আন্তর্জাতিক ইসলামী বিশ্ববিদ্যালয় চট্টগ্রাম

International Islamic University Chittagong

Department of Electrical and Electronic Engineering

Kumira, Sitakunda, Chittagong, Bangladesh

Lab Manual

EEE-3520
Power System Analysis Sessional

Power System & Machine Lab

Program: B.Sc. Engg. (EEE)

International Islamic University Chittagong (IIUC)
Department of Electrical & Electronic Engineering

LECTURE PLAN

EEE-3520: Power System Analysis Sessional

Experiments	No. Of Classes required
A. Up to Midterm	
Introduction	01
Experiment- 01: Transmission Line Equipment	01
Experiment-02: Safety and the Power Supply	01
Experiment-03: Phase Sequence	01
Experiment-04: Real Power and Reactive Power	01
Lab Practice	01
Midterm Lab Exam	01
B. From Midterm to Final	
Experiment-05 Power Flow and Voltage Regulation of a Simple Transmission Line	02
Experiment-06: Phase Angle and Voltage Drop between Sender and Receiver	01
Experiment-07: The Alternator	01
Experiment-08: The Synchronous Motor	01
Lab Practice	01
Final Lab Test	01
Total	14

Marks Distribution

Item	Marks
Class Attendance	10
Lab report	20
Mid-term Exam	10
Final Lab Test	10
Final	50
Total	100

Books of the Courses

Name of the Books	Author	Remarks
Investigations in Electric Power Technology	Lab volt	Lab volt manual
V.K. Metha and Rohit Metha	Principle of power system	Texts
Ashfaq Hussain	Electrical power systems	Texts

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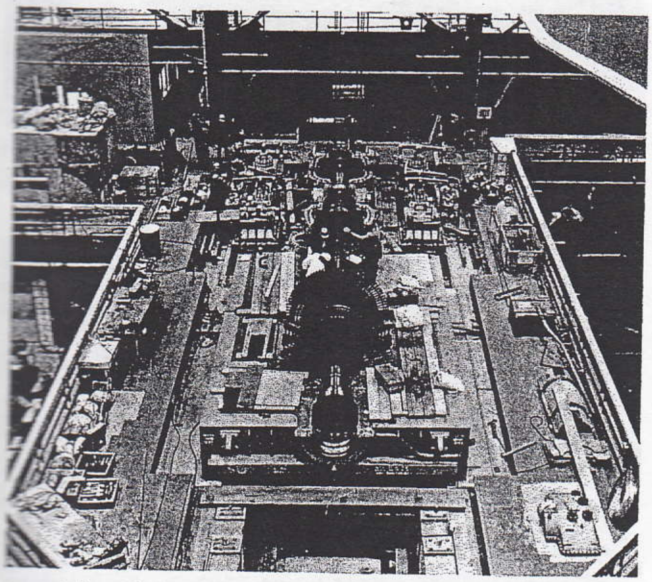
EEE-3520: Power System Analysis Sessional

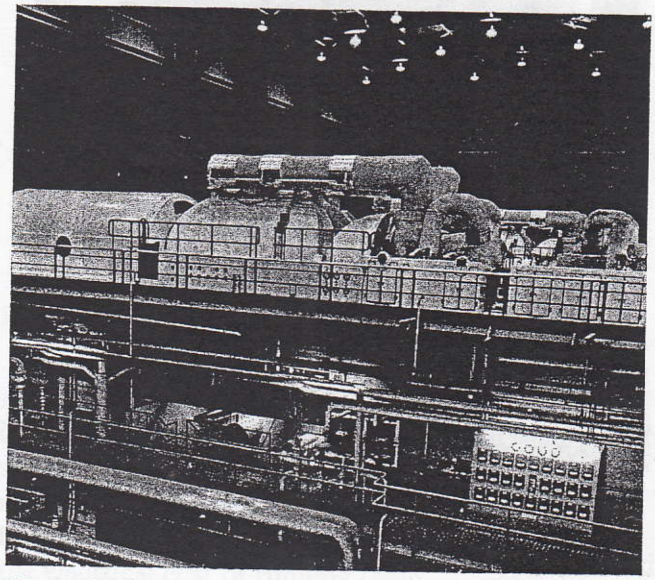
Experiment-01

TRANSMISSION LINE EQUIPMENT

MECHANICAL LOADS, TURBINES AND THE ¼ HP DC MACHINE

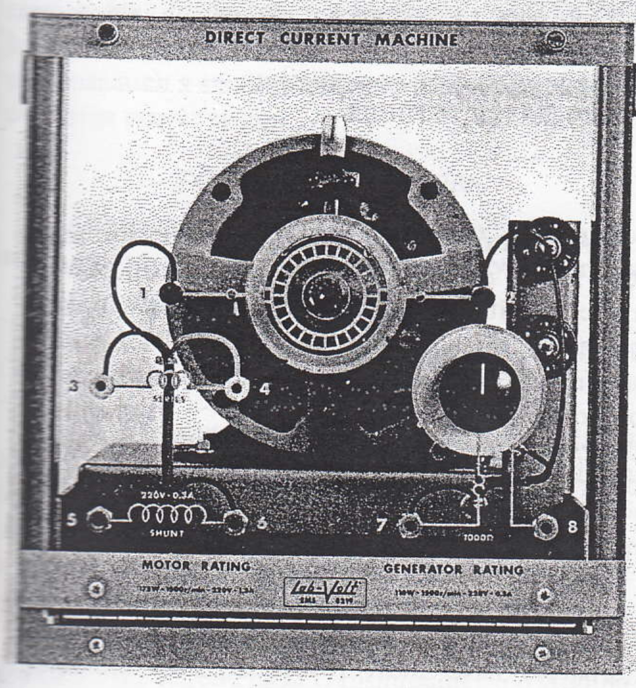


Assembling the many-bladed rotor of a steam turbine in a large thermo-electric station.



View of the completed 3600 rev/min turbo-alternator in operation.

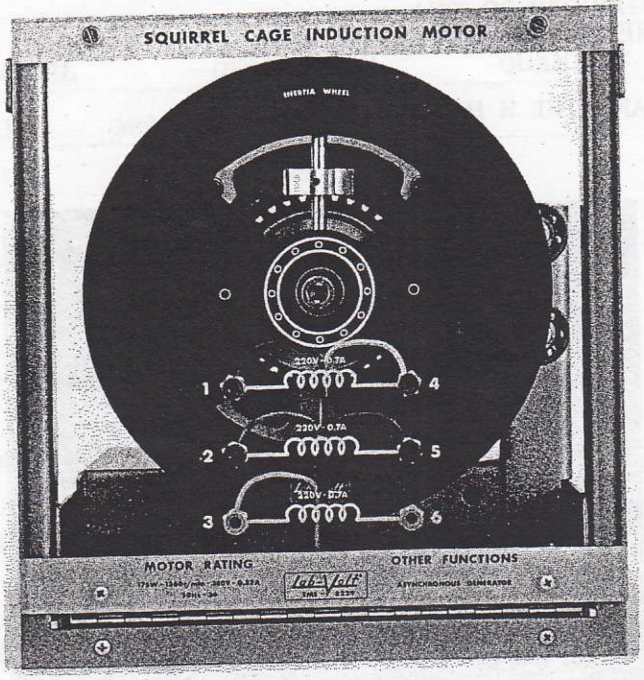
Electric motors drive pumps, fans, hoists, punch presses, and a host of other mechanical tools and devices. It is not easy to incorporate such loads as part of laboratory equipment and so a direct current generator is used instead. When such a generator is belt-coupled to an electric motor, we can easily vary the mechanical load in any way we please. It is possible, therefore, to simulate almost any mechanical load with a DC generator, and this is why the ¼HP DC Machine Module (EMS 8211) is part of the laboratory equipment.

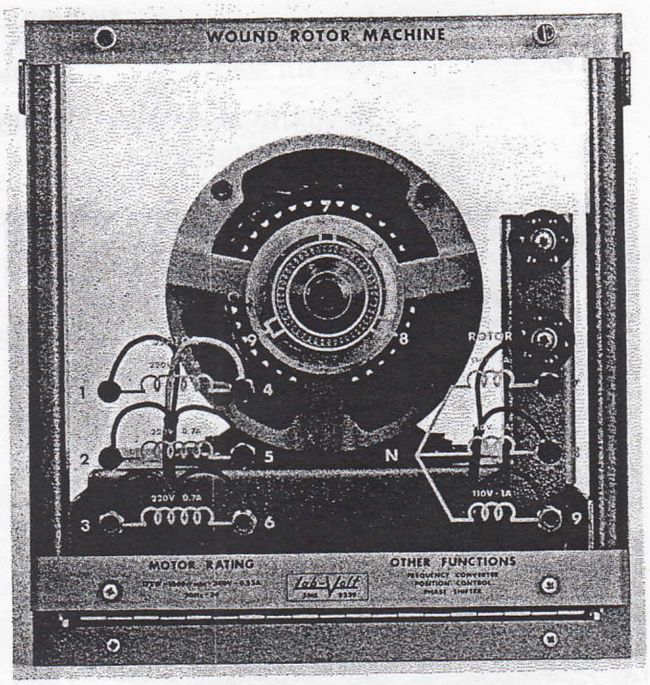


Large alternators which generate electricity are driven by a prime mover which may be a diesel engine, a gas turbine or a steam turbine. In areas where water power is available (such as near waterfalls, rivers and tidal seas) a water turbine is employed. The power delivered by a turbine can be varied by mechanically regulating the flow of water, steam or gas which rushes through it.

It is obviously impractical to bring water, steam or gas turbines into a laboratory to drive alternators; we prefer to use a direct current motor instead. The power developed by such a motor can be easily controlled, and with it, we can duplicate the behavior of any type of turbine.

It is fortunate, indeed, that the ¼HP DC GENERATOR can also be used as a DC MOTOR to do the work of the various turbines mentioned above.





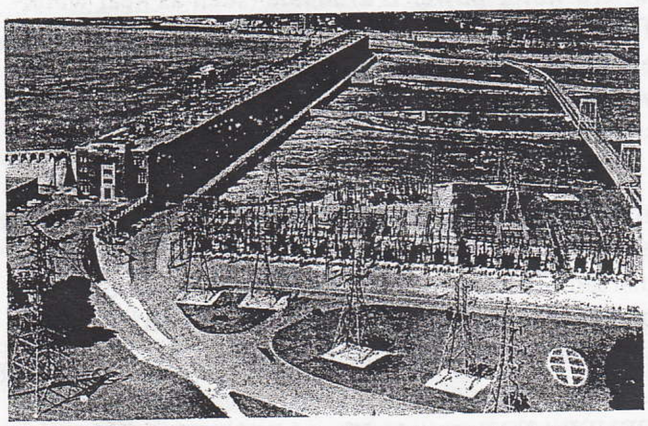
The vast majority of electric motors used in industry are of the three-phase squirrel cage type. They vary in size from fractional to several hundred horsepower but, throughout this broad range, their properties are essentially the same.

The ¼HP Squirrel Cage Induction Motor Module (EMS 8221) is representative of all such industrial motors. Indeed, it may be thought of as being a single, large motor or as representing the combined power of hundreds of small motors.

Owing to the fact that large motors have a relatively large inertia compared to small motors, it is recommended that the flywheel (EMS 8915) be used to depict large-power realism with the ¼HP motor. The flywheel is simply slipped over the shaft and clamped thereto.

In special applications a wound-rotor induction motor may be used instead of a squirrel cage motor. It has basically the same properties, and is exemplified by the Lab-Volt ¼HP Wound Rotor Machine (EMS 8231).

ALTERNATORS, SYNCHRONOUS MOTORS, SYNCHRONOUS CONDENSERS AND THE SYNCHRONOUS MOTOR/GENERATOR MODULE

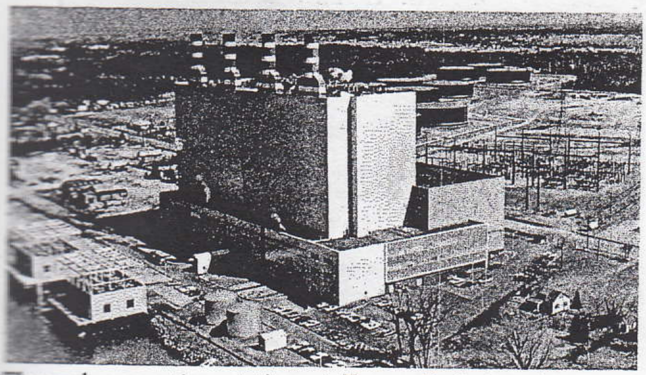


This is Beauharnois Power Station which derives its power from the St. Lawrence River. It is capable of generating 1574MW.

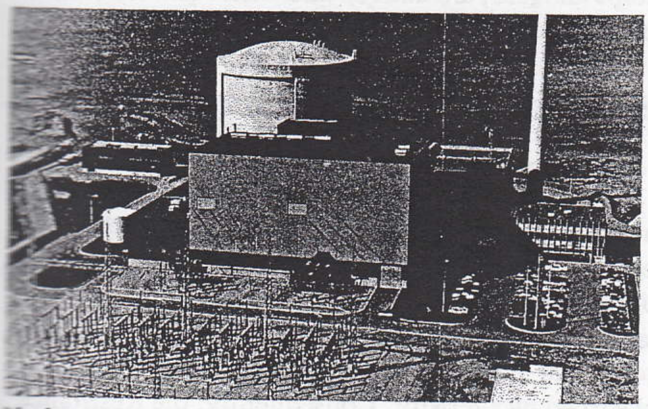
ALTERNATORS

Alternators which generate electricity range from 1 or 2 megawatts (MW) to over 1000MW. In this regard, it is useful to recall that 1MW is about equivalent to 1340 horsepower. Most alternators in the United States are driven by steam turbines and consequently run at high speeds – typically at 1800r/min or 3600r/min. In Canada, where water-power is plentiful, the alternators usually revolve at much lower speeds corresponding to the most efficient speed of water turbines.

High-speed turbo-alternators have long rotors of small diameter, while slow-speed water-wheel alternators have short rotors of large diameter.



Thermal generating station at Tracy. It derives its power from crude oil, ten circular reservoirs of which are located in the background.

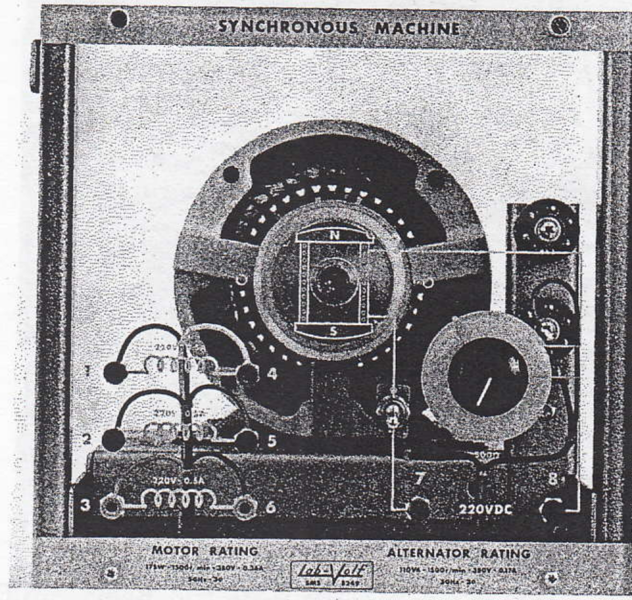


Nuclear power station at Gentilly, Quebec, on the shores of the St. Lawrence River.

Whether the speed is high or low, the electrical properties of the two types of alternators are very much alike. The ¼HP Synchronous Motor / Generator Module (EMS 8241) exhibits to a remarkable degree the properties of enormously larger machines. It is this similarity which enables us to use such a small machine to study the behavior of a large power system.

SYNCHRONOUS MOTORS

Although squirrel cage induction motors are most commonly used in industry, synchronous



motors are often preferred when the power required is in excess of a few hundred horsepower. There are two main reasons: (1) large, low speed synchronous motors are cheaper to build and (2) they can be operated at unity power factor which reduces the electrical cost of running them.

Synchronous motors have salient-pole rotors which carry a DC winding as well as a squirrel cage winding. The Lab-Volt EMS 8241 is constructed in exactly the same way, and has the same properties as a very large industrial synchronous motor.

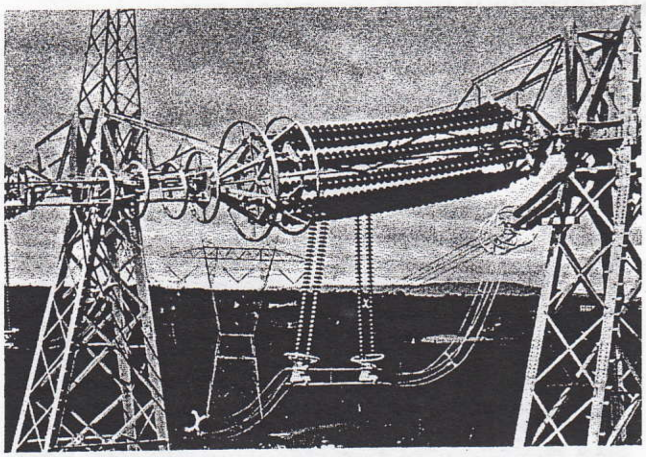
SYNCHRONOUS CONDENSERS

Synchronous condensers are really large synchronous motors which operate at no-load. They are used to regulate the voltage of long, high-voltage transmission lines. The ¼HP Lab-Volt Synchronous Motor/Generator Module can operate as an excellent synchronous condenser and will absorb or deliver reactive power just like a large machine does.

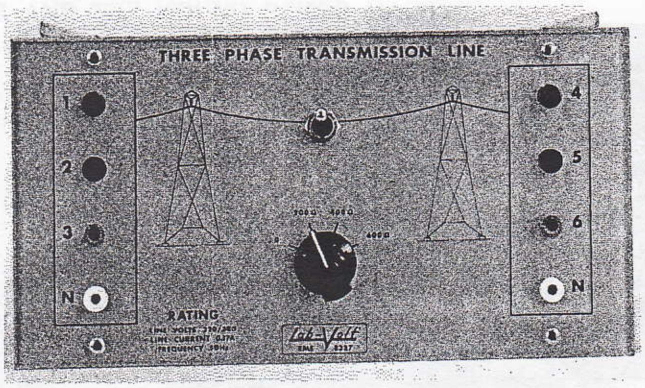
TRANSMISSION LINES AND THE TRANSMISSION LINE MODULE

The transmission line is the link which carries electric power from the generating station to the load. Composed of three or more bare conductors supported by a string of insulators from the cross-arms of ten-story-high towers, it can transport electric power over tens and even hundreds of miles.

It seems strange, therefore, to observe that the Lab-Volt Three-Phase Transmission Line Module (EMS 8329) is conveniently housed in a space no larger than a shoe-box. And yet this miniature line has essentially the same electrical properties as those of a real line which is 60, 120 or 180 miles long. Such long lines create a large magnetic field when they carry an electric current and this field is concentrated in the three coils located inside the module.

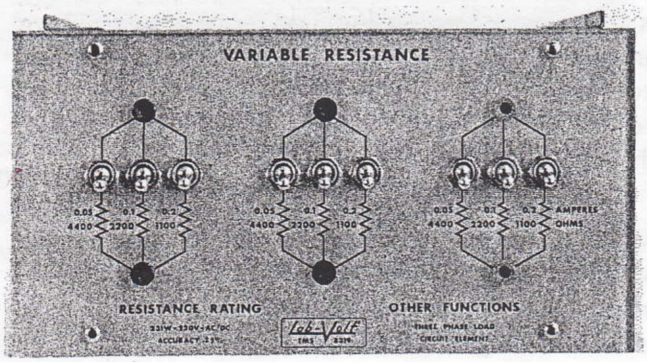


Ten strings of 34 insulators in series carry the tension (both mechanical and electrical) of this 735kV line as it spans the St. Lawrence River.

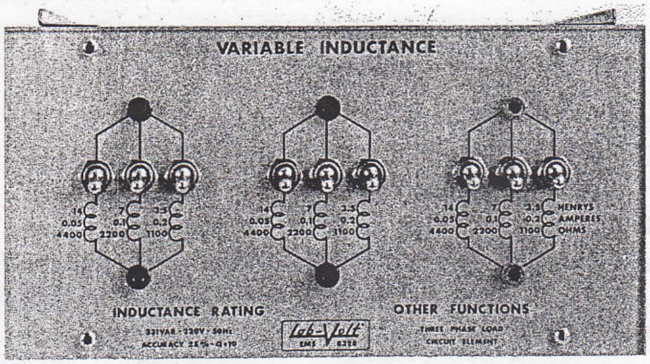


The impedance of the line can be varied in steps of zero, 60 ohms, 120 ohms and 180 ohms per phase.

ELECTRICAL LOADS AND THE RESISTANCE, INDUCTANCE AND CAPACITANCE MODULES

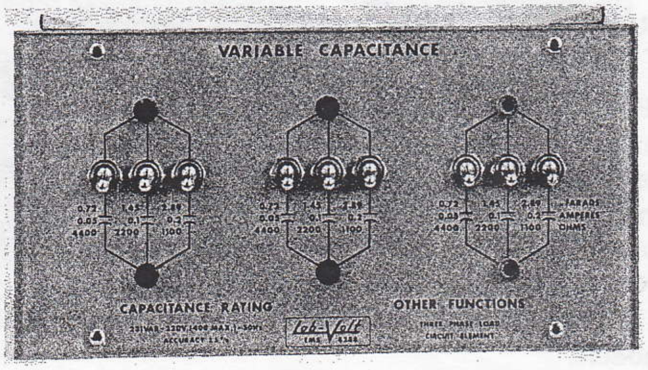


The real and reactive power absorbed by an industry or large city varies considerably throughout the day. The real power is the sum of the real power absorbed by thousands of motors, toasters, lamps, TV sets and electro-chemical processes. This total real power is exactly the same as the power absorbed by a resistor. Consequently, the Resistance Module (EMS 8311) is a simple means by which we can duplicate the real power absorbed by an industrial load.



In the same way, the Inductance Module (EMS 8321) is a simple means whereby we can duplicate the reactive power absorbed by the thousands of motors, transformers, relays, coils and magnets.

Whereas the Inductance Module is considered to absorb reactive power, the Capacitance Module (EMS 8331) can be thought of as being a source, or supplier, of reactive power. Many capacitor banks are installed in factories to reduce the reactive power which they would otherwise draw from the power line. In a very real sense capacitors act as "generators" of the reactive power required by industrial motors.

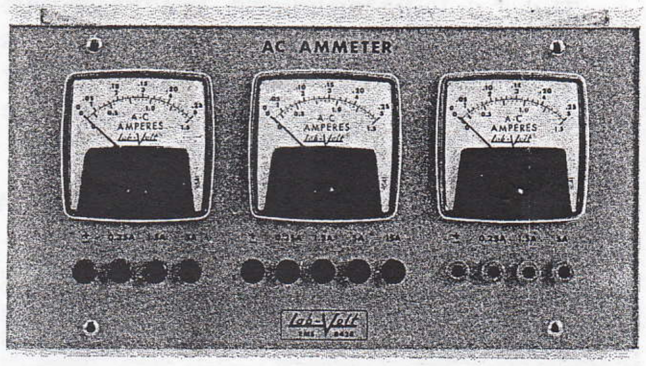


Capacitor banks are also installed in power substations to regulate the voltage or to modify the amount of reactive power carried by a transmission line. The Lab-Volt Capacitance Module has the same properties as these large capacitor banks.

METERING

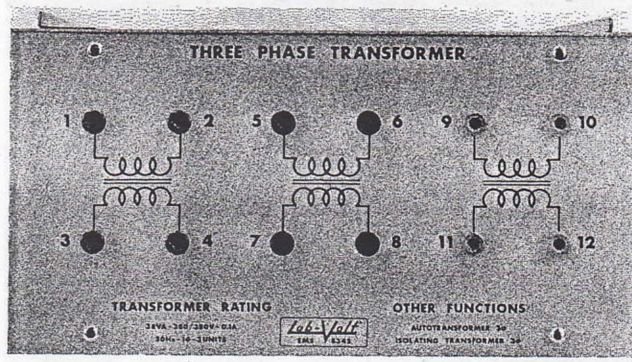
The two AC Metering Modules (EMS 8425 and EMS 8426) enable us simultaneously to measure three voltages and three currents. These modules, fully protected against over-voltages and short-circuits, are ideally suited to make three-phase measurements.

The DC Metering Module (EMS 8412) is convenient when we wish to observe the power of the DC machine.



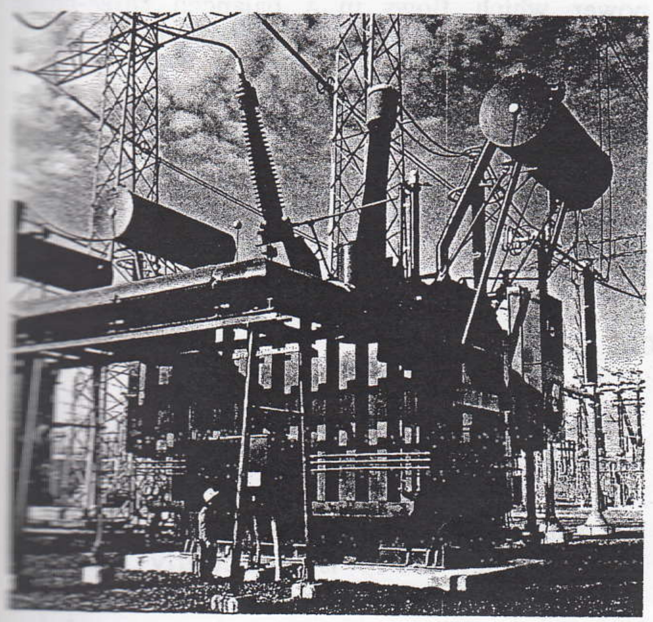
THE THREE-PHASE TRANSFORMER

To transport electric power over great distances, high voltages must be used to ensure adequate stability and reasonable voltage drops at an acceptable cost. On the other hand, electric power can only be generated and used at relatively low voltages. A device is necessary, therefore, to connect the low-voltage generator to the high-voltage line and the high-voltage line to the low-voltage load. This device is the transformer. It is easily one of the most widely used pieces of equipment in the power industry, ranging in size from 1kVA to hundreds of MVA.



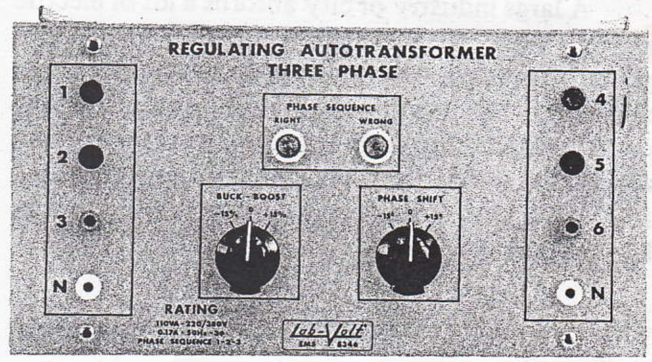
The Three-Phase Transformer Module (EMS 8348) is a small version of the large three-phase transformers used in industry.

THE BUCK-BOOST AND PHASE-SHIFT TRANSFORMER



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

In interconnected power systems, electric power does not always flow along the paths that

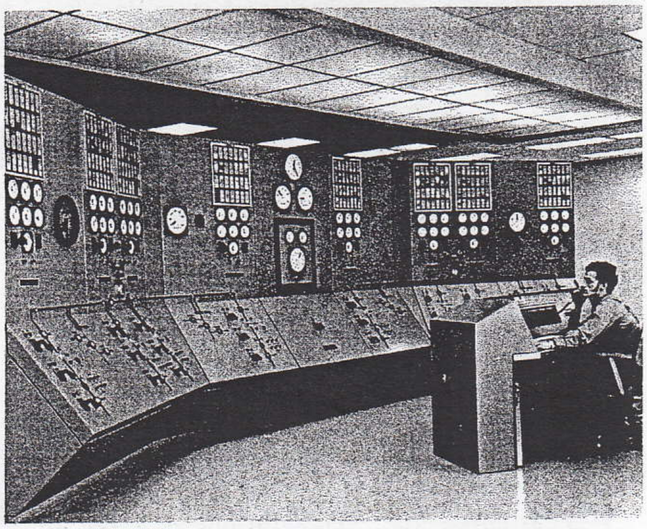


we wish it to follow. Some transmission lines may carry too much power, while others may be underloaded, producing either outages or, at best, uneconomical power transmission.

This situation is remedied by the use of large buck-boost and phase-shift transformers located in appropriate substations. By raising or lowering the secondary voltage or by shifting it either ahead or behind the primary voltage, we can produce very significant changes in the flow of real or reactive power over a transmission line.

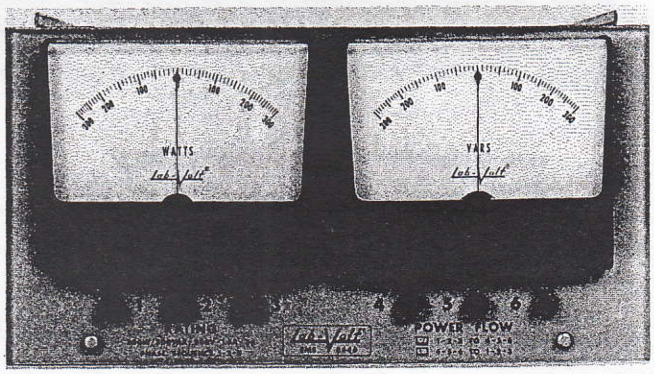
The Lab-Volt Buck-Boost and Phase-Shift Autotransformer Module (EMS 8349) enables us to raise or lower the secondary voltage by 15% or to shift it by 15 degrees ahead or behind the primary voltage. Commercial transformers of this kind are much more elaborate than this simple laboratory module, but the principles are exactly the same.

REAL AND REACTIVE POWER AND THE WATT-VARMETER MODULE



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

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.

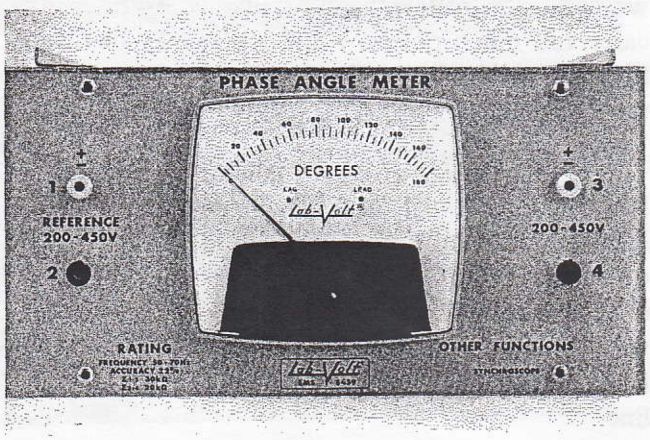


However, another kind of power is needed to create the AC magnetic field in motors, transformers, relays and magnets. This is the so-called reactive power, measured in vars, kilovars or megavars.

The Lab-Volt Watt-Varmeter Module (EMS 8446) 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.

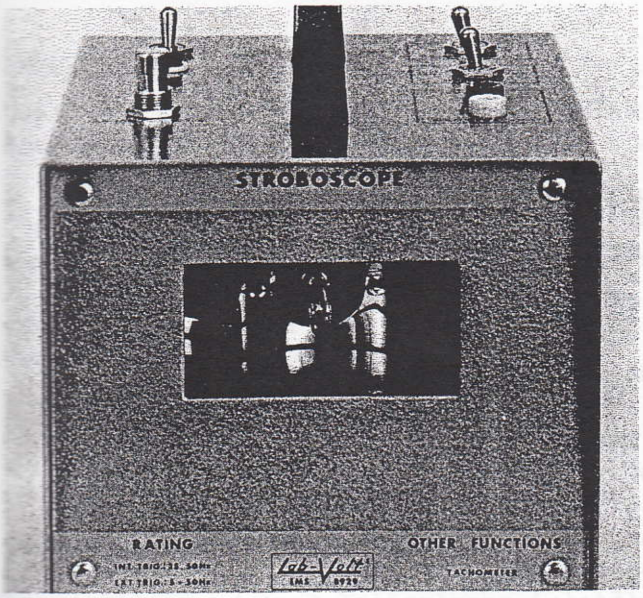
Controlling the flow of electric power is important to electric power companies because it influences not only the revenue but also the electrical stability of the power system.

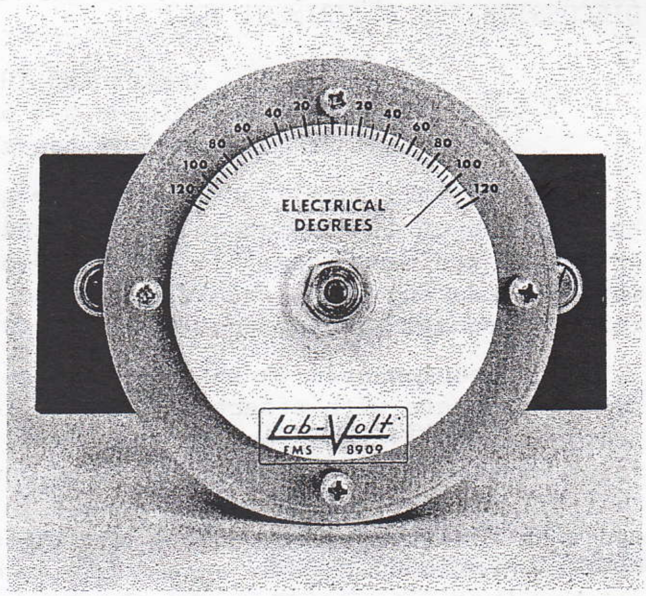
THE PHASE ANGLE METER



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 Lab-Volt Phase Angle Meter Module (EMS 8451) 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 an alternator (EMS 8241) has to be synchronized with an existing power system.





The behavior of alternators and synchronous motors under variable load conditions, and particularly under system disturbances, can be witnessed by means of the special Lab-Volt Strobe Light (EMS 8922). The shift in position of the rotor poles under increased load and the oscillatory swing under transient conditions enables one to understand why sudden load changes should be avoided.

Used in connection with the Mechanical Torque Angle Meter (EMS 8909), the strobe light can be used to make accurate measurements of rotor pole shift in electrical degrees.

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.

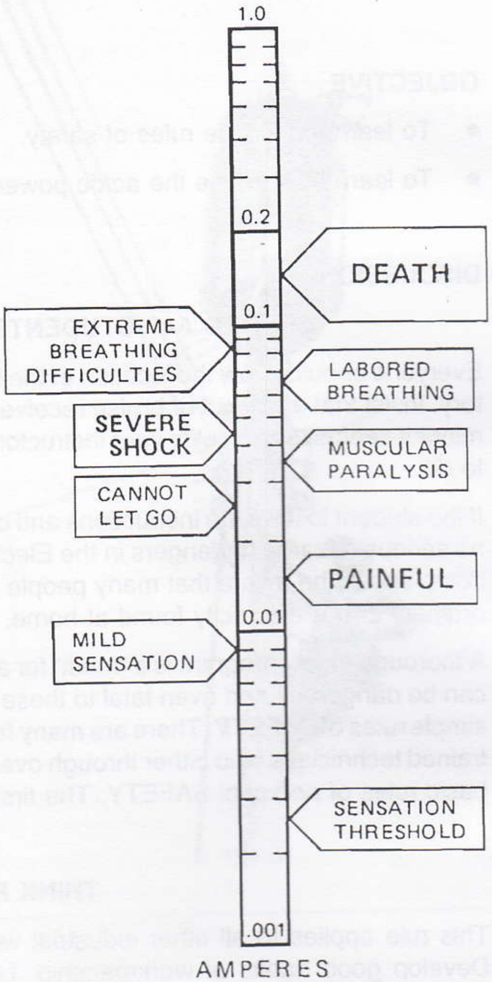


Figure 1-1.

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 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

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

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

k) The low power output = ______ 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.

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.

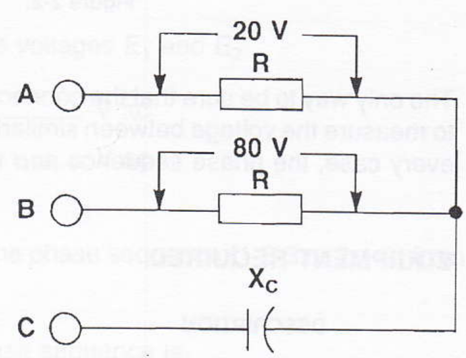


Figure 2-1.

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.

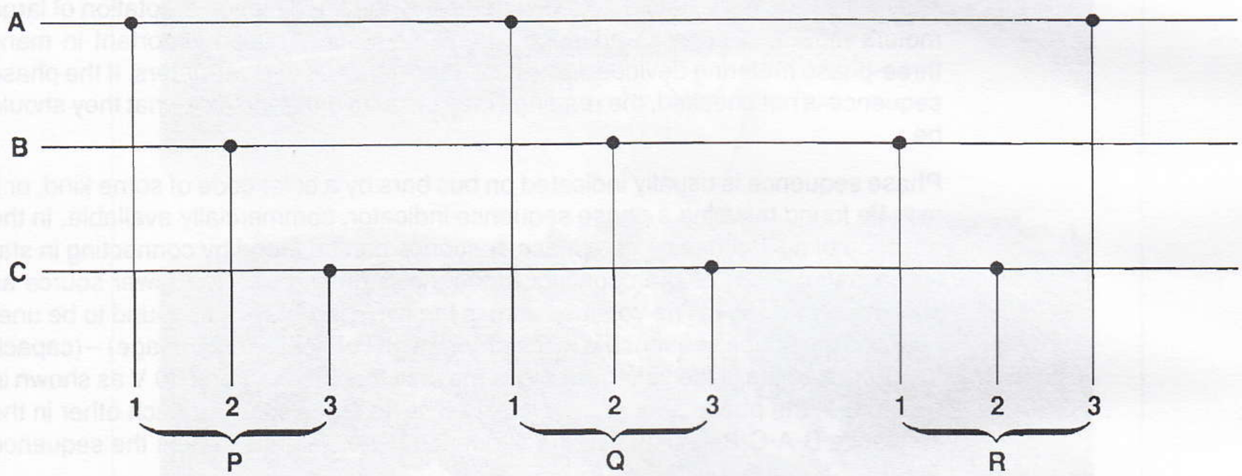


Figure 2-2.

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.

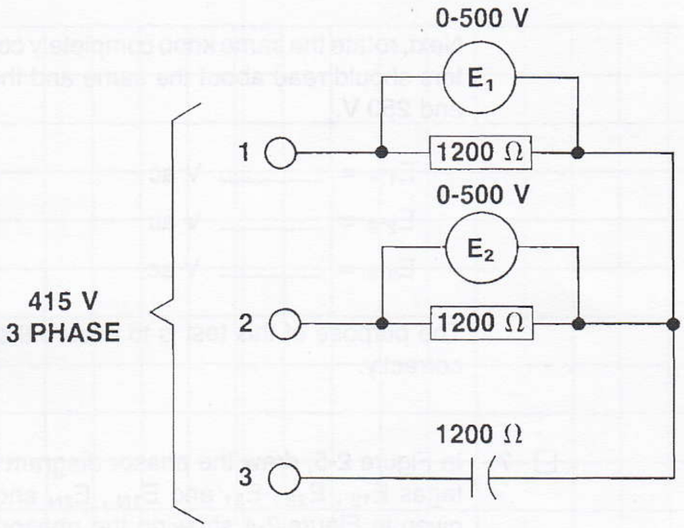


Figure 2-3.

☐ 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.

$E_{1\text{-}4}$ = ______ V ac

$E_{2\text{-}5}$ = ______ V ac

$E_{3\text{-}6}$ = ______ 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.

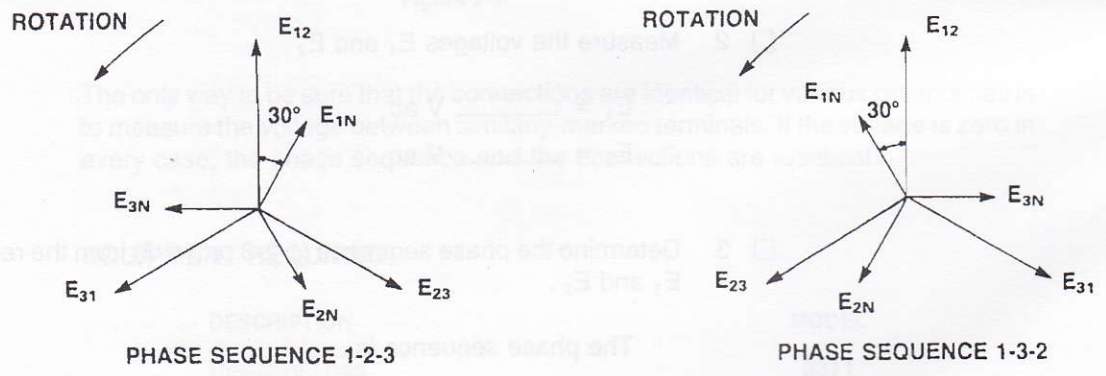


Figure 2-4.

☐ 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.

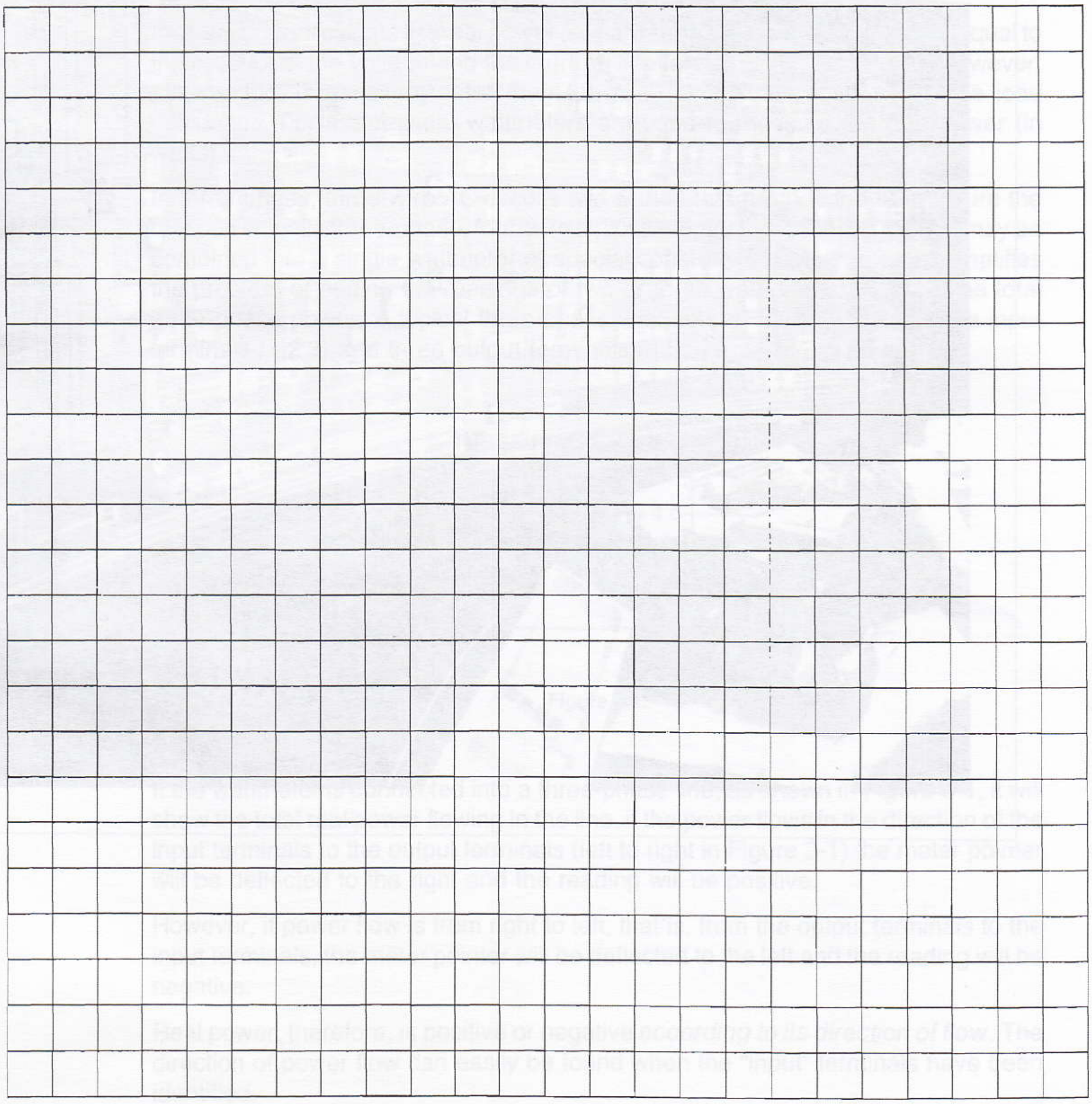
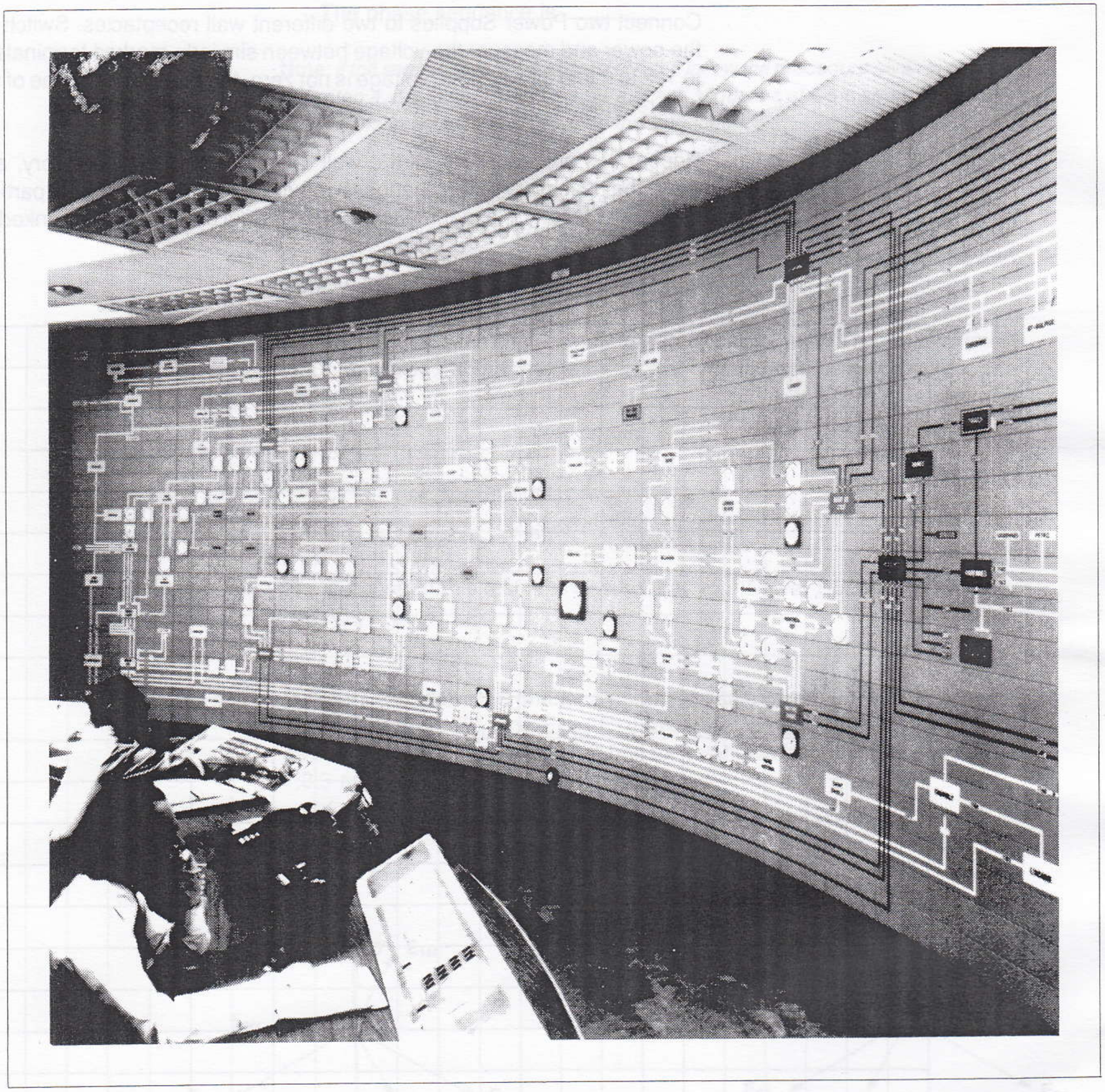


Figure 2-5.



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

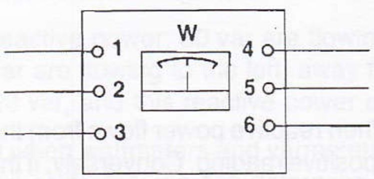


Figure 3-1.

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.

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).

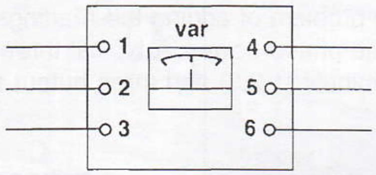


Figure 3-2.

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.

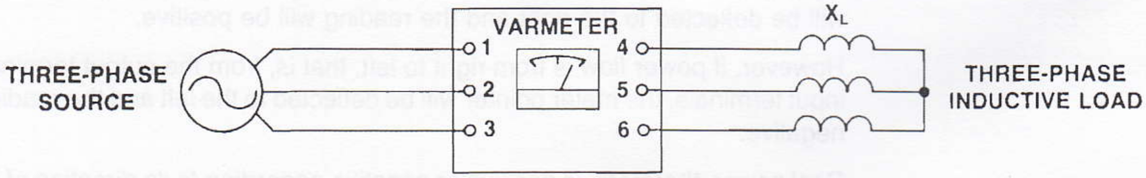


Figure 3-3.

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:

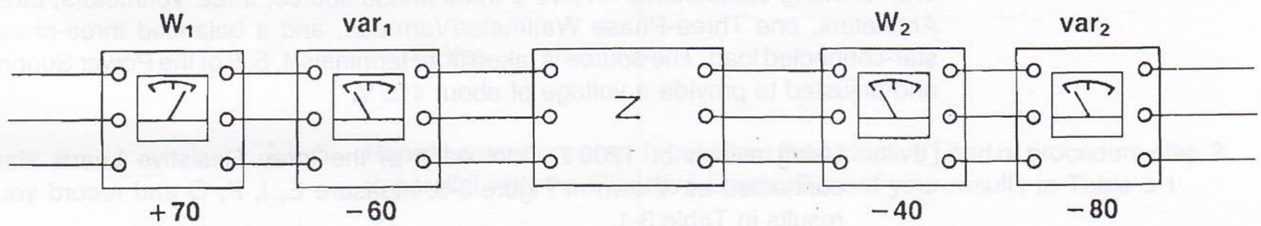


Figure 3-4.

$W_1 = +70$ 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.

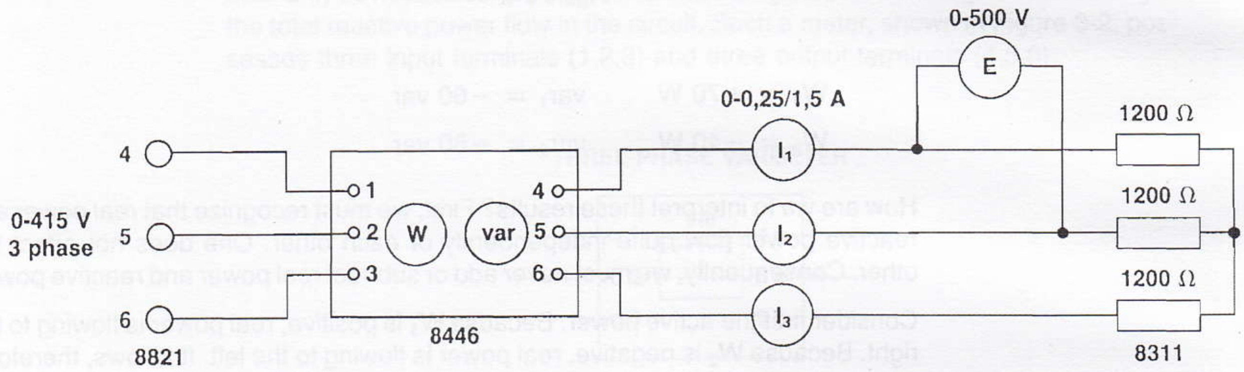


Figure 3-5.

☐ 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	$S = E I \sqrt{3}$
		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).

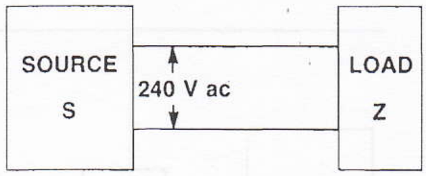


Figure 3-6.

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

____

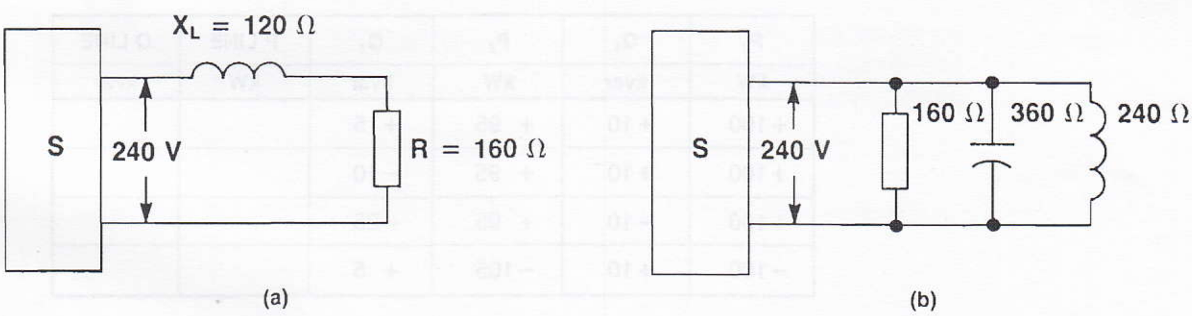


Figure 3-7.

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.

____

____

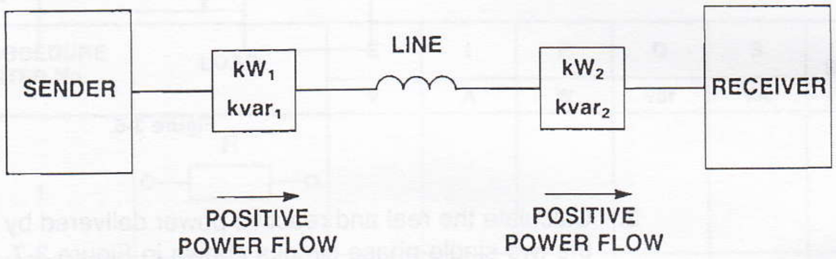


Figure 3-8.

P_1	Q_1	P_2	Q_2	P LINE	Q LINE
kW	kvar	kW	kvar	kW	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.

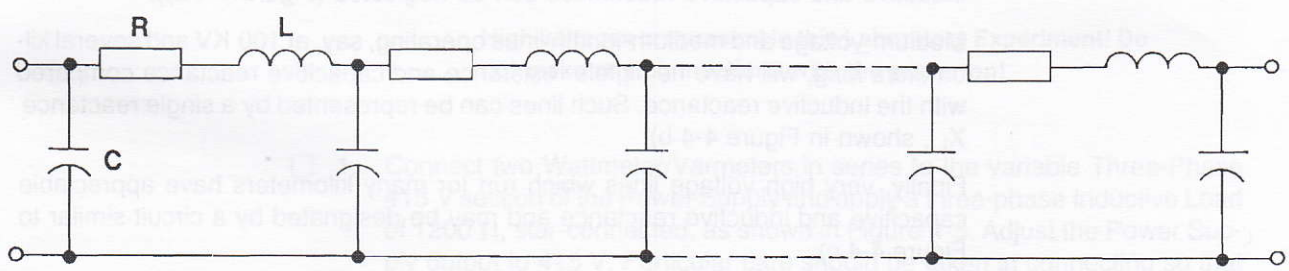


Figure 4-1.

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.

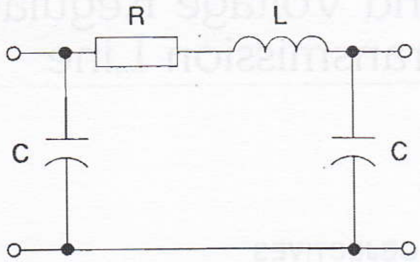


Figure 4-2.

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.

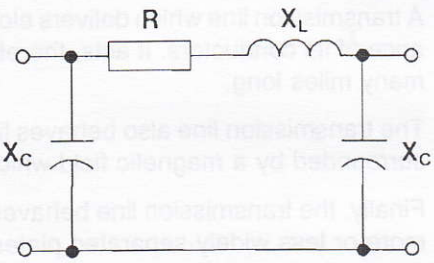


Figure 4-3.

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.

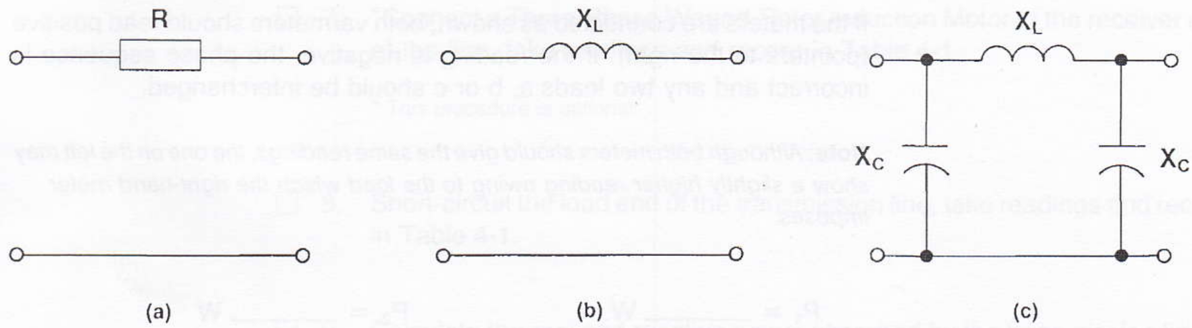


Figure 4-4.

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.

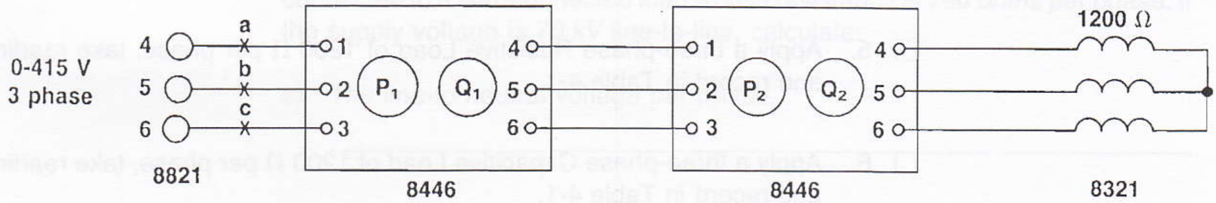


Figure 4-5.

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 P_2 = ________ W

Q_1 = ________ var 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.

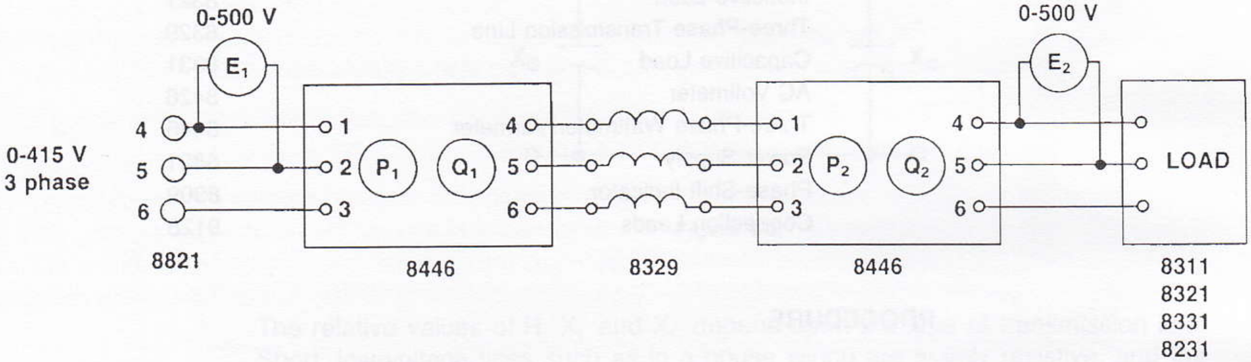


Figure 4-6.

☐ 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								
7	MOTOR	350								
8	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?

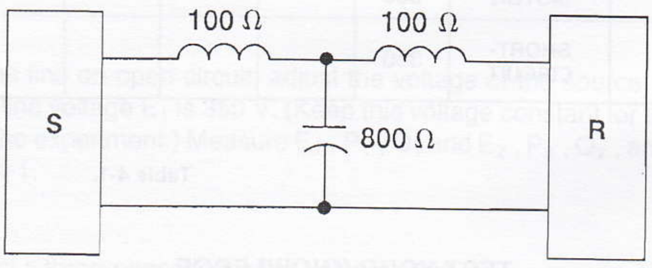


Figure 4-7.

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

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.

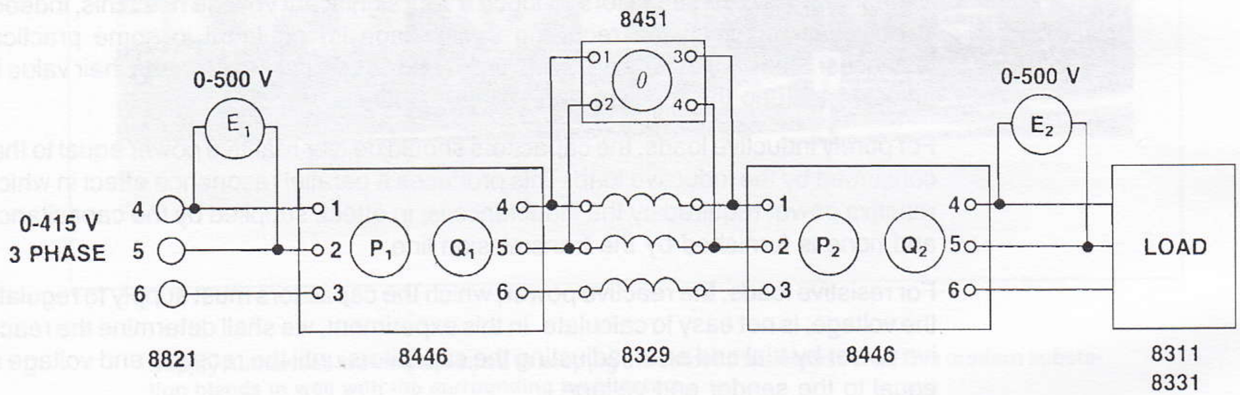


Figure 5-1.

☐ 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	E_1	P_1	Q_1	E_2	P_2	Q_2	ANGLE
Ω	V	W	var	V	W	var	°
∞							
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.

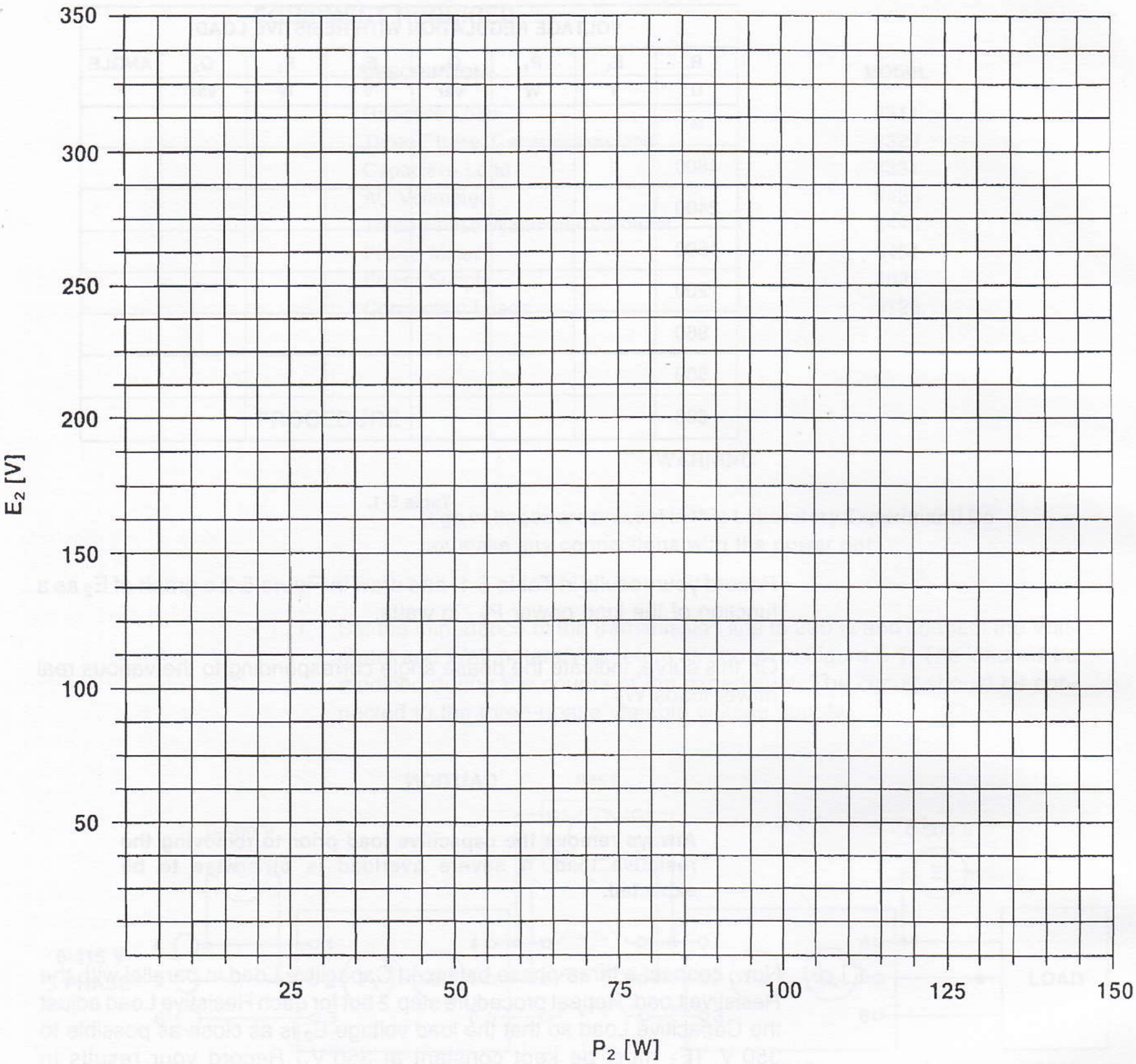


Figure 5-2.

☐ 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.

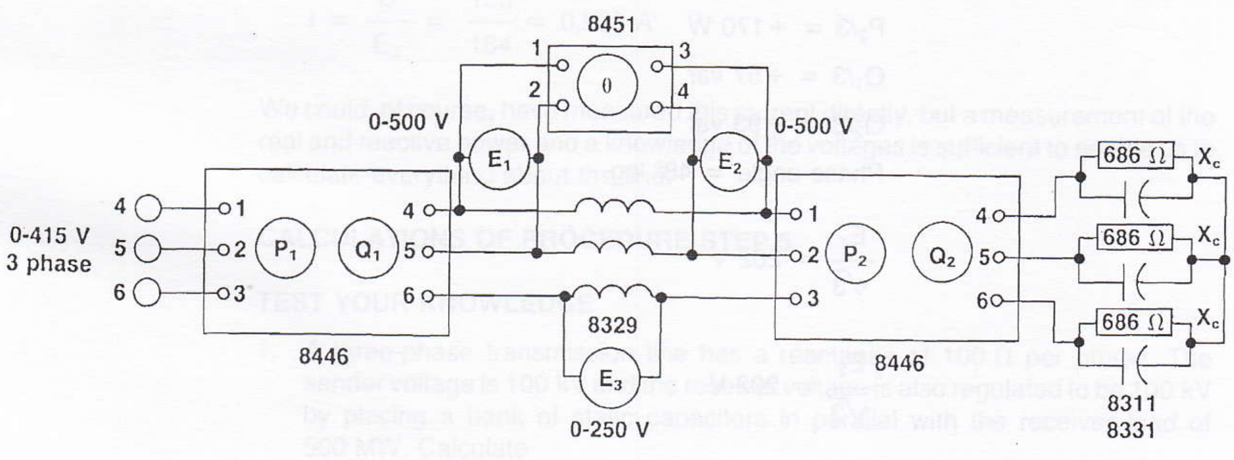


Figure 5-3.

☐ 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:

$E_1 = 350\ \text{V}$ $E_2 = 350\ \text{V}$ $E_3 = 165\ \text{V}$

$P_1 = +600\ \text{W}$ $P_2 = +510\ \text{W}$

$Q_1 = +170\ \text{var}$ $Q_2 = -280\ \text{var}$

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:

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

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

$E_3 = 165\ \text{V}$

$P_1/3 = +200\ \text{W}$

$P_2/3 = +170\ \text{W}$

$Q_1/3 = +57\ \text{var}$

$Q_2/3 = -93\ \text{var}$

Phase angle = 48° lag

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

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

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

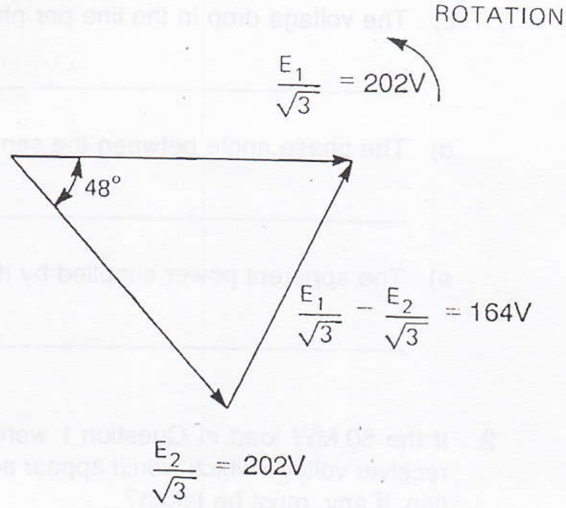


Figure 5-4.

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 ______________________________

____

____

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.

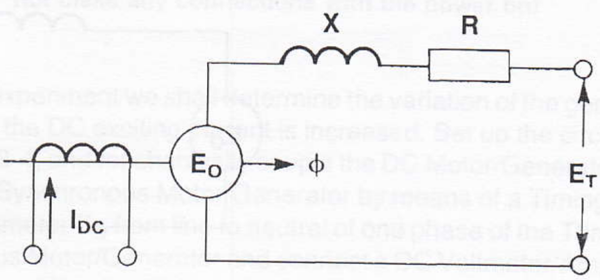


Figure 8-1.

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.

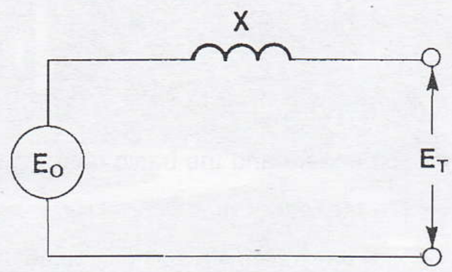


Figure 8-2.

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.

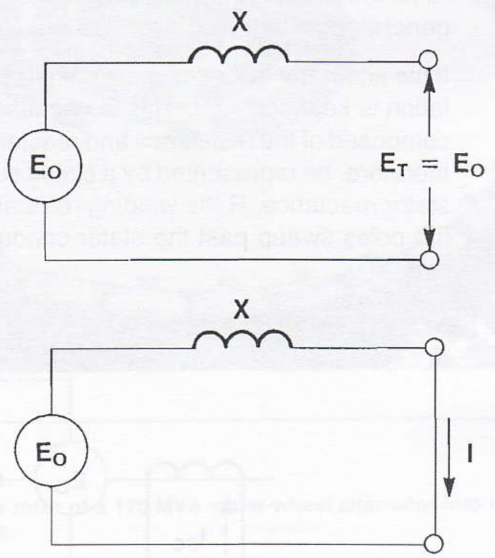


Figure 8-3.

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.

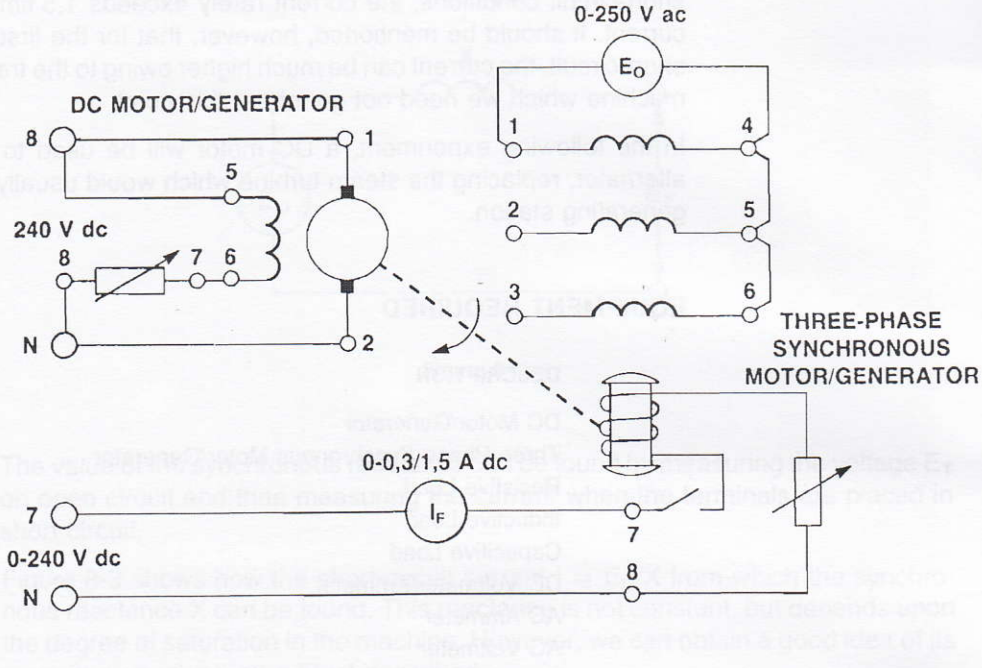


Figure 8-4.

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).

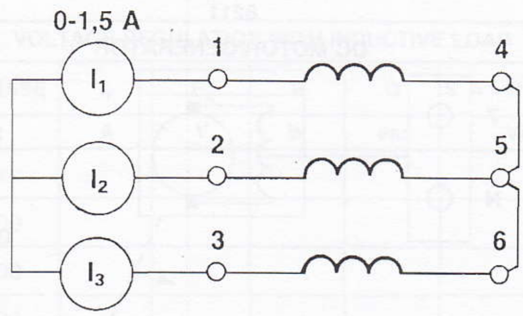


Figure 8-5.

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 $E_O = 260$ V and then with $E_O = 220$ V.

$E_O = 260$ 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.

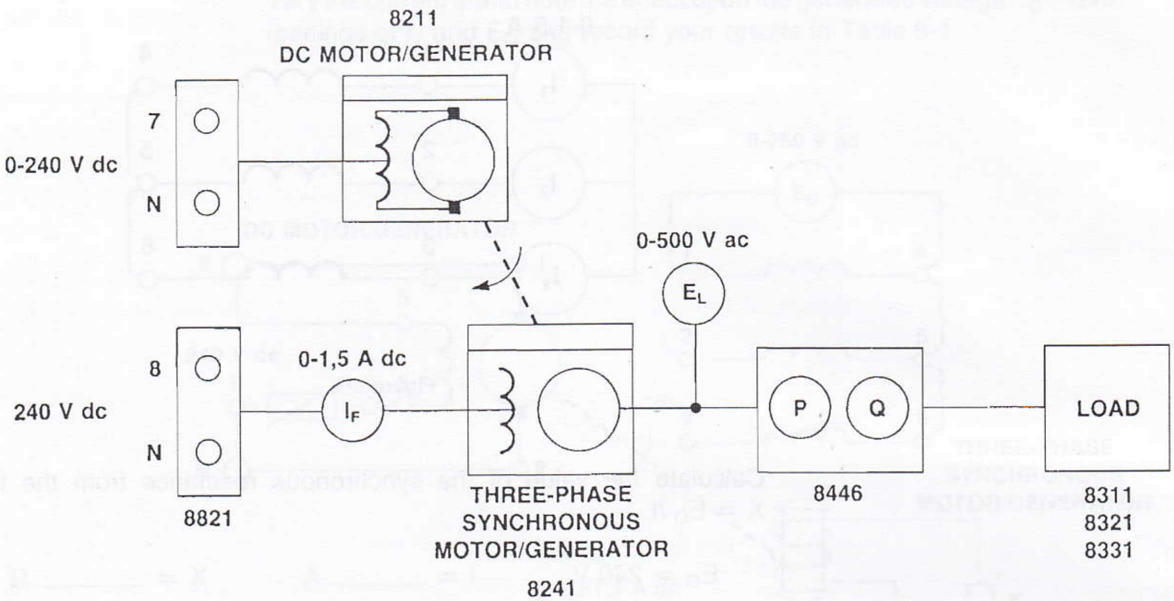


Figure 8-6.

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					
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					
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					
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?

   ____

   ____

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.

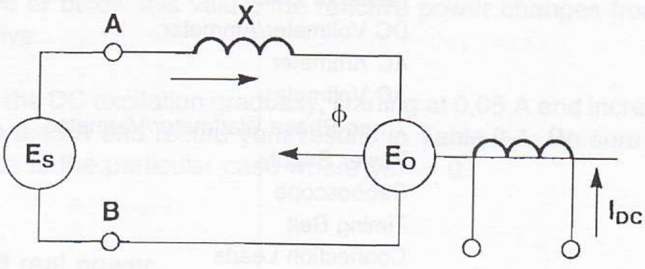


Figure 9-1.

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.

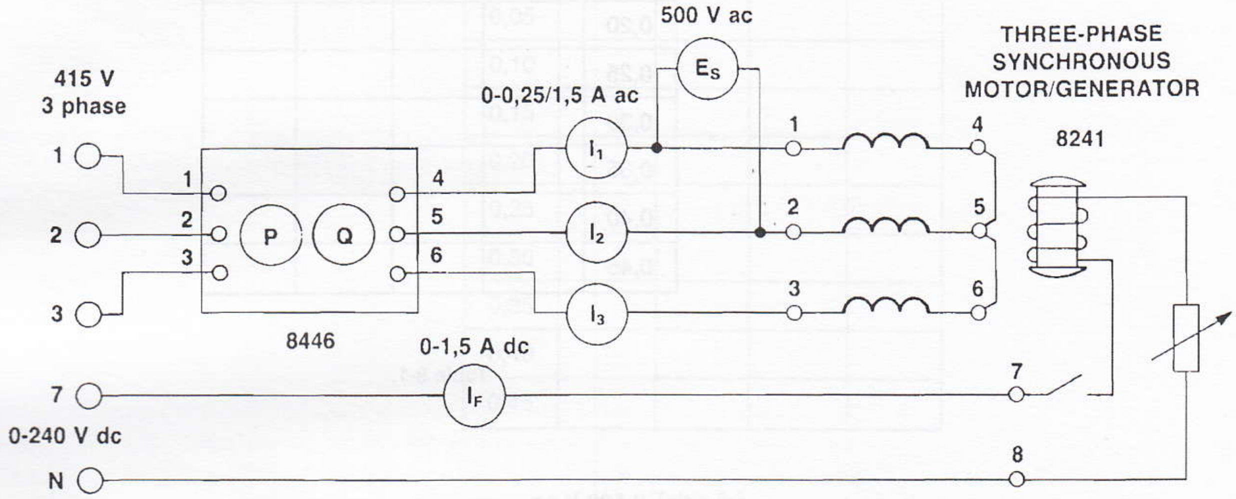


Figure 9-2.

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 A	E_S V	I A	P W	Q var
0,05				
0,10				
0,15				
0,20				
0,25				
0,30				
0,35				
0,40				
0,45				

Table 9-1.

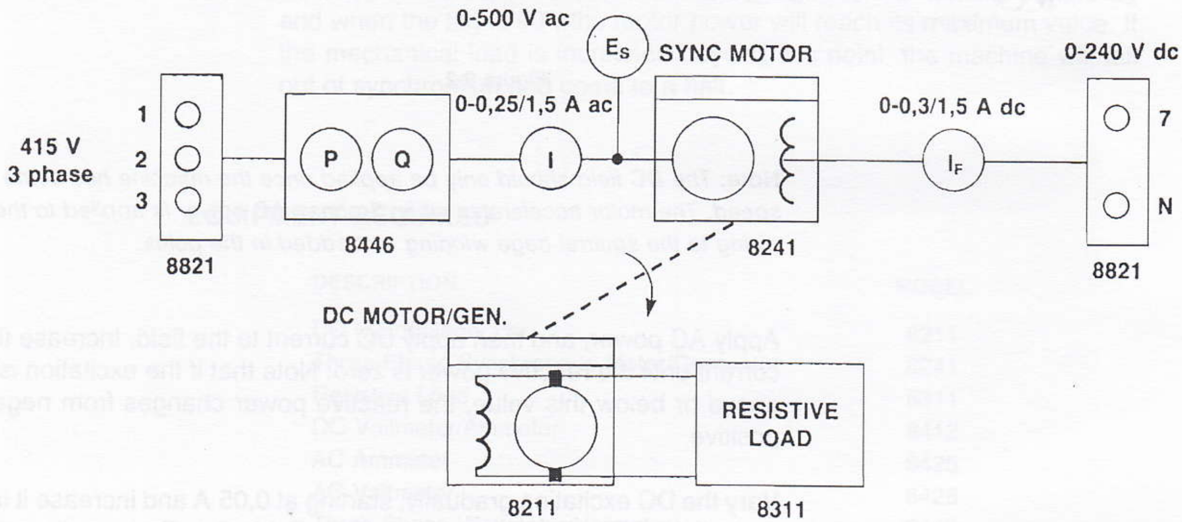


Figure 9-3.

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 A	E_S V	I A	P W	Q 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?

____

____