* the connections are identical.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Resistive Load	8311
Capacitive Load	8331
AC Voltmeter	8426
Power Supply	8821
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Using your Resistive Load, Capacitive Load and AC Voltmeter, connect the circuit to the Power Supply as shown in Figure 2-3. Set the value of each resistor to 1200 Ω, and set the capacitive reactance also to 1200 Ω. Note that the three elements are connected in star to terminals 1-2-3 of the Power Supply.

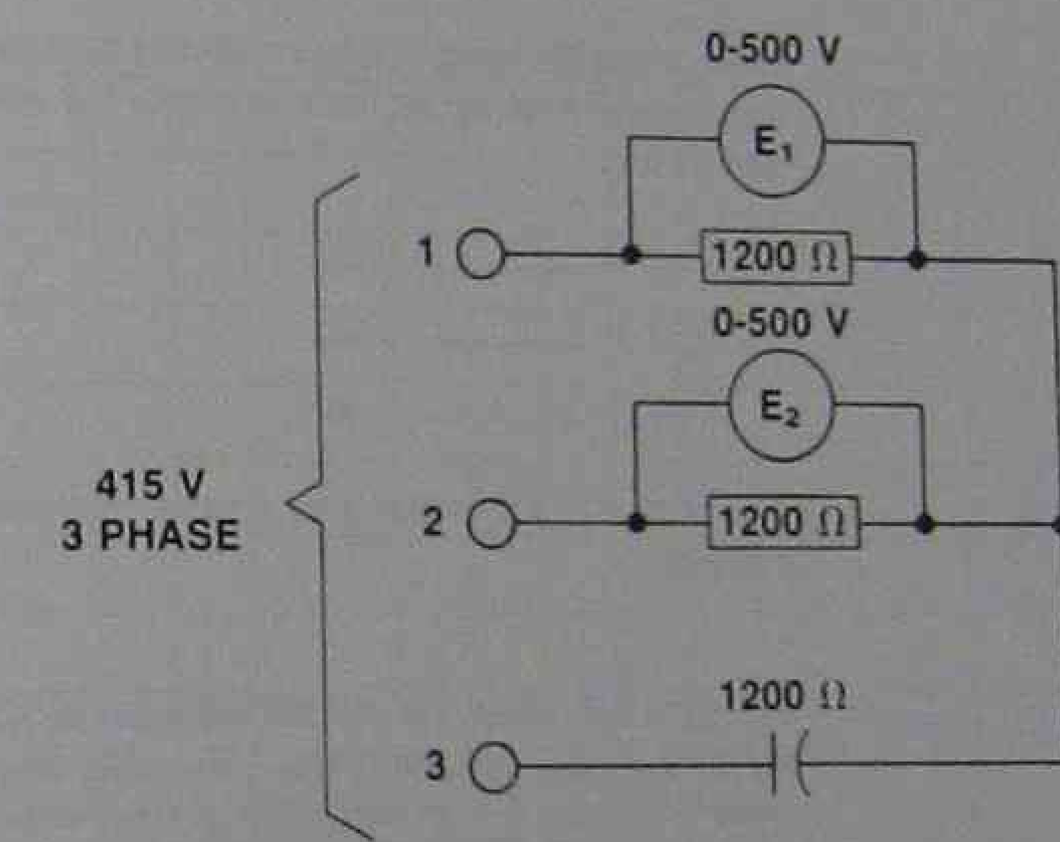


Figure 2-3.

☐ 2. Measure the voltages E_1 and E_2.

E_1 = ______ V ac

E_2 = ______ V ac

☐ 3. Determine the phase sequence (1-2-3 or 2-1-3) from the relative values of E_1 and E_2.

The phase sequence is ______

☐ 4. If the phase sequence is found to be 2-1-3 it is preferable to interchange any two of the phase wires of the wall receptacle to which the Power Supply is connected.

Note: *It is much easier to remember a phase sequence when it is 1-2-3, and in all subsequent experiments we shall assume this sequence has been established.*

☐ 5. Connect the circuit of Figure 2-3 to terminals 4-5-6 of the Power Supply, and determine the phase sequence.

The phase sequence is ______

Note: *If the sequence is 5-4-6 instead of 4-5-6 follow the procedure given in procedure step 4. It is much easier to recall a phase sequence of 4-5-6 and in all subsequent experiments we shall assume this sequence.*

☐ 6. Connect the three voltmeters to Power Supply terminals 1-4, 2-5 and 3-6 respectively. Rotate the control knobs of the variable autotransformer of the Power Supply completely in the clockwise direction, and turn on the Power Supply. The three voltmeters should read zero.

Next, rotate the same knob completely counterclockwise. The three voltmeters should read about the same and the voltage should be between 230 and 250 V.

E_{1-4} = ______ V ac

E_{2-5} = ______ V ac

E_{3-6} = ______ V ac

The purpose of this test is to ensure that your Power Supply is operating correctly.

☐ 7. In Figure 2-5, draw the phasor diagram to scale of the Power Supply voltages E_{12}, E_{23}, E_{31} and E_{1N}, E_{2N} and E_{3N}, based upon the diagrams given in Figure 2-4 showing the phasor relationship for phase sequence 1,2,3 and 1,3,2.

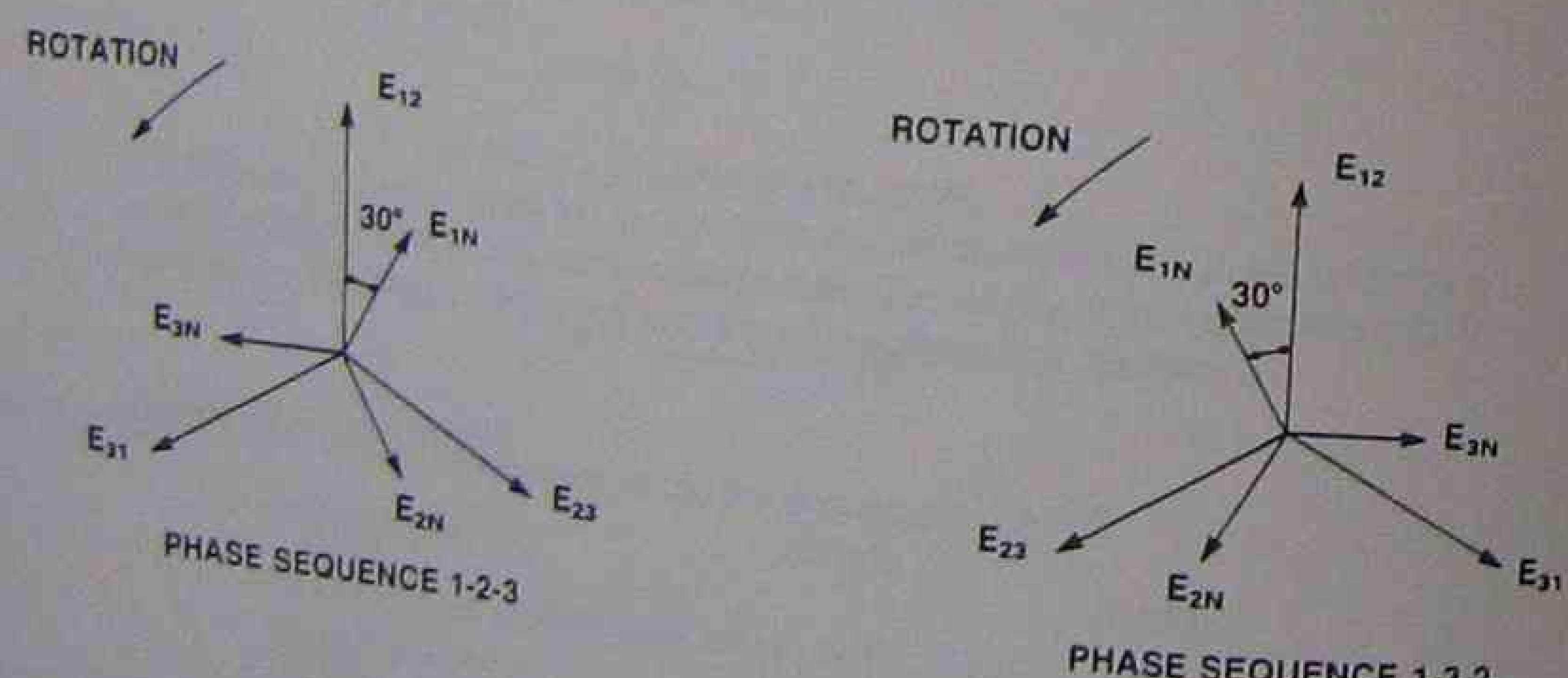


Figure 2-4.

☐ 8. This procedure may be carried out by two collaborating groups. In this procedure, we shall check that similarly-marked terminals at different student positions are at the same potential.

Connect two Power Supplies to two different wall receptacles. Switch on the power and measure the voltage between similarly-marked terminals (1 to 1, 2 to 2 and 3 to 3). If the voltage is not zero, the three wires in one of the wall receptacles must be interchanged.

Repeat this procedure for all the wall receptacles in the laboratory, and make the necessary wiring changes if required. This wiring check is particularly useful for future experiments where different consoles will be linked by transmission lines.

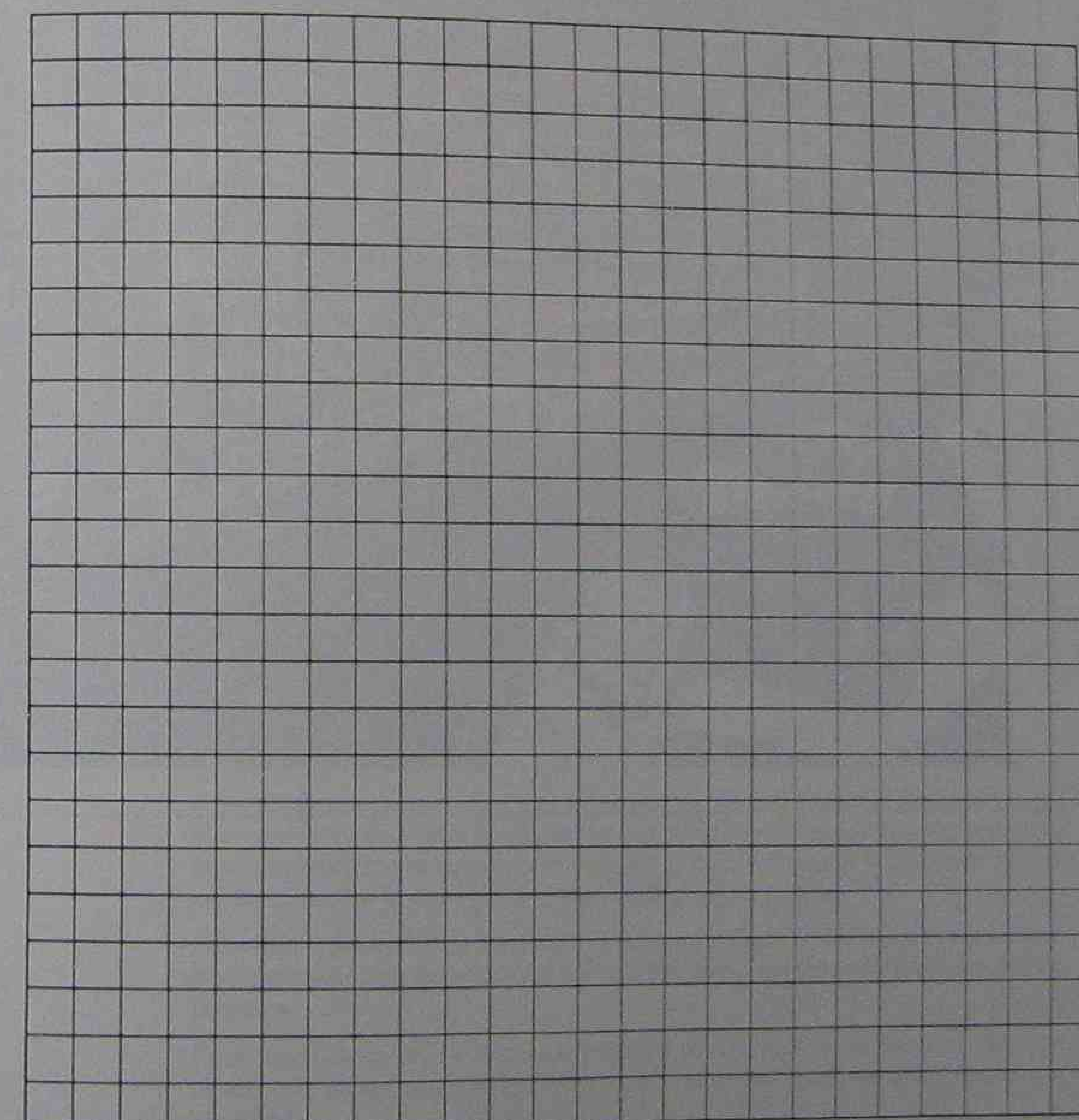
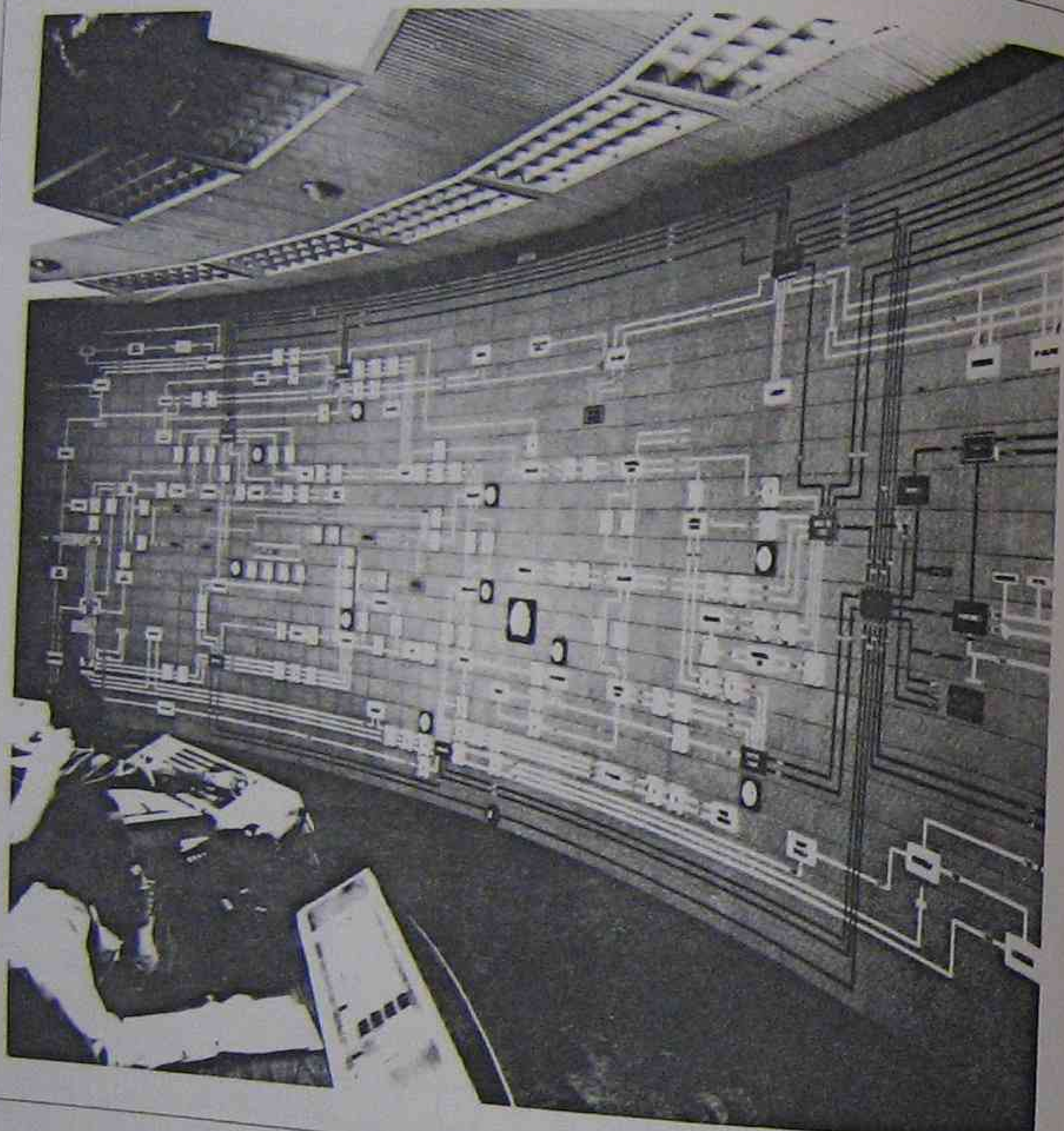


Figure 2-5.



Experiment 3

Real Power and Reactive Power

OBJECTIVES

- To interpret the meaning of positive, negative, real and reactive power.
- To observe the flow of real and reactive power in three-phase circuits.

DISCUSSION

In direct current circuits the real power (in watts) supplied to a load is always equal to the product of the voltage and the current. In alternating current circuits, however, this product is usually greater than the real (or active) power which the load consumes. For this reason, wattmeters are used to measure the real power (in watts).

In three-phase, three-wire AC circuits two wattmeters are needed to measure the real power while three-phase, four-wire circuits require three. These meters may be combined into a single wattmeter of special construction, which greatly simplifies the problem of adding the readings of two or three wattmeters to obtain the total three-phase power. A typical three-phase wattmeter (Figure 3-1) has three input terminals (1,2,3) and three output terminals (4,5,6).

THREE-PHASE WATTMETER

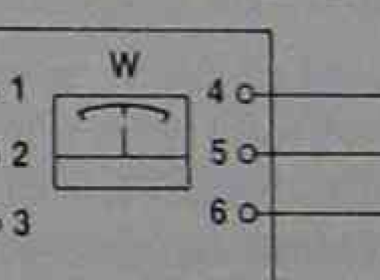


Figure 3-1.

If the wattmeter is connected into a three-phase line, as shown in Figure 3-1, it will show the total real power flowing in the line. if the power flows in the direction of the input terminals to the output terminals (left to right in Figure 3-1) the meter pointer will be deflected to the right and the reading will be positive.

However, if power flow is from right to left, that is, from the output terminals to the input terminals, the meter pointer will be deflected to the left and the reading will be negative.

Real power, therefore, is positive or negative *according to its direction of flow*. The direction of power flow can easily be found when the "input" terminals have been identified.

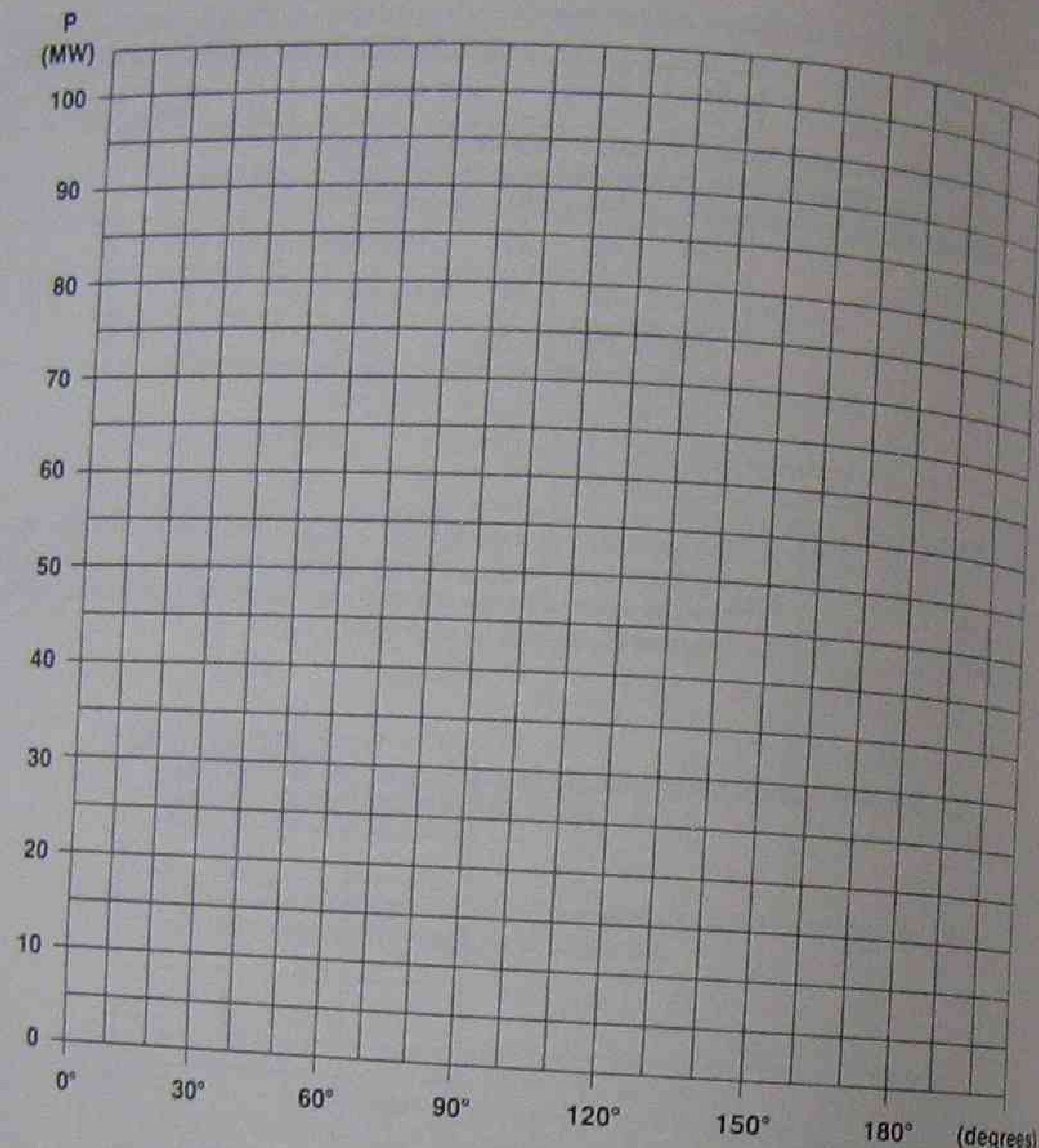
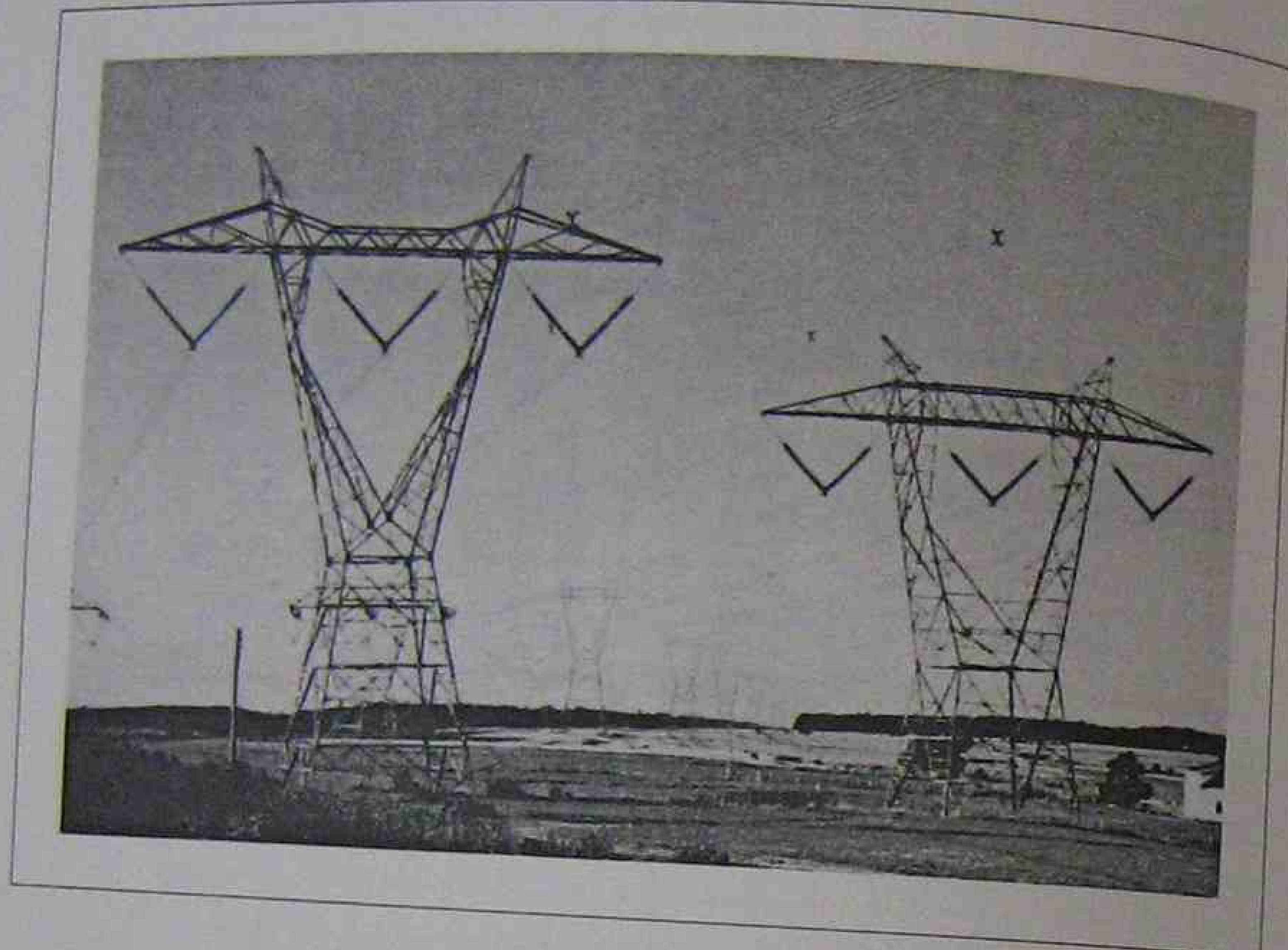


Figure 6-16.



Two three-phase lines side by side enable a larger power flow and improve stability of the system.

Experiment 7

Parallel Lines, Transformers and Power-Handling Capacity

OBJECTIVES

- Study of the real power vs phase angle curve of a transmission line.
- Use of transformers to increase the power-handling capacity of a line.
- Transmission lines in parallel.

DISCUSSION

The real power which can be delivered by a transmission line depends upon the voltages at the sender and receiver ends and the phase angle between them. The real power P of a three-phase line is given by the equation:

$$P = \frac{E_1 - E_2}{X} \sin \phi$$

in which P = total power delivered by the sender to the receiver, in watts.

E_1 = sender end line-to-line voltage, in volts.

E_2 = receiver end line-to-line voltage, in volts.

X = reactance per phase, in ohms.

ϕ = phase angle between E_1 and E_2.

If E_2 lags behind E_1, ϕ is positive.

If E_2 leads E_1, ϕ is negative.

The use of this equation is best illustrated by a simple example. On Figure 7-1, a line having a reactance of 100 Ω per phase has a line-to-line sender voltage of 120 kV and a corresponding receiver voltage of 150 kV. If the receiver voltage lags the sender by 30°, calculate the total power delivered by the three-phase line.

Solution:

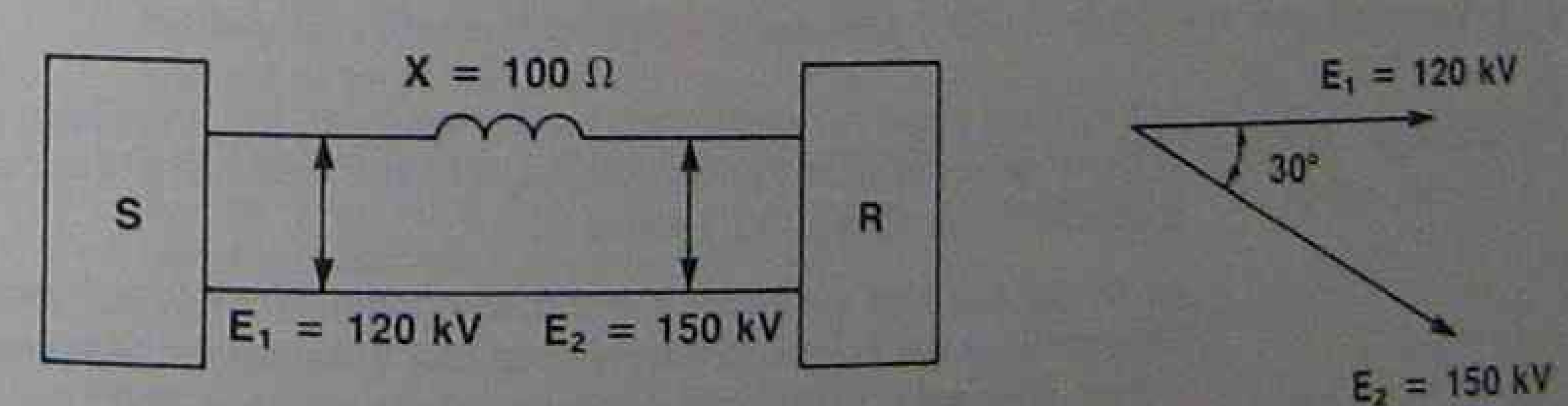


Figure 7-1.

Because the sender voltage leads the receiver voltage, the angle ϕ is positive, hence:

$$P = \frac{E_1 - E_2}{X} \sin \phi$$

$$= \frac{120 \text{ kV} \times 150 \text{ kV}}{100} \sin (+30°)$$

$$= 90\ 000\ 000 \text{ W}$$

$$= 90 \text{ MW}$$

If the sender and receiver voltages are held constant (a situation which is closely met in practice), the power delivered will be dependent on the phase angle ϕ. This relationship between the power P and the angle ϕ is given in Figure 7-2.

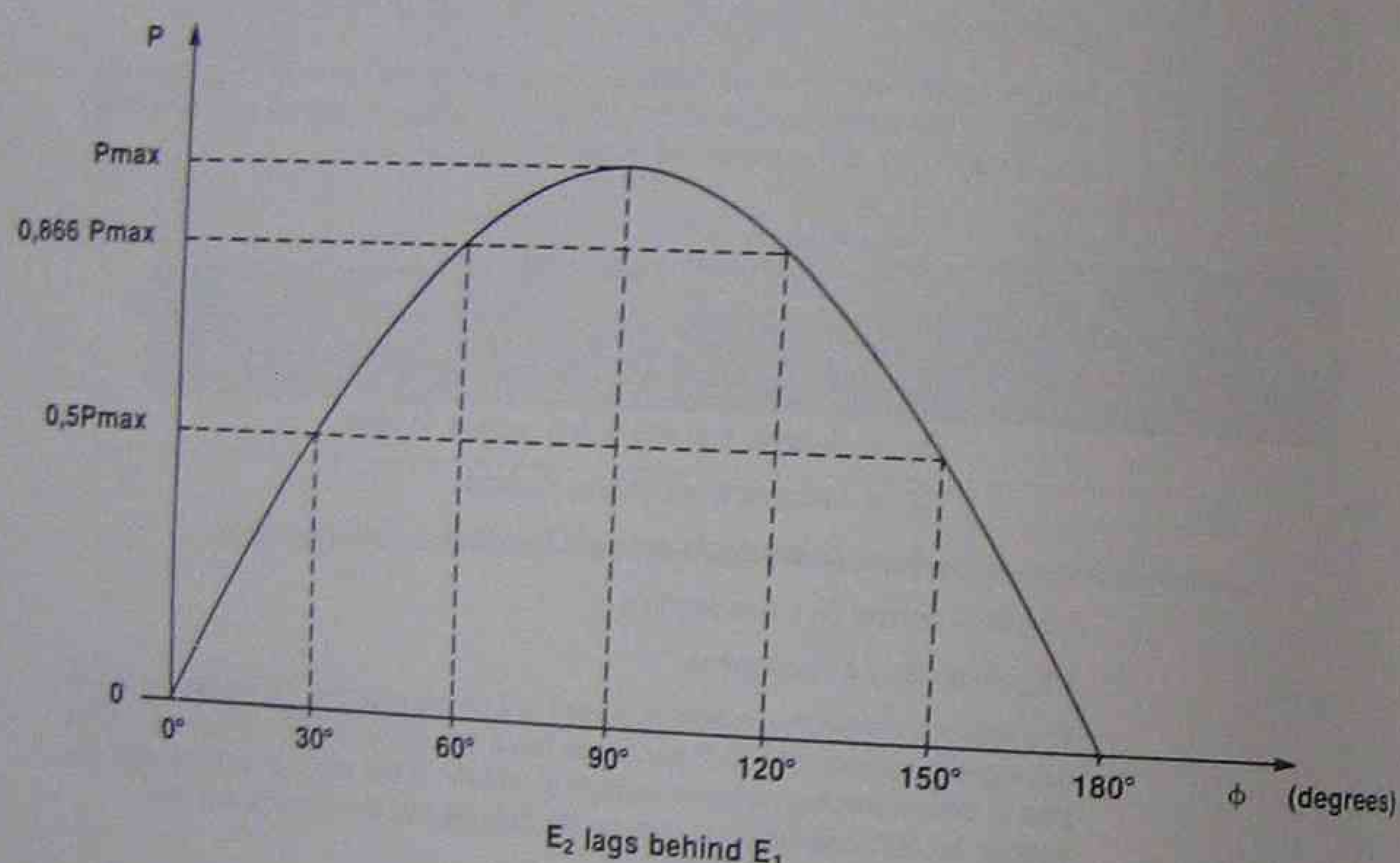


Figure 7-2.

As the phase angle increases from zero, the power, too, increases gradually, and attains a maximum value Pmax for an angle of 90°. One-half of this maximum power is attained when E_2 lags 30° behind E_1.

As we can see from the figure, if the phase angle exceeds 90°, power will still be delivered from the sender to the receiver, but it decreases with increasing angle. Indeed, the power falls to zero when the phase angle is 180°.

When the phase angle exceeds 90°, the transmission line is in an unstable condition, and the power will either fall to zero or it will move to another point (between 0 and 90°) on the power vs phase angle curve.

Consequently, steady, reliable power can only be transmitted from sender to receiver when the phase angle is between zero and 90°. The maximum power which can be transmitted is

$$P_{max} = \frac{E_1 E_2}{X} \sin 90° = \frac{E_1 E_2}{X}$$

It should be noted that any phase angle can exist between zero and 360° or, which is the same thing, between 0° and 180° lag, and 0° and 180° lead. If the power vs phase angle curve is extended to cover all possible angles, we obtain the curve shown in Figure 7-3.

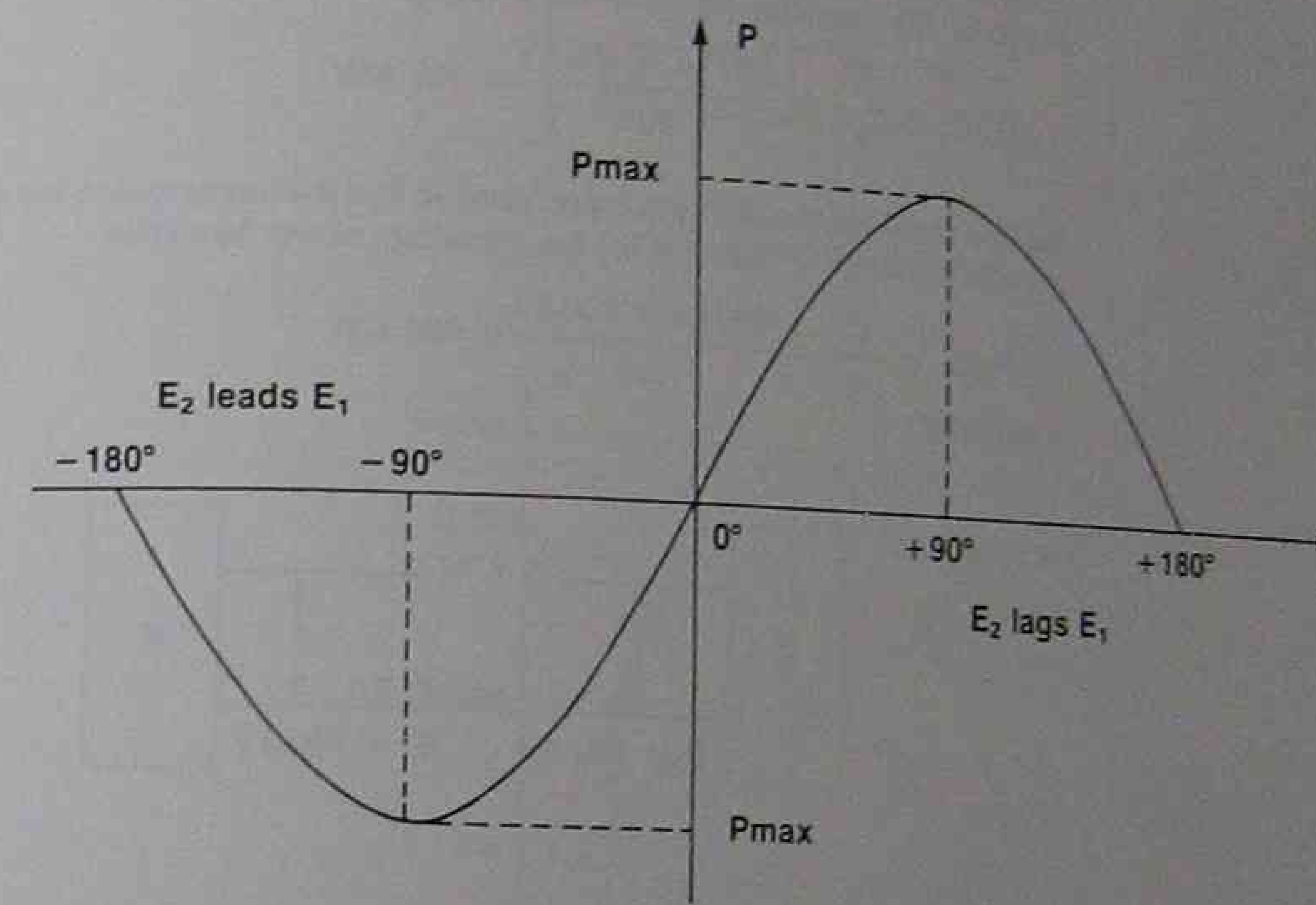


Figure 7-3.

If the angle is between zero and +180° the sender is delivering power to the receiver, but when the angle is between zero and −180°, the receiver is delivering power to the sender. Note that an angle of −90° merely indicates that E_2 is leading E_1. The stable region is between −90 and +90°; it is the only region of interest to us at this time.

In most cases, the sender and receiver voltages are about equal in magnitude, so that if we let $E_1 = E_2 = E$, where E is the transmission line voltage, we find that the maximum power

$$P_{max} = \frac{E^2}{X} \text{W}$$

Transmission Line Voltage

Because the maximum power which a line can deliver depends upon the square of the transmission line voltage E, it is not surprising that high voltages are employed when large blocks of power have to be transmitted. Thus, if the line voltage is doubled, the maximum power is quadrupled.

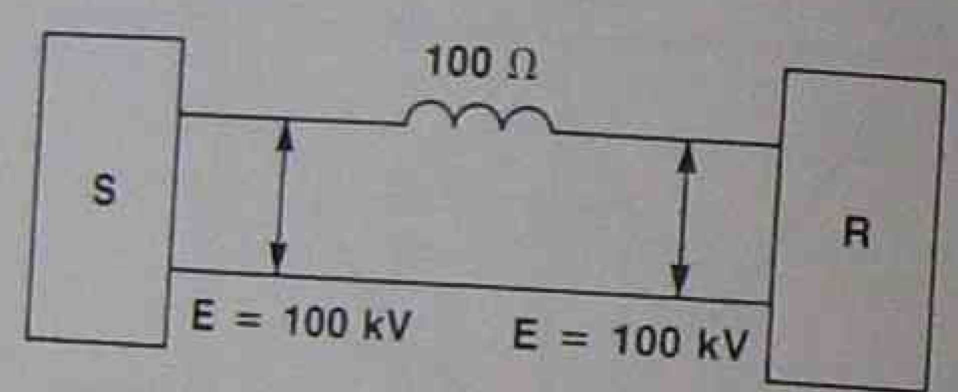
The line voltage can be raised by introducing a step-up transformer at the sender end and a similar step-down transformer at the receiver end. As a result, by using a transformer at each end of a transmission line its power-handling capacity can be significantly improved.

In Figure 7-4 a), a sender and a receiver are connected by a line having a reactance of 100 Ω. The maximum power which can be transmitted is

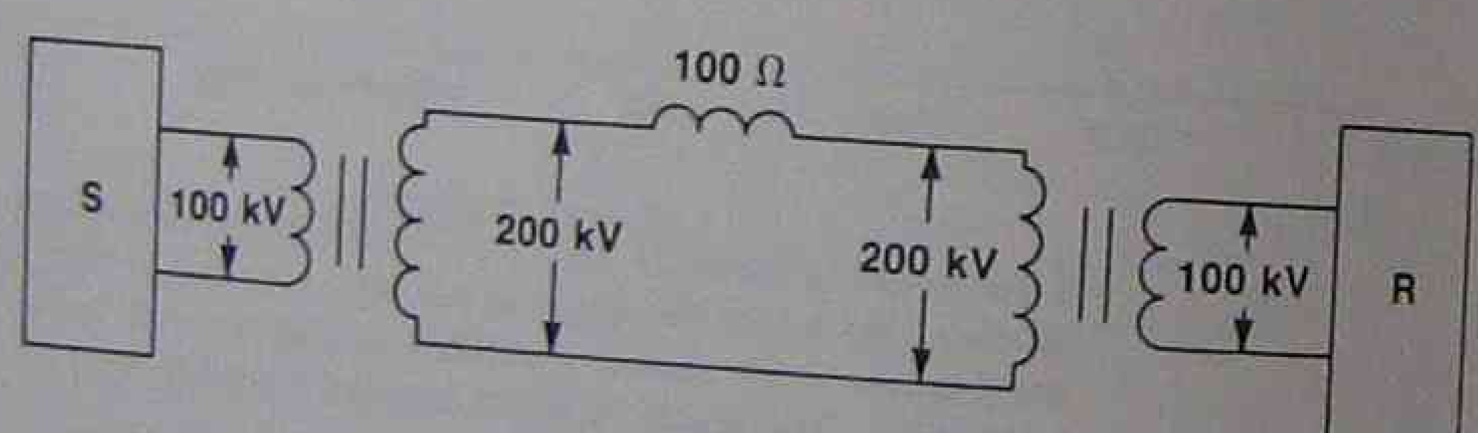
$$P_{max} = \frac{E^2}{X} = \frac{100\text{ kV} \times 100\text{ kV}}{100} = 100\text{ MW}$$

But if we introduce transformers at each end so that the transmission line voltage is doubled to 200 kV, (Figure 7-4 b)) the maximum power becomes

$$P_{max} = \frac{E^2}{X} = \frac{200\text{ kV} \times 200\text{ kV}}{100} = 400\text{ MW}$$



(a)



(b)

Figure 7-4.

Transmission Lines in Parallel

Another way by which increased power can be transmitted from a sender to a receiver is to employ two 3-phase lines in parallel. The two transmission lines may be supported on the cross-arms of the same transmission towers, or two entirely separate lines may be employed.

Two similar lines which are in parallel can obviously carry twice the maximum power of one line alone. (See Figure 7-5.) The power curves for one line and for two lines are shown in Figure 7-6. If both lines are in service and the power transmitted is 0,5 Pmax, the phase angle between the sender and receiver voltages is only 30°, which corresponds to a very stable operating point. The link between S and R is said to be "stiff".

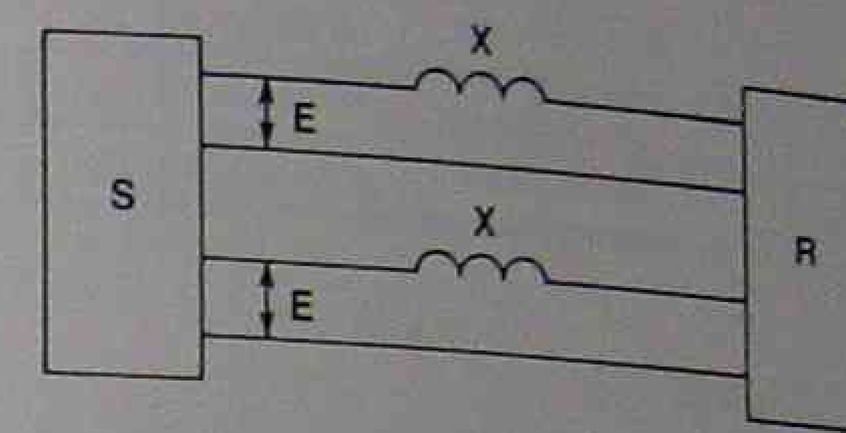


Figure 7-5.

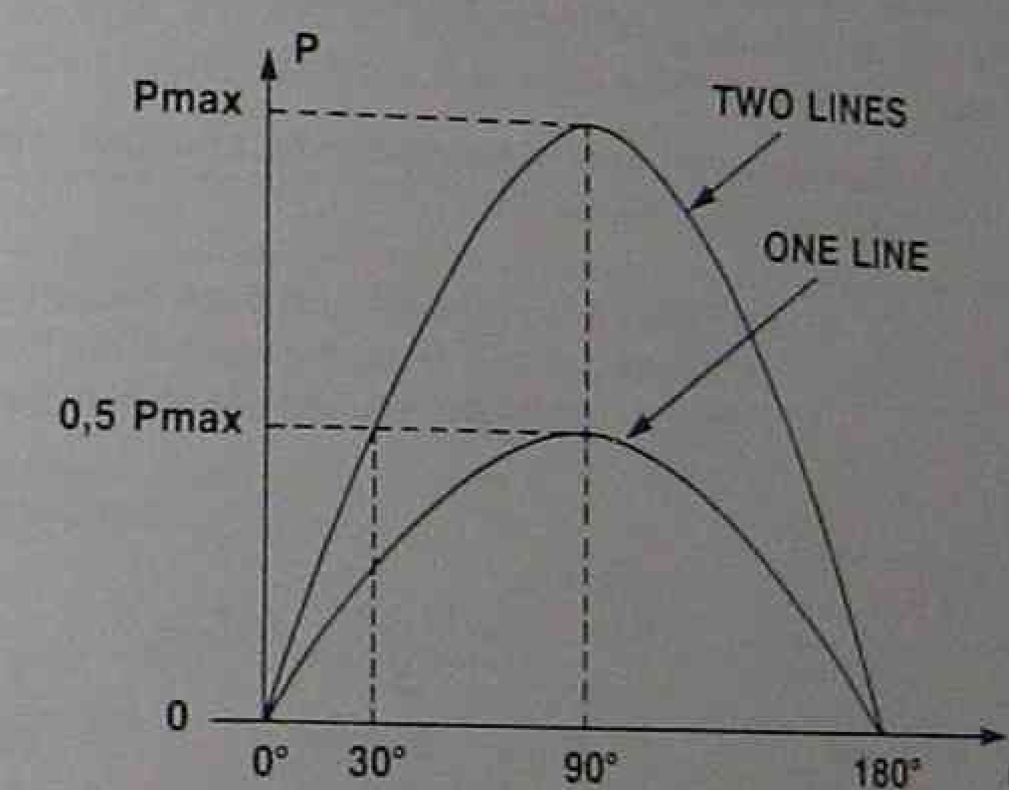


Figure 7-6

However, if one of the lines is suddenly switched out, either by error or due to a fault-clearing action, the power has to be carried by the remaining line. But as we can see from Figure 7-6, 0,5 Pmax corresponds, on the single transmission line, to an angle of 90° which is just on the edge of unstability. In all likelihood the remaining line will be unable to carry the load and its breakers will open, unless the other line is quickly brought back into service.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Three-Phase Synchronous Motor/Generator	8241
Three-Phase Transmission Line	8329
Three-Phase Transformer	8348
Three-Phase Regulating Autotransformer	8349
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Inertia Wheel	8915
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

The first part of this experiment involves a number of problems while the second is a laboratory experience.

☐ 1. On Figure 7-7, stations A and B are linked by a transmission line having a certain reactance X. From the value of the line-to-line voltages, given in the Table 7-1, determine the real power and the direction of its flow.

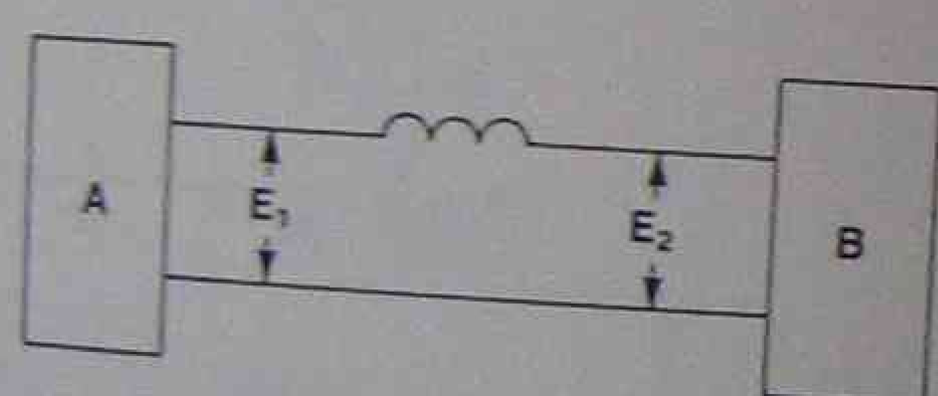


Figure 7-7.

☐ 2. Referring to procedure step 1, calculate the maximum power which could be transported at the given voltages E_1 and E_2 and write your results in Table 7-1.

☐ 3. Either by trigonometry or by scaling off the phasor diagrams, calculate the line current in parts 2 to 6 of procedure step 1.

Note: *The line current is equal to the line voltage drop per phase divided by the reactance. In this calculation it is important to use the line-to-neutral voltages to determine the voltage drop. Write your results in Table 7-1.*

N°	E_1	E_2	X	θ	LAG OR LEAD	P	DIRECTION OF POWER FLOW		LINE CURRENT A
—	kV	kV	Ω	°		kW		kW	—
1	4	4	80	30	E_1 LEADS E_2	+100	A → B	+200	15
2	8	8	80	30	E_1 LEADS E_2				
3	8	6	80	45	E_1 LAGS E_2				
4	8	6	80	45	E_1 LAGS E_2				
5	8	6	80	120	E_1 LEADS E_2				
6	4	12	80	60	E_1 LEADS E_2				

Table 7-1.

☐ 4. Two parallel transmission lines operating at a three-phase line-to-line voltage of 120 kV each, have a line reactance of 60 Ω. If the total power delivered is 84 MW, calculate the phase angle between the sender and receiver voltages. If one of the lines is suddenly opened, will the remaining line be able to carry the load? If so what will its new phase angle become?

____

____

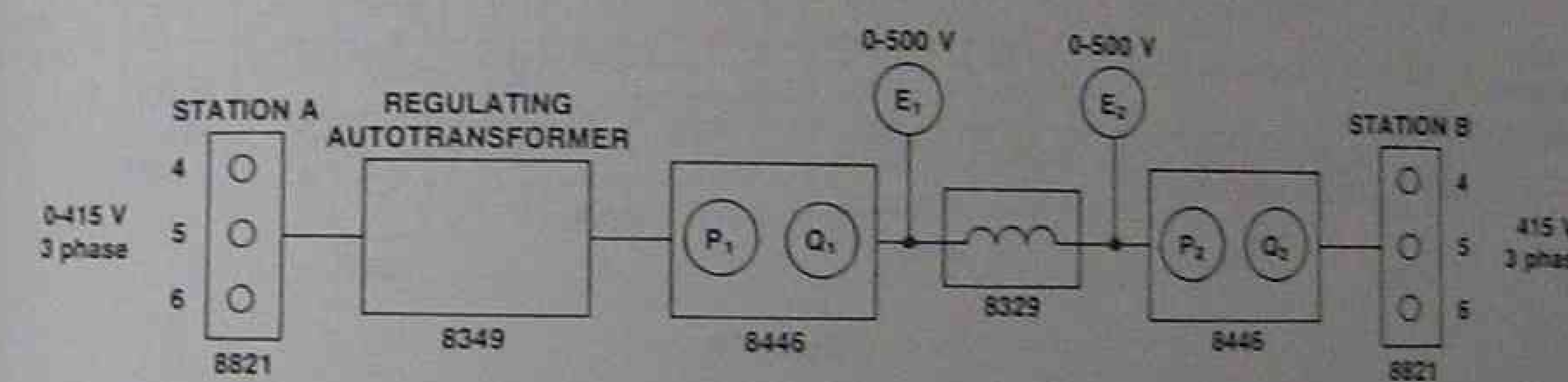


Figure 7-8

☐ *5. Using two independent Power Supplies and a Three-Phase Regulating Autotransformer, set the line reactance to 600 Ω and measure the real power flow when the phase-shift is +15° (Figure 7-8). (E_2 lags E_1 by 15°.) Adjust the voltage of the Power Supply to 415 V.

E_1 = ________ V

E_2 = ________ V

P_1 = ________ W

P_2 = ________ W

Q_1 = _______ var

Q_2 = _______ var

* Procedure Steps 5 to 8 may be carried out by two collaborating groups.

☐ 6. Now, at stations A and B, introduce step-up and step-down transformers connected in delta-star and star-delta respectively. (See Figure 7-9.)

WARNING

High voltages are present in this experiment: 720 V on the sender and receiver ends of the transmission line! Use two voltmeters in series to measure voltages E_1 and E_2.

Note: *This experiment entails the correct connection of the star-delta transformers both as to polarity and phase sequence. Three-phase transformer connections are covered in Experiment 1, Vol. 4 and Experiment 2, Vol. 3 of the Electrical Power Technology Series.*

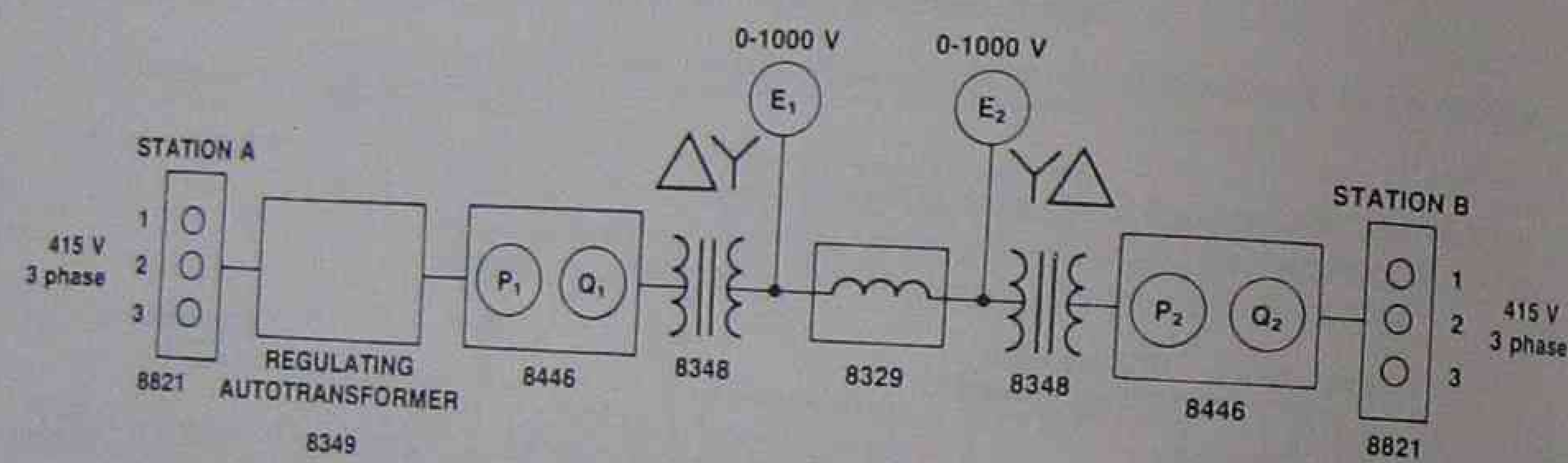


Figure 7-9

Measure the new real power which is transmitted and compare it with the values found in procedure step 5. Explain your results.

E_1 = _______ V

E_2 = _______ V

P_1 = _______ W

P_2 = _______ W

Q_1 = _______ var

Q_2 = _______ var

____

____

☐ 7. It is one of the inescapable facts of nature that when we increase the size of an object, the ratio of its volume to its external surface area increases. In the same way, the inertia of a motor increases more rapidly than its power rating. Consequently, large motors accelerate much more slowly than small motors do. A 0,2 kW motor can reach top speed in a fraction of a second when power is applied, whereas a 10 000 kW motor may take several minutes.

In order for a 0,2 kW machine to exhibit the mechanical properties of a much larger machine, we must increase its inertia artificially. This we can do by adding an inertia wheel. The inertia wheel used in this electric power transmission system gives the 0,2 kW machine an inertia corresponding to that of a machine in the megawatt range. The whole subject of inertia will be seen in more detail in Experiment 13.

a) Connect a 600 Ω transmission line in series with a Wattmeter/Varmeter to the fixed Power Supply terminals as shown on Figure 7-10. Measure E, P, Q in open circuit.

E = _______ V

P = _______ W

Q = _______ var

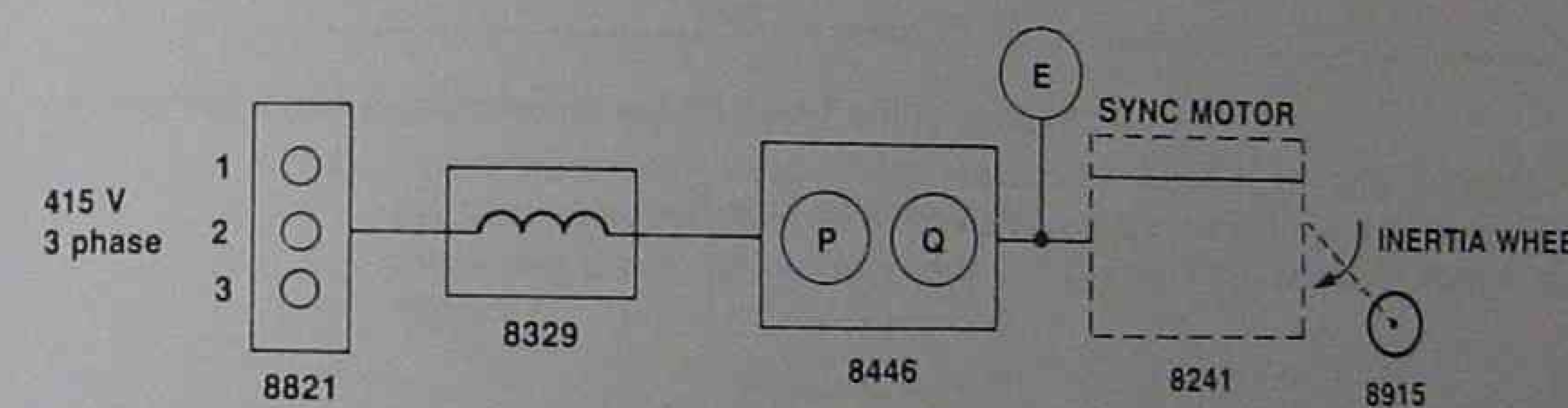


Figure 7-10.

b) Turn off the Power Supply and connect the stator of the Three-Phase Synchronous Motor/Generator to the end of the transmission line. Add the Inertia Wheel on the rotor of the Three-Phase Synchronous Motor/Generator. Turn on the Power Supply and observe the starting of the motor. How long does it take before the motor comes up to speed?

Acceleration time T = _______ s

Measure E, P, Q at the end of acceleration period.

E = _______ V

P = _______ W

Q = _______ var

☐ 8. Now, at the sender and receiver end of the 600 Ω transmission line, insert step-up and step-down transformers connected in delta-star and star-delta respectively (see Figure 7-11). Repeat the same procedure as in procedure step 7.

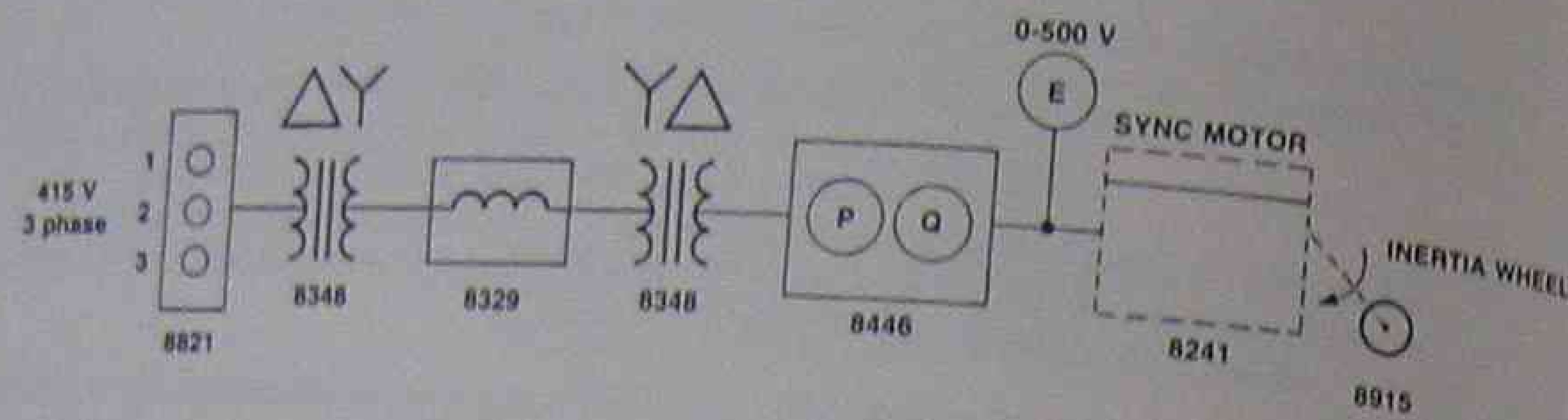


Figure 7-11.

a) Open circuit

E = ______ V

P = ______ W

Q = ______ var

b) Starting of the Three-Phase Synchronous Motor/Generator.

Acceleration time T = ______ s

E = ______ V

P = ______ W

Q = ______ var

Compare your results with the values found in procedure step 7.

Explain why the motor starts more quickly in procedure step 8, although the open circuit voltages are about the same.

______

______

TEST YOUR KNOWLEDGE

1. a) A 3-phase transmission line operating at 300 kV has a line reactance of 200 Ω per phase. Calculate the maximum total power which this line can deliver, in MW.

______

b) What is the phase angle between the sender and receiver voltages when the line delivers 100 MW?

______

c) What is the total amount of power if the phase angle is 1°, 2°, 4°, 8°, 16°, 32°?

______

______

2. a) In Question 1, if the phase angle between sender and receiver increases from 15° to 20° by how much is the real power flow increased?

______

b) If the phase angle increases from 75° to 80°, is the increase in power the same as before?

☐ Yes ☐ No

3. If the transmission line voltage in Question 1 were raised by 20%, by how much would the power-handling capacity of the line be increased?

______

4. a) Two transmission lines having reactances of 100 Ω and 200 Ω are connected in parallel between sender and receiver stations. What is the maximum real power which both lines can deliver if the operating voltage is 100 kV?

______

b) If the line delivers 75 MW, what is the phase angle between sender and receiver voltages?

______

If the 200 Ω line is suddenly taken out of service, what will the new phase angle be?

______

c) In Question 4 (b), if the 100 Ω line is suddenly opened, what will happen?

______

5. A high transmission line voltage reduces copper losses, and permits the transmission of more power. Explain this statement briefly.

____

____

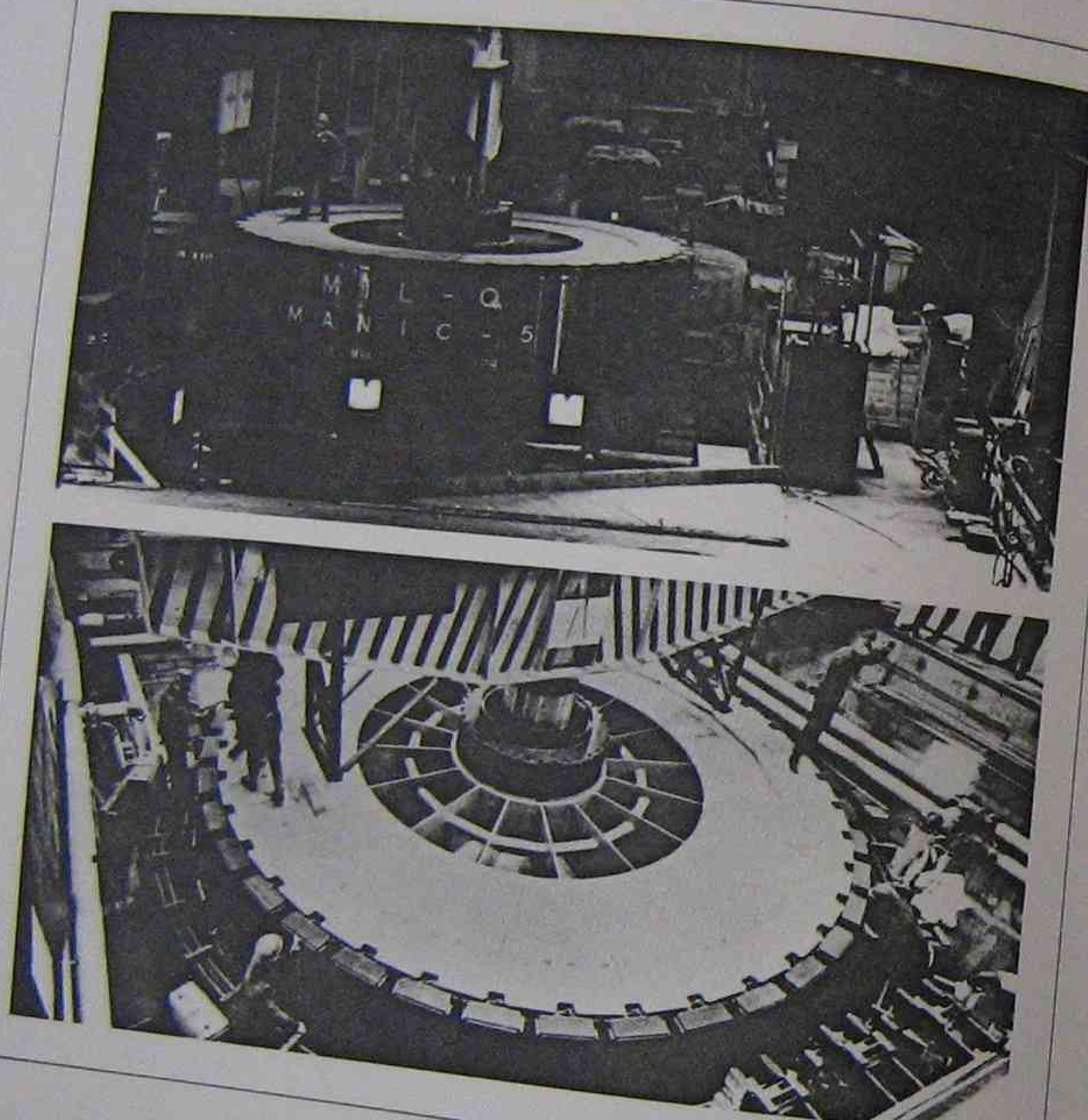
____

6. What is the purpose of step-up and step-down transformers at the sender and receiver ends of a transmission line?

____

____

____



Maneuvering the massive 40-pole rotor of a 170 MVA water-wheel alternator into its stator is a delicate and time-consuming task.

The Alternator

OBJECTIVES

- To understand the basic operation of an alternator.
- To measure the synchronous reactance of an alternator.
- To measure the voltage regulation of an alternator.

DISCUSSION

Electric power is produced in large generating stations which contain one or more alternators (or alternating current generators), and a mechanical means of driving them. The mechanical power is usually provided by steam turbines which, in turn, derive their energy from the heat given off by burning oil, gas or coal or from the heat of a nuclear reaction. In areas where water power is plentiful, hydraulic turbines provide the mechanical power to drive the alternators.

The voltage E_O generated by the alternator depends upon the flux per pole which, in turn, depends upon the DC excitation current which flows in the pole windings. The generator voltage per phase can therefore be varied by adjusting the DC excitation. At no load, the voltage E_T measured at the generator terminals is the same as the generated voltage E_O (see Figure 8-2).

If the alternator is loaded, its terminal voltage will change, even though the DC excitation is kept constant. This is because the alternator has an internal impedance, composed of the resistance and reactance of the stator windings. An alternator can, therefore, be represented by a circuit such as shown in Figure 8-1, in which X is the stator reactance, R the winding resistance and E_O the stator voltage generated as the poles sweep past the stator conductors.

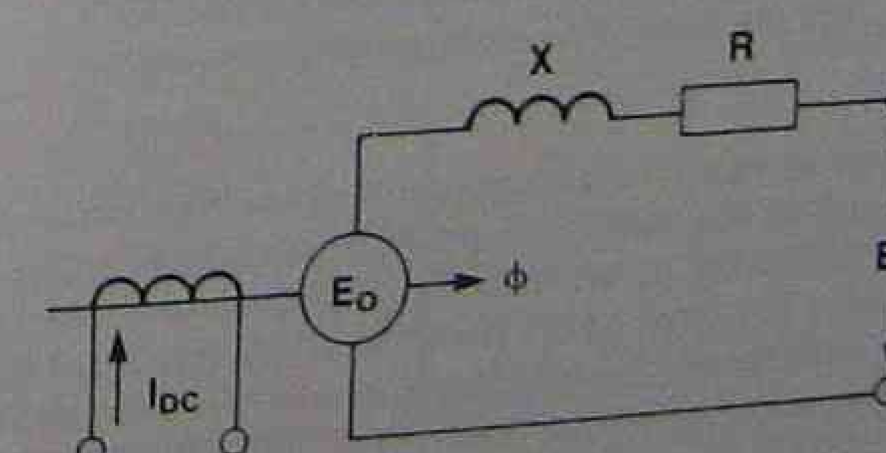


Figure 8-1.

The resistance R is always much smaller than the reactance X, so we can simplify the circuit to that shown in Figure 8-2, without introducing a significant error. The terminal voltage of the generator (per phase) is E_T and X is its so-called synchronous reactance.

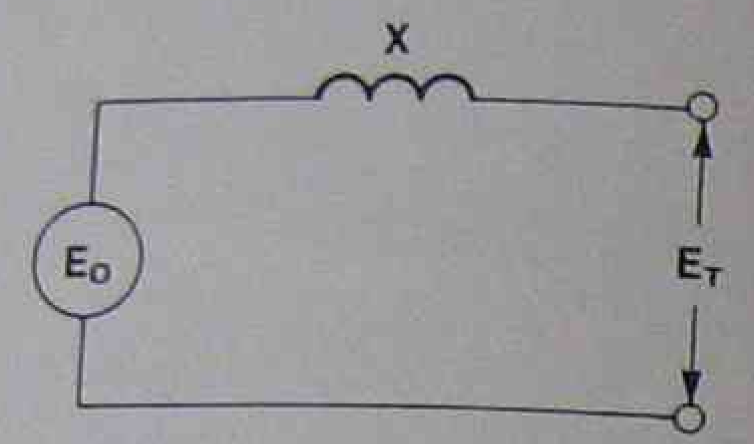


Figure 8-2.

The value of the synchronous reactance can be found by measuring the voltage E_T on open circuit and then measuring the current when the terminals are placed in short circuit.

Figure 8-3 shows how the short-circuit current $I = E_O/X$ from which the synchronous reactance X can be found. This reactance is not constant, but depends upon the degree of saturation in the machine. However, we can obtain a good idea of its magnitude by the method just described.

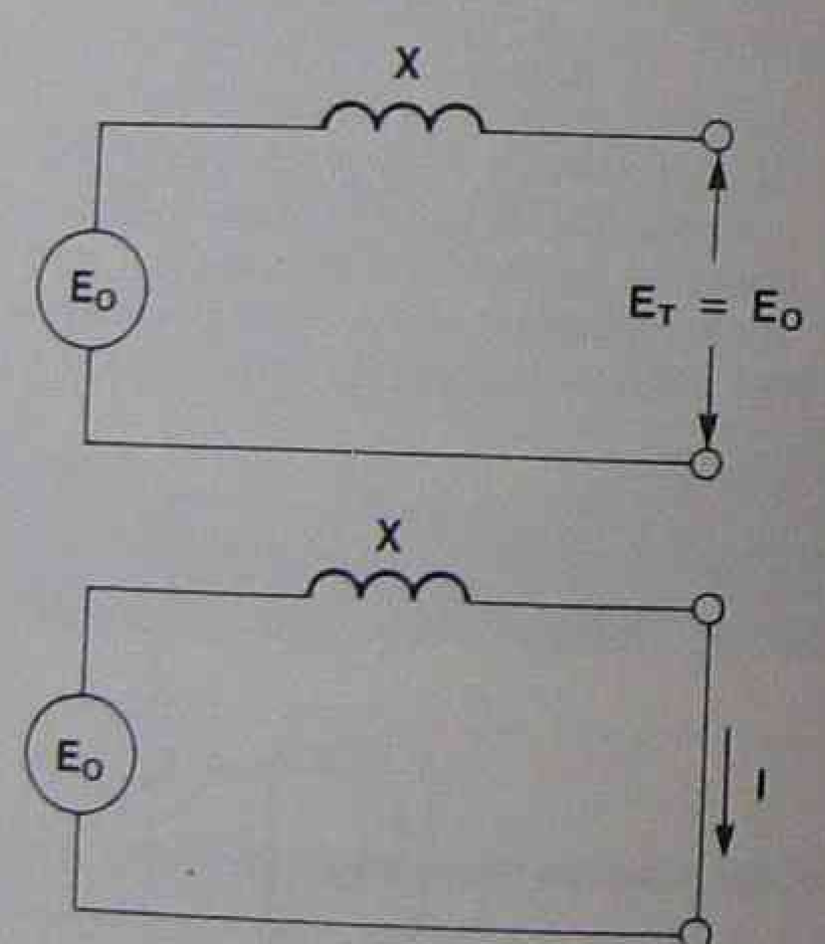


Figure 8-3.

The equivalent circuit of an alternator is, therefore very simple, and with it we can explain all the major properties of this machine. For example, we would expect that if a resistive or an inductive load is connected to the terminals, the terminal voltage E_T

will drop. On the other hand, if a capacitive load is connected to the terminals, a voltage rise is to be expected owing to the resonance effect.

The synchronous reactance of an alternator is always very large, so that even under short-circuit conditions, the current rarely exceeds 1,5 times the normal full-load current. It should be mentioned, however, that for the first few cycles following a short-circuit, the current can be much higher owing to the transient properties of the machine which we need not go into at this point.

In the following experiment, a DC motor will be used to drive the three-phase alternator, replacing the steam turbine which would usually be employed in a real generating station.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
DC Motor/Generator	8211
Three-Phase Synchronous Motor/Generator	8241
Resistive Load	8311
Inductive Load	8321
Capacitive Load	8331
DC Voltmeter/Ammeter	8412
AC Ammeter	8425
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Stroboscope	8922
Timing Belt	8942
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. In this experiment we shall determine the variation of the generated voltage E_O, as the DC exciting current is increased. Set up the circuit as shown in Figure 8-4, and mechanically couple the DC Motor/Generator to the Three-Phase Synchronous Motor/Generator by means of a Timing Belt. Connect AC Voltmeter E_O from line to neutral of one phase of the Three-Phase Synchronous Motor/Generator and connect a DC Voltmeter/Ammeter to measure the exciting current I_F.

Apply power and, using the Stroboscope adjust the speed of the DC Motor/Generator to 1500 r/min exactly. This speed must be kept constant for the remainder of the experiment.

Vary the current I_F and note the effect upon the generated voltage E_O. Take readings of I_F and E_O and record your results in Table 8-1.

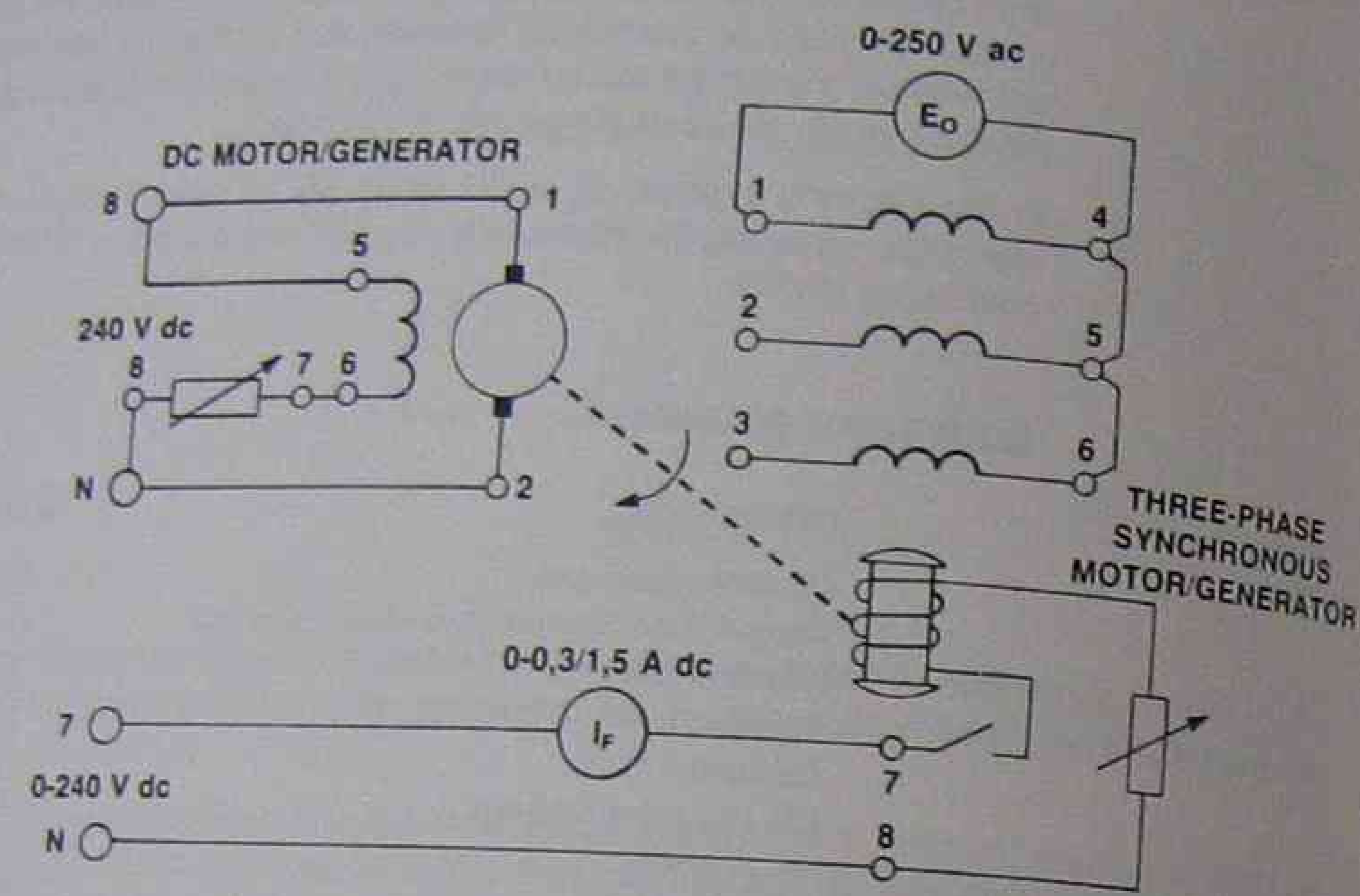


Figure 8-4.

I_F	(A)	0	0,05	0,10	0,15	0,20	0,25	0,30	0,35	0,40	0,45	0,50
E_O	(V)											

Table 8-1.

☐ 2. Find the phase sequence of the generated voltage, with regards to terminals 1, 2, 3.

The phase sequence is ______

Note: *If the phase sequence is not 1-2-3-1-2-3, etc, reverse rotation of the DC Motor/Generator.*

☐ 3. Using the same set-up as in Figure 8-4, adjust the open-circuit voltage E_O to 240 V. Then short-circuit the stator terminals through three AC Ammeters and take their average reading I (see Figure 8-5).

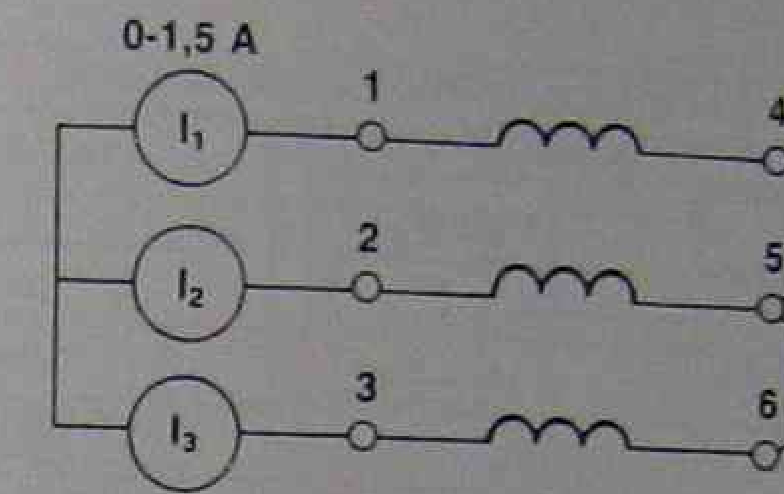


Figure 8-5.

Calculate the value of the synchronous reactance from the formula $X = E_O/I$.

E_O = 240 V   I = ______ A   X = ______ Ω

☐ 4. Repeat procedure step 3 with E_O = 240 V and then with E_O = 220 V.

E_O = 240 V   I = ______ A   X = ______ Ω

E_O = 220 V   I = ______ A   X = ______ Ω

Voltage Regulation

In this experiment we shall find the effect of various loads upon the terminal voltage of the alternator.

☐ 5. Using the same set-up as in Figure 8-4, connect a Resistive Load to the terminals of the DC Motor/Generator and introduce a Wattmeter/Varmeter and a Voltmeter E_L as shown in Figure 8-6.

Adjust the exciting current I_F of the Three-Phase Synchronous Motor/Generator so that the open-circuit voltage E_L = 415 V. Then, keeping the speed and the current I_F constant, vary the Resistive Load and record your results in Table 8-2. Be sure to keep the load resistance balanced so that all phases are equally loaded.

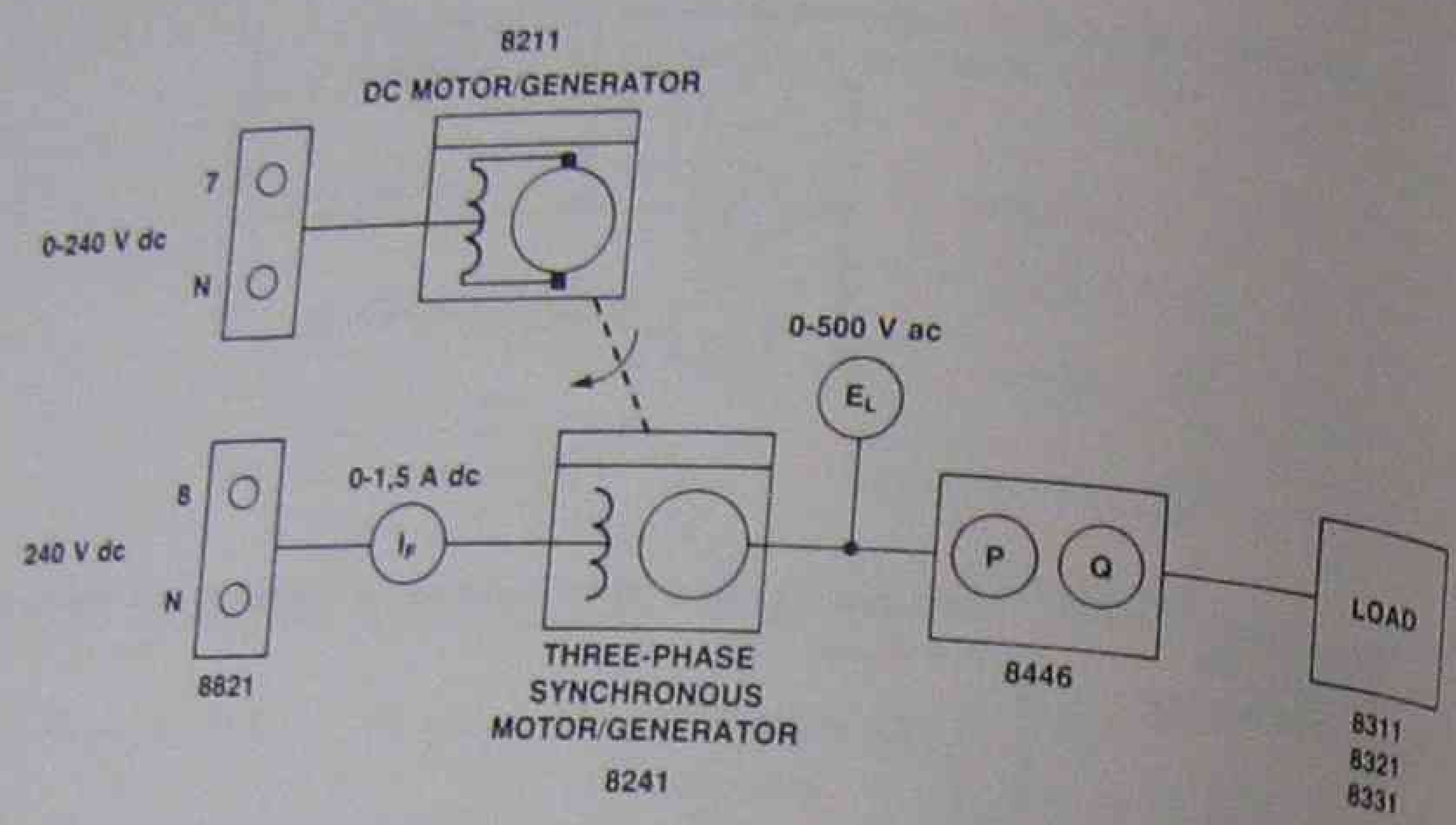


Figure 8-6.

VOLTAGE REGULATION WITH RESISTIVE LOAD					
R/PHASE	I_F	E_L	P	Q	$S = \sqrt{P^2 + Q^2}$
Ω	A	V	W	var	VA
∞					
4800					
2400					
1600					
1600					
1200					
960					
800					
686					

Table 8-2.

☐ 6. Repeat procedure step 5, using an Inductive Load in place of the Resistive Load, and record your results in Table 8-3.

VOLTAGE REGULATION WITH INDUCTIVE LOAD					
X_L/PHASE	I_F	E_L	P	Q	$S = \sqrt{P^2 + Q^2}$
Ω	A	V	W	var	VA
∞					
4800					
2400					
1600					
1600					
1200					
960					
800					
686					

Table 8-3.

☐ 7. Repeat procedure step 5, using a Capacitive Load instead of the resistance, and record your results in Table 8-4. (If the voltage goes off scale, you may connect two voltmeters in series and take the sum of their readings.)

VOLTAGE REGULATION WITH CAPACITIVE LOAD					
X_L/PHASE	I_F	E_L	P	Q	$S = \sqrt{P^2 + Q^2}$
Ω	A	V	W	var	VA
∞					
4800					
2400					
1600					
1600					
1200					
960					

Table 8-4.

Reactive power is the power associated with the charge and discharge of condensers and the increase and decrease of the magnetic fields of inductors when they are part of an alternating current circuit. Because the energy (joules) in a coil merely builds up and decays as the magnetic field increases and decreases in response to the alternating current which it carries, it follows that there is no flow of real power in a coil. On the other hand, a current flows through the coil and a voltage appears across it, so a casual observer is apt to believe that power of some kind is involved. The product of the voltage and current in a coil is called the reactive power, and it is expressed in var or in kilovar (kvar). Reactive power is needed to produce an alternating *magnetic* field.

In the same way, the alternating *electric* field in a capacitor also requires reactive power. Owing to the overwhelming prevalence of electromagnetic devices (as opposed to electrostatic devices), we consider that reactive power, whenever it appears, is the kind of power which has the ability to produce a magnetic field.

Reactive power, just like real power, can be measured with appropriate meters called varmeters. In three-phase circuits, the two or three varmeters which would ordinarily be needed can be combined into a single instrument to give one reading of the total reactive power flow in the circuit. Such a meter, shown in Figure 3-2, possesses three input terminals (1,2,3) and three output terminals (4,5,6).

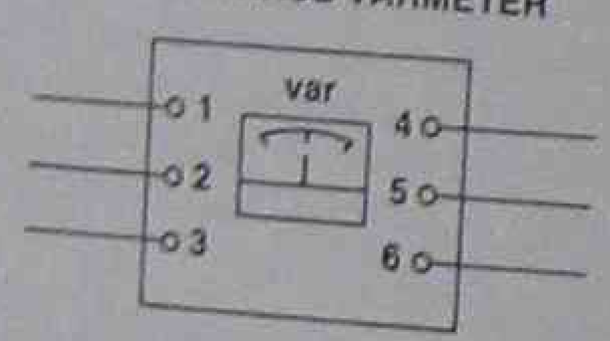


Figure 3-2.

When reactive power flows from the input to the output terminals, the meter will give a positive reading. Conversely, if the flow of reactive power is from the output terminals to the input terminals, a negative reading will result. For example, if a three-phase source and a three-phase coil are connected as shown in Figure 3-3, the flow of reactive power is obviously from left to right, and the varmeter will give a positive reading. Just as with a wattmeter, the direction of reactive power flow can readily be found when the input terminals of the varmeter are identified.

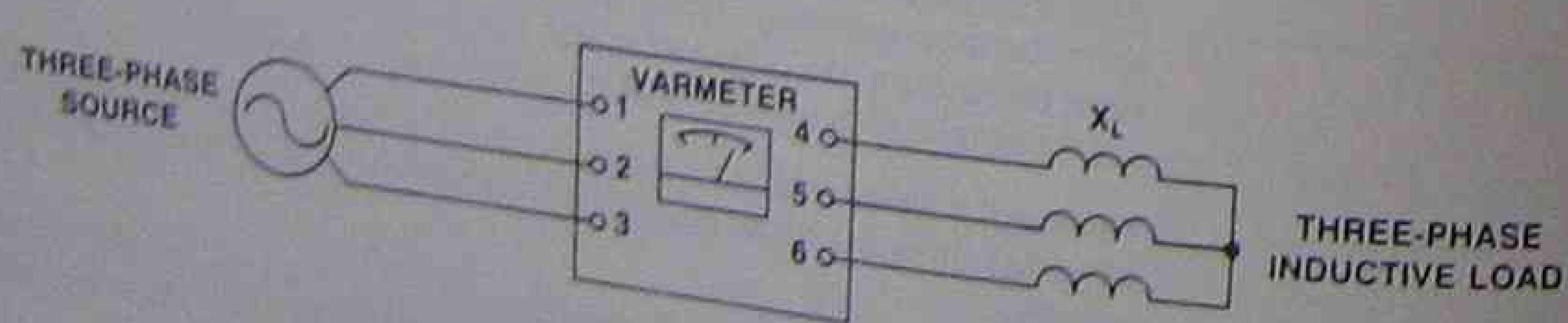


Figure 3-3.

Real Power and Reactive Power

Three-phase alternating circuits may involve many types of circuits and devices, but the flow of active and reactive power can always be determined by introducing wattmeters and varmeters. The example of Figure 3-4 will illustrate how some typical readings can be interpreted. An impedance Z forms part of a larger circuit (not shown), and wattmeters W_1, W_2 and varmeters var_1, var_2 are connected on either side. The input terminals are assumed to be on the left-hand side of each instrument. The meters give the following readings:

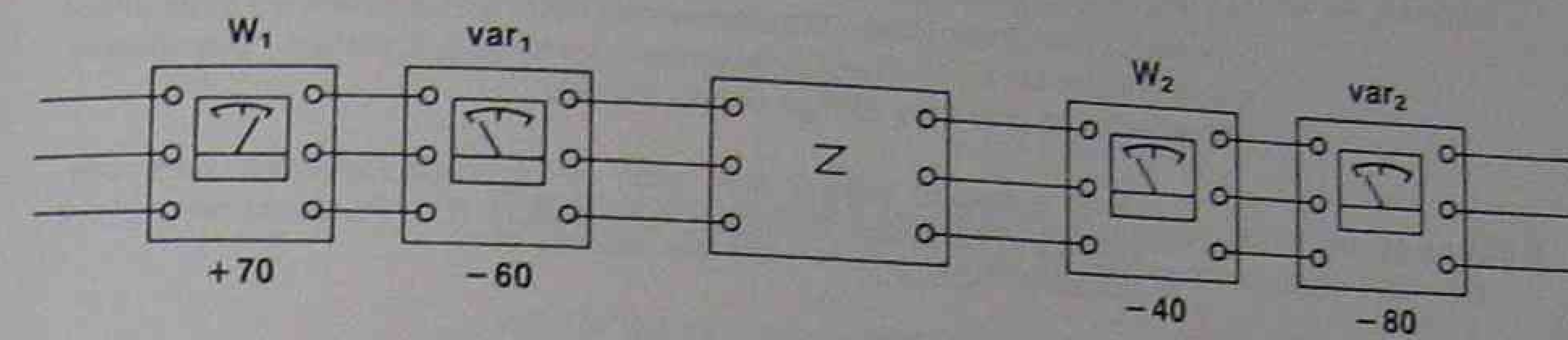


Figure 3-4.

$W_1 = +70$ W $\quad var_1 = -60$ var

$W_2 = -40$ W $\quad var_2 = -80$ var

How are we to interpret these results? First, we must recognize that real power and reactive power flow quite independently of each other. One does not affect the other. Consequently, we must never add or subtract real power and reactive power.

Consider first the active power. Because W_1 is positive, real power is flowing to the right. Because W_2 is negative, real power is flowing to the left. It follows, therefore, that the impedance Z must be absorbing $70 + 40 = 110$ W.

Next, let us look at the reactive power; 80 var are flowing to the left, towards the impedance Z, while 60 var are flowing to the left, away from it. It follows that Z is absorbing $(80 - 60) = 20$ var, and this reactive power creates a magnetic field.

This example shows that when wattmeters and varmeters are connected on either side of an electrical circuit or device, we can determine the real and the reactive power which it produces or absorbs.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Three-Phase Wound-Rotor Induction Motor	8231
Resistive Load	8311
Inductive Load	8321
Capacitive Load	8331
AC Ammeter	8425
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

The following experiments involve a three-phase source, three Voltmeters, three Ammeters, one Three-Phase Wattmeter/Varmeter, and a balanced three-phase star-connected load. The source is taken from terminals 4, 5, 6 of the Power Supply, and adjusted to provide a voltage of about 415 V.

☐ 1. Using a load of 1200 Ω from each of the three Resistive Loads star-connected as shown in Figure 3-5, measure E, I, P, Q and record your results in Table 3-1.

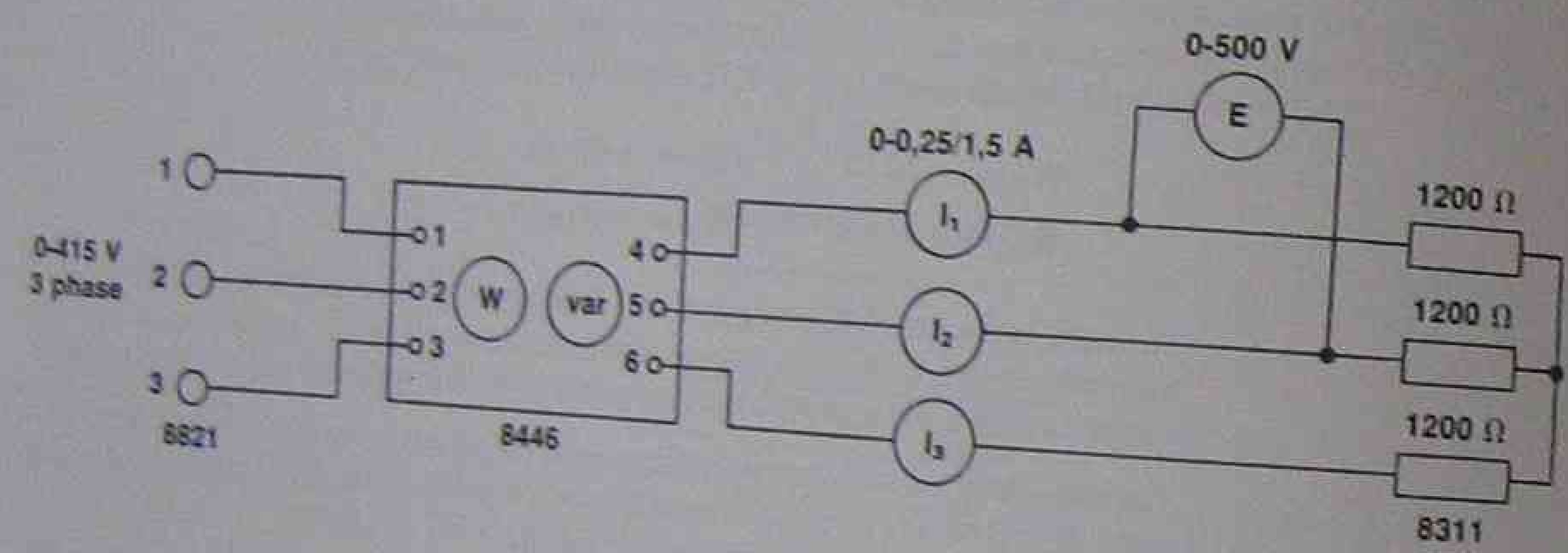


Figure 3-5.

☐ 2. Replace the Resistive Load by three Inductive Loads having a reactance of 1200 Ω, star-connected. Record your results in Table 3-1.

Note: *The leads coming from the source must be connected to terminals 1, 2, 3 of the Three-Phase Wattmeter/Varmeter in the order of their phase sequence. If the phase sequence of the Power Supply is 1-2-3, the varmeter will give the correct reading when terminals 1, 2, 3 of the Power Supply are connected to terminals 1, 2, 3 of the instrument.*

In this experiment the varmeter reading should be positive. If it is negative, the phase sequence is incorrect and two leads of the source should be interchanged.

☐ 3. Repeat procedure step 2, using three Capacitive Loads having a reactance of 1200 Ω, star-connected. Record your results in Table 3-1.

☐ 4. Repeat procedure step 3, but add three Resistive Loads of 1200 Ω (star-connected) in parallel with the Capacitive Loads. Record your results in Table 3-1. Is the real power affected when the Capacitive Loads are switched on and off?

☐ Yes ☐ No

Is the reactive power affected when the Resistive Loads are switched on and off?

☐ Yes ☐ No

☐ 5. Repeat procedure step 1, but place the Inductive Load of procedure step 2 in parallel with the Resistive Loads. Record your results in Table 3-1.

Why is the real power slightly affected when the Inductive Loads are switched on and off?

____

____

Is the reactive power affected when the Resistive Loads are switched on and off?

☐ Yes ☐ No

☐ 6. Repeat procedure step 1, but use an Inductive Load of 1200 Ω in parallel with a Capacitive Load of 1200 Ω, all star-connected. Record your results in Table 3-1. Do you agree that, to all intents and purposes, the Capacitive Load is supplying most of the reactive power required by the Inductive Load?

☐ Yes ☐ No

Would you agree that the Capacitive Load can be considered to be a source of reactive power?

☐ Yes ☐ No

☐ 7. *Repeat procedure step 1, but use a Three-Phase Wound-Rotor Induction Motor at no load instead of the Resistive Load. Record your results in Table 3-1. Does the motor absorb both real and reactive power?

☐ Yes ☐ No

What does the real power accomplish?

____

____

What does the reactive power accomplish?

____

____

* This procedure is optional.

☐ 8. Knowing that the apparent power (S) in volt-amperes (VA) is given by the expression

$$S = \sqrt{P^2 + Q^2},$$

calculate the apparent power in Table 3-1.

PROCEDURE STEP No.	LOAD	E	I	P	Q	S	$S = EI\sqrt{3}$
		V	A	W	var	VA	
1	R						
2	X_L						
3	X_C						
4	R, X_C						
5	R, X_L						
6	X_C, X_L						
7	M						

Table 3-1.

☐ 9. Knowing that the apparent power of a balanced three-phase circuit is given by the equation $S = EI\sqrt{3}$, calculate the apparent power, and compare with the value found in procedure step 8.

TEST YOUR KNOWLEDGE

1. An electrical load Z is connected to the terminals of a 240 V ac source. Show the direction of real and reactive power flow if Z is a) a resistor, b) an inductor, c) a capacitor, d) a resistor and inductor, e) a resistor and capacitor, f) a single-phase motor (See Figure 3-6).

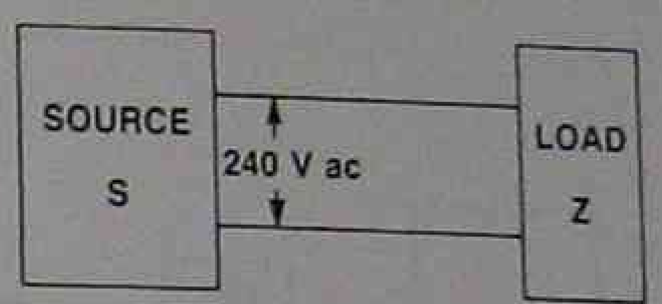


Figure 3-6.

2. Calculate the real and reactive power delivered by the single-phase source in the two single-phase circuits shown in Figure 3-7.

____

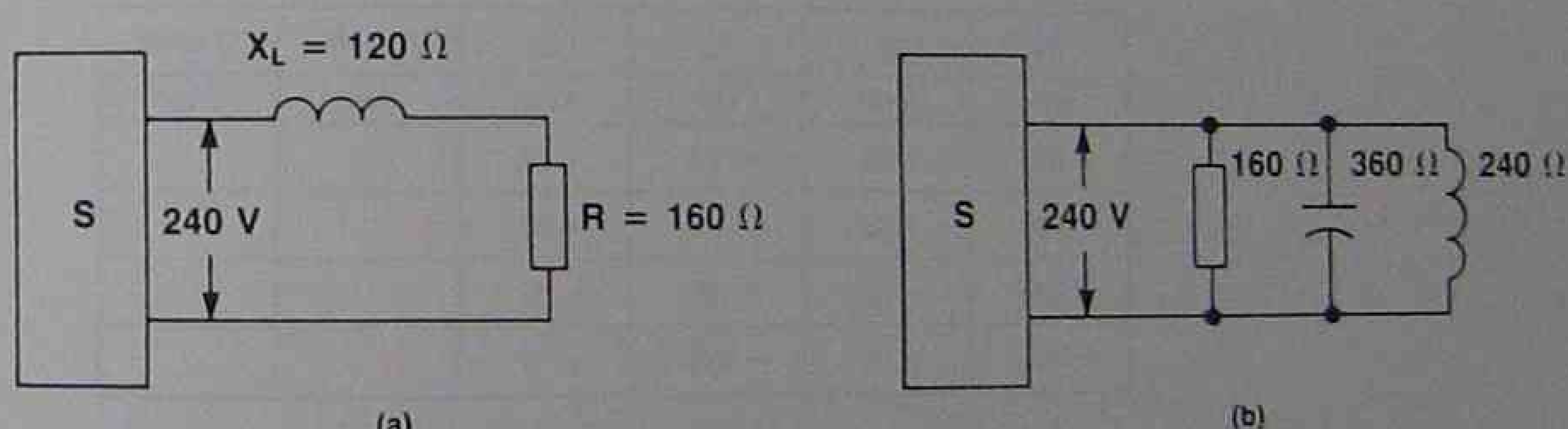


Figure 3-7.

3. A three-phase source having a line-to-line voltage of 69 kV supplies a star-connected resistive load having an impedance of 100 Ω per phase. Calculate the real power delivered.

____

4. Explain what is meant by the statement than an inductor absorbs reactive power while a capacitor supplies reactive power.

5. A three-phase power line, shown schematically in Figure 3-8, delivers real and reactive power as given in Table 3-2. Calculate the real and reactive power absorbed by the line.

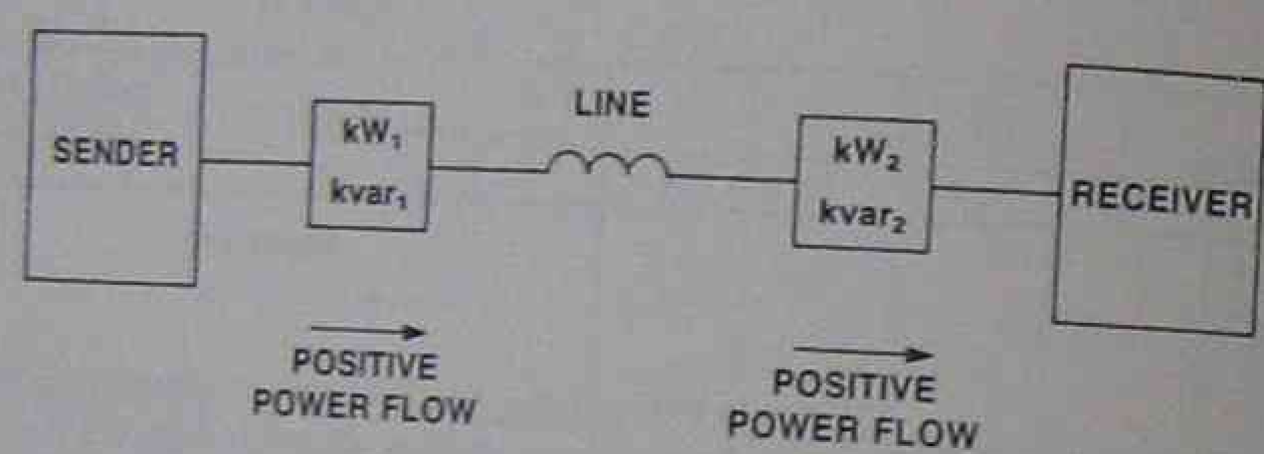


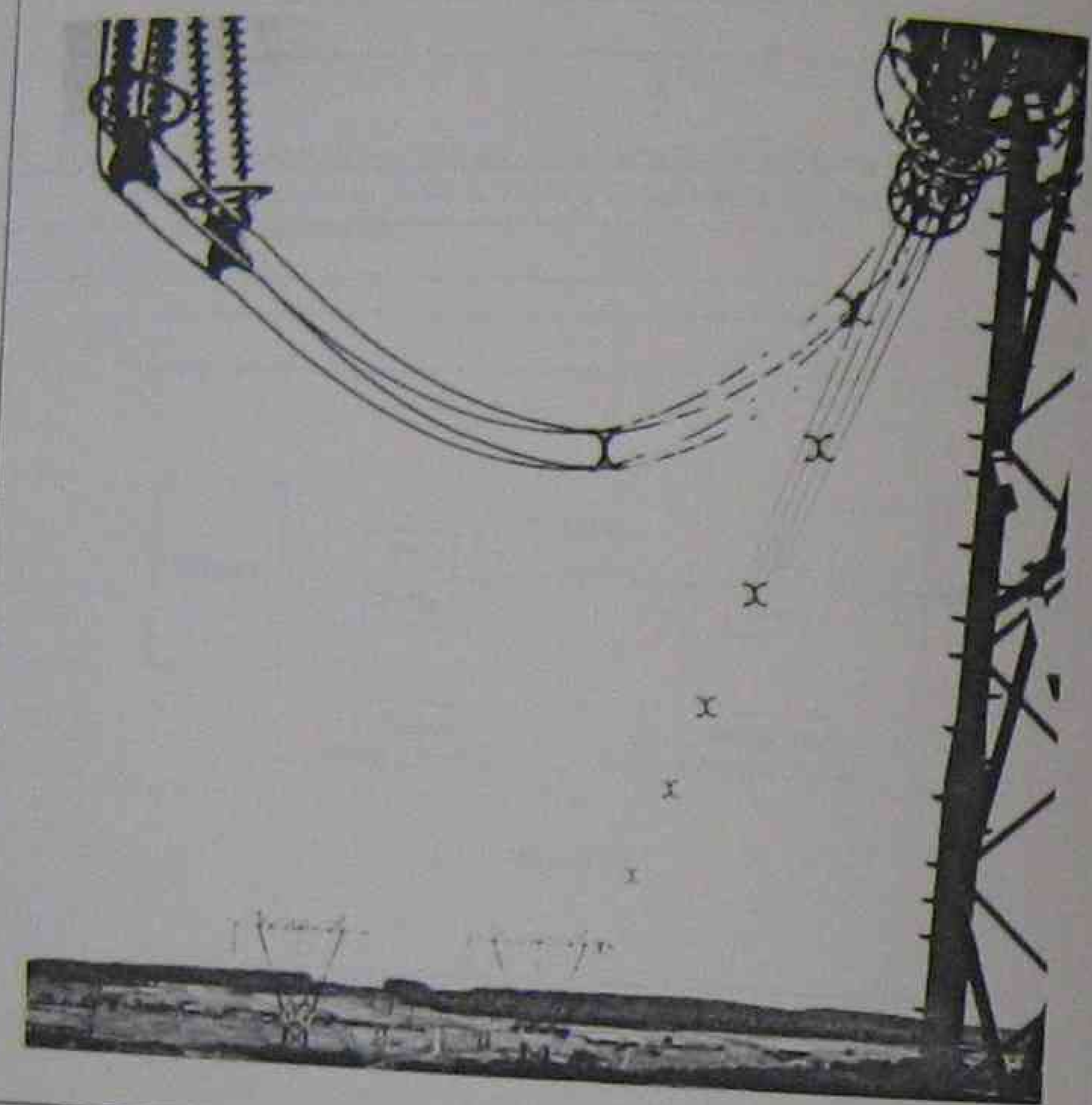
Figure 3-8.

P_1 kW	Q_1 kvar	P_2 kW	Q_2 kvar	P LINE kW	Q LINE kvar
+100	+10	+ 95	+ 5		
+100	+10	+ 95	−10		
+100	−10	+ 95	−25		
−100	+10	−105	+ 5		

Table 3-2.

6. A three-phase line operating at a line-to-line voltage E supplies power to a star-connected load whose impedance is Z ohms per phase. Show that the total apparent power S is given by the equation.

$$S = \frac{E^2}{Z}$$



Power Flow and Voltage Regulation of a Simple Transmission Line

OBJECTIVES

- To observe the flow of real and reactive power in a three-phase transmission line with known, passive, loads.
- To observe the voltage regulation at the receiver end as a function of the type of load.

DISCUSSION

Transmission Lines

A transmission line which delivers electric power dissipates heat owing to the resistance of its conductors. It acts, therefore, as a resistance which, in some cases, is many miles long.

The transmission line also behaves like an inductance, because each conductor is surrounded by a magnetic field which also extends the full length of the line.

Finally, the transmission line behaves like a capacitor, the conductors acting as its more or less widely-separated plates.

The resistance, inductance and capacitance of a transmission lien are uniformly distributed over its length, the magnetic field around the conductors existing side by side with the electric field created by the potential difference between them. We can picture a transmission line as being made up of thousands of elementary resistors, inductors and capacitors as shown in Figure 4-1.

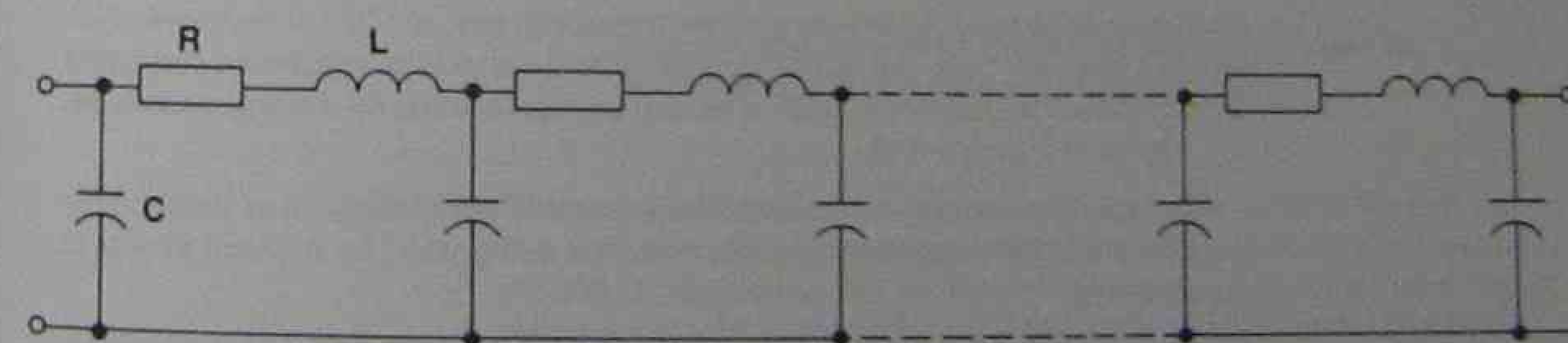


Figure 4-1.

In high frequency work this is precisely the circuit required to explain the behavior of a transmission line. Fortunately, at low frequencies of 50 Hz or 60 Hz, we can simplify most lines so that they comprise one inductance, one resistance and one (or sometimes two) capacitors (for each phase). Such an arrangement is shown in Figure 4-2.

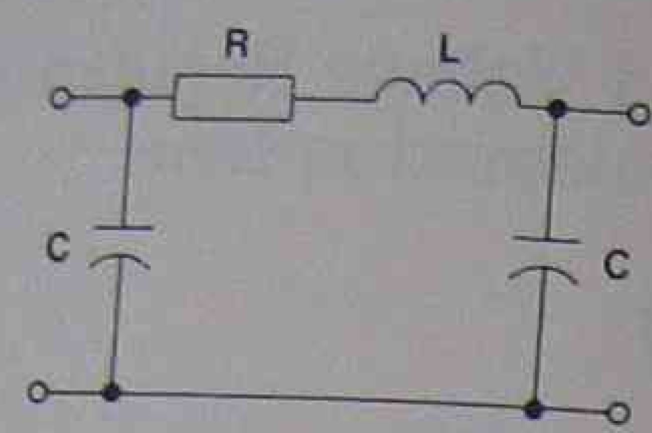


Figure 4-2.

In Figure 4-2, the inductance L is equal to the sum of the inductances of Figure 4-1, and the same is true for the resistance R. The capacitance C is equal to one half the sum of the capacitors shown in Figure 4-1. The inductance L and capacitance C can be replaced by their equivalent reactances X_L and X_C as shown in Figure 4-3.

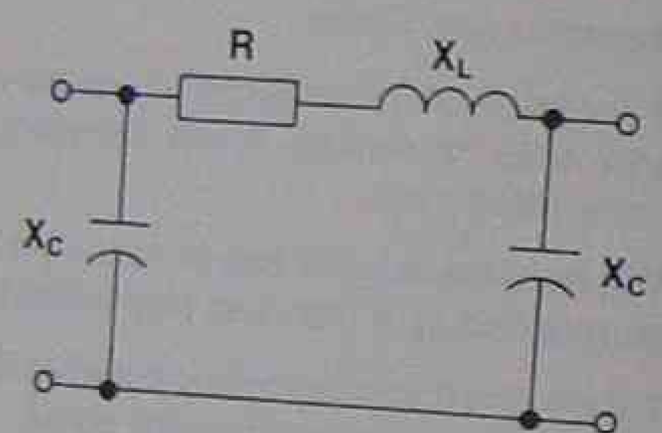


Figure 4-3.

The relative values of R, X_L and X_C depend upon the type of transmission line. Short, low-voltage lines such as in a house wiring are mainly resistive, and the inductive and capacitive reactances can be neglected (Figure 4-4 a)).

Medium-voltage and medium-length lines operating, say, at 100 KV and several kilometers long, will have negligible resistance and capacitive reactance compared with the inductive reactance. Such lines can be represented by a single reactance X_L, shown in Figure 4-4 b).

Finally, very high voltage lines which run for many kilometers have appreciable capacitive and inductive reactance and may be designated by a circuit similar to Figure 4-4 c).

Most transmission lines can be represented by Figure 4-4 b) or 4-4 c), and a good understanding of their behavior can be obtained by the simple inductance of Figure 4-4 b). It is this circuit which will be used in this experiment.

As a matter of interest, typical 50 Hz lines have a series reactance of about 0.4 Ω per kilometer per phase. The shunt capacitive reactance is about 400 000 Ω per kilometer.

Power Flow and Voltage Regulation
of a Simple Transmission Line

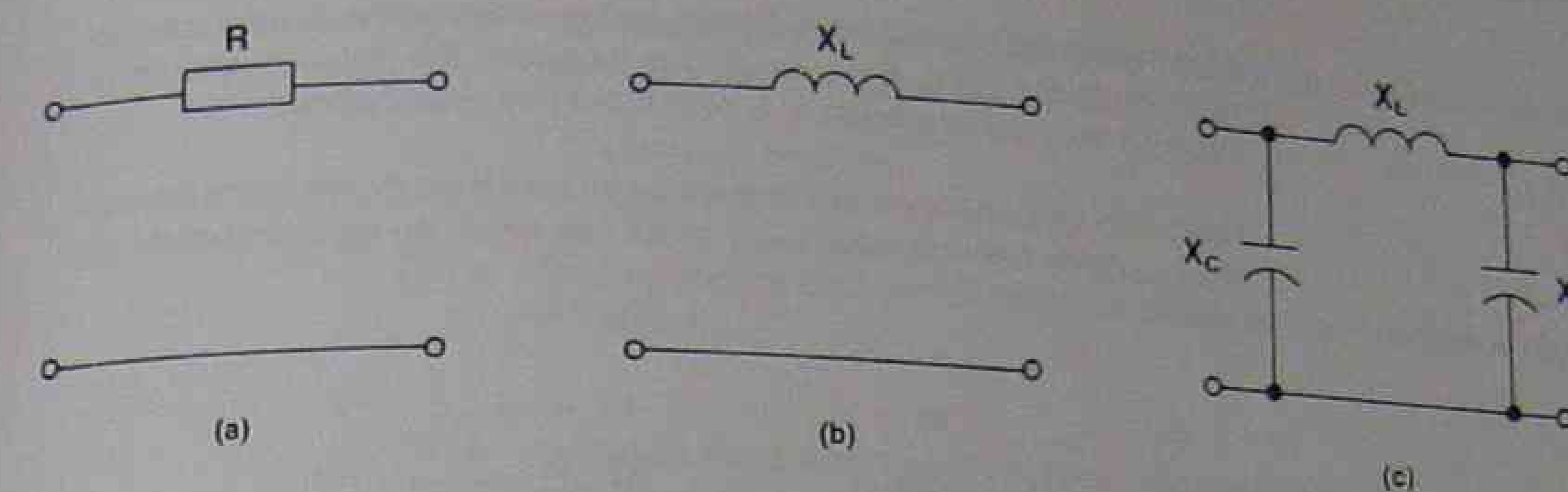


Figure 4-4.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Four-Pole Squirrel-Cage Induction Motor	8221
Three-Phase Wound-Rotor Induction Motor	8231
Resistive Load	8311
Inductive Load	8321
Three-Phase Transmission Line	8329
Capacitive Load	8331
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Phase-Shift Indicator	8909
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Connect two Wattmeter/Varmeters in series to the variable Three-Phase 415 V section of the Power Supply and apply a three-phase Inductive Load of 1200 Ω, star-connected, as shown in Figure 4-5. Adjust the Power Supply output to 415 V. Particular care should be taken in connecting so that the proper phase sequence is applied to the Wattmeter/Varmeters.

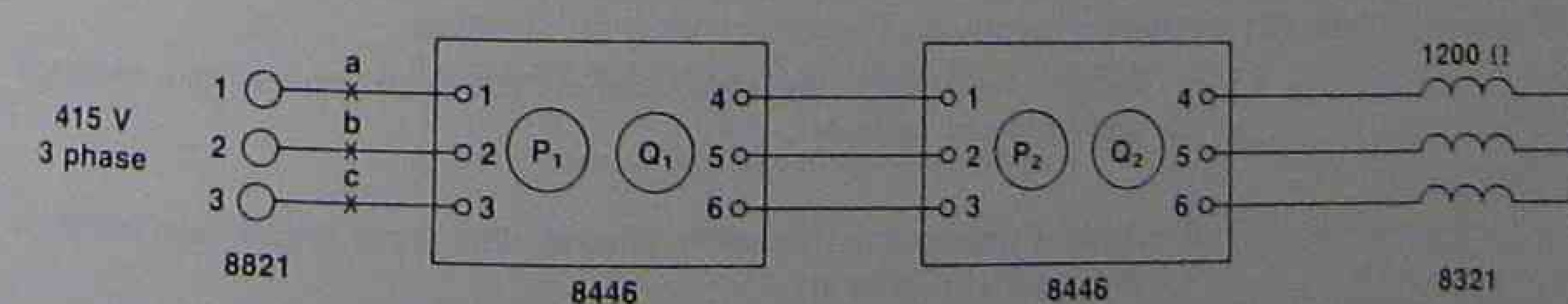


Figure 4-5.

If the meters are connected as shown, both varmeters should read positive (pointers to the right). If the reading is negative, the phase sequence is incorrect and any two leads a, b or c should be interchanged.

Note: *Although both meters should give the same readings, the one on the left may show a slightly higher reading owing to the load which the right-hand meter imposes.*

P_1 = ______ W $\quad$ P_2 = ______ W

Q_1 = ______ var $\quad$ Q_2 = ______ var

☐ 2. Using the variable-voltage AC source, connect the circuit as shown in Figure 4-6, and set the impedance of the transmission line to 400 Ω. Connect an Inductive Load of 1200 Ω in star and apply power. All meters should read positive; if the readings are not positive, check your wiring for phase sequence. We are now ready to proceed with the experiment, using the circuit of Figure 4-6.

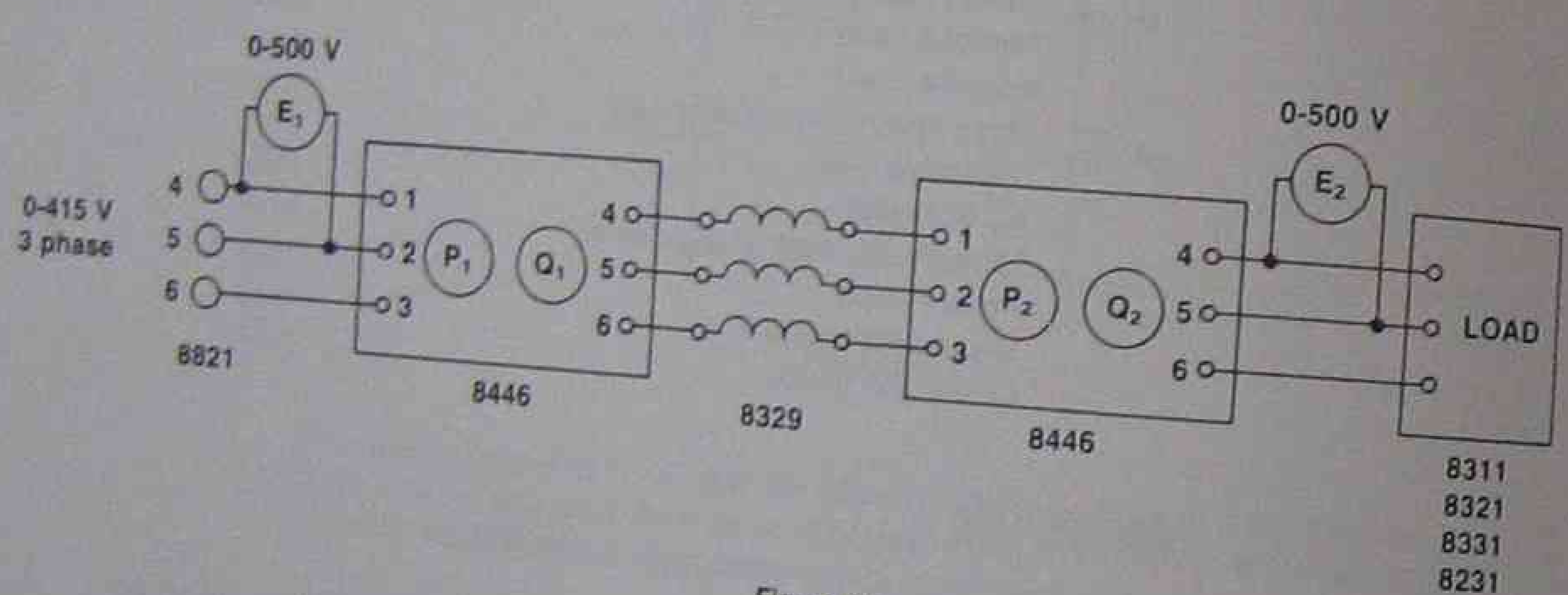


Figure 4-6.

☐ 3. With the line on open circuit, adjust the voltage of the source so that the line-to-line voltage E_1 is 350 V. (Keep this voltage constant for the remainder of the experiment.) Measure E_1, P_1, Q_1 and E_2, P_2, Q_2, and record in Table 4-1.

☐ 4. Connect a three-phase Inductive Load of 1200 Ω per phase, take readings and record in Table 4-1.

☐ 5. Apply a three-phase Resistive Load of 1200 Ω per phase, take readings and record in Table 4-1.

☐ 6. Apply a three-phase Capacitive Load of 1200 Ω per phase, take readings and record in Table 4-1.

☐ 7. *Connect a Three-Phase Wound-Rotor Induction Motor to the receiver end of the line, take readings and record in Table 4-1.

* This procedure is optional.

☐ 8. Short-circuit the load end of the transmission line, take readings and record in Table 4-1.

☐ 9. Calculate the real and reactive power absorbed by the transmission line in procedure steps 4, 5, 6 and record in Table 4-1.

☐ 10. Calculate the voltage regulation of the transmission line from the formula:

$$\% \text{ regulation} = \frac{(E_O - E_L) \times 100}{E_O}$$

in which E_O is the open-circuit voltage and E_L is the voltage under load, both at the load (or receiver end). Record your results in Table 4-1.

PROCEDURE STEP No.	LOAD	E_1	P_1	Q_1	E_2	P_2	Q_2	LINE	LINE	REGULATION
		V	W	var	V	W	var	W	var	%
3	OPEN CIRCUIT	350								
4	INDUCTIVE	350								
5	RESISTIVE	350								
6	CAPACITIVE	350								
8	MOTOR	350								
9	SHORT-CIRCUIT	350								

Table 4-1.

TEST YOUR KNOWLEDGE

1. A three-phase transmission line having a reactance of *120 ohms* per phase is connected to a star-connected load whose resistance is *160 ohms* per phase. If the supply voltage is *70 kV* line-to-line, calculate:

   a) The line-to-neutral voltage per phase.

   ____

b) The line current per phase.

c) The real and reactive power supplied to the load.

d) The real and reactive power absorbed by the line.

e) The line-to-line voltage at the load.

f) The voltage drop per phase in the line.

g) The total apparent power supplied by the source.

h) The total real and reactive power supplied by the source.

2. A transmission line 500 kilometres long has a reactance of *200 ohms* per phase and a line-to-neutral capacitance of *800 ohms* per phase. Its equivalent circuit per phase can be approximated by the circuit shown on Fig. 4-7. If the line-to-line voltage at the sender end *S* is *330 kV*, what is the line-to-line voltage at the receiver end *R* when the load is disconnected?

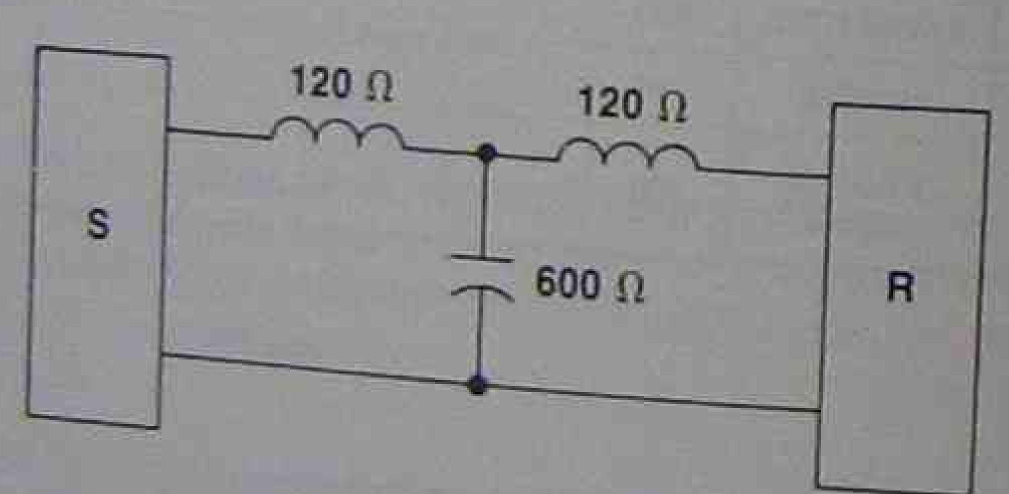


Figure 4-7.

Calculate the reactive power of the source in *kvar*. Is this power supplied or absorbed by the source?

Supply Authorities are very sensitive to keeping the esthetic beauty of a city. This modern substation blends in well with the surrounding architecture.

Experiment 5

Phase Angle and Voltage Drop between Sender and Receiver

OBJECTIVES

- To regulate the receiver end voltage.
- To observe the phase angle between the voltages at the sending and the receiving end of the transmission line.
- To observe the line voltage drop when the sending and receiving end voltages have the same magnitude.

DISCUSSION

In the previous experiment we saw that a resistive or inductive load at the end of a transmission line produces a very large voltage drop, which would be quite intolerable under practical conditions. Motors, relays and electric lights work properly only under stable voltage conditions, close to the potential for which these devices are rated.

We must, therefore, regulate the voltage at the receiver end of the transmission line in some way so as to keep it as constant as possible. One approach which appears promising, is to connect capacitors at the end of the line because, as we saw in Experiment 4, these capacitors produce a very significant voltage rise. This, indeed, is one way by which the receiving end voltage is regulated in some practical instances. Static capacitors are switched in and out during the day, and their value is adjusted to keep the receiver end voltage constant.

For purely inductive loads, the capacitors should deliver reactive power equal to that consumed by the inductive load. This produces a parallel resonance effect in which reactive power required by the inductance is, in effect, supplied by the capacitance and none is furnished by the transmission line.

For resistive loads, the reactive power, which the capacitors must supply to regulate the voltage, is not easy to calculate. In this experiment, we shall determine the reactive power by trial and error, adjusting the capacitors until the receiver end voltage is equal to the sender end voltage.

Finally, for loads which draw both real and reactive power (they are the most common) the capacitors must be tailored to compensate first, for the inductive component of the load and second, for the resistive component.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Resistive Load	8311
Three-Phase Transmission Line	8329
Capacitive Load	8331
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Phase Meter	8451
Power Supply	8821
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Set the impedance of the transmission line to 200 Ω and connect the Voltmeter and Wattmeters/Varmeters as shown in Figure 5-1. The load will be modified during the course of the experiment. The circuit should be connected to the three-phase variable voltage supply.

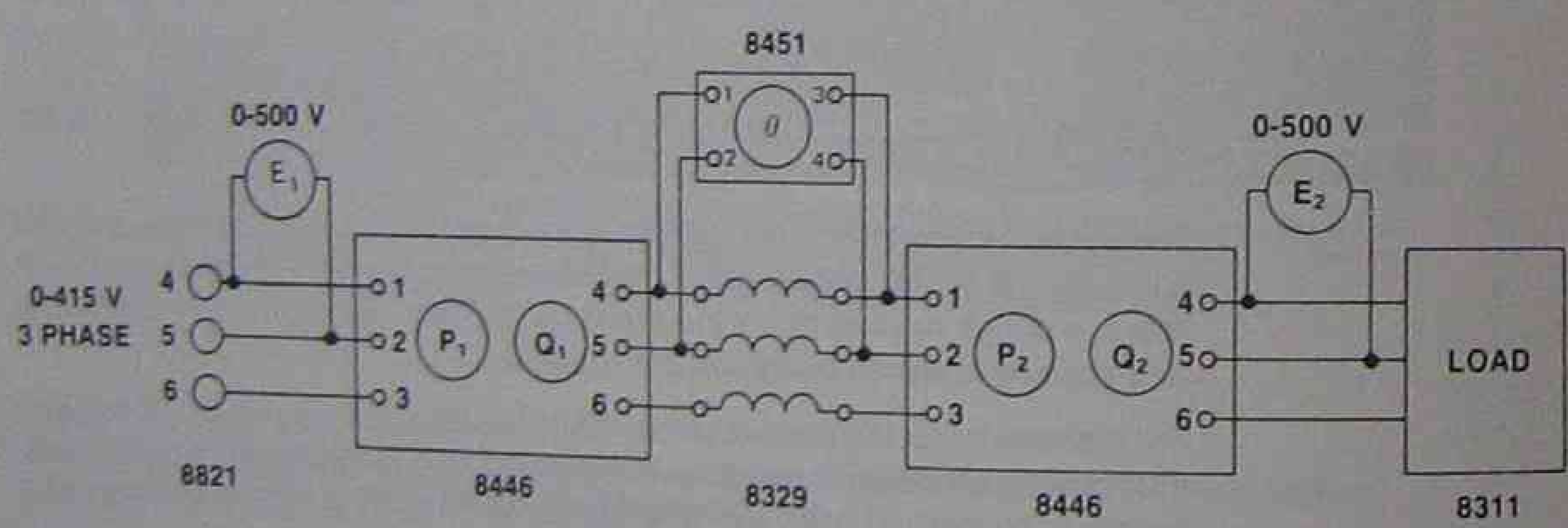


Figure 5-1.

☐ 2. Using a three-phase Resistive Load, adjust E_1 to 350 V and keep it constant for the remainder of the experiment. Increase the Resistive Load in steps, keeping all three-phase balanced. Take readings of E_1, Q_1, E_2, P_2, Q_2 and the phase angle between E_1 and E_2.

Note: *E_1 is chosen as the reference voltage for the phase-angle meter.*

VOLTAGE REGULATION WITH RESISTIVE LOAD							
R Ω	E_1 V	P_1 W	Q_1 var	E_2 V	P_2 W	Q_2 var	ANGLE °
∞							
4800							
2400							
1600							
1200							
960							
800							
686							

Table 5-1.

Record your results in Table 5-1, and draw in Figure 5-2 a graph of E_2 as a function of the load power P_2, in watts.

On this curve, indicate the phase angle corresponding to the various real power loads W_2.

CAUTION

Always remove the capacitive load prior to removing the resistive load. A severe overload is otherwise to be expected.

☐ 3. Now, connect a three-phase balanced Capacitive Load in parallel with the Resistive Load. Repeat procedure step 2 but for each Resistive Load adjust the Capacitive Load so that the load voltage E_2 is as close as possible to 350 V. (E_1 must be kept constant at 350 V.) Record your results in Table 5-2.

Draw a graph of E_2 as a function of P_2, and superimpose it on the previous graph which you drew in procedure step 2. Note that the addition of static capacitors has yielded a much more constant voltage, and furthermore, the power P_2 which can be delivered has increased.

On this curve, indicate the phase angle between E_2 and E_1 as well as the reactive power Q_2 used for the individual resistive load settings.

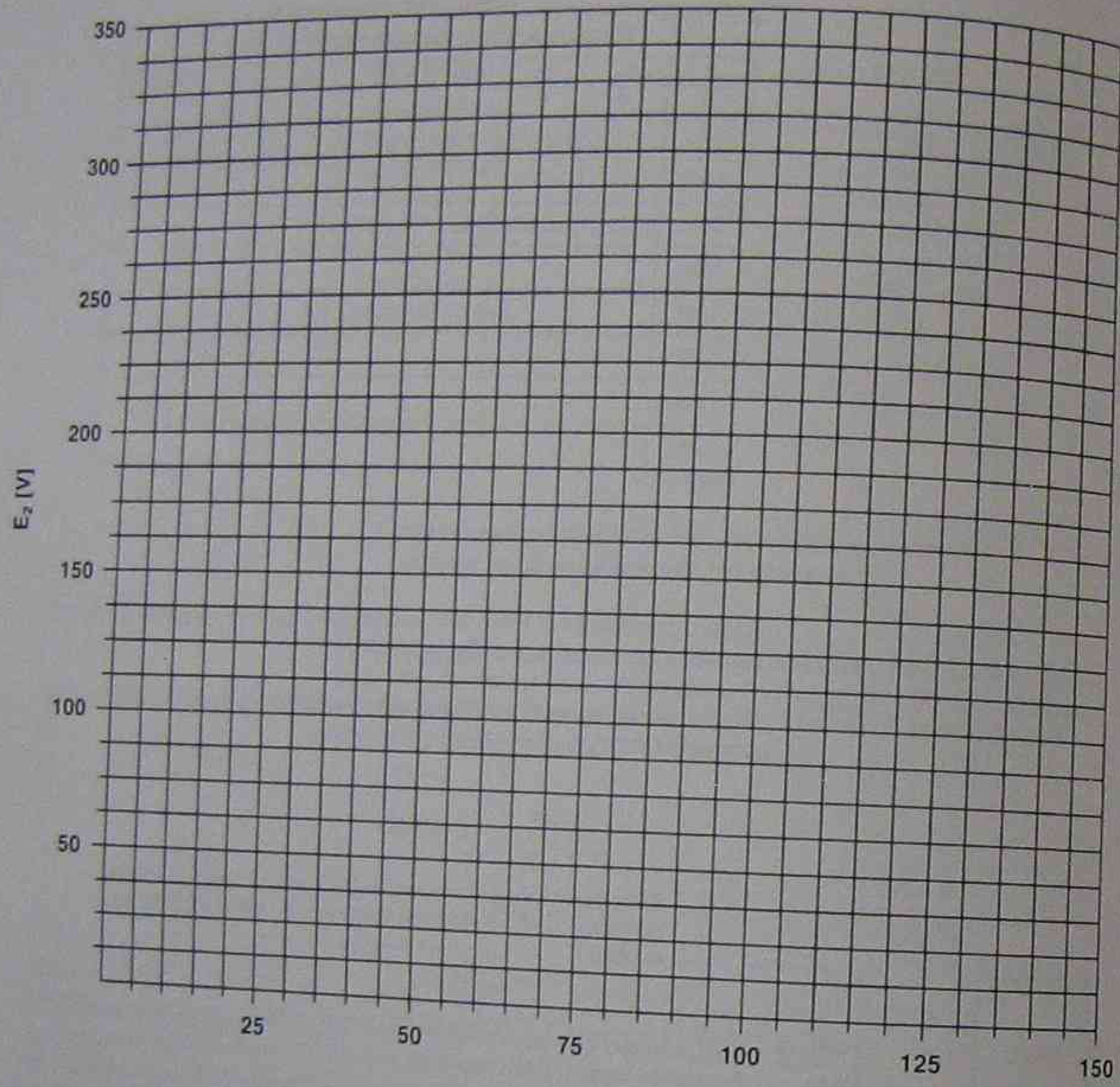


Figure 5-2.

☐ 4. In this experiment, we shall observe a significant voltage drop along a transmission line even when the voltages E_1 and E_2 at the sender and receiver ends are equal in magnitude. How is it possible to have a voltage drop when the voltages at the two ends are equal? The answer is that the drop is due to the phase angle between the two voltages.

Using the circuit shown in Figure 5-3, set the load resistance per phase at 686 Ω, and with E_1 = 350 V, adjust the capacitive reactance until the load voltage is as close as possible to 300 V. Measure E_1, P_1, Q_1, E_2, P_2, Q_2, E_3 and the phase angle.

E_1 = ______ V E_2 = ______ V E_3 = ______ V

P_1 = ______ W P_2 = ______ W

Q_1 = ______ var Q_2 = ______ var

Phase angle = ______ °

VOLTAGE REGULATION WITH RESISTIVE LOAD								
R Ω	X_C Ω	E_1 V	P_1 W	Q_1 var	E_2 V	P_2 W	Q_2 var	ANGLE °
∞								
4800								
2400								
1600								
1200								
960								
800								
686								

Table 5-2.

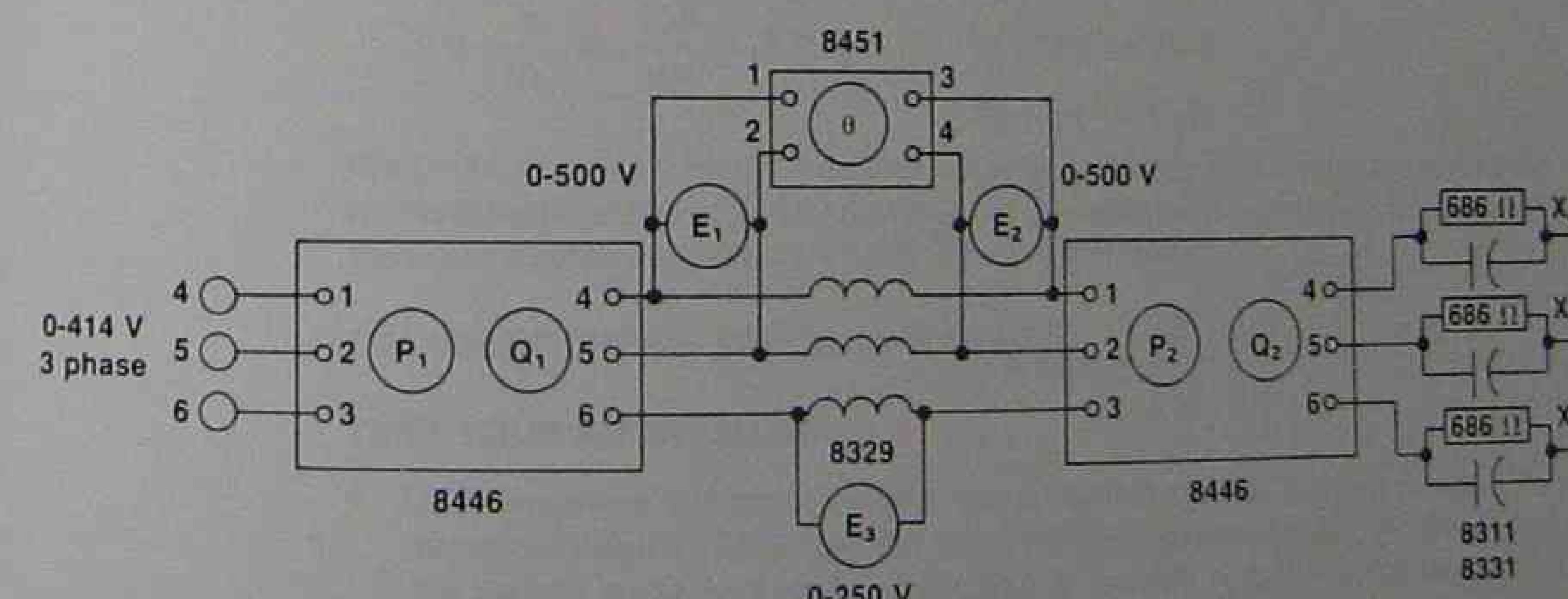


Figure 5-3.

☐ 5. Using the results of procedure step 4, calculate the voltage, current, real power and reactive power per phase. Draw a phasor diagram of the sender and receiver-end voltages, and verify the voltage drop against the measured value. (See sample calculation further in this experiment).

Sample Calculation

To understand the results of procedure step 4, we shall make a brief analysis assuming the following readings:

$E_1 = 350\ V$ $\quad E_2 = 350\ V$ $\quad E_3 = 165\ V$

$P_1 = +600\ W$ $\quad P_2 = +510\ W$

$Q_1 = +170\ var$ $\quad Q_2 = -280\ var$

Phase angle = 48° lag

We shall reduce all voltages and powers to a per-phase basis, assuming a star-connection. Since E_1 and E_2 are the line-to-line voltages, the corresponding line-to-neutral voltages are 0.577 $(1\sqrt{3})$ times the line-to-line voltages.

Real power Q_2 is smaller than P_1 because of the I^2R loss in the transmission line.

Furthermore, the source is delivering 170 var to the right, while the load (owing to the negative sign) is delivering 280 var to the left. As a result, the transmission line is absorbing (170 + 280) = 450 var.

The real and reactive powers per phase are ⅓ of the values indicated above. The per-phase values are therefore as follows:

$E_1/\sqrt{3} = 350/\sqrt{3} = 202\ V$

$E_2/\sqrt{3} = 350/\sqrt{3} = 202\ V$

$E_3 = 165\ V$

$P_1/3 = +200\ W$

$P_2/3 = +170\ W$

$Q_1/3 = +57\ var$

$Q_2/3 = -93\ var$

Phase angle = 48° lag

$$\frac{E_1}{\sqrt{3}} = 202\ V$$

$$\frac{E_2}{\sqrt{3}} = 202\ V$$

$$\frac{E_1}{\sqrt{3}} = \frac{E_2}{\sqrt{3}} = 164\ V$$

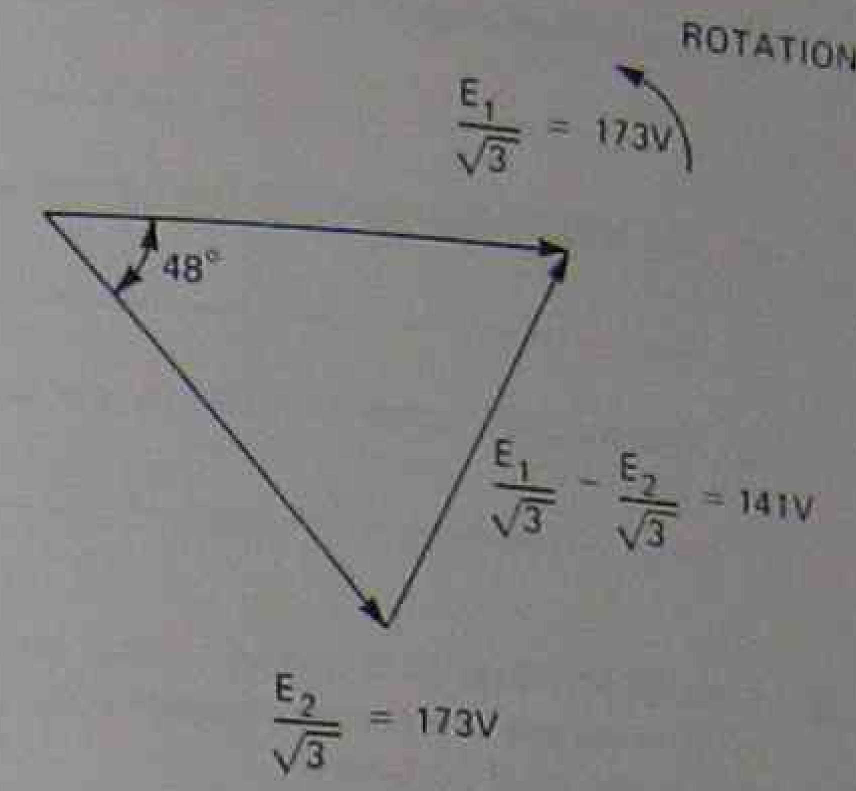


Figure 5-4.

If we draw phasor $E_2/\sqrt{3}$ 48 degrees behind phasor $E_1/\sqrt{3}$, we can scale off the length of the vector $(E_1/\sqrt{3}) - (E_2/\sqrt{3})$. It is found to be 164 V which is very close to the measured voltage drop E_3 in the line.

The reactive power received by the line (per-phase) is (93 + 57) = 150 var.

The real power consumed by the line due to its resistance is (200 − 170) = 30 W.

The apparent power absorbed by the line is $\sqrt{150^2 + 30^2} = 153$ VA.

Since the voltage drop across one line is 164 V, the current in the line must be

$$I = \frac{S}{E_3} = \frac{153}{164} = 0.933\ A$$

We could, of course, have measured this current directly, but a measurement of the real and reactive power and a knowledge of the voltages is sufficient to enable us to calculate everything about the line.

CALCULATIONS OF PROCEDURE STEP 5

TEST YOUR KNOWLEDGE

1. A three-phase transmission line has a reactance of 100 Ω per phase. The sender voltage is 100 kV and the receiver voltage is also regulated to be 100 kV by placing a bank of static capacitors in parallel with the receiver load of 500 MW. Calculate

   a) The reactive power furnished by the capacitor bank.

   ____

   b) The reactive power supplied by the sender.

   ____

c) The voltage drop in the line per phase.

____

d) The phase angle between the sender and receiver voltages.

____

e) The apparent power supplied by the sender.

____

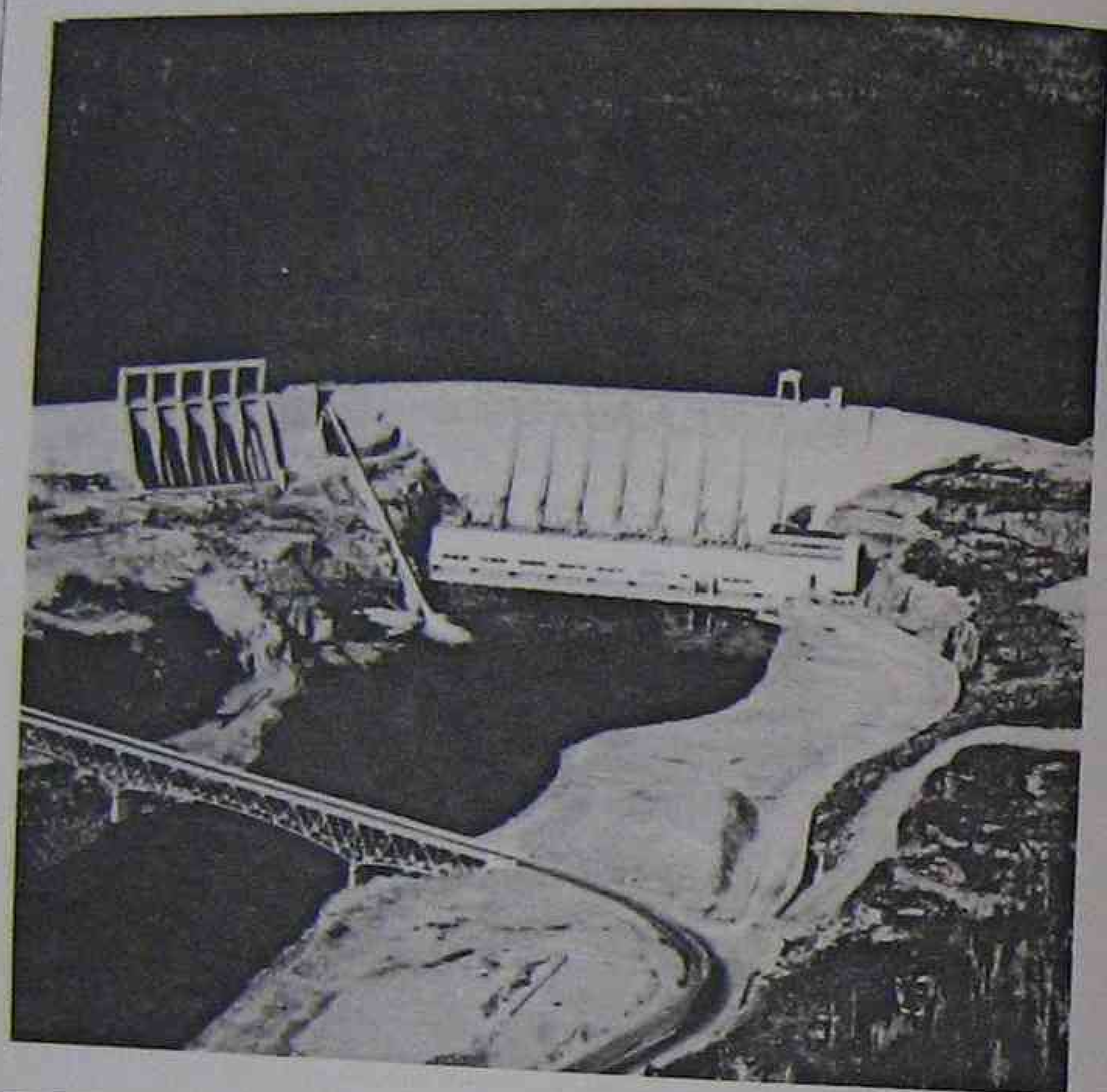
2. If the 50 MW load in Question 1 were suddenly disconnected calculate the receiver voltage which would appear across the capacitor bank. What precaution, if any, must be taken?

____
____
____

3. If a transmission line were purely resistive, would it be possible to raise the receiver end voltage by using static capacitors?

☐ Yes ☐ No

Explain ____
____
____



An aerial view of the Manicouagan Power Station N° 2 Quebec (Canada). The dam is 94 meters high, 692 meters wide and the water falls through a height of 72 meters.

Parameters which affect Real and Reactive Power Flow

OBJECTIVES

- To observe reactive power flow when sender and receiver voltages are different, but in phase.
- To observe real power flow when sender and receiver voltages are equal, but out of phase.
- To study the flow of real and reactive power when sender and receiver voltages are different and out of phase.

DISCUSSION

Transmission lines are designed and built to deliver electric power. Power flows from the generator (sender end) to the load (receiver end) but, in complex interconnected systems, the sender and receiver ends may become reversed. Power in such a line may flow in either direction depending upon the system load conditions which, of course, vary throughout the day. The character of the load also changes from hour to hour, both as to kVA loading and as to power factor. How, then, can we attempt to understand and solve the flow of electric power under such variable conditions of loading, further complicated by the possible reversal of source and load at the two ends of the line?

We can obtain meaningful answers by turning to the voltage at each end of the line. In Figure 6-1 a transmission line having a reactance of X Ω (per phase) has sending and receiving end voltages at E_1 and E_2 V respectively. If we allow these voltages to have any magnitude or phase relationship, we can represent any loading condition we please. In other words, by letting E_1 and E_2 take any values and any relative phase angle, we can cover all possible loading conditions which may occur.

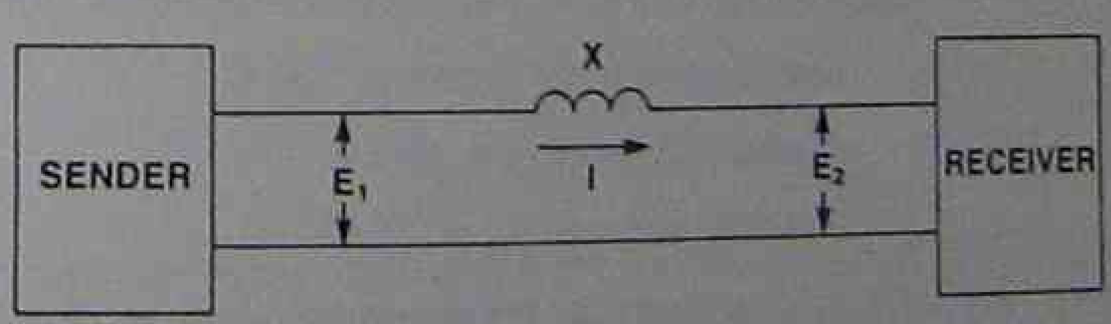


Figure 6-1.

Referring to Figure 6-1, the voltage drop along the line is $E_1 - E_2$; consequently, for a line having a reactance X, the current I can be found by the equation:

$$I = \frac{E_1 - E_2}{X}$$

when $E_1 - E_2$ is the *phasor* difference between the sending and receiving end voltage (refer to Figure 6-2). It should be borne in mind that we are dealing with phasors and that these have both an angle and a magnitude.

Note: *A transmission line is both resistive and reactive, but we shall assume that the reactance is so much larger that the resistance may be neglected.*

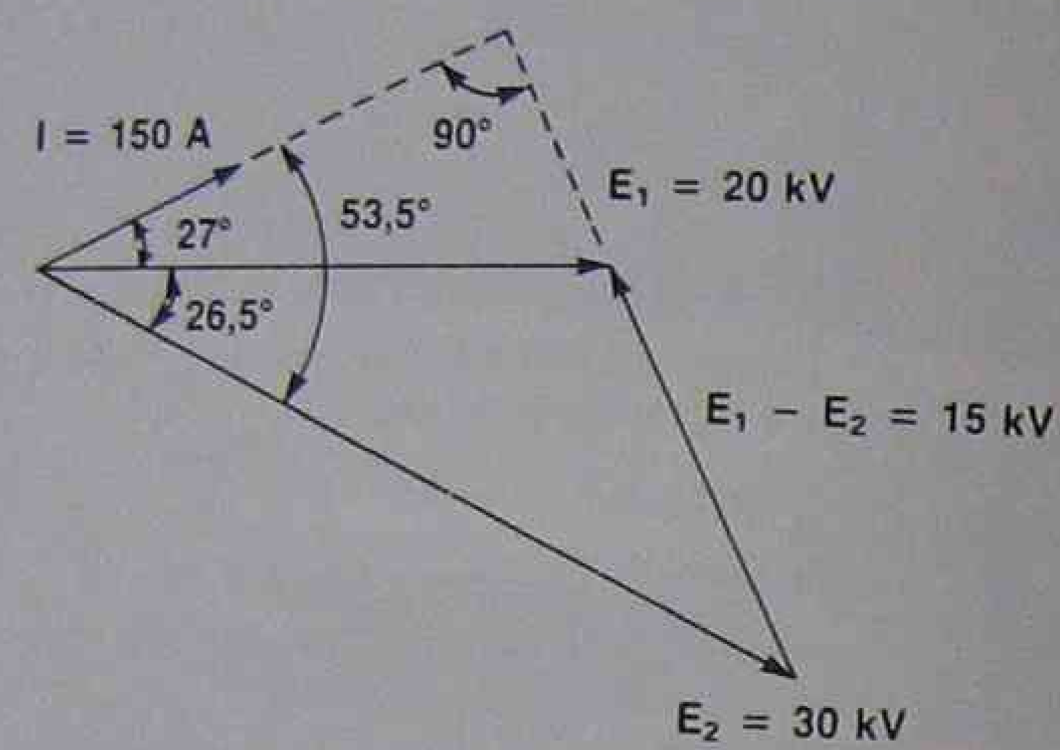


Figure 6-2.

Note: *When determining the sine and cosine of the angle between voltage and current, the current is always chosen as the reference phasor. Consequently, because E_1 lags behind I by 27°, the angle is negative.*

If we know the value of E_1 and E_2, and the phase angle between them, it is a simple matter to find the current I, knowing the reactance X of the line. From this knowledge we can calculate the real and reactive power which is delivered by the source and received by the load.

Suppose, for example, that the properties of a transmission line are as follows:

Line reactance per phase = 100 Ω

Sender voltage (E_1) = 20 kV

Receiver voltage (E_2) = 30 kV

Receiver voltage lags behind sender voltage 26,5°.

These line conditions are represented schematically in Figure 6-3. From the phasor diagram, on Figure 6-2, we find that the voltage drop ($E_1 - E_2$) in the line has a value of 15 kV. The current I has a value of 15 kV/100 Ω = 150 A and it lags behind ($E_1 - E_2$) by 90°. From the geometry of the figure, we find that the current leads E_1 by 27°. The active and reactive power of the sender and the receiver can now be found.

The real power delivered by the sender is

$$150\text{ A} \times 20\text{ kV} \times \cos(-27°) = +2670\text{ kW}.$$

The real power received by the receiver is

$$150\text{ A} \times 30\text{ kV} \times \cos(-53{,}5°) = +2670\text{ kW}.$$

The reactive power delivered by the sender is

$$150\text{ A} \times 20\text{ kV} \times \sin(-27°) = -1360\text{ kvar}.$$

The reactive power received by the receiver is

$$150\text{ A} \times 30\text{ kV} \times \sin(-53{,}5°) = -3610\text{ kvar}.$$

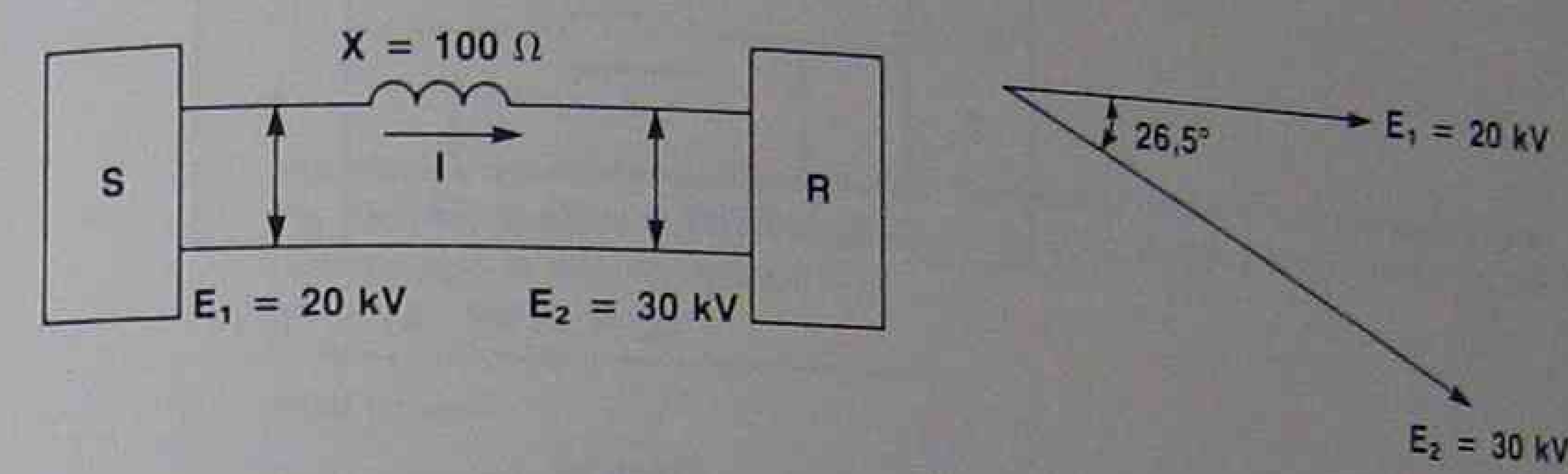


Figure 6-3.

Based upon the results calculated above, if wattmeters and varmeters were placed at the sender and receiver ends they would give readings as shown in Figure 6-4. This means that active power is flowing from the sender to the receiver, and owing to the absence of line resistance, none is lost in transit.

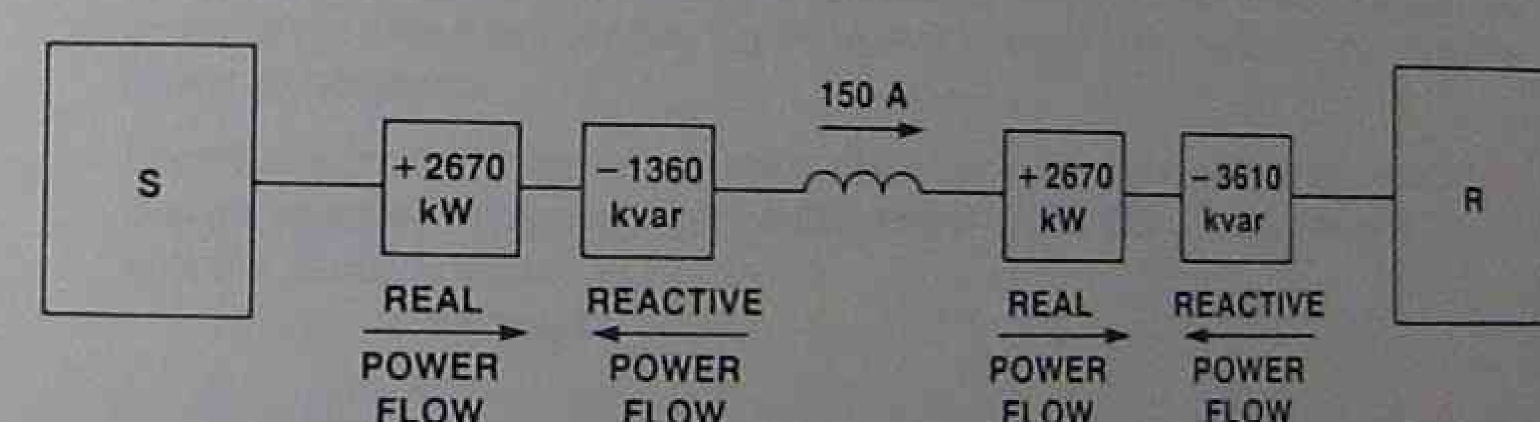


Figure 6-4.

However, reactive power is flowing from receiver to sender and, during transit, 3160 − 1360 = 2250 kvar are consumed in the transmission line. This reactive power can be checked against

$$\text{Line kvar} = I^2X = 150^2 \times 100 = 2250\text{ kvar}.$$

It will be noted that this is not the first time that we have found real power and reactive power flowing simultaneously in opposite directions.

Reactive Power

When the voltages at the sender and receiver ends are in phase, but unequal, reactive power will flow. The direction of flow is always from the higher voltage to the lower voltage.

Consider a transmission line in which the voltage at the sender and receiver ends are 30 kV and 20 kV respectively and the line reactance is 100 Ω (Figure 6-5).

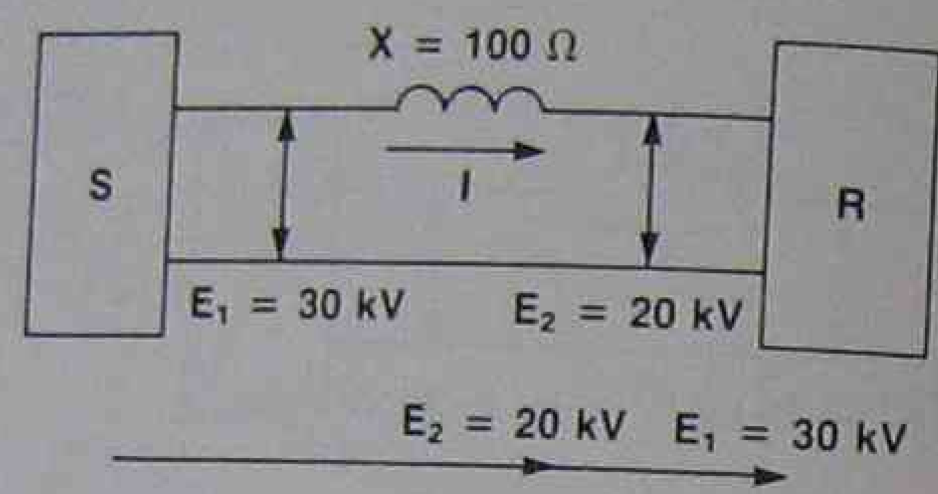


Figure 6-5.

The voltage drop in the line is 10 kV, and the current is 10 kV/100 = 100 A as shown in Figure 6-6.

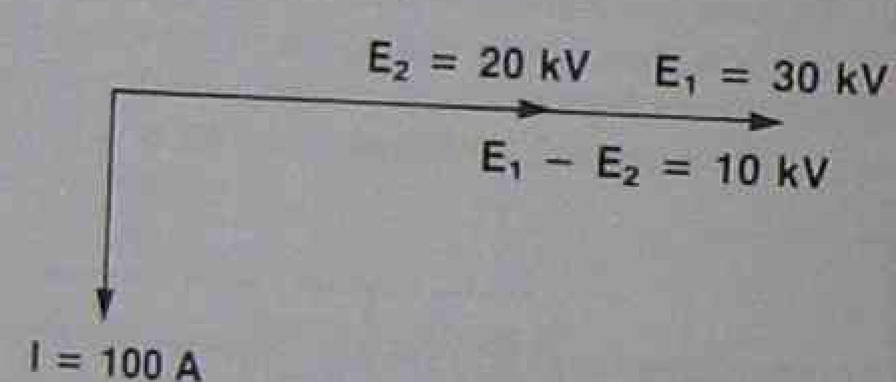


Figure 6-6.

The real power delivered by the sender end is

$100\ A \times 30\ kV \times \cos(+90°) = 0\ W.$

The real power received by the receiver is

$100\ A \times 20\ kV \times \cos(+90°) = 0\ W.$

The reactive power delivered by the sender end is

$100\ A \times 30\ kV \times \sin(+90°) = +3000\ kvar.$

The reactive power received by the receiver is

$100\ A \times 20\ kV \times \sin(+90°) = +2000\ kvar.$

If wattmeters and varmeters were placed at each end, the readings would be as shown in Figure 6-7.

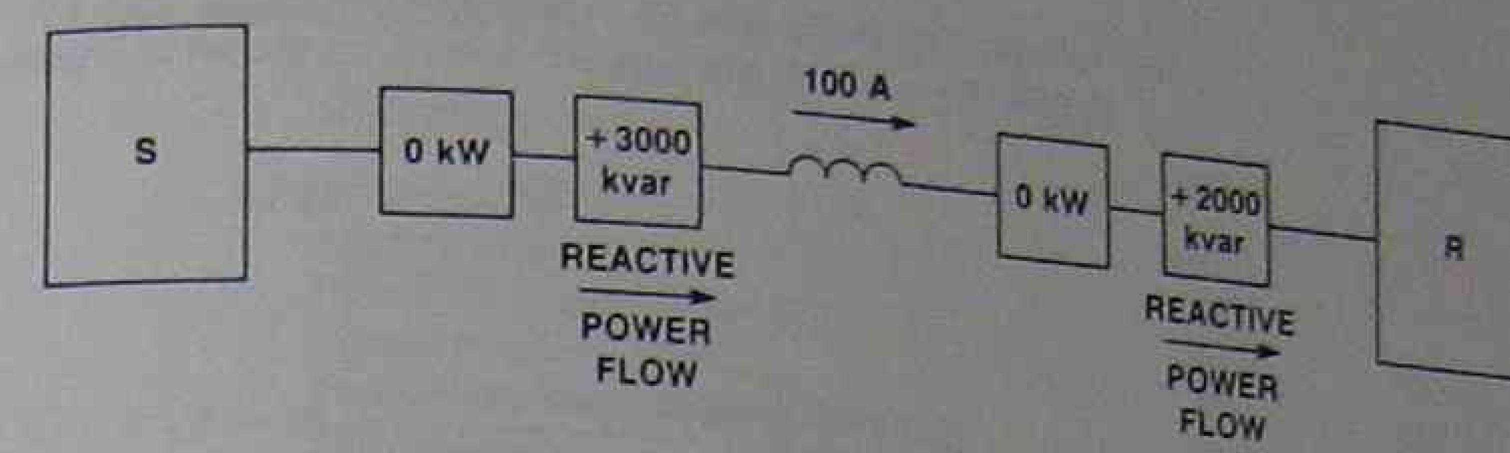


Figure 6-7.

Reactive power flows from the sender to the receiver, and 100 kvar are absorbed in the transmission line during transit. As can be seen, reactive power flows from the high-voltage to the low-voltage side.

Real power

Real power can only flow over a line if the sender and receiver voltages are out of phase. The direction of power flow is from the leading to the lagging voltage end. Again, it should be noted that this rule applies only to transmission lines which are principally reactive.

The phase shift between the sender and receiver voltages can be likened to an electrical "twist", similar to the mechanical twist which occurs when a long steel shaft delivers mechanical power to a load. Indeed, the greater the electrical "twist" the larger will the real power flow become. However, it is found that it attains a maximum when the phase angle between the sender and receiver ends is 90°. If the phase angle is increased beyond this (by increased loading) it will be found that less real power is delivered.

Consider a transmission line in which the voltages at each end are equal to 30 kV and the receiver voltage lags behind the sender by 30°. The line reactance is 100 Ω, and the circuit is shown in Figure 6-8.

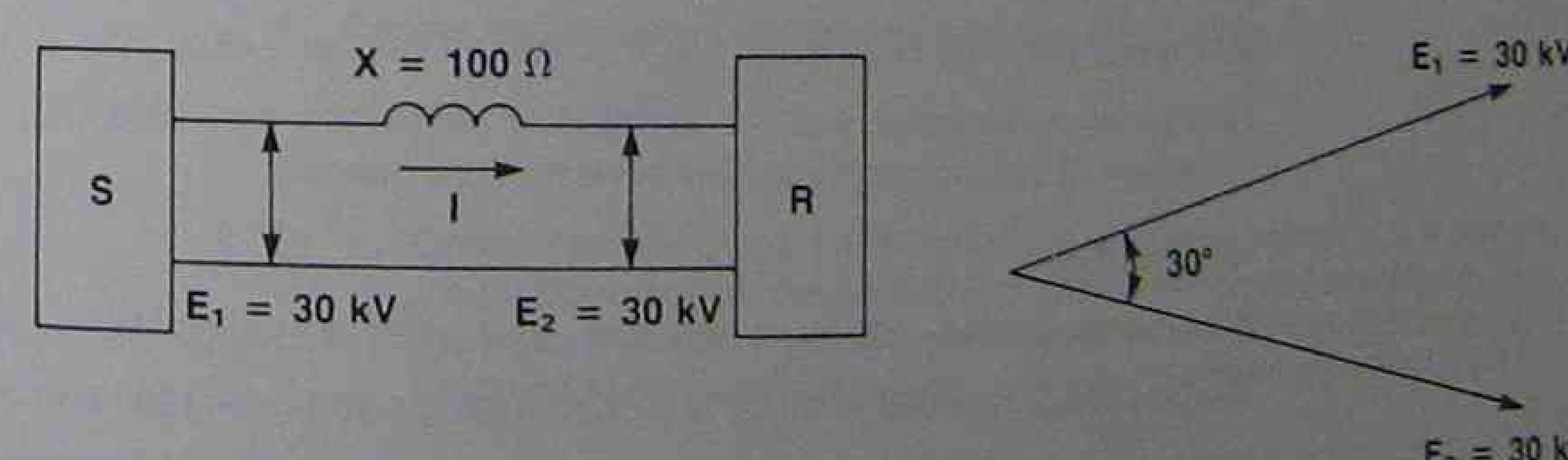


Figure 6-8.

The voltage drop in the line ($E_1 - E_2$) is found to be 15.5 kV, so the current $I = 15\,550/100 = 155$ A and lags 90° behind, as shown in Figure 6-9.

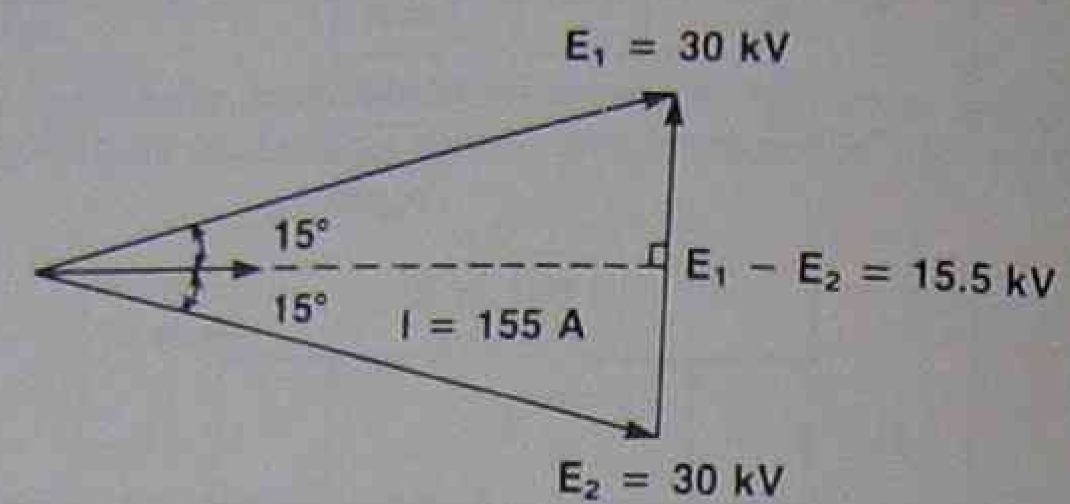


Figure 6-9.

Taking the current as the reference phasor, we can find the real and reactive power associated with the sender and the receiver end as shown in Figure 6-10.

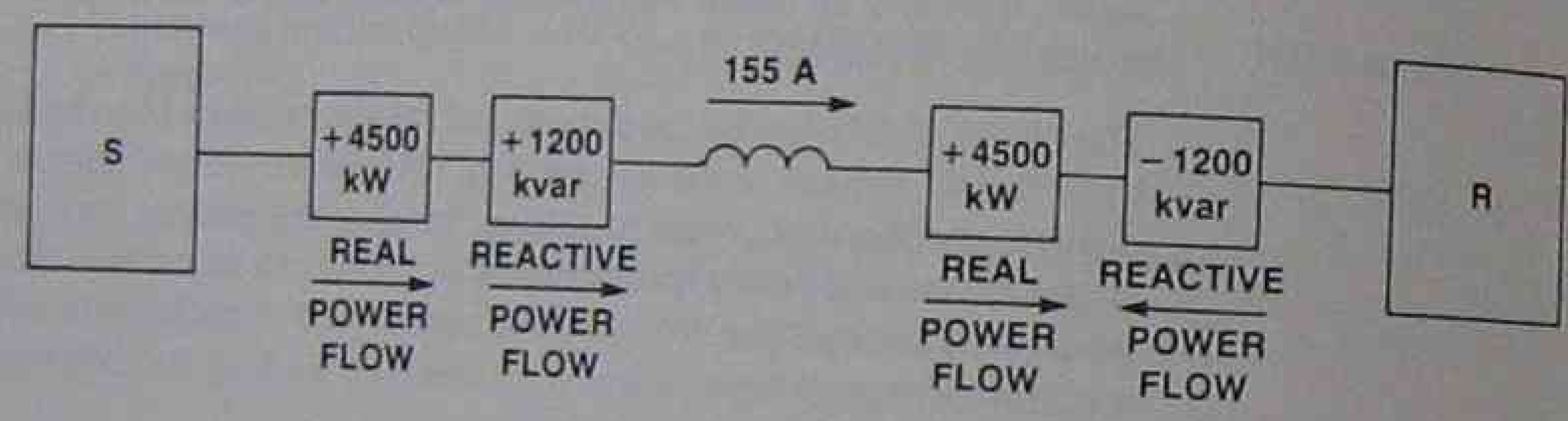


Figure 6-10.

Sender End

Real power delivered = 30 kV × 155 A × cos (+15°) = +4500 kW.

Reactive power delivered = 30 kV × 155 A × sin (+15°) = +1200 kvar.

Receiver End

Real power received = 30 kV × 155 A × cos (−15°) = +4500 kW.

Reactive power received = 30 kV × 155 A × sin (−15°) = −1200 kvar.

The sender delivers both active and reactive power to the line and the receiver absorbs active power from it. However, the receiver delivers reactive power to the line, so that the total reactive power received by the line is 2400 kvar.

This example shows that a phase shift between sender and receiver voltages causes both real and reactive power to flow. However, for angles smaller than 45° the real power considerably exceeds the reactive power.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Resistive Load	8311
Inductive Load	8321
Three-Phase Transmission Line	8329
Capacitive Load	8331
Three-Phase Regulating Autotransformer	8349
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Phase Meter	8451
Power Supply	8821
Connection Leads	9128

PROCEDURE

Note: *These experiments may be carried out by two collaborating groups.*

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

In order to convey a sense of realism to the terms "sender" and "receiver" two consoles manned by two student groups will be used in the following experiments. A transmission line will connect the two consoles (Station A and B) and the active and reactive power flow between them will be studied. The experiment will be conducted in three parts.

1. Sender and Receiver voltages unequal, but in phase.
2. Sender and Receiver voltages equal, but out of phase.
3. Sender and Receiver voltages unequal, and out of phase.

Sender and Receiver voltages unequal, but in phase

☐ 1. Connect a three-phase transmission line between terminals 4, 5, 6 (variable AC output) of two consoles, one of which is designated as station A and the other, station B. Connect the two Three-Phase Wattmeter/Varmeters at each end as well as a Phase Meter as shown schematically in Figure 6-11.

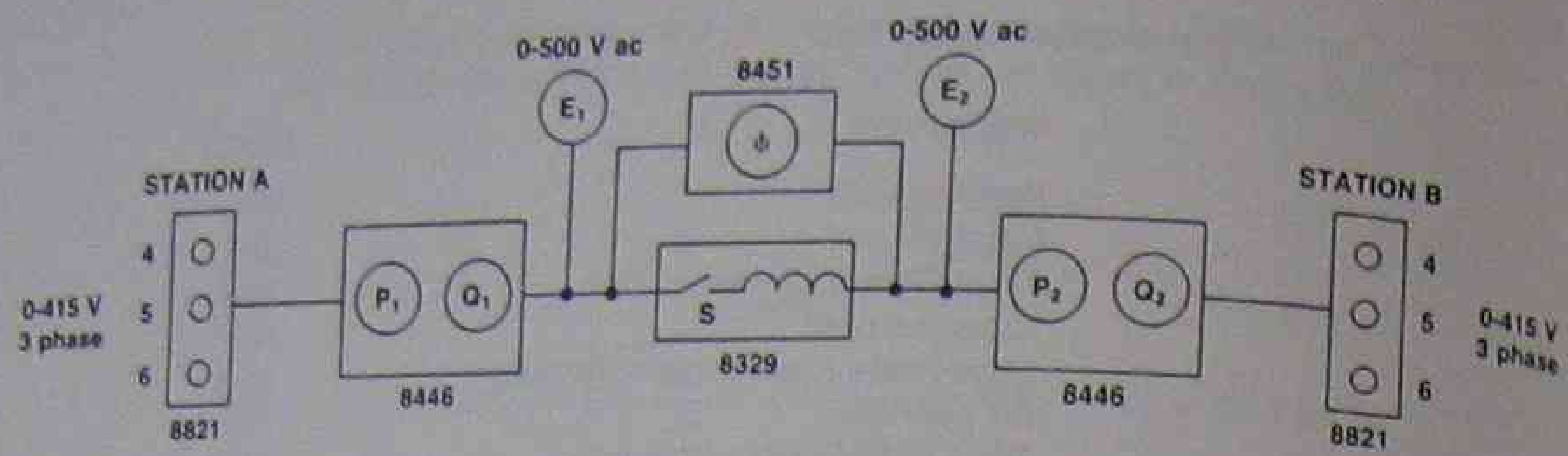


Figure 6-11.

☐ 2. With the transmission line switch S open, adjust the line-to-line voltages so that E_1 and E_2 are both equal to 370 V and observe that the phase angle is zero between terminals 4-5 of station A and terminals 4-5 of station B. (If the phase angle is not zero, see procedure step 8 of Experiment 2).

Is phase angle zero?

☐ Yes ☐ No

☐ 3. Without making any changes, measure the phase angle between terminals 4-5 of station A and terminals 5-4 of station B.

☐ Phase angle lag ☐ Phase angle lead

☐ 4. Without making any changes, measure the phase angle between terminals 4-5 of station A and terminals 5-6 of station B.

☐ Phase angle lag ☐ Phase angle lead

☐ 5. Measure the phase angle between terminals 4-5 of station A and terminals 6-4 of station B.

☐ Phase angle lag ☐ Phase angle lead

☐ 6. By measuring all phase angles between line and neutral of station A and B prove that the phasor diagram for both stations is as given in Figure 6-12.

The purpose of this preliminary phase angle check is to familiarize ourselves with the phase angles between the voltages at the two stations.

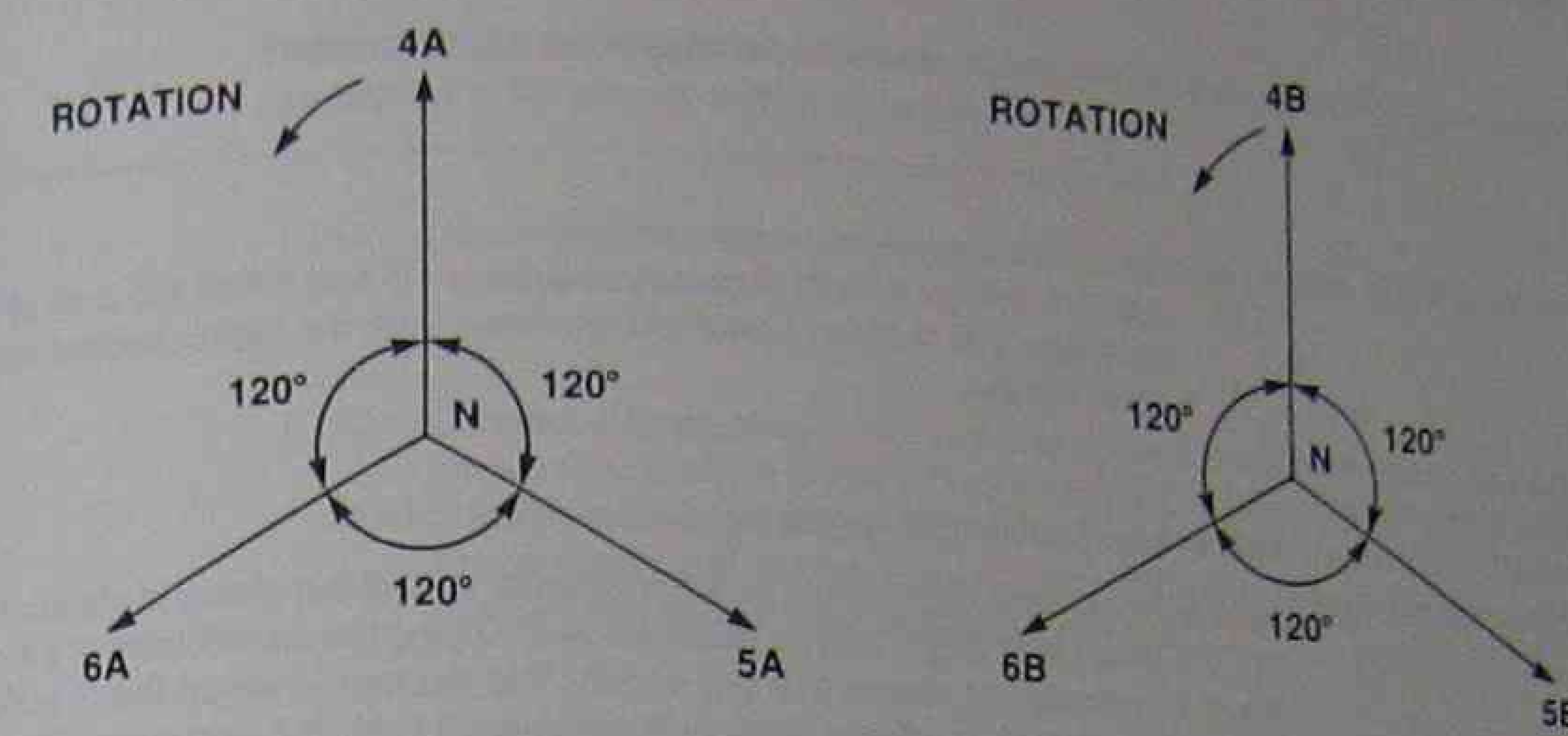


Figure 6-12.

☐ 7. Close the Three-Phase Transmission Line switch; with $E_1 = E_2 = 370$ V, and the transmission line impedance = 200 Ω, observe the Three-Phase Wattmeter/Varmeter readings. There should be no significant power exchange.

P_1 = _______ W

P_2 = _______ W

Q_1 = _______ var

Q_2 = _______ var

☐ 8. Raise station A voltage to 415 V and observe power flow.

P_1 = _______ W

P_2 = _______ W

Q_1 = _______ var

Q_2 = _______ var

Which of the two stations would be considered to be the sender?

____

☐ 9. Reduce station A voltage to 350 V and observe power flow.

P_1 = _______ W

P_2 = _______ W

Q_1 = _______ var

Q_2 = _______ var

Which station would be considered to be the sender?

____

☐ 10. Vary the voltage of both station A and station B and check the truth of the statement that reactive power always flows from the higher voltage to the lower voltage.

Sender and Receiver voltages equal, but out of phase

Use the Three-Phase Regulating Autotransformer to shift the phase of station A by 15°. The phase shift (lag or lead) is obtained by changing the connections of a three-phase transformer by means of a tap switch. The manner in which this is accomplished is explained in greater detail in Experiment 11; for our purposes it is sufficient to know that when the position of the tap-switch is altered, the secondary voltage will either a) be in phase with the primary, b) lag the primary by 15° or, c) lead the primary by 15°.

☐ 11. Connect the phase-shift of the above autotransformer to the variable AC terminals 4, 5, 6 of station A. Adjust the voltage at stations A and B to 380 V with the Phase Meter. Determine the phase angle of the secondary voltage 4, 5, 6 with respect to the variable AC terminals 4, 5, 6 of the Power Supply of station B (see Figure 6-13). Record your readings for the three positions of the phase-shift tap switch in Table 6-1.

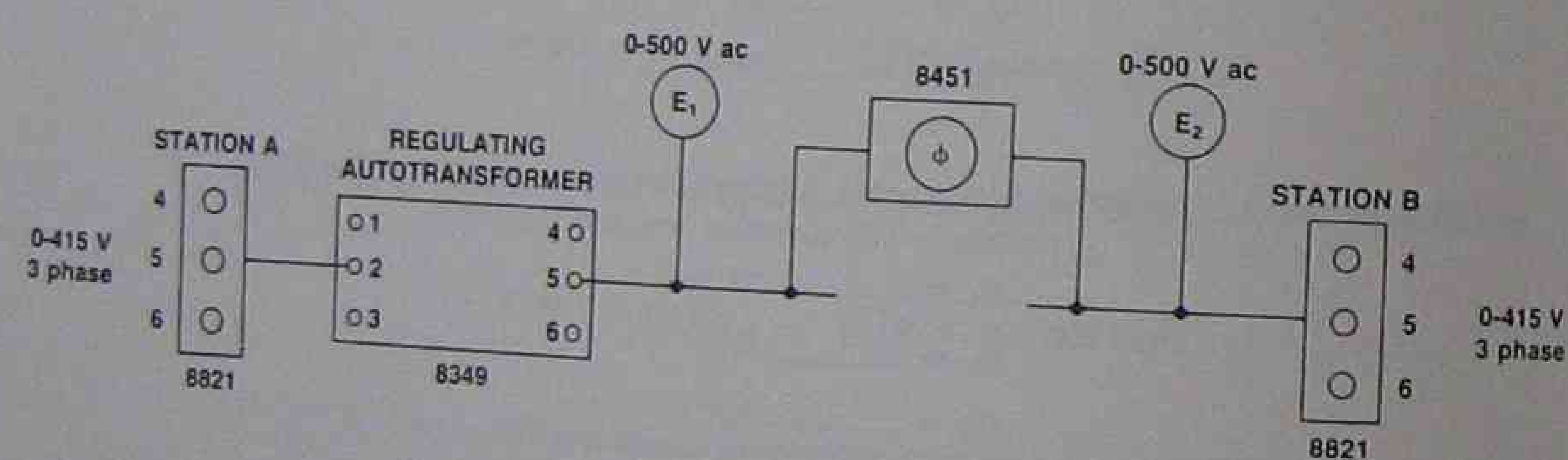


Figure 6-13.

TAP SWITCH POSITION	PHASE ANGLE (LAG/LEAD)	E_1	E_2
°	—	V	V
0			
+15			
−15			

Table 6-1.

Note: *The buck-boost tap switch must be kept at zero and the correct phase sequence must be applied to the primary of the transformer.*

☐ 12. Check that the phase-shift is the same for all three phases, and that all voltages are balanced.

☐ 13. Connect a three-phase, 400 Ω transmission line between secondary terminals 4, 5, 6 of the Three-Phase Regulating Autotransformer and Power Supply terminals of station B (see Figure 6-14). After inserting the Three-Phase Wattmeter/Varmeter at each end of the line, change the tap switch position and record your results in Table 6-2.

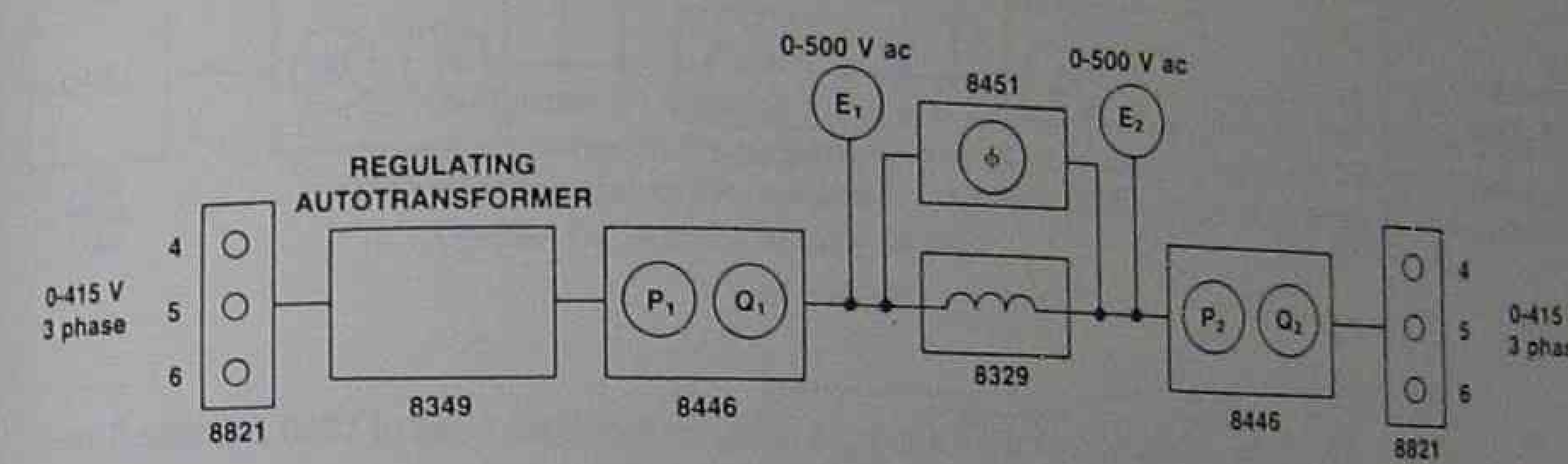


Figure 6-14.

TAP SWITCH POSITION	E_1	P_1	Q_1	E_2	P_2	Q_2	PHASE ANGLE
°	V	W	var	V	W	var	°
0							
+15							
−15							

Table 6-2.

Does this experiment bear out the statement that real power flows from the leading towards the lagging voltage side of a transmission line?

☐ Yes ☐ No

Sender and Receiver voltages unequal, and out of phase

In the following procedure steps we shall connect passive loads (resistive, inductive, and capacitive) at the receiver end of the line. The object of the experiment is to show that a phase shift between sender and receiver voltage occurs only when real power is being delivered to the load.

☐ 14. Using only one console, set up the experiment as shown in Figure 6-15, setting E_1 = 415 V and using a star-connected Resistive Load of 1200 Ω per phase and a 200 Ω Transmission Line. Take readings and record your results in Table 6-3.

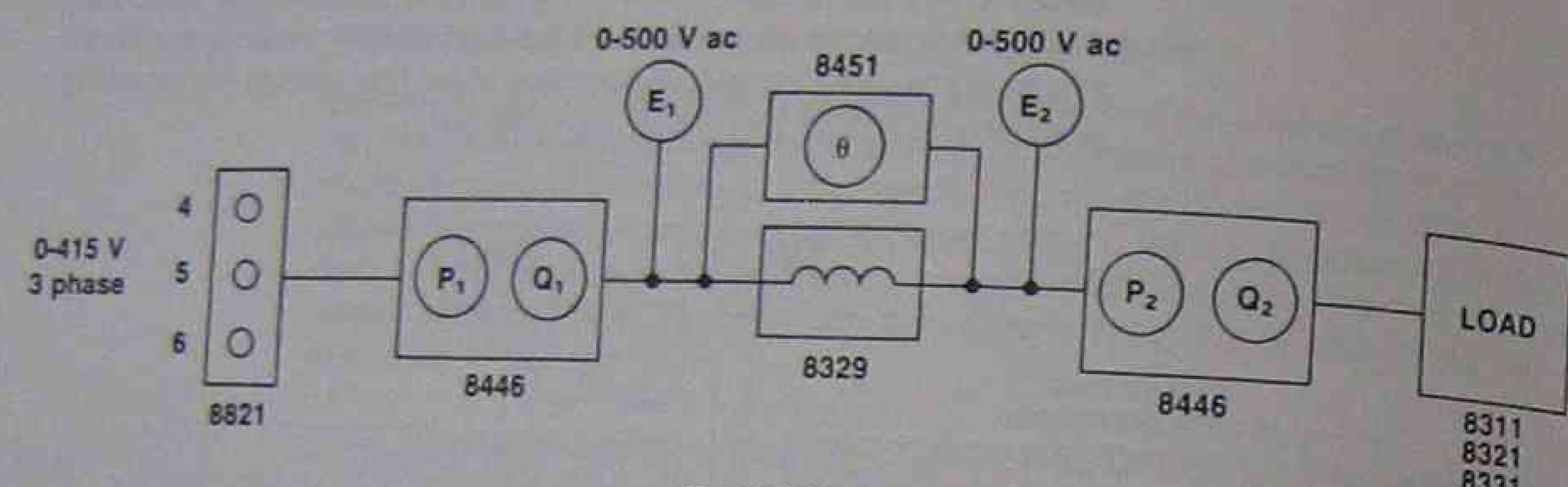


Figure 6-15.

☐ 15. Repeat procedure step 14 using an Inductive Load of 1200 Ω/phase. Take readings and record your results in Table 6-3.

☐ 16. Repeat procedure step 14 using a Capacitive Load of 1200 Ω/phase. Take readings and record your results in Table 6-3.

PROC. STEP	LOAD	E_1	P_1	Q_1	E_2	P_2	Q_2	PHASE SHIFT
		V	W	var	V	W	var	°
14	RESISTIVE							
15	INDUCTIVE							
16	CAPACITIVE							

Table 6-3.

TEST YOUR KNOWLEDGE

1. A three-phase transmission line has a reactance of 100 Ω and at different times throughout the day it is found that the sender and receiver voltages have magnitude and phase angles as given in Table 6-4.

   In each case calculate the real and reactive power of the sender and receiver and indicate the direction of the power flow. The voltages given are line-to-line.

E_S	E_R	PHASE ANGLE		SENDER		RECEIVER	
kV	kV			P	Q	P	Q
				MW	Mvar	MW	Mvar
100	100	60°	E_S LEADS E_R				
120	100	60°	E_S LEADS E_R				
100	120	60°	E_S LEADS E_R				
120	100	30°	E_S LAGS E_R				
120	100	0°					

Table 6-4.

2. In Question 1 assume that $E_S = E_R$ = 100 kV at all times but that the phase angle between them changes in steps of 30° according to the Table 6-5. Calculate the value of the real power in each case as well as its direction of flow, knowing that E_R lags E_S in each case.

φ	SENDER P	RECEIVER Q
°	MW	MW
0		
30		
60		
90		
120		
150		
180		

Table 6-5.

Plot a graph of real power vs phase angle on Figure 6-16.

Is there a limit to the maximum power which such a line can deliver under the static voltage conditions?

☐ Yes ☐ No

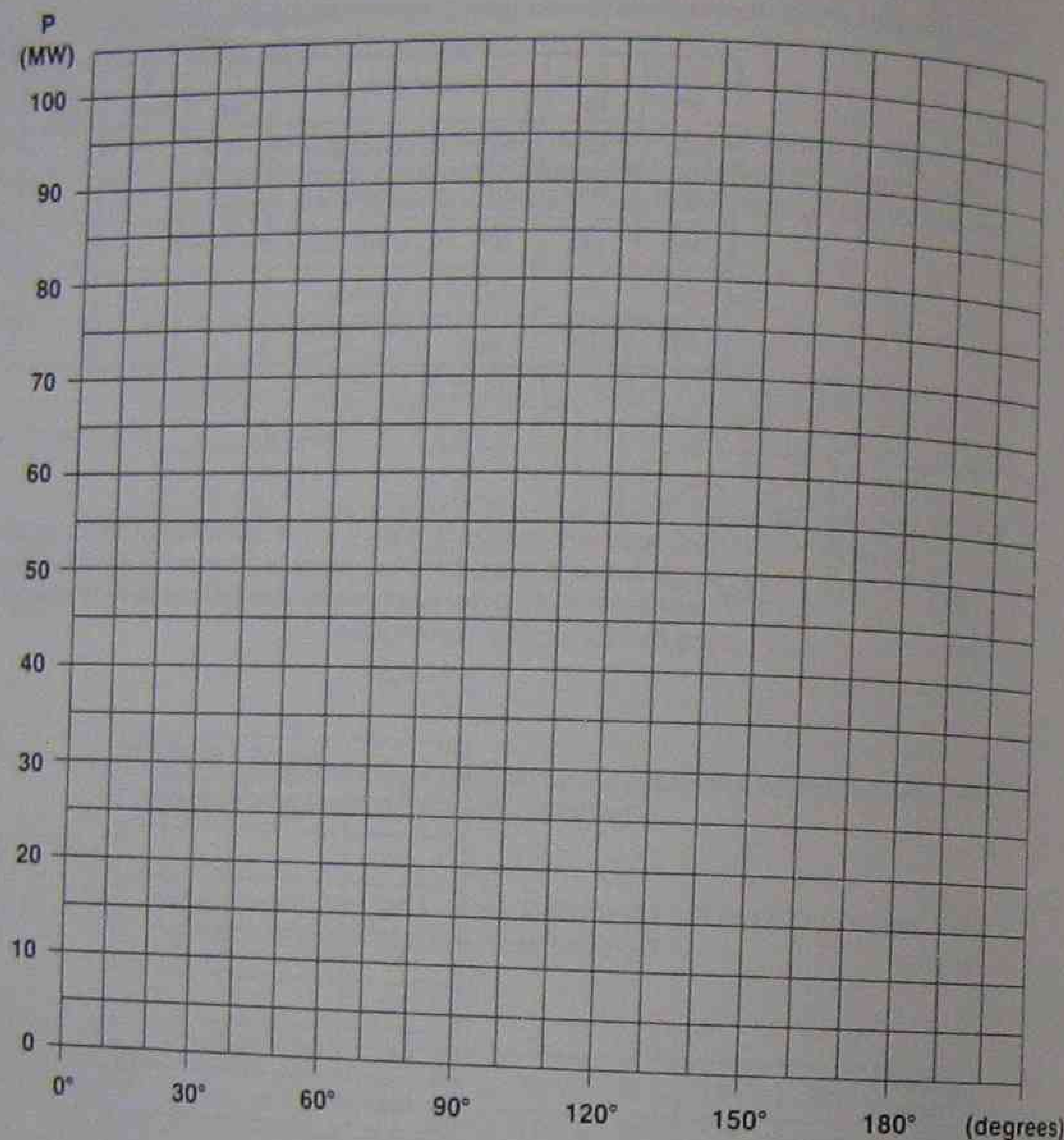
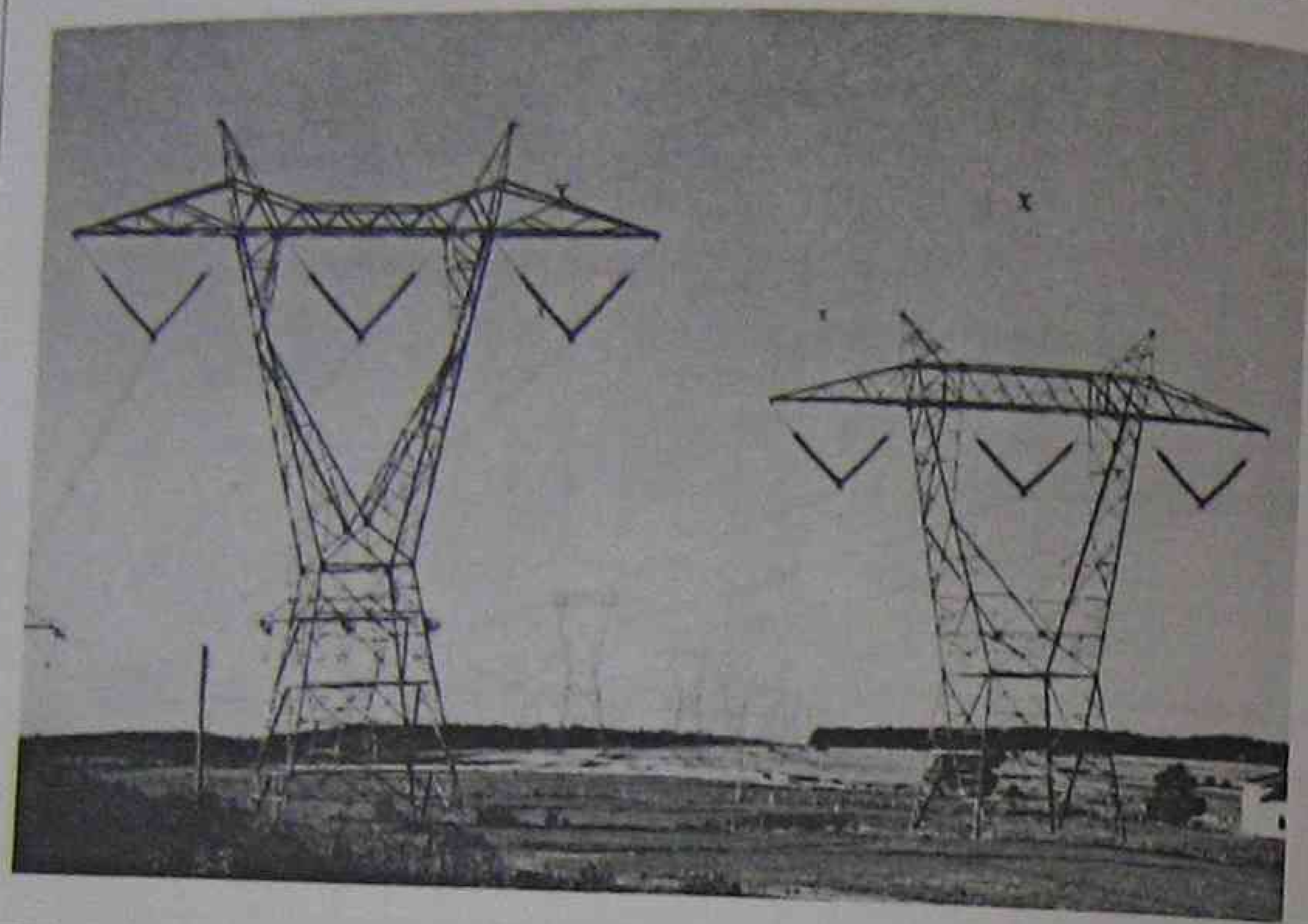


Figure 6-16.



Two three-phase lines side by side enable a larger power flow and improve stability of the system.

Experiment 7

Parallel Lines, Transformers and Power-Handling Capacity

OBJECTIVES

- Study of the real power vs phase angle curve of a transmission line.
- Use of transformers to increase the power-handling capacity of a line.
- Transmission lines in parallel.

DISCUSSION

The real power which can be delivered by a transmission line depends upon the voltages at the sender and receiver ends and the phase angle between them. The real power P of a three-phase line is given by the equation:

$$P = \frac{E_1 - E_2}{X} \sin \phi$$

in which P = total power delivered by the sender to the receiver, in watts.

E_1 = sender end line-to-line voltage, in volts.

E_2 = receiver end line-to-line voltage, in volts.

X = reactance per phase, in ohms.

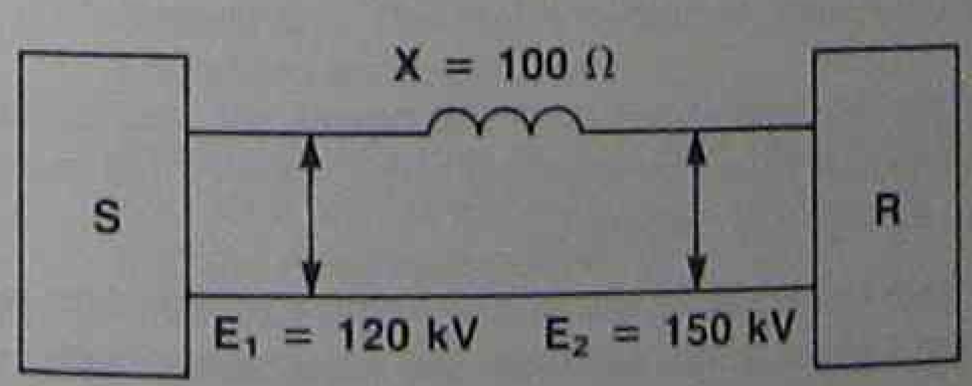
ϕ = phase angle between E_1 and E_2.

If E_2 lags behind E_1, ϕ is positive.

If E_2 leads E_1, ϕ is negative.

The use of this equation is best illustrated by a simple example. On Figure 7-1, a line having a reactance of 100 Ω per phase has a line-to-line sender voltage of 120 kV and a corresponding receiver voltage of 150 kV. If the receiver voltage lags the sender by 30°, calculate the total power delivered by the three-phase line.

Solution:



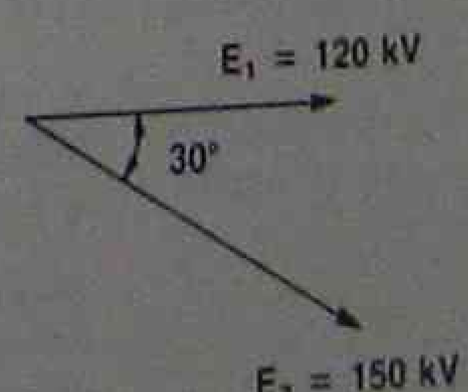


Figure 7-1.

Because the sender voltage leads the receiver voltage, the angle ϕ is positive, hence:

$$P = \frac{E_1 - E_2}{X} \sin\phi$$

$$= \frac{120\ kV \times 150\ kV}{100} \sin(+30°)$$

$$= 90\,000\,000\ W$$

$$= 90\ MW$$

If the sender and receiver voltages are held constant (a situation which is closely met in practice), the power delivered will be dependent on the phase angle ϕ. This relationship between the power P and the angle ϕ is given in Figure 7-2.

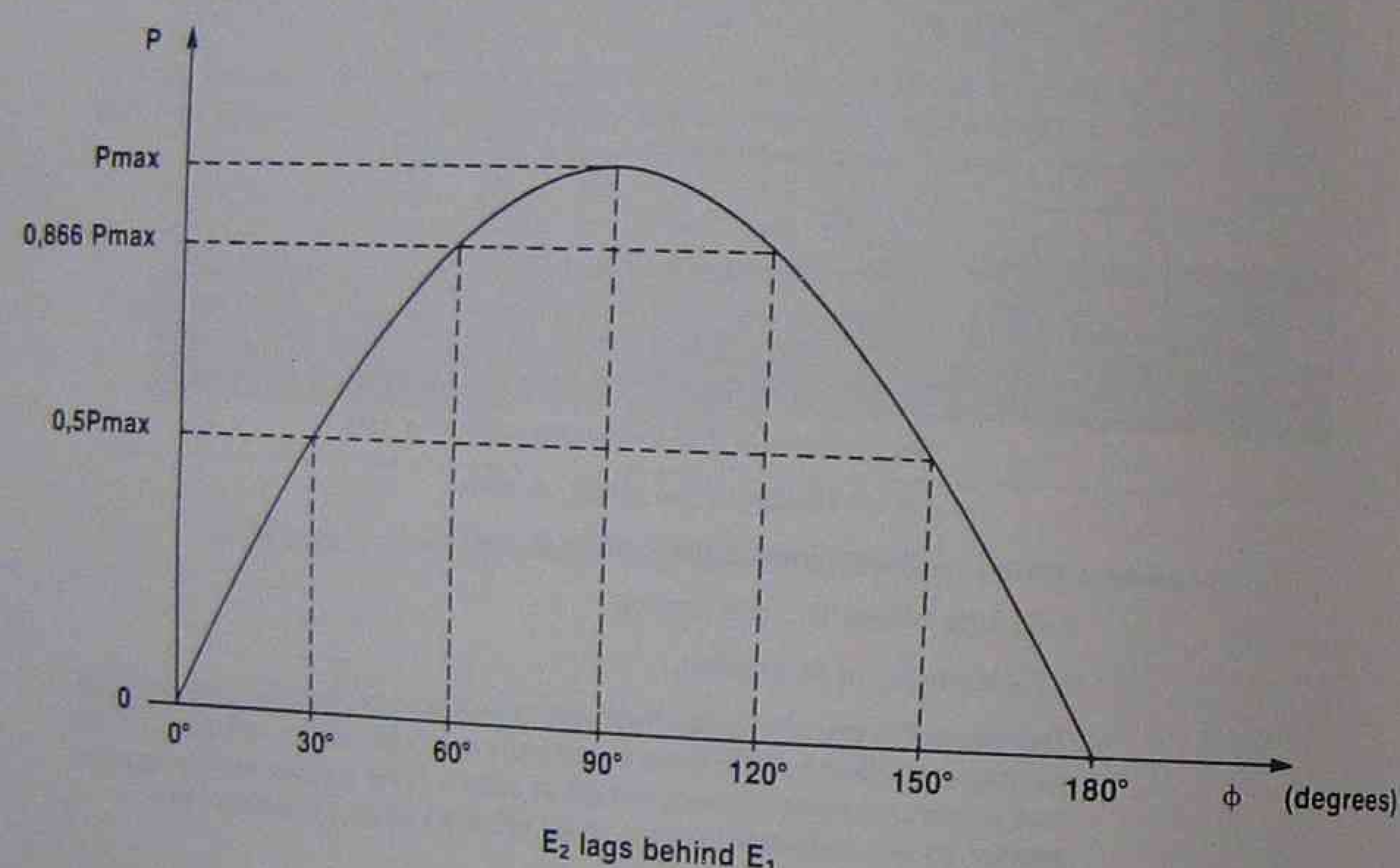


Figure 7-2.

As the phase angle increases from zero, the power, too, increases gradually, and attains a maximum value Pmax for an angle of 90°. One-half of this maximum power is attained when E_2 lags 30° behind E_1.

As we can see from the figure, if the phase angle exceeds 90°, power will still be delivered from the sender to the receiver, but it decreases with increasing angle. Indeed, the power falls to zero when the phase angle is 180°.

When the phase angle exceeds 90°, the transmission line is in an unstable condition, and the power will either fall to zero or it will move to another point (between 0 and 90°) on the power vs phase angle curve.

Consequently, steady, reliable power can only be transmitted from sender to receiver when the phase angle is between zero and 90°. The maximum power which can be transmitted is

$$Pmax = \frac{E_1 E_2}{X} \sin 90° = \frac{E_1 E_2}{X}$$

It should be noted that any phase angle can exist between zero and 360° or, which is the same thing, between 0° and 180° lag, and 0° and 180° lead. If the power vs phase angle curve is extended to cover all possible angles, we obtain the curve shown in Figure 7-3.

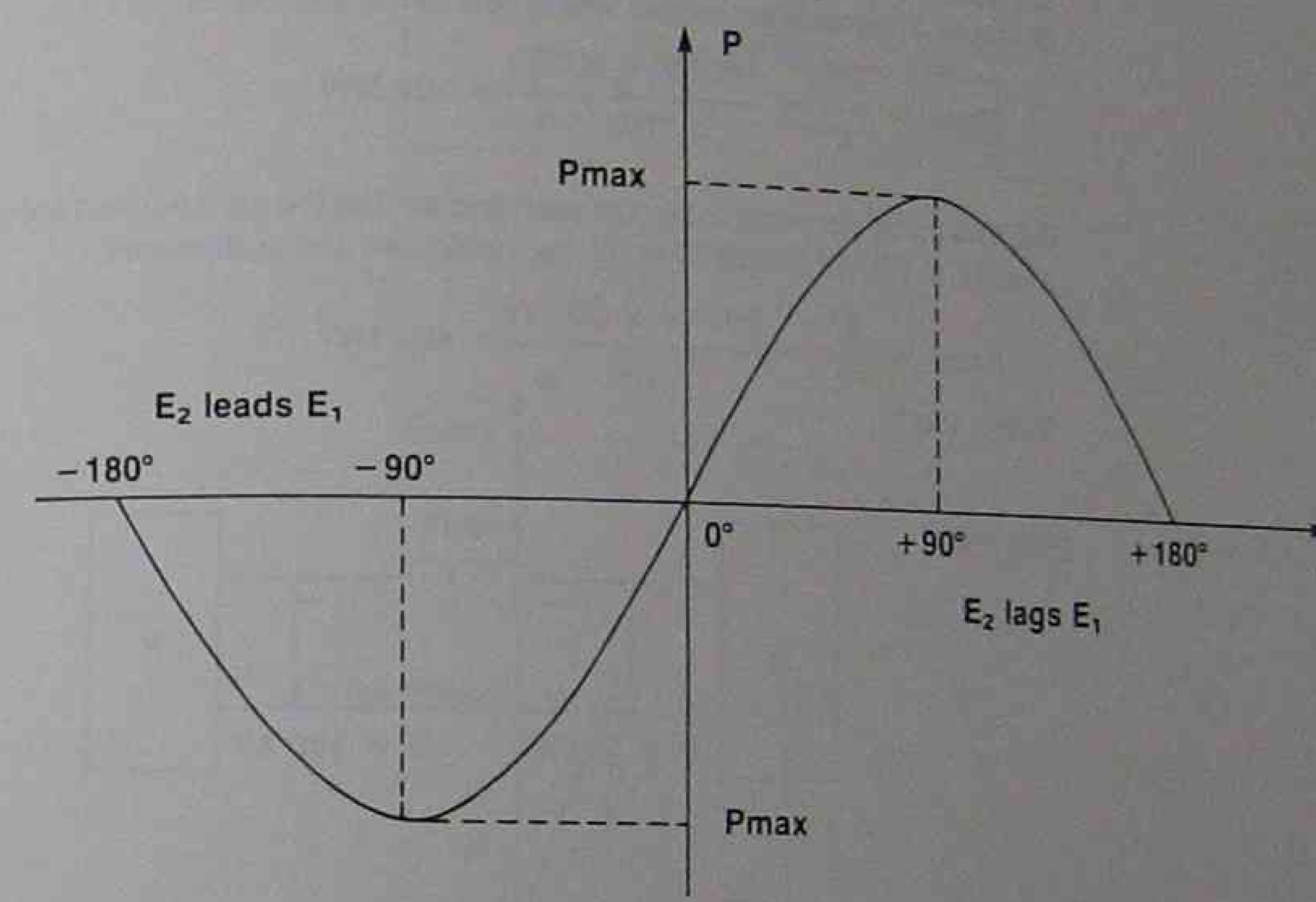


Figure 7-3.

If the angle is between zero and +180° the sender is delivering power to the receiver, but when the angle is between zero and −180°, the receiver is delivering power to the sender. Note that an angle of −90° merely indicates that E_2 is leading E_1. The stable region is between −90 and +90°; it is the only region of interest to us at this time.

In most cases, the sender and receiver voltages are about equal in magnitude, so that if we let $E_1 = E_2 = E$, where E is the transmission line voltage, we find that the maximum power

$$Pmax = \frac{E^2}{X} W$$

Transmission Line Voltage

Because the maximum power which a line can deliver depends upon the square of the transmission line voltage E, it is not surprising that high voltages are employed when large blocks of power have to be transmitted. Thus, if the line voltage is doubled, the maximum power is quadrupled.

The line voltage can be raised by introducing a step-up transformer at the sender end and a similar step-down transformer at the receiver end. As a result, by using a transformer at each end of a transmission line its power-handling capacity can be significantly improved.

In Figure 7-4 a), a sender and a receiver are connected by a line having a reactance of 100 Ω. The maximum power which can be transmitted is

$$Pmax = \frac{E^2}{X} = \frac{100\text{ kV} \times 100\text{ kV}}{100} = 100\text{ MW}$$

But if we introduce transformers at each end so that the transmission line voltage is doubled to 200 kV, (Figure 7-4 b)) the maximum power becomes

$$Pmax = \frac{E^2}{X} = \frac{200\text{ kV} \times 200\text{ kV}}{100} = 400\text{ MW}$$

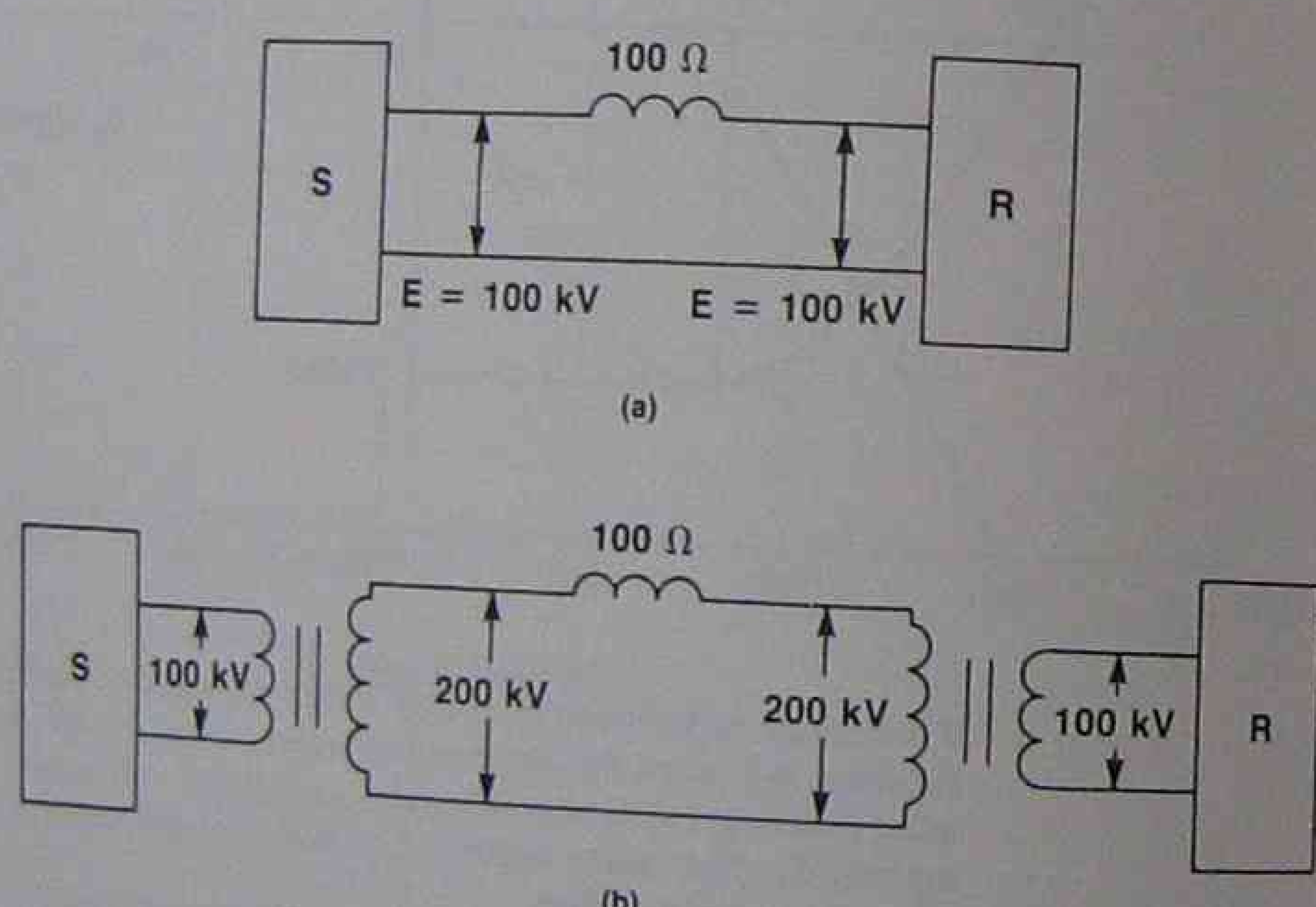


Figure 7-4.

Transmission Lines in Parallel

Another way by which increased power can be transmitted from a sender to a receiver is to employ two 3-phase lines in parallel. The two transmission lines may be supported on the cross-arms of the same transmission towers, or two entirely separate lines may be employed.

Two similar lines which are in parallel can obviously carry twice the maximum power of one line alone. (See Figure 7-5.) The power curves for one line and for two lines are shown in Figure 7-6. If both lines are in service and the power transmitted is 0,5 Pmax, the phase angle between the sender and receiver voltages is only 30°, which corresponds to a very stable operating point. The link between S and R is said to be "stiff".

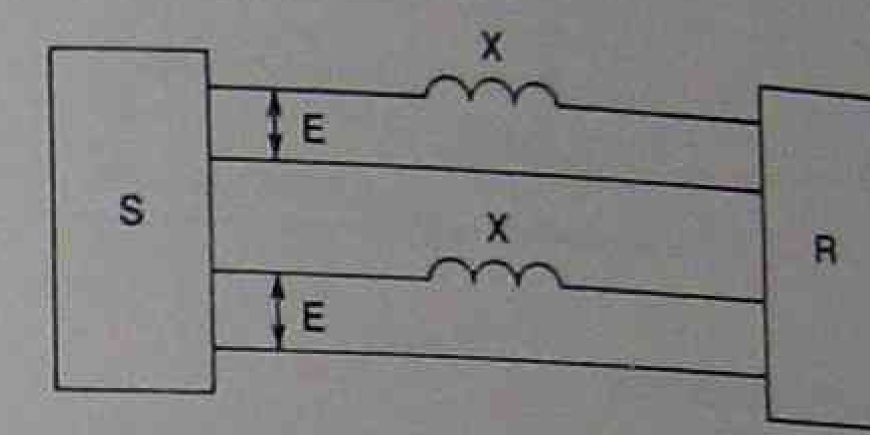


Figure 7-5.

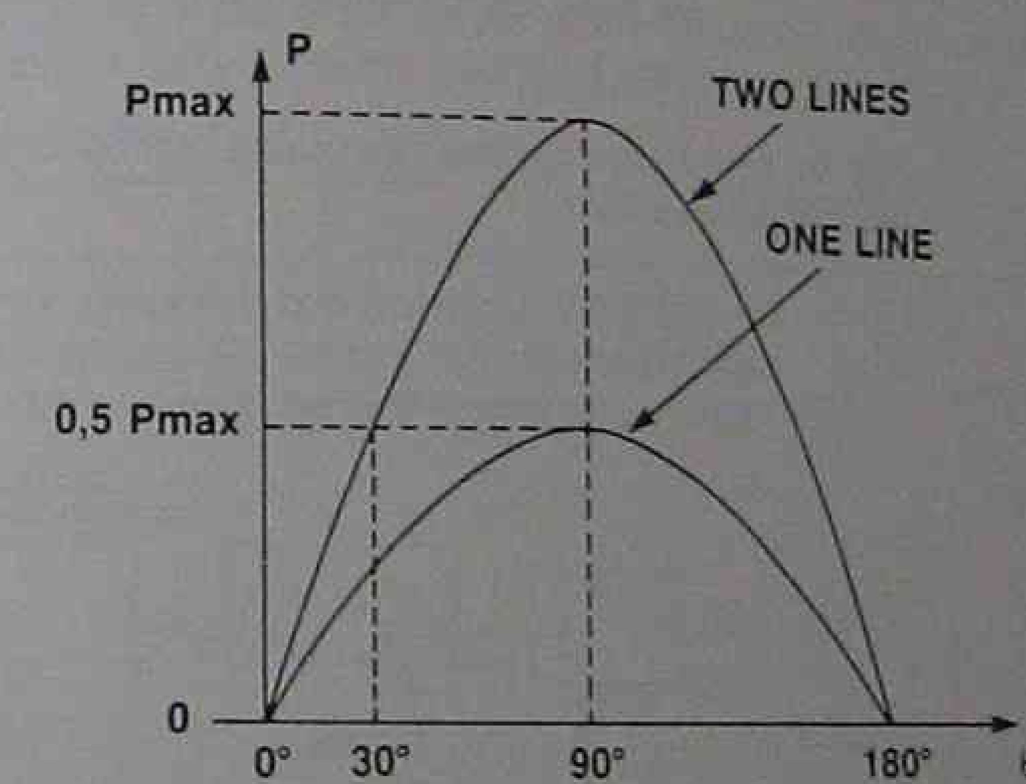


Figure 7-6

However, if one of the lines is suddenly switched out, either by error or due to a fault-clearing action, the power has to be carried by the remaining line. But as we can see from Figure 7-6, 0,5 Pmax corresponds, on the single transmission line, to an angle of 90° which is just on the edge of unstability. In all likelihood the remaining line will be unable to carry the load and its breakers will open, unless the other line is quickly brought back into service.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Three-Phase Synchronous Motor/Generator	8241
Three-Phase Transmission Line	8329
Three-Phase Transformer	8348
Three-Phase Regulating Autotransformer	8349
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Inertia Wheel	8915
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

The first part of this experiment involves a number of problems while the second is a laboratory experience.

☐ 1. On Figure 7-7, stations A and B are linked by a transmission line having a certain reactance X. From the value of the line-to-line voltages, given in the Table 7-1, determine the real power and the direction of its flow.

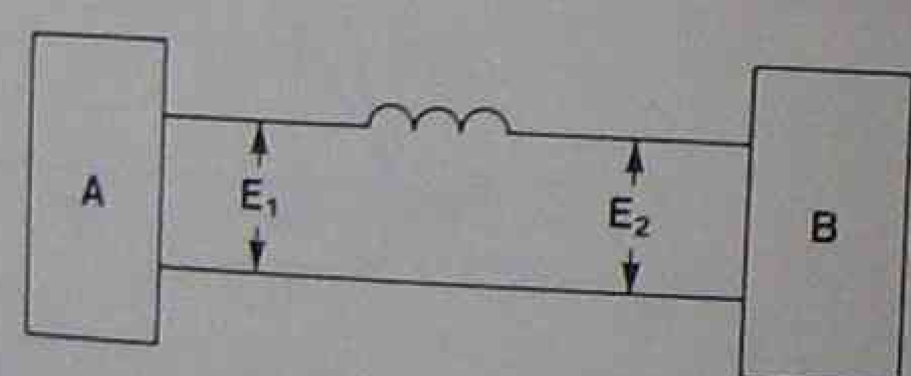


Figure 7-7.

☐ 2. Referring to procedure step 1, calculate the maximum power which could be transported at the given voltages E_1 and E_2 and write your results in Table 7-1.

☐ 3. Either by trigonometry or by scaling off the phasor diagrams, calculate the line current in parts 2 to 6 of procedure step 1.

Note: The line current is equal to the line voltage drop per phase divided by the reactance. In this calculation it is important to use the line-to-neutral voltages to determine the voltage drop. Write your results in Table 7-1.

N°	E_1	E_2	X	θ	LAG OR LEAD	P	DIRECTION OF POWER FLOW		LINE CURRENT A
—	kV	kV	Ω	°		kW		kW	—
1	4	4	80	30	E_1 LEADS E_2	+100	A → B	+200	15
2	8	8	80	30	E_1 LEADS E_2				
3	8	6	80	45	E_1 LAGS E_2				
4	8	6	80	45	E_1 LAGS E_2				
5	8	6	80	120	E_1 LEADS E_2				
6	4	12	80	60	E_1 LEADS E_2				

Table 7-1.

☐ 4. Two parallel transmission lines operating at a three-phase line-to-line voltage of 120 kV each, have a line reactance of 60 Ω. If the total power delivered is 84 MW, calculate the phase angle between the sender and receiver voltages. If one of the lines is suddenly opened, will the remaining line be able to carry the load? If so what will its new phase angle become?

____

____

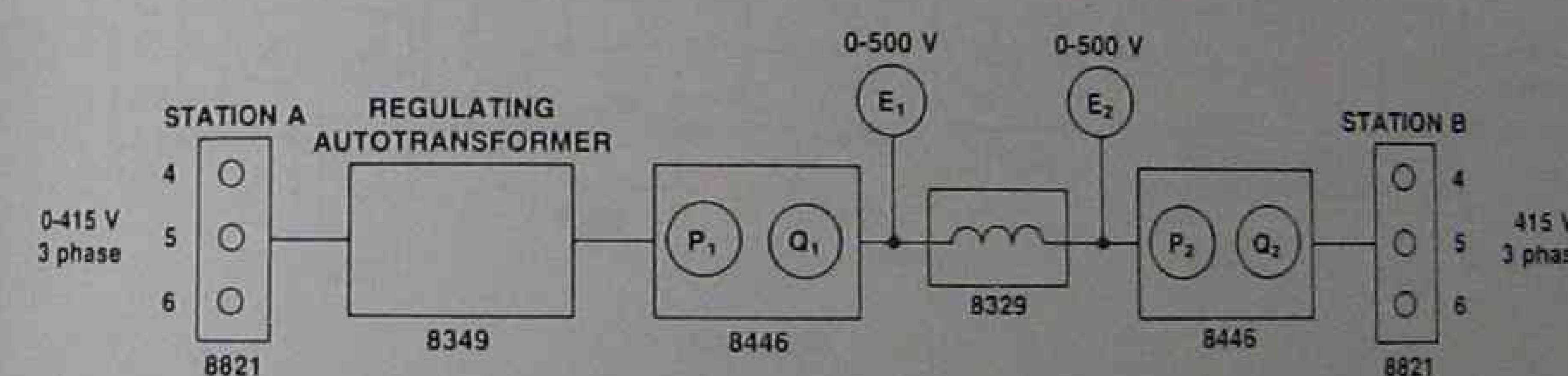


Figure 7-8

☐ *5. Using two independent Power Supplies and a Three-Phase Regulating Autotransformer, set the line reactance to 600 Ω and measure the real power flow when the phase-shift is +15° (Figure 7-8). (E_2 lags E_1 by 15°.) Adjust the voltage of the Power Supply to 415 V.

E_1 = ______ V

E_2 = ______ V

P_1 = ______ W

P_2 = ______ W

Q_1 = ______ var

Q_2 = ______ var

* Procedure Steps 5 to 8 may be carried out by two collaborating groups.

☐ 6. Now, at stations A and B, introduce step-up and step-down transformers connected in delta-star and star-delta respectively. (See Figure 7-9.)

WARNING

High voltages are present in this experiment: 720 V on the sender and receiver ends of the transmission line! Use two voltmeters in series to measure voltages E_1 and E_2.

Note: *This experiment entails the correct connection of the star-delta transformers both as to polarity and phase sequence. Three-phase transformer connections are covered in Experiment 1, Vol. 4 and Experiment 2, Vol. 3 of the Electrical Power Technology Series.*

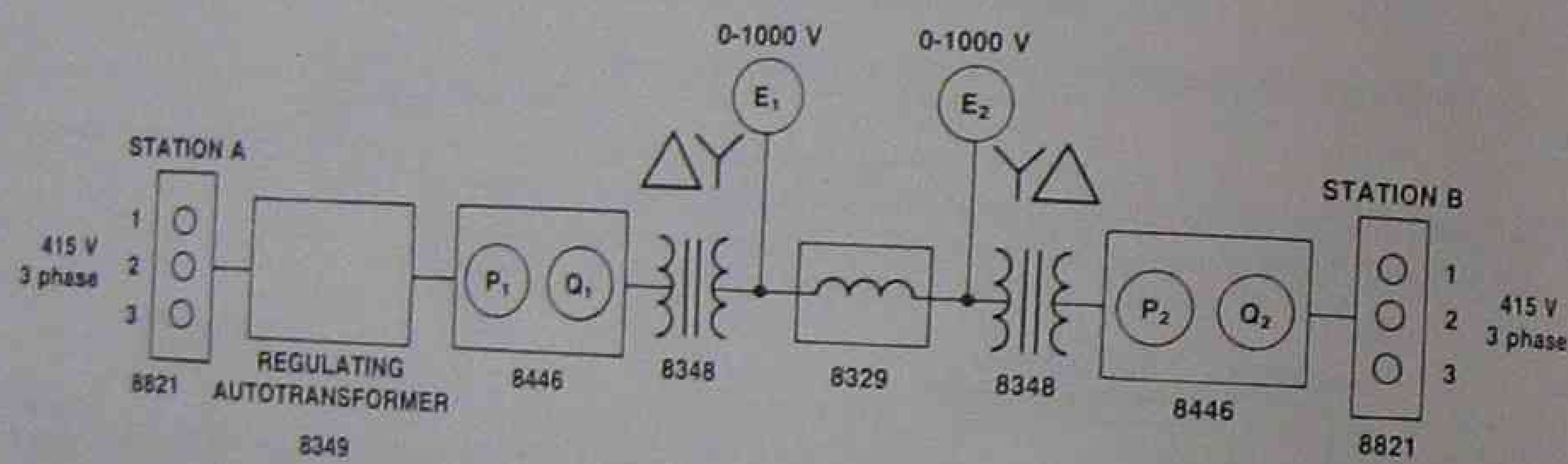


Figure 7-9

Measure the new real power which is transmitted and compare it with the values found in procedure step 5. Explain your results.

E_1 = ______ V

E_2 = ______ V

P_1 = ______ W

P_2 = ______ W

Q_1 = ______ var

Q_2 = ______ var

____

____

☐ 7. It is one of the inescapable facts of nature that when we increase the size of an object, the ratio of its volume to its external surface area increases. In the same way, the inertia of a motor increases more rapidly than its power rating. Consequently, large motors accelerate much more slowly than small motors do. A 0,2 kW motor can reach top speed in a fraction of a second when power is applied, whereas a 10 000 kW motor may take several minutes.

In order for a 0,2 kW machine to exhibit the mechanical properties of a much larger machine, we must increase its inertia artificially. This we can do by adding an inertia wheel. The inertia wheel used in this electric power transmission system gives the 0,2 kW machine an inertia corresponding to that of a machine in the megawatt range. The whole subject of inertia will be seen in more detail in Experiment 13.

a) Connect a 600 Ω transmission line in series with a Wattmeter/Varmeter to the fixed Power Supply terminals as shown on Figure 7-10. Measure E, P, Q in open circuit.

E = ______ V

P = ______ W

Q = ______ var

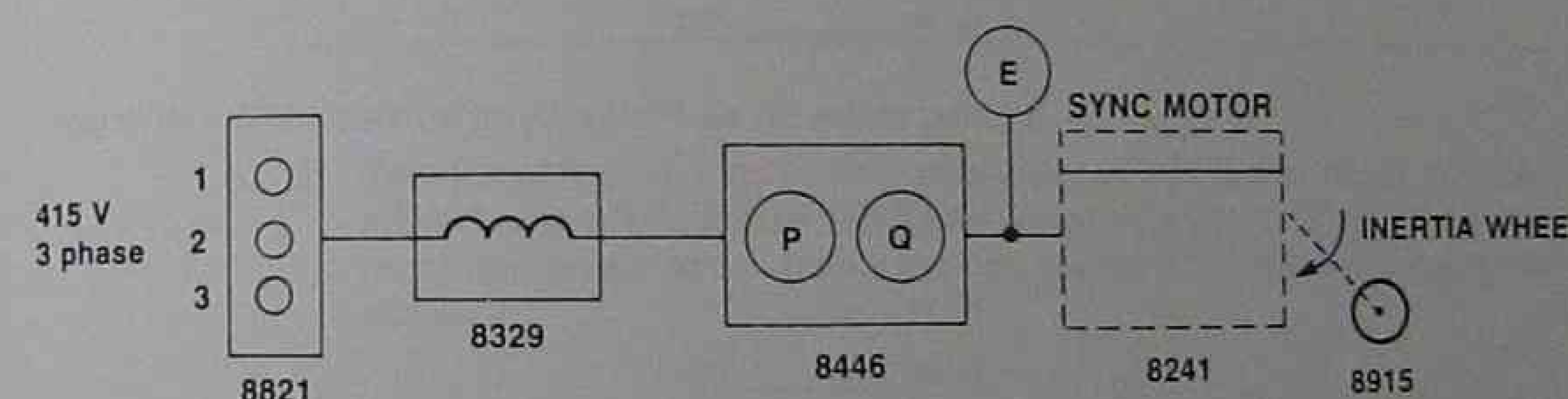


Figure 7-10.

b) Turn off the Power Supply and connect the stator of the Three-Phase Synchronous Motor/Generator to the end of the transmission line. Add the Inertia Wheel on the rotor of the Three-Phase Synchronous Motor/Generator. Turn on the Power Supply and observe the starting of the motor. How long does it take before the motor comes up to speed?

Acceleration time T = ______ s

Measure E, P, Q at the end of acceleration period.

E = ______ V

P = ______ W

Q = ______ var

☐ 8. Now, at the sender and receiver end of the 600 Ω transmission line, insert step-up and step-down transformers connected in delta-star and star-delta respectively (see Figure 7-11). Repeat the same procedure as in procedure step 7.

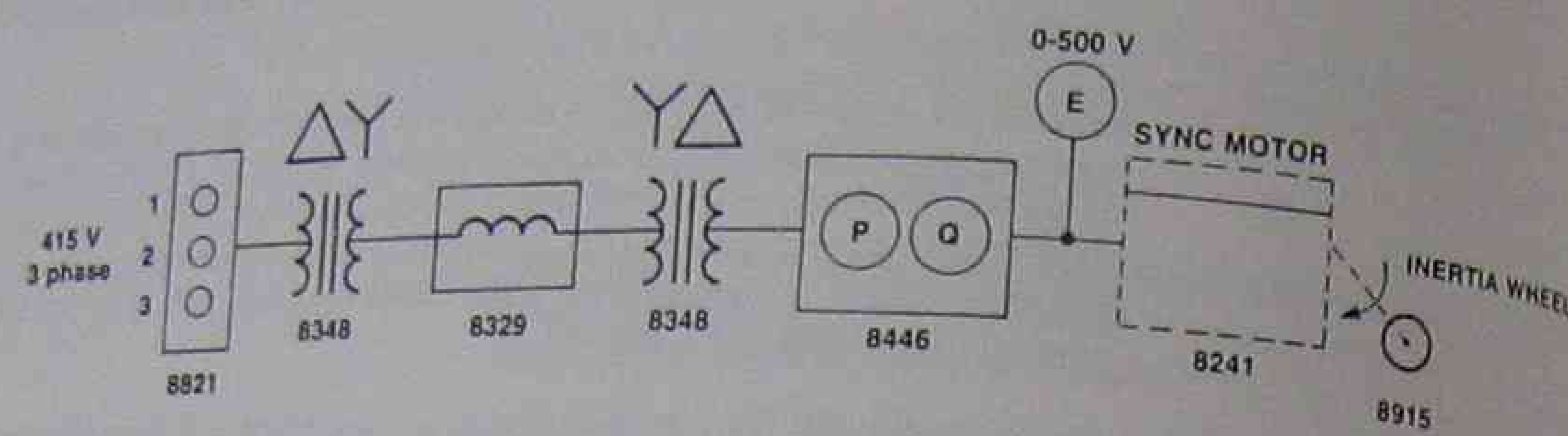


Figure 7-11.

a) Open circuit

E = ______ V

P = ______ W

Q = ______ var

b) Starting of the Three-Phase Synchronous Motor/Generator.

Acceleration time T = ______ s

E = ______ V

P = ______ W

Q = ______ var

Compare your results with the values found in procedure step 7.

Explain why the motor starts more quickly in procedure step 8, although the open circuit voltages are about the same.

______

______

TEST YOUR KNOWLEDGE

1. a) A 3-phase transmission line operating at 300 kV has a line reactance of 200 Ω per phase. Calculate the maximum total power which this line can deliver, in MW.

______

b) What is the phase angle between the sender and receiver voltages when the line delivers 100 MW?

______

c) What is the total amount of power if the phase angle is 1°, 2°, 4°, 8°, 16°, 32°?

______

______

2. a) In Question 1, if the phase angle between sender and receiver increases from 15° to 20° by how much is the real power flow increased?

______

b) If the phase angle increases from 75° to 80°, is the increase in power the same as before?

☐ Yes ☐ No

3. If the transmission line voltage in Question 1 were raised by 20%, by how much would the power-handling capacity of the line be increased?

______

4. a) Two transmission lines having reactances of 100 Ω and 200 Ω are connected in parallel between sender and receiver stations. What is the maximum real power which both lines can deliver if the operating voltage is 100 kV?

______

b) If the line delivers 75 MW, what is the phase angle between sender and receiver voltages?

______

If the 200 Ω line is suddenly taken out of service, what will the new phase angle be?

______

c) In Question 4 (b), if the 100 Ω line is suddenly opened, what will happen?

______

5. A high transmission line voltage reduces copper losses, and permits the transmission of more power. Explain this statement briefly.

______

______

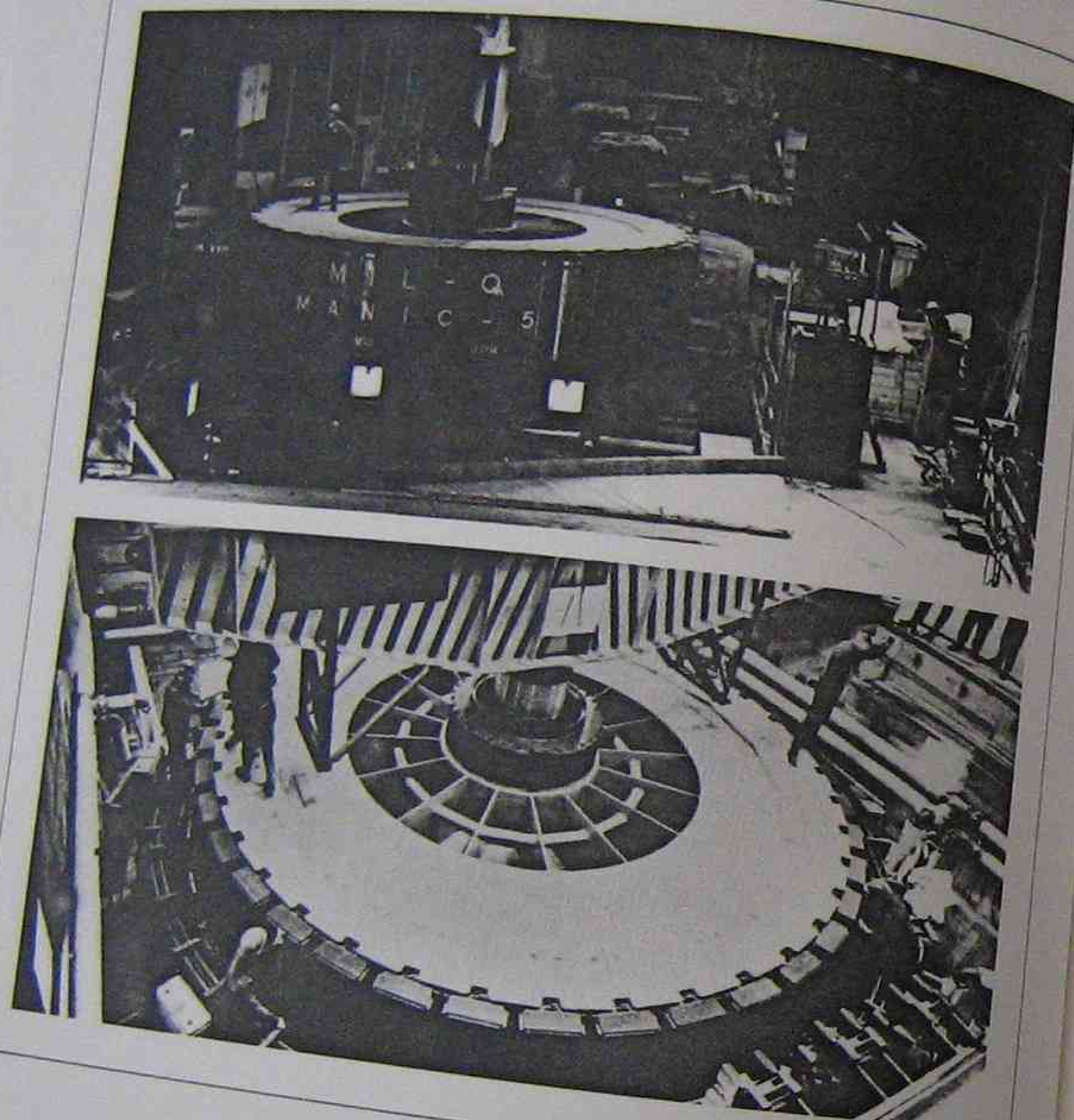
______

6. What is the purpose of step-up and step-down transformers at the sender and receiver ends of a transmission line?

______

______

______



Maneuvering the massive 40-pole rotor of a 170 MVA water-wheel alternator into its stator is a delicate and time-consuming task.

The Alternator

OBJECTIVES

- To understand the basic operation of an alternator.
- To measure the synchronous reactance of an alternator.
- To measure the voltage regulation of an alternator.

DISCUSSION

Electric power is produced in large generating stations which contain one or more alternators (or alternating current generators), and a mechanical means of driving them. The mechanical power is usually provided by steam turbines which, in turn, derive their energy from the heat given off by burning oil, gas or coal or from the heat of a nuclear reaction. In areas where water power is plentiful, hydraulic turbines provide the mechanical power to drive the alternators.

The voltage E_O generated by the alternator depends upon the flux per pole which, in turn, depends upon the DC excitation current which flows in the pole windings. The generator voltage per phase can therefore be varied by adjusting the DC excitation. At no load, the voltage E_T measured at the generator terminals is the same as the generated voltage E_O (see Figure 8-2).

If the alternator is loaded, its terminal voltage will change, even though the DC excitation is kept constant. This is because the alternator has an internal impedance, composed of the resistance and reactance of the stator windings. An alternator can, therefore, be represented by a circuit such as shown in Figure 8-1, in which X is the stator reactance, R the winding resistance and E_O the stator voltage generated as the poles sweep past the stator conductors.

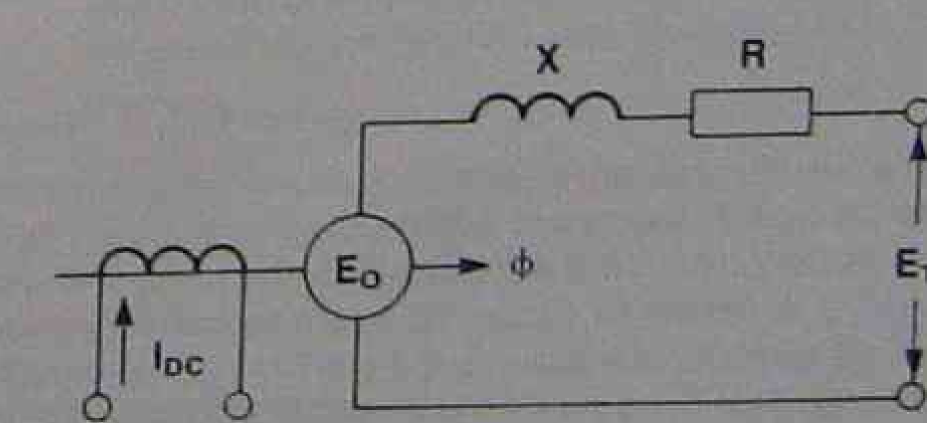


Figure 8-1.

The resistance R is always much smaller than the reactance X, so we can simplify the circuit to that shown in Figure 8-2, without introducing a significant error. The terminal voltage of the generator (per phase) is E_T and X is its so-called synchronous reactance.

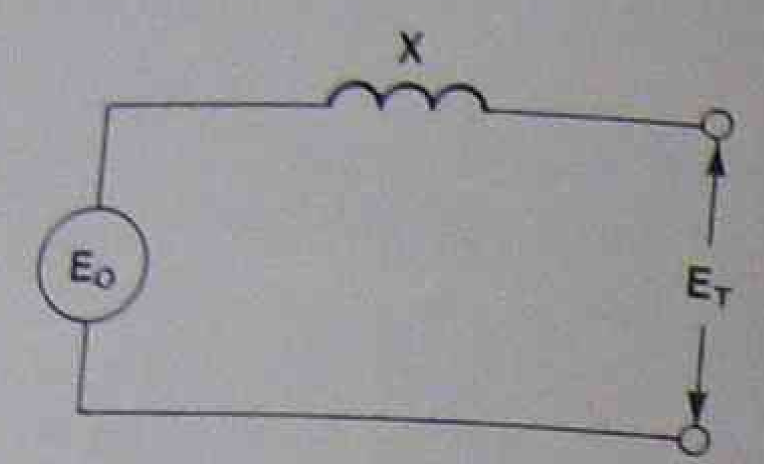


Figure 8-2.

The value of the synchronous reactance can be found by measuring the voltage E_T on open circuit and then measuring the current when the terminals are placed in short circuit.

Figure 8-3 shows how the short-circuit current $I = E_O/X$ from which the synchronous reactance X can be found. This reactance is not constant, but depends upon the degree of saturation in the machine. However, we can obtain a good idea of its magnitude by the method just described.

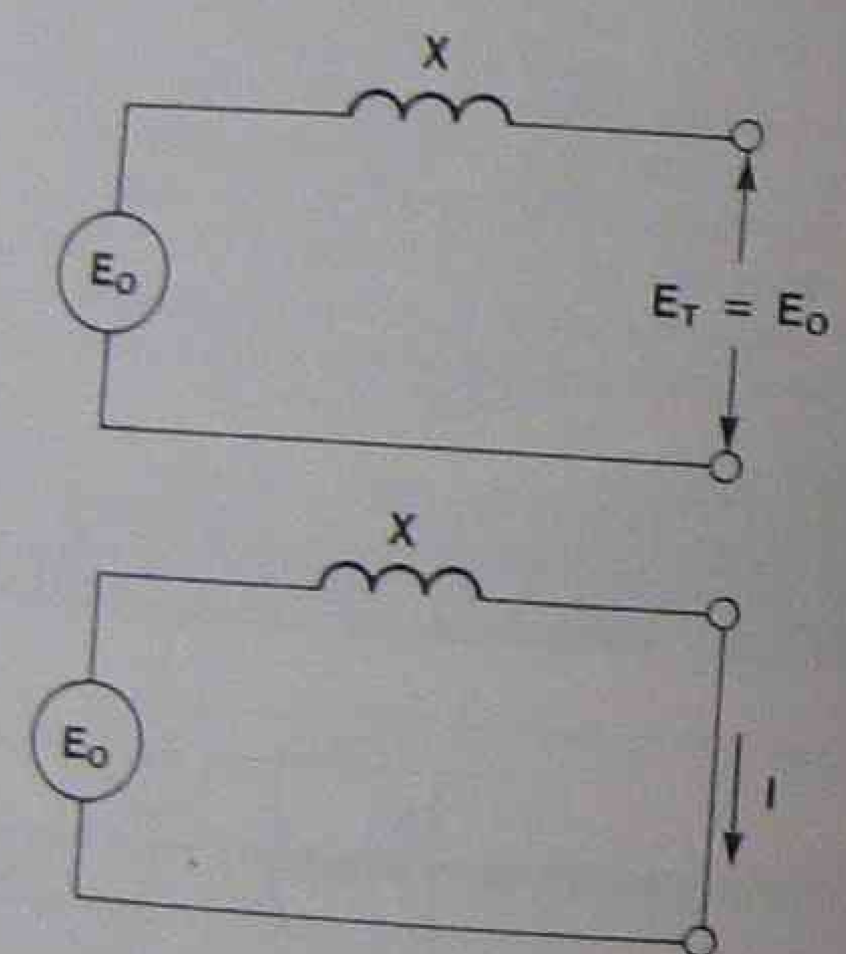


Figure 8-3.

The equivalent circuit of an alternator is, therefore very simple, and with it we can explain all the major properties of this machine. For example, we would expect that if a resistive or an inductive load is connected to the terminals, the terminal voltage E_T

will drop. On the other hand, if a capacitive load is connected to the terminals, a voltage rise is to be expected owing to the resonance effect.

The synchronous reactance of an alternator is always very large, so that even under short-circuit conditions, the current rarely exceeds 1,5 times the normal full-load current. It should be mentioned, however, that for the first few cycles following a short-circuit, the current can be much higher owing to the transient properties of the machine which we need not go into at this point.

In the following experiment, a DC motor will be used to drive the three-phase alternator, replacing the steam turbine which would usually be employed in a real generating station.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
DC Motor/Generator	8211
Three-Phase Synchronous Motor/Generator	8241
Resistive Load	8311
Inductive Load	8321
Capacitive Load	8331
DC Voltmeter/Ammeter	8412
AC Ammeter	8425
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Stroboscope	8922
Timing Belt	8942
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. In this experiment we shall determine the variation of the generated voltage E_O, as the DC exciting current is increased. Set up the circuit as shown in Figure 8-4, and mechanically couple the DC Motor/Generator to the Three-Phase Synchronous Motor/Generator by means of a Timing Belt. Connect AC Voltmeter E_O from line to neutral of one phase of the Three-Phase Synchronous Motor/Generator and connect a DC Voltmeter/Ammeter to measure the exciting current I_F.

Apply power and, using the Stroboscope adjust the speed of the DC Motor/Generator to 1500 r/min exactly. This speed must be kept constant for the remainder of the experiment.

Vary the current I_F and note the effect upon the generated voltage E_O. Take readings of I_F and E_O and record your results in Table 8-1.

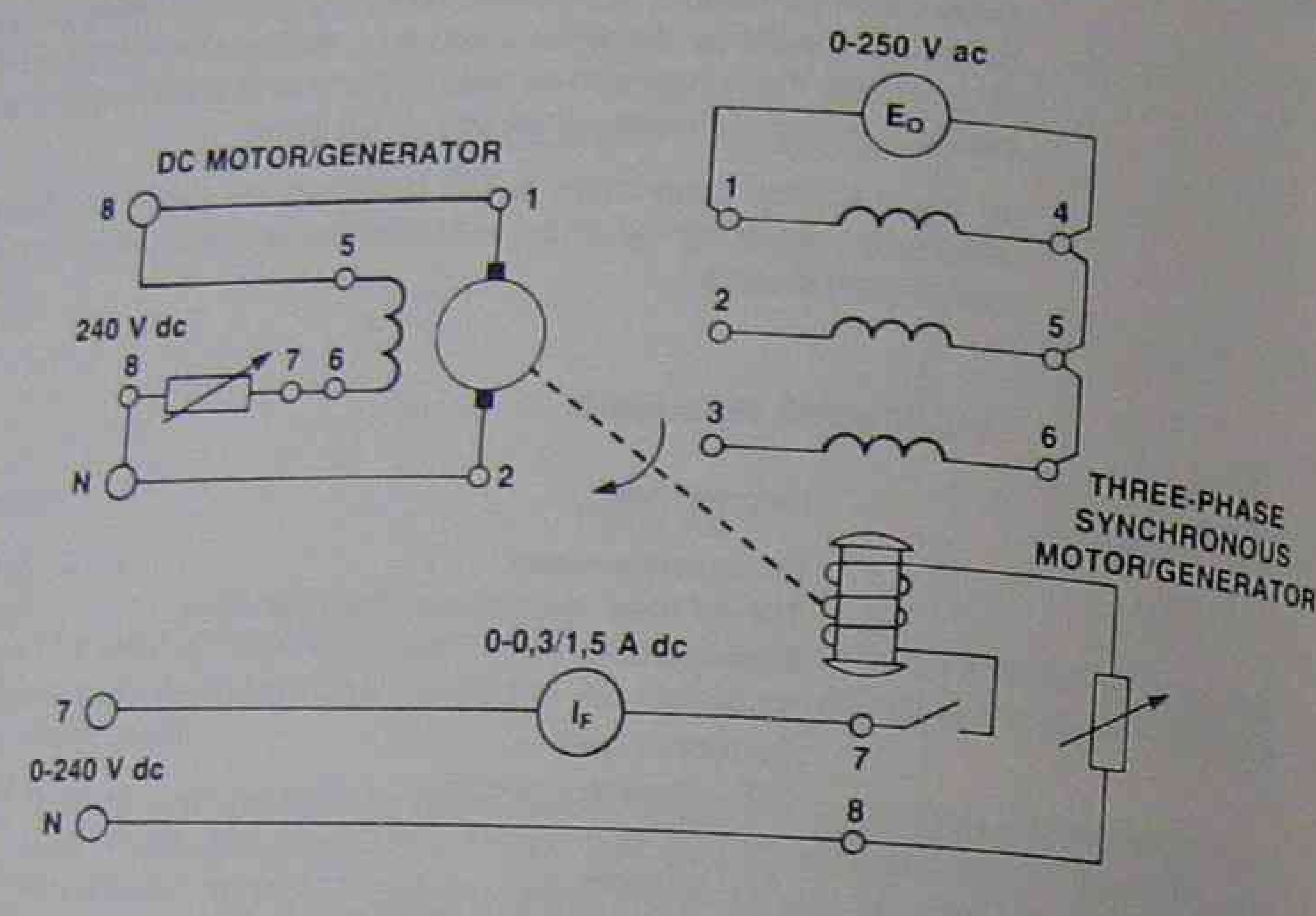


Figure 8-4.

I_F	(A)	0	0,05	0,10	0,15	0,20	0,25	0,30	0,35	0,40	0,45	0,50
E_O	(V)											

Table 8-1.

☐ 2. Find the phase sequence of the generated voltage, with regards to terminals 1, 2, 3.

The phase sequence is ______

Note: *If the phase sequence is not 1-2-3-1-2-3, etc, reverse rotation of the DC Motor/Generator.*

☐ 3. Using the same set-up as in Figure 8-4, adjust the open-circuit voltage E_O to 240 V. Then short-circuit the stator terminals through three AC Ammeters and take their average reading I (see Figure 8-5).

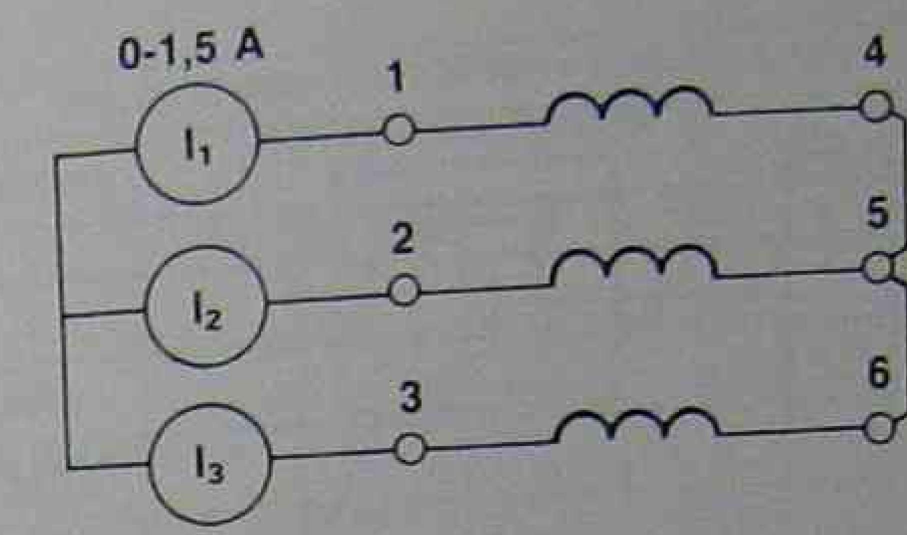


Figure 8-5.

Calculate the value of the synchronous reactance from the formula $X = E_O / I$.

E_O = 240 V I = ______ A X = ______ Ω

☐ 4. Repeat procedure step 3 with E_O = 240 V and then with E_O = 220 V.

E_O = 240 V I = ______ A X = ______ Ω

E_O = 220 V I = ______ A X = ______ Ω

Voltage Regulation

In this experiment we shall find the effect of various loads upon the terminal voltage of the alternator.

☐ 5. Using the same set-up as in Figure 8-4, connect a Resistive Load to the terminals of the DC Motor/Generator and introduce a Wattmeter/Varmeter and a Voltmeter E_L as shown in Figure 8-6.

Adjust the exciting current I_F of the Three-Phase Synchronous Motor/Generator so that the open-circuit voltage E_L = 415 V. Then, keeping the speed and the current I_F constant, vary the Resistive Load and record your results in Table 8-2. Be sure to keep the load resistance balanced so that all phases are equally loaded.

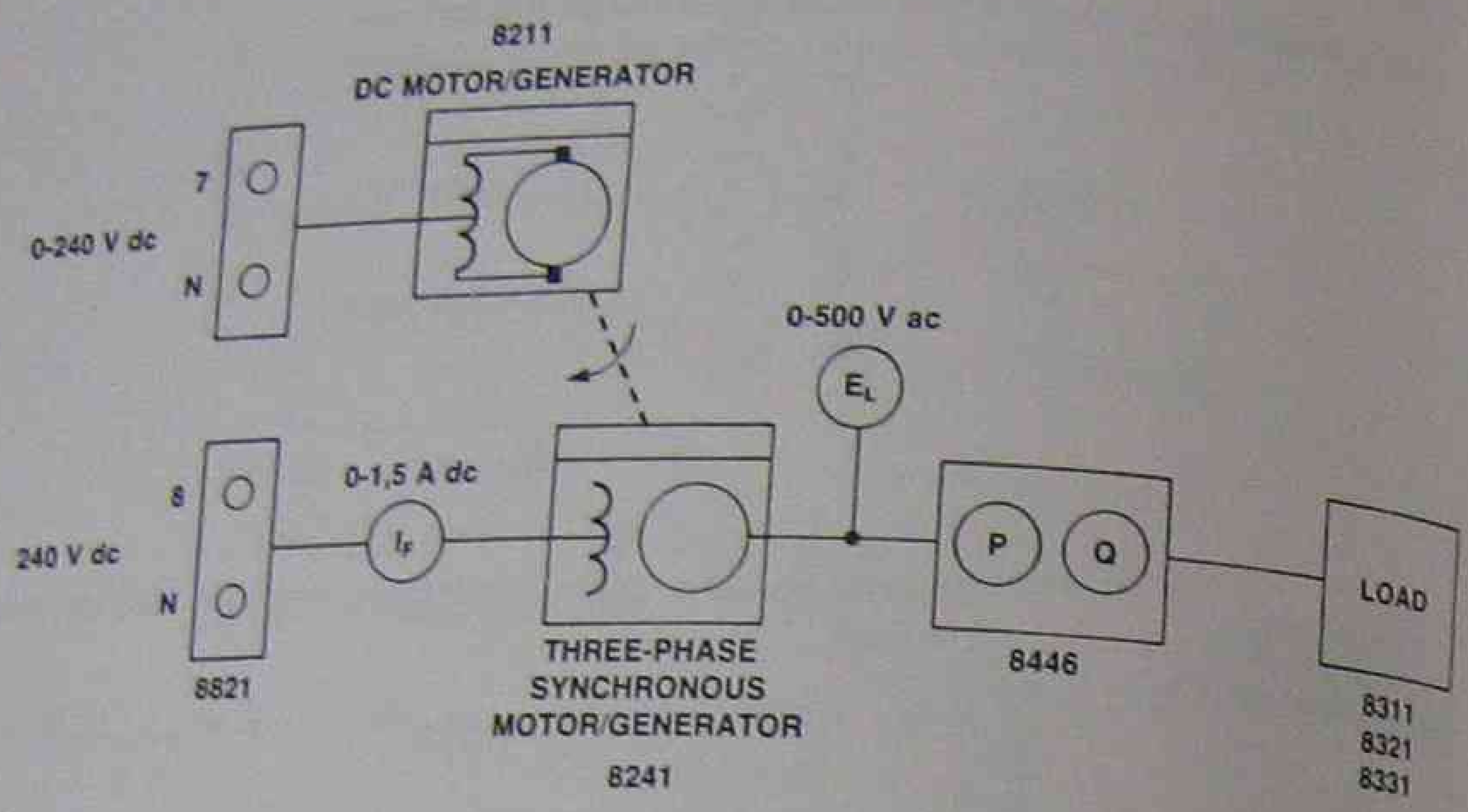


Figure 8-6.

VOLTAGE REGULATION WITH RESISTIVE LOAD					
R/PHASE	I_F	E_L	P	Q	$S = \sqrt{P^2 + Q^2}$
Ω	A	V	W	var	VA
∞					
4800					
2400					
1600					
1600					
1200					
960					
800					
686					

Table 8-2.

☐ 6. Repeat procedure step 5, using an Inductive Load in place of the Resistive Load, and record your results in Table 8-3.

VOLTAGE REGULATION WITH INDUCTIVE LOAD					
X_L/PHASE	I_F	E_L	P	Q	$S = \sqrt{P^2 + Q^2}$
Ω	A	V	W	var	VA
∞					
4800					
2400					
1600					
1600					
1200					
960					
800					
686					

Table 8-3.

☐ 7. Repeat procedure step 5, using a Capacitive Load instead of the resistance, and record your results in Table 8-4. (If the voltage goes off scale, you may connect two voltmeters in series and take the sum of their readings.)

VOLTAGE REGULATION WITH CAPACITIVE LOAD					
X_L/PHASE	I_F	E_L	P	Q	$S = \sqrt{P^2 + Q^2}$
Ω	A	V	W	var	VA
∞					
4800					
2400					
1600					
1600					
1200					
960					

Table 8-4.

TEST YOUR KNOWLEDGE

1. A 150 MW alternator generates an open-circuit line-to-line voltage of 12 kV at nominal DC excitation. When the terminals are placed in short-circuit the resulting current per phase is 8000 A.

a) Calculate the approximate value of the synchronous reactance per phase.

____

b) Draw the equivalent circuit of the alternator per phase under the DC field excitation conditions given above.

c) What is the nominal full load current per phase?

____

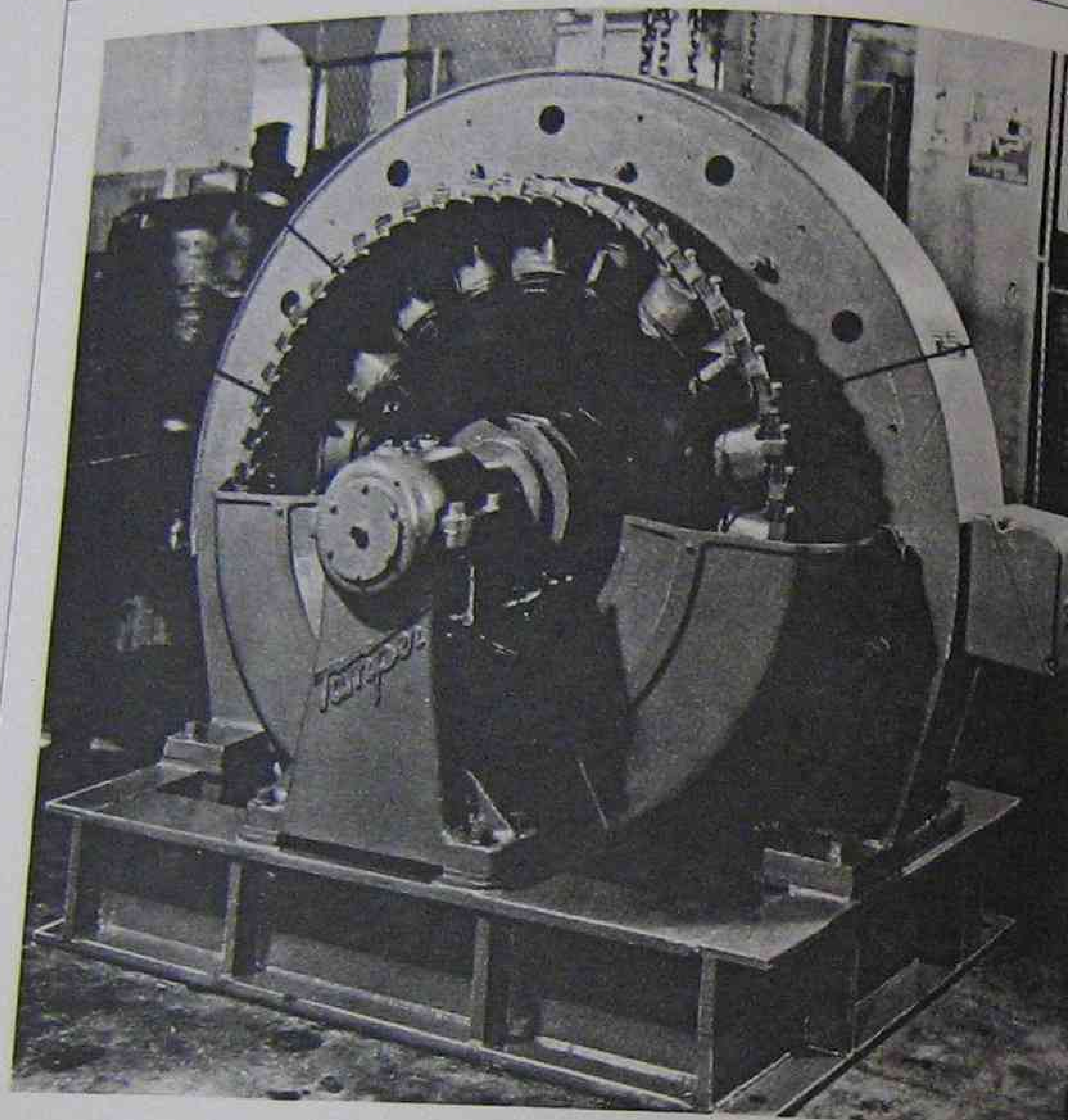
2. a) If the Three-Phase Synchronous Motor/Generator in Question 1 supplies a resistive load of 120 MW at a voltage of 12 kV, what must be the induced voltage E_O ?

____

b) What is the phase angle between E_O and the terminal voltage?

____

____



View of a 220 kW, 220 V, 327 r/min, 60 Hz Synchronous Motor.

The Synchronous Motor

OBJECTIVES

- To observe the behavior of a synchronous motor connected to an infinite bus, as regards:
  - a) Reactive power flow in the synchronous motor.
  - b) Real power flow in the synchronous motor.
  - c) Change in position of the rotor poles.

DISCUSSION

A synchronous motor has the same construction as an alternator, and hence possesses the same electrical properties. Indeed, an alternator can be made to run as a synchronous motor and vice versa, the only distinction being that, as a motor, the machine receives electric power and converts it into mechanical power whereas, as an alternator, it does the reverse.

The circuit of a synchronous motor is identical to that of an alternator, consisting of a synchronous reactance X (per phase) and an induced AC voltage E_O created in the stator by the DC flux from the rotor poles. We shall first study the operation of the motor when it is connected to an infinite bus. As infinite bus is a source of electric power which is so immense that nothing we connect to it will change either its voltage, its frequency or the phase angles between its three phases. An infinite bus is, in effect, a source of voltage which has no internal impedance. The source E_S in Figure 9-1 is considered to be one phase of the infinite bus.

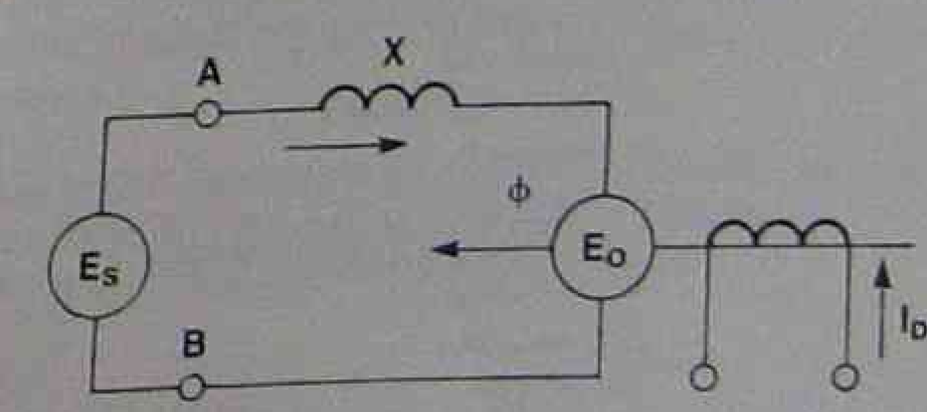


Figure 9-1.

The circuit of Figure 9-1 looks very much like that of a transmission line in which E_S and E_O are the sender and the receiver voltages. In fact, the flow of real and reactive power in this circuit is dictated by the same factors as in the case of a transmission line. Briefly,

a) If E_O is in phase with E_S, and if the two voltages are unequal, reactive power will flow. (If E_O is less than E_S, reactive power will flow from the source to the motor. If E_O is greater than E_S then reactive power will flow from the motor to the source.)

b) If E_O lags behind E_S, real power will flow from the infinite bus to the motor, giving it the energy to carry its mechanical load. Just as in the case of a transmission line, the maximum real power which can be delivered is equal to $(E_S E_O)/X_S$.

To vary the reactive power, E_O must be varied and this is readily done by changing the DC exciting current in the rotor windings.

To increase the real power, (for a fixed value of E_O and E_S) the phase angle between E_O and E_S must increase and this happens automatically when the mechanical load on the motor increases. When operating at no load, only a small amount of mechanical power is needed to overcome the windage and friction losses, consequently the motor draws only a small amount of real electric power. The phase angle between E_S and E_O is small under no-load conditions.

As the mechanical load is increased, E_O lags more and more behind E_S and when the lag is 90°, the motor power will reach its maximum value. If the mechanical load is increased beyond this point, the machine will fall out of synchronism and come to a halt.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
DC Motor/Generator	8211
Three-Phase Synchronous Motor/Generator	8241
Resistive Load	8311
DC Voltmeter/Ammeter	8412
AC Ammeter	8425
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Stroboscope	8922
Timing Belt	8942
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

Excitation and reactive power flow

☐ 1. Set up the experiment of Figure 9-2, connecting the stator to the fixed AC supply via the Three-Phase Wattmeter/Varmeter and the AC Ammeter. The field of the Three-Phase Synchronous Motor/Generator is connected to the variable DC source, in series with a DC Voltmeter/Ammeter.

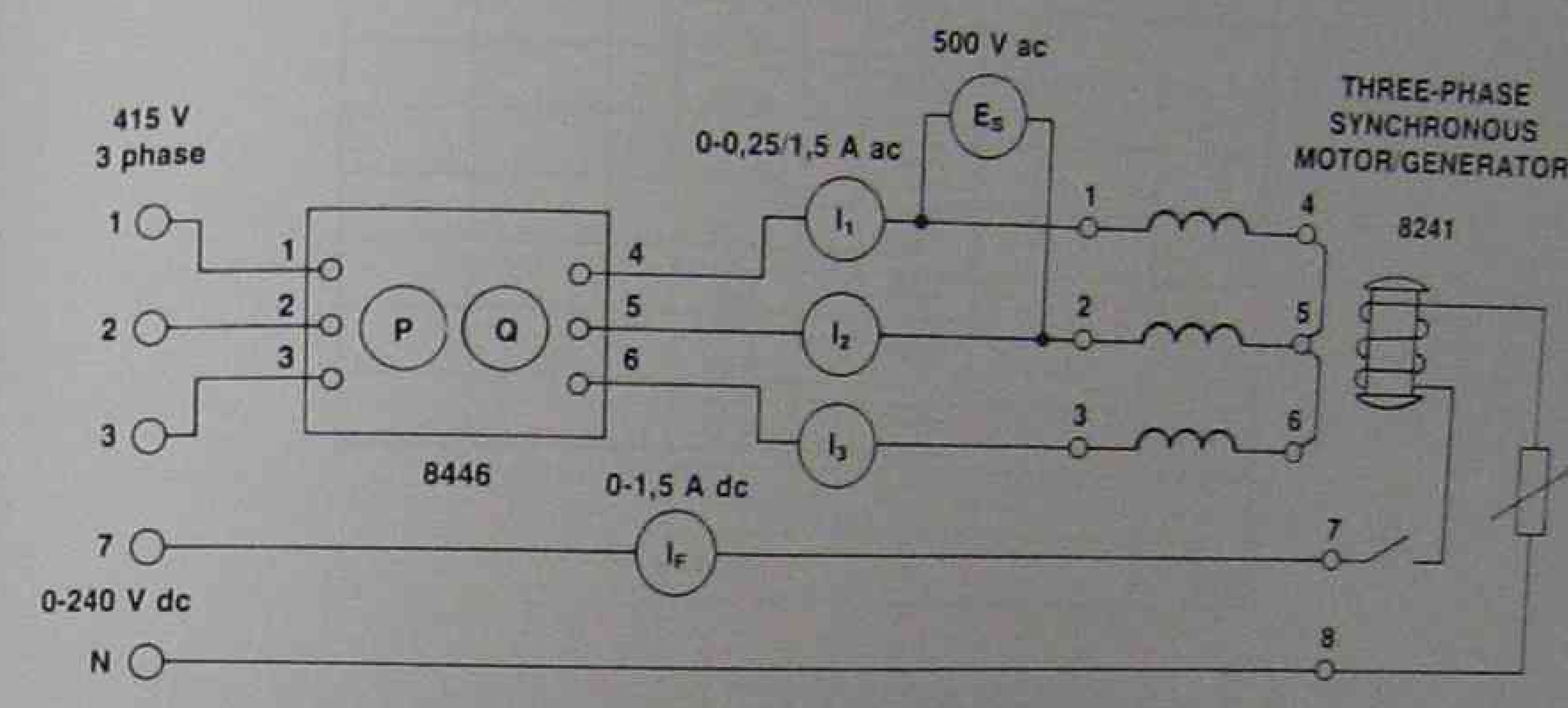


Figure 9-2.

Note: *The DC field should only be applied once the machine has come up to speed. The motor accelerates when 3-phase AC power is applied to the stator owing to the squirrel cage winding embedded in the poles.*

Apply AC power, and then apply DC current to the field. Increase the field current until the reactive power is zero. Note that if the excitation is varied above or below this value, the reactive power changes from negative to positive.

Vary the DC excitation gradually, starting at 0,05 A and increase it in steps up to 0,45 A and record your results in Table 9-1. Be sure to record the values of the particular case where var = 0.

Loading and real power

☐ 2. Couple the DC Motor/Generator to the Three-Phase Synchronous Motor as shown on Figure 9-3 and apply 3-phase AC power to the latter, followed by DC power to the rotor. Adjust the DC excitation so that the reactive power is zero when the generator shunt field current is minimum. Then, keeping the DC excitation of the synchronous motor constant, gradually load the motor by increasing the generator excitation, and observe the increase of active power.

VARIATION OF EXCITING VOLTAGE				
I_F	E_S	I	P	Q
A	V	A	W	var
0,05				
0,10				
0,15				
0,20				
0,25				
0,30				
0,35				
0,40				
0,45				

Table 9-1.

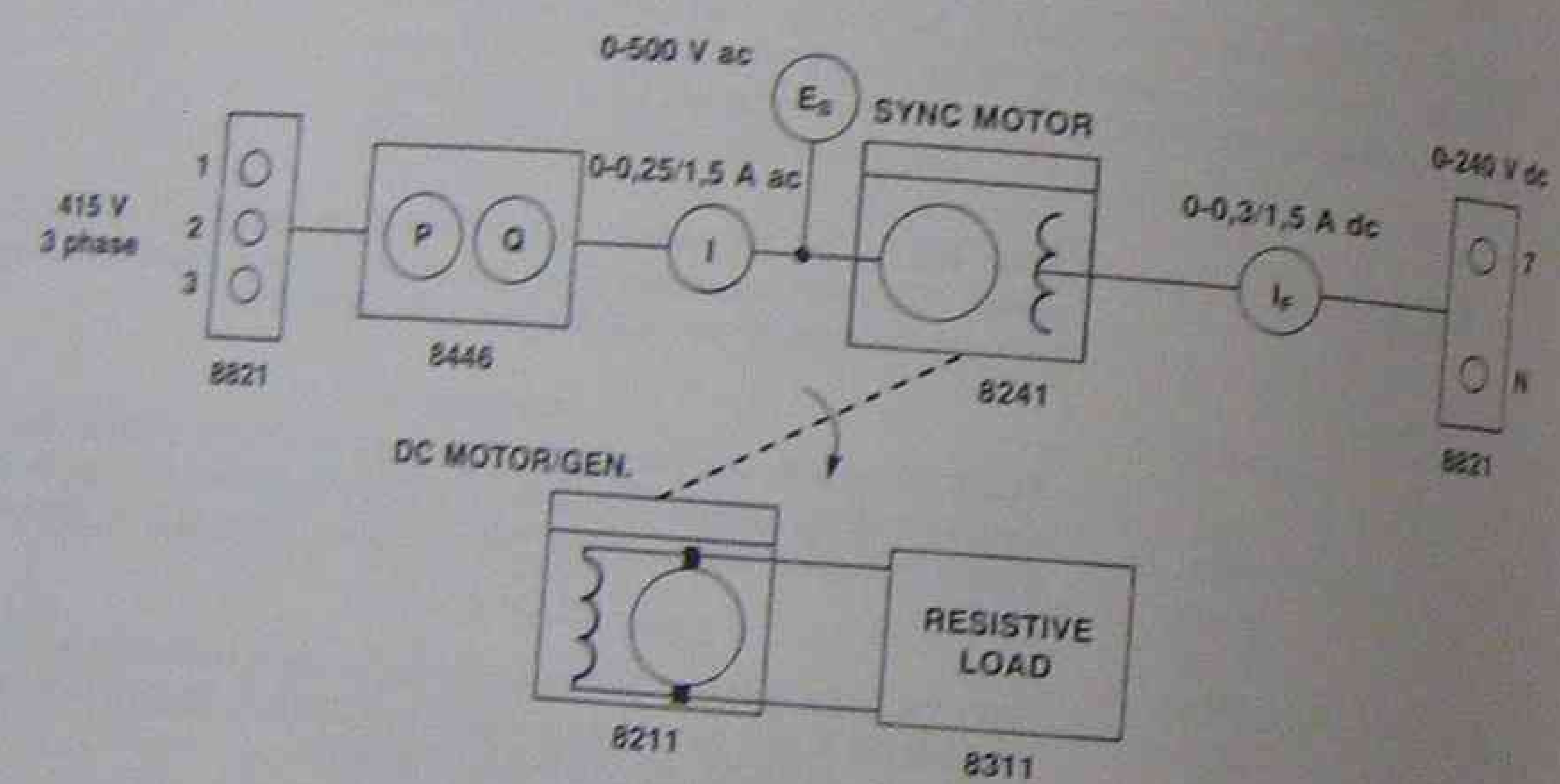


Figure 9-3.

Continue to increase the load until the synchronous motor falls out of step i.e. loses synchronism. Remove power as soon as this happens.

☐ 3. Repeat procedure step 2, but this time observe the position of the rotor with the Stroboscope as the load increases. The changing position of the rotor is the main cause of the increasing phase angle between E_S and E_O.

☐ 4. Repeat procedure step 2, and this time record your results in Table 9-2.

REAL POWER AND LOADING				
I_F	E_S	I	P	Q
A	V	A	W	var
0,05				
0,10				
0,15				
0,20				
0,25				
0,30				
0,35				
0,40				
0,45				

Table 9-2.

TEST YOUR KNOWLEDGE

1. The real power absorbed by a synchronous motor can be found in the same way, and using the same formula as with a transmission line. Explain.

____

____

2. A 2000 kW synchronous motor operates at a three-phase line-to-line voltage of 4 kV. It has a synchronous reactance of 4 Ω per phase.

Calculate:

a) The nominal full load current of the machine when the excitation voltage E_O (line-to-line) is 4 kV.

____

b) The short-circuit current when the excitation voltage E_O (line-to-line) is 4 kV.

____

3. a) In Question 2, if the excitation voltage E_O is equal to the terminal voltage (4 kV), what is the maximum real power which the motor can deliver without losing synchronism?

____

b) What is the rotor pole shift in electrical degrees, corresponding to the nominal load of 2000 kW?

____

4. The motor cannot operate in a stable manner when the rotor poles move beyond an angle of 90 electrical degrees from their no-load position. Can you explain why?

____

____

5. If the motor in Question 2 is at the end of a transmission line which has a reactance of 8 Ω per phase, what is the maximum power which the machine can develop, given that the sender voltage is 4 kV and the induced voltage E_O is also 4 kV (line-to-line)?

____

How does this maximum power compare with the nominal rating of the machine?

____

Calculate by how much the rotor poles move from their no-load position before the motor loses synchronism. Why is this angle less than 90°?

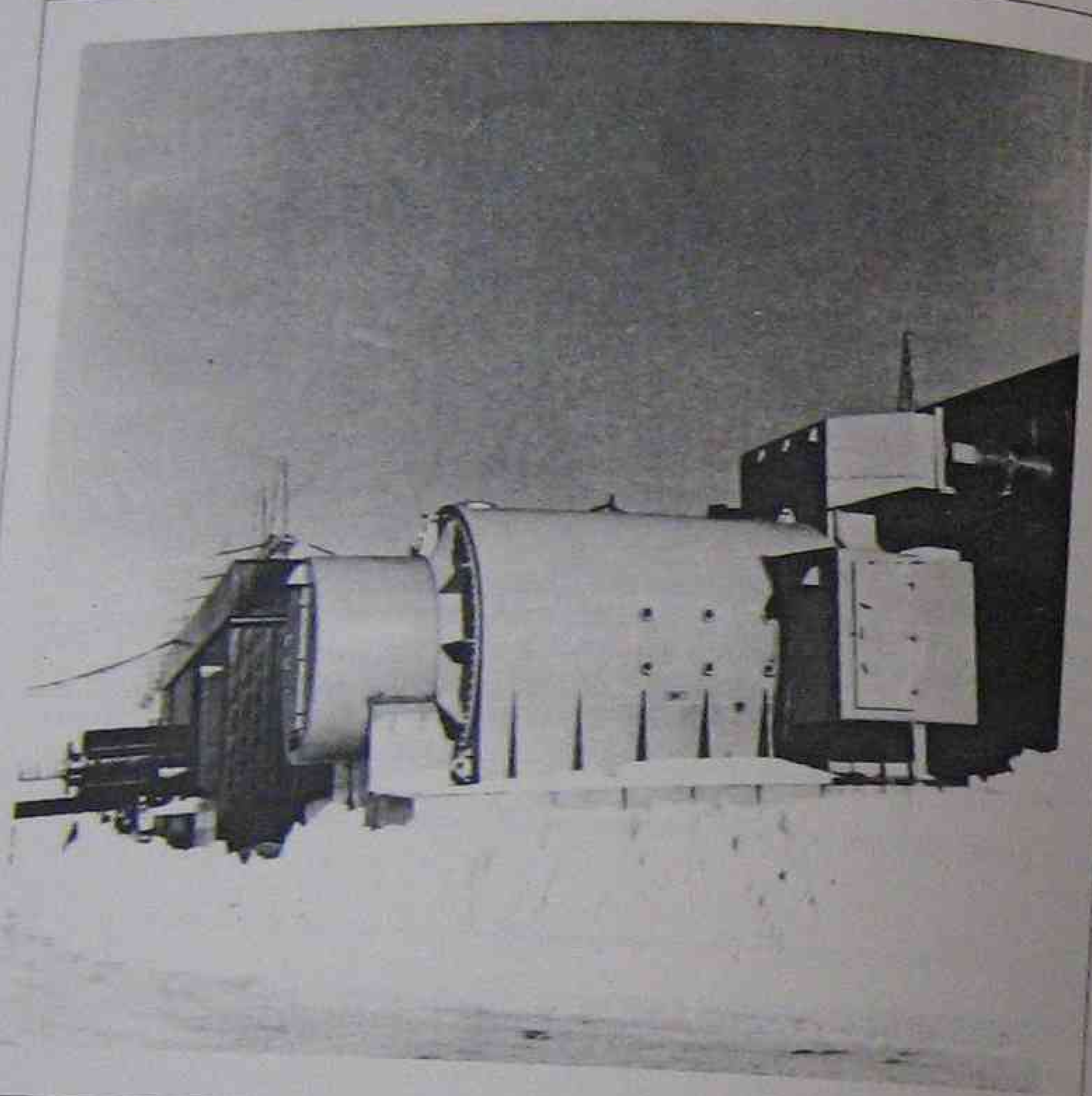
____

____

Between which two voltages is the angle equal to 90° when peak power has been attained?

____

____



Large hydrogen cooled synchronous capacitor to control the flow of reactive power. Installed in Duvernay, Quebec.

The Synchronous Capacitor and Long High Voltage Lines

OBJECTIVES

- To study how a synchronous capacitor can regulate the receiver voltage.
- To study the distributed capacitance and the long, high-voltage line.

DISCUSSION

In Experiment 9, we saw that a synchronous motor at no load is able either to absorb or to deliver power. In essence, it acts wither as a three-phase inductor or as a three-phase capacitor depending upon whether it is under-or over-excited. The fact that such a machine can change gradually from an inductance to a capacitance makes it very useful to regulate the voltage at the end of transmission lines.

When used in this way, the synchronous motor is termed a synchronous capacitor. A better term might have been "synchronous capacitor/inductor", but because these machines must usually supply reactive power to a power system rather than absorb it, the term "capacitor" is appropriate.

We saw, in Experiment 5, how the receiver voltage can be regulated by static capacitors. We shall see how the same result can be obtained much more smoothly with a synchronous capacitor.

Long high-voltage transmission lines have significant capacitance in addition to their inductance. Typically, the capacitive reactance per kilometer is 400 000 Ω and the inductive reactance is 0,4 Ω on a 50 cycle line. This means that for a line which is 250 kilometers long, the inductance per phase is 100 Ω and the capacitive reactance is 1600 Ω. The simplified circuit of such a line may be represented by Figure 10-1, in which the line capacitance is "lumped" in the center of the line instead of being distributed over its entire length. When such a line is fed by a sender voltage E_S, the open-circuit receiver voltage E_R will be considerably higher.

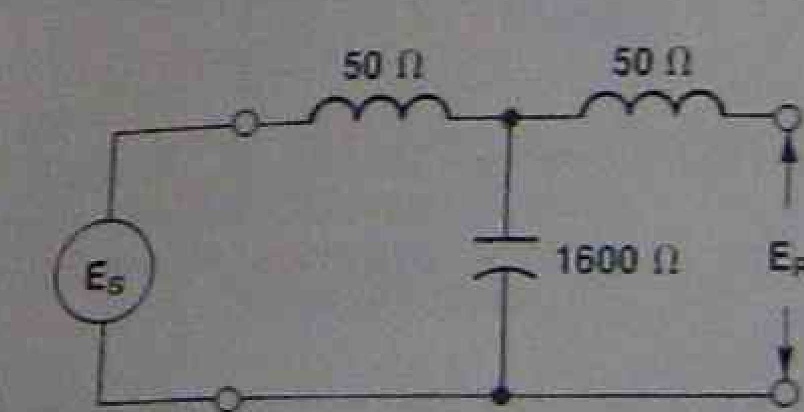


Figure 10-1.

Supply Authorities are very sensitive to keeping the esthetic beauty of a city. This modern substation blends in well with the surrounding architecture.

Phase Angle and Voltage Drop between Sender and Receiver

OBJECTIVES

- To regulate the receiver end voltage.
- To observe the phase angle between the voltages at the sending and the receiving end of the transmission line.
- To observe the line voltage drop when the sending and receiving end voltages have the same magnitude.

DISCUSSION

In the previous experiment we saw that a resistive or inductive load at the end of a transmission line produces a very large voltage drop, which would be quite intolerable under practical conditions. Motors, relays and electric lights work properly only under stable voltage conditions, close to the potential for which these devices are rated.

We must, therefore, regulate the voltage at the receiver end of the transmission line in some way so as to keep it as constant as possible. One approach which appears promising, is to connect capacitors at the end of the line because, as we saw in Experiment 4, these capacitors produce a very significant voltage rise. This, indeed, is one way by which the receiving end voltage is regulated in some practical instances. Static capacitors are switched in and out during the day, and their value is adjusted to keep the receiver end voltage constant.

For purely inductive loads, the capacitors should deliver reactive power equal to that consumed by the inductive load. This produces a parallel resonance effect in which reactive power required by the inductance is, in effect, supplied by the capacitance and none is furnished by the transmission line.

For resistive loads, the reactive power, which the capacitors must supply to regulate the voltage, is not easy to calculate. In this experiment, we shall determine the reactive power by trial and error, adjusting the capacitors until the receiver end voltage is equal to the sender end voltage.

Finally, for loads which draw both real and reactive power (they are the most common) the capacitors must be tailored to compensate first, for the inductive component of the load and second, for the resistive component.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Resistive Load	8311
Three-Phase Transmission Line	8329
Capacitive Load	8331
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Phase Meter	8451
Power Supply	8821
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Set the impedance of the transmission line to 200 Ω and connect the Voltmeter and Wattmeters/Varmeters as shown in Figure 5-1. The load will be modified during the course of the experiment. The circuit should be connected to the three-phase variable voltage supply.

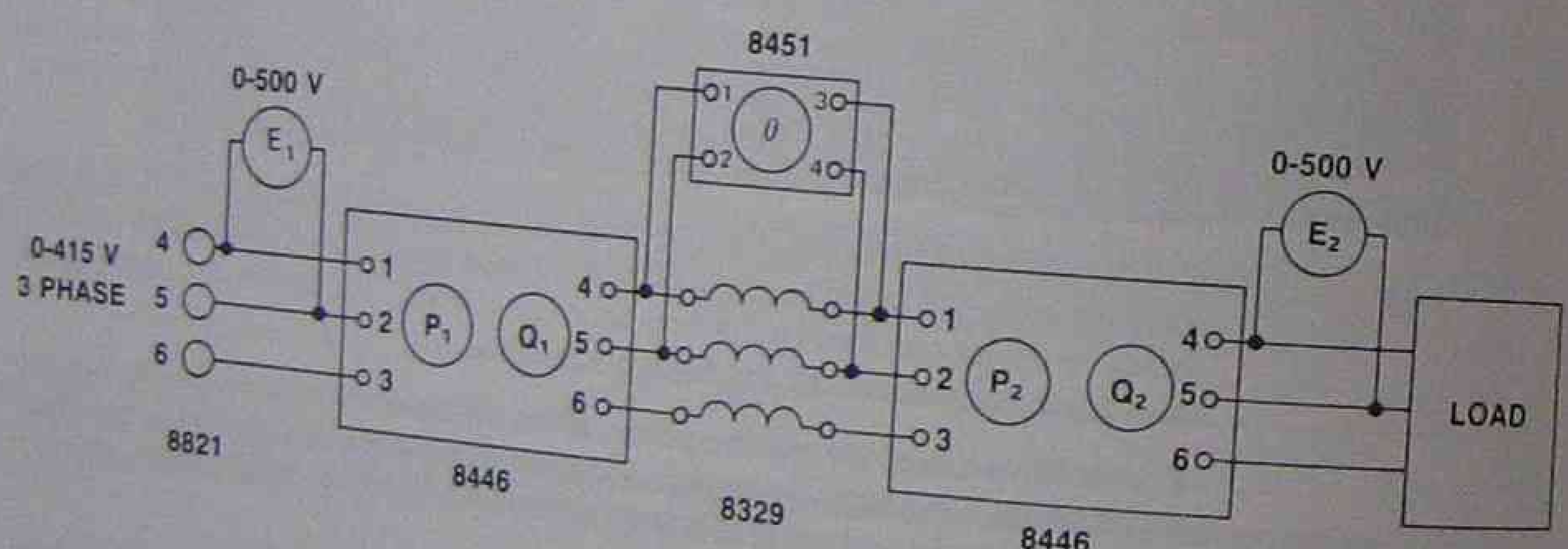


Figure 5-1.

☐ 2. Using a three-phase Resistive Load, adjust E_1 to 350 V and keep it constant for the remainder of the experiment. Increase the Resistive Load in steps, keeping all three-phase balanced. Take readings of E_1, Q_1, E_2, P_2, Q_2 and the phase angle between E_1 and E_2.

Note: *E_1 is chosen as the reference voltage for the phase-angle meter.*

VOLTAGE REGULATION WITH RESISTIVE LOAD

R Ω	E_1 V	P_1 W	Q_1 var	E_2 V	P_2 W	Q_2 var	ANGLE °
∞							
4800							
2400							
1600							
1200							
960							
800							
686							

Table 5-1.

Record your results in Table 5-1, and draw in Figure 5-2 a graph of E_2 as a function of the load power P_2, in watts.

On this curve, indicate the phase angle corresponding to the various real power loads W_2.

CAUTION

Always remove the capacitive load prior to removing the resistive load. A severe overload is otherwise to be expected.

☐ 3. Now, connect a three-phase balanced Capacitive Load in parallel with the Resistive Load. Repeat procedure step 2 but for each Resistive Load adjust the Capacitive Load so that the load voltage E_2 is as close as possible to 350 V. (E_1 must be kept constant at 350 V.) Record your results in Table 5-2.

Draw a graph of E_2 as a function of P_2, and superimpose it on the previous graph which you drew in procedure step 2. Note that the addition of static capacitors has yielded a much more constant voltage, and furthermore, the power P_2 which can be delivered has increased.

On this curve, indicate the phase angle between E_2 and E_1 as well as the reactive power Q_2 used for the individual resistive load settings.

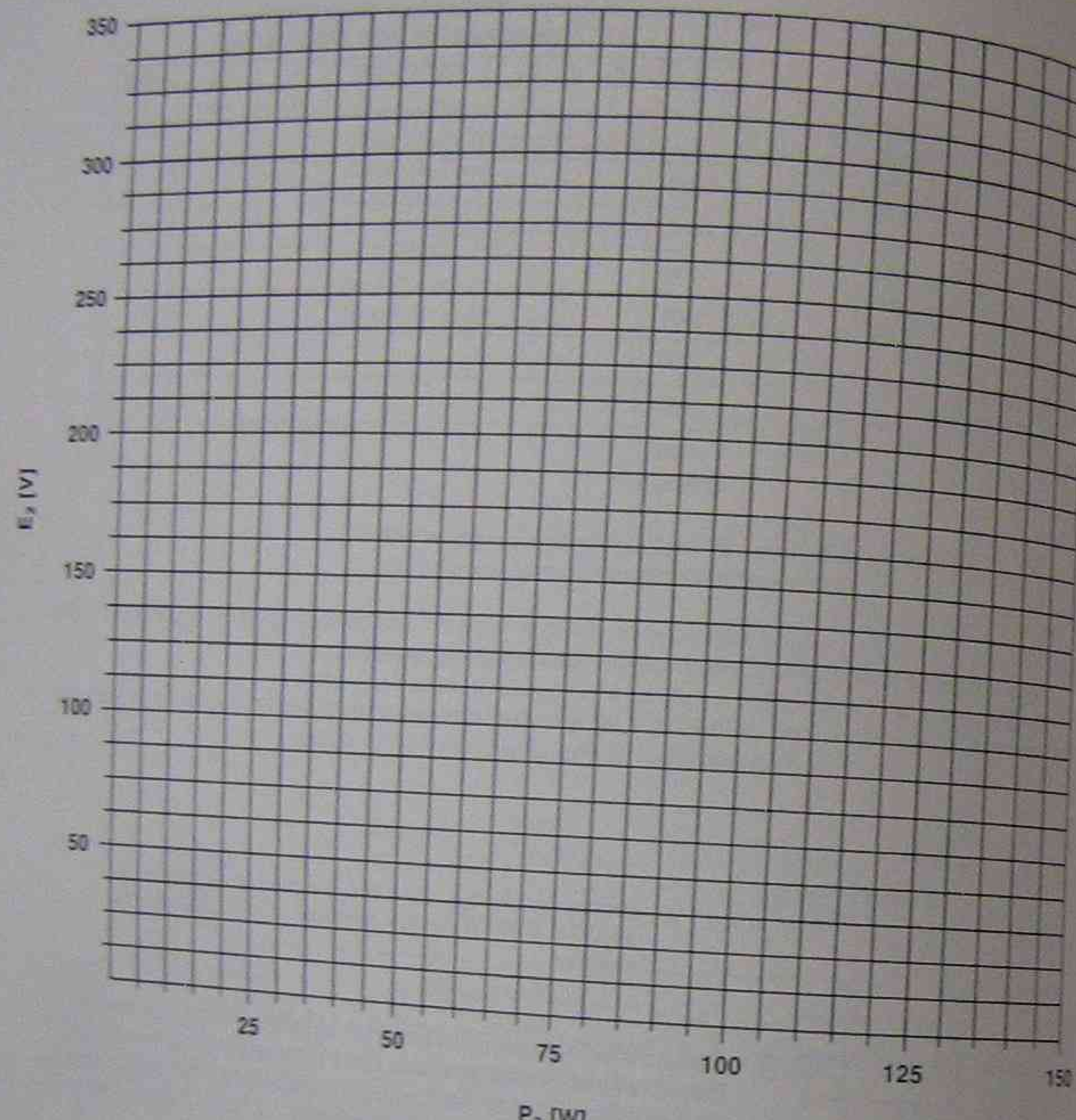


Figure 5-2.

☐ 4. In this experiment, we shall observe a significant voltage drop along a transmission line even when the voltages E_1 and E_2 at the sender and receiver ends are equal in magnitude. How is it possible to have a voltage drop when the voltages at the two ends are equal? The answer is that the drop is due to the phase angle between the two voltages.

Using the circuit shown in Figure 5-3, set the load resistance per phase at 686 Ω, and with E_1 = 350 V, adjust the capacitive reactance until the load voltage is as close as possible to 300 V. Measure E_1, P_1, Q_1, E_2, P_2, Q_2, E_3 and the phase angle.

E_1 = _______ V E_2 = _______ V E_3 = _______ V

P_1 = _______ W P_2 = _______ W

Q_1 = _______ var Q_2 = _______ var

Phase angle = _______ °

VOLTAGE REGULATION WITH RESISTIVE LOAD								
R	X_C	E_1	P_1	Q_1	E_2	P_2	Q_2	ANGLE
Ω	Ω	V	W	var	V	W	var	°
∞								
4800								
2400								
1600								
1200								
960								
800								
686								

Table 5-2.

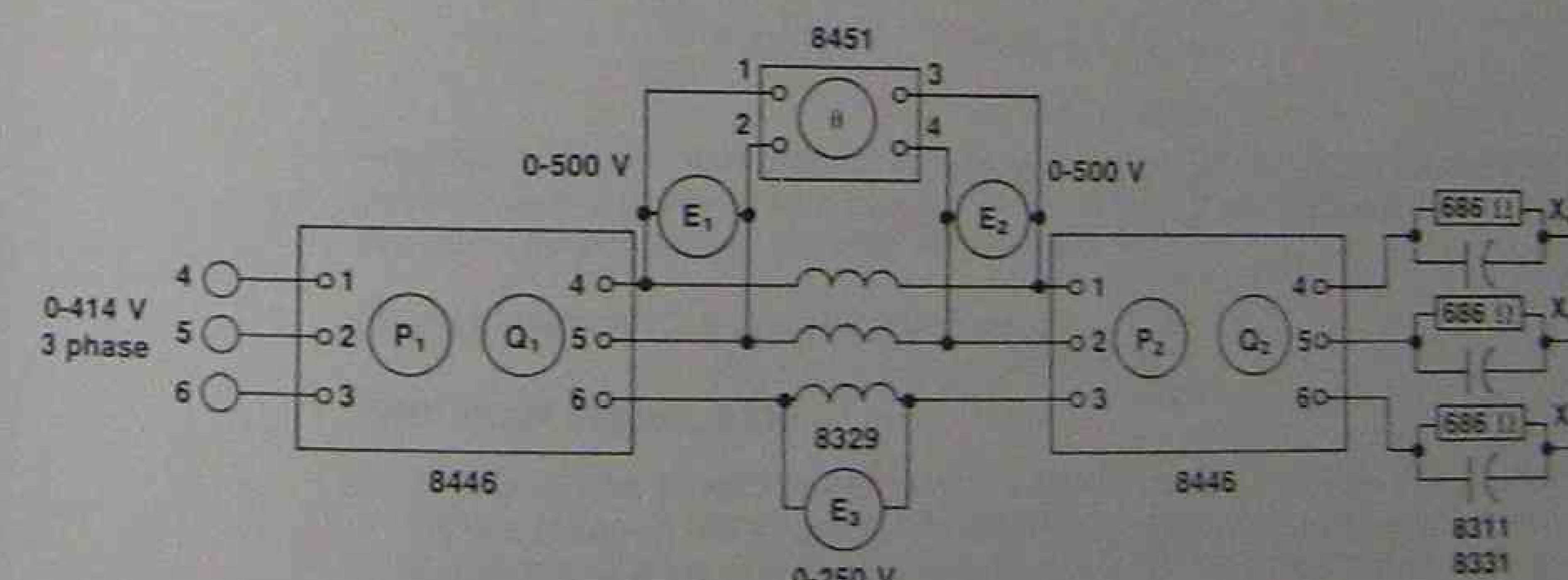


Figure 5-3.

☐ 5. Using the results of procedure step 4, calculate the voltage, current, real power and reactive power per phase. Draw a phasor diagram of the sender and receiver-end voltages, and verify the voltage drop against the measured value. (See sample calculation further in this experiment).

Sample Calculation

To understand the results of procedure step 4, we shall make a brief analysis assuming the following readings:

$E_1 = 350$ V $\quad E_2 = 350$ V $\quad E_3 = 165$ V

$P_1 = +600$ W $\quad P_2 = +510$ W

$Q_1 = +170$ var $\quad Q_2 = -280$ var

Phase angle = 48° lag

We shall reduce all voltages and powers to a per-phase basis, assuming a star-connection. Since E_1 and E_2 are the line-to-line voltages, the corresponding line-to-neutral voltages are 0.577 ($1\sqrt{3}$) times the line-to-line voltages.

Real power Q_2 is smaller than P_1 because of the I^2R loss in the transmission line.

Furthermore, the source is delivering 170 var to the right, while the load (owing to the negative sign) is delivering 280 var to the left. As a result, the transmission line is absorbing (170 + 280) = 450 var.

The real and reactive powers per phase are ⅓ of the values indicated above. The per-phase values are therefore as follows:

$E_1/\sqrt{3} = 350/\sqrt{3} = 202$ V

$E_2/\sqrt{3} = 350/\sqrt{3} = 202$ V

$E_3 = 165$ V

$P_1/3 = +200$ W

$P_2/3 = +170$ W

$Q_1/3 = +57$ var

$Q_2/3 = -93$ var

Phase angle = 48° lag

$$\frac{E_1}{\sqrt{3}} = 202 \text{ V}$$

$$\frac{E_2}{\sqrt{3}} = 202 \text{ V}$$

$$\frac{E_1}{\sqrt{3}} = \frac{E_2}{\sqrt{3}} = 164 \text{ V}$$

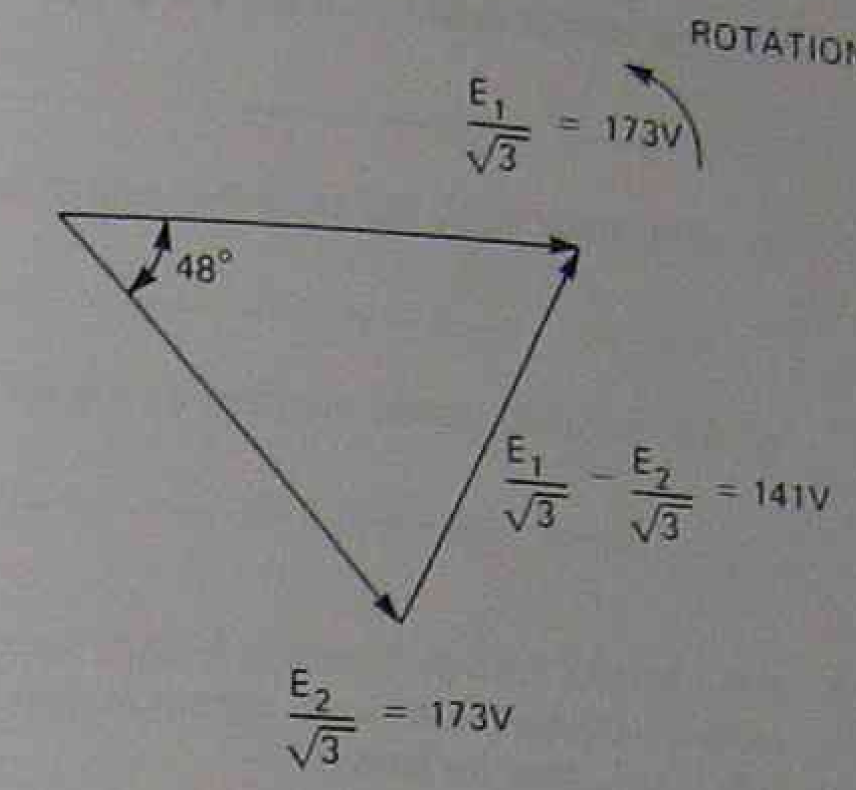


Figure 5-4.

If we draw phasor $E_2/\sqrt{3}$ 48 degrees behind phasor $E_1/\sqrt{3}$, we can scale off the length of the vector $(E_1/\sqrt{3}) - (E_2/\sqrt{3})$. It is found to be 164 V which is very close to the measured voltage drop E_3 in the line.

The reactive power received by the line (per-phase) is (93 + 57) = 150 var.

The real power consumed by the line due to its resistance is (200 − 170) = 30 W.

The apparent power absorbed by the line is $\sqrt{150^2 + 30^2} = 153$ VA.

Since the voltage drop across one line is 164 V, the current in the line must be

$$I = \frac{S}{E_3} = \frac{153}{164} = 0{,}933 \text{ A}$$

We could, of course, have measured this current directly, but a measurement of the real and reactive power and a knowledge of the voltages is sufficient to enable us to calculate everything about the line.

CALCULATIONS OF PROCEDURE STEP 5

TEST YOUR KNOWLEDGE

1. A three-phase transmission line has a reactance of 100 Ω per phase. The sender voltage is 100 kV and the receiver voltage is also regulated to be 100 kV by placing a bank of static capacitors in parallel with the receiver load of 500 MW. Calculate

   a) The reactive power furnished by the capacitor bank.

   ____

   b) The reactive power supplied by the sender.

   ____

c) The voltage drop in the line per phase.

____

d) The phase angle between the sender and receiver voltages.

____

e) The apparent power supplied by the sender.

____

2. If the 50 MW load in Question 1 were suddenly disconnected calculate the receiver voltage which would appear across the capacitor bank. What precaution, if any, must be taken?

____

____

____

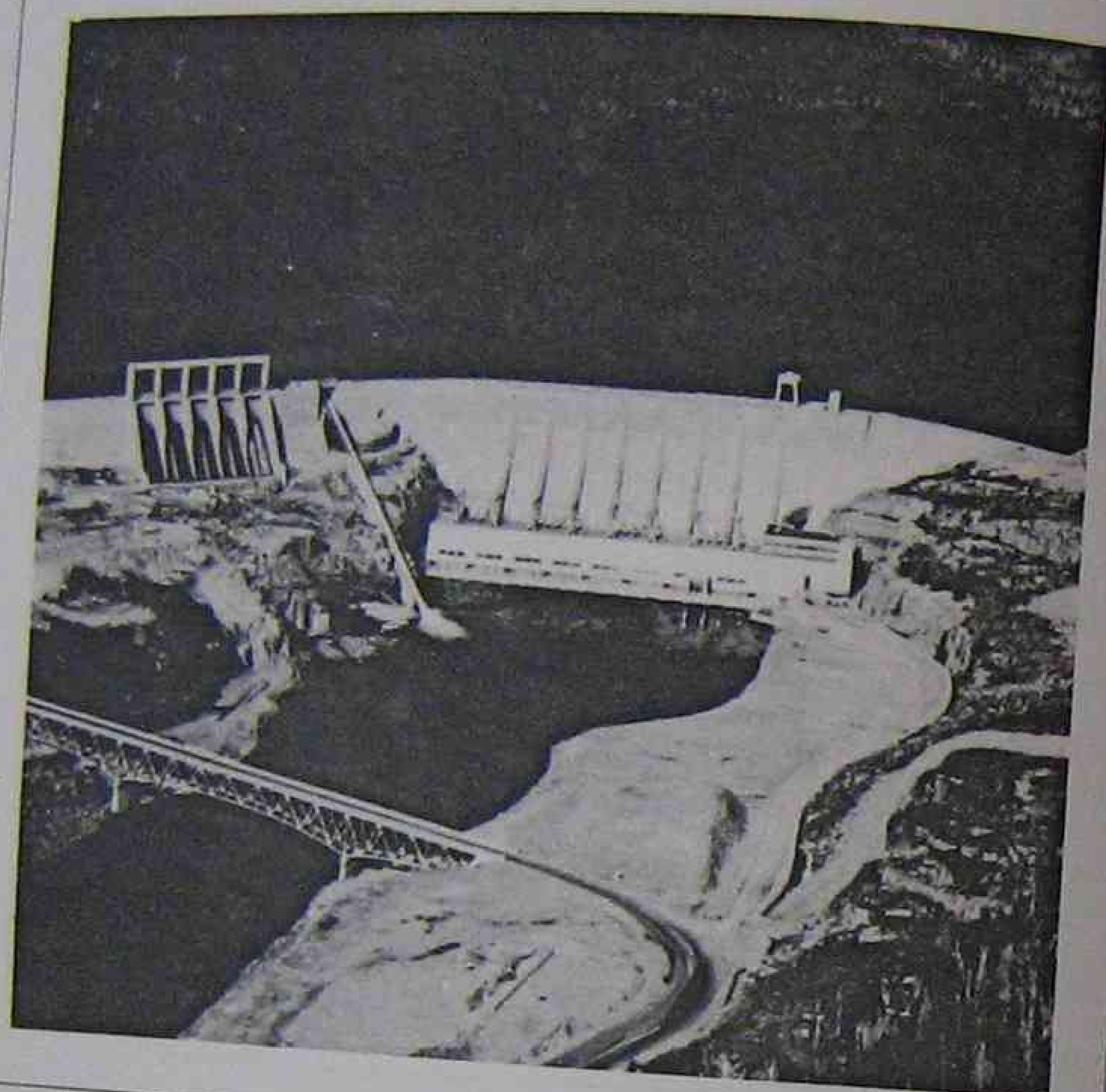
3. If a transmission line were purely resistive, would it be possible to raise the receiver end voltage by using static capacitors?

☐ Yes ☐ No

Explain ______________________________

____

____



An aerial view of the Manicouagan Power Station N° 2 Quebec (Canada). The dam is 94 meters high, 692 meters wide and the water falls through a height of 72 meters.

Experiment 6

Parameters which affect Real and Reactive Power Flow

OBJECTIVES

- To observe reactive power flow when sender and receiver voltages are different, but in phase.
- To observe real power flow when sender and receiver voltages are equal, but out of phase.
- To study the flow of real and reactive power when sender and receiver voltages are different and out of phase.

DISCUSSION

Transmission lines are designed and built to deliver electric power. Power flows from the generator (sender end) to the load (receiver end) but, in complex interconnected systems, the sender and receiver ends may become reversed. Power in such a line may flow in either direction depending upon the system load conditions which, of course, vary throughout the day. The character of the load also changes from hour to hour, both as to kVA loading and as to power factor. How, then, can we attempt to understand and solve the flow of electric power under such variable conditions of loading, further complicated by the possible reversal of source and load at the two ends of the line?

We can obtain meaningful answers by turning to the voltage at each end of the line. In Figure 6-1 a transmission line having a reactance of X Ω (per phase) has sending and receiving end voltages at E_1 and E_2 V respectively. If we allow these voltages to have any magnitude or phase relationship, we can represent any loading condition we please. In other words, by letting E_1 and E_2 take any values and any relative phase angle, we can cover all possible loading conditions which may occur.

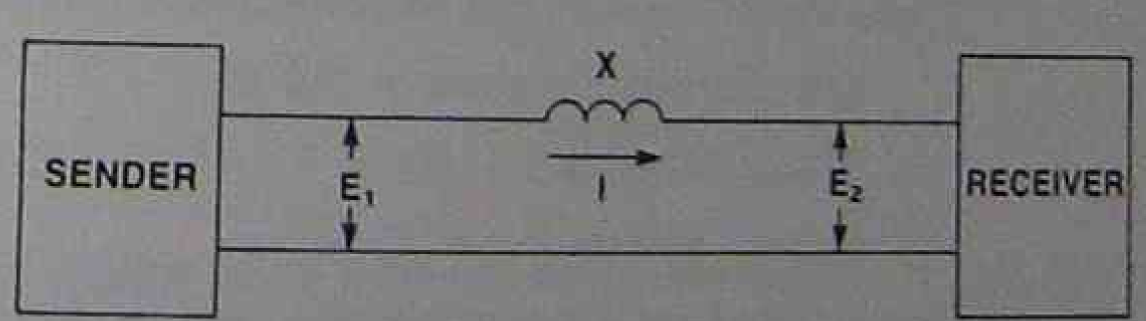


Figure 6-1.

Referring to Figure 6-1, the voltage drop along the line is $E_1 - E_2$; consequently, for a line having a reactance X, the current I can be found by the equation:

$$I = \frac{E_1 - E_2}{X}$$

when $E_1 - E_2$ is the phasor difference between the sending and receiving end voltage (refer to Figure 6-2). It should be borne in mind that we are dealing with phasors and that these have both an angle and a magnitude.

Note: *A transmission line is both resistive and reactive, but we shall assume that the reactance is so much larger that the resistance may be neglected.*

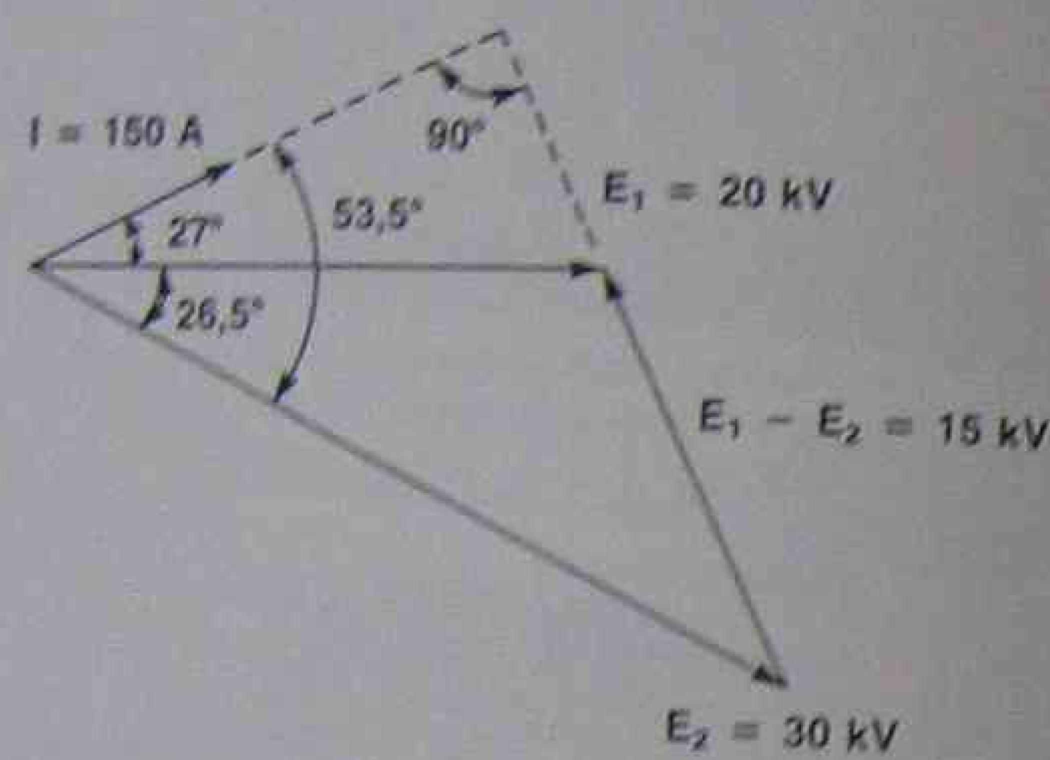


Figure 6-2.

Note: *When determining the sine and cosine of the angle between voltage and current, the current is always chosen as the reference phasor. Consequently, because E_1 lags behind I by 27°, the angle is negative.*

If we know the value of E_1 and E_2, and the phase angle between them, it is a simple matter to find the current I, knowing the reactance X of the line. From this knowledge we can calculate the real and reactive power which is delivered by the source and received by the load.

Suppose, for example, that the properties of a transmission line are as follows:

Line reactance per phase = 100 Ω

Sender voltage (E_1) = 20 kV

Receiver voltage (E_2) = 30 kV

Receiver voltage lags behind sender voltage 26,5°.

These line conditions are represented schematically in Figure 6-3. From the phasor diagram, on Figure 6-2, we find that the voltage drop ($E_1 - E_2$) in the line has a value of 15 kV. The current I has a value of 15 kV/100 Ω = 150 A and it lags behind ($E_1 - E_2$) by 90°. From the geometry of the figure, we find that the current leads E_1 by 27°. The active and reactive power of the sender and the receiver can now be found.

The real power delivered by the sender is

150 A × 20 kV × cos (−27°) = +2670 kW.

The real power received by the receiver is

150 A × 30 kV × cos (−53,5°) = +2670 kW.

The reactive power delivered by the sender is

150 A × 20 kV × sin (−27°) = −1360 kvar.

The reactive power received by the receiver is

150 A × 30 kV × sin (−53,5°) = −3610 kvar.

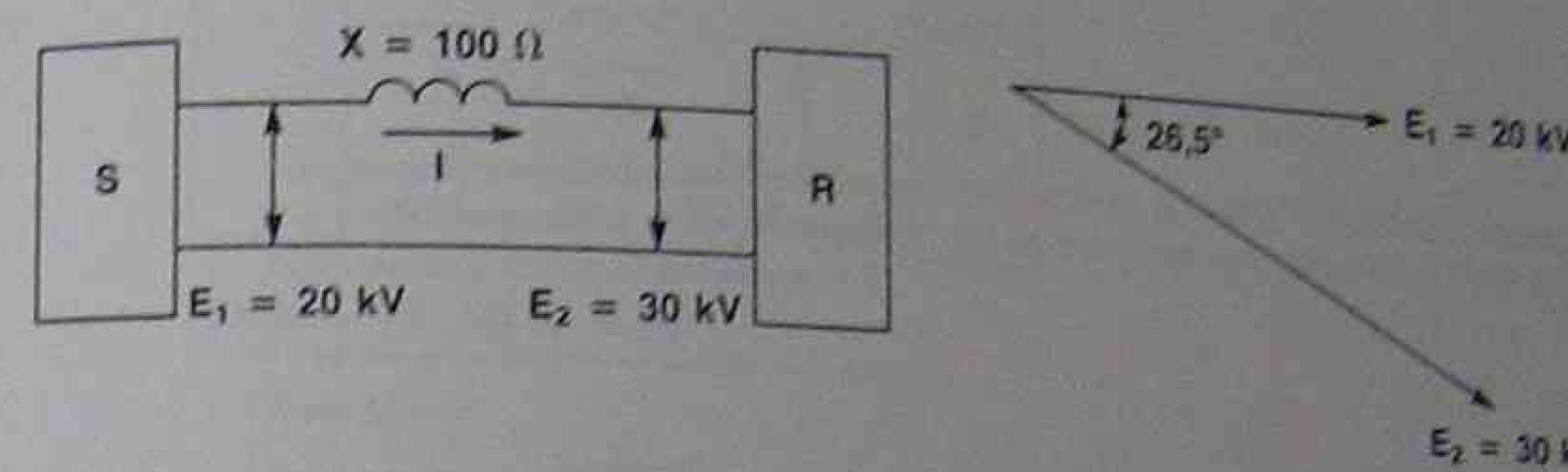


Figure 6-3.

Based upon the results calculated above, if wattmeters and varmeters were placed at the sender and receiver ends they would give readings as shown in Figure 6-4. This means that active power is flowing from the sender to the receiver, and owing to the absence of line resistance, none is lost in transit.

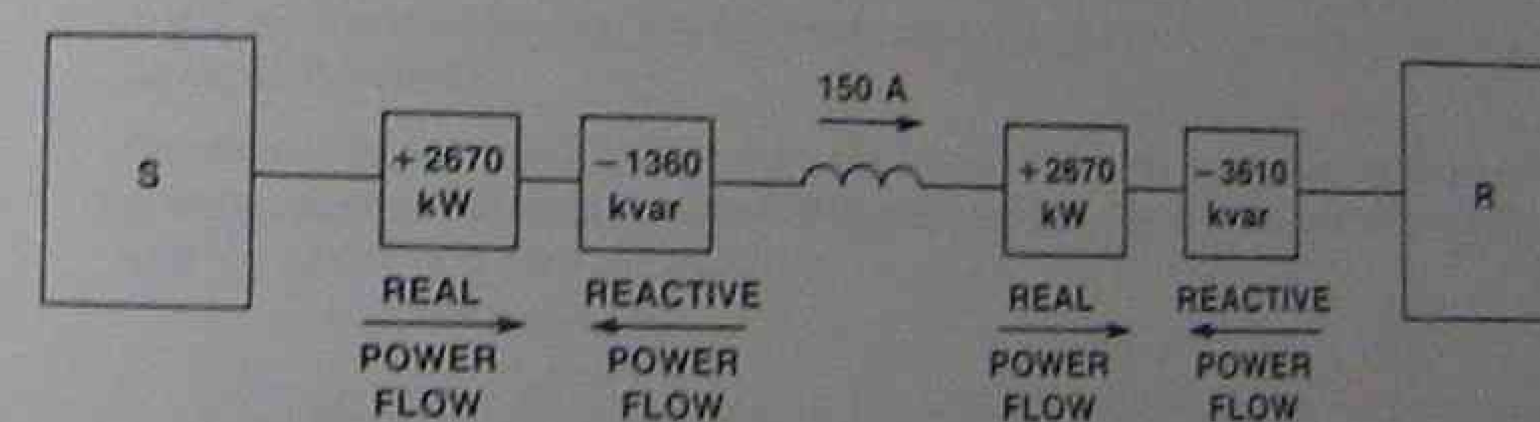


Figure 6-4.

However, reactive power is flowing from receiver to sender and, during transit, 3160 − 1360 = 2250 kvar are consumed in the transmission line. This reactive power can be checked against

Line kvar = $I^2X = 150^2 \times 100 = 2250$ kvar.

It will be noted that this is not the first time that we have found real power and reactive power flowing simultaneously in opposite directions.

Reactive Power

When the voltages at the sender and receiver ends are in phase, but unequal, reactive power will flow. The direction of flow is always from the higher voltage to the lower voltage.

Consider a transmission line in which the voltage at the sender and receiver ends are 30 kV and 20 kV respectively and the line reactance is 100 Ω (Figure 6-5).

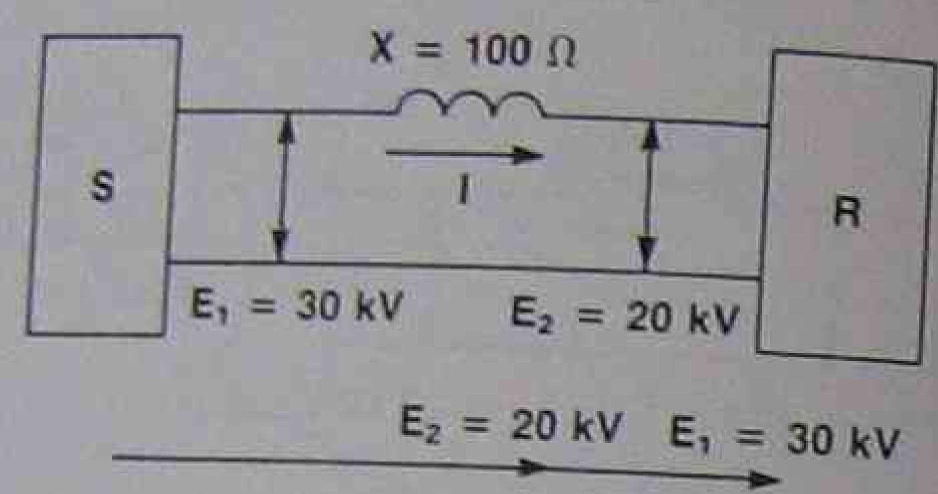


Figure 6-5.

The voltage drop in the line is 10 kV, and the current is 10 kV/100 = 100 A as shown in Figure 6-6.

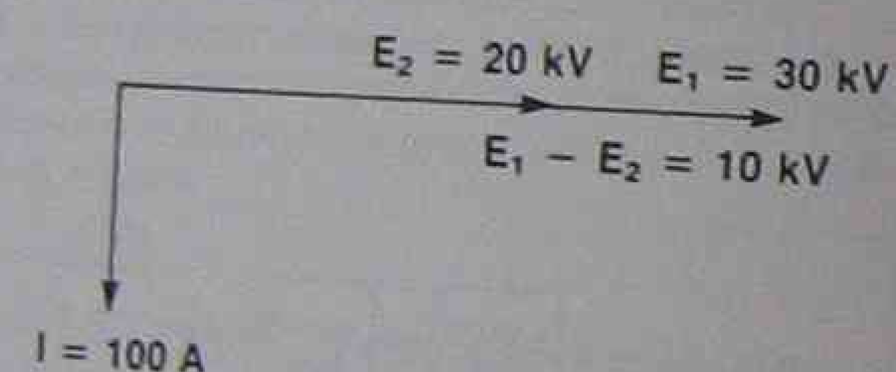


Figure 6-6.

The real power delivered by the sender end is

100 A × 30 kV × cos (+90°) = 0 W.

The real power received by the receiver is

100 A × 20 kV × cos (+90°) = 0 W.

The reactive power delivered by the sender end is

100 A × 30 kV × sin (+90°) = +3000 kvar.

The reactive power received by the receiver is

100 A × 20 kV × sin (+90°) = +2000 kvar.

If wattmeters and varmeters were placed at each end, the readings would be as shown in Figure 6-7.

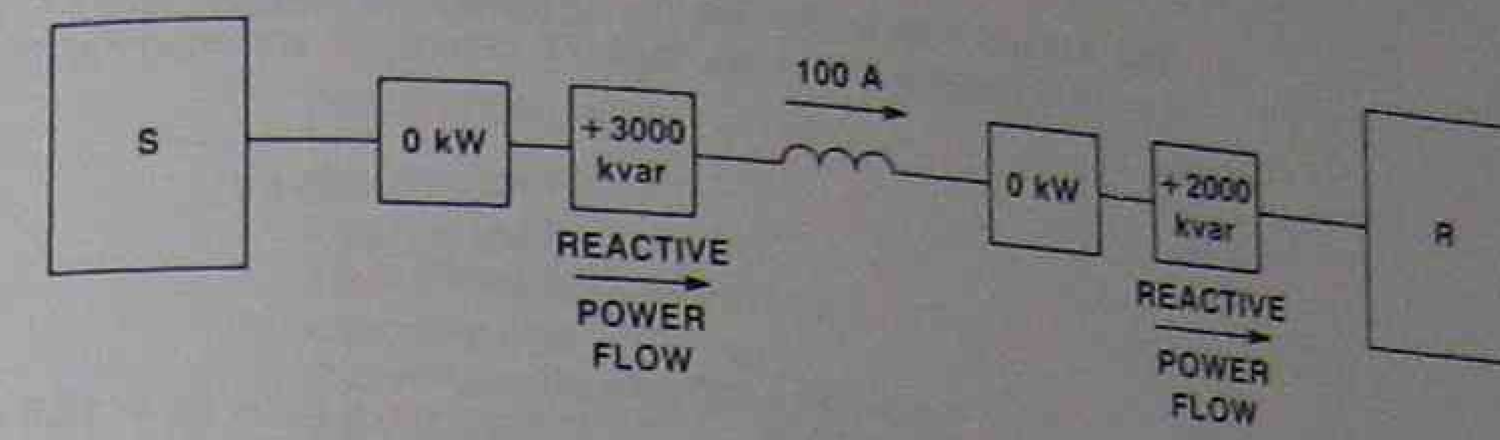


Figure 6-7.

Reactive power flows from the sender to the receiver, and 100 kvar are absorbed in the transmission line during transit. As can be seen, reactive power flows from the high-voltage to the low-voltage side.

Real power

Real power can only flow over a line if the sender and receiver voltages are out of phase. The direction of power flow is from the leading to the lagging voltage end. Again, it should be noted that this rule applies only to transmission lines which are principally reactive.

The phase shift between the sender and receiver voltages can be likened to an electrical "twist", similar to the mechanical twist which occurs when a long steel shaft delivers mechanical power to a load. Indeed, the greater the electrical "twist" the larger will the real power flow become. However, it is found that it attains a maximum when the phase angle between the sender and receiver ends is 90°. If the phase angle is increased beyond this (by increased loading) it will be found that less real power is delivered.

Consider a transmission line in which the voltages at each end are equal to 30 kV and the receiver voltage lags behind the sender by 30°. The line reactance is 100 Ω, and the circuit is shown in Figure 6-8.

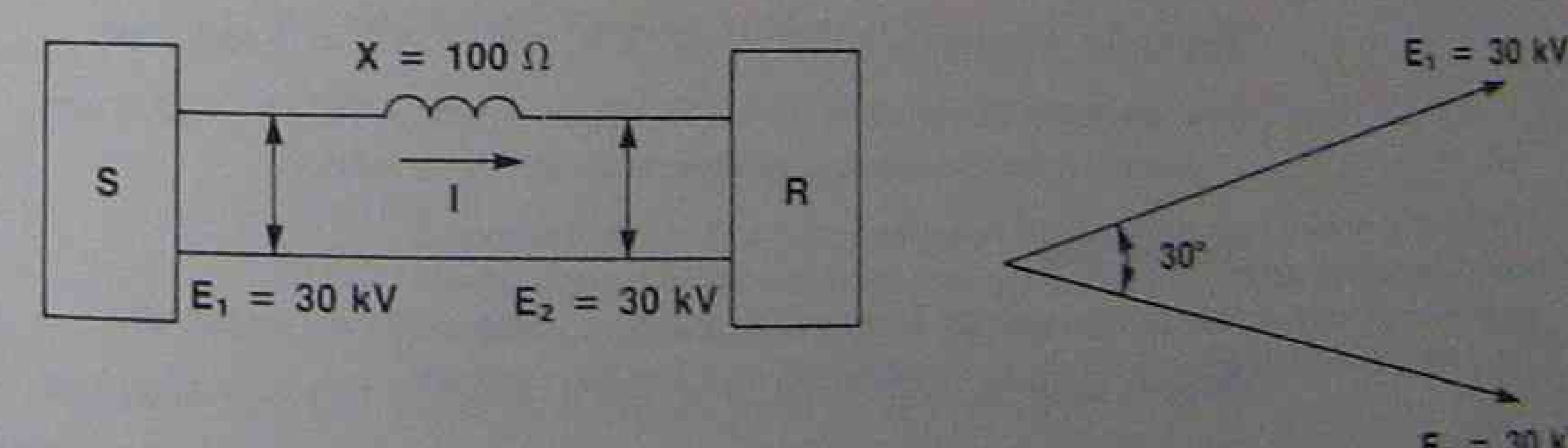


Figure 6-8.

The voltage drop in the line ($E_1 - E_2$) is found to be 15.5 kV, so the current I = 15 550/100 = 155 A and lags 90° behind, as shown in Figure 6-9.

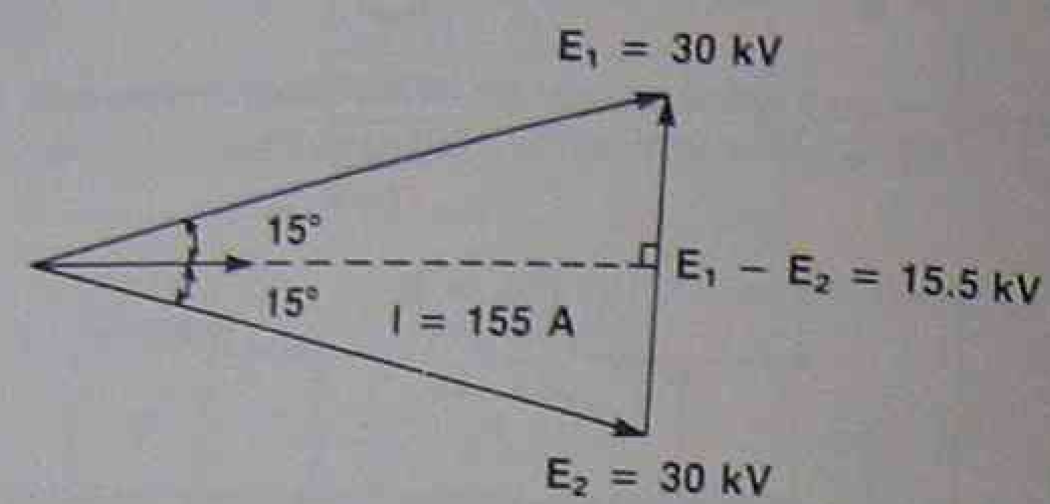


Figure 6-9.

Taking the current as the reference phasor, we can find the real and reactive power associated with the sender and the receiver end as shown in Figure 6-10.

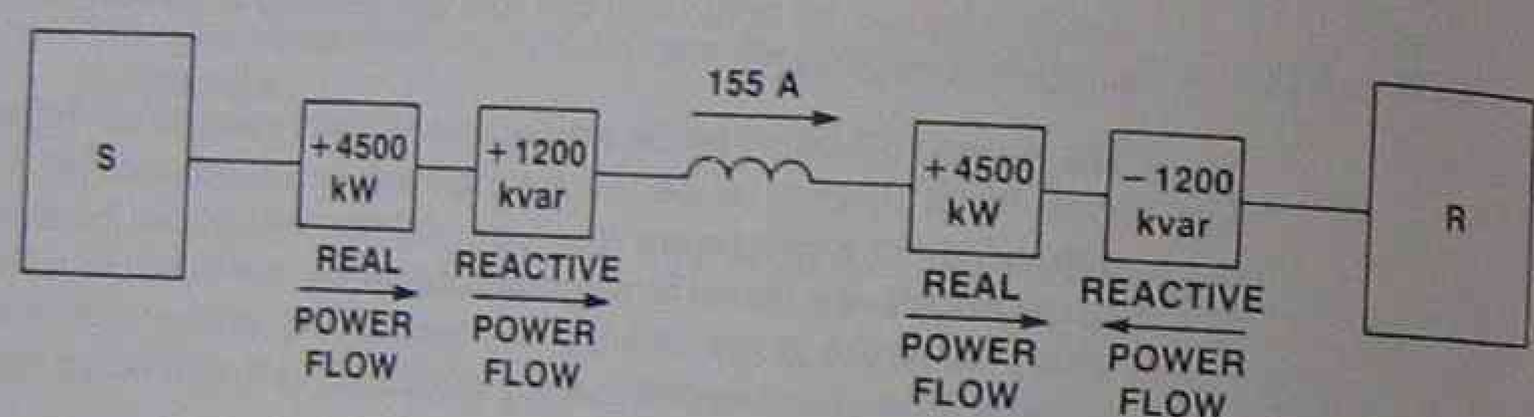


Figure 6-10.

Sender End

Real power delivered = 30 kV × 155 A × cos (+15°) = +4500 kW.

Reactive power delivered = 30 kV × 155 A × sin (+15°) = +1200 kvar.

Receiver End

Real power received = 30 kV × 155 A × cos (−15°) = +4500 kW.

Reactive power received = 30 kV × 155 A × sin (−15°) = −1200 kvar.

The sender delivers both active and reactive power to the line and the receiver absorbs active power from it. However, the receiver delivers reactive power to the line, so that the total reactive power received by the line is 2400 kvar.

This example shows that a phase shift between sender and receiver voltages causes both real and reactive power to flow. However, for angles smaller than 45° the real power considerably exceeds the reactive power.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Resistive Load	8311
Inductive Load	8321
Three-Phase Transmission Line	8329
Capacitive Load	8331
Three-Phase Regulating Autotransformer	8349
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Phase Meter	8451
Power Supply	8821
Connection Leads	9128

PROCEDURE

Note: *These experiments may be carried out by two collaborating groups.*

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

In order to convey a sense of realism to the terms "sender" and "receiver" two consoles manned by two student groups will be used in the following experiments. A transmission line will connect the two consoles (Station A and B) and the active and reactive power flow between them will be studied. The experiment will be conducted in three parts.

1. Sender and Receiver voltages unequal, but in phase.
2. Sender and Receiver voltages equal, but out of phase.
3. Sender and Receiver voltages unequal, and out of phase.

Sender and Receiver voltages unequal, but in phase

☐ 1. Connect a three-phase transmission line between terminals 4, 5, 6 (variable AC output) of two consoles, one of which is designated as station A and the other, station B. Connect the two Three-Phase Wattmeter/Varmeters at each end as well as a Phase Meter as shown schematically in Figure 6-11.

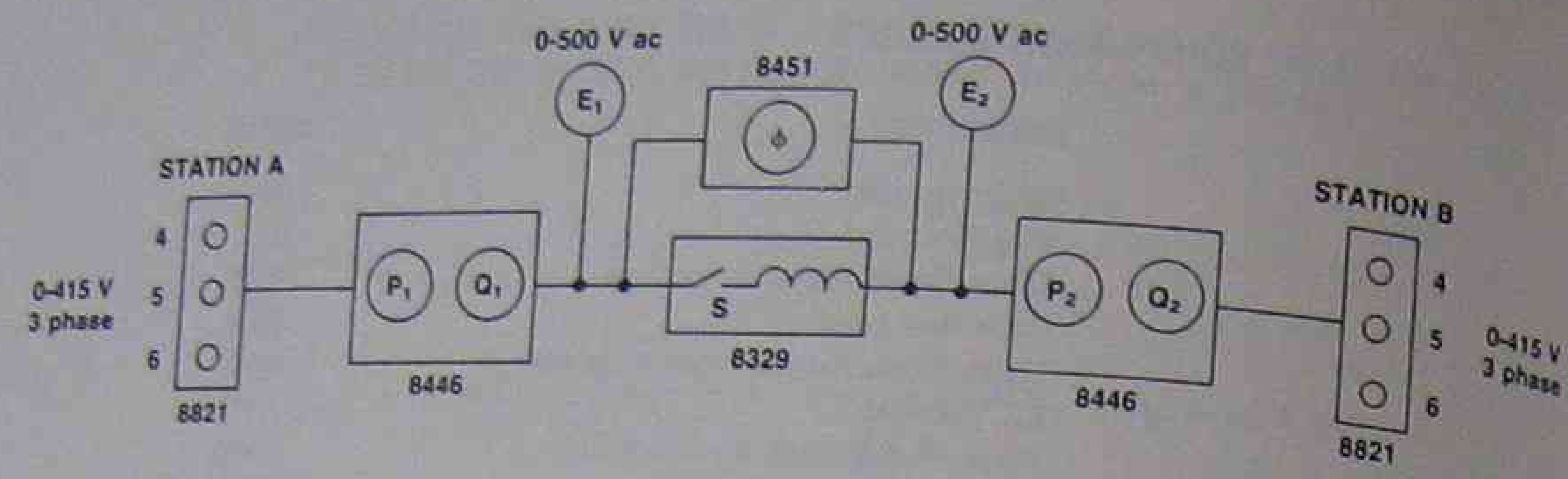


Figure 6-11.

☐ 2. With the transmission line switch S open, adjust the line-to-line voltages so that E_1 and E_2 are both equal to 370 V and observe that the phase angle is zero between terminals 4-5 of station A and terminals 4-5 of station B. (If the phase angle is not zero, see procedure step 8 of Experiment 2).

Is phase angle zero?

☐ Yes ☐ No

☐ 3. Without making any changes, measure the phase angle between terminals 4-5 of station A and terminals 5-4 of station B.

☐ Phase angle lag ☐ Phase angle lead

☐ 4. Without making any changes, measure the phase angle between terminals 4-5 of station A and terminals 5-6 of station B.

☐ Phase angle lag ☐ Phase angle lead

☐ 5. Measure the phase angle between terminals 4-5 of station A and terminals 6-4 of station B.

☐ Phase angle lag ☐ Phase angle lead

☐ 6. By measuring all phase angles between line and neutral of station A and B prove that the phasor diagram for both stations is as given in Figure 6-12.

The purpose of this preliminary phase angle check is to familiarize ourselves with the phase angles between the voltages at the two stations.

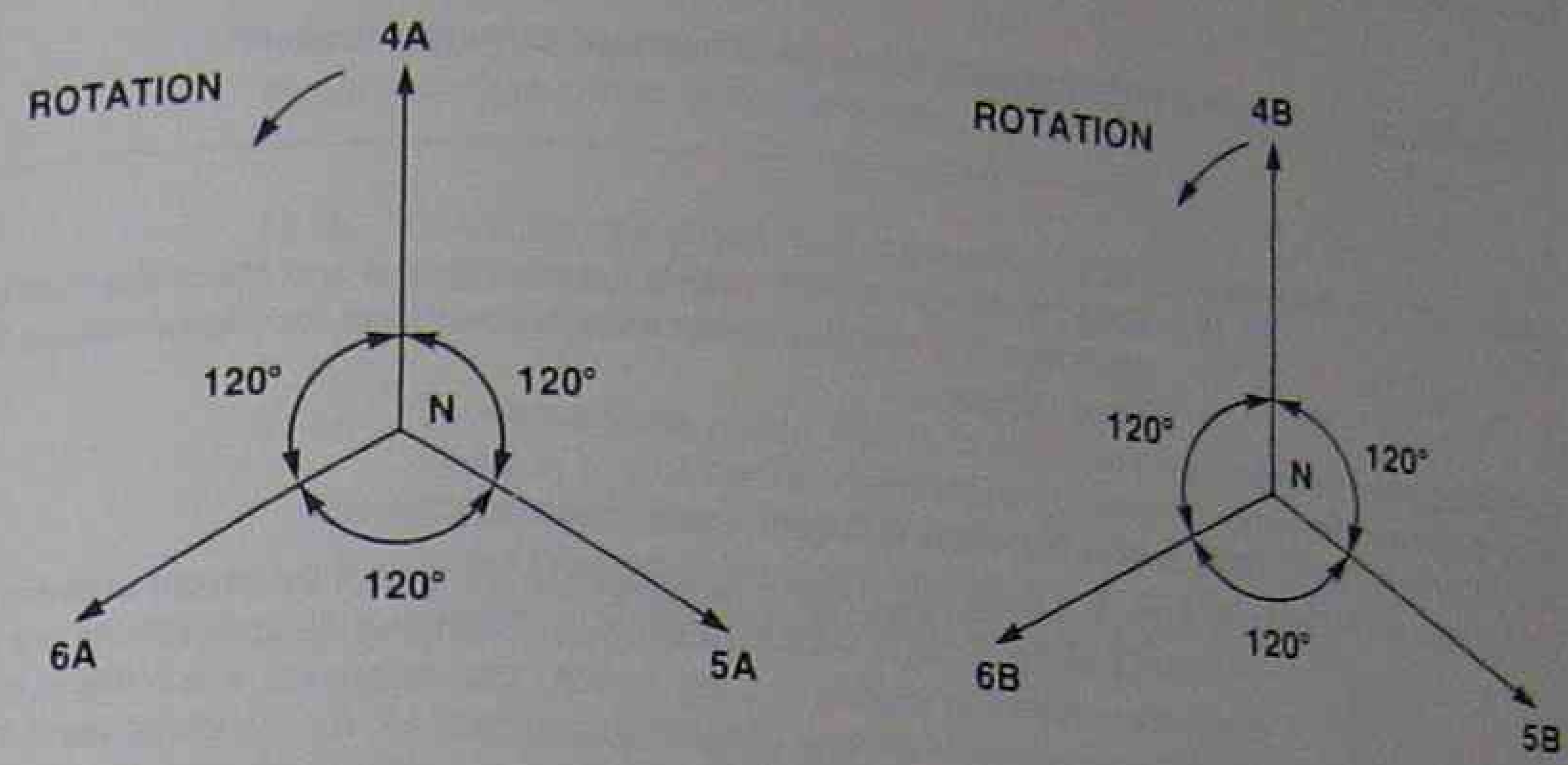


Figure 6-12.

☐ 7. Close the Three-Phase Transmission Line switch; with $E_1 = E_2 = 370$ V, and the transmission line impedance = 200 Ω, observe the Three-Phase Wattmeter/Varmeter readings. There should be no significant power exchange.

P_1 = ______ W

P_2 = ______ W

Q_1 = ______ var

Q_2 = ______ var

☐ 8. Raise station A voltage to 415 V and observe power flow.

P_1 = ______ W

P_2 = ______ W

Q_1 = ______ var

Q_2 = ______ var

Which of the two stations would be considered to be the sender?

____

☐ 9. Reduce station A voltage to 350 V and observe power flow.

P_1 = ______ W

P_2 = ______ W

Q_1 = ______ var

Q_2 = ______ var

Which station would be considered to be the sender?

____

☐ 10. Vary the voltage of both station A and station B and check the truth of the statement that reactive power always flows from the higher voltage to the lower voltage.

Sender and Receiver voltages equal, but out of phase

Use the Three-Phase Regulating Autotransformer to shift the phase of station A by 15°. The phase shift (lag or lead) is obtained by changing the connections of a three-phase transformer by means of a tap switch. The manner in which this is accomplished is explained in greater detail in Experiment 11; for our purposes it is sufficient to know that when the position of the tap-switch is altered, the secondary voltage will either a) be in phase with the primary, b) lag the primary by 15° or, c) lead the primary by 15°.

☐ 11. Connect the phase-shift of the above autotransformer to the variable AC terminals 4, 5, 6 of station A. Adjust the voltage at stations A and B to 380 V with the Phase Meter. Determine the phase angle of the secondary voltage 4, 5, 6 with respect to the variable AC terminals 4, 5, 6 of the Power Supply of station B (see Figure 6-13). Record your readings for the three positions of the phase-shift tap switch in Table 6-1.

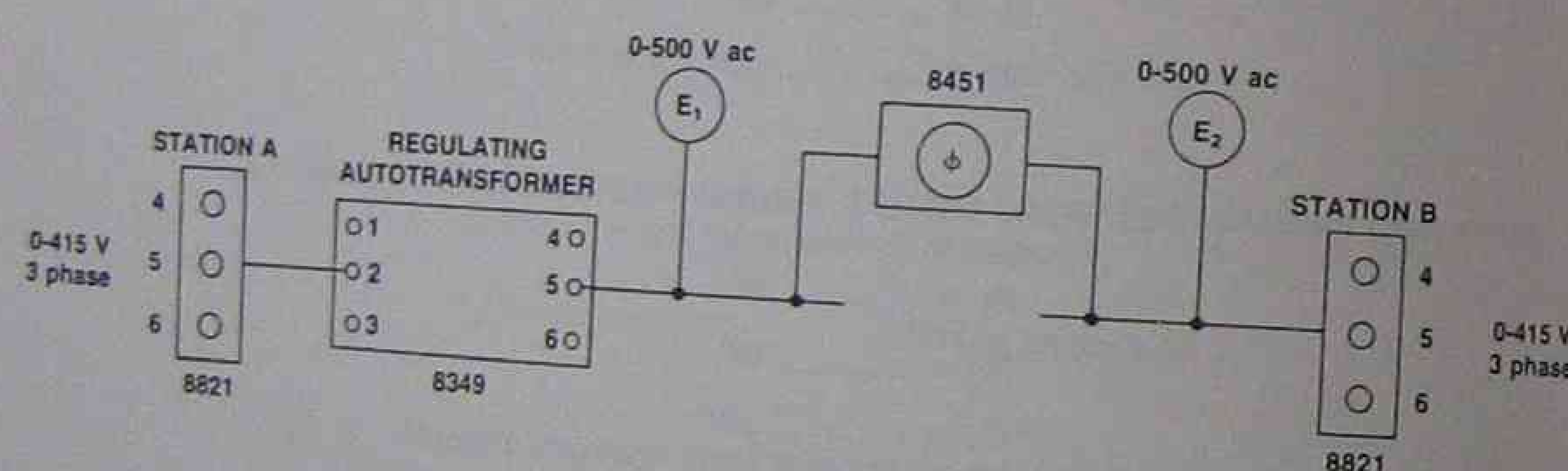


Figure 6-13.

TAP SWITCH POSITION	PHASE ANGLE (LAG/LEAD)	E_1	E_2
°	—	V	V
0			
+15			
−15			

Table 6-1.

Note: *The buck-boost tap switch must be kept at zero and the correct phase sequence must be applied to the primary of the transformer.*

☐ 12. Check that the phase-shift is the same for all three phases, and that all voltages are balanced.

☐ 13. Connect a three-phase, 400 Ω transmission line between secondary terminals 4, 5, 6 of the Three-Phase Regulating Autotransformer and Power Supply terminals of station B (see Figure 6-14). After inserting the Three-Phase Wattmeter/Varmeter at each end of the line, change the tap switch position and record your results in Table 6-2.

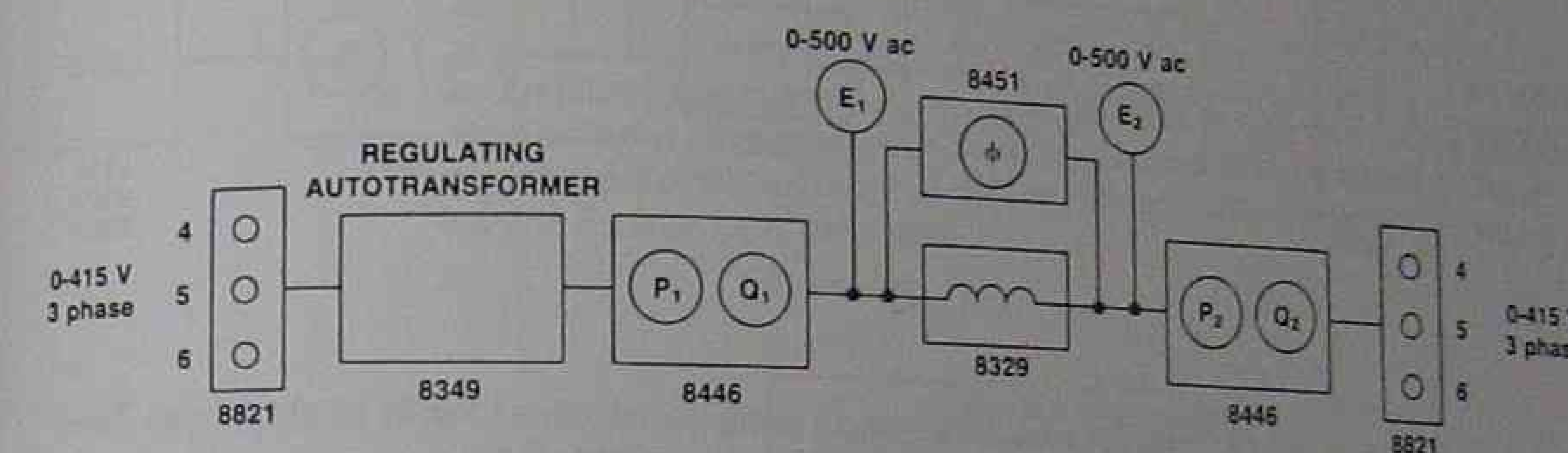


Figure 6-14.

TAP SWITCH POSITION	E_1	P_1	Q_1	E_2	P_2	Q_2	PHASE ANGLE
°	V	W	var	V	W	var	°
0							
+15							
−15							

Table 6-2.

Does this experiment bear out the statement that real power flows from the leading towards the lagging voltage side of a transmission line?

☐ Yes ☐ No

Sender and Receiver voltages unequal, and out of phase

In the following procedure steps we shall connect passive loads (resistive, inductive, and capacitive) at the receiver end of the line. The object of the experiment is to show that a phase shift between sender and receiver voltage occurs only when real power is being delivered to the load.

☐ 14. Using only one console, set up the experiment as shown in Figure 6-15, setting E_1 = 415 V and using a star-connected Resistive Load of 1200 Ω per phase and a 200 Ω Transmission Line. Take readings and record your results in Table 6-3.

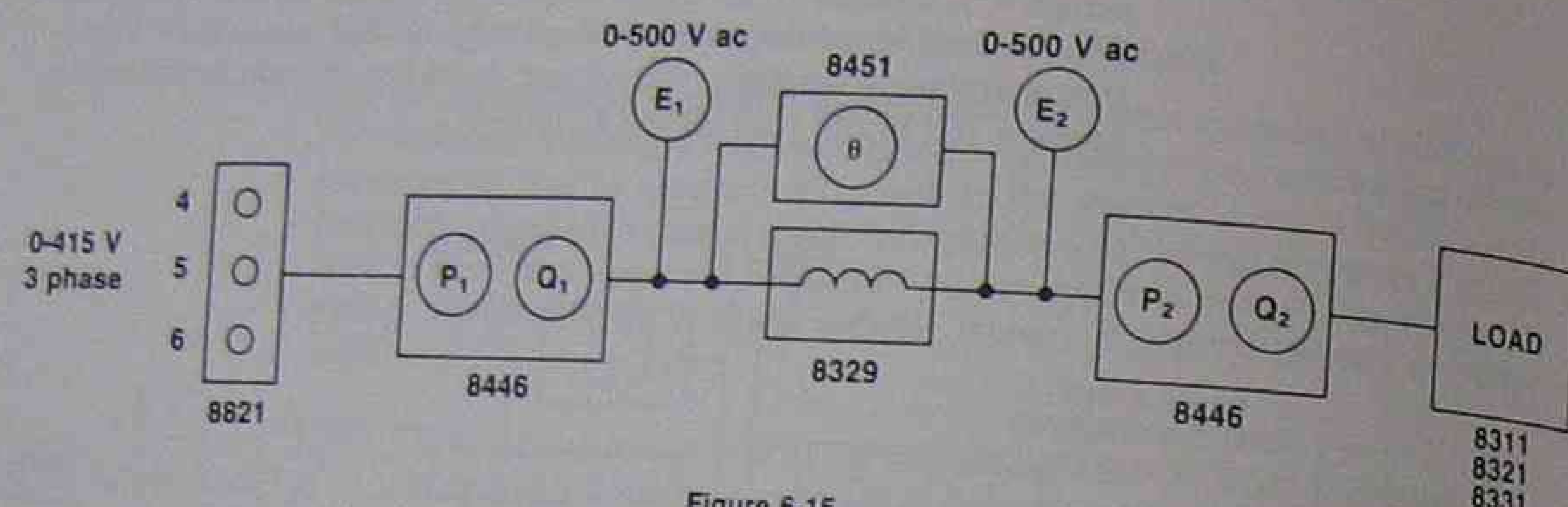


Figure 6-15.

☐ 15. Repeat procedure step 14 using an Inductive Load of 1200 Ω/phase. Take readings and record your results in Table 6-3.

☐ 16. Repeat procedure step 14 using a Capacitive Load of 1200 Ω/phase. Take readings and record your results in Table 6-3.

PROC. STEP	LOAD	E_1	P_1	Q_1	E_2	P_2	Q_2	PHASE SHIFT
		V	W	var	V	W	var	°
14	RESISTIVE							
15	INDUCTIVE							
16	CAPACITIVE							

Table 6-3.

TEST YOUR KNOWLEDGE

1. A three-phase transmission line has a reactance of 100 Ω and at different times throughout the day it is found that the sender and receiver voltages have magnitude and phase angles as given in Table 6-4.

   In each case calculate the real and reactive power of the sender and receiver and indicate the direction of the power flow. The voltages given are line-to-line.

E_S	E_R	PHASE ANGLE	SENDER		RECEIVER	
kV	kV		P MW	Q Mvar	P MW	Q Mvar
100	100	60° E_S LEADS E_R				
120	100	60° E_S LEADS E_R				
100	120	60° E_S LEADS E_R				
120	100	30° E_S LAGS E_R				
120	100	0°				

Table 6-4.

2. In Question 1 assume that $E_S = E_R$ = 100 kV at all times but that the phase angle between them changes in steps of 30° according to the Table 6-5. Calculate the value of the real power in each case as well as its direction of flow, knowing that E_R lags E_S in each case.

ϕ	SENDER P	RECEIVER Q
°	MW	MW
0		
30		
60		
90		
120		
150		
180		

Table 6-5.

Plot a graph of real power vs phase angle on Figure 6-16.

Is there a limit to the maximum power which such a line can deliver under the static voltage conditions?

☐ Yes ☐ No

TEST YOUR KNOWLEDGE

1. A 150 MW alternator generates an open-circuit line-to-line voltage of 12 kV at nominal DC excitation. When the terminals are placed in short-circuit the resulting current per phase is 8000 A.

a) Calculate the approximate value of the synchronous reactance per phase.

____

b) Draw the equivalent circuit of the alternator per phase under the DC field excitation conditions given above.

c) What is the nominal full load current per phase?

____

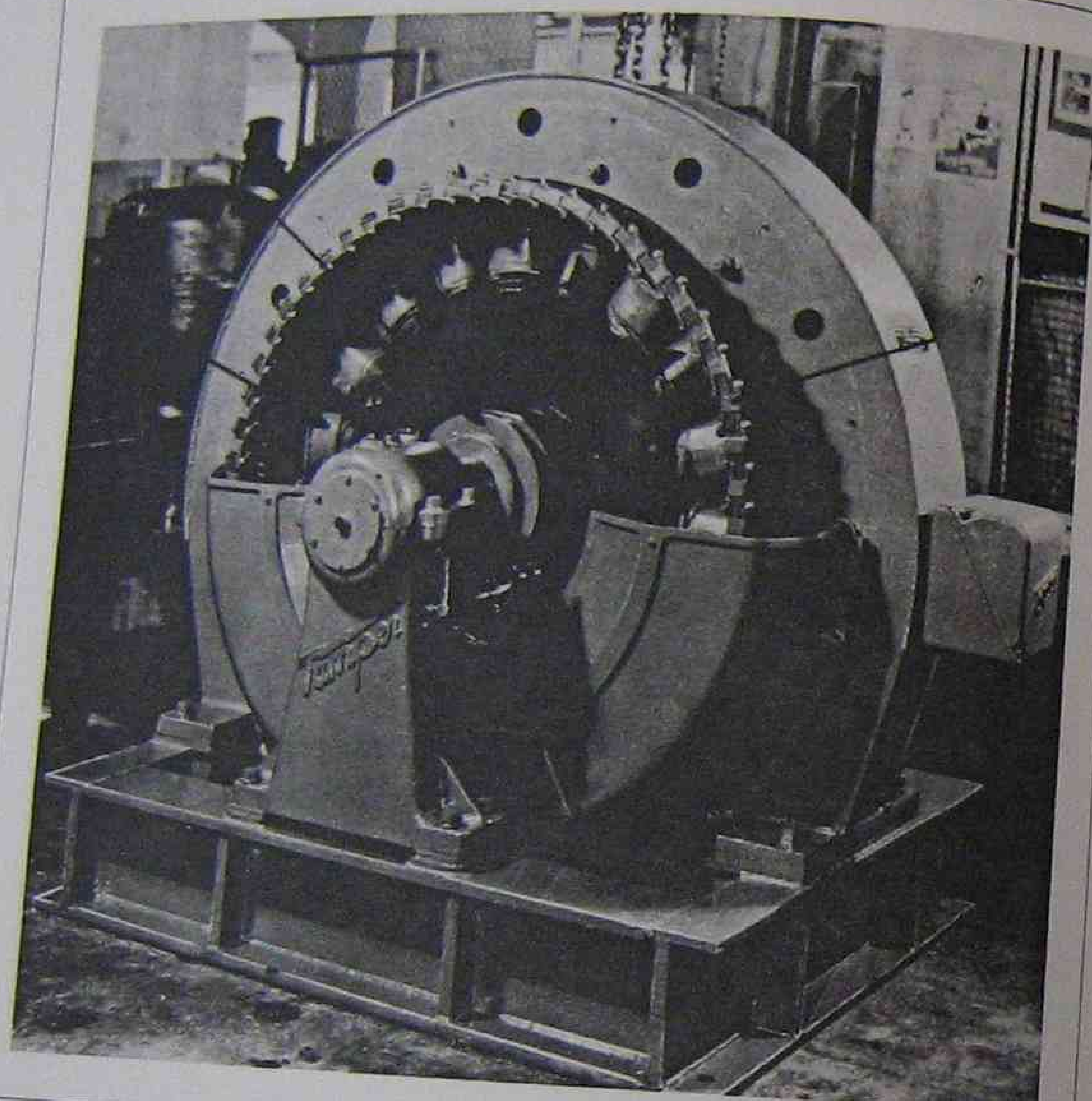
2. a) If the Three-Phase Synchronous Motor/Generator in Question 1 supplies a resistive load of 120 MW at a voltage of 12 kV, what must be the induced voltage E_O ?

____

b) What is the phase angle between E_O and the terminal voltage?

____

____



View of a 220 kW, 220 V, 327 r/min, 60 Hz Synchronous Motor.

The Synchronous Motor

OBJECTIVES

- To observe the behavior of a synchronous motor connected to an infinite bus, as regards:
  a) Reactive power flow in the synchronous motor.
  b) Real power flow in the synchronous motor.
  c) Change in position of the rotor poles.

DISCUSSION

A synchronous motor has the same construction as an alternator, and hence possesses the same electrical properties. Indeed, an alternator can be made to run as a synchronous motor and vice versa, the only distinction being that, as a motor, the machine receives electric power and converts it into mechanical power whereas, as an alternator, it does the reverse.

The circuit of a synchronous motor is identical to that of an alternator, consisting of a synchronous reactance X (per phase) and an induced AC voltage E_O created in the stator by the DC flux from the rotor poles. We shall first study the operation of the motor when it is connected to an infinite bus. As infinite bus is a source of electric power which is so immense that nothing we connect to it will change either its voltage, its frequency or the phase angles between its three phases. An infinite bus is, in effect, a source of voltage which has no internal impedance. The source E_S in Figure 9-1 is considered to be one phase of the infinite bus.

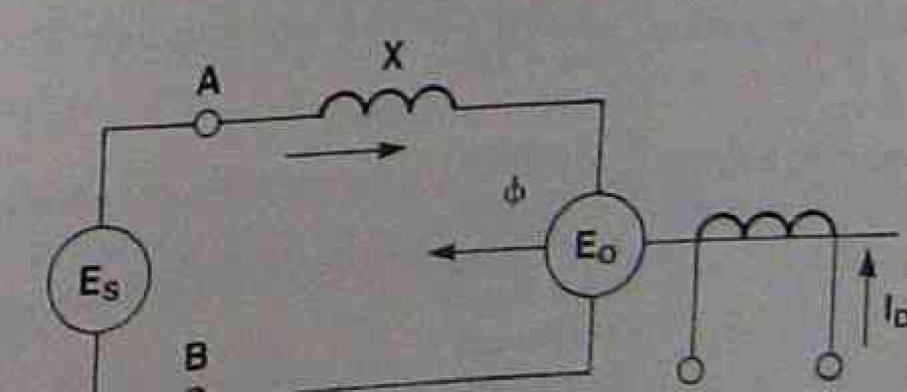


Figure 9-1.

The circuit of Figure 9-1 looks very much like that of a transmission line in which E_S and E_O are the sender and the receiver voltages. In fact, the flow of real and reactive power in this circuit is dictated by the same factors as in the case of a transmission line. Briefly,

a) If E_O is in phase with E_S, and if the two voltages are unequal, reactive power will flow. (If E_O is less than E_S, reactive power will flow from the source to the motor. If E_O is greater than E_S then reactive power will flow from the motor to the source.)

b) If E_O lags behind E_S, real power will flow from the infinite bus to the motor, giving it the energy to carry its mechanical load. Just as in the case of a transmission line, the maximum real power which can be delivered is equal to $(E_S E_O)/X_S$.

To vary the reactive power, E_O must be varied and this is readily done by changing the DC exciting current in the rotor windings.

To increase the real power, (for a fixed value of E_O and E_S) the phase angle between E_O and E_S must increase and this happens automatically when the mechanical load on the motor increases. When operating at no load, only a small amount of mechanical power is needed to overcome the windage and friction losses, consequently the motor draws only a small amount of real electric power. The phase angle between E_S and E_O is small under no-load conditions.

As the mechanical load is increased, E_O lags more and more behind E_S and when the lag is 90°, the motor power will reach its maximum value. If the mechanical load is increased beyond this point, the machine will fall out of synchronism and come to a halt.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
DC Motor/Generator	8211
Three-Phase Synchronous Motor/Generator	8241
Resistive Load	8311
DC Voltmeter/Ammeter	8412
AC Ammeter	8425
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Stroboscope	8922
Timing Belt	8942
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

Excitation and reactive power flow

☐ 1. Set up the experiment of Figure 9-2, connecting the stator to the fixed AC supply via the Three-Phase Wattmeter/Varmeter and the AC Ammeter. The field of the Three-Phase Synchronous Motor/Generator is connected to the variable DC source, in series with a DC Voltmeter/Ammeter.

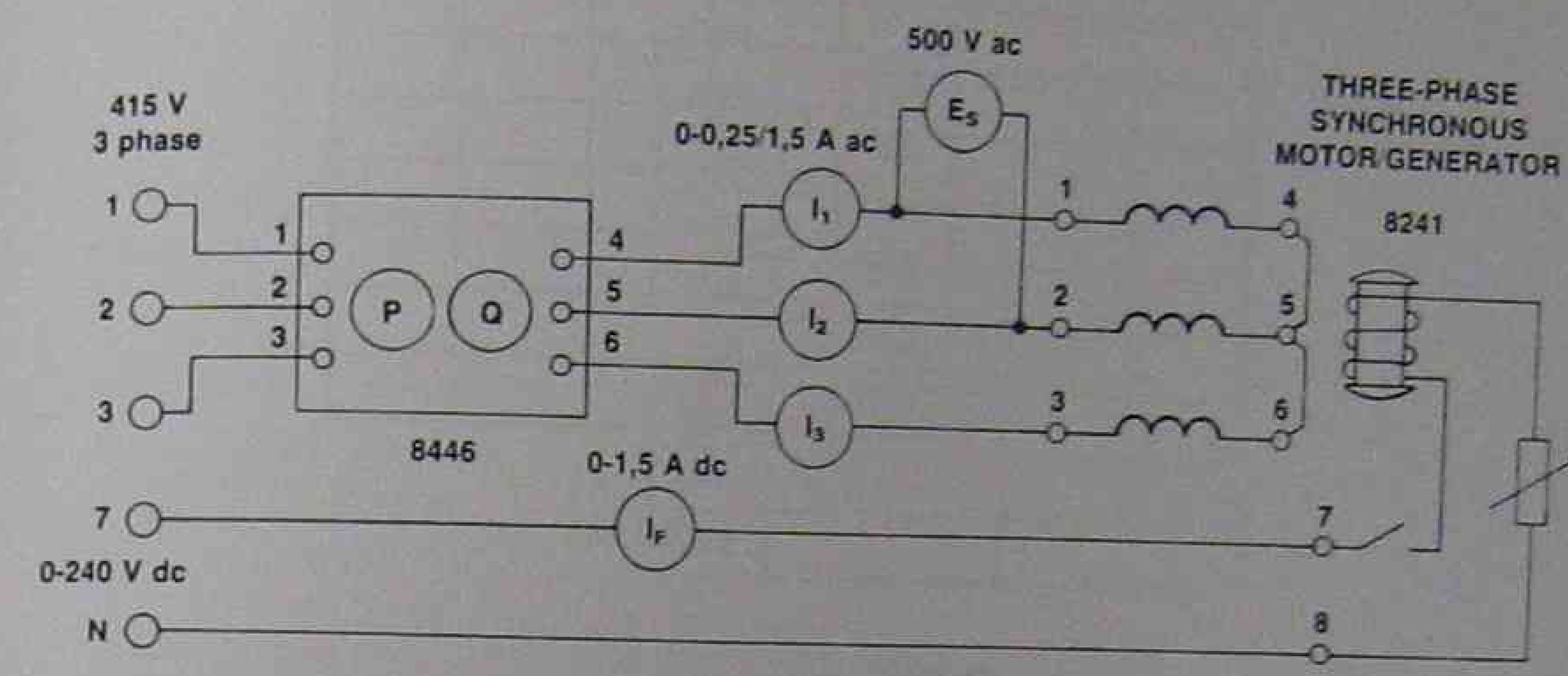


Figure 9-2.

Note: *The DC field should only be applied once the machine has come up to speed. The motor accelerates when 3-phase AC power is applied to the stator owing to the squirrel cage winding embedded in the poles.*

Apply AC power, and then apply DC current to the field. Increase the field current until the reactive power is zero. Note that if the excitation is varied above or below this value, the reactive power changes from negative to positive.

Vary the DC excitation gradually, starting at 0,05 A and increase it in steps up to 0,45 A and record your results in Table 9-1. Be sure to record the values of the particular case where var = 0.

Loading and real power

☐ 2. Couple the DC Motor/Generator to the Three-Phase Synchronous Motor as shown on Figure 9-3 and apply 3-phase AC power to the latter, followed by DC power to the rotor. Adjust the DC excitation so that the reactive power is zero when the generator shunt field current is minimum. Then, keeping the DC excitation of the synchronous motor constant, gradually load the motor by increasing the generator excitation, and observe the increase of active power.

VARIATION OF EXCITING VOLTAGE				
I_F	E_S	I	P	Q
A	V	A	W	var
0,05				
0,10				
0,15				
0,20				
0,25				
0,30				
0,35				
0,40				
0,45				

Table 9-1.

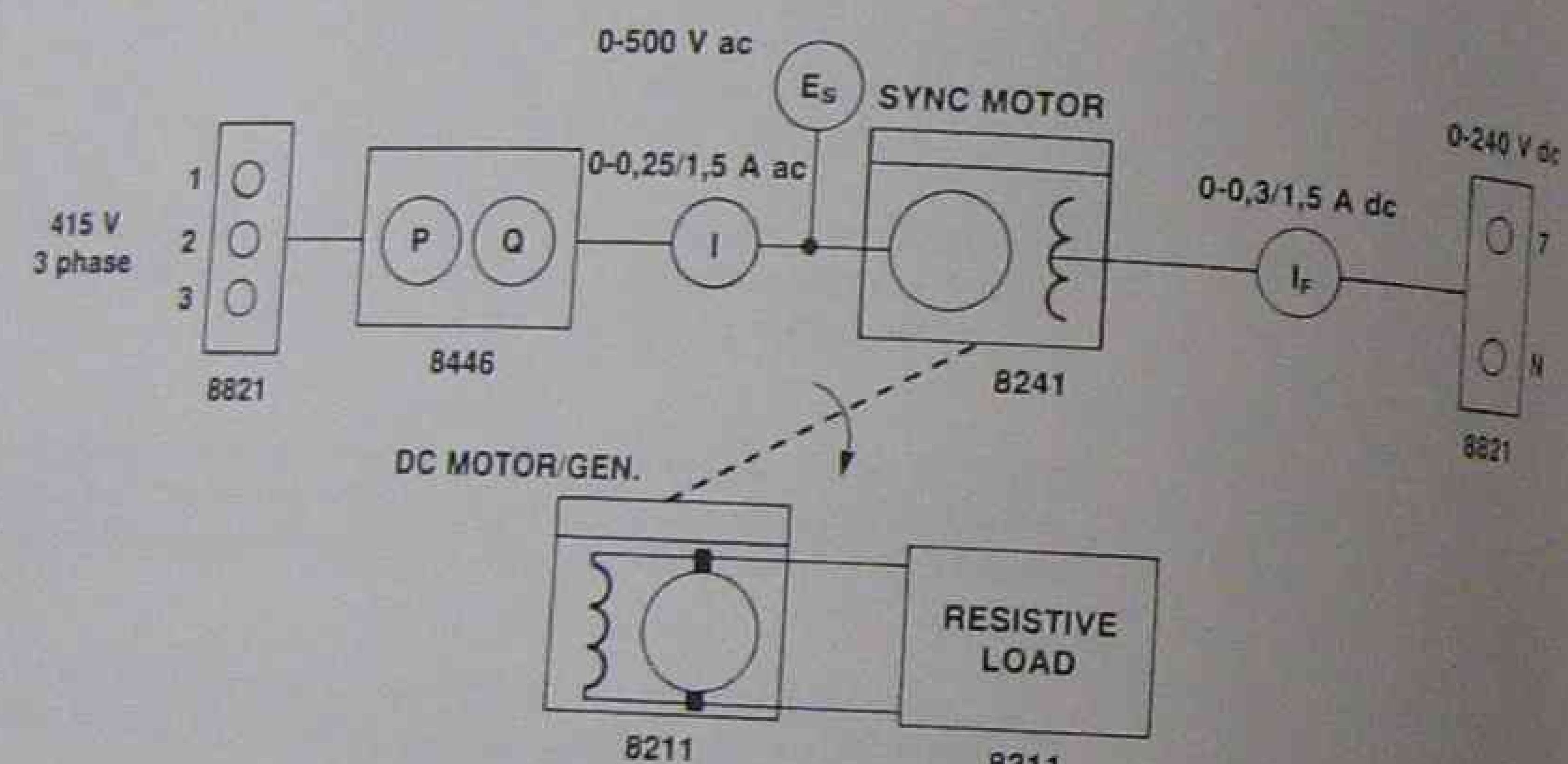


Figure 9-3.

Continue to increase the load until the synchronous motor falls out of step i.e. loses synchronism. Remove power as soon as this happens.

☐ 3. Repeat procedure step 2, but this time observe the position of the rotor with the Stroboscope as the load increases. The changing position of the rotor is the main cause of the increasing phase angle between E_S and E_O.

☐ 4. Repeat procedure step 2, and this time record your results in Table 9-2.

REAL POWER AND LOADING				
I_F	E_S	I	P	Q
A	V	A	W	var
0,05				
0,10				
0,15				
0,20				
0,25				
0,30				
0,35				
0,40				
0,45				

Table 9-2.

TEST YOUR KNOWLEDGE

1. The real power absorbed by a synchronous motor can be found in the same way, and using the same formula as with a transmission line. Explain.

____

____

2. A 2000 kW synchronous motor operates at a three-phase line-to-line voltage of 4 kV. It has a synchronous reactance of 4 Ω per phase.

Calculate:

a) The nominal full load current of the machine when the excitation voltage E_O (line-to-line) is 4 kV.

____

b) The short-circuit current when the excitation voltage E_O (line-to-line) is 4 kV.

____

3. a) In Question 2, if the excitation voltage E_O is equal to the terminal voltage (4 kV), what is the maximum real power which the motor can deliver without losing synchronism?

____

b) What is the rotor pole shift in electrical degrees, corresponding to the nominal load of 2000 kW?

____

4. The motor cannot operate in a stable manner when the rotor poles move beyond an angle of 90 electrical degrees from their no-load position. Can you explain why?

____

____

5. If the motor in Question 2 is at the end of a transmission line which has a reactance of 8 Ω per phase, what is the maximum power which the machine can develop, given that the sender voltage is 4 kV and the induced voltage E_O is also 4 kV (line-to-line)?

____

How does this maximum power compare with the nominal rating of the machine?

____

Calculate by how much the rotor poles move from their no-load position before the motor loses synchronism. Why is this angle less than 90°?

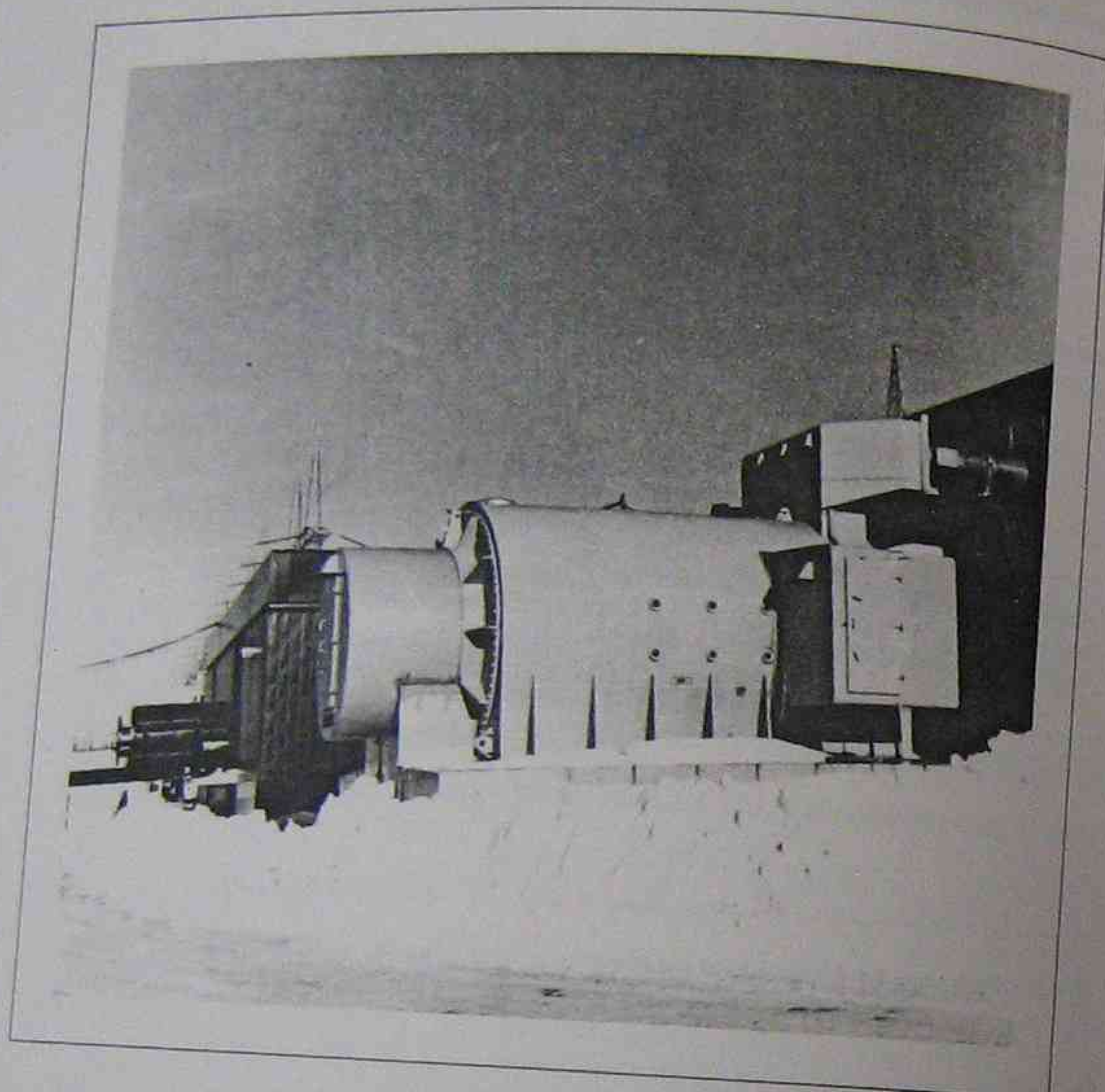
____

____

Between which two voltages is the angle equal to 90° when peak power has been attained?

____

____



Large hydrogen cooled synchronous capacitor to control the flow of reactive power. Installed in Duvernay, Quebec.

Experiment 10

The Synchronous Capacitor and Long High Voltage Lines

OBJECTIVES

- To study how a synchronous capacitor can regulate the receiver voltage.
- To study the distributed capacitance and the long, high-voltage line.

DISCUSSION

In Experiment 9, we saw that a synchronous motor at no load is able either to absorb or to deliver power. In essence, it acts wither as a three-phase inductor or as a three-phase capacitor depending upon whether it is under-or over-excited. The fact that such a machine can change gradually from an inductance to a capacitance makes it very useful to regulate the voltage at the end of transmission lines.

When used in this way, the synchronous motor is termed a synchronous capacitor. A better term might have been "synchronous capacitor/inductor", but because these machines must usually supply reactive power to a power system rather than absorb it, the term "capacitor" is appropriate.

We saw, in Experiment 5, how the receiver voltage can be regulated by static capacitors. We shall see how the same result can be obtained much more smoothly with a synchronous capacitor.

Long high-voltage transmission lines have significant capacitance in addition to their inductance. Typically, the capacitive reactance per kilometer is 400 000 Ω and the inductive reactance is 0,4 Ω on a 50 cycle line. This means that for a line which is 250 kilometers long, the inductance per phase is 100 Ω and the capacitive reactance is 1600 Ω. The simplified circuit of such a line may be represented by Figure 10-1, in which the line capacitance is "lumped" in the center of the line instead of being distributed over its entire length. When such a line is fed by a sender voltage E_S, the open-circuit receiver voltage E_R will be considerably higher.

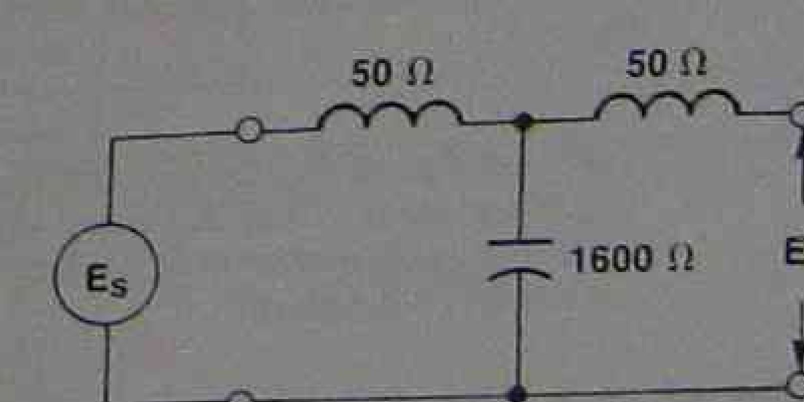


Figure 10-1.

Thus, in the simplified circuit of Figure 10-1, if the sender voltage E_S = 300 kV, the voltage E_R will be about 310 kV, a result which can readily be calculated. Such a voltage rise at the receiver end of a line can be excessive, and it can be prevented economically by connecting an inductive load at the receiver terminals. The synchronous capacitor is ideally suited to this purpose, for it behaves as an inductance when capacitor underexcited.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Three-Phase Synchronous Motor/Generator	8241
Resistive Load	8311
Three-Phase Transmission Line	8329
Capacitive Load	8331
DC Voltmeter/Ammeter	8412
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Connect the Three-Phase Synchronous Motor/Generator which is used as a synchronous capacitor to the end of a three-phase 400 Ω transmission line and, with no DC excitation on the machine, apply power to the sending end using the 3-phase Power Supply adjusted to 415 V. Once the synchronous capacitor is up to speed, apply DC excitation (see Figure 10-2).

Vary the DC excitation and note the effect upon the transmission line voltage.

☐ 2. Take readings of P_1, Q_1, E_1 and P_2, Q_2, E_2 as the DC excitation I_F is varied from zero to 0,50 A. Record your results in Table 10-1, and draw a graph of E_2 as a function of Q_2 on Figure 10-3. What is the effect upon Q_1 as the excitation is varied?

____

____

The Synchronous Capacitor and
Long High Voltage Lines

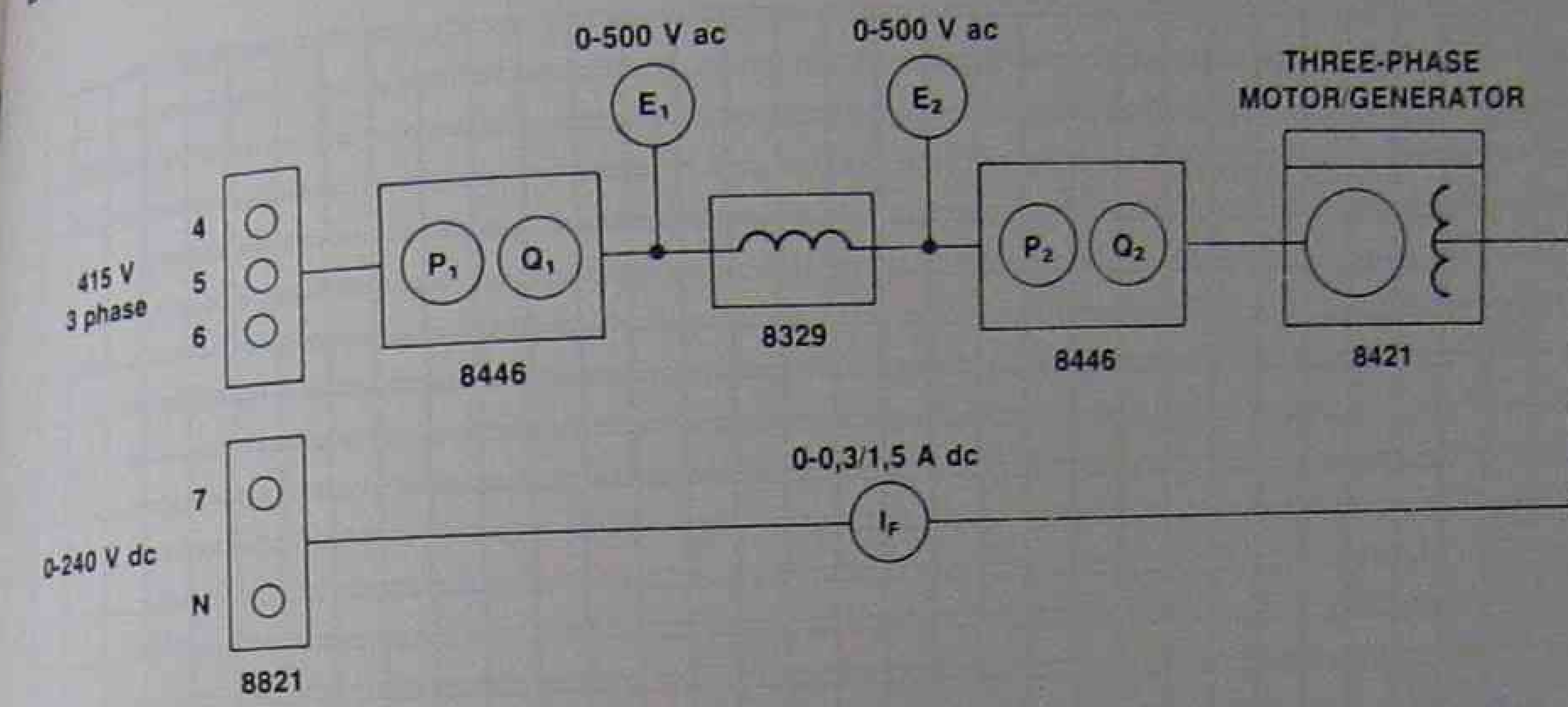


Figure 10-2.

VOLTAGE REGULATION			400 Ω LINE			
I_F A	P_1 W	Q_1 var	E_1 V	P_2 W	Q_2 var	E_2 V
0						
0,05						
0,10						
0,15						
0,20						
0,25						
0,30						
0,35						
0,40						
0,45						
0,50						

Table 10-1.

☐ 3. Repeat procedure step 2 with a line of 200 Ω. Record your results in Table 10-2, and draw a graph of E_2 as a function of Q_2 on Figure 10-4. You will note that the voltage cannot be regulated over as wide a range when the transmission line impedance is lower.

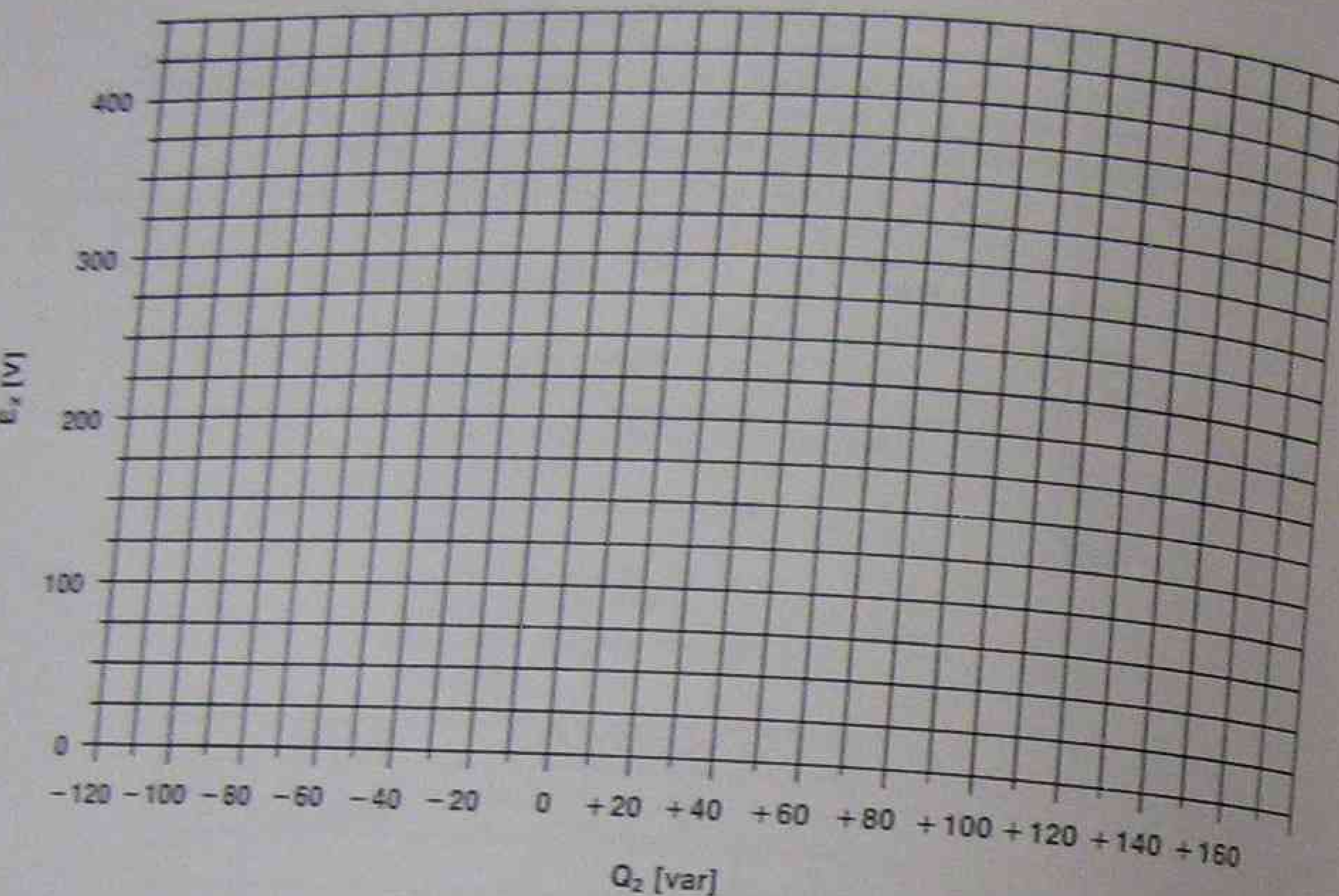


Figure 10-3.

VOLTAGE REGULATION				200 Ω LINE		
I_F	P_1	Q_1	E_1	P_2	Q_2	E_2
A	W	var	V	W	var	V
0						
0,05						
0,10						
0,15						
0,20						
0,25						
0,30						
0,35						
0,40						
0,45						
0,50						

Table 10-2.

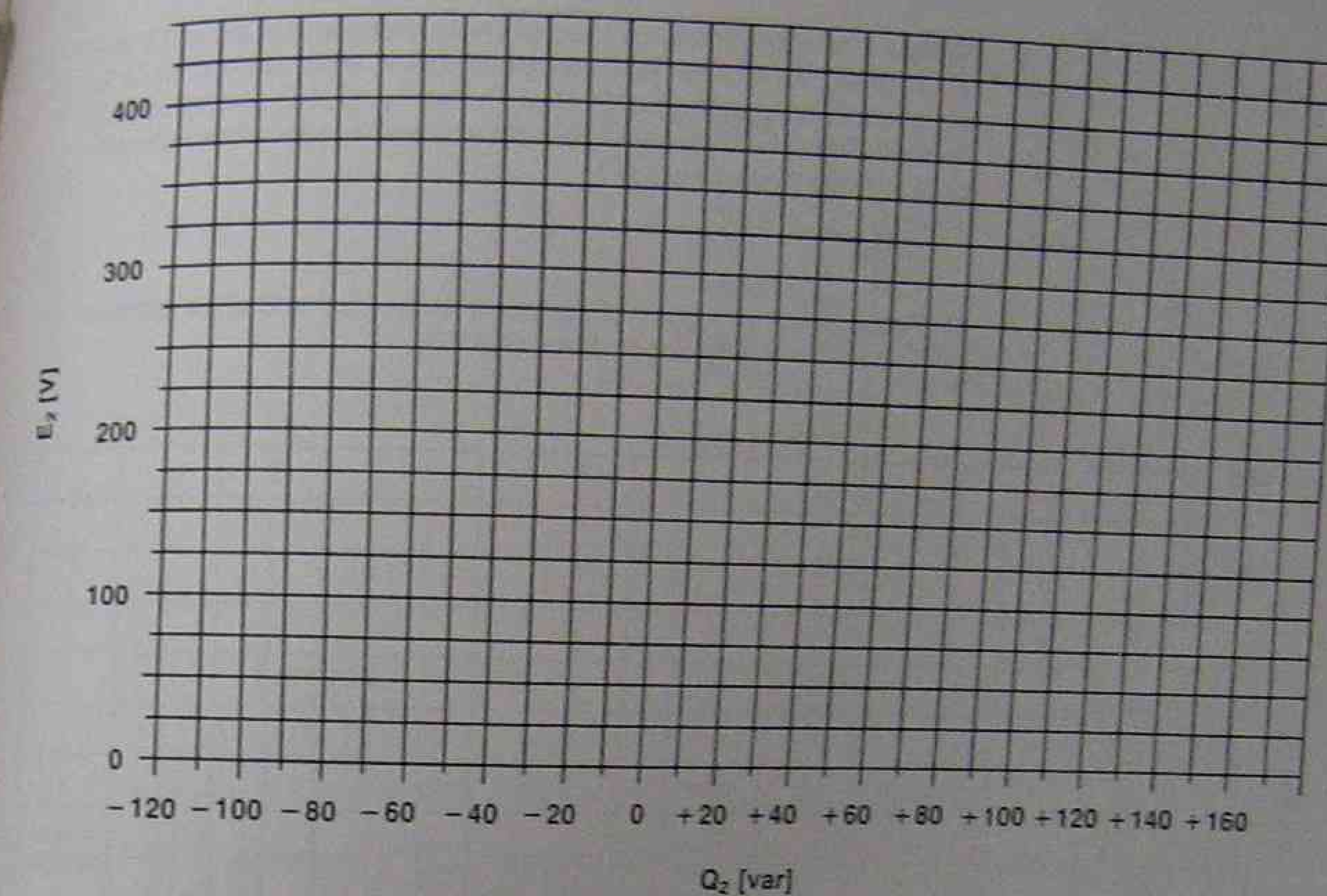


Figure 10-4.

	VOLTAGE REGULATION				400 Ω LINE AND RESISTIVE LOAD		
R/PHASE	I_F	P_1	Q_1	E_1	P_2	Q_2	E_2
Ω	A	W	var	V	W	var	V
∞							
4800							
2400							
1600							
1200							
960							
800							
686							

Table 10-3.

☐ 4. Connect a balanced Resistive Load at the receiving end of the 400 Ω line and maintain the receiver end voltage at 415 V, while the resistance is being varied. Take readings of P_1, Q_1, E_1 and P_2, Q_2, E_2 and record your results in Table 10-3. Is there a limit to the ability of the synchronous capacitor to regulate the line voltage?

☐ Yes ☐ No

On Figure 10-5 draw a graph of real power to the load vs Q of the synchronous capacitor at a receiver voltage of 415 V.

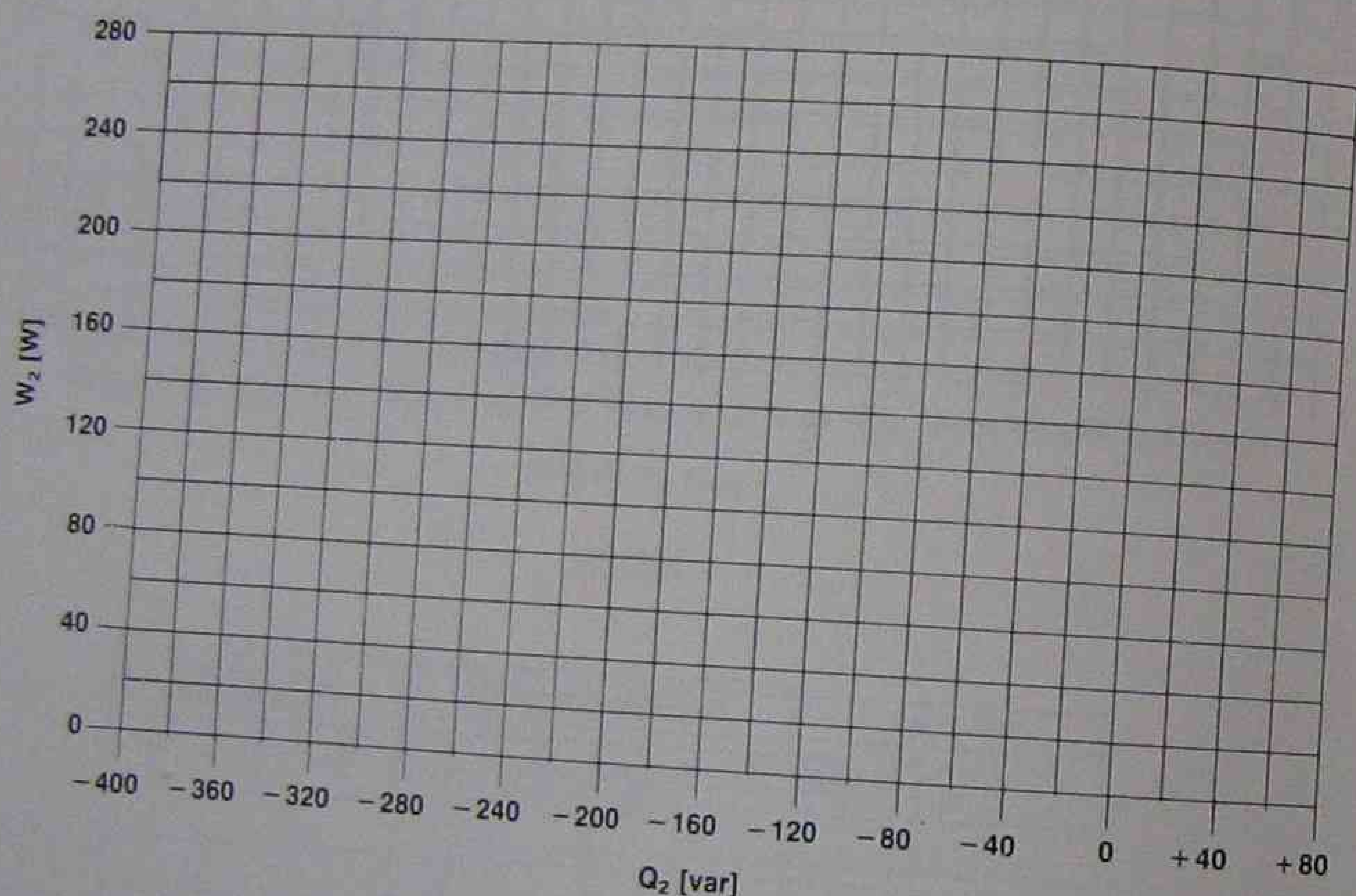


Figure 10-5.

☐ 5. Using two transmission lines in series, each set at 200 Ω, connect a Capacitive Load of 4800 Ω to simulate a long 3-phase line. See Figure 10-6. (The circuit per phase is shown in Figure 10-7.)

Apply power to the sending end using the variable 3-phase supply adjusted to 415 V and measure E_S and E_R on the open-circuit.

E_S = ______ V E_R = ______ V

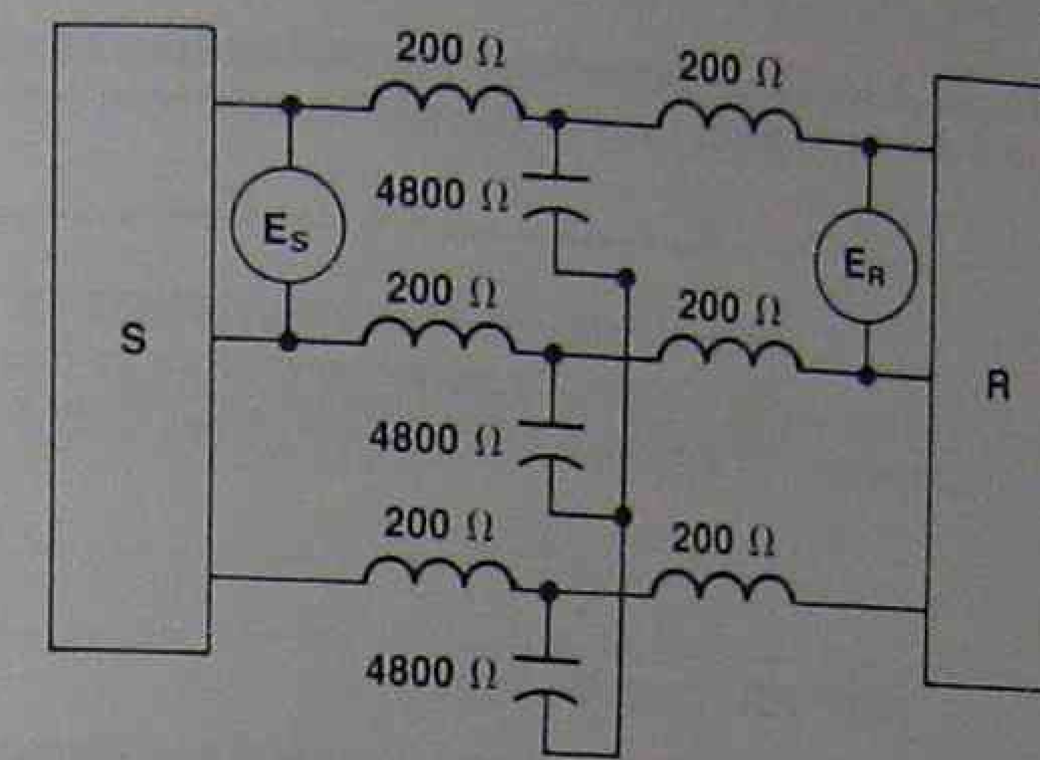


Figure 10-6.

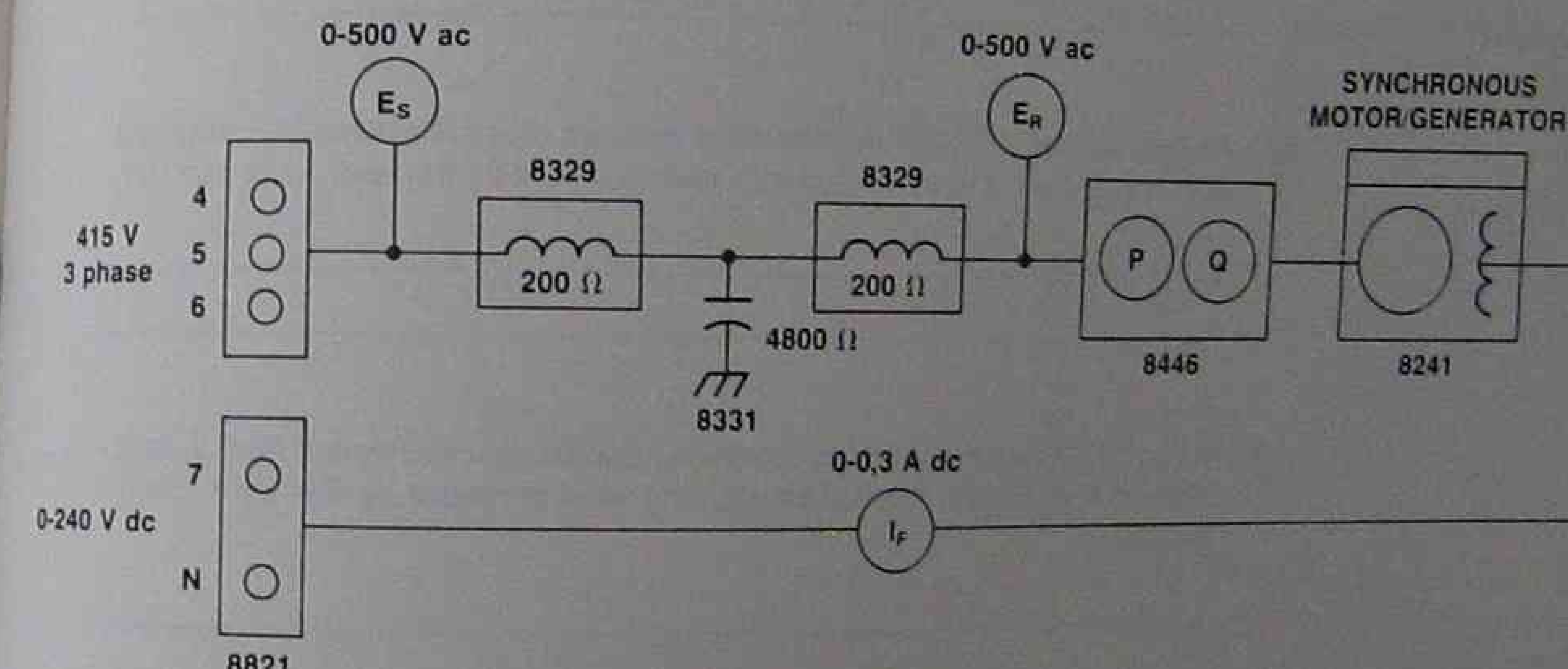


Figure 10-7.

☐ 6. Connect the synchronous capacitor to the receiver terminals and observe that the terminal voltage can readily be varied by changing its DC excitation. Determine the reactive power which the synchronous capacitor must absorb to make the receiver voltage equal to the sender voltage.

Q = ______ var

☐ 7. Set up the circuit of a line twice as long as the one studied in procedure step 5 using two 400 Ω lines in series, and a capacitive reactance (line-to-neutral) of 2400 Ω. Use the same set-up as in procedure step 5.

Apply power to the sending end using the fixed 3-phase supply and measure E_S and E_R on open-circuit.

E_S = ______ V E_R = ______ V

Then connect the synchronous capacitor to the receiver end and note that the voltage can readily be lowered so that $E_S = E_R$ by under-excitation. Measure the reactive power when $E_S = E_R$.

Q = ______ var

TEST YOUR KNOWLEDGE

1. What are some of the advantages of a synchronous capacitor over static capacitor to regulate transmission line voltage?

______

______

2. An over-excited synchronous machine delivers reactive power to a transmission line. Explain this statement and what is meant by the term "over-excited".

______

______

3. An under-excited synchronous machine absorbs reactive power from a transmission line. Explain this statement, and what is meant by the term "under-excited".

______

______

4. A 200 kilometer, 300 kV, 50 Hz transmission line has a reactance of 0,4 Ω per kilometer and a distributed capacitance of 400 000 Ω per kilometer. Draw an equivalent circuit of the line per phase. Calculate the line current per phase at the sender end when the receiver is open. What is the reactive power supplied to the sender?

______

______

______

5. A 150 MW generator having a nominal voltage of 12 kV and a synchronous reactance of 4 Ω is connected to the transmission line of Question 4 via a step-up transformer having a ratio of 12 kV/300 kV. If the excitation voltage E_O

is adjusted to 12 kV (line-to-line) calculate the voltages E_T and E_R at the terminals of the generator and at the end of the transmission line (see Figure 10-8).

______

______

Are there any dangers associated with the resonance effects of distributed line capacitance and the synchronous reactance of a generator?

______

______

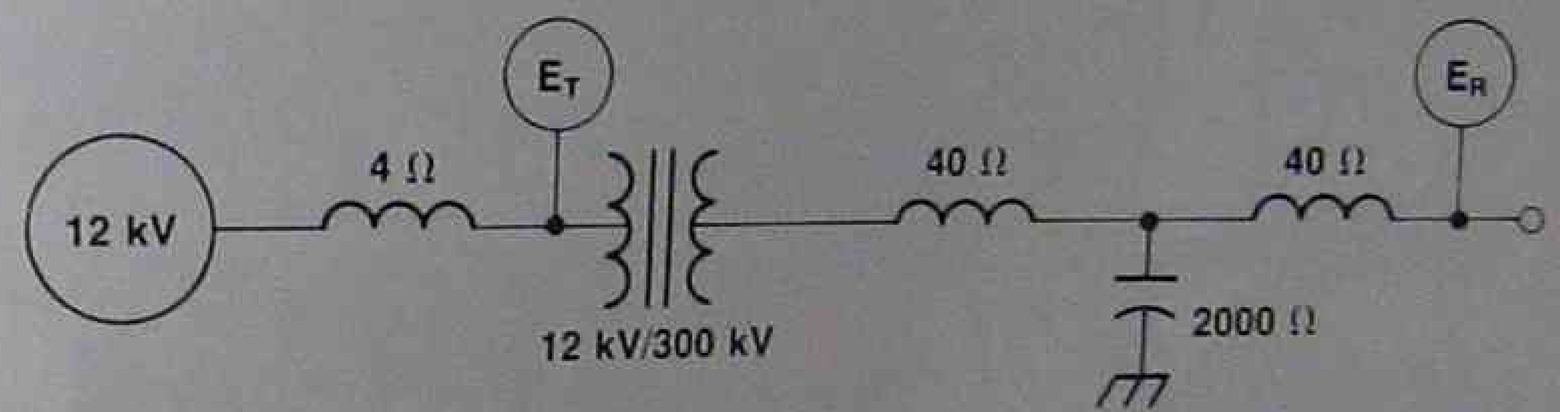


Figure 10-8.

Three-phase, oil-filled, fan-cooled phase-shift transformer. Line-to-line voltage is 300 kV.

Transmission Line Networks and the Three-Phase Regulating Autotransformer

OBJECTIVES

- To observe the division of power between two transmission lines in parallel.
- To learn the properties of a regulating autotransformer.
- To modify the power division between two parallel lines using a regulating auto-transformer.

DISCUSSION

So far, we have observed the behavior of a single transmission line. However, in a practical electric power system there are hundreds of interconnected lines which link the power stations and their widely-dispersed loads.

This grid of transmission lines, of which Figure 11-1 is a simplified example, is far more complex than a simple series-parallel circuit. The flow of active and reactive power over the lines depends not only upon their impedances, but also upon the relative magnitude and phase angles of the sender and receiver voltages. In such a system, the power flow in a particular line may be too high (or too low), bearing in mind the capacity of the line and/or the economics of transmission.

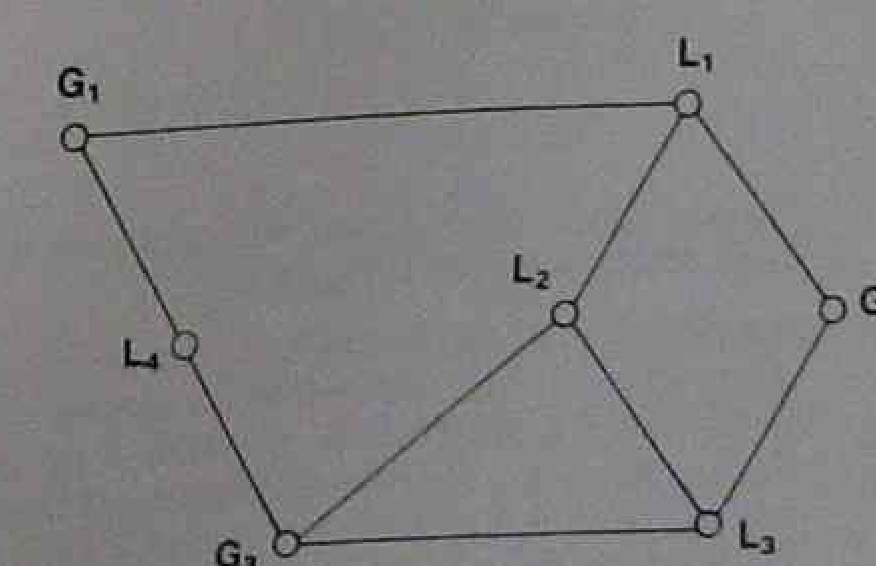


Figure 11-1

Under these circumstances, the flow of real power can be modified by shifting the phase of either the receiver or the sender-end voltage. Similarly, reactive power flow can be modified by raising or lowering one of these two voltages.

To raise or lower the voltage is a simple matter which can be done by an automatic tap-changing autotransformer, located at either end of the transmission line.

A phase shift can be effected by a rotatable transformer similar to a wound-rotor induction motor. However, in most large installations static phase-shifting transformers are employed, the degree of shift depending upon the tap setting.

The principle of the regulating autotransformer can be understood by referring to Figure 11-2, which shows the primary windings a_1, b_1, c_1 of a three-phase star-connected transformer. Secondary windings a_2, b_2, c_2 are also star-connected, but secondary windings a_3, b_3, c_3 are not yet connected together. Voltages inducted in windings a_1, a_2, a_3 will all be in phase as will be the voltages induced in windings b_1, b_2, b_3 and c_1, c_2, c_3.

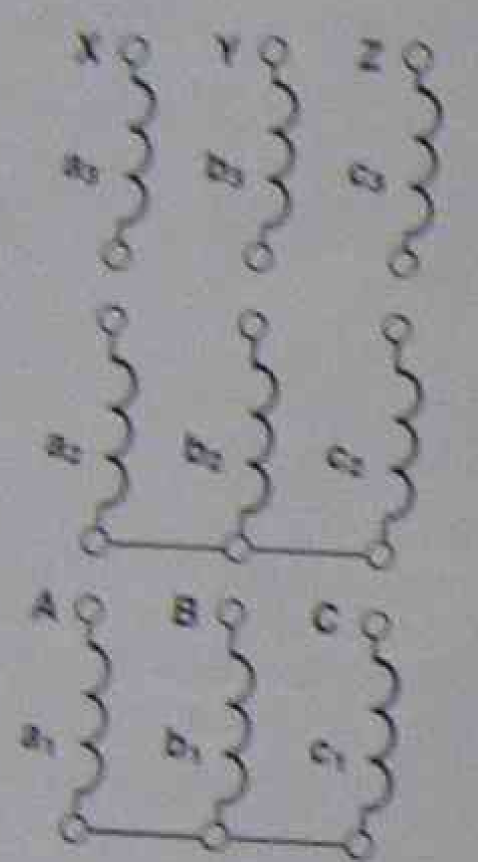


Figure 11-2.

However, these three groups of voltages are respectively 120° out of phase with each other, as shown in Figure 11-3.

If windings a_2 a_3, b_2 b_3 and c_2 c_3 are connected in series, the voltage between terminals X, Y and Z will be in phase with the voltage between terminals A, B and C as shown in Figure 11-3. However, if we connect in series windings a_2 b_3, b_2 c_3, and c_2 a_3, the phasor diagram will be as shown in Figure 11-4, and the voltage between terminals X, Y and Z will be out of phase with the voltage between terminals A, B and C. The degree of phase shift depends upon the relative magnitudes of the voltages a_2 b_2 c_2 and a_3 b_3 c_3. (If these voltages are all equal, the phase shift will be 60°.)

With appropriate taps on a three-phase transformer, and a selector switch, it is possible to step-shift the secondary voltage with respect to the primary by as much as 30°. Furthermore, provision can be made so that the phase angle can be progressively changed from lagging to leading and vice versa.

Referring to Figure 11-1, suppose we wish to modify the real power flow in line L_2-L_3. If we wish to increase the real power, the phase angle between the voltages at L_2 and L_3 will have to be increased. On the other hand, should we wish to reduce the real power to zero, the two voltages will have to be brought in phase. Such phase

angle changes can be accomplished by a phase-shift transformer located at either end of the line L_2-L_3.

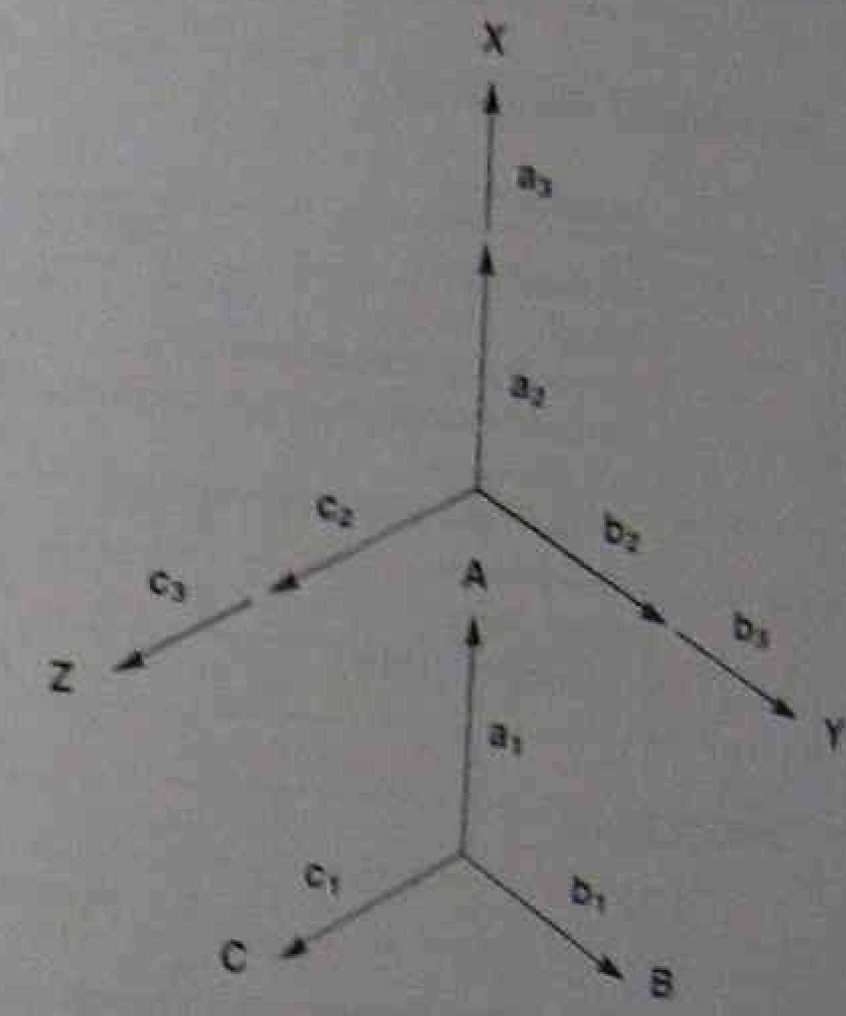


Figure 11-3.

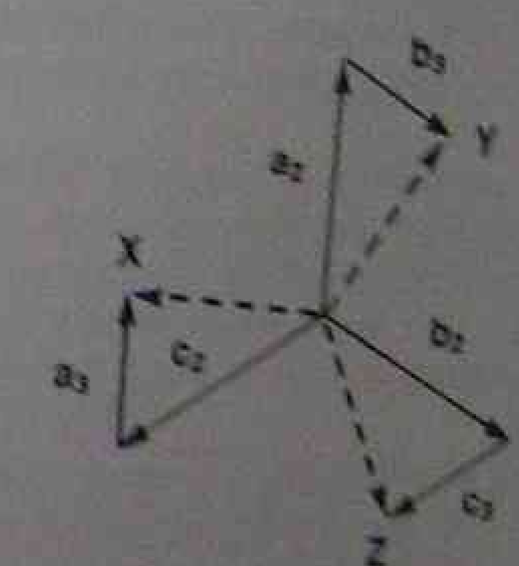


Figure 11-4.

A change in real power over line L_2-L_3 will affect the real power in the other lines, particularly those lines which converge at nodes L_2 and L_3. This is often the reason for modifying the power in line L_2-L_3 in the first place.

Reactive power can similarly be controlled by boosting (raising) or bucking (lowering) the voltage at either end of the line. Thus, if the voltage at L_2 is raised, reactive power will flow towards L_3. The same result will be obtained if the voltage is reduced at station L_3. In this regard, we should note that the voltage is only boosted or bucked on the transmission line itself – we must not change the voltage level of the other lines which are connected to points L_2 and L_3.

In the following experiment we shall study the load distribution between two parallel transmission lines and how this distribution is modified by a Three-Phase Regulating Autotransformer.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Resistive Load	8311
Inductive Load	8321
Three-Phase Transmission Line	8329
Three-Phase Regulating Autotransformer	8349
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Phase Meter	8451
Power Supply	8821
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. With the variable three-phase AC source set at 415 V connect the Three-Phase Regulating Autotransformer as shown schematically in Figure 11-5.

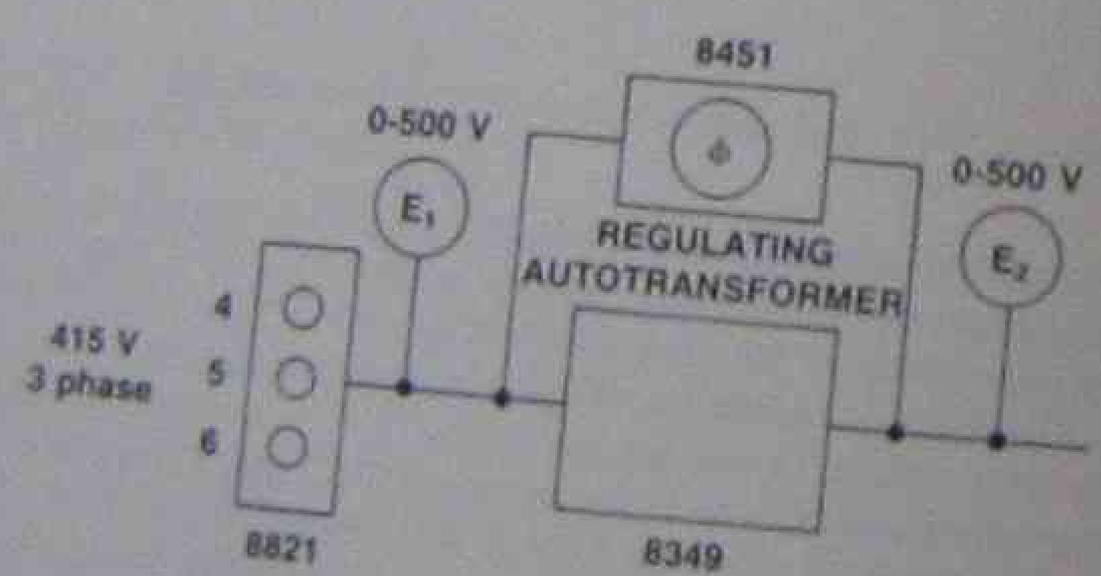


Figure 11-5.

Change the setting of the buck-boost selector tap switch and record the voltages and the phase angle between them. Then change the setting of the phase-shift tap switch and note the effect upon the voltages and the phase angle. Note that by changing both tap switches, the phase angle and the voltage E_2 can be varied independently. Record your results in Table 11-1.

Note the effect of an incorrect phase sequence upon the operation of the transformer. State what happens.

____

____

SETTING		READING			
BUCK BOOST	PHASE SHIFT	E_1	E_2	ϕ	LAG LEAD
%	°	V	V	°	—
0	0				
0	+15				
0	−15				
−15	0				
−15	+15				
−15	−15				
+15	0				
+15	+15				
+15	−15				

Table 11-1.

☐ 2. Set up the circuit of Figure 11-6, using two transmission lines in parallel feeding a star-connected resistive-inductive load of 1200 Ω. Set both transmission line impedances at 200 Ω and adjust E_1 to 415 V. Note that each line carries the same amount of real and reactive power when there is no phase-shift of buck-boost of the autotransformer.

Change the setting of the phase-shift selector switch and note the large effect upon the flow of real power in each line. Note that the reactive power is only slightly affected.

Now, change the setting of the buck-boost selector switch and note the large effect upon the reactive power distribution between the two lines. Note that the real power is only moderately affected. Record your results in Table 11-2.

☐ 3. Repeat procedure step 2 with line 1 set to zero impedance and record your results in Table 11-3. Note that under normal circumstances this corresponds to a very short line, which naturally would tend to carry all the active and reactive load. Observe that by changing the phase-shift and the voltage ratio (buck-boost) of the autotransformer the flow of power can be drastically modified.

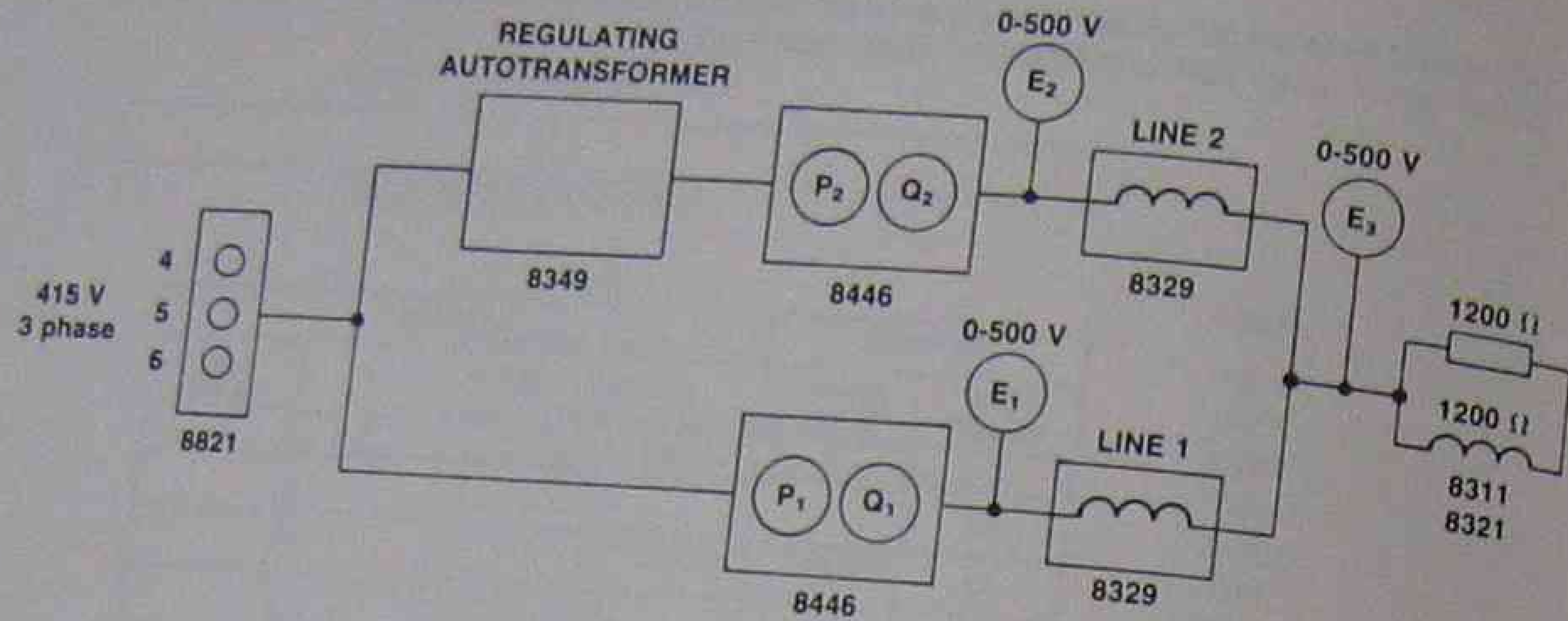


Figure 11-6.

SETTING				MEASUREMENTS						
LINE 1 IMP	LINE 2 IMP	BUCK BOOST	PHASE SHIFT	P_1	Q_1	P_2	Q_2	E_1	E_2	E_3
Ω	Ω	%	°	W	var	W	var	V	V	V
200	200	0	0							
200	200	0	+15					415		
200	200	0	−15							
200	200	+15	0							
200	200	−15	+ 0							
200	200	+15	+15							
200	200	−15	−15							

Table 11-2

☐ 4. Repeat procedure step 2 using two lines of 600 Ω each. Note that the power flow is not modified as much as before, owing to the high impedance of the lines. To obtain a large change in power division between the two lines, a larger phase-shift would be required, as well as a larger buck-boost range.

SETTING				MEASUREMENTS						
LINE 1 IMP	LINE 2 IMP	BUCK BOOST	PHASE SHIFT	P_1	Q_1	P_2	Q_2	E_1	E_2	E_3
Ω	Ω	%	°	W	var	W	var	V	V	V
0	200	0	0							
0	200	0	+15					415		
0	200	0	−15							
0	200	+15	0							
0	200	−15	+0							
0	200	+15	+15							
0	200	−15	−15							

Table 11-3

TEST YOUR KNOWLEDGE

1. On Figure 11-7 two transmission lines having reactances per phase of 100 Ω and 200 Ω are connected in parallel. A phase-shift transformer T_1 is introduced into the 200 Ω line, close to the receiver, so that the real power be divided equally between the two lines. If the sender and receiver voltages are both 100 kV line-to-line, calculate the maximum real power delivered, and the phase angle needed for the phase-shift transformer.

____

____

____

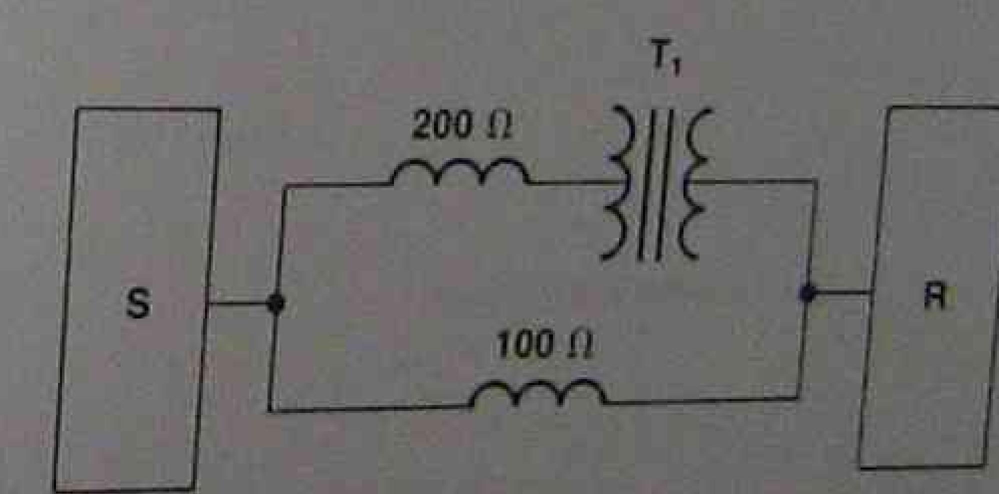


Figure 11-7.

2. In Question 1 if there were no phase-shift transformer, what would be the maximum power which could be delivered over both lines?

____

____

3. Does the phase-shift transformer in Question 1 increase the maximum power the 200 Ω line can deliver?

☐ Yes ☐ No

4. *In the circuit of Figure 11-8 comprising two transmission lines in parallel, the sender and receiver voltages are both 100 kV line-to-line. A phase-shift transformer T_1 and a buck-boost transformer T_2 are adjusted so that the sender delivers the same amount of real and reactive power to each line. If the receiver absorbs 50 MW, calculate

a) the phase-shift of T_1

b) the voltage ratio of T_2.

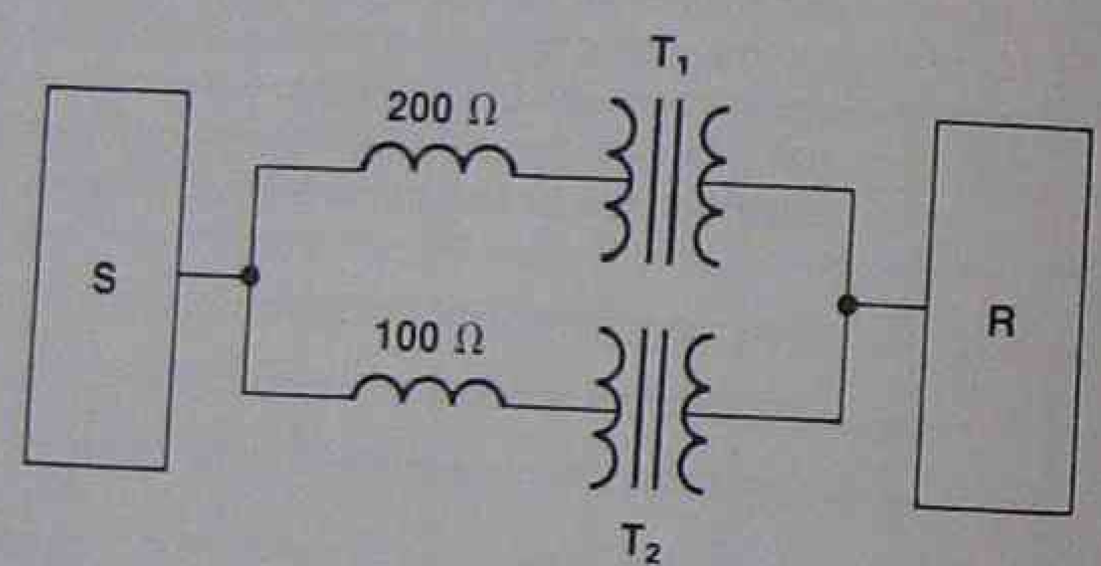
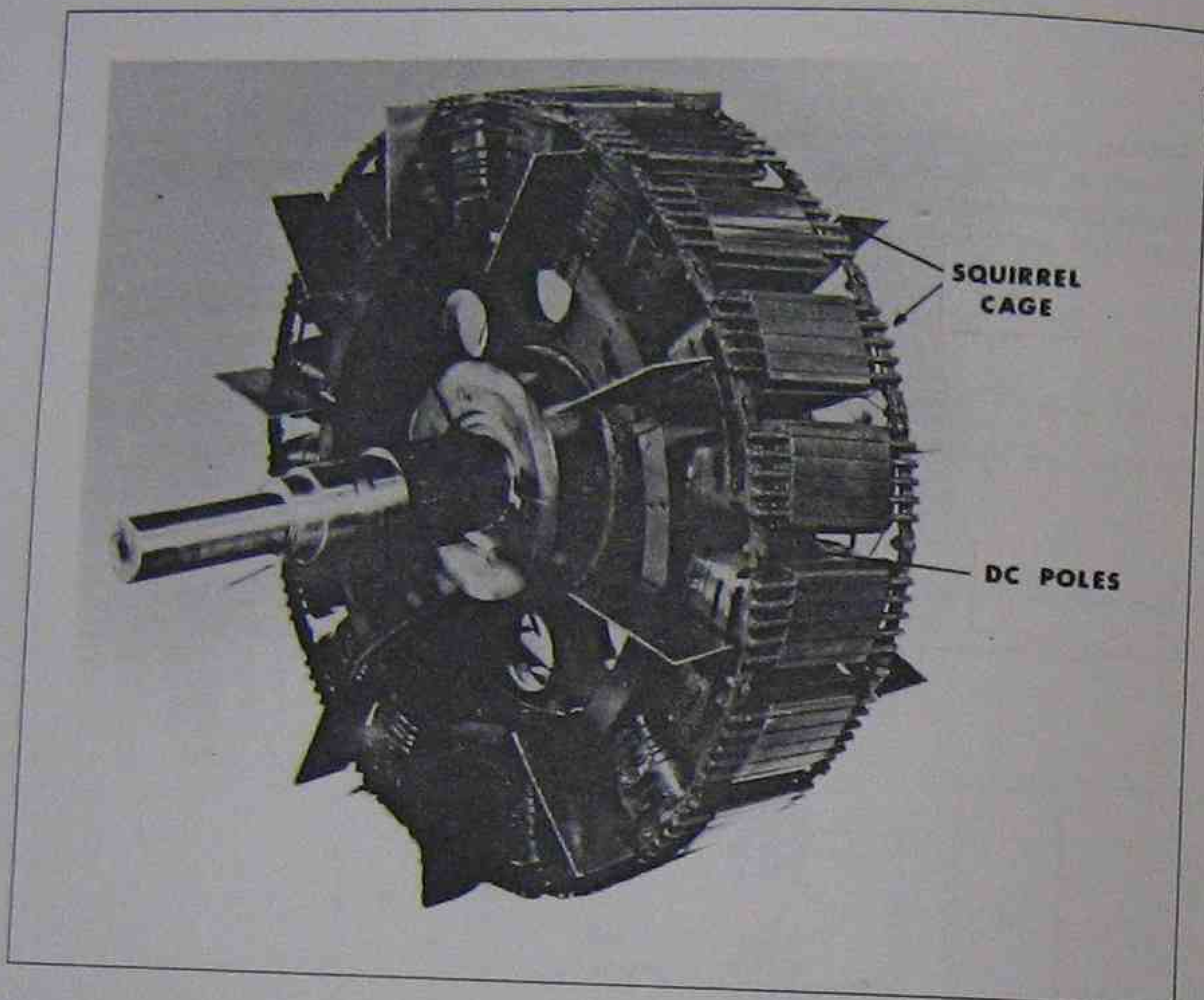


Figure 11-8.

* This is an engineering problem.



This photograph of the rotor of the Synchronous motor shown on Page 9-1, illustrates very well the 22 DC poles and the squirrel cage winding.

The Synchronous Motor Under Load

OBJECTIVES

- To observe the behavior of a synchronous motor under load.
- To observe the mechanical shift of the rotor as the load is increased.
- To determine the load limit of the motor.
- To observe the effect of field excitation upon the load-carrying capacity of the motor.

DISCUSSION

We recall from Experiment 9 that the circuit of a synchronous motor can be represented by Figure 1-21, in which X is the synchronous reactance, E_O the voltage induced by the flux from the rotor and E_1 is the supply voltage.

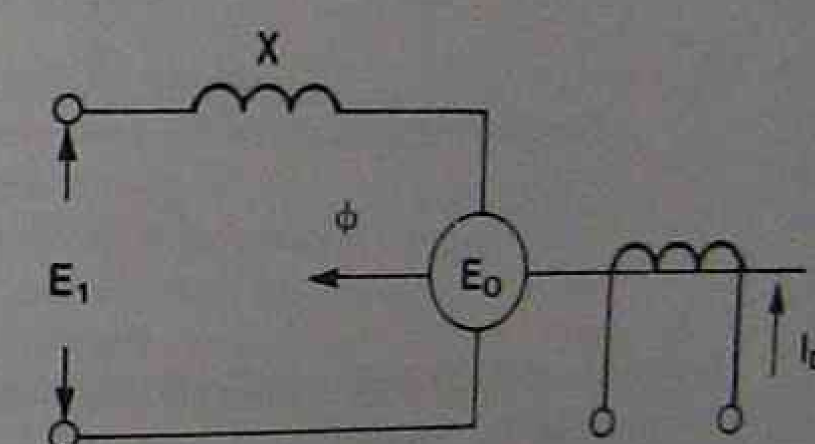


Figure 12-1.

Just as for a transmission line circuit, the real power delivered to the motor is given by the equation

$$P = \frac{E_1 E_O}{X} \sin \theta$$

where θ is the phase angle between E_1 and E_O. The maximum power the motor can receive is, therefore, $E_1 E_O / X$ and this occurs when $\theta = 90°$. The mechanical power output will be slightly less owing to the losses in the motor.

How does the angle θ change? It increases as the mechanical load on the motor increases, owing to the fact that the increased torque tends to make the motor run at a lower speed. This tendency to slow down is translated, first, into a shift of the rotor poles relative to the revolving field of the stator. It is precisely this mechanical shift which causes the voltage E_O to lag behind E_1 as the mechanical load rises. This pole shift is observable with a synchronized stroboscope.

As seen from the equation $P = E_1E_O \sin \theta / X$ for a given power P and supply voltage E_1, the phase angle θ will increase if the DC excitation is lowered. If the field is reduced sufficiently, θ will approach 90° at which time the motor will be on the verge of falling out of synchronism.

In salient pole machines, the phase angle where the motor pulls out is less than 90° – usually around 70°. This is due to the reluctance torque created by the salient poles. However, for our purposes, the equation for power gives a satisfactory picture of what happens to a synchronous motor under load.

Synchronous Motor and Transmission Line

Consider a system composed of a transmission line whose impedance is X_1 Ω to which is connected a synchronous motor having a synchronous reactance of X_2 Ω and an induced voltage E_O, as shown in Figure 12-2.

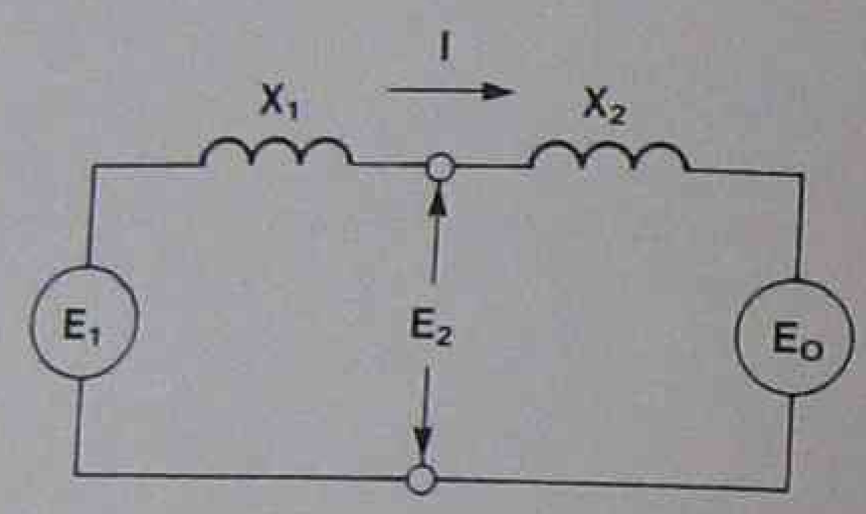


Figure 12-2.

The power which can be transmitted from the source E_1 to the synchronous motor is now given by the equation

$$P = \frac{E_1E_O}{(X_1 + X_2)} \sin \theta,$$

where θ is the phase angle between E_1 and E_O. The maximum power which can be transmitted is therefore $P_{max} = E_1E_O/(X_1 + X_2)$, and this occurs when $\theta = 90°$. On the other hand, the power delivered to the motor is also given by:

$$P = \frac{E_2E_O}{X} \sin \alpha$$

where E_2 is the terminal voltage and α the angle between E_2 and E_O. Since E_2 must lie between the phasors E_1 and E_O (see Figure 12-3), it is obvious that when maximum power is being delivered, angle α is less than 90°. In other words, the motor will pull out of synchronism before the angle between E_2 and E_O has attained 90°.

The reason for this is because a synchronous motor attains its maximum power at $\alpha = 90°$, provided that E_O and the terminal voltage E_2 are constant. In the case of the transmission line the terminal voltage E_2 is not fixed, but depends upon the magnitude of the load. This is why the motor attains its maximum power before the angle α has reached 90° (see Figure 12-3 (b)). By trigonometry it is possible to show that the

value of α, when the power is maximum, is given by the equation:

$$\tan \alpha = (X_2/X_1)(E_1/E_O)$$

Thus if $X_1 = X_2$ and $E_1 = E_O$, $\tan \alpha = 1$ and α is 45°.

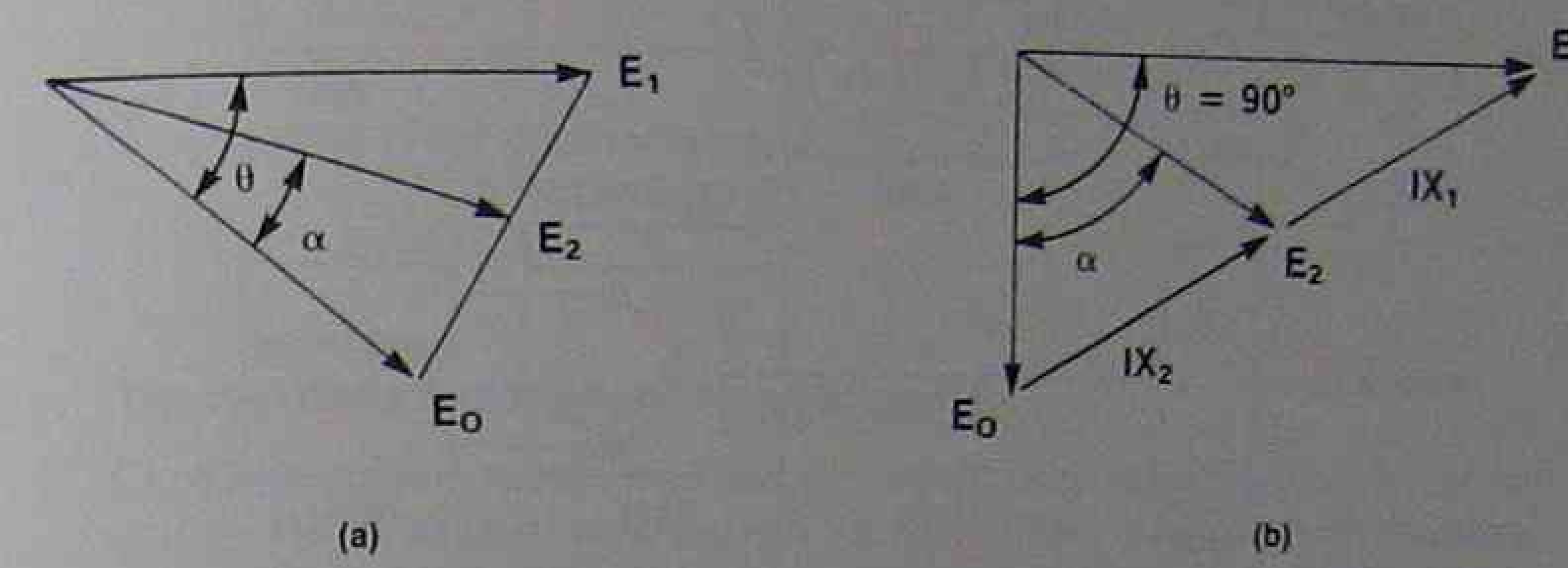


Figure 12-3.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
DC Motor/Generator	8211
Three-Phase Synchronous Motor/Generator	8241
Resistive Load	8311
Three-Phase Transmission Line	8329
DC Voltmeter/Ammeter	8412
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Phase-Shift Indicator	8909
Stroboscope	8922
Timing Belt	8942
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Connect the Three-Phase Synchronous Motor/Generator to a variable three-phase source and couple the rotor to the DC separately excited shunt generator and to the mechanical torque angle measuring device, using instrumentation as shown in Figure 12-4. (Use two Three-Phase Wattmeter/Varmeter in parallel.)

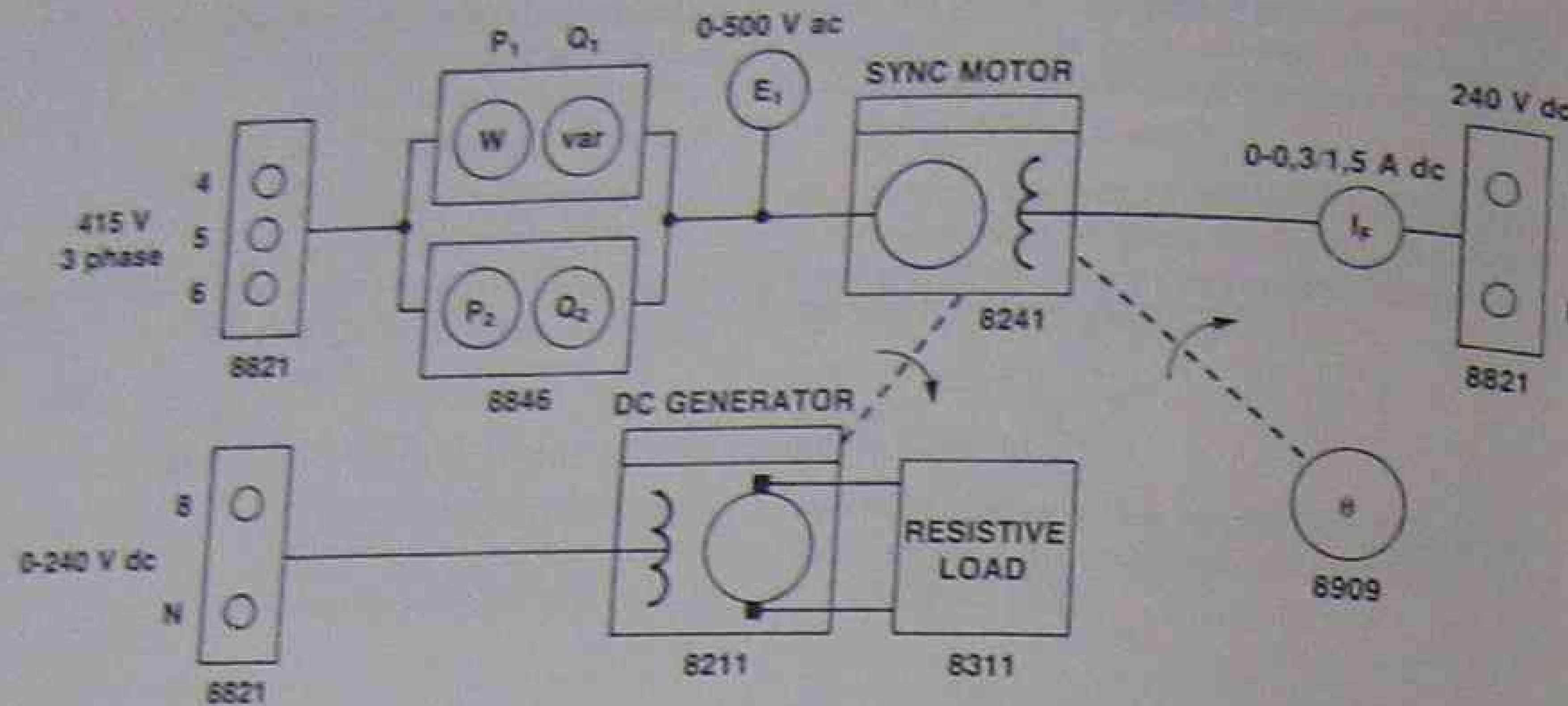


Figure 12-4.

With the motor uncoupled, start the motor. Adjust E_1 to 415 V and adjust the field excitation so that the reactive power drawn by the motor is zero. After this adjustment, keep the DC field current constant. (Under these conditions, the induced voltage E_O is equal to the applied voltage E_1.) Using the Stroboscope, adjust the Phase-Shift Indicator to zero. note P_1, Q_1, and I_F and record your results in Table 12-1. (Take the sum of the readings of each instrument for P_1 and Q_1.)

θ	E_1	P_1	Q_1	I_F	E_O
°	V	W	var	A	V
0	380				380
10					
20					
30					
40					
50					
60					

Table 12-1.

The maximum motor power depends upon E_1

☐ 3. With E_1 = 415 V, set the field current to the same value as in Table 12-1. Set the load so that the phase shift = 20°. Gradually reduce the voltage E_1 and note the phase shift of the poles. At what angle does the motor fall out of step?

____

What is the corresponding voltage E_1 ?

E_1 = ______ V

The maximum motor power depends upon E_O

☐ 4. In order to reduce the field current sufficiently connect one section of the Resistive Load in series with the field of the Three-Phase Synchronous Motor/Generator and use the two remaining sections to load the DC generator. With E_1 = 415 V and the field current as in Table 12-1, set the load so that the phase shift = 20°. Then gradually reduce the field current and note the phase shift of the poles. At what range does the motor fall out of step?

____

What is the corresponding field current?

____

☐ 5. Set up the experiment so that E_O = 275 V and E_1 = 415 V. Determine the phase angle as well as P_1 and Q_1. Record your results in Table 12-2.

θ	E_1	P_1	Q_1	I_F	E_O
°	V	W	var	A	V
0	380				250
10					
20					
30					
40					
50					
60					

Table 12-2.

Effect of Transmission Line Impedance

☐ 6. Set E_1 = 415 V, E_O = 415 V and note the real power P_1 just before the motor falls out of step. Note also the phase angle of E_O compared to E_1 by the phase shift of the poles.

P_1 = ______ W θ = ______ °

Now introduce a three-phase 400 Ω line in series with the motor, and with $E_O = E_1$ = 415 V, increase the load until the motor loses synchronism. What is the real power P_1 just before this occurs?

P_1 = ______ W

What is the corresponding phase angle between E_O and E_1 ?

θ = ______ °

Trigger the Stroboscope from the voltage E_2 applied to the motor and note the rotor pole phase shift as the load is increased. At what phase angle does the motor pull out of step?

α = ______ °

Explain why this angle is much less than 90°.

____

____

TEST YOUR KNOWLEDGE

1. A synchronous motor of 1000 kW, 2,3 kV, 3-phase has a synchronous reactance of 2,6 Ω per phase. Calculate the phase-shift of the poles in electrical degrees when the motor develops 500 kW, given that the excitation voltage E_O = 2,3 kV line-to-line.

____

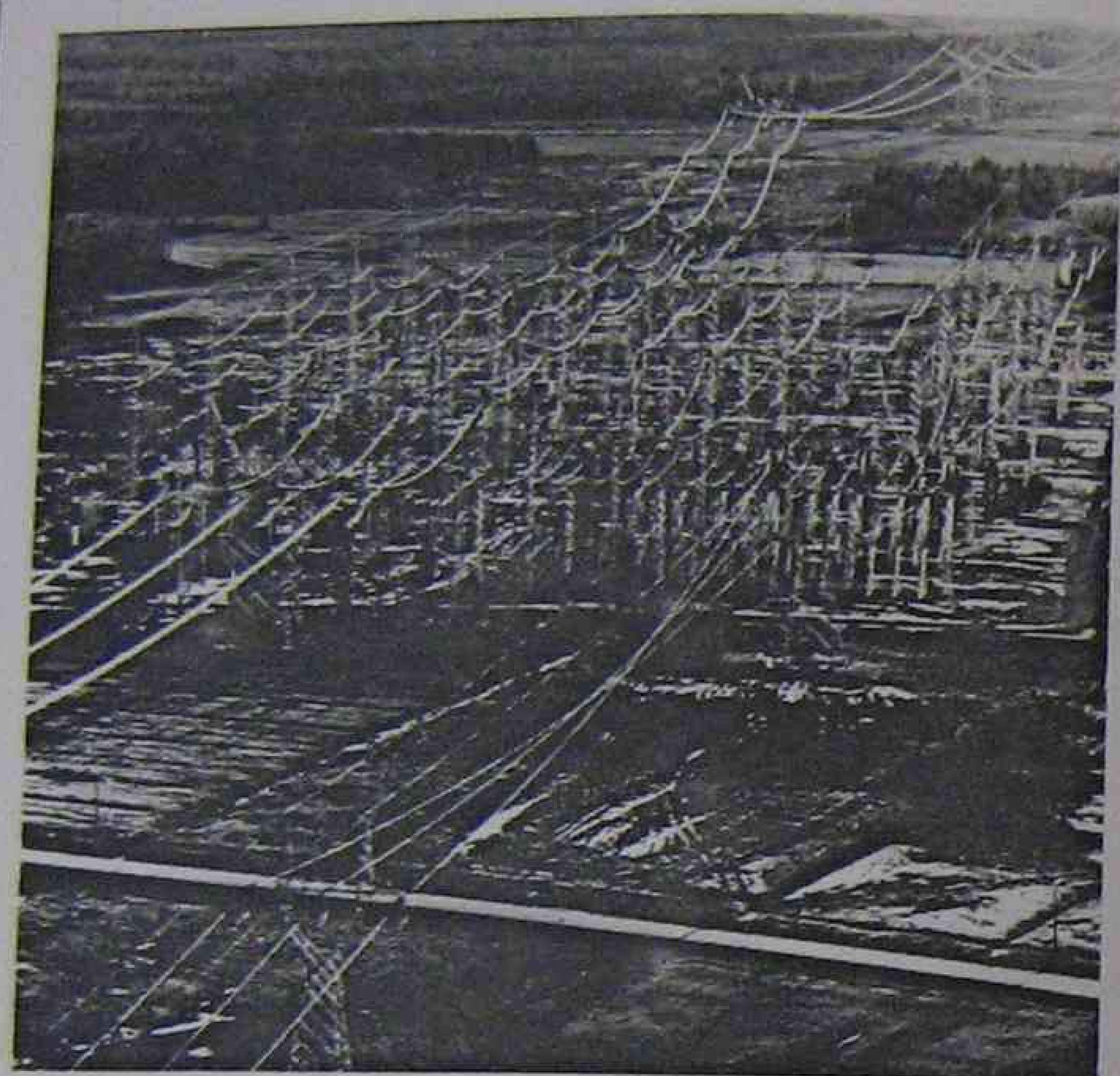
____

2. If the motor in Question 1 is located at the end of a transmission line whose reactance per phase is 3 Ω, by how many electrical degrees will the poles shift from their no load position if the motor produces 500 kW?

____

3. In Question 2 what is the maximum power the motor can develop before it falls out of synchronism?

____



This large 735 kV switching station enables a spin-off of electric power and also serves as an intermediate voltage-regulating station.

Hunting and System Oscillation

OBJECTIVES

- To observe the hunting of a synchronous motor.
- To study how inertia and reactance affect the frequency of oscillation.

DISCUSSION

This experiment is concerned with the behavior of synchronous motors when they are subjected to sudden load changes. In order to simplify the explanation, let us suppose that the power vs phase angle curve of a large motor has a peak value of 2 MW as shown in Figure 13-1. Assuming that the no-load rotor position is as shown in Figure 13-1 (a), the poles will fall back by 30° when the load is raised to 1 MW. The 30° angle is a direct consequence of the given curve. This indeed is what happens when the load on the motor is very gradually increased from zero to 1 MW.

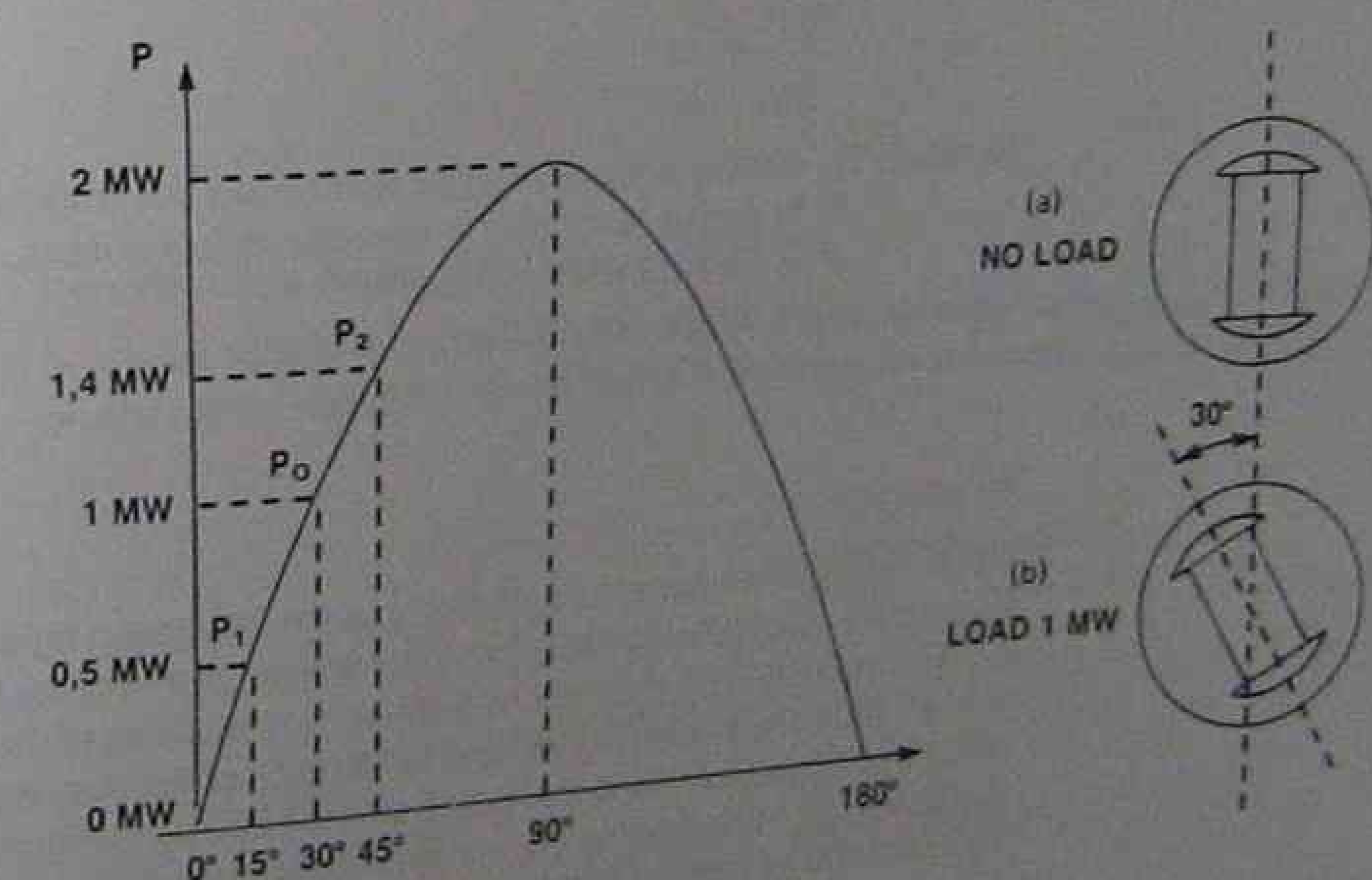


Figure 13-1.

But if a 1 MW load is applied suddenly, the rotor will fall behind by more than 30° and may swing as far as 45 or 50° from its no-load position. In a way, the rotor overshoots the 30° mark which it should reach, with the result that the motor develops, for a while, a motive power considerably in excess of 1 MW. For example, if the rotor swings to an angle of 45°, the motor will develop 1,4 MW while the mechanical load is still only 1 MW. This difference of 0,4 MW accelerates the rotor, urging it back to the 30° point of stability. But when rotor reaches this new position, it is going too fast, and overshoots the mark by such a wide margin that the angle may become as small as 15°. At this new angle, the motor only develops 0,5 MW which is much less than the 1 MW mechanical load. Consequently, the rotor slows down and, in so doing, will again approach, reach, and then overshoot the 30° point.

Referring to Figure 13-1, the rotor will oscillate between 15° (P_1) and 45° (P_2) in its attempt to reach the 30° point (P_O) of stable operation. The motor is said to "hunt" or oscillate during this transition period. The swing to the right and left of P_O will become progressively smaller and, after a minute or so, the rotor will cease to "hunt", having now "found" the stable point P_O. The process by which the oscillations become smaller and smaller is called damping. The damping is rendered particularly effective if the motor poles are equipped with a squirrel-cage winding.

Any sudden changes either in the mechanical load, the supply voltage or a momentary power interruption will cause a synchronous motor (or alternator) to hunt.

The frequency of hunting depends mainly upon the inertia of the machine, its speed of rotation and its peak power. An approximate formula is

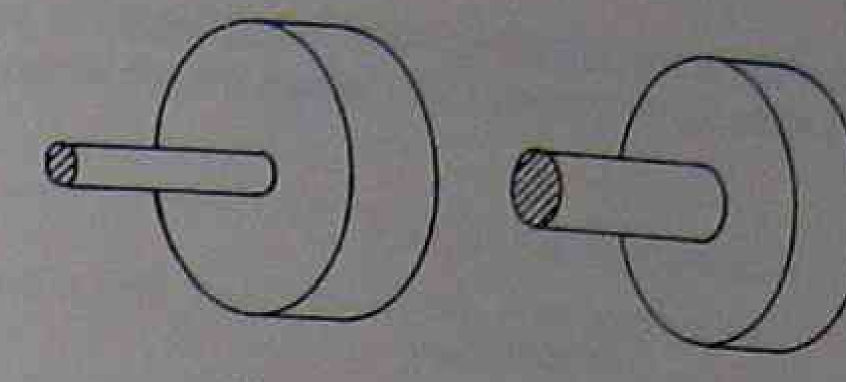
$$F_H = \frac{7200}{N}\sqrt{\frac{Pf}{J}}$$

in which F_H = frequency of oscillation in cycles per minute.
N = speed of rotation in revolutions per minute.
P = peak power in kilowatts.
f = supply-line frequency in hertz.
J = moment of inertia in $kg{\cdot}m^2$.

An analogy

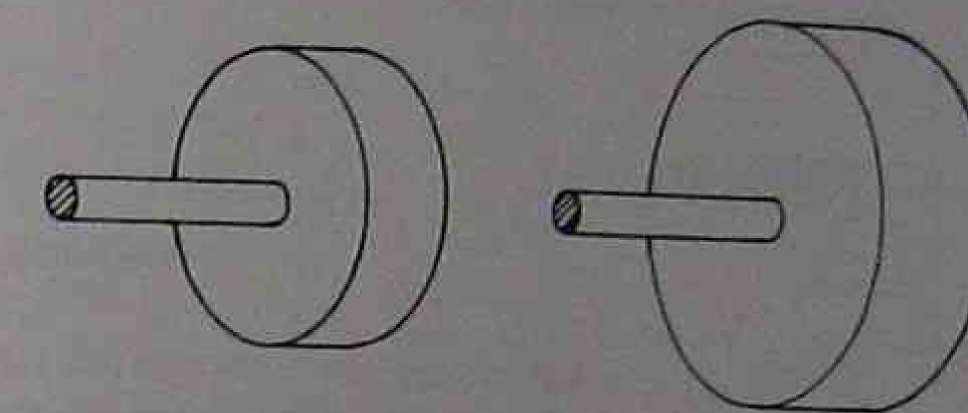
It may help in understanding the phenomenon of hunting by using an analogy. In Figure 1-32 a large inertia wheel (representing the inertia of the synchronous motor) is fixed to the end of a shaft whose stiffness is a measure of the power which it can deliver. Thus, the shaft in Figure 13-2 (b) is much stiffer than that of Figure 13-2 (a) and hence, for a given twist, it can deliver more power. In Figure 13-3, two different inertia wheels, representing the inertia of two different machines, are fixed to the end of shafts of equal stiffness.

Our intuition tells us that if the shafts are twisted through an angle of, say, 30° and then suddenly released, they will oscillate but at different frequencies. For a given inertia, the thick shaft (representing large power) of Figure 13-2 (b) will hunt much faster than the shaft of Figure 13-2 (a). Also, with a given power level, the shaft with a larger inertia wheel (representing more inertia) of Figure 13-3 (b) will hunt much slower than the shaft of Figure 13-3 (a).



(a) (b)

Figure 13-2.



(a) (b)

Figure 13-3.

Synchronous Motor and Transmission Line

In Figure 13-4 is shown the circuit of a synchronous motor having a synchronous reactance X_S connected to the end of a transmission line whose reactance is X_L.

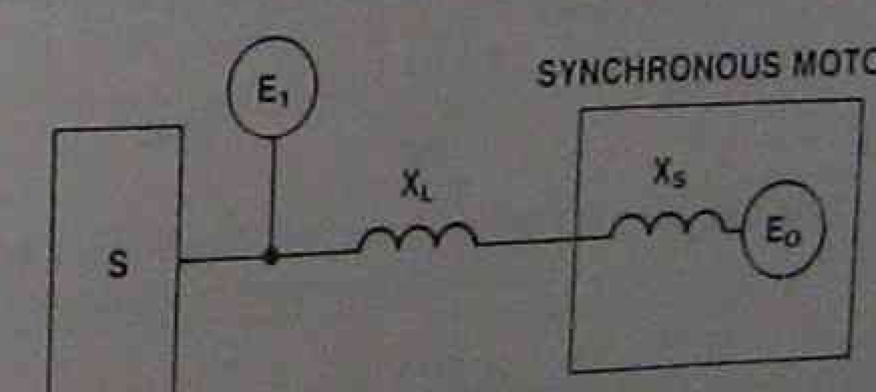


Figure 13-4.

Assuming the sender voltage and the induced voltage are both equal to E, the peak power which can be delivered to the motor is

$$P = \frac{E^2}{X_L + X_S}.$$

This is less than the peak power if the motor were directly connected to S, and as a result, the frequency of hunting will be lower.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
Three-Phase Synchronous Motor/Generator	8241
Three-Phase Transmission Line	8329
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Inertia Wheel	8915
Stroboscope	8922
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Connect the Three-Phase Synchronous Motor/Generator to the fixed AC terminals of the Power Supply, and adjust the DC excitation so that the reactive power supplied to the motor is zero (see Figure 13-5).

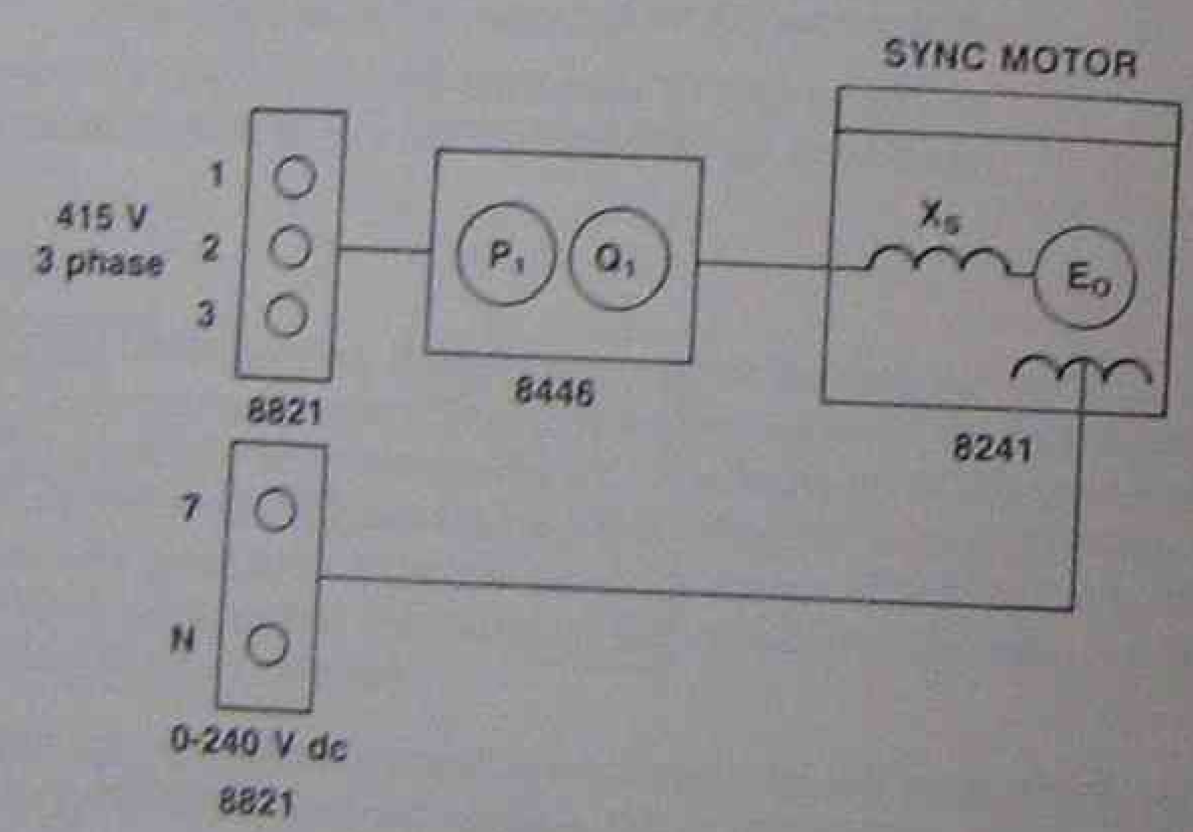


Figure 13-5.

Switch the AC power on and off and, with the Stroboscope, observe the hunting of the rotor.

☐ 2. Repeat procedure step 1, after having added the Inertia Wheel to the motor shaft to increase its inertia. What is the frequency of oscillation?

____

Compare it with your observation in procedure step 1.

☐ 3. Repeat procedure step 2, but feed the motor via a 480 Ω transmission line, setting $Q_2 = 0$ (see Figure 13-6). To start the motor, you can set the line impedance to zero, in order to limit the voltage drop across the line due to high starting current.

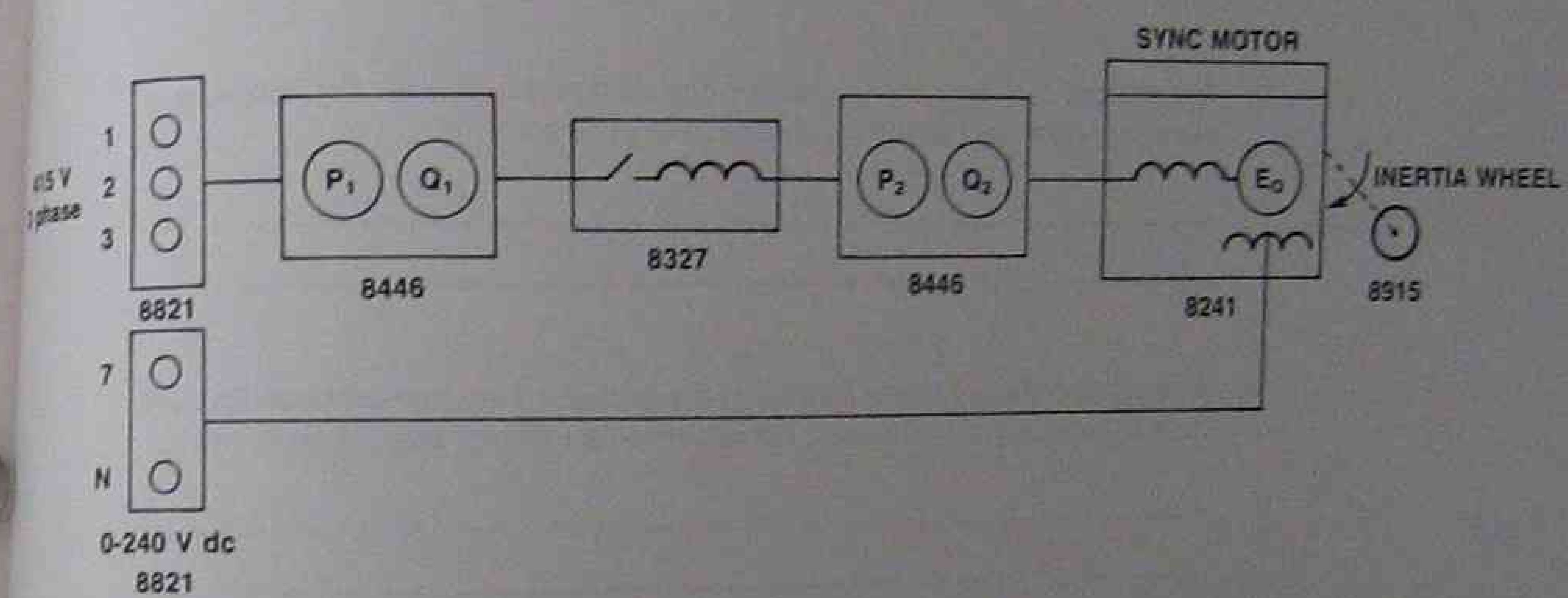


Figure 13-6.

The frequency of hunting is considerably reduced, owing to the reduced peak power which is now available to the motor. What is the frequency of oscillation?

____

☐ 4. Repeat procedure step 3, but without the Inertia Wheel. What happens to the frequency of hunting?

____

Is it just as easy as before to maintain synchronism by rapidly reclosing the power circuit breaker?

☐ Yes ☐ No

TEST YOUR KNOWLEDGE

1. An alternator has a rating of 200 MW, 13,2 kV, 50 Hz, 375 r/min. Under nominal excitation (E_O = 13,2 kV) the machine is able to deliver a peak power of 300 MW. It is found that the natural frequency of oscillation is 20 cycles per minute.

   a) What is its approximate moment of inertia?

   ____

   b) What is the value of the synchronous reactance per phase?

   ____

2. The voltage, in a large city, increases and decreases periodically, following a momentary power interruption. Explain this phenomenon.

   ____

   ____

3. A large synchronous motor located at the end of a long transmission line will hunt more slowly than if it were connected to an infinite bus. Explain why.

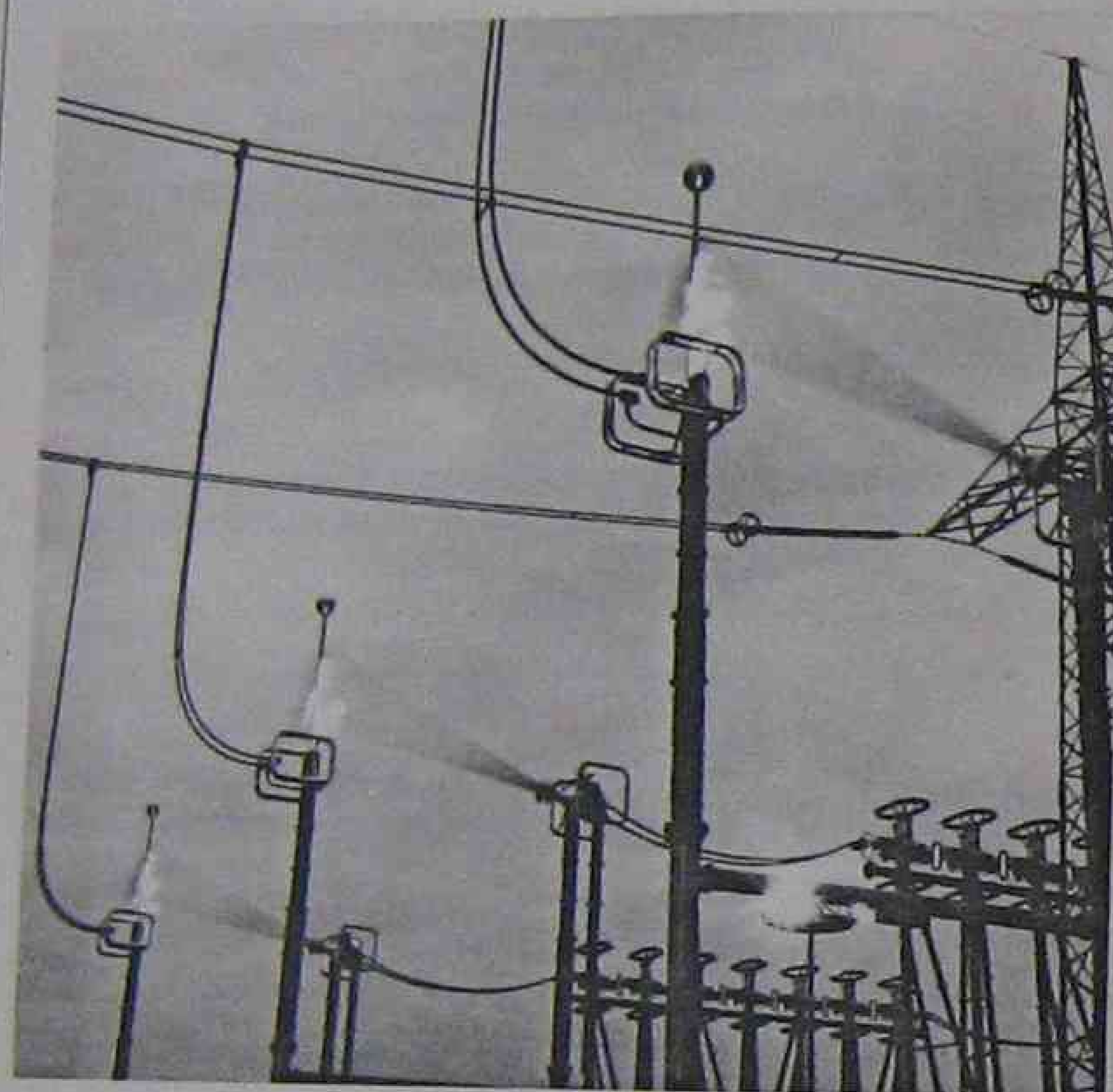
   ____

   ____

4. The moment of inertia of the 175 W machine with its inertia wheel is 0,034 kg·m^2 and its synchronous reactance is about 480 Ω per phase. If this motor is connected to a 3-phase source of 415 V and if the excitation voltage E_O = 415 V (line-to-line) calculate the natural frequency of oscillation under no-load conditions. Does this value correspond to the value you found by experiment?

   ____

   ____



Simultaneous opening of a three-phase disconnect switch draws three arcs as power is extinguished in a line.

Power System Transients

OBJECTIVES

- To observe voltage and power fluctuations under abnormal transmission line conditions.
- To observe voltage and power fluctuations due to line switching.

DISCUSSION

Transmission line disturbances include a) short circuits, b) unforeseen open circuits, and c) switching surges. Such disturbances may be caused by many different factors and are usually of short duration. For example an accidental short-circuit requires immediate opening of the relevant circuit breakers, which are often immediately reclosed, on the assumption that the short-circuit has been cleared. Such a rapid opening and reclosing will produce a local electrical disturbance and cause voltage and power fluctuations, but will not result in loss of synchronism of the synchronous motors which form part of the load. In other words, the system will continue to function because its stability limit has not been exceeded.

The opening and closing of circuit breakers according to a planned schedule will similarly produce temporary disturbances in a large interconnected system. Such is the case for two parallel transmission lines when one of them is suddenly opened (or closed).

Because large synchronous motors are an important part of a total system load, the importance of maintaining stability cannot be over-emphasized. Thus, as soon as the poles of a synchronous motor approach the critical 90° point (on the power vs phase angle curve) there is an imminent danger of losing synchronism which may cause the complete collapse of the system in the vicinity of the disturbance. In fact, it may be prevent the disturbance from spreading throughout the entire interconnected system. Circuit breakers play an important part in maintaining system stability, and they must respond quickly to command signals.

The inertia of synchronous machines helps to keep a system in synchronism, and, in some cases, the inertia of a machine is increased beyond ordinary design considerations, for the sole reason of enhancing stability. Large machines have a relatively higher inertia than smaller machines.

An electrical disturbance is usually accompanied by a significant voltage drop manifested by the dimming lights of a brown-out. The lighting often rises and falls in intensity, which reflects the rising and falling voltage of a system which is hunting.

EQUIPMENT REQUIRED

DESCRIPTION	MODEL
DC Motor/Generator	8211
Three-Phase Synchronous Motor/Generator	8241
Resistive Load	8311
Three-Phase Transmission Line	8329
AC Voltmeter	8426
Three-Phase Wattmeter/Varmeter	8446
Power Supply	8821
Inertia Wheel	8915
Stroboscope	8922
Timing Belt	8942
Connection Leads	9128

PROCEDURE

WARNING

High voltages are present in this Laboratory Experiment! Do not make any connections with the power on!

☐ 1. Connect the Three-Phase Synchronous Motor/Generator to the end of two transmission lines in parallel which, in turn, are connected to a 415 V variable AC source. Couple a DC shunt generator to the motor and provide for resistance loading. Introduce metering for power and voltage, and add the Inertia Wheel to the Three-Phase Synchronous Motor (see Figure 14-1).

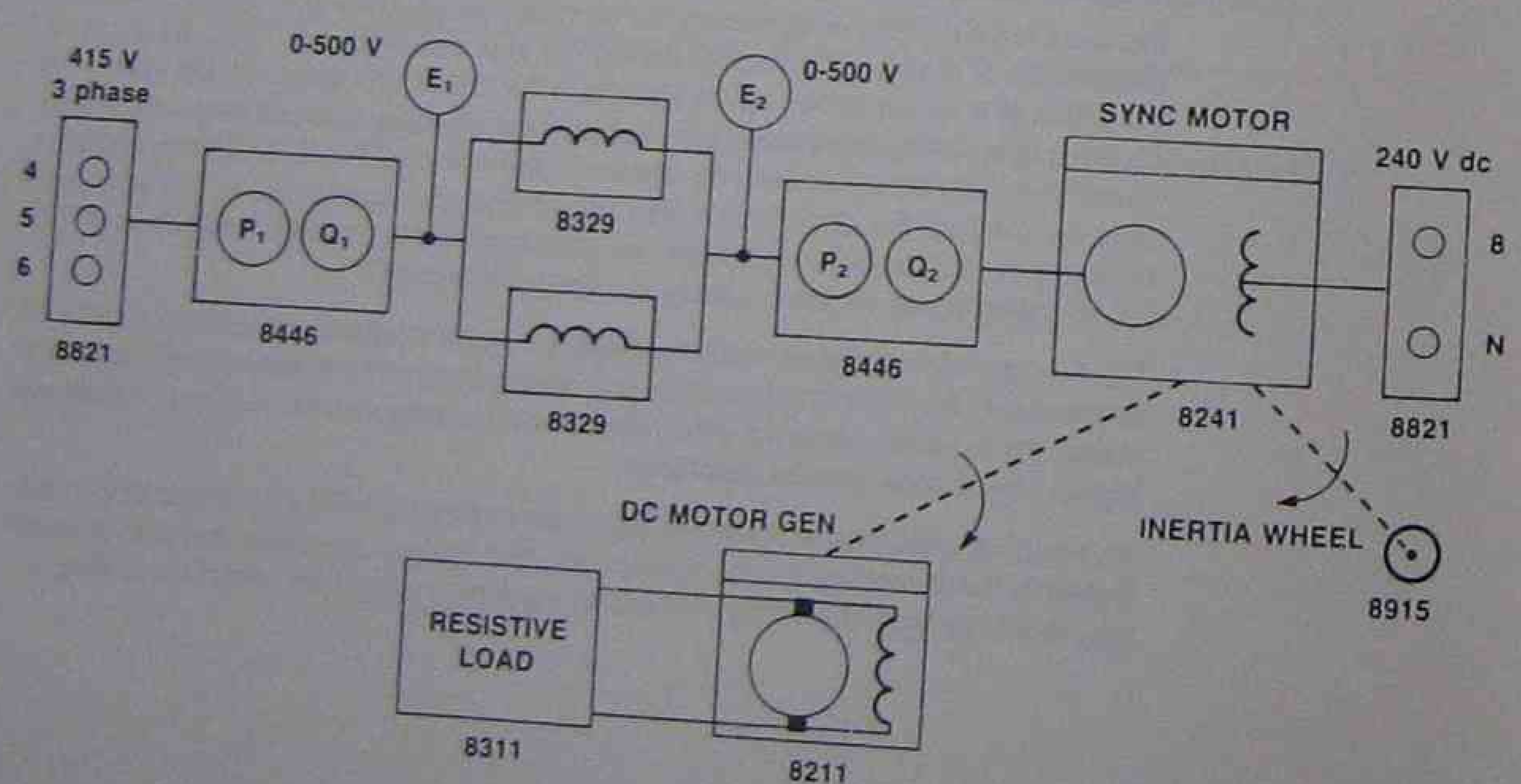


Figure 14-1.

☐ 2. With zero line impedance and minimum loading (shunt field rheostat control knob fully ccw), start up the system. Then set each transmission line to an impedance of 400 Ω. Set the load resistance to 1200 Ω and adjust the shunt field rheostat so that $W_2 = 175$ W. Adjust the DC excitation of the synchronous motor so that $E_2 = E_1 = 415$ V. Vary the load suddenly by switching the 1200 Ω load resistance of the DC generator. Observe the power and voltage fluctuations and, with the Stroboscope, the position of the poles.

Try to switch the load in step with the natural frequency of the system. By so doing you may be able to make the system lose synchronism with a load smaller than normally required.

☐ 3. Once the system is running stably (with $E_2 = E_1 = 415$ V and $W_2 = 175$ W), open one of the parallel transmission lines and observe power and voltage fluctuations. The system should not lose synchronism in this experiment. Explain the behavior and estimate the frequency of oscillation.

____

Then reclose the open line and again observe power and voltage fluctuation. Why is the frequency of oscillation higher than before?

____

____

☐ 4. Repeat procedure step 3, but adjust the load so that $W_2 = 250$ W. Open the circuit breaker of one of the parallel lines; the system should lose synchronism and come to a halt.

Start it up again, and this time open and quickly reclose one transmission line breaker. For about how long can the breaker be left open without the system losing synchronism?

____

____

☐ 5. With conditions again normal and $E_2 = E_1 = 415$ V, and $V_2 = 75$ W), momentarily short-circuit two of the three wires feeding the synchronous motor. Observe what happens and record your results.

____

For how long can this short circuit be sustained without the system losing synchronism?

____

KLYDONOGRAPH. It is found that if a potential difference is applied between the faces of a photographic plate, the emulsion is affected and on developing a figure is obtained. When the emulsion side is at a higher potential than the other side, the figure consists of fine lines radiating from the point of contact; when it is at a lower potential, the figure is a complete and fairly definite circle. The latter, or negative, figure is the more useful as its size is definite. The magnitude of the figure depends upon the magnitude of the potential and its frequency or steepness of wave-front. Thus 50-cycle potentials produce only a small figure, whilst high-frequency or steep-fronted waves produce a large figure. If the film is allowed to run past the electrodes (that on the emulsion side is usually pointed and the other flat), the developed film gives a long line with wide bands. The long narrow line corresponds to the normal operating voltage, and the wide bands to high-frequency discharges or steep-fronted surges. Useful qualitative information has been obtained by the use of the klydonograph, but because of the dependence of the size of the figure on frequency or steepness of wave-front the results are not quantitative.

SURGE CREST AMMETER. The principle of this instrument is the measurement of the residual magnetism in a piece of magnetic material, which has been magnetized by the surge current. From the residual magnetism the peak of the surge current is deduced.

EXAMPLES X

1. Explain what is meant by the surge impedance of a transmission line and derive its value in terms of the line constants. Derive expressions for the values of the transmitted and reflected waves of current and voltage relative to those of the incident waves at a point where the surge impedance changes from Z_1 to Z_2.

A rectangular wave of 200 kV. amplitude travels along a line having a surge impedance of 500 Ω. to a transition point where it is connected to a line of 50 Ω. surge impedance. Determine the values of the transmitted and reflected voltage and current waves. (*Lond. Univ.*, 1954.)

2. Describe and explain the occurrences immediately following the sudden application of a steady voltage to one end of a transmission line open at the far end.

A surge voltage e is travelling along a line of surge impedance Z_A connected at its far end to a line of surge impedance Z_B. Show how to calculate the magnitude of the voltage surges transmitted through and reflected from the junction, explaining all assumptions and approximations. (*B.Sc. Lond. Univ.*, 1933.)

3. Describe with the aid of sketches one good type of lightning arrester. What auxiliary equipment is used in conjunction with the arrester to safe guard the apparatus in the power stations? (*Nat. Cert.*, 1935.)

4. An overhead line is joined to a three-phase underground cable. What apparatus is necessary to protect the cable against surges? Give a diagram of connections. Knowing the surge impedance of each circuit show how to calculate the proportion of the surge that enters the cable. (*B.Sc. Lond. Univ.*, 1931.)

5. Enumerate and explain briefly the causes of surges in a transmission line. Describe methods of preventing such surges and of protecting substation apparatus against damage due to them other than by the use of lightning arresters which discharge the surge to earth. (*Lond. Univ.*, 1932.)

6. Explain the reasons leading to the general practice of earthing the neutral point of a power system and discuss the relative merits of earthing it (*a*) solidly, and (*b*) through an impedance.

An earth electrode consists of a pipe 6 ft. long and 1 in. dia. buried vertically with its upper end at ground level in soil having a uniform resistivity of 10 000 Ω. per cm. per cm.[2] Estimate the potential difference between the electrode and a point on the ground 5 ft. away from it when 100 A. are flowing through the electrode to earth. (*Lond. Univ.*, 1934.)

7. Explain the principle of the cathode-ray oscillograph and describe briefly the construction of such an instrument suitable for recording transmission line surges.

What means are employed in an instrument used for this purpose to secure good photographic sensitivity and to prevent fogging of the recording plate by the ray before and after the passage of the surge? (*Lond. Univ.*, 1933.)

8. Two single transmission lines A and B with earth return are connected in series and at the junction a resistance of 2 000 Ω. is connnected between the lines and earth. The surge impedance of line A is 400 Ω. and of B 600 Ω. A rectangular wave having an amplitude of 100 kV. travels along line A to the junction.

Develop expressions for and determine the magnitude of the voltage and current waves reflected from and transmitted beyond the junction. What value of resistance at the junction would make the magnitude of the transmitted wave 100 kV.? (*Lond. Univ.*, 1949.)

9. An underground cable having an inductance of 0·3 mH. per mile and a capacitance of 0·4 μF. per mile is connected in series with an overhead line having an inductance of 2·0 mH. per mile and a capacitance of 0·014 μF. per mile.

Calculate the values of the reflected and transmitted waves of voltage and current at the junction due to a voltage surge of 100 kV. travelling to the junction (*a*) along the cable, and (*b*) along the overhead line.

Explain how the waves would be modified if the cable and line were of considerable length. (*Lond. Univ.*, 1947.)

10. Explain the function and principle of operation of an arc-suppression coil for use on a 3-phase system.

A 33-kV., 3-phase, 50 c/s, overhead line, 50 miles long, has a capacitance to earth for each line of 0·016 μF. per mile.

Determine the inductance and kVA. rating of the arc-suppression coil suitable for this system. (*Lond. Univ.*, 1947.)

11. Describe the construction and explain the operation of a modern type of surge or lightning arrester, and explain at what part of the circuit it would be most satisfactory. (*Lond. Univ.*, 1947.)

12. Describe with the aid of diagrams, the function and operation of the Petersen coil protective device, and derive an expression for the reactance of the coil in terms of the capacitance of the protected line. What are the merits and demerits of the system? (*Lond. Univ.*, 1949.)

CHAPTER X

VOLTAGE TRANSIENTS AND LINE SURGES

Introduction. There are various ways in which a transmission line may experience voltages greater than the working value, and it is necessary to provide protective apparatus to prevent or minimize the destruction of the plant. Internal causes producing a voltage rise are (1) resonance, (2) switching operations, (3) insulation failure, and (4) arcing earths: a very important external cause is lightning.

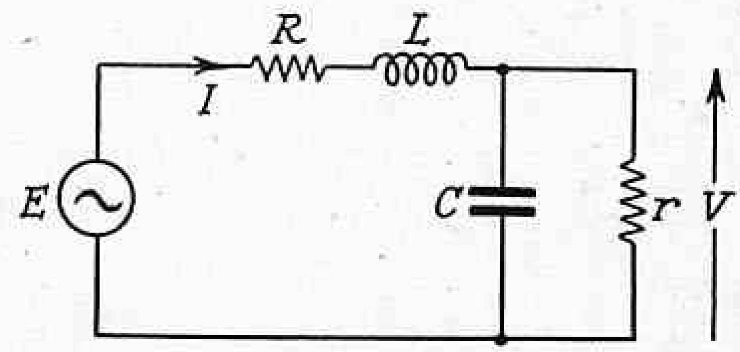


FIG. 237. RESONANCE

Resonance. The effect of resonance is most easily understood by considering the voltage at the end of a lightly loaded cable of short length. The alternator and transformers may be represented by their leakage inductance L, and the cable by a capacitance C. The system is then as shown in Fig. 237, where R represents the resistance of the alternator winding, transformers and cable, and r the resistive load. The total impedance of the circuit is

$$Z = R + j\omega L + \frac{(1/j\omega C)r}{1/j\omega C + r} = R + j\omega L + \frac{r}{1 + j\omega Cr},$$

the current is

$$I = E/Z,$$

and the voltage on the cable is

$$V = I \times r/(1 + j\omega Cr),$$

since the latter expression represents the impedance of the parallel combination of C and r. Substituting for I in terms of E we get

$$V/E = \left(\frac{r}{1 + j\omega Cr}\right) \div \left(R + j\omega L + \frac{r}{1 + j\omega Cr}\right)$$

$$= \frac{1}{1 + (R + j\omega L)(1/r + j\omega C)}$$

$$= \frac{1}{(1 - \omega^2 LC + R/r) + j\omega(L/r + CR)}$$

The magnitude of (V/E) is

$$|V/E| = [(1 - \omega^2 LC + R/r)^2 + \omega^2(L/r + CR)^2]^{-\frac{1}{2}} \quad . \quad (112)$$

Let us consider the case of an unloaded line first. In this case $r = \infty$, so that

$$|V/E| = [(1 - \omega^2 LC)^2 + \omega^2 C^2 R^2]^{-\frac{1}{2}} \quad . \quad . \quad (112a)$$

If we consider that C can vary, by the insertion of different lengths of cable, $|V/E|$ varies in the manner shown in Fig. 238. The maximum value occurs when

$$C = \frac{1}{\omega^2 L + R^2/L} = \frac{1}{\omega^2 L(1 + R^2/\omega^2 L^2)} \simeq \frac{1}{\omega^2 L},$$

when $$|V/E| = \frac{1}{\omega CR\sqrt{(1 + R^2/\omega^2 L^2)}} \simeq \frac{1}{\omega CR} \simeq \frac{\omega L}{R}.$$

A reasonable value of L in a 33 kV. system is 0·05 henry, and the resonating capacitance is then

$$C \simeq \frac{1}{(2\pi \,.\, 50)^2 \times 0{\cdot}05} = 202\ \mu\text{F.},$$

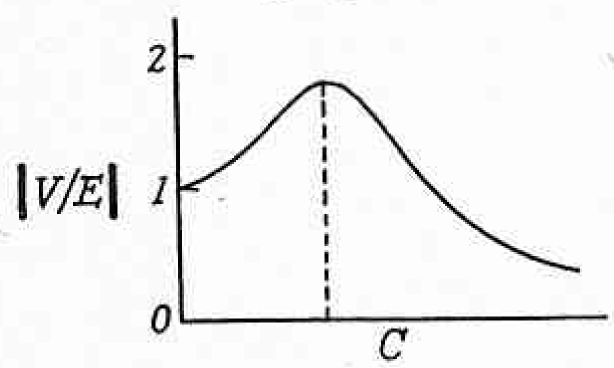


FIG. 238. RESONANCE

which is the capacitance of some hundreds of miles of cable. Resonance in short lines will thus never occur at the fundamental frequency. If we consider the fifth harmonic, which is often present to the extent of 2 or 3 per cent, we see that resonance can occur. The capacitance required is

$$C = \frac{1}{(2\pi \,.\, 250)^2 \times 0{\cdot}05} = 8{\cdot}1\ \mu\text{F.},$$

which is provided by a cable of length about 28 miles. If we assume a 10 per cent harmonic, the value of V_5 is

$$|V_5| = |E_5| \times 2\pi \,.\, 250L/R = 0{\cdot}10\,|E_1| \times 2\pi \,.\, 250L/R,$$

where E_1 is the fundamental, and E_5 the fifth harmonic. If we take $R = 5$, we find that

$$|V_5| = 1{\cdot}57\,|E_1|,$$

so that the fundamental voltage of $E_1 = 33$ kV. has a fifth harmonic of magnitude 52 kV. (r.m.s.). The peak value between phases may then be $\sqrt{2} \times 85$ kV. in place of the normal value of $\sqrt{2} \times 33$ kV.

The effect of a load is seen by comparing equations (112a) and (112). It is seen that the term (R/r) is an additive constant in the first term on the right-hand side of the equations and alters the condition for the neutralization of reactance, whilst the term (L/r) causes a considerable damping of the resonance. Let us take $r = 200$ ohms, which corresponds to a load of 5 000 kW. Then with the values of L, C, and E_5 taken above, we find that

$$1 - \omega^2 LC + R/r \simeq 5/200 = 0{\cdot}025$$

and $$\omega(L/r + CR) = \omega CR(1 + L/CRr) = 7{\cdot}2\omega CR = 0{\cdot}46.$$

The first term is thus negligible compared with the second, so that we may take

$$|V_5/E_5| \simeq \frac{1}{\omega(L/r + CR)} = \frac{1}{7{\cdot}2\omega CR} \simeq \frac{\omega L}{7{\cdot}2R},$$

so that V_5 is reduced by the factor 7·2 and has a magnitude of $52 \div 7{\cdot}2 = 7{\cdot}2$ kV. The resonance voltage has been therefore effectively damped by the load.

Switching. A switching operation produces a sudden change in the circuit conditions, and is accompanied by a *transient state* which leads from the earlier to the later steady (a.c.) states. The behaviour

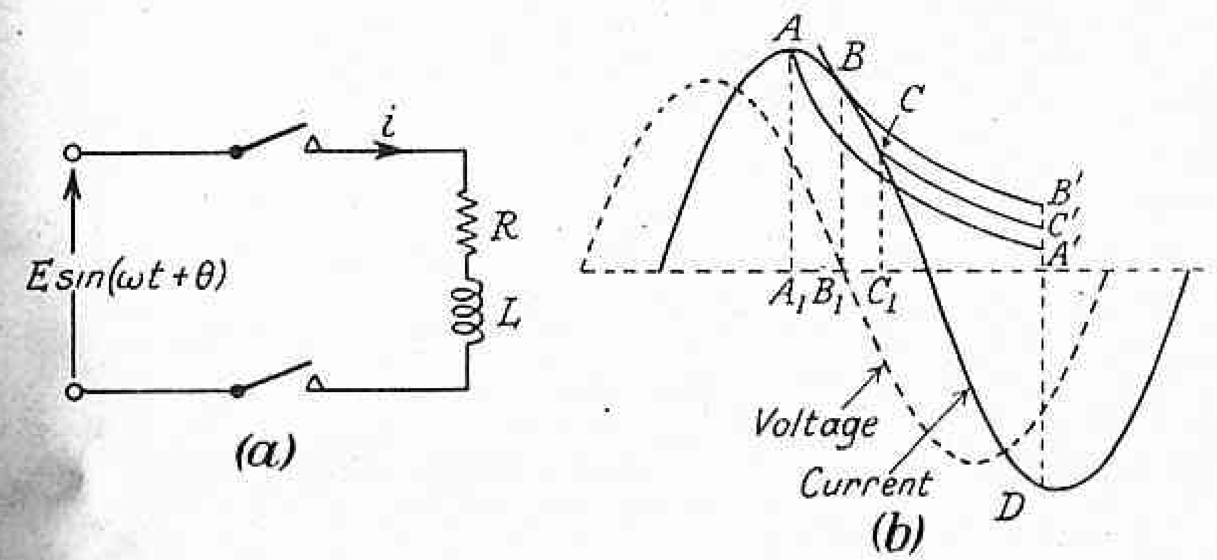


FIG. 239. SWITCHING-IN AN INDUCTIVE RESISTANCE

of the system can be explained with exactness only by means of *travelling waves*, which will be explained later; but in short systems the behaviour is sufficiently well explained if we consider the circuit to be composed of lumped resistances, inductances, and capacitances. The method used is that given on pages 214–16, where we showed that a current of twice the normal peak value can be obtained when an alternator is short-circuited.

Transients in Circuits with Lumped Constants. There are two interesting cases which we will solve, the switching-in of an inductive load and the switching-in of an open-circuited line.

Fig. 239 (a) represents the switching-in of a load of inductance L and resistance R. The equation for the circuit is

$$L(di/dt) + Ri = E \sin(\omega t + \theta),$$

of which the solution is (see page 215)

$$i = A\varepsilon^{-(R/L)t} + \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right).$$

The constant A is determined by the fact that $i = 0$ at the time $t = 0$, so that we find that

$$i = -\frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}$$
$$+ \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} \sin\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right) \quad . \quad (103)$$

The first term represents the *transient current* which decays exponentially. It has an initial value equal and opposite to that of the a.c. component at the time of switching (so that the initial current is zero).

If the circuit is very inductive $\omega L \gg R$, and we may put

$$\sqrt{[R^2 + (\omega L)^2]} \simeq \omega L$$

and

$$\tan^{-1}(\omega L/R) = \pi/2.$$

The current then becomes

$$i = (E/\omega L)\,[\sin(\omega t + \theta - \pi/2) - \varepsilon^{-(R/L)t}\sin(\theta - \pi/2)]$$
$$= (E/\omega L)\,[\varepsilon^{-(R/L)t}\cos\theta - \cos(\omega t + \theta)].$$

During the early period after switching $\varepsilon^{-(R/L)t}$ does not decay rapidly from the value of unity, and the current is therefore approximately

$$i = (E/\omega L)\,[\cos\theta - \cos(\omega t + \theta)], \quad (113)$$

and varies between the values of $(E/\omega L)\,[\cos\theta - 1]$ and $(E/\omega L)\,[\cos\theta + 1]$. The peak value is thus

$$(E/\omega L)\,(1 + |\cos\theta|),$$

i.e. $(1 + |\cos\theta|)$ times the normal peak value. The maximum peak is thus obtained when $\theta = 0$ and is twice the normal peak. This condition occurs when the circuit is closed at zero voltage and the current is

$$i = (E/\omega L)\,[1 - \cos\omega t], \quad . \quad . \quad . \quad (114)$$

which varies between zero (at $t = 0$) and $(2E/\omega L)$ (at $t = \pi/\omega$).

It can be shown that, whatever the power factor of the circuit may be, the maximum "doubling" effect is obtained when the circuit is closed at zero voltage. Fig. 239 (*b*) shows the normal sinusoidal current. If the circuit is switched in at A the transient has initial amplitude AA_1, if at B the amplitude BB_1, and if at C the amplitude CC_1. The transients corresponding to these switching points are represented by the curves AA', BB', CC' and must be subtracted from the sine wave. The total current at any instant is thus the vertical distance between the sine wave and the appropriate transient curve. It is clear that if the circuit is switched in at position B the current is greater than if switched at any other

position, since the transient curves have the same time factor $\varepsilon^{-Rt/L}$ and have the same decay rate. The topmost curve is clearly seen to be that whose slope at the point of contact with the sine wave is equal to the slope of the sine wave. Let us consider this as the time $t = 0$. Equating slopes we get

$$\left[-\frac{R}{L}\sin\left(\theta - \tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}\right]_{t=0}$$
$$= \left[\omega\cos\left(\omega t + \theta - \tan^{-1}\frac{\omega L}{R}\right)\right]_{t=0}$$

i.e. $$-(\omega L/R) = \tan\,[\theta - \tan^{-1}(\omega L/R)],$$

which gives $\theta = 0$ or π. If $\theta = 0$ or π the voltage is zero at $t = 0$, i.e. the maximum doubling occurs if the circuit is closed at the instant of zero voltage.

Suppose the load has a power factor of 0·8 lagging,

$$\omega L/R = 0{\cdot}6/0{\cdot}8 = 0{\cdot}75.$$

If the circuit is closed at zero voltage the current is

$$i = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\left[\sin\left(\omega t - \tan^{-1}\frac{\omega L}{R}\right) + \sin\left(\tan^{-1}\frac{\omega L}{R}\right)\varepsilon^{-(R/L)t}\right]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}}\,[\sin(\omega t - 36^\circ\,52') + 0{\cdot}6\varepsilon^{-1{\cdot}33\omega t}].$$

For this case the voltage and currents in Fig. 239 (*b*) must be reversed. The maximum current occurs when $di/dt = 0$, i.e. when

$$\cos(\omega t - 36^\circ\,52') = 0{\cdot}6 \times 1{\cdot}33\varepsilon^{-1{\cdot}33\omega t} = 0{\cdot}8\varepsilon^{-1{\cdot}33\omega t}.$$

Let $\omega t - 36^\circ\,52' = \phi$, so that

$$\omega t = \phi + 36^\circ\,52' = \phi + 0{\cdot}64 \text{ radians}.$$

The equation becomes

$$\varepsilon^{1{\cdot}33\phi}\cos\phi = 0{\cdot}8\varepsilon^{-0{\cdot}853} = 0{\cdot}34.$$

ϕ	1	1·5	1·54
$\varepsilon^{1{\cdot}33\phi}$	3·78	7·39	7·76
$\cos\phi$	0·540	0·0707	0·0308
$\varepsilon^{1{\cdot}33\phi}\cos\phi$	2·04	0·52	0·24

We may take $\phi = 1{\cdot}53$ radians $= 87° 40'$, so that

$$i_{max} = \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [\sin 87° 40' + 0{\cdot}6\varepsilon^{-1{\cdot}33\omega t}]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [1 + 0{\cdot}34\varepsilon^{-1{\cdot}33 \times 1{\cdot}533}]$$
$$= \frac{E}{\sqrt{[R^2 + (\omega L)^2]}} [1{\cdot}044],$$

and the peak does not exceed the normal value by more than 4·5 per cent.

Fig. 240 represents the switching-in of an open-circuited line; we assume for simplicity that the e.m.f. is constant and equal to E,

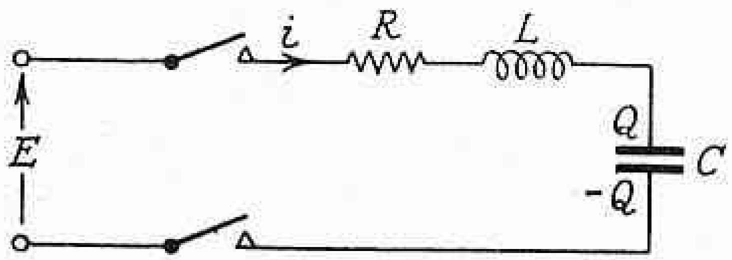


FIG. 240. SWITCHING-IN AN OPEN-CIRCUITED LINE

but the same method is applicable for an a.c. case. The equation for the current is

$$L(di/dt) + Ri + Q/C = E$$

where $i = dQ/dt$.

The voltage at the end of the line is $V = Q/C$. Substituting for i in terms of Q we get

$$L(d^2Q/dt^2) + R(dQ/dt) + Q/C = E,$$

the solution of which is

$$Q = CE + \varepsilon^{-(R/2L)t} (A \cos \alpha t + B \sin \alpha t),$$

where $\alpha = \sqrt{[(1/LC) - (R^2/4L^2)]}$, and A and B are constants which are determined by the initial conditions. At the instant, $t = 0$, of switching-in Q and i are zero. These conditions give

$$A = -CE \text{ and } B = AR/2L\alpha,$$

so that $V = Q/C = E - E\varepsilon^{-(R/2L)t} [\cos \alpha t + (R/2L\alpha) \sin \alpha t]$

$$\left.\begin{aligned} &= E - E[1/\alpha\sqrt{(LC)}]\varepsilon^{-(R/2L)t} \cos [\alpha t - \cos^{-1} (\alpha\sqrt{(LC)})], \\ \text{and } i &= dQ/dt = (E/\alpha L)\,\varepsilon^{-(R/2L)t} \sin \alpha t. \end{aligned}\right\} \quad (115)$$

If the resistance is negligible the voltage and current reduce to

$$\left.\begin{aligned} V &= E - E \cos [t/\sqrt{(LC)}] \\ \text{and} \quad i &= [E\sqrt{(C/L)}] \sin [t/\sqrt{(LC)}], \end{aligned}\right\} \quad . \quad . \quad (115a)$$

since $\alpha = 1/\sqrt{(LC)}$ in this case.

The voltage in this case oscillates sinusoidally between 0 and $2E$, whilst the current is a sine wave of peak value $E\sqrt{(C/L)}$. Fig. 241 shows the voltage and current for the case of no resistance (curves A) and for some resistance (curves B).

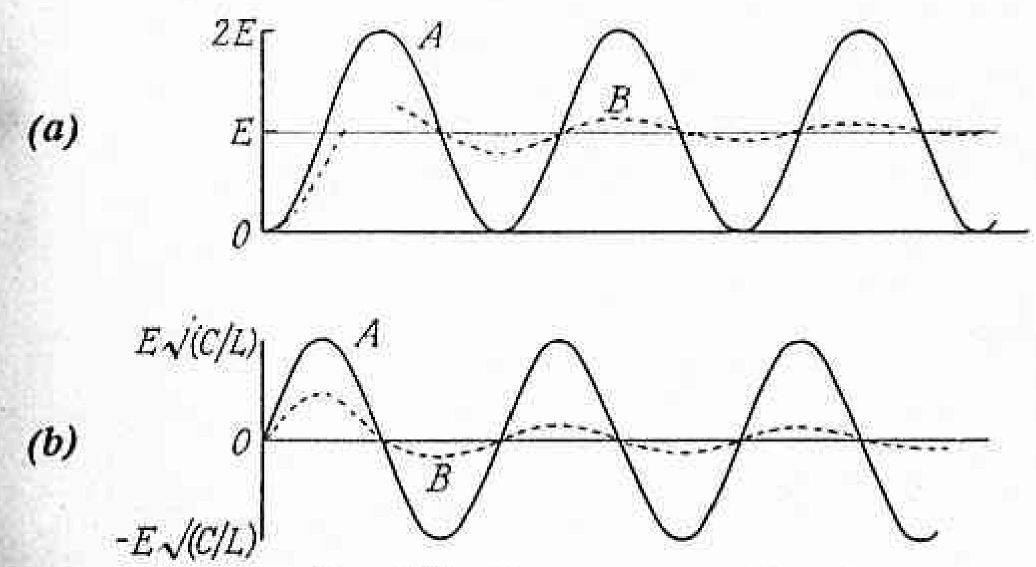


FIG. 241. OPEN-CIRCUITED LINE
(a) Voltage. (b) Current.

Switching Surges. We have found that when an e.m.f. E is switched on to a line, which we replaced by an inductance L and a capacitance C, the voltage oscillates sinusoidally between 0 and $2E$ whilst the current varies similarly between $-E\sqrt{(C/L)}$ and

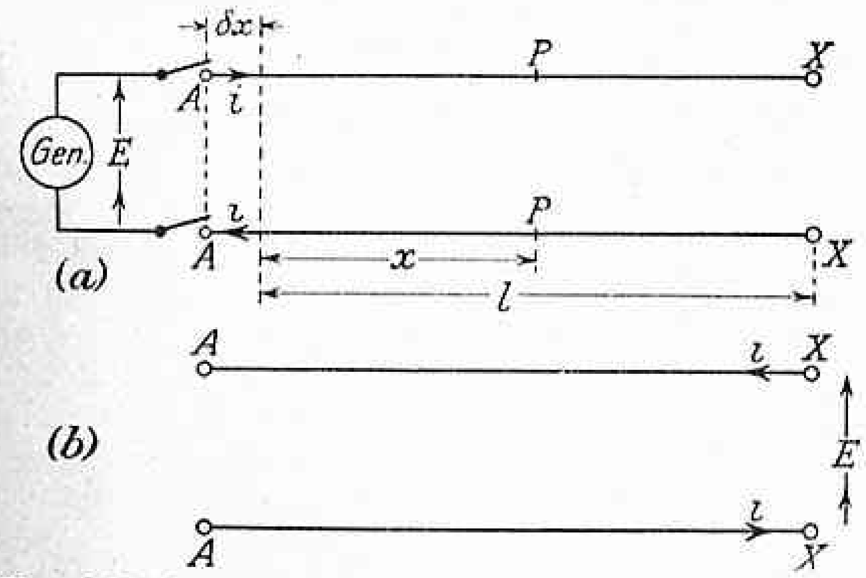


FIG. 242. SWITCHING SURGE ON OPEN-CIRCUITED LINE

$+E\sqrt{(C/L)}$. It is clear that this does not represent the state of affairs with exactness, for any transfer of energy must travel with a velocity less than that of light, so that the far end of a line is unaffected for the finite time that it takes the energy wave to reach it. It therefore follows that part of the line may be passing current and maintaining a voltage whilst a further part has neither current nor voltage. We will consider the case of the switching-in of an unloaded line from this point of view, and will make the simplifying assumption that resistance and leakage are negligible. Fig. 242 (*a*) shows the arrangement; the line has inductance L and capacitance C per unit length and is open at the far end XX.

At the instant of switching an e.m.f. E is placed on the line at AA, and a current i passes to the right in the upper conductor and to the left in the lower conductor. Suppose that in a very small time δt the conditions of a current i and a voltage E are established along a length δx of the line. The e.m.f. E is balanced by the back e.m.f. generated by the magnetic flux which is produced by the current in this length of the line. The inductance of the length δx is $L\delta x$, so that the flux built up is $iL\delta x$ and the back e.m.f. is the rate of build-up, viz. $iL(\delta x/\delta t)$. We have therefore

$$\begin{aligned} E &= iL(\delta x/\delta t) \\ &= iLv, \qquad (116) \end{aligned}$$

where v is the velocity of the wave.

The current i carries a charge $i\delta t$ in the time δt, and this charge remains on the line to charge it up to the potential E. Since the capacitance of the length δx of the line is $C\delta x$, its charge is $EC\delta x$. We have therefore

$$i\delta t = EC\delta x,$$

or

$$\begin{aligned} i &= EC(\delta x/\delta t) \\ &= ECv. \qquad (117) \end{aligned}$$

The switching of an e.m.f. E on to the line results therefore in a wave of current i and velocity v where i and v are given by equations (116) and (117). Multiplying these equations we get

$$Ei = iLvECv = EiLCv^2,$$

so that

$$v = 1/\sqrt{(LC)}. \qquad (118)$$

Substituting for v in equation (118) we find that

$$\left.\begin{aligned} i &= E\sqrt{(C/L)} = E/Z \\ Z &= \sqrt{(L/C)}. \end{aligned}\right\} \qquad (119)$$

where

Z is called the *surge impedance* or *natural impedance* of the line; it is a pure resistance for a line without resistance or leakage, and has a value of 400 to 600 ohms for an overhead line and 40 to 60 ohms for a cable. The velocity of the wave on an overhead line is approximately equal to the velocity of light, for

$$\begin{aligned} L &= [1 + 4 \text{ logh } (D/r)] \times 10^{-9} \text{ H. per cm.} \\ &\simeq 4 \text{ logh } (D/r) \times 10^{-9} \text{ H. per cm.} \end{aligned}$$

and

$$\begin{aligned} C &\simeq \frac{1}{4 \text{ logh } (D/r)} \text{ cm. per cm.} \\ &= \frac{1}{9 \times 10^{11}} \frac{1}{4 \text{ logh } (D/r)} \text{ F. per cm.} \end{aligned}$$

so that

$$\begin{aligned} v &= \frac{1}{\sqrt{(LC)}} = \sqrt{(10^9 \times 9 \times 10^{11})} \text{ cm. per sec.} \\ &= 3 \times 10^{10} \text{ cm. per sec.} \\ &= c, \end{aligned}$$

the velocity of light.

The velocity in a cable is $c/\sqrt{\varepsilon}$, where ε is the dielectric constant. v is thus about 186 000 miles per sec. on an overhead line, and 186 000 $\div \sqrt{3{\cdot}6}$ = 98 000 miles per sec. in a cable.

We have shown that a wave of voltage E and current $i = E/Z$, travels towards the right along the line with a velocity v. Such a wave is called a *pure travelling wave*. At any part PP of the line nothing happens until the wave reaches it (at time $t = x/v$), and then the current jumps from zero to i and the voltage from zero to E. This goes on until the wave reaches the open end of the line (XX) at time $t = l/v$. When the wave reaches XX, the current there is i; but this current has no capacitance to charge up, so that it must cease immediately.

The open end of the line has thus a disturbing influence which neutralizes the current completely; this disturbing influence then travels back along the line towards AA, and can therefore be represented by a pure travelling wave moving towards the left and carrying a current $-i$. A travelling wave must possess a voltage and a current whose ratio is Z, the surge impedance of the line. If the current is to the left in the upper conductor and to the right in the lower from the end XX, it is seen from Fig. 242 (*b*) that the voltage is E, i.e. the upper conductor is E volts above the lower. For if an e.m.f. E were switched in at XX the current would be in the direction required and as shown. The disturbing effect of the open end of the line is thus to introduce another pure travelling wave, which moves to the left with velocity v, has a voltage E, and a current i in the opposite direction to that previously flowing. It is convenient to consider a current to the right in the upper conductor as positive, and a current to the left in the upper conductor as negative. The new travelling wave, which moves to the left, has therefore a voltage E and a current $-E/Z$. In general, a wave (E_1, i_1) moving to the right satisfies the relation

$$i_1 = E_1/Z, \qquad (120)$$

while a wave (E_2, i_2) moving to the left satisfies the relation

$$i_2 = -E_2/Z. \qquad (121)$$

The result of the new travelling wave is to establish an extra voltage E at any point of the line that it passes so that a resulting voltage of $2E$ is produced, whilst the current is neutralized. Thus the conditions at the point PP of the line are such that its voltage and current values are (0, 0) from $t = 0$ until $t = x/v$, (E, i) from $t = x/v$ until $t = (2l - x)/v$, and $(2E, 0)$ from $t = (2l - x)/v$ onwards. This goes on until the disturbing wave reaches the generator at AA at time $t = 2l/v$; by this time the line has voltage $2E$ and zero current at every point. When this instant occurs, the voltage at the generator terminals is $2E$. But the generator is supposed to maintain a voltage E at AA, so that another wave is called into play to reduce $2E$ to E. This wave must therefore have potential $-E$, and as it moves to the right it must have a current $-E/Z = -i$ by equation (120). As this wave travels from AA to XX it reduces the voltage to E and produces a current $-i$. Thus the voltage drops from $2E$ to E at the point PP at time $t = (2l + x)/v$ and the current jumps from zero to $-i$. When this third wave reaches XX it establishes a current $-i$ there, which must be neutralized by a fourth wave travelling to the left with current $+i$, and voltage $-iZ = -E$ by equation (121). As this fourth wave travels from XX to AA, the current vanishes at any point it passes, and the voltage becomes $E - E = 0$ at every point. The line is thus completely discharged and has no current, and a complete cycle of travelling waves has been finished. If the line were completely without resistance and leakage, this cycle would be repeated indefinitely. The current at AA, the current and voltage at the mid-point of the line, and the voltage at XX are shown in Fig. 243.

It is interesting and instructive to compare the exact description of the switching phenomenon with the approximate description derived by considering the line as composed of a lumped inductance and capacitance. In both descriptions the potential at any point varies between 0 and $2E$; but in the exact description the time-variation of the potential depends greatly upon the point considered (see Fig. 243, last two curves) and changes in jumps, whilst in the approximate method the time-variation is sinusoidal. The current varies between $+i$ and $-i$ in both cases, where $i = E/Z$ and $Z = \sqrt{(L/C)}$; but again the time-variations are radically different. There is one further difference, viz. the periodicity of the two descriptions. In the approximate method the frequency is $1/2\pi\sqrt{(LC)}$; whilst in the exact method a complete cycle is of duration $4l/v$, so that the frequency is

$$v/4l = 1/4l\sqrt{(LC)} = 1/4\sqrt{(L_0C_0)},$$

where L_0 and C_0 are the total inductance and capacitance. The difference is therefore in replacing the 2π by 4.

Before entering on a somewhat more general description of

travelling waves, it is worth while considering the energy properties of the simple waves we have described.

Energy Considerations. A wave of voltage E and current i carries a power of Ei. A simple travelling wave therefore transmits a power Ei with a velocity v. As this wave travels it establishes a magnetic field with energy $\frac{1}{2}Li^2$ per cm. length of the line and an electrostatic field with energy $\frac{1}{2}CE^2$ per cm. length. From equations

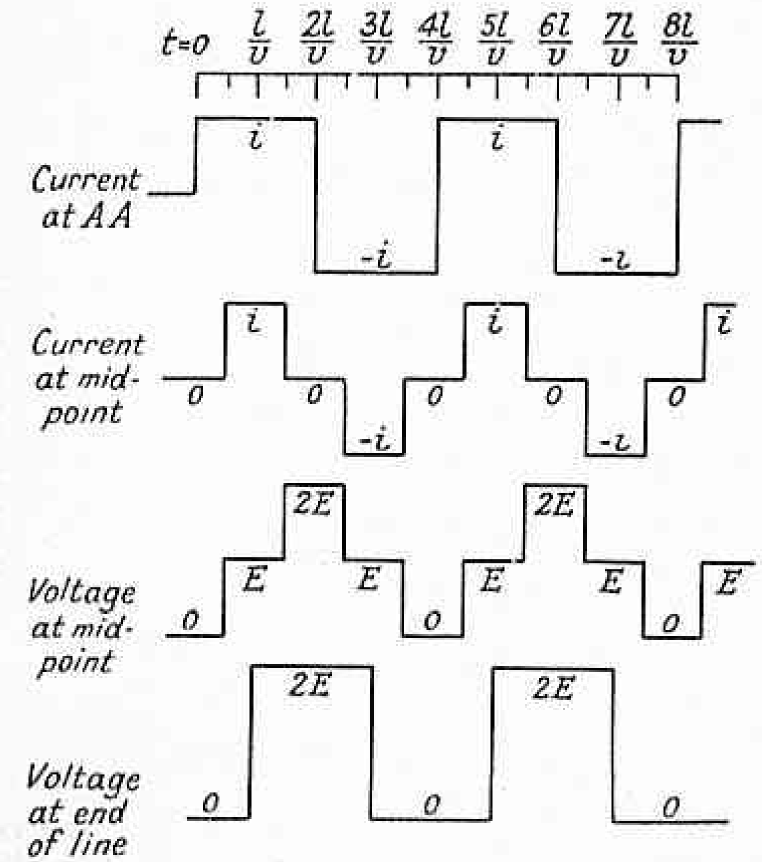


FIG. 243. CURRENT AND VOLTAGE IN SWITCHING SURGE

(116) and (117) it is seen that the magnetic and electrostatic energies delivered by a simple wave are equal, for

$$\tfrac{1}{2}Li^2 = \tfrac{1}{2}(iLv)\,(i/v) = \tfrac{1}{2}(Ei/v)$$
$$= \tfrac{1}{2}(E/v)\,(ECv) = \tfrac{1}{2}CE^2.$$

Each of these is equal to $\frac{1}{2}Ei/v$, which is half the total energy delivered by the wave in the time it passes along the part of the line. The energy of the wave is thus half absorbed as magnetic and half as electrostatic energy.

When a pure travelling wave of voltage E and current i moves to the right and meets an open-circuited line, we said that the disturbing effect of the open end is to bring into action a reflected wave of voltage E and current $-i$ (travelling to the left). It will be seen that this is consistent with the conservation of energy, and is in fact demanded by this principle. For suppose that the disturbance engenders a wave with a current $-i$, the latter being required in order to neutralize the current at the open end of the line. Suppose that the voltage attached to this wave is E'. When the wave has travelled a distance XY (Fig. 244), the voltage over XY is $E + E'$ whilst the current is zero. The energy associated with this part of the line is now

$$\tfrac{1}{2}C \,.\, XY \,.\, (E + E')^2,$$

whereas previously it was

$$\tfrac{1}{2}C \,.\, XY \,.\, E^2 + \tfrac{1}{2}L \,.\, XY \,.\, i^2 = C \,.\, XY \,.\, E^2,$$

since $\frac{1}{2}Li^2 = \frac{1}{2}CE^2$. The gain in energy has been derived from the first (incident) wave, which feeds energy into the section XY at a rate Ei; the gain is thus Ei multiplied by the time that the reflected wave takes to travel from X to Y, viz. $Ei \times (XY/v)$. If the principle of conservation of energy is to hold, then

$$\tfrac{1}{2}C \,.\, XY \,.\, (E + E')^2 = C \,.\, XY \,.\, E^2 + Ei(XY/v),$$

or $$\tfrac{1}{2}(E + E')^2 = E^2 + Ei/Cv = E^2 + E^2$$

(by equation (117)),

so that $$(E + E')^2 = 4E^2,$$

i.e. $$E' = E.$$

The principle of the conservation of energy thus demands that the reflected wave at an open end shall have a voltage equal to that of the incident wave; the current is equal and opposite to that of the incident wave since no current can leave the open end.

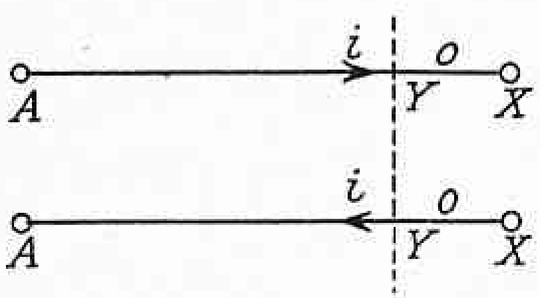


FIG. 244. ENERGY CONSIDERATIONS IN SURGES

Sudden Interruption of a Circuit. We have described in full the surge that takes place when a generator is suddenly switched on to a line that is open at the far end. The phenomenon that takes place when the far end is terminated by a finite impedance will be considered in the section on the reflection and transmission of travelling waves. The method employed above serves to describe the events that occur when a current in a circuit is suddenly interrupted, by the action of a circuit-breaker, say.

Suppose that a circuit has a current i, which is suddenly interrupted by the breakers S, S (Fig. 245). The disturbance produces two travelling waves moving from S, S to the right and to the left. The wave travelling to the right has a current $- i$, and must

therefore have a voltage $- E$, where $E = iZ$; line A is therefore $- E$ volts above line B. The wave travelling to the left has a current $- i$, and must therefore have a voltage $+ E$, where $E = iZ$; C is therefore $+ E$ volts above D. These waves progress in a normal manner until they meet abrupt changes in the line, when they are reflected and transmitted in the ways described later. It should be

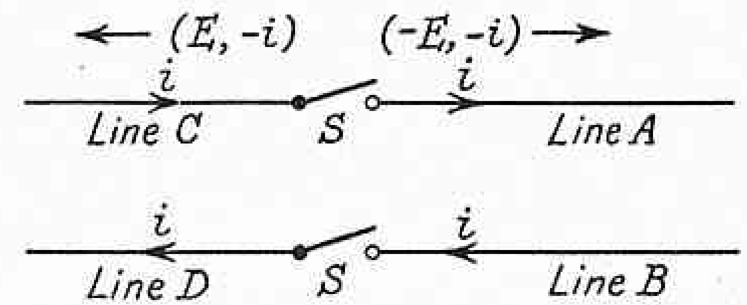


FIG. 245. SUDDEN INTERRUPTION OF A CIRCUIT

noted that if only one break is made, so that B and D are always commoned, the voltage between A and C is $2E$.

The surge voltage E is superposed on the normal voltage in that part of the line which remains connected to the generator.

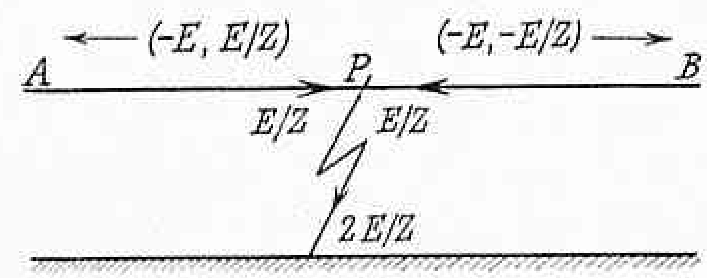


FIG. 246. SURGES DUE TO A FAILURE OF INSULATION

Insulation Failure or Earthing of a Line. Suppose that a line AB, at potential E, is earthed at a point P. The effect of earthing is to introduce a voltage $- E$ at P, and two equal waves of voltage $- E$ travel along PA and PB. The wave travelling to the right has a current of $- E/Z$, and that to the left $+ E/Z$. Both these currents pass through P to earth, so that the current to earth is $2E/Z$. Fig. 246 shows the waves and currents in the system.

As these waves travel to the ends of the line they reduce the voltage to zero; and when they reach the open ends, reflected waves are set up which reduce the voltage to $E - E - E$, i.e. $- E$, and the current is neutralized. When the reflected waves reach P, the portions of the line along which they have travelled will be charged to $- E$. The current at P can be reversed by a flashover in the opposite direction, and the result is a periodic flashover with reversals of potential on the line and currents at P until the stored energy is dissipated by damping.

Reflection and Transmission of Travelling Waves. Suppose that a travelling wave (E, i) moves along a line of surge impedance Z and meets a termination of resistance R (Fig. 247). If R is not equal to Z, the end of the line cannot have the voltage E and current i since $E/i = Z$. There is therefore a disturbance which

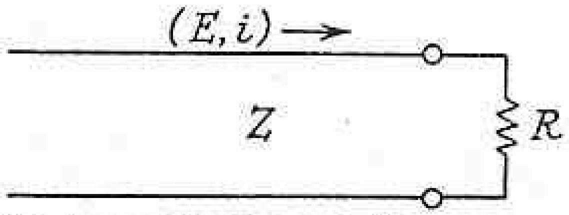


Fig. 247. Reflection of a Travelling Wave

produces a reflected wave (E', i') moving towards the left. The following relations exist.

$$E = iZ,$$
$$E' = -i'Z.$$

The total voltage at the end is $E + E'$ and the total current is $i + i'$, so that

$$E + E' = R(i + i').$$

These equations give

$$Z(i - i') = R(i + i')$$

so that $$i' = [(Z - R)/(Z + R)]i$$
and $$E' = -i'Z = [(R - Z)/(Z + R)]E. \quad (122)$$

The total current and voltage are

$$i + i' = [2Z/(Z + R)]i$$
and $$E + E' = [2R/(Z + R)]E. \quad (123)$$

If the line is open at the end, $R = \infty$ so that the total current is zero and the total voltage is $2E$, as found before.

If the line is shorted at the end, $R = 0$ so that the current is doubled and the voltage drops to zero.

The case for a finite resistance termination is given by equations (122) and (123). When the termination is not a pure resistance, the result is still given by these equations but they must be evaluated by the operational calculus.

Junction of Two Lines. Fig. 248 shows the case of two lines of surge impedances Z_A and Z_B. A wave (E, i) travels along the left-hand line and meets the junction. So far as a travelling wave is concerned the right-hand line can be considered to have an impedance Z_B, so that the case is the same as that shown in Fig. 247,

provided Z is replaced by Z_A and R by Z_B. The reflected wave is thus (E', i') where

$$i' = [(Z_A - Z_B)/(Z_A + Z_B)]i$$
and $$E' = [(Z_B - Z_A)/(Z_A + Z_B)]E. \quad (122a)$$

The transmitted wave must clearly have a voltage equal to the total voltage at the junction and a current equal to the total. Thus the transmitted wave is (E'', i'') where

$$i'' = i + i' = (2Z_A/(Z_A + Z_B)]i$$
and $$E'' = E + E' = (2Z_B/(Z_A + Z_B)]E. \quad (123a)$$

Example. Deduce a simple expression for the natural impedance of a transmission line. A transmission line has a capacitance of 0·0125 μF. per mile and an inductance of 1·5 mH. per mile. This overhead line is continued

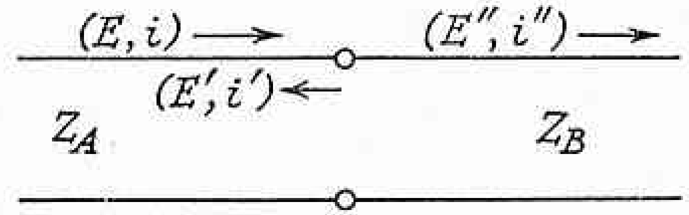


Fig. 248. Effect of a Sudden Change in the Line on Travelling Waves

by an underground cable with a capacitance of 0·3 μF. per mile and an inductance of 0·25 mH. per mile. Calculate the rise of voltage produced at the junction of the line and cable by a wave with a crest value of 50 kV. travelling along the cable. (*Lond. Univ.*, 1931.)

The natural impedance is $\sqrt{(L/C)}$. The value for the cable is

$$Z_A = \sqrt{\left[\frac{0{\cdot}25 \times 10^{-3}}{0{\cdot}3 \times 10^{-6}}\right]} = \sqrt{833} = 28{\cdot}9\ \Omega.,$$

whilst the value for the overhead line is

$$Z_B = \sqrt{\left[\frac{1{\cdot}5 \times 10^{-3}}{0{\cdot}0125 \times 10^{-6}}\right]} = \sqrt{120\ 000} = 346{\cdot}4\ \Omega.$$

The reflected wave has a crest voltage

$$E' = [(Z_B - Z_A)/(Z_B + Z_A)] \times 50 \text{ kV}.$$
$$= (317{\cdot}5/375{\cdot}3) \times 50 \text{ kV}. = \underline{42{\cdot}3 \text{ kV}.},$$

so that the maximum voltage at the junction is 92·3 kV.

The next example shows the calculation of the reflected and transmitted waves at a point where a line forks.

Example. Obtain the law for the behaviour of a voltage surge with vertical wave-front which, after travelling in a transmission line of inductance L and capacitance C per unit length, reaches a fork where the line splits into two sections having line constants L_1C_1 and L_2C_2 respectively. Neglect resistance and attenuation and obtain the distribution of voltage and current immediately after the wave-front has reached the fork.

An overhead transmission line has a surge impedance of 700 Ω., and a voltage wave of 10 000 V. travelling along it. The wave is assumed to be of infinite length and the wave-front is vertical. At a certain point the overhead line terminates and the circuit is continued by two cables in parallel. The surge impedance of one cable is 100 Ω., and that of the other is 200 Ω. Calculate the voltage and current in the overhead line and in the two cables immediately after the travelling wave has reached the fork.

(*Lond. Univ.*, 1927.)

Fig. 249 represents the arrangement schematically. The surge impedances are

$$Z = \sqrt{(L/C)},\ Z_1 = \sqrt{(L_1/C_1)},\ \text{and}\ Z_2 = \sqrt{(L_2/C_2)}.$$

Let the incident wave be (E, i) travelling to the right, the reflected wave (E', i') travelling to the left, and the transmitted waves (E'', i_1'') and (E'', i_2'') travelling towards the right. The transmitted waves clearly have the same voltage as they are in parallel. Equations (120) and (121) give the relations

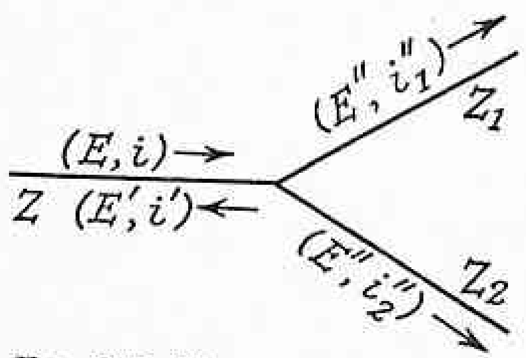


FIG. 249. TRAVELLING WAVES AT JUNCTION OF LINES

$$E = iZ,$$
$$E' = -i'Z,$$
$$E'' = i_1''Z_1,$$
and
$$E'' = i_2''Z_2.$$

The current entering the fork must be equal to the current leaving, so that

$$i + i' = i_1'' + i_2'' \quad . \quad . \quad . \quad . \quad (124)$$

The voltage at the junction is

$$E + E' = E'' \quad . \quad . \quad . \quad . \quad . \quad (125)$$

These six equations are sufficient to find E', E'', i, i', i_1'', and i_2'' for an incident wave of given magnitude E. Substituting for the currents in terms of the voltages we see that equation (124) becomes

$$E - E' = E''Z\left(\frac{1}{Z_1} + \frac{1}{Z_2}\right).$$

Adding this to equation (125) we get

$$2E = E''(1 + Z/Z_1 + Z/Z_2),$$

so that the voltage at the fork is

$$E'' = \frac{2E}{1 + Z/Z_1 + Z/Z_2} = 2E\frac{1/Z}{1/Z + 1/Z_1 + 1/Z_2}.$$

The transmitted currents are

$$i_1'' = E''/Z_1 \text{ and } i_2'' = E''/Z_2,$$

whilst the incident current is $i = E/Z$.

The reflected voltage is

$$E' = E'' - E = E\frac{1/Z - 1/Z_1 - 1/Z_2}{1/Z + 1/Z_1 + 1/Z_2}$$

and the current is $i' = -E'/Z$. It is seen that the reflected wave is zero when

$$1/Z = 1/Z_1 + 1/Z_2,$$

i.e. when the parallel combination of the surge impedances of the outgoing lines at the fork is equal to the surge impedance of the line along which the incident wave travels.

In the example $Z = 700$, $Z_1 = 100$, $Z_2 = 200$, and $E = 10\ 000$. We then have

$$i = 10\ 000/700 = \underline{14{\cdot}3}\text{ A.},$$

$$E' = 10\ 000\,\frac{\frac{1}{700} - \frac{1}{100} - \frac{1}{200}}{\frac{1}{700} + \frac{1}{100} + \frac{1}{200}} = -\ \underline{8\ 260}\text{ V.}$$

$$i' = -E'/Z = 8\ 260/700 = \underline{11{\cdot}8}\text{ A.},$$

$$E'' = E + E' = 10\ 000 - 8\ 260 = \underline{1\ 740}\text{ V.},$$

$$i_1'' = E''/Z_1 = \underline{17{\cdot}4}\text{ A. and } i_2'' = E''/Z_2 = \underline{8{\cdot}7}\text{ A.}$$

The cables thus have the beneficial effect of reducing the surge voltage from 10 kV. to 1·74 kV.

Effect of a Capacitance. Suppose that a wave (E, i) meets a termination composed of the parallel combination of a capacitance C and resistance R, as shown in Fig. 250. The problem is the same as that shown in Fig. 247, except that R in equations (123) must be replaced by

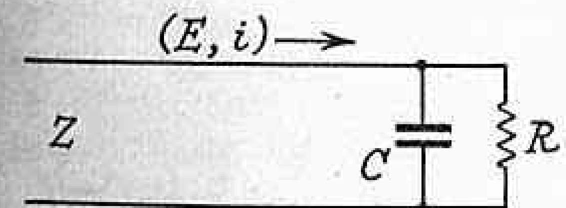


FIG. 250. EFFECT OF SHUNT CAPACITANCE ON TRAVELLING WAVE

$$\frac{(1/pC)R}{1/pC + R} = \frac{R}{1 + pCR},$$

where $p = d/dt$.

The voltage at the termination is thus

$$E_T = E + E' = \frac{2R/(1 + pCR)}{Z + R/(1 + pCR)} E$$

$$= \frac{2R}{Z(1 + pCR) + R.} E.$$

It must be remembered that $p = d/dt$ and E is a voltage which is zero until $t = 0$ and E after $t = 0$. E_T may be found in the following way.

$$E = \frac{Z(1 + pCR) + R}{2R} E_T$$

$$= \tfrac{1}{2}(pCZ + Z/R + 1)E_T$$

$$= \tfrac{1}{2}CZ(dE_T/dt) + \tfrac{1}{2}(Z/R + 1)E_T.$$

This is a linear differential equation for E_T of which the solution is

$$E_T = \frac{2E}{Z/R + 1} + A\varepsilon^{-[(Z + R)/CZR]t},$$

where A is an arbitrary constant and is determined by the fact that E_T can rise at a finite rate from its zero value. This gives

$$A = -2E/(Z/R + 1)$$

so that

$$E_T = \frac{2E}{Z/R + 1}[1 - \varepsilon^{-[(Z + R)/CZR]t}]$$

$$= E_{T0}[1 - \varepsilon^{-[(Z + R)/CZR]t}],$$

where E_{T0} is the voltage at the end when there is no capacitance. Fig. 251 shows the graph of E_T. The effect of the capacitance is to cause the voltage at the end to rise to the full value gradually instead of abruptly, i.e. it flattens the wave front. It is usual to specify the condition of the wave-front by stating the time the wave takes to increase from 10 to 90 per cent of its value and multiplying by 1·25. If the wave reaches x of its value in time t

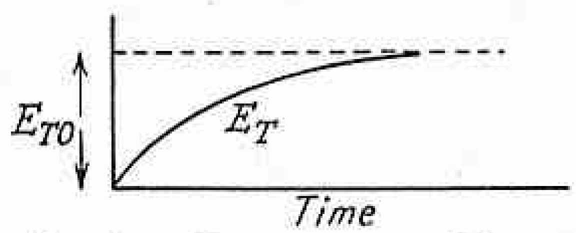


FIG. 251. FLATTENING OF WAVE DUE TO SHUNT CAPACITANCE

$$1 - \varepsilon^{-[(Z + R)/CZR]t} = x,$$

so that

$$t = \frac{CZR}{Z + R} \operatorname{logh}\left(\frac{1}{1 - x}\right).$$

The specifying time in this case is therefore

$$1{\cdot}25 \,.\, [CZR/(Z + R)]\,[\operatorname{logh} 10 - \operatorname{logh} 1{\cdot}11] \text{ sec.}$$

$$= 2{\cdot}75\, CZR/(Z + R) \text{ sec.}$$

In the case of a capacitance at a point of a line which stretches in both directions away from it, $Z = R$ and the time is

$$1{\cdot}37CZ \text{ sec.}$$

Thus a 10 000 $\mu\mu$F. capacitance in a line of surge impedance 500 ohms flattens the wave so that the time of the wave-front becomes

$$1{\cdot}37 \times 10^{-8} \times 500 \text{ sec.} = 6{\cdot}9\ \mu\text{sec.}$$

Flattening the wave-front has a very beneficial effect, as it reduces the stress on the line-end windings of a transformer connected to the line.

Lightning. With the increase of high-voltage overhead lines the problem of lightning is assuming greater importance, and much

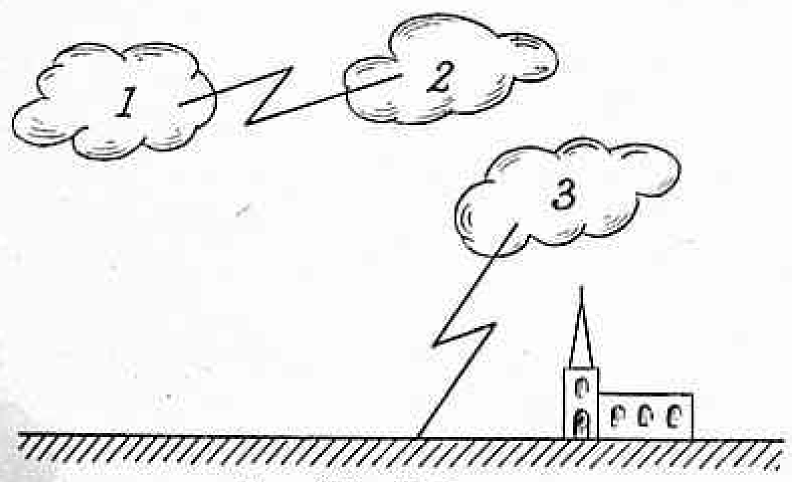


FIG. 252. B STROKE

damage is done yearly by lightning. There are two main ways in which lightning affects a line: by a direct stroke, and by electrostatic induction. The way in which thunderclouds get charged up to very high potentials is complicated and not known precisely.

A direct stroke can take place in several ways. In one way the charged cloud induces a charge of opposite sign on tall objects, such as tall masts, church spires, etc. The electric stress at the top points of these objects causes ionization of the air, and eventually a direct stroke takes place between the cloud and the object. Such a stroke is known as the *A stroke*, and is characterized by the comparatively long time taken to produce it and the fact that it strikes the highest point, usually a lightning conductor. Another way results in a much more sudden stroke, which is produced in the manner shown in Fig. 252. Three clouds are involved, and the potential of cloud 3 is decreased by the presence of the charged cloud 2. When cloud 1 flashes over to cloud 2, both these clouds are discharged rapidly; then cloud 3 assumes a much higher potential and flashes to earth very rapidly. This is the *B stroke*, and is characterized by its rapidity and the fact that it ignores tall objects and reaches earth in a random manner. A direct stroke may cause a potential of 10 million volts, and shatter insulators and towers in its vicinity. The most that can be hoped from protective devices is that they will limit the damage and prevent the resulting travelling waves from affecting the plant. Fortunately direct strokes are rare.

The majority of surges in a transmission system are due to lightning, and are caused by electrostatic induction in the manner

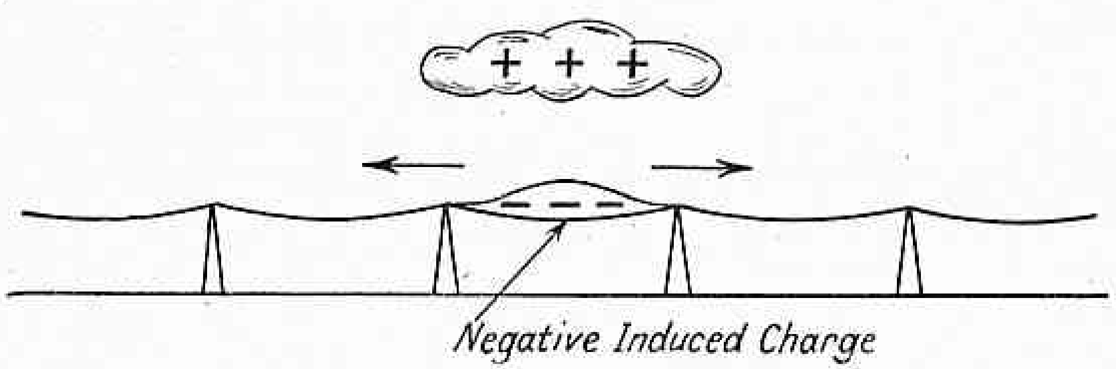


FIG. 253. SURGE DUE TO ELECTROSTATIC INDUCTION

indicated in Fig. 253. A positively charged cloud is above the line and induces a negative charge on the line by electrostatic induction. The induced positive charge leaks slowly to earth via the insulators. When the cloud discharges to earth or to another cloud, the negative charge on the line is isolated as it cannot flow quickly to earth over the insulators. The line thus acquires a high negative potential, which is a maximum at the place nearest the cloud and falls slowly

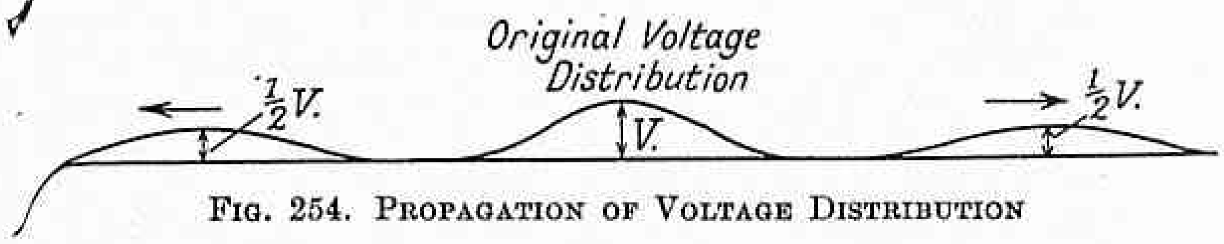


FIG. 254. PROPAGATION OF VOLTAGE DISTRIBUTION

to a small value at a distance. The charge will flow from a higher to a lower potential and the result is travelling waves in both directions. The two waves will be equal and thus each will have half the potential of the charge at the time of the discharge of the cloud; they will also have the space-voltage distribution of the original charge, as shown in Fig. 254. The waves travel in exactly the same way as the waves due to switching, so that the current at any point of the line is the voltage divided by the surge impedance. In a line without resistance or leakage the waves travel without change of shape, but the effect of resistance and leakage is to attenuate the wave and to flatten the wave-front.

The steepness of the wave-front depends upon the space-voltage distribution. If the wave reaches its maximum in 1 000 ft., the time

that it takes for the wave to reach the maximum when it passes a point is

$$\frac{1\ 000}{186\ 000 \times 5\ 280}\ \text{sec.} = 1{\cdot}02\ \mu\text{sec.}$$

Waves have been recorded with wave-fronts of 1 to 80 μsec. and wave-tails of 3 to 200 μsec. A very steep wave-front may be obtained when a thundercloud is near a building which the line enters. The building screens the line inside from the cloud, so that the induced charge stops abruptly at the building. Extra precautions are therefore necessary where an overhead line enters a building.

Arcing Earths. In the early days of transmission it was the practice to insulate the neutral point of three-phase lines, for then

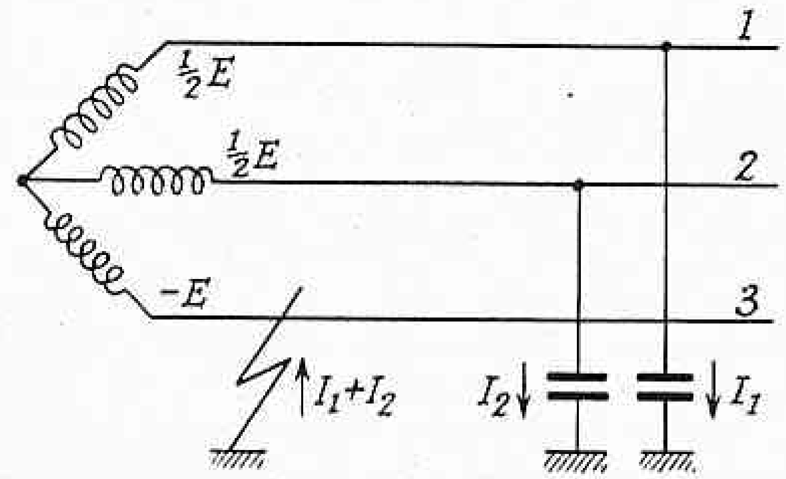


FIG. 255. ARCING GROUND IN THREE-PHASE LINE

an earth on one phase would not put the line out of action; this also eliminated the longitudinal (or zero phase-sequence) current and resulted in a decrease of interference with communication lines. Insulated neutrals gave no trouble with short lines and comparatively low voltages, but it was found that when the lines became long and the voltages high a serious trouble was caused by *arcing earths*, which produced severe voltage oscillations of three to four times the normal voltage. These oscillations were cumulative, and hence very destructive. Arcing earths are eliminated in this country and in America by solid earthing of the neutral, whilst in Germany the neutral is earthed through an inductance (a *Petersen coil*).

There are two accepted theories of arcing earths, in one of which the arc is extinguished at the normal frequency, and in the other at the frequency of oscillation of the line. Let us consider the *normal-frequency arc-extinction theory* for a three-phase line.

Fig. 255 shows a three-phase line. Suppose that line 3 arcs to earth when its voltage to neutral is a maximum $-E$. At this instant lines 1 and 2 have voltage $+\frac{1}{2}E$. Before the arcing earth objects and reaches earth in a random manner. A direct stroke may cause a potential of 10 million volts, and shatter insulators and towers in its vicinity. The most that can be hoped from protective devices is that they will limit the damage and prevent the resulting travelling waves from affecting the plant. Fortunately direct strokes are rare.

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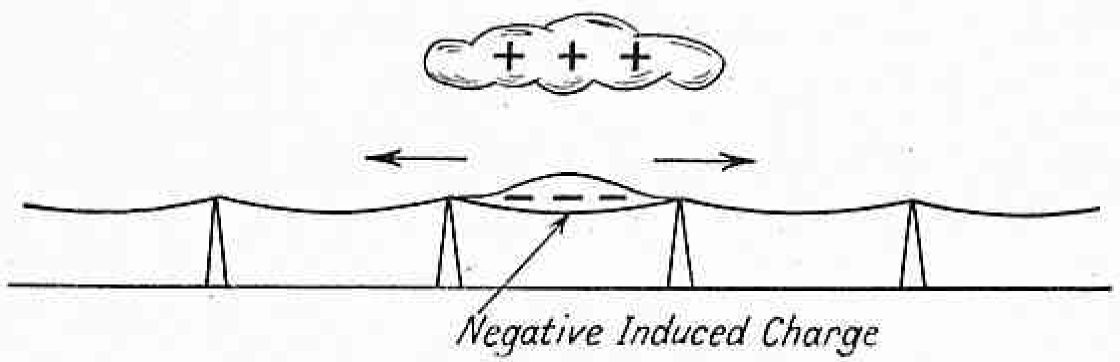

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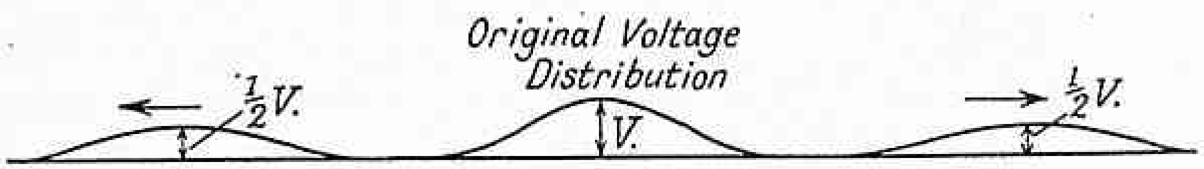

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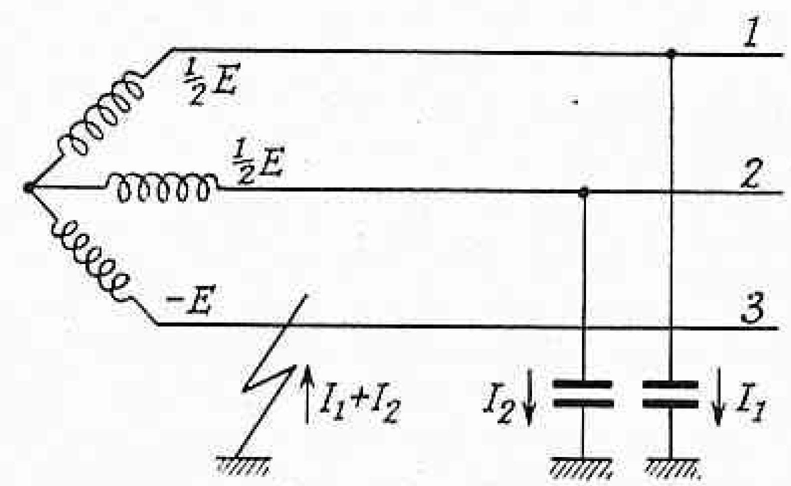

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Fig. 255 shows a three-phase line. Suppose that line 3 arcs to earth when its voltage to neutral is a maximum $-E$. At this instant lines 1 and 2 have voltage $+\frac{1}{2}E$. Before the arcing earth occurs the capacitances of the lines cause the neutral to be at or near the earth potential, so that the earthing of line 3 causes a sudden voltage of $+E$ to be applied to lines 1 and 2. The ultimate steady state would then be for the lines 1 and 2 to be at potential $\frac{3}{2}E$. But we have shown that when an e.m.f. E is suddenly switched into a circuit of low resistance, the voltage in the circuit oscillates between 0 and $2E$ with a frequency $1/2\pi\sqrt{(LC)}$ (see equations (115*a*) *et seq.*), where L and C are the inductance and capacitance in the circuit. The voltage of lines 1 and 2 will therefore oscillate rapidly between the original value of $\frac{1}{2}E$ and $\frac{1}{2}E + 2E = \frac{5}{2}E$. The high frequency oscillation dies out rapidly. The arc is fed through the capacitances of the lines, as shown in Fig. 255, and will go out when the sum of the capacitance currents passes through zero. The capacitance currents lead the voltages by 90°, so that when their sum $I_1 + I_2$ is zero the line voltages are $E_1 = -\frac{3}{2}E$, $E_2 = -\frac{3}{2}E$, and $E_3 = 0$. If the arc were to remain extinct, the voltages would have to be these values plus E, viz. $E_1 = -\frac{1}{2}E$, $E_2 = -\frac{1}{2}E$, and $E_3 = +E$. Thus the faulty line 3 would have a maximum voltage again, and so arc to earth again. In other words, when line 3 arcs to earth the capacitance currents of lines 1 and 2 maintain the arc until the voltage of line 3 attains its opposite maximum voltage with respect to the neutral; then at the instant when the capacitance currents would allow the arc to go out, line 3 arcs again to ground. We saw that at the instant that the arc is extinct the lines are at potentials $-\frac{3}{2}E$, $-\frac{3}{2}E$, and 0. The charges due to these potentials diffuse rapidly through the system in an oscillatory manner, with the average voltage $\frac{1}{3}(-\frac{3}{2}E - \frac{3}{2}E + 0) = -E$ as the mean position. This is equivalent to an insertion of an e.m.f. of $\frac{1}{2}E$ in lines 1 and 2, so that an added voltage E is applied to these lines. When the arc restrikes, lines 1 and 2 acquire potentials of $-\frac{5}{2}E$ plus this new value $-E$, so that the maximum voltage is $\frac{7}{2}E$. We see therefore that the healthy lines are subjected to a voltage of $3\frac{1}{2}$ times the normal value. As this state can be maintained for a considerable length of time, in a known case 30 min., by the continued arcing, it is very dangerous.

Petersen Coil. We have seen that the capacitance currents I_1 and I_2 maintain the arc even when the voltage of the faulty line 3 is too low to restrike it. In fact these currents have the particularly harmful effect of maintaining the arc until the very moment when the voltage of line 3 is sufficiently high to restrike it. If the neutral is earthed through an inductance L of such a value that the current it passes neutralizes $I_1 + I_2$, the normal frequency follow current through the arc is

$$I_L + I_1 + I_2 = 0.$$

The arc is then extinguished except for the brief moments when the voltage of line 3 passes through its maximum value and can restrike it.

It has been found that the Petersen coil is completely effective in preventing any damage by an arcing earth, and is therefore used extensively on the Continent. The coil is usually provided with tappings, so that its value can be adjusted to suit the capacitances of the system. It is found that effective operation is secured when the inductance is 90 to 110 per cent of the theoretical value for exact neutralization of the capacitance currents.

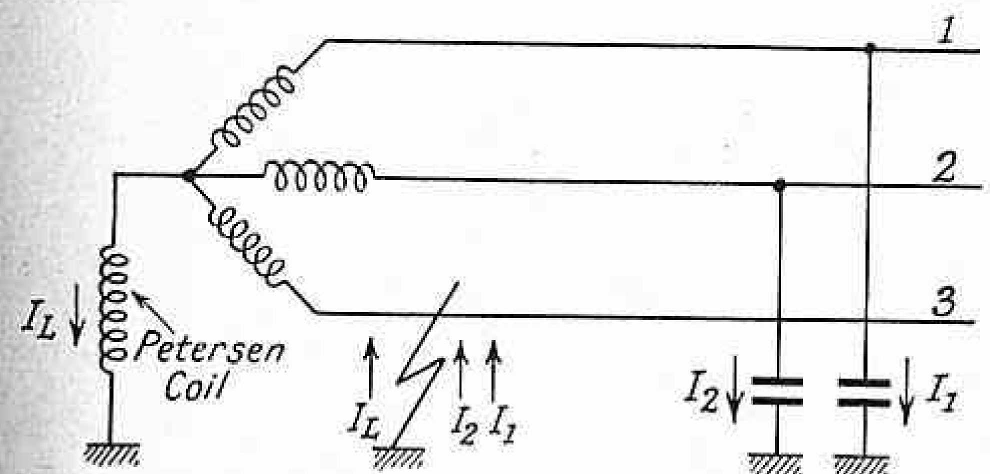

FIG. 256. PETERSEN COIL

Lightning and Over-voltage Protection. The insulation of a transmission system is always designed to withstand voltages of twice the normal value for a reasonable length of time, as switching surges often produce voltages of this magnitude. It is clearly uneconomical to design the system so that the insulation can withstand the very high voltages that may be encountered from extraneous or fault conditions, and recourse is had to protective devices which are adjusted to break down before the insulation, or otherwise prevent a dangerous voltage from damaging the insulation.

Dangerous voltage rises are found to be due to the following: (1) surges due to direct lightning strokes or induced voltages, (2) arcing earths, (3) comparatively low-voltage high-frequency oscillations, (4) static overvoltage. The protective apparatus for these classes are: (1) ground wire and lightning arresters, (2) earthing of neutral solidly or through a Petersen coil, (3) surge absorber or capacitance, (4) water-jet earthing resistance, earthing inductance, or solid earthing of the neutral point.

It is true to say that with the advent of high-voltage overhead lines, such as the Grid, the main cause of damage is lightning. We have seen that most travelling waves due to lightning are caused by electrostatic induction. The latter can be reduced considerably by the use of earth wires running above the transmission line and earthed at every pole or tower. If C_1 is the capacitance of the cloud to the line and C_2 the capacitance of the line to ground, the induced voltage on the line is $C_1/(C_1 + C_2)$ times the cloud voltage. The presence of the earth wire *above* the line causes a considerable increase in C_2 and reduction of the line voltage. The induced voltage could be very much reduced by an array of earth wires above the line, but this is too expensive to install in practice.

The earth wire also provides considerable protection against direct strokes (of the A type), provided the earth resistance of the earth wire is kept low. If the current in the stroke is I and the earth resistance is R, the voltage of the earth wire is IR, and unless R is low this voltage may be sufficient to cause a flash-over from the earth wire to the lines. The earth resistance should be of the order of 10 to 20 ohms.

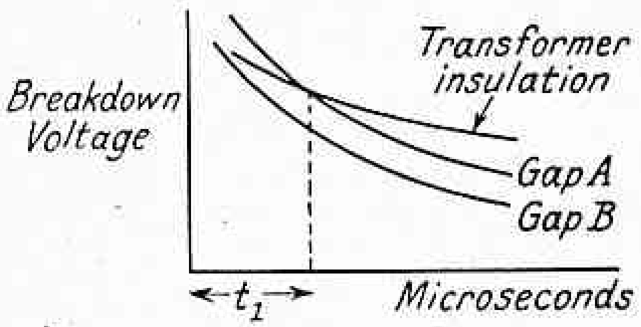

FIG. 257. VARIATIONS OF BREAKDOWN VOLTAGE WITH TIME OF APPLICATION

The earth wire affords an additional protective effect by causing an attenuation of any travelling waves that are set up, by acting as a short-circuited secondary. For this reason its resistance should not be too large. It is usually made of steel, which has a high permeability and thus possesses a resistance which increases with frequency.

Having reduced the magnitude of induced voltages by means of an earth wire, we still find it necessary to install protective apparatus to prevent, or at least minimize, the damage due to the surges that do occur. It is, moreover, essential that the system shall be considered as a whole from the point of view of protection, so that the least essential and most accessible parts protect the more important apparatus; this involves the *co-ordination of system insulation*. The problem is rendered difficult by the fact that the breakdown voltages of the various parts of the system and of the protective apparatus behave differently with time; thus a horn gap which is set to flash-over at 100 kV. at 50 cycles may require 200 kV. in a wave lasting for 20 μsec., or 300 kV. in a wave lasting for 5 μsec. We define the *impulse ratio* of any piece of apparatus as the ratio of the breakdown voltage of a wave of specified duration to the breakdown voltage of a 50-cycle wave; thus the horn gap has an impulse ratio of 2 at 20 μsec., and 3 at 5 μsec. When a method of co-ordinated insulation is considered, the impulse ratio of the various parts must be known or the protection will not be adequate. Fig. 257 illustrates the point. Suppose that the insulation of a transformer to be protected has the breakdown voltage-time characteristic shown. Gap A may be set to break down at a lower voltage than, say, 80 per cent of the breakdown voltage of the insulation at 50 cycles. The gap, nevertheless, does not protect the transformer, as its characteristic rises more rapidly than that

of the transformer insulation as the duration of the wave decreases. Then for waves of duration less than t_1 the transformer insulation breaks down before the gap. It is necessary to narrow the gap so that the characteristic is as shown for gap B before the transformer is completely protected. In practice it is not possible to narrow the gap so much that the insulation is protected for waves of the smallest duration, as then the gap would flash over at very low voltages at 50 cycles; a compromise is reached by protecting the insulation for voltages of waves down to a certain minimum time, which is found experimentally to be comparatively harmless.

Sphere Gap. A sphere gap in which the spacing is small compared with the diameter of the spheres has the useful advantage that the

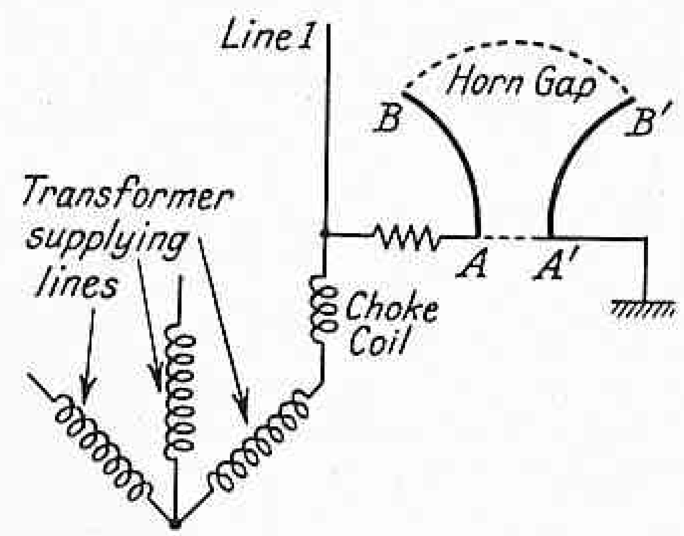

FIG. 258. HORN GAP WITH CHOKE COIL AND RESISTANCE

impulse ratio is unity. If then the apparatus is protected against 50-cycle waves, it is protected against a wave of any duration. Unfortunately, when the sphere gap flashes over, the power current maintains the arc, which requires only a very low voltage to maintain it, and the arc is not self-extinguishing. The circuit-breakers would have to intervene to break the arc current and the service is interrupted. For this reason the sphere gap is not of use.

Horn Gap. Fig. 258 shows a simple sketch of the horn gap. The gap is set so that a flash-over occurs between A and A' at a voltage of 150 to 200 per cent of the normal voltage. The power current creates an arc, which may be considered to be a flexible conductor. A flexible electric circuit moves so as to embrace as many lines of magnetic force as possible, so that the arc is forced up to the position BB'. Another factor tending to blow the arc up to BB' exists when BB' is above AA', for then the arc heats the air and forms a vertical draught. The result is that the arc is forced up to BB', where the gap is wide and the normal voltage is insufficient to maintain it. The arc is thus extinguished, usually in about 3 sec.

The horn gap cannot rupture arc currents much in excess of

10 amperes, and as the arc is a dead short circuit it is necessary to limit the current to a small value. This is done by inserting a resistance, between the line and the horn on the line side, which reduces the current to about 5 amperes. The efficacy of the horn gap is seriously reduced by the resistance. The resistance is a water column, oil-immersed metal wire, carbon rod, or carborundum, and is made as non-inductive as possible.

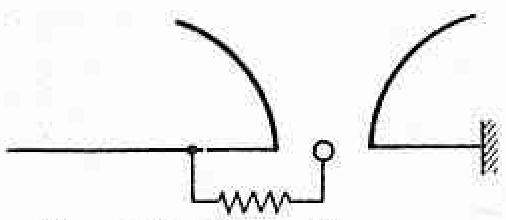

Fig. 259. Horn Gap with Auxiliary Electrode

It is found that high-frequency waves concentrate at the line-end turns of a transformer, so that although the magnitude of the wave on the line is not very great, the stress at the turns near the line is very high and may cause puncture between turns. This difficulty is overcome by the insertion of choke coils, as shown in Fig. 258.

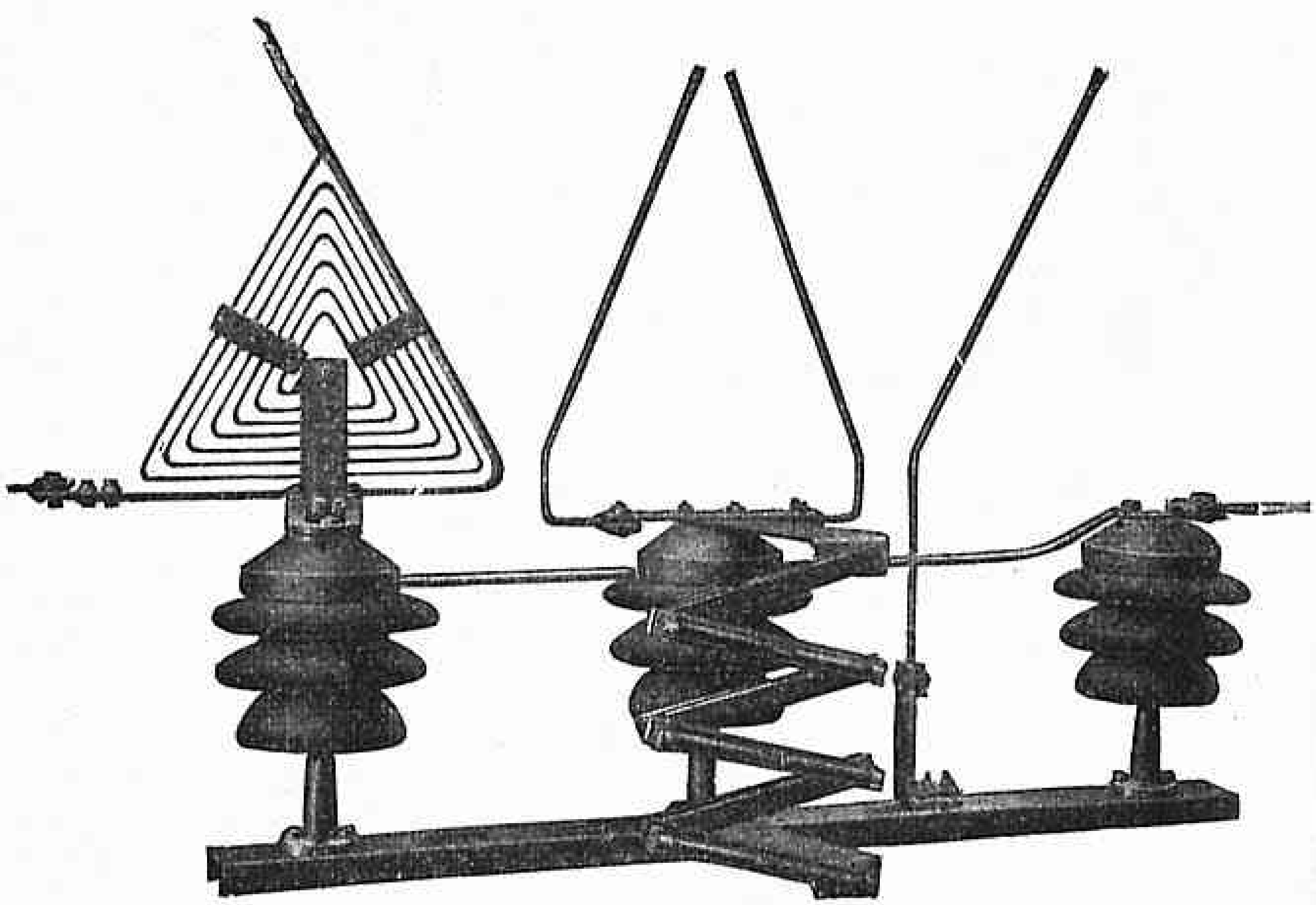

Fig. 260. Burke Arrester
(Metropolitan-Vickers)

The high-frequency wave is then reflected back to the horn gap, where the doubled voltage causes a flash-over. The choke is without effect on the low-frequency power wave.

For small settings the horn gap is sensitive to corrosion or pitting of the horns, so that it does not maintain its setting. This difficulty is overcome in the arrester shown in Fig. 259. The main gap is

set for a voltage well above that to be protected. The auxiliary gap has a platinum electrode, which possesses the character of permanence. When an over-voltage occurs the auxiliary gap flashes over and ionizes the air, and then the main gap flashes over.

Burke Arrester. Fig. 260 shows the Burke arrester. The line current passes through a triangular pancake choke coil, one side of which forms half of the main gap. Severe over-voltages flash across the main and auxiliary gap direct to earth. Less severe voltages flash over the main gap only, and the current is then limited by the resistance.

Multi-gap Arrester. This consists of a number of small gaps in series with a limiting resistance. Another resistance is placed across some of the gaps adjacent to the limiting resistance.

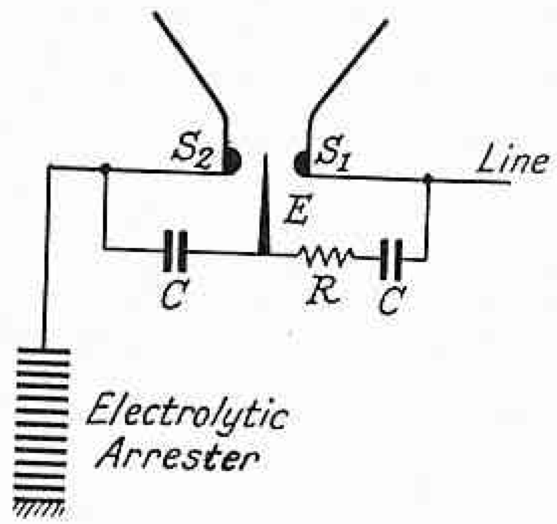

Fig. 261. Impulse Gap with Electrolytic Arrester

Impulse Protective Gap. It was pointed out that the sphere gap has an impulse ratio of unity, but suffers from the disadvantage that the arc between its electrodes is not self-extinguishing. The horn-gap, however, extinguishes the arc but has a high impulse ratio, 2 or 3. The impulse protective gap is designed to have a low impulse ratio, even less than unity, and to extinguish the arc. Fig. 261 shows a diagram of the impulse gap. S_1 and S_2 are sphere-horn electrodes, and are connected to the line and an electrolytic arrester, respectively. An auxiliary needle electrode E is placed mid-way between S_1 and S_2, and is connected to them via (R, C) and C. At the power frequency the impedance of the capacitances C is very much greater than that of R, so that the potential of E is mid-way between those of S_1 and S_2 and the electrode has no effect on the flash-over between them. At very high frequencies the impedance of C is small, so that E is at the potential of S_2 and the gap is effectively half the previous value. Flash-over takes place between S_1 and E at a voltage less than that required to flash-over between S_1 and S_2. An impulse ratio less than unity can thus be obtained. The electrolytic arrester on the earth side extinguishes the arc.

Electrolytic Arrester. This is the earliest type of arrester with a large discharge capacity. The action depends upon the fact that a thin film of aluminium hydroxide immersed in electrolyte presents a high resistance to a low voltage, but a low resistance to a voltage above a critical value. The critical breakdown voltage is about 400 volts, and voltages higher than this cause a puncture and a free flow of current. The insulating film of hydroxide is formed by applying a direct voltage up to the critical value to aluminium plates immersed in the electrolyte; during the formation of the

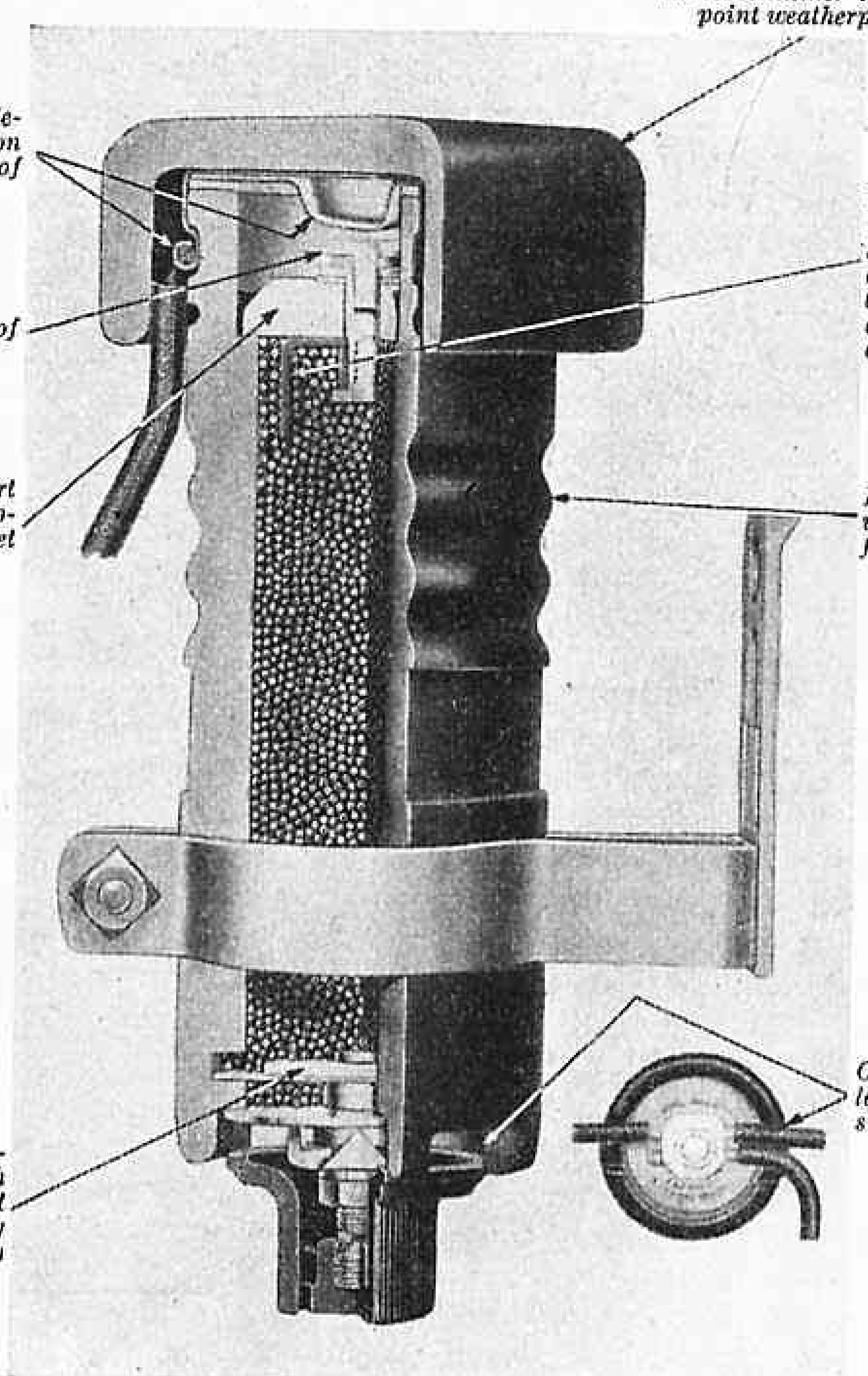

Fig. 262. Oxide-film Arrester
(*B. T.-H.*)

film, current passes fairly readily, but when the film is formed the current ceases.

Stacks of films are arranged one above the other and the total critical voltage is equal to the critical voltage of each film multiplied by the number of films.

Daily supervision and reforming of the films is essential, and for

this reason the arrester is being replaced by the more robust oxide-film and auto-valve arresters. The electrolytic arrester is used in conjunction with an impulse gap, for the continual leakage and capacitance currents would damage the arrester.

Oxide-film Arrester. Fig. 262 shows the construction of the oxide-film arrester of the pellet type. The lead peroxide pellets are in a column of $2\frac{1}{4}$ in. diameter, the length of the column being 2 in. per kV. of rating. The tube contains a series spark-gap. A single tube system is available for voltages up to 25 kV. when the neutral is solidly earthed, and 18 kV. when the neutral is isolated or earthed through an inductance coil. For higher voltages several units are placed in series.

The pellets have a diameter of approximately $\frac{3}{32}$ in. and are made of lead peroxide with a thin porous coating of litharge.

Auto-valve Arrester. This consists of a number of flat discs of a porous material stacked one above the other and separated by thin mica rings. The material is made of specially prepared clay with a small admixture of powdered conducting substance. The discharge occurs in the capillaries of the material and is thus constrained to be a glow discharge, in which there is a voltage drop of about 350 volts per unit. The narrow gaps between the blocks are of sufficient total width to prevent flash-over due to the normal voltage, so that no current flows in the arrester under normal conditions. This arrester is very effective, robust and cheap, and is being rapidly introduced into modern high voltage systems.

Thyrite Arrester. Thyrite is a dense inorganic compound of a ceramic nature, which has a resistance that decreases rapidly from a high value at low currents to a low value at high currents. The current increases 12·6 times when the voltage is doubled; thus if the current-voltage relation for a given block of thyrite is

$$E = kI^n,$$

then $$2E = k(12{\cdot}6I)^n,$$

so that $$2 = 12{\cdot}6^n,$$

i.e. $$n = \log 2 \div \log 12{\cdot}6 = 0{\cdot}27.$$

Thus the voltage varies approximately as the fourth root of the current. Fig. 263 shows the current-voltage curve of the 11 kV. thyrite arrester of Fig. 264. There are eleven thyrite discs sprayed on both sides to provide a good surface contact; each disc has a diameter of 6 in. and thickness $\frac{3}{4}$ in., and will discharge several thousand amperes without the slightest tendency to flash over the outside edge. When passing 2 000 amperes each disc has a voltage of only 5 kV. At the normal voltage of 11 kV. to earth, the peak voltage is $(11\sqrt{2} \div \sqrt{3})$ kV. = 9 kV. and the current in the arrester is only 3·2 amperes. When one phase is earthed the peak voltage on the other phases is $11 \times \sqrt{2} = 15{\cdot}6$ kV. and the arrester passes

25 amperes. A series gap is provided to prevent current from flowing at the normal voltage. The value of k for the stack is 6 500, or 600 per disc.

When the gap and arrester flash over, a high current flows for the duration of the surge, which is discharged to earth rapidly as is shown by oscillographic records; there appears to be absolutely no time-lag in the thyrite itself. The normal frequency follow-current is very small, 3·2 amperes in a healthy system, and only 25 amperes in a system with an earthed phase. The gap is easily able to clear this small follow-current.

Some modern modifications of the thyrite arrester include a type in which resistance blocks of a ceramic nature are spaced at equal distances from one another. The total gap length is adjusted so

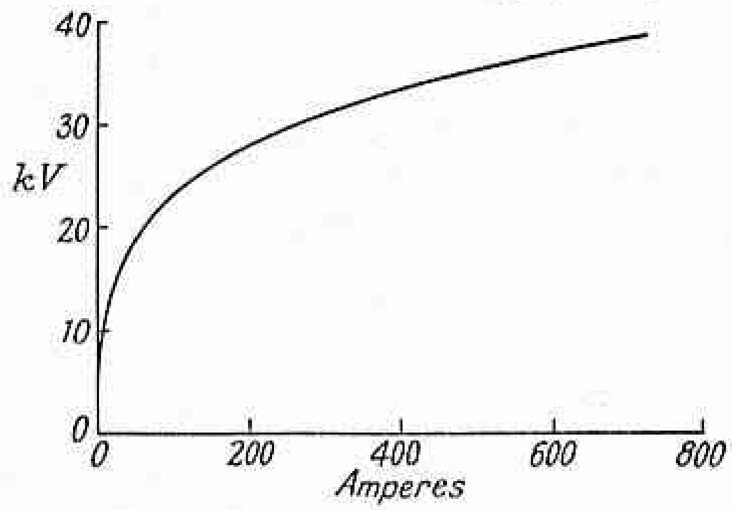

FIG. 263. VOLTAGE-CURRENT CURVE OF THYRITE ARRESTER

that the gaps flash over at twice normal voltage; it is claimed that the distributed gaps behave better than a single gap. Round knobs are provided between the electrodes of the gaps so as to reduce the time-lag. The action of the resistance blocks is similar to that of thyrite.

Condensers. We have shown on pages 290–22 that the effect of a condenser, placed between the line and earth, on a travelling wave is to reduce the steepness of the wave-front. This effect protects the windings of a transformer near the line, since a steep wave-front causes very high stresses in these turns.

The condenser, moreover, protects the transformer against comparatively low-voltage, high-frequency waves. The normal-frequency voltage produces only a very small current in the condenser, so that negligible loss is caused during normal operation.

The latest type of condenser used for protective purposes has a dielectric of acetyl cellulose, the electrodes being silver plating on the strips of the dielectric.

Surge Absorber. A pure condenser of the type described in the previous section cannot dissipate the energy in the wave-front of a travelling wave or in a high-frequency oscillation. It merely reflects

the energy away from the apparatus to be protected, and the energy is dissipated in the resistance of the line conductors and the earthing resistances. If a resistance is placed in series with the condenser, the combination can dissipate part of the energy in addition to diverting it from the apparatus. Such a combination is called a *surge absorber*.

Another type of absorber consists of an inductance across which is placed a resistance. This combination is placed in series with the

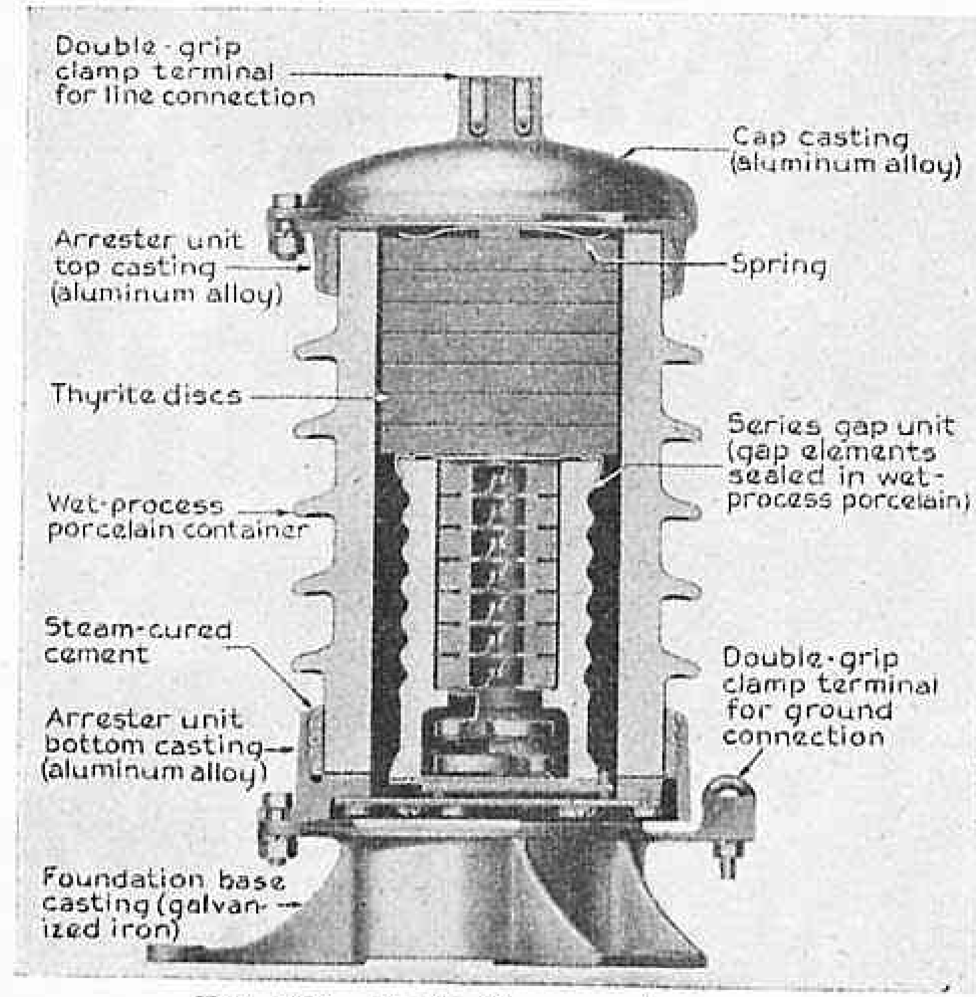

FIG. 264. 11 kV. THYRITE ARRESTER
(*International General Electric Co. of New York, Ltd.*)

line. Steep wave-fronts or high-frequency waves find the inductance a high impedance path and are forced through the resistance, where they are dissipated. The normal-frequency currents find the inductance a low impedance path and pass through it without much loss.

The *Ferranti surge absorber* consists of an inductance coil, which is coupled magnetically, but not electrically, to a metal shield and/or the steel tank which contains it. The coil is of a cylindrical or pancake form, depending upon the voltage; for voltages above 33 kV. the coil is cylindrical and has inside it a metal shield in which currents are induced. The absorber is enclosed in a cylindrical boiler-plate tank, provided with porcelain-guarded terminals, and is vacuum-impregnated with a light transformer oil. Fig. 265 shows a 66 kV. surge absorber of this kind. The equivalent circuit of this absorber is shown in Fig. 266. There is a filter effect which prevents high frequency currents from passing freely through the absorber;

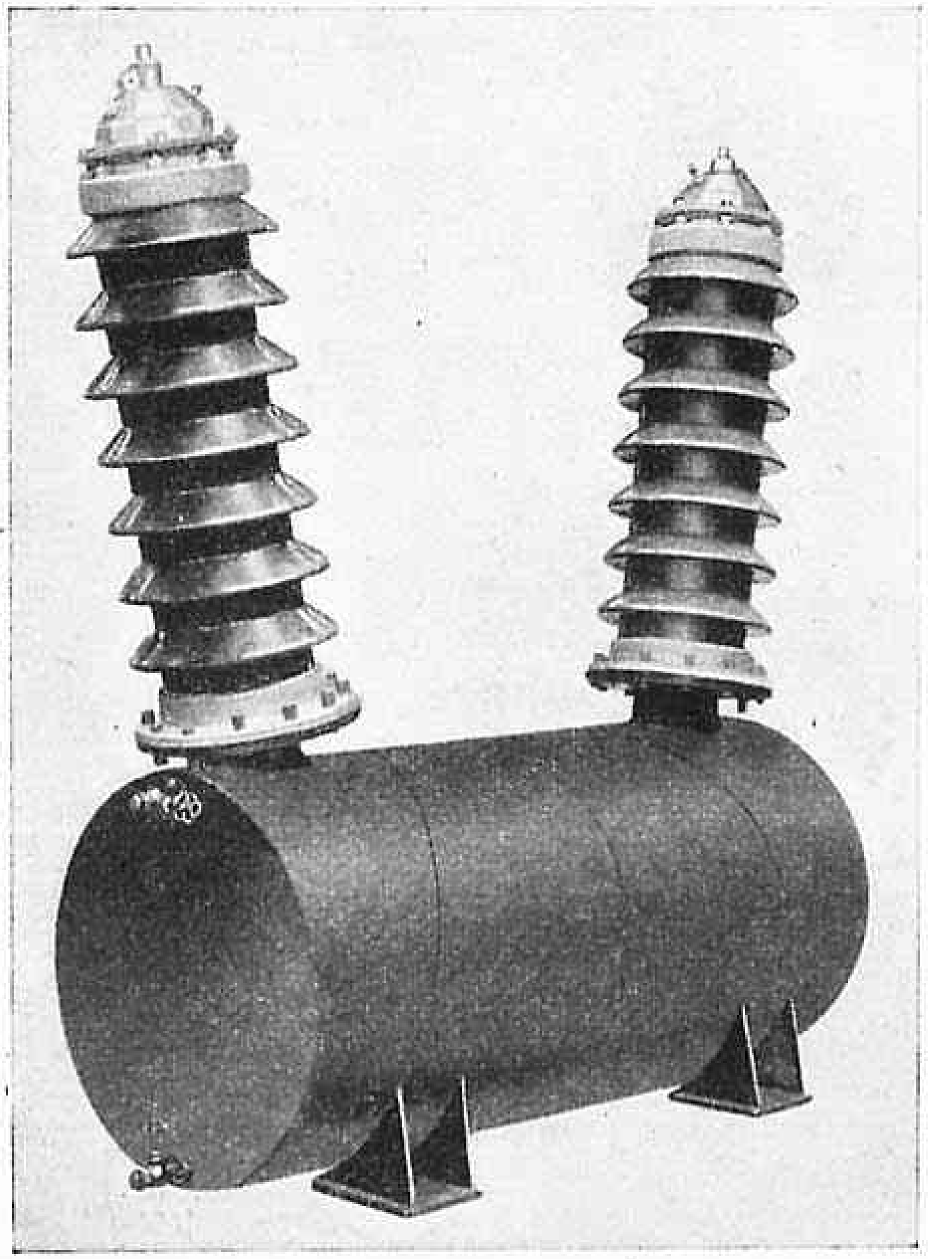

FIG. 265. FERRANTI SURGE ABSORBER
(I.E.E. Students' Journal)

also energy is transferred from the wave by the mutual induction between the coil and the shield and tank into the latter two, where the energy is dissipated as heat.

Recording of Transmission Line Surges. There are three methods of recording transmission line surges, by the high-voltage cathode-ray oscillograph, the klydonograph, and the surge-crest ammeter. These will be described briefly.

HIGH-VOLTAGE CATHODE-RAY OSCILLOGRAPH. This is the only instrument capable of delineating the voltage-time characteristic of a wave. Fig. 267 shows a high-speed cathode-ray oscillograph manufactured by Metropolitan-Vickers. The tube is continuously evacuated and the pressure in the deflection tube is 10^{-4} mm. of mercury or less. The cathode is cold and at a potential of 50 or 60 kV. above the anode, which is earthed.

The essential process is the following. A supply of electrons is obtained by the ionization of the residual gas in the discharge tube, and these are made to travel with an enormous velocity under the accelerative effect of the applied voltage. The electrons pass through a hole in the anode and proceed in a straight line, until they pass between the time deflection plates. The time deflection plates have applied between them a voltage which varies rapidly and uniformly

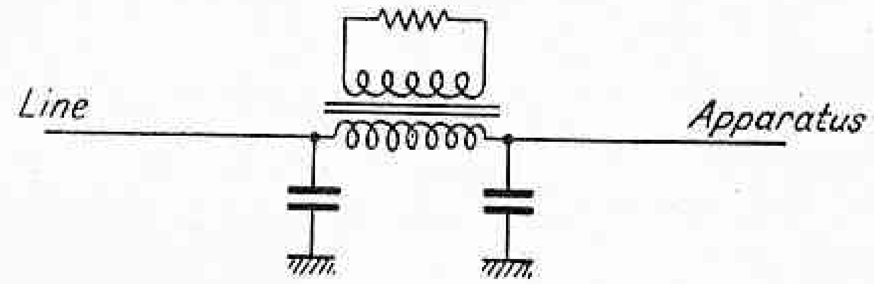

FIG. 266. EQUIVALENT CIRCUIT OF FIG. 268

from zero to a maximum value; the electron beam then undergoes a deflection, that is proportional to the time from a given instant. The beam then passes between the voltage deflection plates, between which the wave (or a fraction of it) is applied. The voltage deflection plates produce a deflection at right angles to the time deflection, so that the electron beam, which strikes the photographic plate at the end of the tube, traces out the voltage-time curve of the wave.

In order to photograph waves of only a few microseconds duration the utmost sensitivity is required. This sensitivity is achieved in the following way. The electron beam impinges directly on the sensitive plate, which must therefore be inside the evacuated tube. The velocity of the electrons must be very great, and a high voltage of 50 kV. or more is used to accelerate the electrons. It is quite clear that the electron beam must not impinge on the plate when there is no wave, otherwise the plate would be completely fogged. The beam is diverted from the photographic chamber by beam trap plates and a beam trap tube. When there is no wave, there is a voltage between the beam trap plates which deflects the beam from the straight path that leads through a small hole in a diaphragm at the bottom of the beam trap tube. It is seen that the axis of the discharge tube is inclined at an angle to the axis of the main tube. The reason for this is that although the electron beam is prevented from reaching the photographic plate by means of the beam trap plates during the absence of a surge or wave, there are retrograde

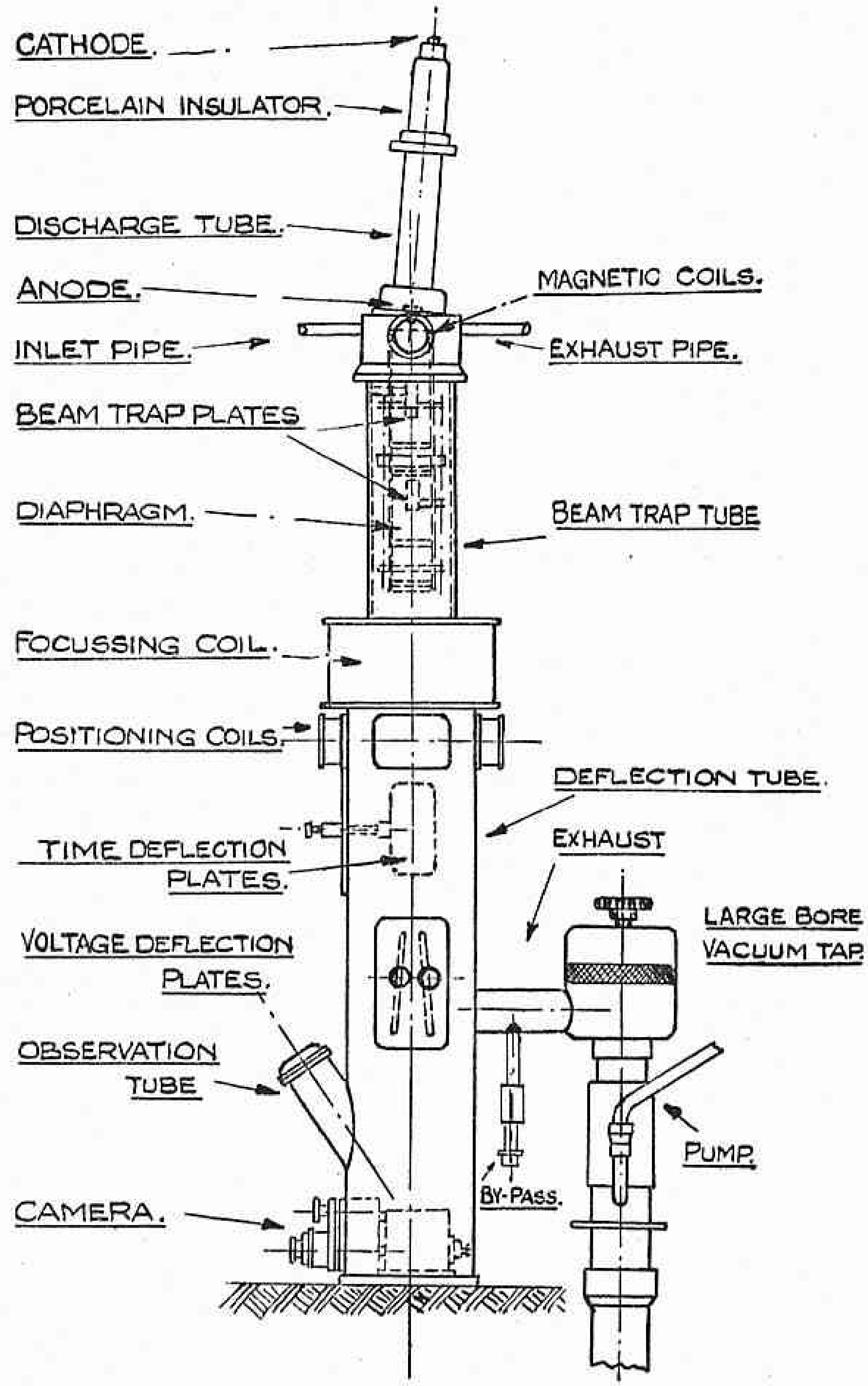

FIG. 267. HIGH-SPEED CATHODE-RAY OSCILLOGRAPH
(*Metropolitan-Vickers*)

rays consisting of atoms that are not much affected by the beam trap. These rays consist of relatively heavy particles and are thus not easily deflected, so that if they are moving along the axis towards the plate they will do so whether the beam trap is operating or not. Their very property of not being deflected easily is used to get rid of them by inclining the axis of the discharge tube. The

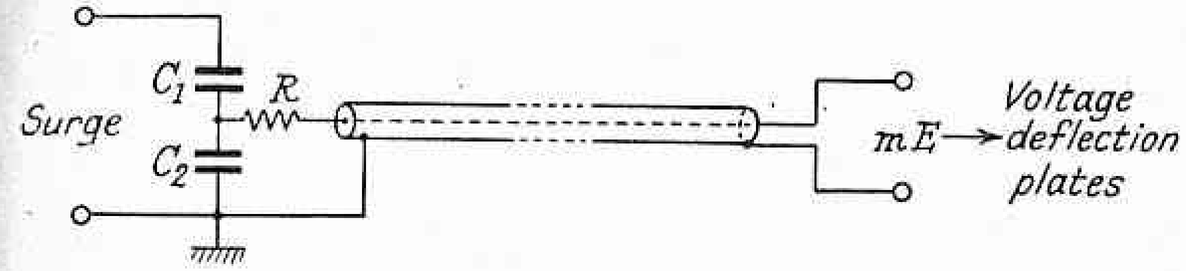

FIG. 268. POTENTIAL DIVIDER AND DELAY CABLE

retrograde rays and the electron beam travel along the axis of the discharge tube towards the anode. Magnetic coils then deflect the electron beam along the main axis, so that the beam can enter the beam trap tube; but the retrograde waves are not deflected from their inclined path and are prevented from entering the main tube.

The electron beam is focused and positioned by magnetic coils.

When a surge arrives it is sent direct to a trigger device which removes the voltage between the beam trap plates, and the electron beam travels to the plate. Meanwhile the surge is put across a potential divider connected to a *delay cable*, which transmits a known fraction of the wave to the voltage deflection plates after a delay of a fraction of a microsecond. The delay cable is a concentric cable, with air or rubber dielectric. Fig. 268 shows the arrangement of the potential divider and the delay cable; R is equal to the surge impedance of the cable. If the capacitance C_1 is ten times the capacitance of the cable, no distortion is introduced and the ratio of step-down is $C_1/(C_1 + C_2)$.

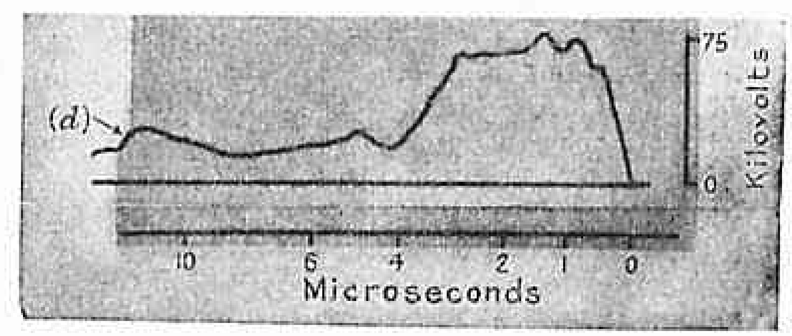

FIG. 269. VOLTAGE ACROSS LINE TURNS OF TRANSFORMER
(*I.E.E. Journal*)

Fig. 269 shows a cathode-ray oscillograph of the voltage appearing across 10 per cent of the line end turns of a transformer winding.* It is seen that in this case the time base is not quite linear.

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