ELECTRIC POWER
TRANSMISSION SYSTEM

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Printed in Canada
March 1993
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 counterparts 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, we 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](image1)

![Figure 2](image2)

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](image3)

![Figure 4](image4)
"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.](image)

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.](image)  ![Figure 7.](image)
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.

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:

![Diagram](image1.png)

**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*.

![Diagram](image2.png)

**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.

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These experiments are suggested for students who may wish to extend their knowledge and understanding of transmission line. Several of these experiments involve Lab-Volt equipment which is not a regular part of the Transmission Line program.

Appendix A  Cross-Reference List of Required Equipment vs Experiments
Required equipment for each Laboratory Experiment
Introduction

TRANSMISSION LINE EQUIPMENT

Mechanical Loads, Turbines and the DC Motor/Generator

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 DC Motor/Generator is part of the laboratory equipment.

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

Large generators 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 generators; 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.

This can be achieved readily because the DC Motor/Generator can also be used as a dc motor to do the work of the various turbines mentioned above.

The Four-Pole Squirrel-Cage Induction Motor and the Three-Phase Wound-Rotor Induction Motor

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 Four-Pole Squirrel-Cage Induction Motor 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 Inertia Wheel be used to depict large-power realism with the 0.2 kW 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. Such machines have basically the same properties, as the Three-Phase Wound-Rotor Induction Motor.

Generators, Synchronous Motors, Synchronous Capacitors and the Synchronous Motor / Generator

Generators

Generators used in power stations range from 1 megawatt to over 1000 megawatts (MW) are driven by steam turbines and consequently run at high speeds — typically at 1500 r/min or 3000 r/min. Where water power is used, the generators usually revolve at much lower speeds corresponding to the most efficient speed of water turbines.

High speed turbo-generators have long rotors of small diameter, while slow-speed hydro-electric turbines generators have short rotors of large diameter.
This is Beauharnois Power Station which derives its power from the St-Lawrence River. It is capable of generating 1574 MW.

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

Whether the speed is high or low, the electrical characteristics of the two types of generators are very much alike. The Three-Phase Synchronous Motor/Generator exhibits the electrical characteristics 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.
Nuclear power station at Gentilly, Quebec, on the shores of the St-Lawrence River.

Synchronous motor

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 kilowatts. 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 Three-Phase Synchronous Motor/Generator is constructed in exactly the same way, and has the same properties as a very large industrial synchronous motor.

Synchronous Capacitors

Synchronous capacitors are really large synchronous motors which operate at no-load. They are used to regulate the voltage of long, high-voltage transmission lines. The Three-Phase Synchronous Motor/Generator can operate as an excellent synchronous capacitor 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 kilometers.

It seems strange, therefore, to observe that the Three-Phase Transmission Line 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 100, 200 or 300 km 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.

The impedance of the line can be varied in steps of zero, 200 $\Omega$, 400 $\Omega$ and 600 $\Omega$ per phase.
Ten strings of 34 insulators in series carry the tension (both mechanical and electrical) of this 735 kV line as it spans the St-Lawrence River.
Resistive, Inductive, and Capacitive Loads

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 Resistive Load is a simple means by which we can duplicate the real power absorbed by an industrial load.

In the same way, the Inductive Load is a simple means whereby we can duplicate the reactive power absorbed by the thousands of motors, transformers, relays, coils and inductors.
Whereas the Inductive Load is considered to absorb reactive power, the Capacitive Load 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 Capacitive Load has the same properties as these large capacitor banks.

Metering

The AC Ammeter and the AC Voltmeter enable us simultaneously to measure the voltages and three currents. These modules, fully protected against over-voltages and short-circuits, are ideally suited to make three-phase measurements.
The DC Voltmeter/Ammeter 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 1 kVA to hundreds of MVA.

The Three-Phase Transformer is a small version of the large three-phase transformers used in industry.

The Regulating Autotransformer

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 step-up and step-down transformers (buck-boost), as well as 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 Three-Phase Regulating Autotransformer enables us to raise or lower the secondary voltage by 15% or to shift it by 15° 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.
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.

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 Stroboscopy 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

<table>
<thead>
<tr>
<th>MODEL</th>
<th>DESCRIPTION</th>
<th>QUANTITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>8110</td>
<td>Mobile Console</td>
<td>1</td>
</tr>
</tbody>
</table>
| 8211   | DC Motor/Generator Module:  
\( \frac{3}{4} \text{hp}, 1800 \text{rpm}, 120 \text{Vdc} \) motor  
120W, 1800rpm, 120Vdc generator                                                                                       | 1        |
| 8221 * | Squirrel-Cage Induction Motor Module:  
\( \frac{3}{4} \text{hp}, 1670 \text{rpm}, 120/208 \text{V}, 3\phi \)                                                                                   | 1        |
| 8231 * | Wound-Rotor Induction Motor Module:  
\( \frac{3}{4} \text{hp}, 1500 \text{rpm}, 120/208 \text{V}, 3\phi \)                                                                                   | 1        |
| 8241   | Synchronous Motor/Generator Module:  
\( \frac{3}{4} \text{hp}, 1800 \text{rpm}, 120/208 \text{V}, 3\phi \) motor  
120VA, 1800rpm, 120/208V, 3φ generator                                                                 | 1        |
| 8311   | Resistance Module:  
**Loading capacity 0 to 252W in 12W steps, three separate sections, 5% accuracy, 1φ/3φ/dc**                                                                                                                                                        | 1        |
| 8321   | Inductance Module:  
**Loading capacity 0 to 252var in 12var steps, three separate sections, 5% accuracy, 1φ/3φ, 60Hz**                                                                                                      | 1        |
| 8329   | Three-Phase Transmission Line Module:  
Impedance 60, 120, 180Ω  
0.33A, 3φ, 60Hz                                                                                                            | 2        |
| 8331   | Capacitance Module:  
**Loading capacity 0 to 252var in 12var steps, three separate sections, 5% accuracy, 1φ/3φ, 60Hz**                                                                                           | 1        |
| 8348   | Three-Phase Transformer Module:  
40VA, 208/208V, 0.2A; 60Hz, 1φ, 3 units                                                                                                             | 1        |
| 8349   | Buck-Boost and Phase Shift Transformer Module:  
120VA, 208V, 60Hz  
Buck/Boost +15%, 0, -15%  
Phase Shift +15°, 0, -15°                                                                                                           | 1        |
| 8412   | DC Metering Module:  
0-500mAdc, 2% accuracy  
0-2.5/5Adc, 2% accuracy  
0-20/200Vdc, 2% accuracy                                                                                                             | 1        |
| 8425   | AC Metering Module:  
0-0.5/2.5/8Aac, 2% accuracy (2)  
0-0.5/2.5/8/25Aac, 2% accuracy                                                                                                                                                                             | 1        |

*Optional Equipment*  

<table>
<thead>
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<th>DESCRIPTION</th>
<th>QUANTITY</th>
</tr>
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</table>
| 8426   | AC Metering Module:  
0-100/250Vac, 2% accuracy (3)                                                                                                                                                                       | 1        |
| 8446   | Three-Phase Watt-Varimeter Module:  
300-0-300 W, 300-0-300 var  
240V, 1.5A, 3φ, 60Hz                                                                                                                                   | 2        |
| 8451   | Phase Angle Meter Module:  
0 to 180° lag or lead, isolated inputs, impedance 10kΩ, 100V to 250V, 1 φ, 50 to 70Hz                                                                                                               | 1        |
| 8821   | Power Supply Module:  
**Input**  
120/208V, 15A, 3φ  
(4 wires plus ground)                                                                                                                                     | 1        |
|        | **Output**  
(120V, 15A, 1φ)  
120Vdc, 2A                                                                                                                              |          |
|        | **Output**  
(0-120V, 5A, 3φ)  
0-120Vdc, 8A                                                                                                                               |          |
|        | **Volmeter**  
0-250Vac/Vdc                                                                                                                                       |          |
| 8909   | Mechanical Torque Angle Meter:  
Synchronous motor pole-shift indicator 0 to ± 120 electrical degrees, adjustable zero                                                                                                           | 1        |
| 8915   | Inertia Wheel:  
Inertia = 0.625 lb·ft·^2 (0.026kg·m·^2)                                                                                                             | 1        |
| 8922   | Strobe Light:  
**Trigger Frequency (f)**  
**Int:** 60Hz  
**Ext:** 120Hz max  
**Trigger Voltage:** 10-250V rms  
**Maximum Flash Rate:** 60Hz  
**Flash Duration:** 20µs  
**Ext. Trigger Input Z**  
15kΩ  
Flash occurs when rising trigger voltage passes through zero  
Power requirements ¾A, 120V, 60Hz 1φ                                                                                                               | 1        |
| 8942   | Timing Belt                                                                                                                                                                                               | 1        |
| 9128   | Connection Leads  
40 stack up banana plug patch cords 15 A, continuous operation                                                                                                                       | 1        |
Single-phase, oil-filled, step-down transformer from 4kV to 120/240V for suburban distribution.
OBJECT
1. To learn the simple rules of safety.
2. To learn how to use the ac/dc power supply.

DISCUSSION

TO ALL STUDENTS AND TEACHERS:

Know the location of the FIRST AID supply in your shop or lab. 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 with a degree of accuracy, there are no serious hazards or dangers in the Electro Mechanical Systems of learning. Many people receive fatal shocks every year from the ordinary 120 volt electricity found in the 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 industrial work as well as 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 be a clown! Jokes are fun and so is "horsing around", but not near moving machinery or electricity. There are generally three kinds of accidents which appear all too frequently among electrical students and technicians. 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 Fig. 1-1.

Notice that it is the current that does the damage. Currents above 100 milliamperes or only one tenth of an ampere are fatal. A workman who has contacted currents above 200 milliamperes may live to see another day if given rapid treatment. Currents below 100 milliamperes 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 .................. ohms (resistance)
From hand to foot .................. ohms (resistance)
Now wet your fingers and repeat the measurements:

From right to left hand \( \text{ohms (resistance)} \)

From hand to foot \( \text{ohms (resistance)} \)

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 \( \text{ohms} \) for wet skin and large contact area, to 500,000 \( \text{ohms} \) for dry skin. Considering the resistance of your body previously measured, and 100 milliamperes as a fatal current, what voltages might prove fatal for you to contact.

Use the formula: \( \text{Volts} = 0.1 \times \text{ohms} \).

Contact between two hands (dry):
\( \text{volts} \)

Contact between one hand and one foot (dry):
\( \text{volts} \)

Contact between two hands (wet):
\( \text{volts} \)

Contact between one hand and foot (wet):
\( \text{volts} \)

DO NOT ATTEMPT TO PROVE THIS!

Nine 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 grounding prong of a three wire input plug. This eliminates the 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 procedures of work.

5. DO NOT WORK ON WET FLOORS. Your contact resistance to ground is substantially reduced. 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. WORK WITH ONE HAND BEHIND YOU OR IN YOUR POCKET. A current between two hands crosses your heart and can be more lethal than a current from hand to foot. A wise technician always works with one hand. Watch your TV serviceman.

8. 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 the cause of an accident.

9. 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 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 hit in the eyes or on his 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 Module EMS 8821 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, 120/208 volt, four wire (with fifth wire ground) system. Power is brought in through a five prong, 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 120Vac** is made available for the use of accessory equipments such as oscilloscopes and TVM’s. This power is brought out to a standard grounding type receptacle rated at 15A.
2. **Fixed 120/208 volts, 3φ power** is brought out to four terminals, labeled 1, 2, 3 and N. **Fixed 208 volts 3φ** may be obtained from terminals 1, 2 and 3. **Fixed 208 volts ac** may be obtained between terminals 1 and 2, 2 and 3 or 1 and 3. **Fixed 120 volts 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 **15A per phase.**

3. **Variable 120/208 volts, 3φ power** is brought out to four terminals, labeled 4, 5, 6 and N. **Variable 3φ 0-208 volts** may be obtained from terminals 4, 5 and 6. **Variable 0-208 volts ac** may be obtained between terminals 4 and 5, 5 and 6 or 4 and 6. **Variable 0-120 volts 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 **5A per phase.**

4. **Fixed 120Vdc** is brought out to terminals labeled 8 and N. The current rating of this supply is **2A.**

5. **Variable 0-120Vdc** is brought out to terminals labeled 7 and N. The current rating of this supply is **8A.**

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 **15A 3φ 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 200A may be drawn.

All of the power sources may be used simultaneously providing that the total current drawn does not exceed the **15A per phase** input breaker rating. Your power supply, if handled properly, will provide years of reliable operation and will present no danger to you.
INSTRUMENTS AND COMPONENTS

Power Supply Module \hspace{1cm} EMS 8821
AC Metering Module (250V) \hspace{1cm} EMS 8426
Connection Leads \hspace{1cm} EMS 9128

EXPERIMENTS

Caution: 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 Module EMS 8821. 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 120Vac receptacle.
   g) The fixed 120/208 volt output terminals (labeled 1, 2, 3 and N).
   h) The variable 0-120/208 volt output terminals (labeled 4, 5, 6 and N).
   i) The fixed dc output terminals (labeled 8 and N).
   j) The variable dc output terminals (labeled 7 and N).
   k) The common reset button.

2. State the ac or dc voltage and the rated current available from each of the following terminals:
   a) Terminals 1 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   b) Terminals 2 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   c) Terminals 3 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   d) Terminals 4 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   e) Terminals 5 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   f) Terminals 6 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   g) Terminals 7 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   h) Terminals 8 and N =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   i) Terminals 1, 2 & 3 =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   j) Terminals 4, 5 & 6 =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]
   k) The receptacle =
      \[
      \ldots V \quad \ldots A \quad \ldots
      \]

3. Examine the interior construction of the module. Identify the following items:
   a) The 3φ 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 prong twist lock connector.

4. Insert the Power Supply Module 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 3φ 120/208 volts.

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 3φ 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.

\[ V_{dc \, minimum} = \ldots \quad V_{dc \, maximum} = \ldots \]

- c) Return the voltage to zero by turning the control knob to its full \textit{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.

\[ V_{ac \, minimum} = \ldots \quad V_{ac \, maximum} = \ldots \]

- c) Return the voltage to zero and turn off the power supply by placing the on-off breaker switch in its "\textit{down}" position.
- 7. What other ac voltages are affected by turning the control knob?

Terminals \ldots and \ldots = \ldots \textit{Vac}

Terminals \ldots and \ldots = \ldots \textit{Vac}

Terminals \ldots and \ldots and \ldots = \ldots \textit{Vac}

- 8. For each of the following conditions:
- a) Connect the 250\textit{Vac} meter across the terminals specified.
- b) Turn on the power supply.
- c) Measure and record the voltage.
- d) Turn off the power supply.

Terminals 1 and 2 = \ldots \textit{Vac}

Terminals 2 and 3 = \ldots \textit{Vac}

Terminals 3 and 1 = \ldots \textit{Vac}

Terminals 1 and N = \ldots \textit{Vac}

Terminals 2 and N = \ldots \textit{Vac}

Terminals 3 and N = \ldots \textit{Vac}

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

- 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 = \ldots \textit{Vdc}

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

- 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.
- c) Return the voltage to zero and turn off the power supply.

Terminals 4 and 5 = \ldots \textit{Vac}

Terminals 5 and 6 = \ldots \textit{Vac}

Terminals 6 and 4 = \ldots \textit{Vac}

Terminals 4 and N = \ldots \textit{Vac}

Terminals 5 and N = \ldots \textit{Vac}

Terminals 6 and N = \ldots \textit{Vac}
This three-phase 735kV transmission line easily spans the Sagueney River.
OBJECT

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 wye two equal resistors and a capacitor to the three terminals of the power source as shown in Fig. 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 20V and 80V as shown in Fig. 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.

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. Fig. 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 it 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.

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.

INSTRUMENTS AND COMPONENTS
Power Supply Module (2)  
(120/208V 3φ, 0-120/208V 3φ)  
Resistance Module  
Capacitance Module  
AC Metering Module  
(250/250/250V)  
Connection Leads  
EMS 8821  
EMS 8311  
EMS 8331  
EMS 8426  
EMS 9128

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

☐ 2-1) Using your EMS resistance, capacitance and metering modules, connect the circuit to the power supply as shown in Fig. 2-3. Set the value of each resistor to 300 ohms, and set the capacitive reactance also to 300 ohms. Note that the three elements are connected in wye to terminals 1-2-3 of the power supply.

☐ 2-2) Measure the voltages $E_1$ and $E_2$.

$$E_1 = \ldots$$

$$E_2 = \ldots$$

☐ 2-3) 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 \ldots

☐ 2-4) 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.

(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).

☐ 2-5) Connect the circuit of Fig. 2-3 to terminals 4-5-6 of the power supply, and determine the phase sequence.

The phase sequence is \ldots

Note: If the sequence is 5-4-6 instead of 4-5-6 follow the procedure given in 2-4. It is much easier to recall a phase sequence of 4-5-6 and in all subsequent experiments we shall assume this sequence).

☐ 2-6) Connect the three voltmeters to power supply terminals 1-4, 2-5, and 3-6, respectively. Rotate the variable auto-transformer completely in the clockwise direction, and turn on the power supply. The three voltmeters should read zero.

Next, rotate the variable auto-transformer completely counterclockwise. The three voltmeters should read about the same and the voltage should be between 110 and 130 volts.

$$E_{14} = \ldots$$

$$E_{25} = \ldots$$

$$E_{36} = \ldots$$

The purpose of this test is to ensure that your power supply is operating correctly.

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

☐ *2-8) In this experiment 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.

* This experiment may be carried out by two collaborating groups.
Repeat this experiment 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 together by transmission lines.

**Fig. 2-4**

**Fig. 2-5**
This control and dispatch center enables station operators to monitor the flow of real and reactive electric power in an area covering thousands of square miles.
OBJECT
1. To interpret the meaning of positive, negative, real and reactive power.
2. 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 (Fig. 3-1) has three input terminals (1, 2, 3) and three output terminals (4, 5, 6).

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 Fig. 3-2, possesses three input terminals (1, 2, 3) and three output terminals (4, 5, 6).

![Three-Phase Wattmeter](image)

Fig. 3-1

![Three-Phase Varmeter](image)

Fig. 3-2

If the wattmeter is connected into a three-phase line, as shown in Fig. 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 Fig. 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.
shown in Fig. 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.

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 Fig. 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:

\[
W_1 = +70\, \text{W} \quad \var_1 = -60\, \text{VAR}
\]
\[
W_2 = -40\, \text{W} \quad \var_2 = -80\, \text{VAR}
\]

How are we to interpret these results? First, we must recognize that real power and reactive power flow quite independently of each other. The 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 \( 70 + 40 = 110 \) watts.

Next, let us look at the reactive power; \( 80 \) \text{VAR} are flowing to the left, towards the impedance \( Z \), while \( 60 \) \text{VAR} are flowing to the left, away from it. It follows that \( Z \) is absorbing \( (80 - 60) = 20 \) \text{VAR}, and this 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.

**INSTRUMENTS AND COMPONENTS**

- Power Supply Module (120/208 V 3φ)  
  EMS 8821
- Resistance Module  
  EMS 8311
- Inductance Module  
  EMS 8321
- Capacitance Module  
  EMS 8331
- AC Metering Module (2.5/2.5/2.5A)  
  EMS 8425
- AC Metering Module (250V)  
  EMS 8426
- Three-Phase Watt-Varmeter Module (300W - 300VAR)  
  EMS 8446
- Connection Leads  
  EMS 9128
- Wound Rotor Induction Motor Module  
  EMS 8231
- Squirrel Cage Induction Motor Module (optional)  
  EMS 8221

**EXPERIMENTS**

Caution: 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 watt-varmeter and a balanced...
three-phase wye connected load. The source is taken from terminals 4, 5, 6 of the power supply, and adjusted to provide a voltage of about 208 volts.

☐ 3-1) Using a load of three 300Ω resistances connected in wye as shown in Fig. 3-5, measure E, I, W, var and record your results in Table 3-1.

☐ 3-2) Replace the resistive load by three inductances having a reactance of 300 ohms, connected in wye. Record your results in Table 3-1.

Note: The leads coming from the source must be connected to terminals 1, 2, 3 of the watt/vatmeter in the order of their phase sequence. If the phase sequence of the power supply is 1-2-3, the variometer 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 variometer reading should be positive. If it is negative, the phase sequence is incorrect and two leads of the source should be interchanged.

☐ 3-3) Repeat Experiment 3-2, using three capacitances having a reactance of 300 ohms, connected in wye. Record your results in Table 3-1.

☐ 3-4) Repeat Experiment 3-3, but add three resistances of 300 ohms (wye connected) in parallel with the capacitive load. Record your results in Table 3-1. Is the real power affected when the capacitive load is switched in and out? Is the reactive power affected when the resistive load is switched in and out? Is the reactive power affected when the resistive load is switched in and out? Is the reactive power affected when the inductive load is switched in and out?

☐ 3-5) Repeat Experiment 3-1, but place the inductive load of Experiment 3-2 in parallel with the resistive load. Record your results in Table 3-1.

Why is the real power slightly affected when the inductive load is switched in and out?

Is the reactive power affected when the resistive load is switched in and out?

☐ 3-6) Repeat Experiment 3-1, but use an inductive load of 300 ohms in parallel with a capacitive load of 300 ohms, all connected in wye. Record your results in Table 3-1. Do you agree that, to all intents and purposes, the capacitance is supplying most of the reactive power required by the inductance?

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

☐ 3-7) Repeat Experiment 3-1, but use a three-phase induction motor at no load in place of the resistive load. Record your results in Table 3-1. Does the motor absorb both real and reactive power?

What does the real power accomplish?

What does the reactive power accomplish?

☐ 3-8) Knowing that the apparent power in volt-amperes (VA) is given by the expression

\[ VA = \sqrt{W^2 + var^2} \]

Calculate the apparent power VA in Table 3-1.
<table>
<thead>
<tr>
<th>EXPERIMENT NO.</th>
<th>LOAD</th>
<th>E (V)</th>
<th>I (A)</th>
<th>W</th>
<th>var</th>
<th>VA</th>
<th>E I \sqrt{3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>3-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-5</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3-6</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>3-7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3-1

3-9) Knowing that the apparent power of a balanced three-phase circuit is given by the equation \( VA = EI / \sqrt{3} \), calculate this power, and compare with the value found in Experiment 3-8.

QUESTIONS AND PROBLEMS

1. An electrical load \( Z \) is connected to the terminals of a 120 volt AC source. Show the direction of real and reactive power flow if \( Z \) is composed of a) a resistance, b) an inductance, c) a capacitance, d) a resistance and inductance, e) a resistance and capacitance, f) a single-phase motor. See Fig. 3-6.

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

Fig. 3-6

3. A three-phase source having a line-to-line voltage of 69kV supplies a wye-connected resistive load having an impedance of 100 ohms per phase. Calculate the real power delivered.
4. Explain what is meant by the statement that an inductor absorbs reactive power while a capacitor supplies reactive power.

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

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

\[
P = \frac{E^2}{Z}
\]
Each phase of this 735kV line is composed of four conductors which are held apart by cross-like spacers.
OBJECT
1. To observe the flow of real and reactive power in a three-phase transmission line with known, passive, loads.
2. 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 stretches 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 line 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 Fig. 4-1.

In high frequency work this is precisely the circuit which has to be used to explain the behavior of a transmission line. Fortunately, at low frequencies of 50Hz or 60Hz, 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 Fig. 4-2.

In Fig. 4-2, the inductance L is equal to the sum of the inductances of Fig. 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 Fig. 4-1. The inductance L and capacitance C can be replaced by their equivalent reactances $X_L$ and $X_C$ as shown in Fig. 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 (Fig. 4-4a).

Medium-voltage and medium-length lines operating, say, at 100KV and several miles 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 Fig. 4-4(b).

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

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

As a matter of interest, typical 60Hz lines have a series reactance of about 0.8 ohm per mile per phase. The shunt capacitive reactance is about 200,000 ohms per mile.*

**INSTRUMENTS AND COMPONENTS**

- Power Supply Module (120/208V 3φ, 0-120/208V 3φ) **EMS 8821**
- Resistance Module **EMS 8311**
- Inductance Module **EMS 8321**
- Three-Phase Transmission Line Module **EMS 8329**
- Capacitance Module **EMS 8331**
- AC Metering Module (250V/250V) **EMS 8426**
- Three-Phase Watt-Varmeter Module (2) (300W/300var) **EMS 8446**
- Connection Leads **EMS 9128**
- Wound Rotor Induction Motor Module (optional) **EMS 8231**
- or Squirrel Cage Induction Motor Module (optional) **EMS 8221**

**EXPERIMENTS**

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


4-1) Connect two watt-varmeters in series to the variable three-phase 208 V power supply and apply a three-phase inductive load of 300 ohms, wye connected, as shown in Fig. 4-5. Adjust the power supply output to 208 V. Particular care should be taken in connecting so that the proper phase sequence is applied to the watt-varmeters.

If the meters are connected as shown, both varmeters should read positive when the polarity reversing switch is in the (+) position. 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.

\[ W_1 = \ldots \quad W_2 = \ldots \]

\[ var_1 = \ldots \quad var_2 = \ldots \]

4-2) Using the variable-voltage AC source, connect the circuit as shown in Fig. 4-6, and set the impedance of the transmission line to 120 ohms. Connect an inductive load of 300 ohms in wye and apply power. All meters should read positive if their polarity switches are in the (+) position. 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 Fig. 4-6.

4-3) With the line on open circuit, adjust the voltage of the source so that the line-to-line voltage...
$E_1$ is 150 volts. (Keep this voltage constant for the remainder of the experiment). Measure $E_1$, $W_1$, $\text{var}_1$, and $E_2$, $W_2$, $\text{var}_2$, and record in Table 4-1.

4-4) Connect a three-phase inductive load of 300 ohms per phase, take readings and record in Table 4-1.

4-5) Apply a three-phase resistive load of 300 ohms per phase, take readings and record in Table 4-1.

4-6) Apply a three-phase capacitive load of 300 ohms per phase, take readings and record in Table 4-1.

4-7) Connect a three-phase induction motor to the receiver end of the line, take readings and record in Table 4-1.

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

4-9) Calculate the real and reactive power which is absorbed by the transmission line in Experiments 4-4, 4-5, 4-6 and record in Table 4-1.

4-10) 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.

<table>
<thead>
<tr>
<th>EXPERIMENT NO.</th>
<th>LOAD</th>
<th>$E_1$ (V)</th>
<th>$W_1$ (W)</th>
<th>$\text{var}_1$ (vars)</th>
<th>$E_2$ (V)</th>
<th>$W_2$ (W)</th>
<th>$\text{var}_2$ (vars)</th>
<th>LINE WATTS</th>
<th>LINE vars</th>
<th>REGULATION (%)</th>
</tr>
</thead>
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<tr>
<td>4-3</td>
<td>OPEN CIRCUIT</td>
<td>150</td>
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<tr>
<td>4-4</td>
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<tr>
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<tr>
<td>4-6</td>
<td>CAPACITIVE</td>
<td>150</td>
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<tr>
<td>4-7</td>
<td>MOTOR</td>
<td>150</td>
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<tr>
<td>4-8</td>
<td>SHORT-CIRCUIT</td>
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</table>

Table 4-1
QUESTIONS AND PROBLEMS

1. A three-phase transmission line having a reactance of 120 ohms per phase is connected to a wye-connected load whose resistance is 160 ohms per phase. If the supply voltage is 70kV 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 which is 300 miles long has a reactance of 240 ohms per phase and a line-to-neutral capacitance of 600 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 $330kV$, what is the line-to-line voltage at the receiver end $R$ when the load is disconnected?

Calculate the reactive power of the source in kvar. Is this power supplied or absorbed by the source?
Power companies are very sensitive to keeping the esthetic beauty of a city. This modern substation blends in well with the surrounding architecture.
OBJECT
1. To regulate the receiver end voltage.
2. To observe the phase angle between the voltages at the sending and the receiving end of the transmission line.
3. 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.

INSTRUMENTS AND COMPONENTS

Power Supply Module
(0-120/208V 3φ) E8821
Resistance Module E8311
Three-Phase Transmission Line Module E8329
Capacitance Module E8331
AC Metering Module
(250V/250V/250V) E8426
Three-Phase Watt-Varimeter (2)
(300W/300var) E8446
Phase Angle Meter E8451
Connection Leads E9128

EXPERIMENTS

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

☐ 5-1) Set the impedance of the transmission line to 120 ohms and connect voltmeters and wattmeters as shown in Fig. 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.

☐ 5-2) Using the power supply control knob, adjust $E_1$ to 200 volts and keep it constant for the remainder of the experiment. Increase the resistive...
<table>
<thead>
<tr>
<th>R (Ω)</th>
<th>E₁ (V)</th>
<th>W₁ (W)</th>
<th>var₁ (var)</th>
<th>E₂ (V)</th>
<th>W₂ (W)</th>
<th>var₂ (var)</th>
<th>ANGLE (°)</th>
</tr>
</thead>
<tbody>
<tr>
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</table>

Table 5-1

load in steps, keeping all three phases balanced. Take readings of $E₁$, $W₁$, $var₁$, $E₂$, $W₂$, $var₂$ and the phase angle between $E₁$ and $E₂$.

Note: $E₁$ is chosen as the reference voltage for the phase-angle meter.

Record your results in Table 5-1, and draw in Fig. 5-2 a graph of $E₂$ as a function of the load power $W₂$, in watts.

On this curve, spot the phase-angle corresponding to the various real power loads $W₂$.

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

☐ 5-3) Now, connect a three-phase balanced capacitive load in parallel with the resistive load. Repeat Experiment 5-2 but for each resistive load adjust the capacitive load so that the load voltage $E₂'$ is as close as possible to 200 volts. ($E₁$ must be kept constant at 200 volts). Record your results in Table 5-2.

Draw a graph of $E₂$ as a function of $W₂$, and superpose it on the previous graph which you drew in Experiment 5-2. Note that the addition of static capacitors has yielded a much more constant voltage, and furthermore, the power $W₂$ which can be delivered has increased.

On this curve, spot the phase angle between $E₂$ and $E₁$ as well as the reactive power $var₂$ which was used for the individual resistive load settings.

☐ 5-4) In this experiment, we shall observe a significant voltage drop along a transmission line even when the voltages $E₁$ and $E₂$ 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 Fig. 5-3, set the load resistance per phase at 171.4 ohms, and with $E₁ = 200$ volts, adjust the capacitive reactance until the load voltage is as close as possible to 200V. Measure $E₁$, $W₁$, $var₁$, $E₂$, $W₂$, $var₂$, $E₃$ and the phase angle.
Using the results of Experiment 5-4, 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 on Page 5-6).
<table>
<thead>
<tr>
<th>R (Ω)</th>
<th>X_C (Ω)</th>
<th>E_1 (V)</th>
<th>W_1 (W)</th>
<th>var_1 (var)</th>
<th>E_2 (V)</th>
<th>W_2 (W)</th>
<th>var_2 (var)</th>
<th>ANGLE (°)</th>
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Table 5-2

![Diagram](image_url)

Fig. 5-3

PHASE ANGLE AND VOLTAGE DROP BETWEEN SENDER AND RECEIVER
SAMPLE CALCULATION

To understand the results of Experiment 5-4, we shall make a brief analysis assuming the following readings.

\[
\begin{align*}
E_1 &= 300V \\
E_2 &= 300V \\
E_3 &= 140V \\
W_1 &= +600W \\
W_2 &= +510W \\
\text{var}_1 &= +170\text{var} \\
\text{var}_2 &= -280\text{var} \\
\text{phase angle} &= 48^\circ \text{ lag}
\end{align*}
\]

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

Real power \( W_2 \) is smaller than \( W_1 \) because of the \( PR \) 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 1/3 of the values indicated above; the per-phase values are therefore as follows:

\[
\begin{align*}
E_1 / \sqrt{3} &= 300 / \sqrt{3} = 173V \\
E_2 / \sqrt{3} &= 300 / \sqrt{3} = 173V \\
E_3 &= 140V \\
W_1 / 3 &= +200W \\
W_2 / 3 &= +170W \\
\text{var}_1 / 3 &= +57\text{var} \\
\text{var}_2 / 3 &= -93\text{var} \\
\text{phase-angle} &= 48^\circ \text{ lag}
\end{align*}
\]

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 141 volts, which is very close to the measured voltage drop \( E_0 \) in the line.

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

The real power consumed by the line due to its resistance is \((200 - 170) = 30\text{ Watts}\).

The apparent power absorbed by the line is

\[ \sqrt{150^2 + 30^2} = 153 \text{ volt-amperes} \]

Since the voltage across one line is 141 volts, the current in the line must be

\[ I = \frac{VA}{E_3} = \frac{153}{141} = 1.08A \]

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.
QUESTIONS AND PROBLEMS

1. A three-phase transmission line has a reactance of 100 ohms per phase. The sender voltage is 100kV and the receiver voltage is also regulated to be 100kV by placing a bank of static capacitors in parallel with the receiver load of 50MW.

   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 50MW load in Problem 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? Explain.
An aerial view of the Manicouagan Power Station No. 2. The dam is 310 feet high, 2270 feet wide and the water falls through a height of 237 feet.
OBJECT

1. 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.

3. 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 Fig. 6-1 a transmission line having a reactance of \( X \) ohms (per phase) has voltages \( E_1 \) and \( E_2 \) at each end. 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 \( E_2 \) possess any values and any relative phase angle, we can cover all possible loading conditions which may occur.

Referring to Fig. 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:

\[
I = \frac{E_1-E_2}{X}
\]

(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).

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 ohms
- **Sender voltage** = 20 kV
- **Receiver voltage** = 30 kV

Receiver voltage lags behind sender voltage 26.5 degrees.

These line conditions are represented schematically in Fig. 6-2. From the phasor diagram, on Fig. 6-3, 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 \( \Omega \) = 150 A and it lags behind \( (E_1-E_2) \) by 90 degrees. From the geometry of the figure, we find that the current leads \( E_1 \) by 27
degrees. The active and reactive power of the sender and the receiver can now be found.

**Real Power delivered by the sender**

\[ 150A \times 20kV \times \cos(-27°) = +2670kW. \]

**Real Power received by the receiver**

\[ 150A \times 30kV \times \cos(-53.5°) = +2670kW. \]

**Reactive Power delivered by the sender**

\[ 150A \times 20kV \times \sin(-27°) = -1360kvar. \]

**Reactive Power received by the receiver**

\[ 150A \times 30kV \times \sin(-53.5°) = -3610kvar. \]

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 degrees, the angle is negative.

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 Fig. 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.

However, reactive power is flowing from receiver to sender and, during transit, \((3610-1360) = 2250kvar\) are consumed in the transmission line. This reactive power can be checked against Line kvar \( = I^2 X = 150^2 \times 100 = 2250kvar. \) 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 30kV and 20kV respectively and the line reactance is 100 ohms (Fig. 6-5).

The voltage drop in the line is 10kV, and the current is \( 10kV/100 = 100A \) as shown in Fig. 6-6.
The real power delivered by the sender end = $100A \times 30kV \times \cos (+90^\circ) = 0W$.

The real power received by the receiver = $100A \times 20kV \times \cos (+90^\circ) = 0W$.

The reactive power delivered by the sender end = $100A \times 30kV \times \sin (+90^\circ) = +3000kvar$.

The reactive power received by the receiver = $100A \times 20kV \times \sin (+90^\circ) = +2000kvar$.

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

Reactive power flows from the sender to the receiver, and $100kvar$ 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 degrees. 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 $30kV$ and the receiver voltage lags behind the sender by 30 degrees. The line reactance is $100 \text{ ohms}$, and the circuit is shown in Fig. 6-8.

The voltage drop in the line ($E_1 - E_2$) is found to be $15.5kV$, so the current $I = 15500/100 = 155A$ and lags 90 degrees behind, as shown in Fig. 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.

**SENDER END**

Real Power delivered =

$30kV \times 155A \times \cos (+15^\circ) = +4500kW$. 

LABORATORY EXPERIMENT NO. 6
Reactive Power delivered = 
30kV × 155A × sin (+15°) = +1200 kvar.

RECEIVER END

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

Reactive Power received = 
30kV × 155A × 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.

INSTRUMENTS AND COMPONENTS

Power Supply Module (2)  
(120/208V 3φ 0-120/208 3φ)  
EMS 8821
Resistance Module  
EMS 8311
Inductance Module  
EMS 8321
Three-Phase Transmission Line Module  
EMS 8329
Capacitance Module  
EMS 8331
Three-Phase Buck-Boost and Phase Shift Transformer Module  
EMS 8349
AC Metering Module (250V/250V)  
EMS 8426
Three-Phase Watt-Varmeter Module (2)  
(300W-3000W)  
EMS 8446
Phase Angle Meter Module  
EMS 8451
Connection Leads  
EMS 9128

EXPERIMENTS*

Caution: 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

- 6-1) Connect a three phase transmission line between the terminals 4, 5, 6 (variable AC output) of two consoles, one of which is designated as station A and the other, station B. Connect wattmeters, varmeters, voltimeters at each end as well as a phase angle meter as shown schematically in Fig. 6-11.

- 6-2) With the transmission line switch S open, set the line-to-line voltages $E_1 = E_2 = 180V$ 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 Experiment 2-8.

Phase angle is zero:  □ yes   □ no

- 6-3) 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) □ (lead)

- 6-4) 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) □ (lead)

* These experiments may be carried out by two collaborating groups.
6-5) Measure the phase angle between terminals 4-5 of station A and terminals 6-4 of station B.

Phase angle = 

6-6) 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 Fig. 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.

6-7) Close the transmission line switch; with \( E_1 = E_2 = 180V \), and the transmission line impedance = 60 ohms, observe the watt-meter readings. There should be no significant power exchange.

\[
\begin{align*}
W_1 &= \\
W_2 &=
\end{align*}
\]

6-8) Raise station A voltage to 200V and observe power flow.

\[
\begin{align*}
var_1 &= \\
var_2 &=
\end{align*}
\]

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

6-9) Reduce station A voltage to 160V and observe power flow.

\[
\begin{align*}
W_1 &= \\
W_2 &=
\end{align*}
\]
\[ \text{var}_1 = \quad \text{var}_2 = \quad \]

Which station would be considered to be the sender? 

- **6-10** 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**

A phase shift transformer (EMS module 8349) will be used to shift the phase of station A by 15 degrees. 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 degrees or, c) lead the primary by 15 degrees.

- **6-11** Connect the phase-shift transformer to fixed AC terminals 4, 5, 6 of station A. Adjust voltage at stations A and B to 208 V, with the phase angle meter, determine the phase angle of the secondary voltage 4, 5, 6 with respect to variable AC terminals 4, 5, 6 of the power supply of station B (see Fig. 6-13). Record your readings for the three positions of the phase-shift tap-switch in 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.

- **6-12** Check that the phase-shift is the same for all three phases, and that all voltages are balanced.

<table>
<thead>
<tr>
<th>TAP SWITCH POSITION</th>
<th>PHASE ANGLE (LAG/LEAD)</th>
<th>( E_1 ) (V)</th>
<th>( E_2 ) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+15°</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-15°</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 6-1**

- **6-13** Connect a three-phase, 120 ohm transmission line between secondary terminals 4, 5, 6 of the phase shift transformer and power supply terminals of station B (See Fig. 6-14). After inserting watt-vomets at each end of the line, change the tap-switch position of the phase-shift transformer and record your results in 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?

**SENDER AND RECEIVER VOLTAGES UNEQUAL AND OUT OF PHASE**

In the following experiments we shall connect passive loads (resistance, inductance and capacitance) 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. 

- **6-14** Using only one console, set up the experiment as shown in Fig. 6-15, setting \( E_1 = 200V \) and using a wye connected resistive load of 300Ω per phase and a 60 ohm transmission line. Take readings and record your results in Table 6-3.
6-15) Repeat Experiment 6-14 using an inductive load of 300 ohms/phase. Take readings and record your results in Table 6-3.

6-16) Repeat Experiment 6-14 using a capacitive load of 300 ohms/phase. Take readings and record your results in Table 6-3.

Table 6-2

<table>
<thead>
<tr>
<th>TAP SWITCH POSITION</th>
<th>$E_1$ (V)</th>
<th>$W_1$ (W)</th>
<th>var$_1$ (var)</th>
<th>$E_2$ (V)</th>
<th>$W_2$ (W)</th>
<th>var$_2$ (var)</th>
<th>PHASE ANGLE ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXP.NO. 6-13</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0^\circ$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$+15^\circ$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$-15^\circ$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-3

<table>
<thead>
<tr>
<th>EXP. NO.</th>
<th>LOAD</th>
<th>$E_1$ (V)</th>
<th>$W_1$ (W)</th>
<th>var$_1$ (var)</th>
<th>$E_2$ (V)</th>
<th>$W_2$ (W)</th>
<th>var$_2$ (var)</th>
<th>PHASE SHIFT ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-14</td>
<td>RESISTIVE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-15</td>
<td>INDUCTIVE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6-16</td>
<td>CAPACITIVE</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
QUESTIONS AND PROBLEMS

1. A three-phase transmission line has a reactance of 100 ohms 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.

<table>
<thead>
<tr>
<th>$E_s$ (kV)</th>
<th>$E_r$ (kV)</th>
<th>PHASE ANGLE</th>
<th>SENDER</th>
<th>RECIPIENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>100</td>
<td>60° $E_s$ leads $E_r$</td>
<td>MW</td>
<td>Mvar</td>
</tr>
<tr>
<td>120</td>
<td>100</td>
<td>60° $E_s$ leads $E_r$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>120</td>
<td>60° $E_s$ leads $E_r$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>100</td>
<td>30° $E_s$ lags $E_r$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120</td>
<td>100</td>
<td>0°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-4

2. In Problem 1 assume that $E_s = E_r = 100kV$ 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.

<table>
<thead>
<tr>
<th>$\theta$</th>
<th>MW SENDER</th>
<th>MW RECEIVER</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>60°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>90°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>120°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>150°</td>
<td></td>
<td></td>
</tr>
<tr>
<td>180°</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 6-5

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.

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

Is there a limit to the maximum power which such a line can deliver under the static voltage conditions?
Fig. 6-16
LABORATORY EXPERIMENT NO. 7

PARALLEL LINES, TRANSFORMERS AND POWER-HANDLING CAPACITY

Two three-phase lines side by side enable a larger power flow and improve stability of the system.
OBJECT
1. Study of the real power vs phase angle curve of a transmission line.
2. Use of transformers to increase the power-handling capacity of a line.
3. 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.

$$ P = \frac{E_1 E_2 \sin \theta}{X} $$

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.
- $\theta$ = phase angle between $E_1$ and $E_2$.

If $E_2$ lags behind $E_1$, $\theta$ is positive.

If $E_2$ leads $E_1$, $\theta$ is negative.

The use of this equation is best illustrated by a simple example. On Fig. 7-1 a line having a reactance of 100 ohms 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 degrees, calculate the total power delivered by the three-phase line.

Solution:

Because the sender voltage leads the receiver voltage, the angle $\theta$ is positive, hence:

$$ P = \frac{E_1 E_2 \sin \theta}{X} $$

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

$$ = 90,000,000W $$

$$ = 90MW. $$

If the sender and receiver voltages are held constant (a situation which is closely met in practice), the power delivered will depend exclusively upon the phase angle $\theta$. This relationship between the power $P$ and the angle $\theta$ is given in Fig. 7-2.

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

As we can see from the figure, if the phase angle exceeds 90 degrees, 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 degrees.

When the phase angle exceeds 90 degrees, 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 90º) 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 degrees. The maximum power which can be transmitted is

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

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

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

If the angle is between zero and $+180$ degrees the sender is delivering power to the receiver, but when the angle is between zero and $-180$ degrees, the receiver is delivering power to the sender. Note that an angle of $-90$ degrees merely indicates that $E_2$ is leading $E_1$. The stable region is between $-90$ and $+90$ degrees; 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 $P_{\text{max}} = \frac{E^2}{X}$ watts.
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 Fig. 7-4(a), a sender and a receiver are connected by a line having a reactance of 100 ohms. The maximum power which can be transmitted is

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

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

$$P_{\text{max}} = \frac{200kV \times 200kV}{100} = 400\text{MW}$$

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 Fig. 7-5). The power curves for one line and for two lines are shown in Fig. 7-6. If both lines are in service and the power transmitted is $0.5P_{\text{max}}$, the phase angle between the sender and receiver voltages is only 30 degrees, which corresponds to a very stable operating point. The link between $S$ and $R$ is said to be "stiff".

---

**Fig. 7-4**

**Fig. 7-5**

**Fig. 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 Fig. 7-6, 0.5Pmax corresponds, on the single transmission line, to an angle of 90 degrees which is just on the edge of instability. 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.

INSTRUMENTS AND COMPONENTS

- Power Supply Module (2) (120-208V 3φ) EMS 8811
- Synchronous Motor/Generator EMS 8241
- Three-Phase Transmission Line Module EMS 8329
- Three-Phase Transformer Module (2) EMS 8348
- Three-Phase Buck-Boost and Phase-Shift Transformer Module EMS 8349
- AC Metering Module (2) (250V/250V) EMS 8426
- Three-Phase Watt-Var meter Module (2) (300W-300var) EMS 8446
- Flywheel EMS 8915
- Connection Leads EMS 9128

EXPERIMENTS

Caution: 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 part comprises a laboratory experience.

- 7-1) On Fig. 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.

- 7-2) In Problem 7-1, calculate the maximum power which could be transported at the given voltages E1 and E2 and write your results in Table 7-1.

- 7-3) Either by trigonometry or by scaling off the vector diagrams, calculate the line current in parts 2 to 6 of Problem 7-1.

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.

<table>
<thead>
<tr>
<th>N°</th>
<th>E1 (kV)</th>
<th>E2 (kV)</th>
<th>X (Ω)</th>
<th>θ (°)</th>
<th>LAG OR LEAD</th>
<th>P (kW)</th>
<th>DIRECTION OF POWER FLOW</th>
<th>Pmax (kW)</th>
<th>LINE CURRENT (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>4</td>
<td>80</td>
<td>30</td>
<td>E1 leads E2</td>
<td>100</td>
<td>A → B</td>
<td>200</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>8</td>
<td>80</td>
<td>30</td>
<td>E1 leads E2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>6</td>
<td>80</td>
<td>45</td>
<td>E1 lags E2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>6</td>
<td>80</td>
<td>45</td>
<td>E2 lags E1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>6</td>
<td>80</td>
<td>120</td>
<td>E2 leads E1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>4</td>
<td>12</td>
<td>80</td>
<td>60</td>
<td>E1 leads E2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7-1
7-4) Two parallel transmission lines operating at a three-phase line-to-line voltage of 120kV each, have a line reactance of 60 ohms. If the total power delivered is 84MW, 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?

\[ W_2 = \ldots \]

\[ \varphi_1 = \ldots \]

\[ \varphi_2 = \ldots \]

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

Caution: High voltages are present in this experiment: 360V 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 wye-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.

Measure the new real power which is transmitted and compare it with the values found in Experiment 7-5. Explain your results.

\[ E_1 = \ldots \quad E_2 = \ldots \]

* Experiments 7-5 to 7-8 may be carried out by two collaborating groups.

7-5) Using two independent power supplies and a phase-shift transformer, set the line reactance to 180 ohms and measure the real power flow when the phase-shift is +15 degrees (Fig. 7-8). Adjust the voltage of the power supply to 208 V.

\[ E_1 = \ldots \]

\[ E_2 = \ldots \]

\[ W_1 = \ldots \]
7-7) 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 horsepower. Consequently, large motors accelerate much more slowly than small motors do. A ¾ hp motor can reach top speed in a fraction of a second when power is applied, whereas a 10,000 hp motor may take several minutes.

In order for a ¾ hp machine to exhibit the mechanical properties of a much larger machine, we must increase its inertia artificially. This we can do by adding a flywheel. The flywheel used in this electric power transmission system endows the ¾ hp machine with 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 No. 13.

7-8) Now, at the sender and receiver end of the 180 ohm transmission line, insert step-up and step-down transformers connected in delta-wye and wye-delta respectively (See Fig. 7-11). Repeat the same procedure as in Experiment 7-7.

a) Open circuit

b) Starting of the synchronous motor.

Acceleration time $T = \ldots$

Measure $E$, $W$, $\text{var}$ at the end of acceleration period.

$E = \ldots$

$W = \ldots$

$\text{var} = \ldots$

---

Fig. 7-10

PARALLEL LINES, TRANSFORMERS AND POWER-HANDLING CAPACITY
\[ E = \ldots \]
\[ W = \ldots \]
\[ \text{var} = \ldots \]

Compare your results with the values found in Experiment 7-7.

Although the open circuit voltages are about the same, explain why the motor starts more quickly in Experiment 7-8.

---

**QUESTIONS AND PROBLEMS**

1. a) A 3-phase transmission line operating at 300kV has a line reactance of 200 ohms 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 degree? 2 degrees? 4 degrees? 8 degrees? 16 degrees? 32 degrees?

---

2. a) In Problem 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?

---

3. If the transmission line voltage in Problem 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 ohms and 200 ohms 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 100kV?

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

   If the 200 ohm line is suddenly knocked out of service, what will the new phase angle become?

   c) In Problem 4(b), if the 100 ohm 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 170MVA water wheel alternator into its stator is a delicate and time-consuming task.
OBJECT
1. To understand the basic operation of an alternator.
2. To measure the synchronous reactance of an alternator.
3. 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 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 Fig. 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 Fig. 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.

As shown in Fig. 8-3, 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.

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 here.

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.

INSTRUMENTS AND COMPONENTS

Power Supply Module (120Vdc, 0-120Vdc) EMS 8821
DC Motor/Generator Module EMS 8211
Synchronous Motor/Generator Module EMS 8241
Resistance Module EMS 8311
Inductance Module EMS 8321
Capacitance Module EMS 8331
DC Metering Module (0.5/2.5A) EMS 8412
AC Metering Module (2.5/2.5/2.5A) EMS 8425
AC Metering Module (100/250V) EMS 8426
Three-Phase Watt-Varmeter Module 300 W-300 var EMS 8446
Strobe Light EMS 8922
Timing Belt EMS 8942
Connection Leads EMS 9128

EXPERIMENTS

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

☐ 8-1) 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 Fig. 8-4, and mechanically couple the DC shunt-connected motor to the alternator by means of a timing belt. Connect AC voltmeter $E_o$ from line to neutral of one phase of the alternator and connect a DC ammeter to measure the exciting current $I_F$.

Apply power and, using the strobe light, adjust the speed of the DC motor to 1800r/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.

☐ 8-2) Find the phase sequence of the generated voltage, with regard to terminals 1, 2, 3.

The phase sequence is

Note: If the phase sequence is not 1-2-3-1-2-3, etc, reverse direction of rotation of the DC motor.

☐ 8-3) Using the same set-up as in Fig. 8-4,
adjust the open-circuit voltage $E_o$ to 120 volts. Then short-circuit the stator terminals through three AC ammeters and take their average reading $I$ (see Fig. 8-5).

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

- $E_o = 120V$  $I =$  $X =$  

☐ 8-4) Repeat Experiment 8-3 with $E_o = 140V$ and then with $E_o = 100V$.

![Fig. 8-5](image)

- $E_o = 140V$  $I =$  $X =$  

- $E_o = 100V$  $I =$  $X =$  

☐ 8-5) Voltage regulation

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

Using the same set-up as in Fig. 8-4, connect a resistive load to the generator terminals and introduce a watt-vameter and a voltmeter $E_L$ as shown in Fig. 8-6.

Adjust the exciting current $I_F$ of the alternator so that the open-circuit voltage $E_L = 208$ volts. 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.

☐ 8-6) Repeat Experiment 8-5, using an inductive load in place of the resistance, and record your results in Table 8-3.

☐ 8-7) Repeat Experiment 8-5, using a capacitive load in place 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).

QUESTIONS AND PROBLEMS

1. A 150MW alternator generates an open-circuit line-to-line voltage of 12kV at nominal DC excitation. When the terminals are placed in short-circuit the resulting current per phase is 8000A.
   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 alternator in Problem 1 supplies a resistive load of 120MW at a voltage of 12kV, what must be the induced voltage $E_o$?

   

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

   

LABORATORY EXPERIMENT NO. 8
Fig. 8-6

<table>
<thead>
<tr>
<th>R/PHASE (Ω)</th>
<th>I_F (A)</th>
<th>E_L (V)</th>
<th>W</th>
<th>var</th>
<th>\sqrt{(W)^2 + (var)^2} (VA)</th>
</tr>
</thead>
<tbody>
<tr>
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Table 8-2
### Voltage Regulation with Inductive Load

<table>
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<tr>
<th>$X_L/PHASE (\Omega)$</th>
<th>$I_F$ (A)</th>
<th>$E_L$ (V)</th>
<th>$W$</th>
<th>var</th>
<th>$\sqrt{(W)^2 + (\text{var})^2}$ (VA)</th>
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*Table 8-3*

### Voltage Regulation with Capacitive Load

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<th>$I_F$ (A)</th>
<th>$E_L$ (V)</th>
<th>$W$</th>
<th>var</th>
<th>$\sqrt{(W)^2 + (\text{var})^2}$ (VA)</th>
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<tbody>
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*Table 8-4*
View of a 300HP, 2200V, 327 rev/min Synchronous Motor.
OBJECT

1. 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. An 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 Fig. 9-1 is considered to be one phase of the infinite bus.

The circuit of Fig. 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 $(E_s E_o) / X_r$.

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 degrees, 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.

INSTRUMENTS AND COMPONENTS

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Code</th>
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<tbody>
<tr>
<td>Power Supply Module</td>
<td>EMS 8821</td>
</tr>
<tr>
<td>DC Motor/Generator Module</td>
<td>EMS 8211</td>
</tr>
<tr>
<td>Synchronous Motor/Generator Module</td>
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</tr>
<tr>
<td>Resistance Module</td>
<td>EMS 8311</td>
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<tr>
<td>DC Metering Module</td>
<td>EMS 8412</td>
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<tr>
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<td>EMS 8922</td>
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<td>Timing Belt</td>
<td>EMS 8942</td>
</tr>
<tr>
<td>Connection Leads</td>
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</table>

EXPERIMENTS

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

☐ 9-1) Excitation and reactive power flow
Set up the experiment of Fig. 9-2, connecting the stator to the fixed AC supply via the watt-varmeter and three AC ammeters. The field of the synchronous motor is connected to the variable DC source, in series with a DC ammeter.

Note: The DC field should only be applied once

<table>
<thead>
<tr>
<th>VARIATION OF EXCITING VOLTAGE</th>
<th>REAL POWER AND LOADING</th>
</tr>
</thead>
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<td>$I_F$ (A)</td>
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Table 9-1

Table 9-2

THE SYNCHRONOUS MOTOR
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 0.1A and increase it in steps to 0.7A and record your results in Table 9-1. Be sure to record the values of the particular case where \( \text{var} = 0 \).

- 9-2) Loading and real power

Couple a dc shunt generator to the synchronous motor as shown on Fig. 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.

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

- 9-3) Repeat Experiment 9-2, but this time observe the position of the rotor with a strobe light as the load increases. The changing position of the rotor is the root cause of the increasing phase angle between \( E_s \) and \( E_o \).

- 9-4) Repeat Experiment 9-2, and this time record your results in Table 9-2.

QUESTIONS AND PROBLEMS

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

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

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

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

3. a) In Problem 2 if the excitation voltage \( E_o \) is equal to the terminal voltage (4kV), 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 2000kW?
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 Problem 2 is at the end of a transmission line which has a reactance of 8 ohms per phase, what is the maximum power which the machine can develop, given that the sender voltage is 4kV and the induced voltage $E_o$ is also 4kV (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 degrees?

Between which two voltages is the angle equal to 90 degrees when peak power has been attained?
Large hydrogen cooled synchronous condenser to control the flow of reactive power. Installed in Duvernay, Quebec.
OBJECT
1. To show how a synchronous condenser can regulate the receiver voltage.
2. 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 reactive power. In essence, it acts either 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 called a synchronous condenser. A better term might have been "synchronous condenser/inductor"; but because these machines must usually supply reactive power to a power system rather than absorb it, the term "condenser" 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 condenser.

Long high-voltage transmission lines have significant capacitance in addition to their inductance. Typically, the capacitive reactance per mile is 200,000 ohms and the inductive reactance is 0.8 ohm on a 60 cycle line. This means that for a line which is 150 miles long, the inductance per phase is 120 ohms and the capacitive reactance is 1333 ohms. The simplified circuit of such a line may be represented by Fig. 10-1, in which the line capacitance is "lumped" in the center of the line instead of being distributed over its entire length. When a line is fed by a sender voltage \( E_s \), the open-circuit receiver voltage \( E_r \) will be considerably higher.

Thus, in the simplified circuit of Fig. 10-1, if the sender voltage \( E_s = 300kV \), the voltage \( E_r \) will be about \( 314kV \), 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 presented economically by connecting an inductive load at the receiver terminals. The synchronous condenser is admirably suited to this purpose, for it behaves as an inductance when it is under-excited.

The synchronous condenser can, therefore, be employed to raise the voltage when the loading is high, and to lower the voltage when the loading is light.

INSTRUMENTS AND COMPONENTS
Power Supply Module
(120-208V 3φ, 0-120Vdc) \( \text{EMS 8821} \)
Synchronous Motor/Generator Module \( \text{EMS 8241} \)
Resistance Module \( \text{EMS 8311} \)
Capacitance Module \( \text{EMS 8331} \)
Three-Phase Transmission Line
Module (2) \( \text{EMS 8329} \)
Three-Phase Transformer Module (2) \( \text{EMS 8348} \)
DC Metering Module
(0.5/2.5A) \( \text{EMS 8412} \)
AC Metering Module
(250V/250V) \( \text{EMS 8426} \)
Three-Phase Watt-Varmeter (2)
(300W-300var) \( \text{EMS 8446} \)
Connection Leads (2) \( \text{EMS 9128} \)

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

☐ 10-1) Connect the synchronous machine to the end of a three-phase 120 ohm transmission line and, with no DC excitation on the machine, apply power to the sending end using the 3-phase supply. Adjust to 208 V. Once the synchronous condenser is up to speed, apply DC excitation. (See Fig. 10-2).

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

☐ 10-2) Take readings of \( W_1 \), \( \text{var}_1 \), \( E_1 \) and \( W_2 \), \( \text{var}_2 \), \( E_2 \) as the DC excitation \( I_F \) is varied from zero to 0.8A. Record your results in Table 10-1, and draw a graph of \( E_2 \) as a function of \( \text{var}_2 \) on Fig. 10-3. What is the effect upon \( \text{var}_1 \) as the excitation is varied?
10-3) Repeat Experiment 10-2 with a line of 60 ohms. Record your results in Table 10-2, and draw a graph of $E_2$ as a function of $\text{var}_2$ on Fig. 10-4. You will note that the voltage cannot be
### VOLTAGE REGULATION 60Ω LINE

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<tr>
<th>(I_F) (A)</th>
<th>(W_1) (W)</th>
<th>(\text{var}_1) (var)</th>
<th>(E_1) (V)</th>
<th>(W_2) (W)</th>
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**Table 10-2**
regulated over as wide a range when the transmission line impedance is lower.

10-4) Connect a balanced resistive load at the receiving end of the 120 ohm line and maintain the receiver end voltage at 210 volts, while the resistance is being varied. Take readings of \( W_1, \text{var}_1, E_1 \) and \( W_2, \text{var}_2, E_2 \) and record your results in Table 10-3. Is there a limit to the ability of the synchronous condenser to regulate the line voltage? On Fig. 10-5 draw a graph of real power to the load vs \text{var} of the synchronous condenser at a receiver voltage of 210 volts.

10-5) Using two transmission lines in series, each set at 60 ohms, connect a capacitive reactance of 1200 ohms so as to simulate a 3-phase line which is about 150 miles long. (See Fig. 10-6).

Apply power to the sending end using the variable 3-phase supply adjusted to 208 V and measure \( E_s \) and \( E_r \) on open-circuit.

\[
E_s = \quad E_r =
\]

10-6) Connect a synchronous condenser 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 condenser must absorb to make the receiver voltage equal to the sender voltage.

\[
\text{var} =
\]

10-7) Set up the circuit of a 300 mile high-voltage line (the circuit per phase is shown in Fig. 10-7) using two 120 ohm lines in series, and a capacitive reactance (line-to-neutral) of 600 ohms. Use the same set-up as in Procedure 10-5.

Apply power to the sending end using the fixed 3-phase supply and measure \( E_s \) and \( E_r \) on open-circuit.

\[
E_s = \quad E_r =
\]

Then connect the synchronous condenser 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 \( E_s = E_r \).

\[
\text{var} =
\]
## VOLTAGE REGULATION
### 120Ω LINE AND RESISTIVE LOAD

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<th>I_F (A)</th>
<th>W_1 (W)</th>
<th>var_1 (var)</th>
<th>E_1 (V)</th>
<th>W_2 (W)</th>
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</table>

*Table 10-3*

![Graph of W2 vs. var2](image)

*Fig. 10-5*
QUESTIONS AND PROBLEMS

1. What are some of the advantages of a synchronous condenser over static condensers 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."

THE SYNCHRONOUS CONDENSER AND LONG HIGH VOLTAGE LINES 10-7
4. A 100-mile, 300kV, 60Hz transmission line has a reactance of 0.8 ohm per mile and a distributed capacitance of 200,000 ohms per mile. 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 150MW alternator having a nominal voltage of 12kV and a synchronous reactance of 4 ohms is connected to the transmission line of Problem 4 via a step-up transformer having a ratio of 12kV/300kV. If the excitation voltage \( E_e \) is adjusted to 12kV (line-to-line) calculate the voltages \( E_T \) and \( E_R \) at the terminals of the alternator and at the end of the transmission line. (See Fig. 10-8).

Are there any dangers associated with the resonance effects of distributed line capacitance and the synchronous reactance of an alternator?
Three-phase, oil-filled, fan-cooled phase-shift transformer. Line to line voltage is 300kV.
The principle of the phase-shift transformer can be understood by referring to Fig. 11-2, which shows the primary windings \( a_1, b_1, c_1 \) of a three-phase wye-connected transformer. Secondary windings \( a_2, b_2, c_2 \) are also connected in wye, but secondary windings \( a_3, b_3, c_3 \) are not yet connected together. Voltages induced 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 in \( c_1, c_2, c_3 \). However, these three groups of voltages are respectively 120 degrees out of phase with each other, as shown in Fig. 11-3.

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.

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.
If windings $a_2$, $b_2$, $c_2$ and $a_3$, $b_3$, $c_3$ 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 Fig. 11-3. However, if we connect in series windings $a_2$, $b_2$, $c_2$, and $a_3$, $b_3$, $c_3$, the phasor diagram will be as shown in Fig. 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 degrees).

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 degrees. Furthermore, provision can be made so that the phase angle can be progressively changed from lagging to leading and vice-versa.

Referring to Fig. 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 $L_2$-$L_3$.

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 the end-points $L_2$ 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 phase-shift and buck-boost transformer.

**INSTRUMENTS AND COMPONENTS**

- Power Supply Module (0-120/208V 3φ)  
  *EMS 8821*
- Resistance Module  
  *EMS 8311*
- Inductance Module  
  *EMS 8321*
- Three-Phase Transmission Line Module (2)  
  *EMS 8329*
- Buck-Boost, Phase-Shift Transformer Module  
  *EMS 8349*
- AC Metering Module (250V/250V/250V)  
  *EMS 8426*
- Three-Phase Watt-Varneter Module (2) (300W-300var)  
  *EMS 8446*
- Phase Angle Meter Module  
  *EMS 8451*
- Connection Leads  
  *EMS 9128*

**EXPERIMENTS**

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

**11-1)** With the variable three-phase AC source set at 200 volts connect the phase-shift auto-transformer as shown schematically in Fig. 11-5. Change the setting of the buck-boost 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...


<table>
<thead>
<tr>
<th>SETTING</th>
<th>READING</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUCK BOOST</td>
<td>PHASE SHIFT</td>
</tr>
<tr>
<td>0</td>
<td>0°</td>
</tr>
<tr>
<td>0</td>
<td>+15°</td>
</tr>
<tr>
<td>0</td>
<td>-15°</td>
</tr>
<tr>
<td>-15%</td>
<td>0°</td>
</tr>
<tr>
<td>-15%</td>
<td>+15°</td>
</tr>
<tr>
<td>-15%</td>
<td>-15°</td>
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<tr>
<td>+15%</td>
<td>0°</td>
</tr>
<tr>
<td>+15%</td>
<td>+15°</td>
</tr>
<tr>
<td>+15%</td>
<td>-15°</td>
</tr>
</tbody>
</table>

Table 11-1

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.

11-2) Set up the circuit of Fig. 11-6, using two transmission lines in parallel feeding a wye-connected resistive-inductive load of 300 ohms. Set both transmission line impedances at 60 ohms, and adjust $E_1$ to 200 V. Note that each line carries the same amount of real and reactive power when there is no phase-shift or 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.

11-3) Repeat Experiment 11-2 with line 1 set to zero impedance and record your results in Table 11-2. 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.

11-4) Repeat Experiment 11-2 using two lines of 180 ohms 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.

QUESTIONS AND PROBLEMS

1. On Fig. 11-7 two transmission lines having
<table>
<thead>
<tr>
<th>SETTING</th>
<th>MEASUREMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>LINE 1 IMP (Ω)</td>
</tr>
<tr>
<td>11-2</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
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<tr>
<td></td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>60</td>
</tr>
</tbody>
</table>

Table 11-2

reactances per phase of 100 ohms and 200 ohms are connected in parallel. A phase-shift transformer $T_1$ is introduced into the 200 ohm line, close to the receiver, in order that the real power be divided equally between the two lines. If the sender and receiver voltages are both 100kV line-
2. In Problem 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 Problem 1 increase the maximum power which the 200 ohm line can deliver?

4.* In the circuit of Fig. 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 $50MW$, calculate a) the phase-shift of $T_1$ and b) the voltage ratio of $T_2$. 

This is an engineering problem.

11-6

LABORATORY EXPERIMENT NO.11
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.
OBJECT
1. To observe the behavior of a synchronous motor under load.
2. To observe the mechanical shift of the rotor as the load is increased.
3. To determine the load limit of the motor.
4. 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 Fig. 12-1, in which $X$ is the synchronous reactance, $E_o$ the voltage induced by the flux from the rotor and $E_I$ is the supply voltage.

![Fig. 12-1](image)

Just as for a transmission line circuit, the real power delivered to the motor is given by the equation

$$P = \frac{E_I E_o \sin \theta}{X}$$

where $\theta$ is the phase angle between $E_I$ and $E_o$. The maximum power which the motor can receive is, therefore, $E_I E_o/X$ and this occurs when $\theta = 90$ degrees. The mechanical power output will be slightly less owing to the losses in the motor.

How does the angle $\theta$ 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 $E_I$ as the mechanical load rises. This pole shift is observable with a synchronized strobe light.

Owing to the equation $P = \frac{E_I E_o \sin \theta}{X}$ it can be seen that for a given power $P$ and supply voltage $E_I$, the phase angle $\theta$ will increase if the DC excitation is lowered. If the field is reduced sufficiently, $\theta$ will approach 90 degrees 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 degrees—usually around 70 degrees. This is due to the reluctance torque created by the saliency of the 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 $X_1$ ohms to which is connected a synchronous motor having a synchronous reactance of $X_2$ ohms and an induced voltage $E_o$, as shown in Fig. 12-2.

![Fig. 12-2](image)

The power which can be transmitted from the source $E_I$ to the synchronous motor is again given by the equation $P = \frac{E_I E_o \sin \theta}{(X_1 + X_2)}$, where $\theta$ is the phase angle between $E_I$ and $E_o$. The maximum power which can be transmitted is therefore $P_{max} = E_I E_o/(X_1 + X_2)$, and this occurs when $\theta = 90$ degrees. On the other hand, the power delivered to the motor is also given by:

$$P = \frac{E_2 E_o}{X} \sin \alpha$$

where $E_2$ is the terminal voltage and $\alpha$ the angle between $E_2$ and $E_o$. Since $E_2$ must lie between the phasors $E_I$ and $E_o$ (see Fig. 12-3), it is obvious that when maximum power is being delivered, angle $\alpha$ is less than 90 degrees. In other words, the motor will pull out of synchronism before the angle between $E_2$ and $E_o$ has attained 90 degrees.

But how can this be? It is because a synchronous motor attains its maximum power at $\alpha = 90$ degrees, provided that $E_o$ and the terminal voltage $E_2$ are fixed. 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 $\alpha$ has reached 90 degrees. (See Fig. 12-3 (b).) By trigonometry it is possible to show that the value of $\alpha$ when the power is maximum is given by the equation

$$\tan \alpha = \left(\frac{X_2}{X_1}\right) \left(\frac{E_1}{E_0}\right)$$

Thus if $X_1 = X_2$ and $E_1 = E_0$, $\tan \alpha = 1$ and $\alpha$ is 45 degrees.

**INSTRUMENTS AND COMPONENTS**

- Power Supply Module $(0-120/208V \ 3\phi, \ 120V dc)$ - EMS 8821
- DC Motor/Generator Module - EMS 8211
- Synchronous Motor/Generator Module - EMS 8241
- Resistance Module - EMS 8311
- Three-Phase Transmission Line Module - EMS 8329
- DC Metering Module $(0.5/2.5A)$ - EMS 8412
- AC Metering Module $(250V)$ - EMS 8426
- Three-Phase Watt-Varmeter Module $(2) (300W-300var)$ - EMS 8446
- Mechanical Torque Angle Measuring Device - EMS 8909
- Strobe Light - EMS 8922
- Timing Belt - EMS 8942
- Connection Leads - EMS 9128

**EXPERIMENTS**

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

- **12-1)** Connect the synchronous motor 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 Fig. 12-4. (Use two watt-varmeter modules in parallel).

The field of the synchronous motor is connected in series with an external resistance $R_f$ (use two sections of a resistance module EMS 8311).
<table>
<thead>
<tr>
<th>$\theta$ (DEGREES)</th>
<th>$E_1$ (V)</th>
<th>$W_1$ (W)</th>
<th>$\text{var}_1$ (VAR)</th>
<th>$I_F$ (A)</th>
<th>$E_o$ (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>200</td>
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<td></td>
<td>200</td>
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<td>60</td>
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</table>

Table 12-1

With the motor uncoupled, start the motor. Adjust $E_1$ to 200V 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 a strobe light, adjust the mechanical torque angle measuring device to zero. Note $W_1$, $\text{var}_1$, and $I_F$ and record your results in Table 12-1. (Take the sum of the readings of each instrument for $W_1$ and $\text{var}_1$.)

12-2) Couple the synchronous motor to the DC generator. Gradually increase the generator load, and observe the real and reactive power drawn by the motor. Note also the phase shift of the poles as the load increases. Record your results in Table 12-1.

12-3) The maximum motor power depends upon $E_o$

With $E_1 = 200$ volts, 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 $E_1$?

12-4) The maximum motor power depends upon $E_o$

With $E_1 = 200$ volts 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 angle does the motor fall out of step? What is the corresponding field current?

12-5) Set up the experiment so that $E_o = 150$ volts and $E_1 = 200$ volts. Determine the phase angle as well as $W_1$ and $\text{var}_1$. Record your results in Table 12-2.

12-6) Effect of Transmission Line Impedance

Set $E_1 = 200$ volts, $E_o = 200$ volts and note the real power $W_1$ 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.

\[
W_1 = \quad \theta =
\]

Now introduce a three-phase 120 ohm line in series with the motor, and with $E_o = E_1 = 200$ volts, increase the load until the motor loses
<table>
<thead>
<tr>
<th>θ (DEGREES)</th>
<th>$E_1$ (V)</th>
<th>$W_1$ (W)</th>
<th>$\varphi_1$ (var)</th>
<th>$I_F$ (A)</th>
<th>$E_O$ (V)</th>
</tr>
</thead>
<tbody>
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<td>0</td>
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</tbody>
</table>

Table 12-2

Synchronism. What is the real power $W_1$ just before this occurs? $W_1 =$ __________. What is the corresponding phase angle between $E_o$ and $E_1$? $\theta =$ ________________.

Trigger the strobe light 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? $\alpha =$ ________________.

Explain why this angle is much less than 90 degrees.

QUESTIONS AND PROBLEMS

1. A synchronous motor of 1000 kW, 2.3 kV, 3-phase has a synchronous reactance of 2.6 ohms per phase. Calculate the phase-shift of the poles in electrical degrees when the motor develops 500 HP, given that the excitation voltage $E_o = 2.3 kV$ line-to-line.

   Note: 1 HP = 746 W.

2. If the motor in Problem 1 is located at the end of a transmission line whose reactance per phase is 3 ohms, by how many electrical degrees will the poles shift from their no load position if the motor produces 500 HP?

3. In Problem 2 what is the maximum horsepower the motor can develop before it falls out of synchronism?
This large 735kV switching station enables a spin-off of electric power and also serves as an intermediate voltage-regulating station.
OBJECT
1. To observe the hunting of a synchronous motor.
2. 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 \(2MW\) as shown in Fig. 13-1. Assuming that the no-load rotor position is as shown in 13-1 (a), the poles will fall back by 30 degrees when the load is raised to \(1MW\). The 30 degree 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 \(1MW\).

But if a \(1MW\) load is applied suddenly, the rotor will fall behind by more than 30 degrees and may swing as far as 45 or 50 degrees from its no-load position. In a way, the rotor overshoots the 30 degree mark which it should reach, with the result that the motor develops, for a while, a motive power considerably in excess of \(1MW\). For example, if the rotor swings to an angle of 45 degrees, the motor will develop \(1.4MW\) while the mechanical load is still only \(1MW\). This difference of \(0.4MW\) accelerates the rotor, urging it back to the 30 degree point of stability. But when the 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 degrees. At this new angle, the motor only develops \(0.5MW\) which is much less than the \(1MW\) mechanical load. Consequently, the rotor slows down and, in so doing, will again approach, reach, and then overshoot the 30 degree point.

Referring to Fig. 13-1, the rotor will oscillate between 15° \((Pf\) \(1\)) and 45° \((Pf\) \(2\)) in its attempt to reach the 30° point \((Pf\) \(0\)) of stable operation. The motor is said to "hunt" or oscillate during this transition period. The swing to the right and left of \(Pf\) \(0\) will become progressively smaller and, after a minute or so, the rotor will cease to "hunt", having now "found" the stable point \(Pf\) \(0\). 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

\[ F_H = \frac{35200}{N} \sqrt{\frac{P_f}{f}} \]

![Diagram](image)
in which

\[ F_H = \text{frequency of oscillation in cycles per minute.} \]

\[ N = \text{speed of rotation in revolutions per minute.} \]

\[ P = \text{peak power in kilowatts.} \]

\[ f = \text{supply-line frequency in hertz.} \]

\[ J = \text{moment of inertia in lb-ft}^2. \]

AN ANALOGY

It may help in understanding the phenomenon of hunting by using an analogy. In Fig. 13-2 a large flywheel (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 Fig. 13-2 (b) is much stiffer than that of Fig. 13-2 (a) and hence, for a given twist, it can deliver more power. In Fig. 13-3, two different flywheels, 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 degrees and then suddenly released, they will oscillate but at different frequencies. For a given inertia, the thick shaft (representing large power) of Fig. 13-2 (b) will hunt much faster than the shaft of Fig. 13-2 (a). Also, with a given power level, the shaft with a larger flywheel (representing more inertia) of Fig. 13-3 (b) will hunt much slower than the shaft of Fig. 13-3 (a).

SYNCHRONOUS MOTOR AND TRANSMISSION LINE

In Fig. 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 \( X_L \).

![Fig. 13-4](image)

Assuming the sender voltage \( E_I = \) induced voltage \( E_o = E \), 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.

INSTRUMENTS AND COMPONENTS

<table>
<thead>
<tr>
<th>Power Supply Module</th>
<th>(120/208V 3φ, 0-120Vdc)</th>
<th>EMS 8821</th>
</tr>
</thead>
<tbody>
<tr>
<td>Synchronous Motor/Generator Module</td>
<td>EMS 8241</td>
<td></td>
</tr>
<tr>
<td>Three-Phase Transmission Line Module</td>
<td>EMS 8329</td>
<td></td>
</tr>
<tr>
<td>Three-Phase Watt-Varmeter Module (2) (300W-300var)</td>
<td>EMS 8446</td>
<td></td>
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<tr>
<td>Flywheel</td>
<td>EMS 8915</td>
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<tr>
<td>Strobe Light</td>
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</tr>
<tr>
<td>Connection Leads</td>
<td>EMS 9128</td>
<td></td>
</tr>
</tbody>
</table>

EXPERIMENTS

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

☐ 13-1) Connect a three-phase synchronous motor 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 Fig. 13-5).

Switch the AC power on and off and, with a strobe light, observe the hunting of the rotor.

☐ 13-2) Repeat Experiment 13-1, after having added a flywheel to the motor shaft to increase its inertia. What is the frequency of oscillation? Compare it with your observa-
tion in Experiment 13-1.

13-3) Repeat Experiment 13-2, but feed the motor via a 120 ohm transmission line, setting var₂ = 0. (See Fig. 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.

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? In this experiment is it easy to maintain synchronism by rapidly reclosing the power circuit breaker?

13-4) Repeat Experiment 13-3, but without the flywheel. What happens to the frequency of hunting? Is it just as easy as before to maintain synchronism by rapidly reclosing the power circuit breaker?

QUESTIONS AND PROBLEMS

1. An alternator has a rating of 200MW, 13.2kV, 60Hz, 450r/min. Under nominal excitation (E₀ = 13.2kV) the machine is able to deliver a peak power of 300MW. 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 1/4HP machine with its flywheel is 0.8 lb-ft² and its synchronous reactance is about 100 ohms per phase. If this motor is connected to a 3-phase source of 208V and if the excitation voltage E₀ = 208V (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.
OBJECT
1. To observe voltage and power fluctuations under abnormal transmission line conditions.
2. 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 they 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 as evidenced by 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 degree 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 necessary to open other critical circuit breakers to 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.

INSTRUMENTS AND COMPONENTS
Power Supply Module (0-120/208V 3φ, 120Vdc) EMS 8821
DC Motor/Generator Module EMS 8211
Synchronous Motor/Generator Module EMS 8241
Resistance Module EMS 8311
Three-Phase Transmission Line Module (2) EMS 8329
AC Metering Module (250V/250V) EMS 8426
Three-Phase Watt-Variometer Module (2) (300W-300var) EMS 8446
Flywheel EMS 8915
Strobe Light EMS 8922
Timing Belt EMS 8942
Connection Leads EMS 9128

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

☐ 14-1) Connect a synchronous motor to the end of two transmission lines in parallel which, in turn, are connected to a 200V variable AC source. Couple a DC shunt generator to the motor and provide for appropriate resistance loading. Introduce metering for power and voltage, and add the flywheel to the synchronous motor (See Fig. 14-1).

☐ 14-2) 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 120 ohms. Set the load resistance to 300 ohms and adjust the shunt field rheostat so that \( W_2 = 150W \). Adjust the DC excitation of the synchronous motor so that \( E_2 = E_1 = 200V \). Vary the load suddenly by switching the 300 ohm load resistance of the DC generator. Observe the power and voltage fluctuations and, with a strobe light, the position of the poles.

Try to switch the loading 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 much smaller than would ordinarily be able to cause instability.

☐ 14-3) Once the system is running stably (with \( E_2 = E_1 = 200V \), and \( W_2 = 150W \)), 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?


14-3) Repeat Experiment 14-3, but adjust the load so that $W_2 = 200W$. 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?

14-5) With conditions again normal and $E_2 = E_1 = 200V$ and $W_2 = 100W$, 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?

QUESTIONS AND PROBLEMS

1. The circuit breaker of a large alternator which is delivering power to a system opens suddenly and, in a fraction of a second, is again reclosed. Explain what happens while the circuit breaker is open considering a) alternator speed of rotation, b) phase-shift between the alternator terminal voltage and the system voltage.

2. If the breaker in Problem 1 was open for 1 second it would be impossible to reclose it without creating a serious overload on the alternator and a corresponding serious disturbance of the system. Explain why.
High voltage circuit breaker. The large insulator to the right is in reality a current transformer.
## TRANSMISSION LINE

### CROSS-REFERENCE LIST OF REQUIRED EQUIPMENT VS EXPERIMENTS

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* Two groups collaborate.
EXPERIMENT 15-4

Phase-shifts of 3-phase transformers

Many interesting experiments on phase-shifts can be made by using the three-phase transformer EMS 8348, whose six windings are brought out independently. The 30 degree phase-shift inherent in a wye-delta primary-secondary connection can be measured. (See Fig. 15-4). Then, by interconnecting primary and secondary windings, it is possible to obtain various voltages and phase-shifts, using the transformer in an auto-transformer. (See Fig. 15-5).

The transformer can also be used as a grounding transformer to create an artificial but "hard" neutral.

With an oscilloscope it is also possible to observe third harmonic line-to-neutral distortion on Y-Y ungrounded transformer.
ADDITIONAL EXPERIMENTS

The following experiments are suggested for students who may wish to extend their knowledge and understanding of transmission lines. Several of these experiments involve Lab-Volt EMS equipment which is not a regular part of the Transmission Line program.

EXPERIMENT 15-1

Real and Reactive power flow as a function of the phase shift between sender and receiver voltages

A wound-rotor induction machine EMS 8231 is required, acting as a 0-360 degree phase shifter. The experiment can be set up as shown in Fig. 15-1.

$S$ and $R$ are the terminals of the fixed and variable 3-phase AC power supply. Adjust $E_2$ so that $E_1 = E_2$ with the line on open circuit. Vary the position of the rotor and note that the phase angle $\theta$ varies. Grasp the pulley of the wound-rotor machine, and when the phase angle is zero, close the line switch $S$. The rotor should come to a rest position, when it does not tend to rotate. If no such position exists, the phase sequence is wrong, and any two lines from sender $S$ must be interchanged.

If the rotor position is now moved, while keeping $E_1 = E_2$, it is possible to draw a graph of real and reactive power flow as a function of the phase-shift $\theta$. It can also be shown that maximum power transfer corresponds to a phase angle of 90 degrees.

EXPERIMENT 15-2

Transmission line faults, balanced and unbalanced

Symmetrical component theory can be illustrated by using line-to-line and line-to-neutral short-circuits on the transmission line as shown on Fig. 15-2 and 15-3. Positive, negative and zero sequence impedance can be found, using the standard voltmeter and ammeter modules which are part of the Electric Power Transmission Line program.

![Single-phase line-to-line fault](Fig. 15-2)

![Double line-to-neutral fault](Fig. 15-3)

EXPERIMENT 15-3

Positive, negative and zero sequence impedances of a synchronous machine

These impedances can be found by the standard methods employed for larger machines. However, correct results and correlation can only be obtained by taking into account the resistance of the windings.