ELECTROMGNTIC ENGERY CONVERSION

LABORATORY MANUAL

EE 3309

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March 2017

DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING
CALIFORNIA STATE UNIVERSITY, LOS ANGELES
Lab-volts Systems, Inc

CONTENTS

These laboratory note are reproduced in part from the Lab-volt

PREFACE

INTRODUCTION

Welcome!

You have signed up for the Electric Machines Laboratory, the most close-to-reality laboratory you will ever have on electric machines and its applications. The laboratory you are about to experience has been designed to fulfill the need for "hands on" experience so useful for the engineering student.

The main purpose of the Electric Machines Laboratory is to provide students with experience related to the connections, tests and characteristics of the most commonly used types electric machines as well as handling of the most basic instrumentation used in today's industry.

This laboratory manual is, in general, an attempt to accomplish the following goals:
1) Complete understanding of the purpose of every single device and equipment used through the schematic apparatus interconnection approach.
2) Learn how to do tests on machines taking into account set up sequence, safety, and reporting steps for easy of follow up.
3) Practical training in laboratory techniques (i.e. Troubleshooting, problem solving, etc.).
4) Develop ability and practice in technical report writing as well as to develop the skill and practice of optimal presenting of laboratory experiment results.

This manual was designed as an aid to instruction of the electric machine laboratory. It is divided into thirteen laboratory sessions of three hours. Each lab session is stand alone, and consists of several interrelated experiments.

The general topics covered by this work are single- and three-phase systems, single- and three-phase transformers, single- and three-phase induction machines, synchronous machines, and DC machines. The experiments are mostly tests of general acceptation for determining of characteristics and operation of electrical apparatus. Some emphasis is given to the basic control of machines.

LABORATORY

PASSIVE LOADS AND INSTRUMENTATION CONNECTION FOR EXPERIMENTAL SET HP

OBJECTIVES
The three main objectives of this lab session are to discuss the lab rules, to learn how to connect the fundamental instrumentation to be used throughout this semester, and how to set up the experiments using the passive load modules.

The specific objectives of this lab session are:
1)   To learn the basic safety rules in the lab.
2)   To learn how to prepare the lab reports.
3)   To learn how to use the ohmmeter.
4)   To learn how to use the voltmeter.
5)   To learn how to measure DC and single-phase power.
6)   To familiarize with the LVDAM-EMS system.
7)   To learn how to identify a node in a circuit.
8)   To understand how the load modules work.
9)   To learn how to use the power supply.
10)   To learn how to obtain the equivalent resistance, inductance and capacitance from the load modules.

BEFORE YOU BEGIN:
     Check **the Student Guide**

INTRODUCTION

In this experiment, you will be introduced to the passive load modules and taught its operation and how to connect them to form more complex load circuits.
Your instructor must check your circuit before you energize it in order to prevent accidents and short-circuits. There will be many groups in each laboratory section and the instructor could lack time to check every single circuit if there is not some kind of order in the connections because there are many ways to connect a circuit. To maximize the instructor time, we have designed a simple way to connect things around such that the instructor can easily find any errors in the connection and the student will be safe from possible electric shock hazards present when electric devices are not connected properly.

These guidelines will be reviewed a several times in the semester. This is the best way to develop an understanding of circuit interconnection and prepare you for the practical exam (given at the end of the course) and also because that way you will have the opportunity to contribute with what we expect to be part of your knowledge.
In this experiment, you will start using the resistance module. The operation of the ohmmeter is given and you are asked to complete a table of equivalent resistance from a

single module. Then you are prompted to notice the similarity between the three load modules (inductive, capacitive and resistive). Then a simple circuit is connected and current, voltage and power are to be measured on it.

AC AND DC **METERS**

DC waveforms are those which polarity doesn't change upon time. Their instantaneous value can be variable or fixed as shown on Figure 1.la

An alternating wave is one that is continually reversing (alternating) its polarity. The number of times that a complete change of polarity (a completed cycle) occurs in one second is called the line frequency. In America (including PR) the operating voltage frequency is 60 Hertz (cycles per second). Mo

st European countries use 50 Hertz as their electrical operating frequency. Samples of ac waveforms can be seen on Figure1.lb.

(a)   (b)
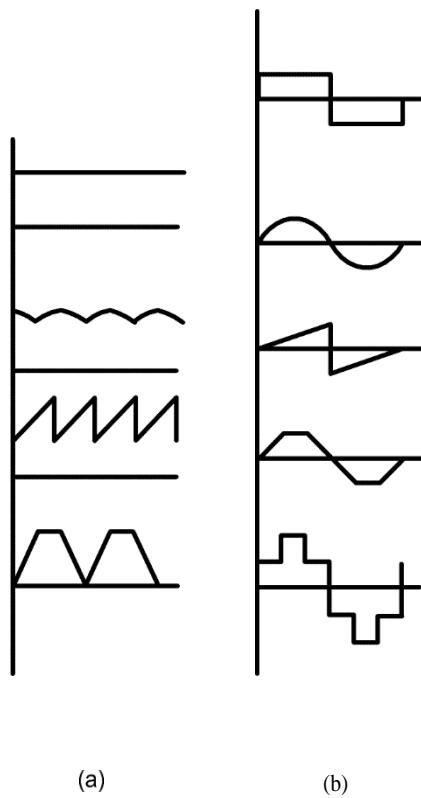
FIGURE 1.I

Theory and practice shows that the sine wave is the type of waveform most suited to run electric machinery. The sinusoidal waveform permits us to obtain the highest efficiency from transformers, motors and generators, and also results in q u i e t e s t operation.

AC voltmeters and ammeters are design to measure the effective or RMS value of the voltage or current wave. The effective value of an alternating current is defined as the square root of the mean of the squares of the instantaneous v a l u e s taken over any integral number of cycles. In contrast, DC voltmeters and ammeters are designed to measure average values. The average values and effective values are formulated as:

$$I_{avg.} \ \frac{1}{T}\int_{0}^{T}i(t)\ dt \qquad\qquad V_{avg.} = \frac{1}{T}\int_{0}^{T}v(t)\ dt$$

$$I_{RMS} \ \sqrt{\frac{1}{T}\int_{0}^{T}i(t)^2\ dt} \qquad V_{RMS} = \sqrt{\frac{1}{T}\int_{0}^{T}v(t)^2\ dt}$$

Voltage is measured by using a voltmeter. Voltmeters have a high internal resistance and are always connected in parallel with a circuit or component such as a resistor. See Figure 1.2 below.

DC
Voltmeter
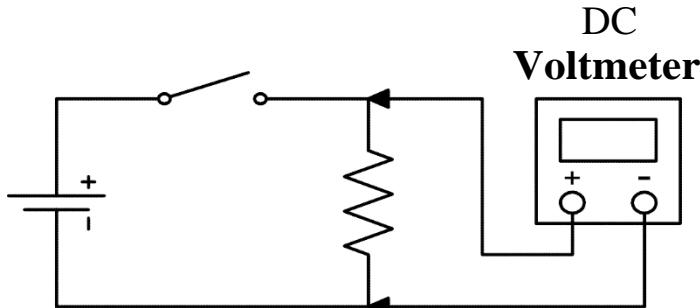
FIGURE 1.2

Note that the polarities of a DC voltmeter terminal must be observed to obtain a positive meter reading. If the connections are reversed, the pointed will deflect in the negative direction.

The ampere is the unit of electric current. Current is measured by using an ammeter. Ammeters have low internal resistance and are always connected in series with a circuit such as a resistor. See Figure 1.3.

DC
Voltmeter
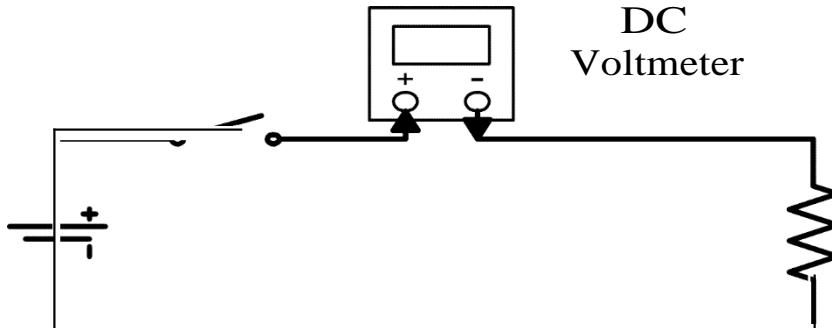
FIGURE 1.3

Note the polarity must be maintained in the dc ammeter for proper pointer deflection as for dc voltmeter.

Naturally, there are AC instruments designed to indicate rms (effective values). AC Voltmeters and ac meters are connected similarly as DC ones, but without polarity restrictions since they measure alternating signals.

DC AND SINGLE-PHASE POWER CALCULATIONS

In DC circuits the power (in watts) supplied to a resistive load is always equal to the product of the voltage and the current. In alternating current circuits the product of the voltage and the current does not always give an answer that can be stated in watts.

Apparent power (S in volt-amperes) is defined as the product of the AC voltage and the AC current. Apparent power is only equal to real power when the load circuit is entirely resistive. When the load in the circuit is not entirely resistive, the apparent power (VA) can be quite different from the real power (W).

A wattmeter is an instrument that is designed to read the real power consumed by the circuit in the output (or load) side. The analog wattmeter is so designed to read the average power in AC circuits through a magnetic circuit arrangement. The coil that measures the current is called the current coil, and the coil that measures the voltage is called the potential (or voltage) coil (See Figure 1.4). The coils in the wattmeter are so disposed that a torque is developed on a movable element proportional to the product of the voltage and in-phase current at every instant. If the voltage and current are DC, the power in watts supplied to a load is always the product of the voltage and the current. Power in AC circuits is a time varying quantity. However, because the mechanical inertia of the moving element, the wattmeter mechanically averages the time-varying torque and gives an indication of the average power.

In the laboratory a virtual wattmeter will be used to calculate consumed power. This virtual wattmeter will calculate the power from voltage and current digital measures

SOUR
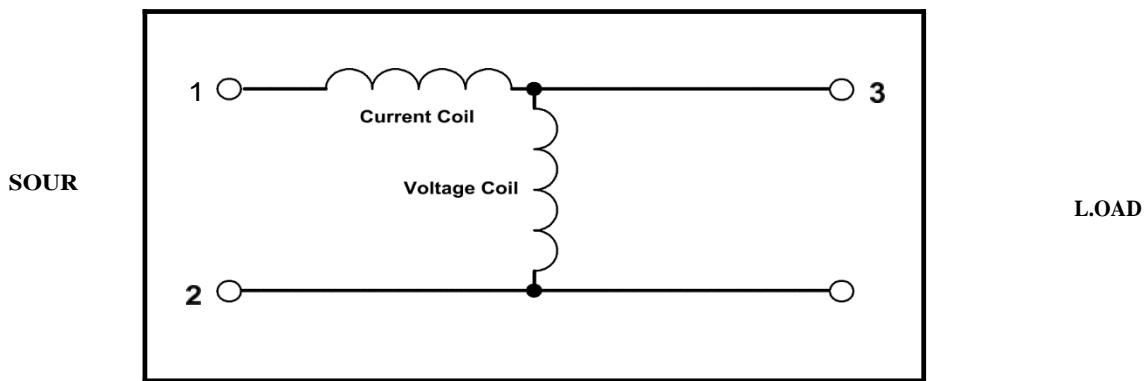
L.OAD

FIGURE 1.4

Reactive power may be inductive or capacitive depending of which reactive element is dominant in the circuit. The apparent power supplied to a load is the simple product of the AC RMS voltage and AC RMS current. The real power supplied to a load is measured by a wattmeter or it can be calculated as:
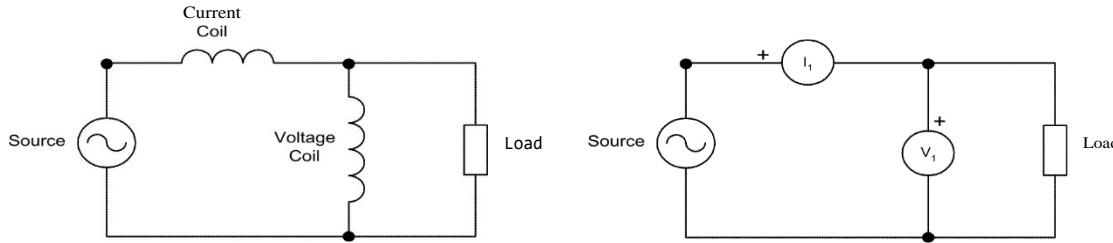
FIGURE 1.5

$$P = I,'*R.$$

The reactive power can be calculated by the equation:

$$Reactive\ Power = \sqrt{(Apparent\ power)^2 - (Real\ power)^2}$$

The real power can be found if the phase angle (the angle between the voltage and the current waveforms) is known with:

$$Real\ power = E.I.cos\varphi = Apparent\ Power.cos\varphi$$

The ratio of real to apparent power is called the power factor of an AC circuit. The value of the power factor depends on how much the current and voltage is out of phase. When the voltage and current are in phase, the real power is equal to the product of voltage and current (unity power factor). When current and voltage are out of phase by 90', as in purely inductive or capacitive circuits, the power factor is zero.

Alternating current motors draw reactive power from the supply line to create the magnetic field that they require. In addition, such motors also absorb real power, most of which is converted into mechanical power, while the rest is dissipated in the form of heat.

The reactive power travels back and forth between the motor and the AC supply. Reactive power does no useful work, except insofar as it creates the magnetic field for the motor. If a capacitor is placed in parallel with the motor, and the reactive power drawn by the capacitor is exactly equal (but of opposite sign) to that drawn by the motor, then one reactive power will neutralize the other. The result of this is that the power transmission line no longer needs to carry any reactive power at all. This can result in a very substantial reduction of current in the transmission line, which improves line regulation and reduces need for large diameter transmission wires.

RESISTANCE MEASUREMENTS

Ensure that no voltage is present in the circuit or component under test before taking resistance measurements. Low voltage applied to a meter set to measure resistance causes inaccurate readings. High voltage applied to a meter set to measure resistance causes meter damage. Check first how to use DC and AC voltmeters.

To measure resistance using an ohmmeter, apply the procedure (see Figure 1.6):
    1. Check that all power is OFF in the circuit or component under test.

2. Set the function switch to the resistance position, which is marked as 11.
3. Plug the black test lead into the common jack.
4. Plug the red test lead into the resistance jack.
5. Ensure that the meter batteries are in good condition. A battery symbol is displayed when the batteries are low

6. Connect the meter leads across the component under test. Ensure that the contact between the test leads and the circuit is good.
7. Read the resistance displayed on the meter. Check the circuit schematic for parallel paths. Parallel paths with the resistance under test cause reading errors. Do not touch exposed metal parts of the test leads during the test. Resistance of your body can cause reading errors.
8. Turn the meter off after measurements are taken to save battery life.
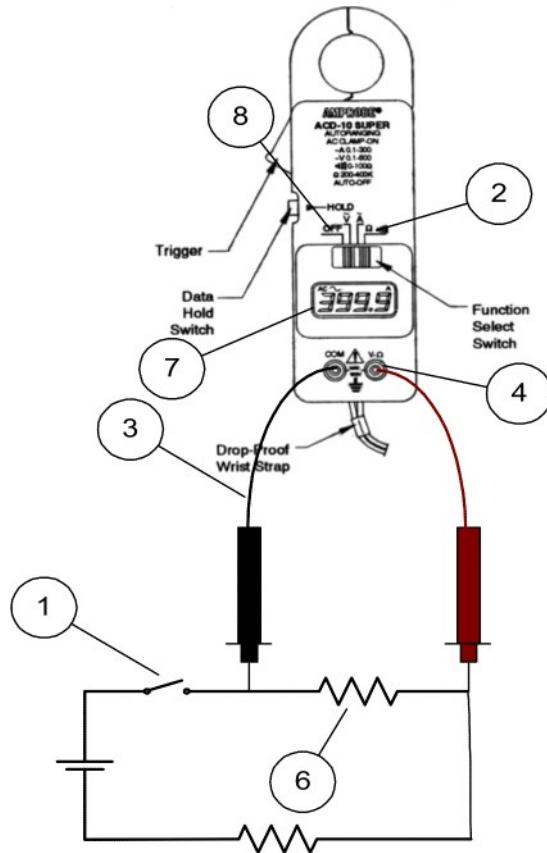
FiGURE 1.6 RESISTANCE MEASUREMENT

FAMILIARIZATION WITH THE LVDAM-EMS SYSTEM

The Lab-Volt Data Acquisition and Management (LVDAM-EMS) is software for Window consisting of four separate applications which are called Metering, Oscilloscope, Phasor Analyzer, and Harmonic Analyzer. These applications form a complete set of instruments consisting of a panel of meters (voltmeters, ammeters, power meters, programmable meters, etc.) an eight-channel oscilloscope, a six-channel phasor analyzer, and a harmonic analyzer.

METERING

The metering application in LVDAM-EMS allows measurements of electrical and mechanical parameters in electromechanical systems as well as in power electronics circuits. It contains voltmeters (El, E2, E3), ammeters (I1, I2, I3), electrical power

meters (PQS1, PQS2, PQS3), programmable meters (A, B, C, D, E, and F), a torque meter (T), a speed meter (N), and a mechanical power meter (Pin). All meter settings, which are, the meter range, the meter status (on or off), etc., can be changed according to your needs. Values measured with the various meters can be recorded in a data table to plot graphs.

The Data Acquisition Interface (DAI) Module shown in Figure 1.7 contains six sections: voltage jacks, current jacks, Torque and Speed (T & N) jacks, etc. By the moment and in this laboratory session, it is sufficient to know how to measure voltage, current and electrical power. The experiments contained in this laboratory session will guide the student in the familiarization with the LVDAM-EMS System.
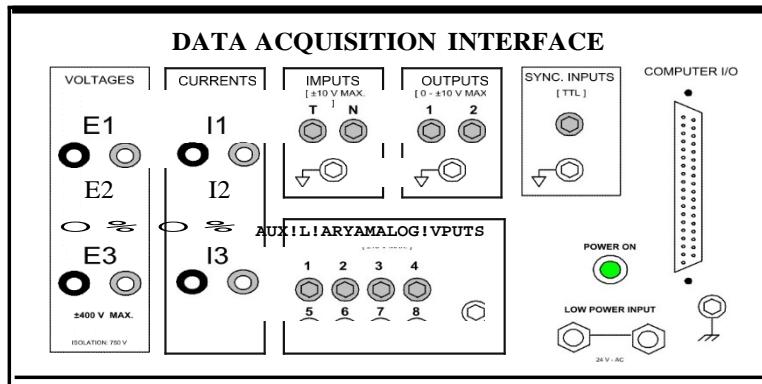
FIGURE 1.7 DATA **ACQUISITION INTERFACE MODULE**

PASSIVE ROAD MODULES

The passive load modules to be used in the lab are:

The Resistance Module	(EMS 8311),
The Inductance Module	(EMS 8321),
The Capacitance Module	(EMS 8331).

Every load module contains nine single elements (each one in series with a toggle switch) grouped in identical sections of three elements each. If the toggle switch is open (down position) then the element is not connected, if it is closed then the element is connected across the terminals as shown in the Figure 1.8. If you toggle two or all the switches in one section, the elements will be paralleled connected.
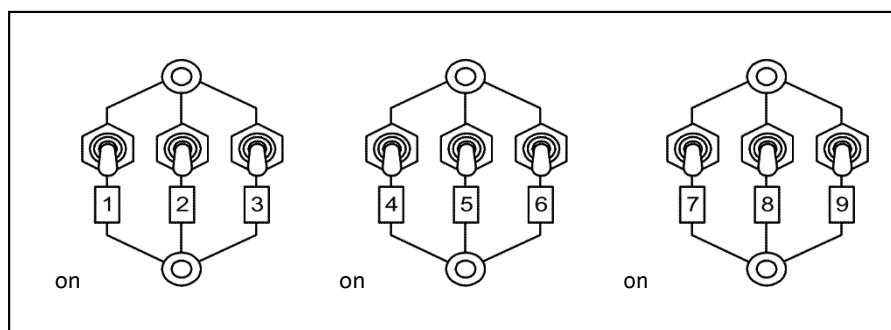
FIGURE 1.8 VARIABLE PASSIVE LOAD MODULE

As you can verify, all load modules have the same impedance load even though that they are different elements (i.e. resistance, capacitance and inductance loads all have the same values of ohms for each modules).

The resistance is the property of elements of offering opposition to the flow of current causing as a result electrical energy conversion into heat energy.

When a group of resistors is connected in series, the equivalent resistance is equal to the sum of the values of the resistors. Thus, if a resistor, having a resistance of 5 ohms is connected in series with one having a resistance of 20 ohms, as in Figure 1.9a, the total resistance is 25 ohms.
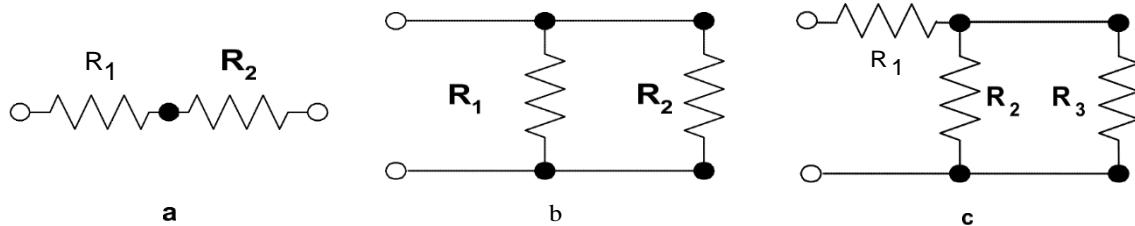
FIGURE 1.9

The equivalent resistance in a series connection is formulated as:

$$R_T = R_1 + R_2 + R_3 + \ldots$$

When two or more resistors are connected in parallel between two terminals, the resultant resistance is always less than that of the lowest resistor. The parallel scheme for two resistances can be shown by referring to Figure 1.9b.

For example, if R equals 5 ohms, and Rd is 20 ohms, it is clear the total is less than 5 ohms. The equivalent resistance of a number of resistors in parallel is found from the equation:

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots$$

Other possibility for connecting resistors is the series-parallel connection shown in Figure 1.9c.

Inductance is that property of an electric circuit that tends to prevent a change in current. Inductance is measured in henrys (H). Ideal inductors don't dissipate electric energy, they can only store and release it. However, in practice, all inductors dissipate some real power, with the result that the wattmeter will not read zero. This is so because an inductor always has some resistance and is subject to I'R losses.

In an inductor, the current lags behind the voltage by 90 electrical degrees. For the unique case when this happens, the apparent power (the product of AC voltage and current) is also called the reactive power (VAR) and it carries a ( ) sign.

The inductive reactance is the resistance offered to the flow of alternating current by the presence of inductance in the circuit. It is measured in Ohms and is equal to the ratio E/I.

The inductive reactance also depends upon the frequency and the inductance in henrys and can be expressed mathematically as:

$$X_L = 2\pi fL$$

Where: X_L = inductive reactance in Ohms.

   L = inductance in henrys.

   f = frequency in cycles per second (Hertz).

When two or more inductors are connected in series the total inductance is the sum of their individual inductances:

When two or more inductors are connected in parallel the total inductance is found by:

$$1/L_T = 1/L_1 + 1/L_2 + 1/L_3 + 1/L_4 + 1/L_5 + ...$$

.

Capacitance may be defined as a measure of the amount of electrical charge that a device can store in the dielectric (insulation) between two conductors (plates) when a given voltage is applied. The basic unit of capacitance is the farad (F). Since the farad is so large a quantity, measurements are made in microfarads (|F). A capacitor has the ability to store electrical energy by virtue of the electrostatic field that is set up between its plates. The quantity of energy stored depends upon the capacitance and upon the square of the voltage.

A capacitor does not dissipate electric energy, it can only store it and the release it. Since no power is dissipated in the capacitor, the wattmeter will indicate zero. There will, however, be a voltage drop across the capacitor and current will flow in the circuit. The product of capacitor voltage and current is the apparent power. The current leads the voltage by 90 electrical degrees because of which the apparent power associated with a capacitor is also called the reactive power (VAR) and it carries a (-) sign.

Capacitive reactance is the resistance offered to the flow of alternating voltage by the presence of capacitance in the circuit. It is measured in Ohms and is equal to the ratio of E/I. Reactance also depends upon frequency and the capacitance in farads. The mathematical expression for the capacitive reactance is:

$$\frac{1}{2\pi fC}$$

Where: X_C capacitive reactance in Ohms.

   C = capacitance in farads.

   f — frequency in cycles per second (Hertz).

   $2\times = 6.2832$

When two or more capacitors are connected in parallel the total capacitance is the sum of their individual capacitances:

$$C_T = C_1 + C_2 + C_3 + C_4 + C_5 + ...$$

When two or more capacitors are connected in series the total capacitance is found by:

$$1/C_T = 1/C_1 + 1/C_2 + 1/C_3 + 1/C_4 + 1/C_5 + ...$$

PRELAB

No prelab will be given for this experiment.

EXPERIMENT 1.1 THE PASSIVE LOAD MODULEs, How Do THEY WORK?

1 EQUIRED EQUIPMENT

Hand Ohmmeter	
Resistance Module	EMS 8311
Inductance Module	EMS 8321
Capacitance Module	EMS 8331
Data Acquisition Interface Module	EMS 9062

PROCEDURE

Step 1: Check the construction of the Resistance Module EMS 8311 shown in Figure 1.8 and realize that the resistance is in series with the toggle switch S.

Step 2: Position the three toggle switches down for an off state and using your hand Ohmmeter check that there is infinite resistance of each one of the resistance in the section shown in Figure 1.10 (all three are internally connected in parallel when S is on).

Step 1: Position any toggle switch up for an on state and using your hand Ohmmeter check that there is nominal resistance. Repeat for all the resistances in all the three sections (only one "on" at a time). Record your results.

Step 2: Calculate and measure the equivalent resistance for each parallel combination on Table 1.1.

Step 3: Calculate and measure the equivalent resistance for each series combination on Table 1.2.

Step 4: Calculate and measure the equivalent resistance for each series-parallel combination on Table 1.3.

Step 5: Demonstrate that the impedance of the inductive, capacitive and resistive load modules is the same from their values of henrys, farads and ohms at 60 Hz.

Step 6: Calculate the impedance of each module section and record your results in Table 1.4 for a 50 Hz frequency.

on
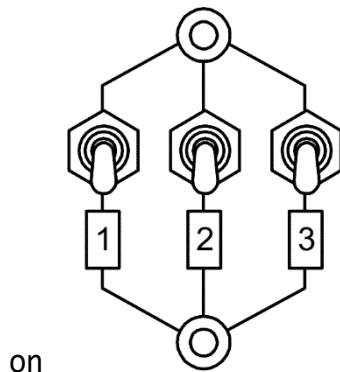
FIGURE 1.10

PARALLEL EQUIVALENT RESISTANCE		
COMBINATION	MEASURED	CALCULATED
300&600		
300&1200		
600&1200		
600&600		
600&600&1200		

TABLE 1.I

SERIES EQUIVALENT RESISTANCE		
COMBINATION	MEASURED	**CALC ULATED**
300&600		
300&1200		
600&1200		
600&600		
600&600&1200		

TABLE 1.2

' See the connection diagram on Figure 1.9c

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	SERIES-PARALLEL' EQUIVALENT RESISTANCE	
COMBINATION	**MEASURED**	CALCULATED
300&(1200//1200)		
300&(600//600)		
600&(1200//1200)		
600&(300//1200)		
1200&(300//300)		

TABLE 1.3

	LEFT	**MIDDLE**	RIGHT
RESISTANCE MODULE			
INDUCTANCE MODULE			
CAPACITANCE MODULE			

TABLE 1.4

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Experiment 1.2
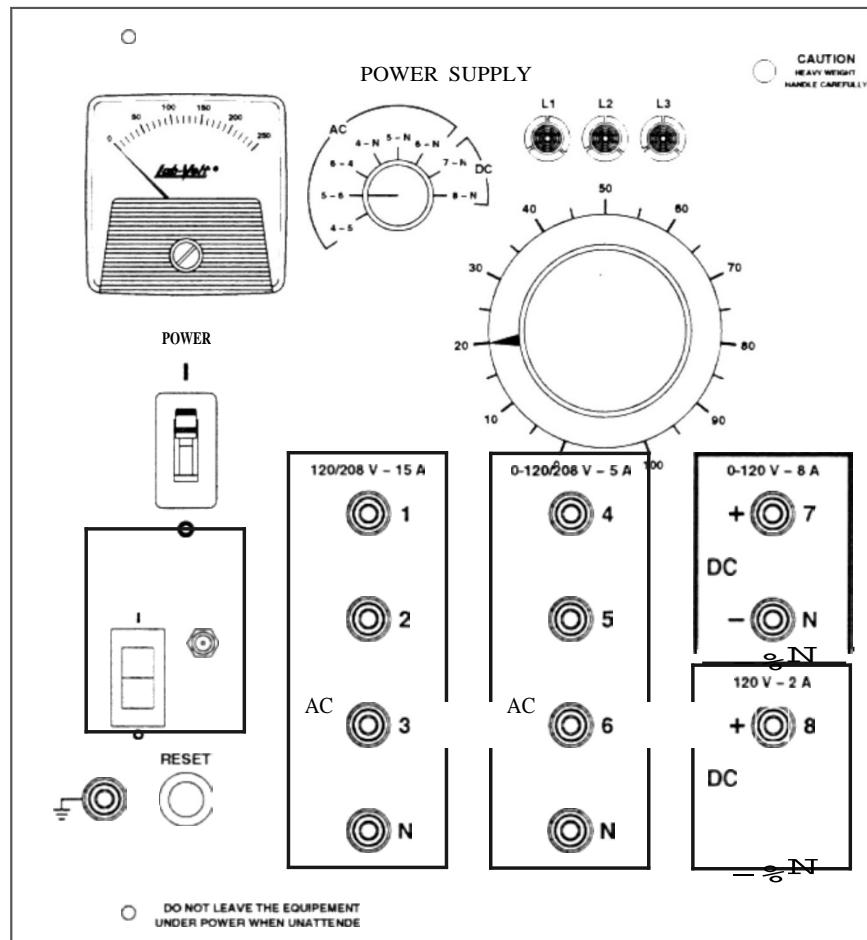
THE LVDAM-EMS' AMMETER AND VOLTMETER SYSTEM

Equipment: Power Supply, DAI, Variable resistance (8311)

Preliminary considerations and safety tips

1. Never make any connections when the main switch is ON!

2. Before turning the module ON:

   a) double-check your wiring;

   b) make sure that the voltage adjustment knob is in the "zero" position.

Power supply

Voltmeter channel selector

Main switch

DAI switch

Voltage adjustment knob

DC variable

DC fixed

AC fixed   AC variable

The power supply module has five outputs:

1. Terminals 1, 2, 3, and N — a fixed-voltage, 3-phase, 4-wire output;

2. Terminals 8 and N — a fixed-voltage DC output;

3. Terminals 4, 5, 6, and N — a variable-voltage, 3-phase, 4-wire output;

4. Terminals 7 and N — a variable-voltage DC output;

5. A fixed-voltage low power AC output — no front terminals.

Besides the main 3-phase on-off circuit breaker on the front panel (main switch), all the outputs have their own circuit breakers. They can be reset by a common reset button on the front panel.

The variable-voltage AC and DC outputs are controlled by the single knob on the front panel. A build-in AC/DC voltmeter indicates all the variable AC and the variable and fixed DC output voltages according to the position of the voltmeter selection switch.

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The rated current of each output may be exceeded considerably for short periods of time without harming the module or triggering the circuit breakers. This feature is important while studying motors under overload or starting conditions (when high currents may be drawn for short periods of time).

All the power sources can be used simultaneously provided that the total current drawn does not make the main switch

tips. Power Supply

Specifications:
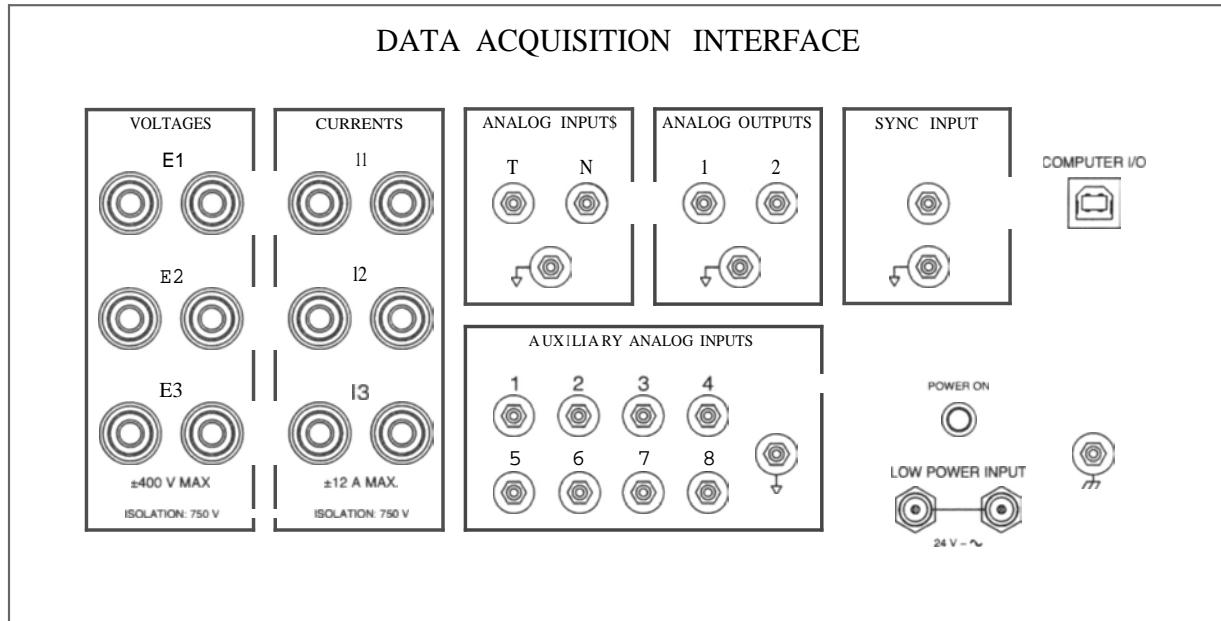
Power requirement: 120/208 V, 15 A, 60 Hz, 3-phases;
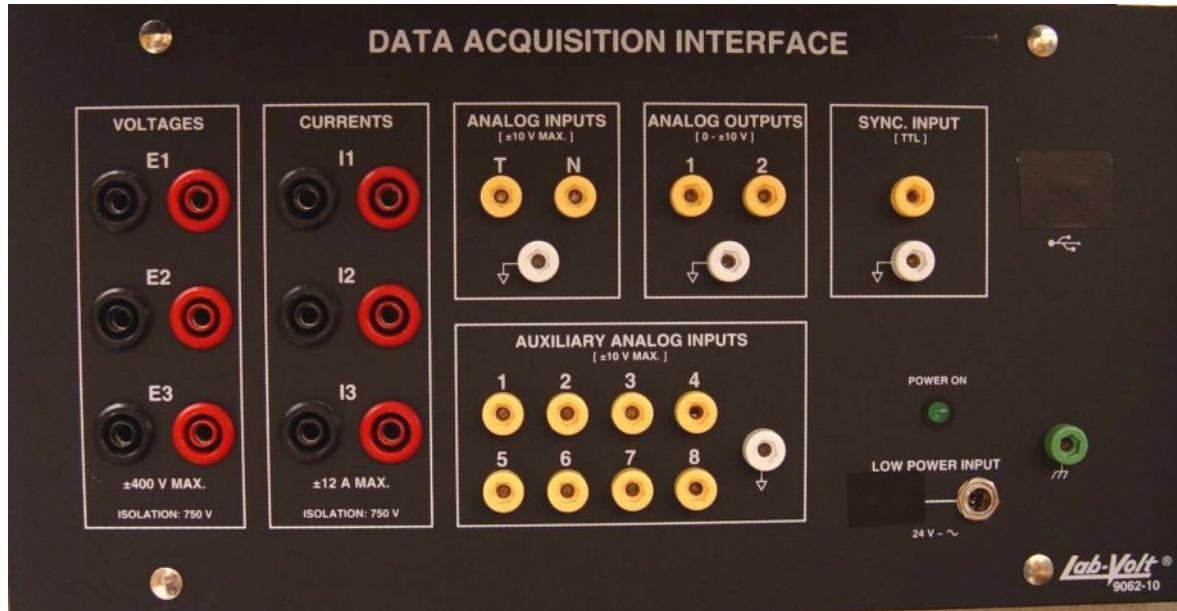
Fixed outputs: 120/208 V, 15 A, 60 Hz, 3 phases
                        120 V, 15 A, 60 Hz, 1 phase
                          24 V, 3 A, 60 Hz, 1 phase
                        120 V, 2 A, DC;

Variable outputs: 0-120/208 V, 5 A, 60 Hz, 3 phases
                        0-120 V, 5 A, 60 Hz, 1 phase
                        0-120 V, 8 A, DC;

AC/DC voltmeter: 0-250 V.

Data acquisition interface (DAI)

INPUTS El to E3 and II to I3 are fully protected against over-voltage and short-circuit conditions. These inputs are also electrically isolated from the circuitry in the DAI module through the isolators. Each of these isolators has two measuring ranges (high and low); the range selection is controled by the software. The rating of the low and high ranges are:

DAI MODULE VERSION	INPUTS E1 TO E3		INPUTS 11 TO 13	
	LOW RANGE	HIGH RANGE	LOW RANGE	HIGH RANGE
9062-10, -11, -12 9062-B0, -B1, -B2	±100 V	±400 V	±3.0 A	±12 A

ANALOG INPUTS T and N are used to measure the torque and the speed of a motor. ANALOG INPUT T is designed to receive the output signal of a torque sensor with a sensitivity of 0.3 N-m/V. Similarly, ANALOG INPUT N is designed to receive the output signal of a speed sensor with a sensitivity of 500 r/m/V.

ANALOG OUTPUTS provide a voltage whose amplitude can be set between -10 V and +10 V by software. Each voltage can be used to control a device in an electric power circuit.

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AUXILIARY ANALOG INPUTS 1 to 8 are low voltage inputs (±10 V max). These inputs can be connected to the outputs of voltage isolators, current isolators, torque sensors, speed sensors, etc. to measure various types of parameters. Each of them is programmable through the software.

SYNC. INPUT is a digital input (TTL level) that can be used for external synchronization of the oscilloscope in the Lab-Volt system.

Running Lab-Volt
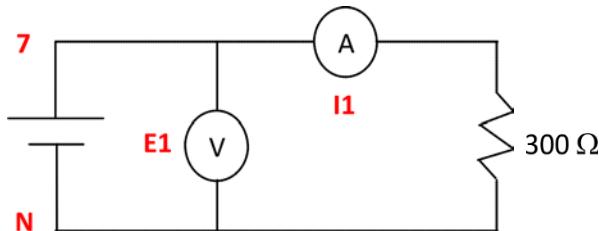
Lab-Volt can run in either one of the following two modes: acquisition and simulation. In the acquisition mode, the parameters measured by the system come from samples of the signals applied to the inputs of the DAI. In the simulation mode, the parameters measured by the system come from computer-simulated input signals; therefore, the DAI module is not required. The following procedure describes how to run Lab-Volt.

1. Make sure the DAI module is connected to the USB port of the computer. *Note.' normally, it is connected.*

2. Power ON the module by the illuminated (DAI) switch. The "power on" led must turn green.

3. Start the Lab-Volt program. *Note. Lab-Volt will automatically try to connect to the DAI module.*

4. If the system is able to establish connection to the DAI, the icon in the lover right comer should indicate that the connection is established. The Lab-Volt is set in the acquisition mode and ready to be used. Go to step 6.

5. If the system is unable to establish connection to the DAI, a message box should appear offering you to chose one of the following options:

   1) retry the connection — the system will try to connect once again.

   2) work in stand-alone mode — the system will be set in the simulation mode and ready to be used without the DAI module.

6. To start an instrument, chose the corresponding command in the "Instruments" menu or click the corresponding button on the Instruments bar.

Experiment:

Caution! When actual equipment is used, high voltages may be present. NEVER make or modify any connection with the power ON unless otherwise instructed.

1) Construct the following circuit:

while using a resistor from the "variable resistance" set:
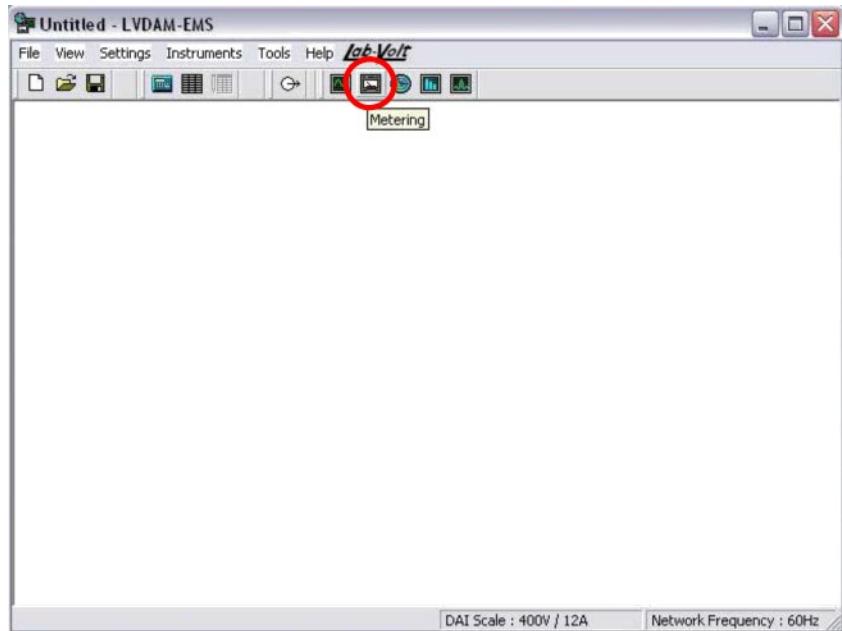
Note: the switch is ON when it is in the "upper" position. Switches allow connecting resistors in parallel and, therefore, change the equivalent resistance of the circuit (load).
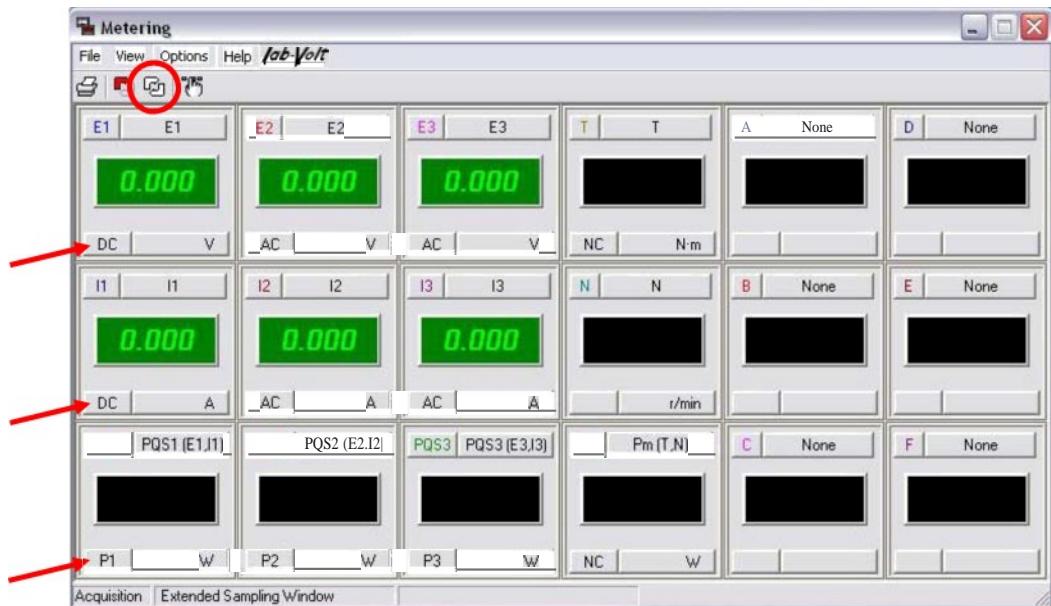
2) Have your instructor check your wiring.

3) Predict (using the Ohm's law) the value of the current flowing through the load and power dissipated by it assuming that the voltage across the load is 30 V.

4) Turn on the DAI and the power supply (make sure the voltage control knob is in the "zero" position).

5) Apply a DC voltage of approximately 30 V by adjusting the knob. You may control the voltage by the El voltmeter and also by the voltmeter on the power supply. Note: the voltmeter channel selector must be set to the "7-N DC" position.

Part I: <u>Metering window</u>

6) Start Lab-Volt; start the Metering Window

7) In the Metering Window select "continuous acquisition" (red circle).
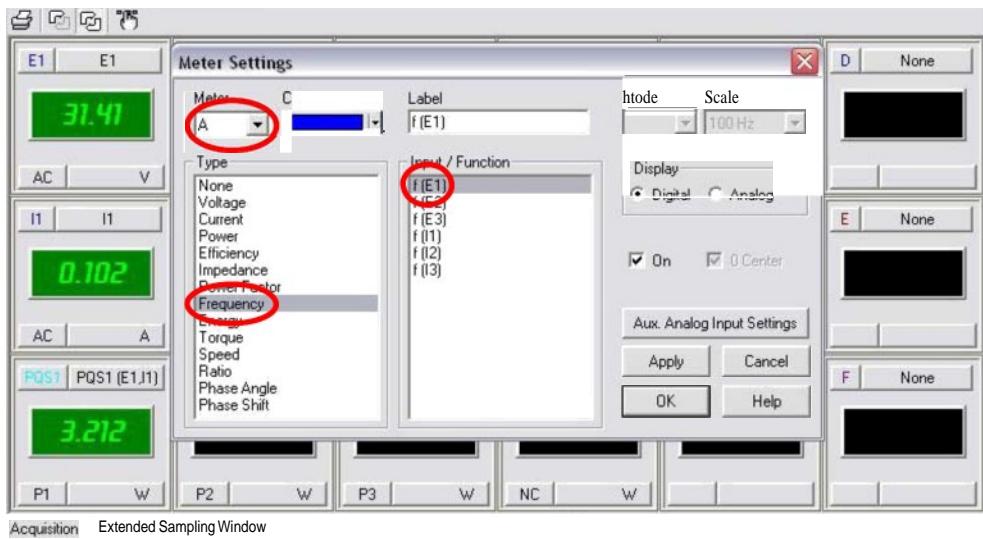
8) You will see the numerical values of voltages and currents measured for channels El, E2, E3, II, I2, and I3. By default, all the channels are set measure AC. Change the channels you use to the DC mode by clicking the indicated buttons. Turn on meter PQS1 and set it as an active power (P) meter.

9) Record the current flowing through the load and the power dissipated by it.

10) In the Metering window, select the "manual refresh mode". Change the value of the load resistance by closing another switch on the "resistive load" module. While doing this, observe that the values displayed by meters do not change to reflect the load change since the meters are not refreshed automatically. Select the "automatic refresh" mode again and observe changed values of measured voltage, current, and power.

11) Turn OFF the main power and replace the DC power source by the variable AC source (use the PS terminals 4 and N this time). Note: you don't need to turn off the DAI power.

12) In the Metering window, set the voltmeter El and the ammeter II to the AC mode. Set the programmable meter A as a frequency meter (function f(EI)) and programmable meter B as an ohmmeter (impedance function RXZ(E1,I1)), turn on these meters.
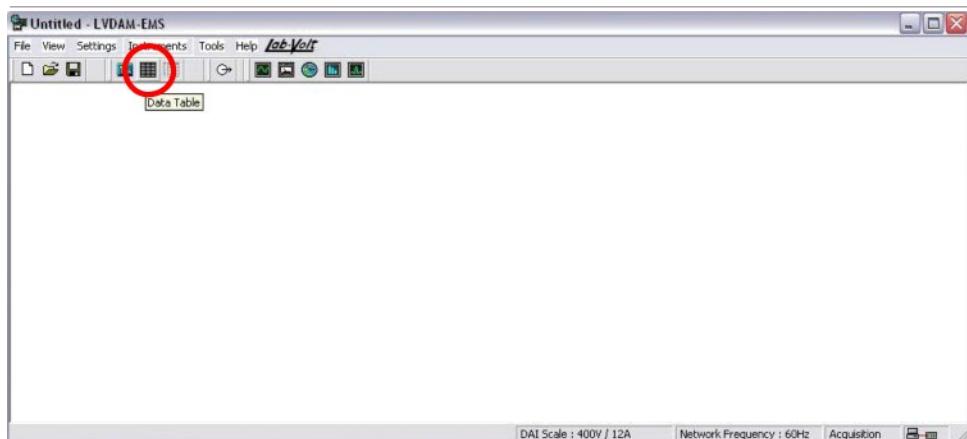
To do this, go to the Metter settings interface and select the appropriate meter, type, and input/function.
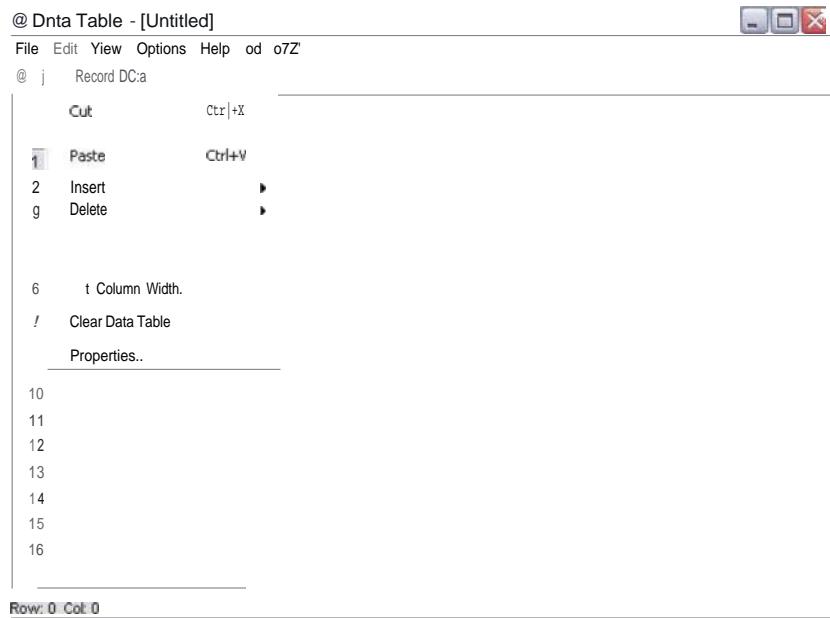
13) Turn the Power Supply on and slowly adjust the output voltage to approximately 30 V by the voltage control knob. While doing this, observe that the measured voltages and currents are changing continuously since the meters are in the "continuous refresh" mode. Also observe that meters A and B indicate the network frequency and the value of the resistor.

Part II: Data table
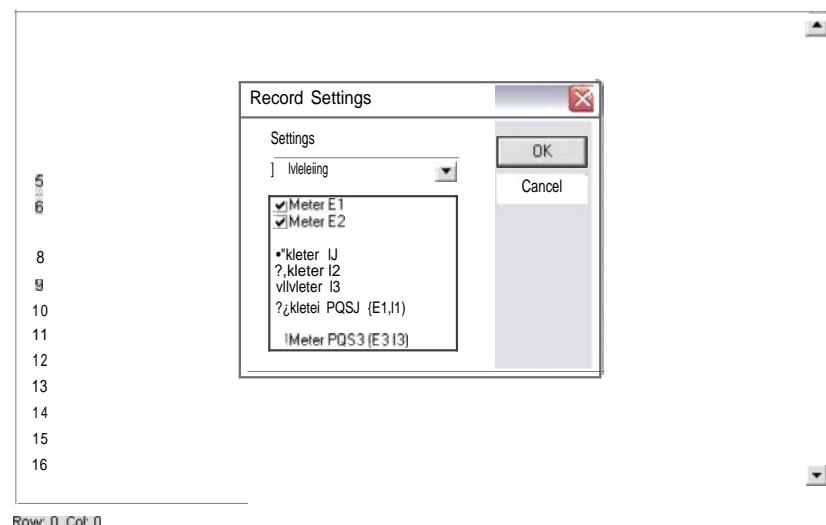
14) Open the Data table window. An Excel-like spreadsheet will appear.

15) In the Data table, record the values by "Edit \ Record Data"

@ Dnta Table - [Untitled]

File Edit Yiew Options Help   od o7Z'
@ j   Record DC:a

Cut   Ctr|+X

Paste   Ctrl+V
2   Insert   ▶
g   Delete   ▶

6   t Column Width.
!   Clear Data Table
     Properties..

10
11
12
13
14
15
16

Row: 0 Col 0

You will be prompt to the "Record Settings" menu where you can select the channels to be recorded in the table.

Record Settings

Settings
]   Meleiing   ▼   OK
                              Cancel
☑Meter E1
☑Meter E2

•"kleter IJ
?,kleter I2
vllvleter I3
?¿kletei PQSJ {E1,I1)

IMeter PQS3 (E3 I3)

Row: 0 Col 0

16) On the power supply, increase the voltage by approximately 5 V. Record values displayed by the meters to the Data Table by repeating step 15. Note, the same channels you have selected previously will be recorded this time.

30

	E1 (V)	E2 (v)	E3 (V)	I1 (A)	I2 (A)	I3 (A)	PQS1 (EI,I1) (W)	I(E1 (Hz
0	3138	0.4	0 39	0 1		0	3.21	
1	352¿	0.4	0.39	0 12			4 06	5
8								
10								

17) Repeat step 16 and record values for total of 10 voltage steps.

18) Return the voltage control knob to the "zero" position and turn off the Power Supply.

19) In the Data table window, open the Graph window.

	E1 (V)	E2 (V)	E3 (V)	I1 (A)	I2 (A)	I3 (A)	PQS1 (E1,I1) (W)	f (E1 (Hz
0	31.38	0.4	0.39	0.1	0	0	3.21	
1	35.27	0.4	0J9	0.12	0	0	4.06	5

20) In the Graph window, you may choose specific data to be plotted. Plot a graph of the power (PQSI) dissipated by the resistor as a function of the voltage (EI) applied to it.

Properties of graphs (colors, data used, etc.) can be changed by the "Options" menu.

The data entered to the Data table can also be saved in a file.

21) Save your data in a file for later

processing. <u>In your report:</u>

1. Compare the actual current flowing through the load and the power dissipated by it (as
   measured in 9) with the values that you have predicted. Discuss possible sources of discrepancy.

2. Using Matlab, plot the power dissipated by the resistor as a function of the voltage applied to it. Plot the theoretical graph for the resistor used in the experiment (300 D) on the same figure. On a separate figure, plot the absolute error function, i.e. the difference between the measured power and its predicted values. What is your conclusion? What are possible sources for discrepancy?

<u>Note:</u> to load the data recorded in a data table by the Lab-Volt software to Matlab, use the *read tbl.in* routine provided. Place the *read tbl.in* file together with the data file to a directory (folder) specified in Matlab's paths (for instance, the current Matlab directory) and then refer to the Matlab help by typing "help read tbl".

Experiment 1.2

Impedance.

Equipment: Power Supply, DAI, Variable resistance (8311), Variable capacitance (8331), Variable inductance (8321)

Theory :

The impedance of serial connection of elements can be computed as:

$$Z = \sqrt{R^2 + \left(X_L - X_C\right)^2}$$

Which indicates that, if the reactance are equal, the impedance is simply a circuit resistance with a phase angle of zero.

The magnitude of the impedance of parallel connection of elements can be computed as:

$$Z = \frac{RX_C}{\sqrt{R^2 + X_C^2}}$$

$$Z = \frac{RX_L}{\sqrt{R^2 + X_L^2}}$$

When a circuit contains both inductive and capacitive elements, first solve for the total combined reactance and then use its magnitude in the above expressions for the impedance. For series circuits:

$$X = X_L - X_C$$

For parallel circuits:

$$X = \frac{X_L X_C}{X_L - X_C}$$

The phase angle can be found from

$$\cos\theta = \frac{R}{Z}$$

A voltage drop across a resistor is:

$$E_R = I_R R$$

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A voltage drop across an inductor is:

A voltage drop across a capacitor is: $$E_c = I_c X_c$$

Experiment:

1) Using the Variable resistance and the Variable capacitance modules,

Construct the following circuit as indicated in Figure 03-2:
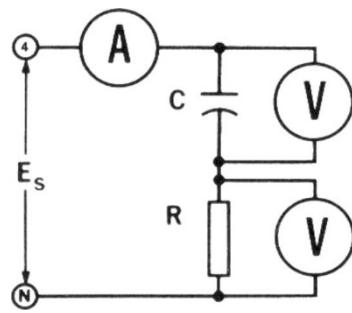
Figure 03-2.

Include an additional voltmeter (EI) to measure the input AC voltage.

Set a resistance of the load to 150 D (use two 300 D resistors wired in parallel) and the reactance to 100 f2 (use three capacitors with reactance of 300 G wired in parallel).

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In the Metering window, open the Meter Settings dialog; select meter "A", assign a meter type "Phase shift" between El and II (input voltage and the circuit current), and apply changes.
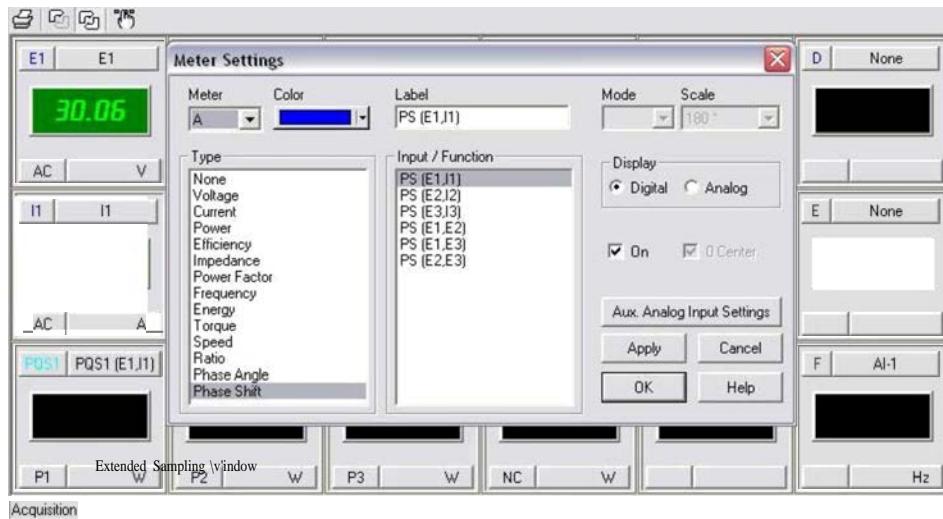
Figure 03-3.

Apply an input AC voltage of approximately 30 V and record the current through the circuit, input voltage, voltage drops across the circuit elements, and the phase shift between the input voltage and the circuit current.

Start the Phasor analyzer.

Figure 03-4.

Observe a phase shift between El and 11 (input voltage and the circuit current).

2) Replace the capacitive load by the inductive load using the Variable inductance module.
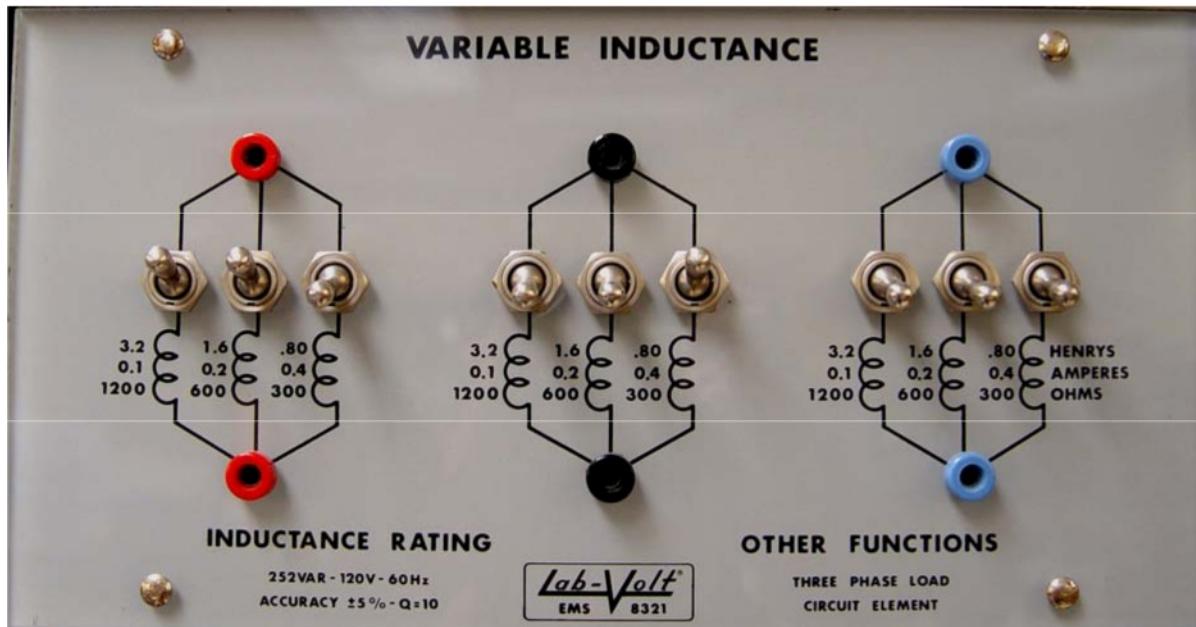
Figure 03-5.

The circuit will correspond to the diagram in Figure 03-6:
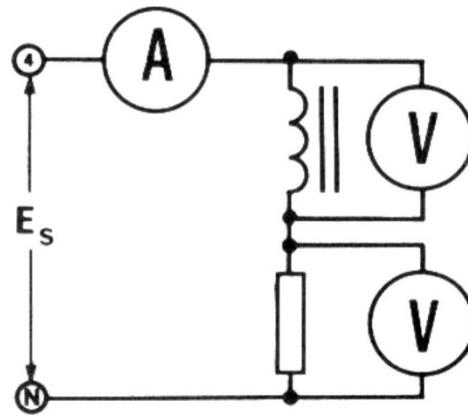
Figure 03-6.

Include an additional voltmeter (EI) to measure the input AC voltage.

Set a resistance of the load to 150 II (use two 300 D resistors wired in parallel) and the reactance to 100 f2 (use three inductances with reactance of 300 f2 wired in parallel).

Apply an input AC voltage of approximately 30 V and record the current through the circuit, input voltage, voltage drops across the circuit elements, and the phase shift between the input voltage and the circuit current.

3) Using the Variable resistance, Variable capacitance, and Variable inductance modules, construct the circuit shown in Figure 03-7:
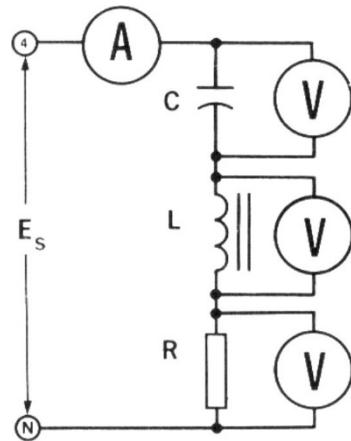
Figure 03-7.

First, connect one of the voltmeters (EI) to control the input voltage. Set the load resistance R to 100 Ω, and the reactances X_C = 150 Ω, X_L = 300 Ω.. Apply an input voltage Ed of approximately 30 V. Observe and record the exact values of input voltage, circuit current and the phase shift between E_d an I.

Next, without turning the PS OFF and readjusting the input voltage, reconstruct the circuit Figure 03-7 by connecting the voltmeter El back to its original position. Note: use extra caution when making any connections while the power in the circuit is ON even though the circuit voltages are relatively low!

Record the current through the circuit and the voltage drops across the circuit elements. Observe that the circuit current must be (almost) exactly equal to the value you recorded previously. Also note that voltage across one of the reactive elements may be higher than the input voltage!

4) Construct the circuit shown in Figure 03-8.
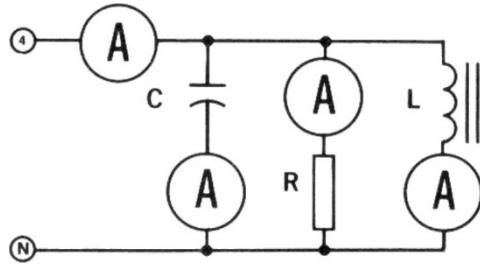
Figure 03-8.

Note: since only three ammeters are available, first replace one of the load ammeters by a wire and use this ammeter to measure the current through the circuit. Also, connect the El voltmeter to measure the input voltage.

Set the load resistance to 100 D and both load reactances to 300 D. Apply an input AC voltage of approximately 30 V and record the values of input voltage, circuit current and phase shift between them.

Turn the power OFF without touching the voltage adjustment knob. Modify your circuit such that all three ammeters will measure load currents. Turn ON the PS and record the values of currents through the resistive, capacitive, and inductive loads.

Turn OFF the PS and disassemble your circuit.

In your report:

For the values of resistance and reactance used in Part 1, calculate the load impedance and the phase angle between the input voltage E, and the circuit current. For the measured input voltage and the calculated impedance, evaluate the circuit current. Is the calculated value of circuit current approximately equal to its measured value? Using the calculated circuit current, calculate the voltages across the resistor and the capacitor. Are these values approximately equal to the values measured in Part 1? Discuss possible sources of discrepancy.

2. For the values of resistance and reactance used in Part 2, calculate the load impedance and the phase angle between the input voltage E and the circuit current. For the measured input voltage and the calculated impedance, evaluate the circuit current. Is the calculated value of circuit current approximately equal to its measured value? Using the calculated circuit current, calculate the voltages across the resistor and the capacitor. Are these values approximately equal to the values measured in Part 2? Discuss possible sources of discrepancy.

3. For the values of resistance and reactances used in Part 3, calculate the load impedance and the phase angle between the input voltage E, and the circuit current. For the

measured input voltage and the calculated impedance, evaluate the circuit current. Is the calculated value of circuit current approximately equal to its measured value? Using the calculated circuit current, calculate the voltages across the resistor, the inductor, and the capacitor. Are these values approximately equal to the values measured in Part 3? Discuss possible sources of discrepancy. Assuming that reactances of inductive and capacitive loads are both equal to 150 D, predict and report the value for the load impedance.

4. For the values of resistance and reactances used in Part 4, calculate the load impedance and the phase angle between the input voltage Ed and the circuit current. Are the calculated and measured values of the phase shift approximately equal? Using the measured input voltage and the values of resistance and reactances set for the loads, calculate the currents through each load. Do the measured values of load currents approximate their calculated values? Calculate the total current flowing through the circuit and compare it to the value you measured in Part 4. Are they approximately equal? Discuss possible sources of discrepancy.

Lab 2: <u>3-phase circuits.</u>

Objective: to *study voltage-current relationships in 3-phase circuits,' to learn to make delta and Y connections,' to calculate and measure real, apparent, and reactive powers.*

Equipment: Power Supply, DAI, Variable resistance (8311), Variable inductance

Theory:

The total 3-phase power supplied to a 3-phase load is a sum of powers dissipated by each of the load resistors and is constant if the load is balanced. This property makes 3-phase circuits quite attractive. Therefore, it is important to ensure that the load is balanced.

Since our PS is Y-connected, the ratio of line-to-line voltage to line-to-neutral must approximately

Denoting the impedance angle as 6, the real three-phase power can be calculated

$$P = \sqrt{3} E_{line} I_{line} \cos \theta = 3 \frac{E_{load}^2}{R}$$

The reactive three-phase power can be calculated

$$Q = \sqrt{3} E_{line} I_{line} \sin \theta = 3 \frac{E_{load}^2}{X}$$

The apparent three-phase power can be calculated as:

$$S = \sqrt{3} E_{line} I_{line} = \sqrt{P^2 + Q^2}$$

The power factor is

$$PF = \cos \theta = \frac{P}{S}$$

See class notes for definitions of real, reactive, and apparent powers.

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Experiment:

Part I — **resistive load**

1) Using the Power Supply (PS) and the DAI module (Metering window), measure following line-to-line voltages:
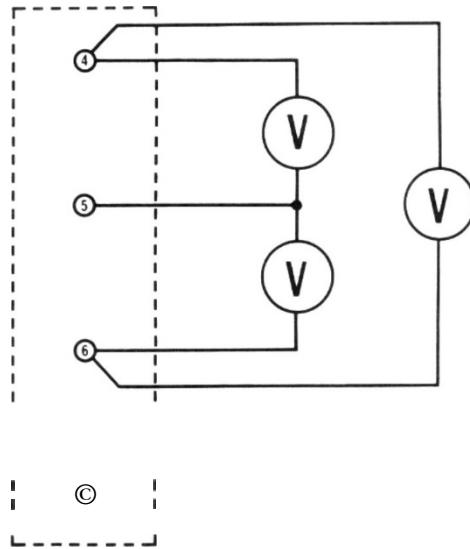
Figure 02-1

To do this, connect three AC voltmeters to the indicated terminals of PS, turn the and adjust its output voltage to its highest value (turn the voltage adjusting knob to its most right position). Record these values of line-to-line voltage.

2) Turn the power OFF and reconnect three voltmeters to measure the voltage from each

3) Start the Oscilloscope and observe three line-to-neutral voltages. What do you conclude regarding the phase shift between them? Export your Oscilloscope data to a file.

4) Construct the following circuit using the "Variable resistance"
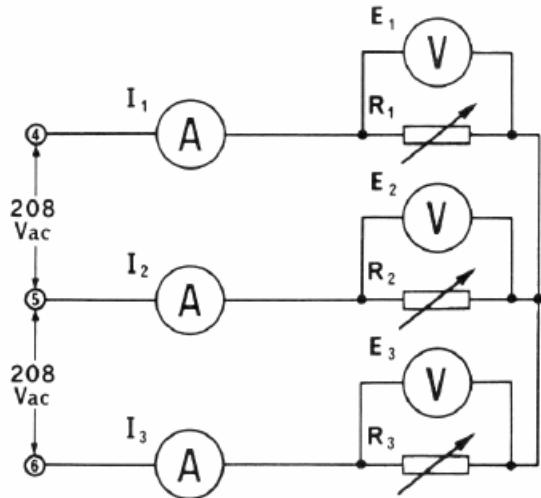
Figure 02-2

Notice that this circuit represents a "Y"-connected load. Set the load resistance to 600 Ω and apply a voltage of 120 V (line-to-neutral). In the metering window, turn ON three power meters and set them to Watts. Record the values to a Data table.

5) Connect the "A"-circuit as shown in Figure 02-3:
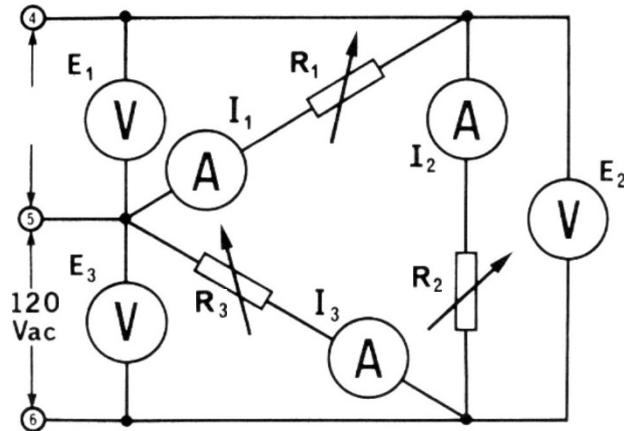
Figure 02-3

To test that the circuit is connected correctly, turn all load resistors OFF (all switches in lower positions), apply an input voltage of approximately 30 V and then turn ON the load switches for 600 Ω resistors one after another. While doing this, the corresponding ammeters must start reading non-zero currents. When all three load resistors (of equal ratings) are connected, the currents reported by three ammeters should be approximately equal. Note: in this configuration, ammeters read the load currents.

Once the correct wiring is verified, apply an AC voltage of 120 V (while controlling input voltages by the voltmeters) and record values of voltages, currents, and powers your Data table. Turn the PS OFF.

6) Reconnect the AC ammeters to read the line currents as depicted in Figure 02-4.
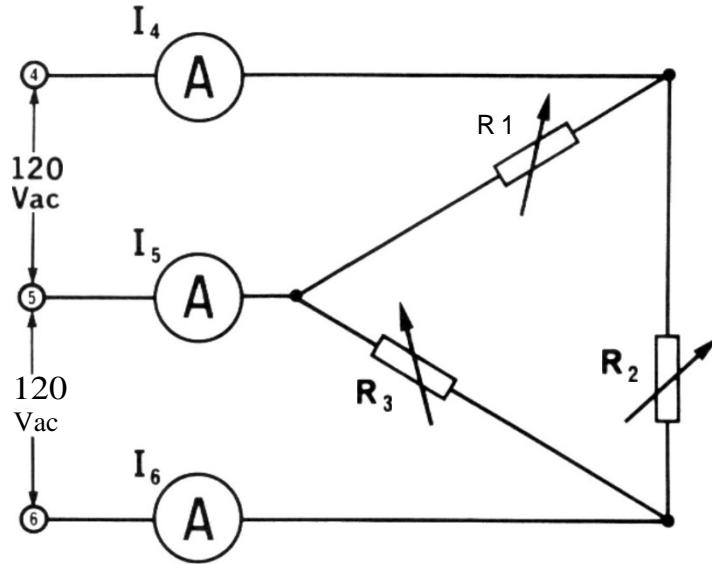
Figure 02-4

Leave the voltmeters in the circuit to read the line-to-line voltages as in Figure 2-3. Apply an AC voltage of 120 V and record values of voltages, currents, and powers to your Data table. Turn the PS OFF.

7) Construct a "Y"-connected load similar to one depicted in Figure 02-2 but without Any meters. Connect the load's neutral to the neutral of PS through the ammeter. Set three load resistances to 600 G and apply an input voltage of approximately 30 V. The current through the neutral wire must be approximately zero since the load is balanced. Next, unbalance the load by inserting a 1200 G resistor in parallel to one of the load resistors. Do you observe any changes in the value of current?

Part II — **inductive load**

8) Construct the "Y"-connected load as indicated in Figure 02-5:
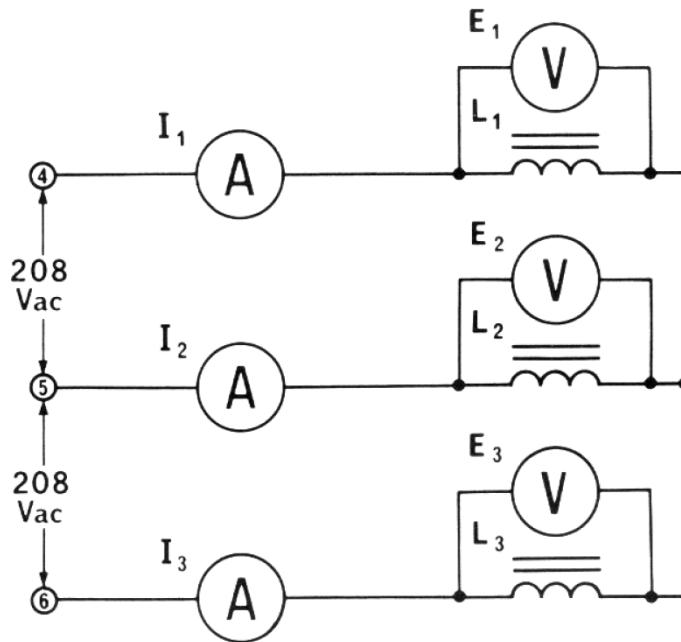
Figure 02-5

Set the power meters in the Metering window to measure VARs, set each inductance section to reactance of 600 Ω and apply the AC voltage of 120 V line-to-neutral. Record the values of line currents, voltages across the inductances, and reactive powers for each inductive load to your Data table. Turn the PS OFF.

8) Construct the circuit shown in Figure 02-6:
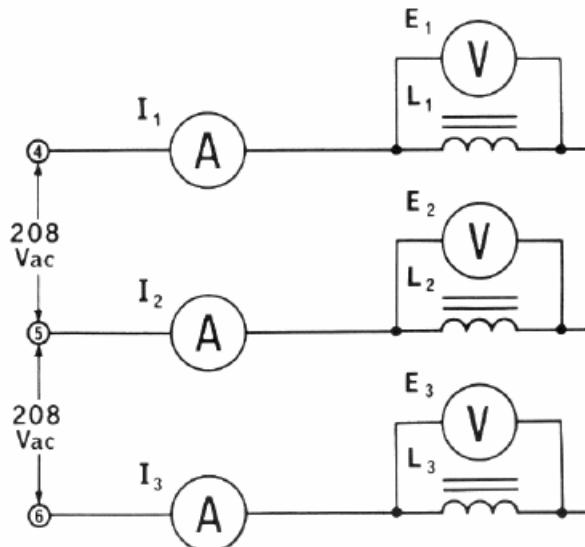
Figure 02-6

After verifying the correct wiring, set the resistance of each load to 600 Ω and the reactance of each inductive load to 600 D. Apply an AC voltage of 120 V line-to-neural and record the measured values of line currents, voltages across the inductances, and reactive powers to your Data table. Turn the PS OFF.

10) Reconnect voltmeters as shown in Figure 02-7
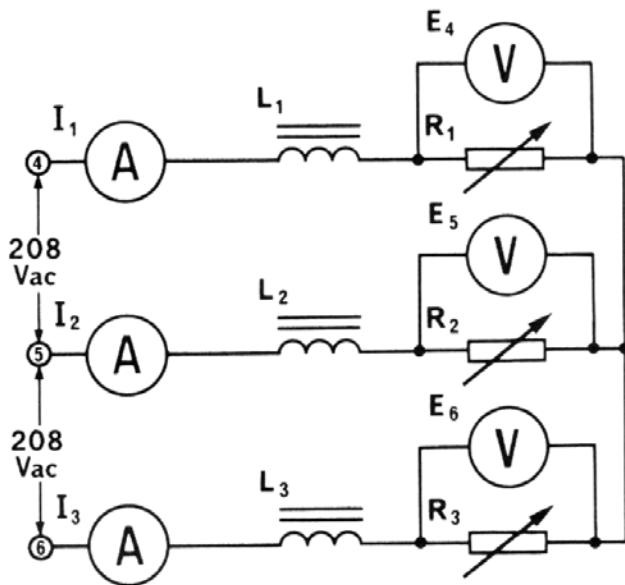
Figure 02-7

Apply an AC voltage of 120 V line-to-neural and record the measured values of line currents, voltages across the resistors, and real powers dissipated in the three resistors to your Data table. Turn the PS OFF. Save the Data table and disassemble your circuit.

In your report:

Calculate the ratio of the average line-to-line voltage to the average line-to-neutral voltage for measurements in Parts 1 and 2. Does this ratio approximately equal to

Using Matlab and the data exported from the Oscilloscope, plot (on the same axes) the three line-to-neutral voltages. What is the approximate phase difference between them?

Using Matlab and the Data table you recorded in Part 4, report the line currents and the voltages across the load resistors you have measured. Are the voltages and currents reasonably well balanced? Calculate the power dissipated by each load and compare it to the measured values. Discuss possible sources of discrepancy. Calculate the total 3-phase power.

4. Using Matlab and the Data table you recorded in Part 5, report the load currents and the line-to-line voltages you have measured. Are the voltages and currents reasonably well balanced? Calculate the power dissipated by each load and compare it to the measured values. Discuss possible sources of discrepancy. Calculate the total 3-phase power.

5. Using Matlab and the Data table you recorded in Part 6, report the line currents you have measured. Calculate the average load current and the average line current. Calculate the ratio of the average line current to the average load current. Is this ratio approximately equal to?

6. Describe your observations in Part 7. What do you conclude regarding unbalancing the load?

7. Using Matlab and the Data table you recorded in Part 8, report the line currents and the voltages across the loads that you have measured. Are the voltages and currents reasonably well balanced? Calculate the reactive power for each of the inductive loads and compare it to the measured values. Discuss possible sources of discrepancy. Calculate the total 3-phase reactive power.

8. Using Matlab and the Data table you recorded in Parts 9 and 10, report the line currents and the voltages across the inductances and across the resistors that you have measured. Are the voltages and currents reasonably well balanced? Calculate the reactive power for each of the inductive loads and compare it to the measured values. Calculate the real power for each of the resistive loads and compare it to the measured values. Discuss possible sources of discrepancy. Calculate the total 3-phase real power. Calculate the total 3-phase reactive power. Calculate the total 3-phase apparent power. Calculate the power factor using the total 3-phase real and apparent powers.

LABORATORY 3

THREE-PHASE CIRCUITS) ANALYSIS AND POWER MEASUREMENT

OBJECTIVES

The main objectives of this lab session are to show how to connect two-wattmeter to measure three-phase real power, to compare wye and delta 3ϕ -loads, and study the effect of reactive load on the circuit power factor. The student will also learn how to relate the line and phase voltages and currents in three-phase circuits.

The specific objectives of this lab session are:
1) To learn how to make wye and delta loads connection.
2) To study the relationship between line and phase voltages, and line and phase currents in wye and delta configuration.
3) To learn how to connect and operate two-wattmeter to measure three-phase power.
4) To learn how to determine the reactive, apparent power and power factor in three-phase circuits using the two-wattmeter method.
5) To connect wye-delta parallel loads.
6) To calculate power in three-phase circuits.

IIEFERENCES
1) Guru, B.S. and Hiziroglu, H.R. *Electric machinery and transformers,* 3 ed., Oxford University Press, U.S.A., 2001

INTRODUCTION

Three-phase circuits are no more complicated to solve than single-phase circuits. In the majority of cases they are symmetrical and have identical impedances in each of the three branches. Each brand can be treated exactly like a single-phase circuit, because a balanced three-phase circuit is simply a combination of three single-phase circuits. Anyway, both unbalanced and balanced conditions are covered in this session.

Electric power is almost entirely generated, transmitted, and distributed in the form of three-phase power. The advantages of three-phase alternating current electric systems are:
1) An AC voltage supply can be changed to any desired value by means of transformers. This permits generation, transmission, distribution and utilization of electric energy at the most economical and safe voltage level.
2) Three-phase windings make more efficient use of the iron and copper in generators and motors. Therefore, three-phase motors, generators, and transformers are simpler, cheaper, and more efficient than their single-phase counterparts.
3) A three-phase transmission line requires less copper than a single-phase line to transmit a given amount of power at a given voltage over a given distance. This means that three-phase transmission lines can deliver more power for a given weight and cost.

4) Three-phase motors have a constant net torque, whereas single-phase motors (except commutator motors) have a pulsating torque.
5) Single-phase motors (except commutator motors) are not self-starting, whereas three-phase are.

Alternating current is universally used throughout the world for driving motors and for powering electrical equipment. A characteristic of the AC current is that its direction is always reversing or alternating.

Depending on the power supply, the voltage waveform may be sinusoidal, square, triangular, etc. Sinusoidal waveforms have proved to give the highest efficiency when operating transformers, motors and generators. Also, in a linear circuit, a sinusoidal voltage waveform always produces a sinusoidal current waveform.

A three-phase load can be connected to the supply in delta or in wye. A balanced three-phase system consists of three sinusoidal ac voltages and/or currents with equal amplitudes and 120' phase shifts with respect to one another.
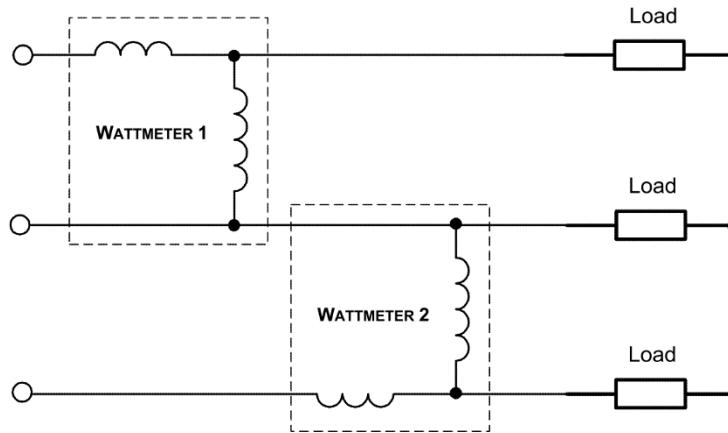
In three-phase systems knowledge of the total power delivered to the load is important. If the system is balanced and the power delivered to one phase can be measured by means of one wattmeter, the total power is three times the single wattmeter reading. To measure the power delivered by a three-phase, 4-wire system, three single-phase wattmeter could be connected to measure the power in each of the phases and the readings added to obtain the total power. For the case of three-phase load 3-wire system, it is not possible to do this. A solution is to use two-wattmeter that are connected in a special way called the two-wattmeter method'. In the two-wattmeter method, the algebraic sum of the two-wattmeter readings gives the value of the total power, whether the system is balanced or not.

Mathematical analysis shows that connecting the current coils to measure the current in two of the three lines, while connecting the two voltage coils between these lines and the remaining line, allows the total power delivered by a three-phase 3 wire system to be measured. The total power is the algebraic sum of the two-wattmeter readings, and this method of power measurement is known as the two-wattmeter method. In appendix B, the reader can find the two-wattmeter method analysis.

For balanced loads at unity power factor, the indications of the two-wattmeter will be identical. When the load power factor is 50 percent, one meter will indicate zero and the other will indicate the total three-phase power. At power factors lower than 50 and higher than 0 percent, one meter reading will be negative. At power factors lower than 100 and higher than 50 percent, both meter readings will be positive but not equal. At zero power factor the wattmeter will have identical indications but have opposite signs, indicating zero power.

The two-wattmeter method only applies for three-phase three wire systems. If a three-phase four-wire system is to be measured, we must use three single—phase wattmeters to read power.

FIGURE 3.1

The three-phase power measures in the machine lab are going to be calculated digitally. Two ac ammeters and two ac voltmeters are needed for the two-wattmeter method. See Figure 3.4 and preview the connections for the two power readings. Polarity-marked shown are very important to make the correct calculation of power. Once the connection is made, the computer can calculate the real, reactive and apparent power.

The apparent power, reactive power and power factor in a three-phase system can be determined by the equations:

$$S_{3\phi} = \sqrt{3} \times I_{line} \times V_{line}$$

$$Q_{3\phi} = \sqrt{S_{3\phi}^{2} - P_{3\phi}^{2}}$$

$$p.f = \frac{P_{3\phi}}{S_{3\phi}}$$

In these experiments, the student is introduced to both delta and wye AC circuits containing reactive elements and fed from a fixed AC source.

A I   MARKABLE SINGLE-PHASE TO 3-PHASE TRANSFORMATION

It sometimes happens that a large single-phase unity power factor load has to be connected to a 3-phase line. This can create a badly unbalanced system. However, it is possible to balance the three phases perfectly by connecting a capacitive reactance and an inductive reactance across the other two lines. The reactance must each have impedances times greater' than the value of the load resistance Figure 3.2.

---

[3] $| X_L| = R \sqrt{3}$, and $| X_C| = R \sqrt{3}$
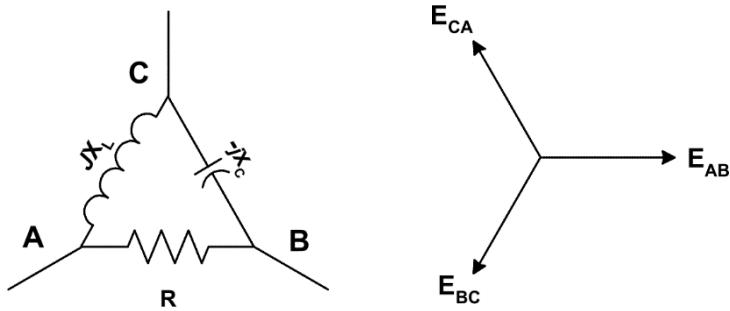
FIGURE 3.2

Furthermore, given the phase sequence[4] f the line voltages, it is essential that the three impedances be connected as indicated. If the capacitive and inductive reactances are interchanged, the 3-phase system becomes completely unbalanced.

PRELAB

1) Read appendix about the two-wattmeter method.
2) For the circuit shown in Figure 3.3 with $R_L = 85.7\Omega$ and $V_s = 120$ V$_{ac}$
   Determine:
   - a)   The line and phase load voltages.
   - b)   The three-phase power delivered by the power source.
   - c)   The power dissipated by each resistance.
   - d)   What is the power factor of the load?
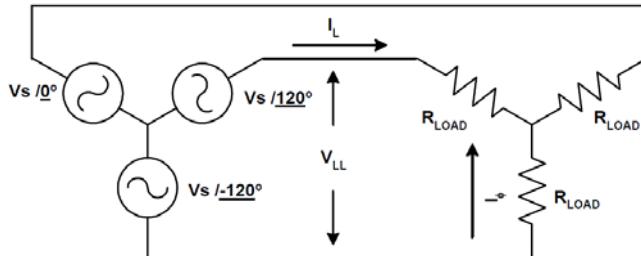
FIGURE 3.3

3) Use the appendix information on the power supply and three-phase wattmeter to analyze the circuit shown in Figure 3.4 if:
   $V_{12} = V_{23} = V_{34} = 208$ V
   $WI = 70$ W (WI & W2 are the lectures of the two-wattmeter set
   $W_2 = 150$ W
   $PF = 0.65$ lagging, determine:
   - a) Find the line and phase currents.
   - d) Calculate the line and phase load voltages.
   - e) Find the phase impedance.

I) Determine the total power delivered by the power source.
g) Determine the reactive power consumed by each load.
h) The instantaneous power supplied by the source and the instantaneous power consumed by each load. Sketch both of them and discuss the difference.
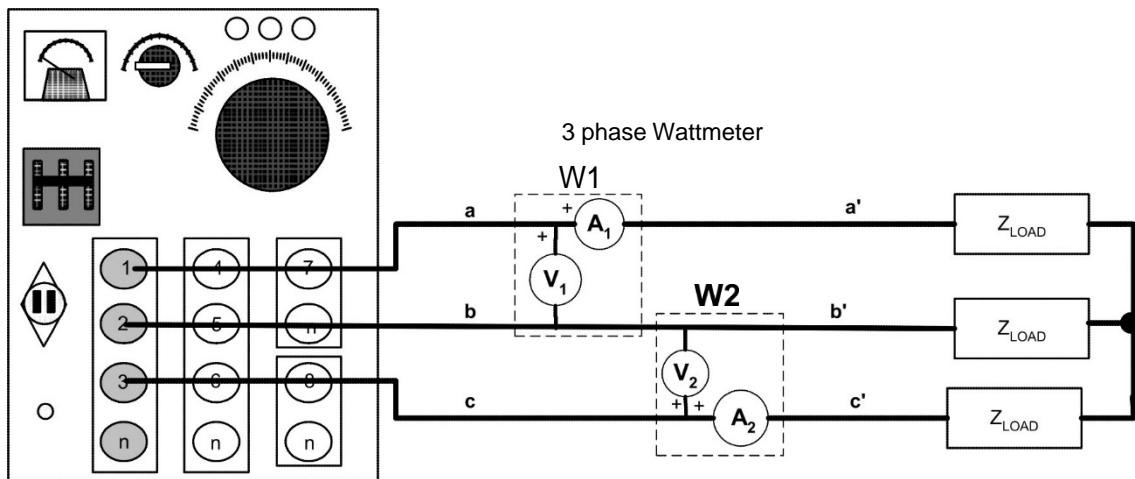
FIGURE 3.4

4) Place a delta connected capacitive load (ZC = 100 Ω) in parallel to the previous resistive load as shown in Figure 3.5. However, the load is now connected to the variable ac output 4, 5, and 6 and the line-to-line voltage is adjusted to 120Vac. Determine:
   a)   The wattmeters reading (W and W each) .
   b)   IT. IR and Ic-
   c)   Calculate the per-phase capacitance.
   d)   Calculate the line and phase voltages for the resistive and capacitive loads.
   e)   Determine the real power delivered by the power source.
   f)   Determine the reactive power delivered by the power source.
   g)   Determine the power factor.
   h)   What is the effect of adding a capacitive load to the previous circuit?
   i)   The instantaneous power supplied by the source and the instantaneous power consumed by each load. Sketch both of them and discuss the difference.

' Use the internal wattmeter connection shown in Figure 3.2 and consider V;=120/0 V, V =120/—120 V and V,=l20/l20   V
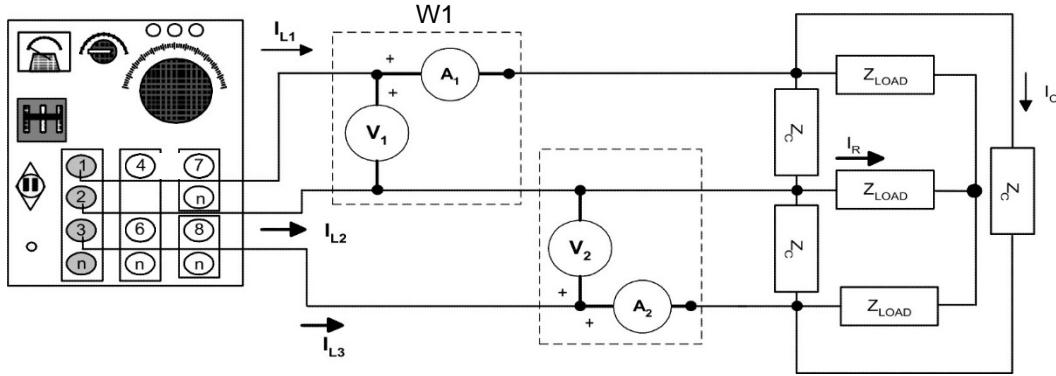
FIGURE 3.5

5) Now, connect an inductive load ($Z_L = 100\Omega$) in series with the parallel delta-wye load as shown in Figure 3.6. **For this** connection V **ine** to line **50Vac:**

  a) Draw the circuit diagram for this load connection (assume that the power supply is wye connected).

  b) Find IT. IR, I_L and Ic-

  c) Calculate the per-phase inductance.

  d) Calculate the line and phase load voltages at the resistive And capacitive loads.

  e) Determine the three-phase real power delivered by the power source.

  I) Determine the three-phase reactive power delivered by the power source.

  g) Determine the power factor.

  h) Determine the wattmeter's readings.

  i) The instantaneous power drawn by the total load.
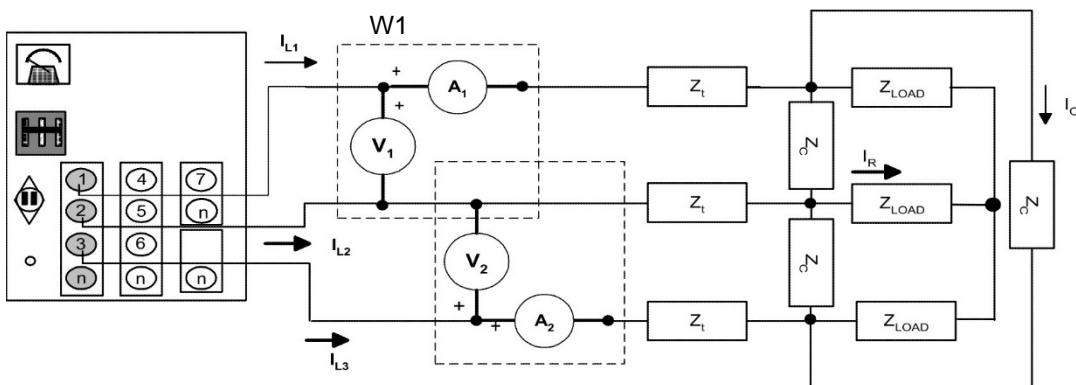
FIGURE 3.6

6. A 300Ω resistance is connected between phases A and B of a 120V, 3-phase line, wherein $E_{AB} = 120 \ \llcorner 0$ V, $E_{BC} \ 120 \ \llcorner -120$ V, $E_{CA} = 120 \ \llcorner 120$ V. Calculate the load currents and line currents:

  a.When the single-phase load is connected alone on the 3-phase line.

  b. When balancing reactance's are added across the remaining lines, as shown in Figure 3.2.

Experiment 3.1   Wye Connected Loads

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Resistance Module	EMS 8311
Inductance Module	EMS 8321
Capacitance Module	EMS 8331
Data Acquisition Interface Module	EMS 9062

PROCEDURE

Step 1: Connect the circuit shown in Figure 3.7 using R = 300 Ω XL = 300 Ω, XC= 400 Ω. Use the fixed AC output of the power supply as your power source. Use variable terminals 4,5,6 at 120 Vac. DO NOT CONNECT THE NEUTRAL OF THE POWER SUPPLY TO THE CIRCUIT!

Step 2: Ensure that the DAI LOW POWER INPUT is connected to the main supply, and the flat cable from the computer is connected to the DAI. Connect the DAI'S three-phase wattmeter (two-wattmeter method) configuration to measure the power consumed by the load as shown in Figure 3.7.

Step 3: Substitute the AC ammeters by the marked leads (one at a time), as shown in Figure 3.8 to measure currents I_1, I_2, and I_3.

Step 4: Turn on the power supply and complete the columns marked as "Y load" in Tables 3.1 and 3.2.

Step 5: Turn off the power supply.
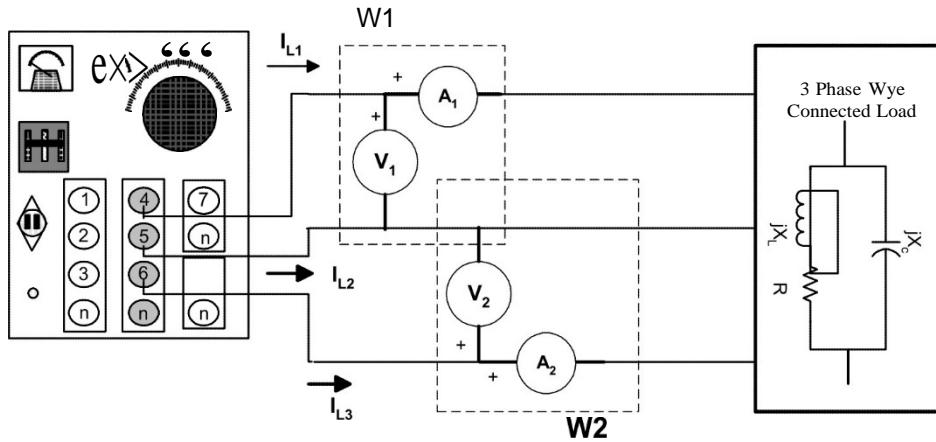
FIGURE 3.7

Step 6: Substitute the AC ammeter to measure I_{C1}, I_{C2} and I_{C3} as shown in Figure 3.8. Repeat steps 4 and 5.

Step 7: Substitute the AC ammeter to measure I_{R1}, I_{R2} and I_{R3} as shown in Figure 3.8. Repeat steps 4 and 5. Turn off the power supply

Step 8: Substitute the AC ammeter as shown in Figure 3.8 to measure I_{L1}, I_{L2} and I_{L3}

Step 9: Now measure the voltages VR, VxL, and Vxc using your ac voltmeter module. Complete Tables 3.1 and 3.2.
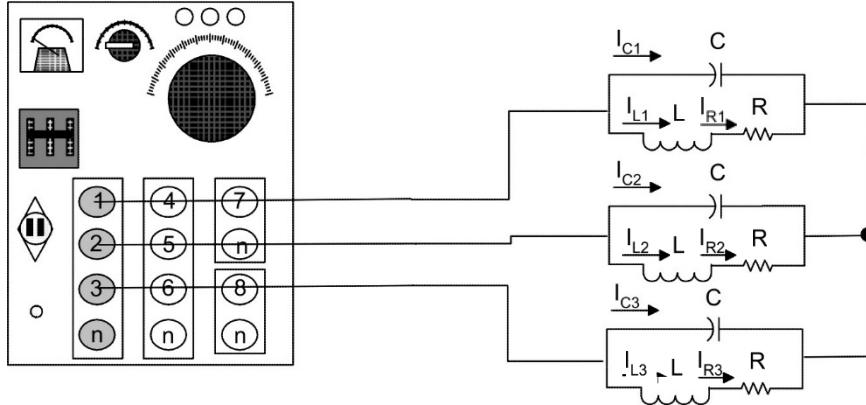
FIGURE 3.8

Step 10: Now, using your single-phase wattmeter configuration, measure the power in phase 1 as shown in the Figure 3.9. Notice that the phase-l's current pass through the current coil (the DAI II 's terminals), and the voltage coil (DAI El's terminals) is connected in parallel with phase 1. Write your measure at table 3.2.

Step 11: Now, using the same procedure as step 10, connect the single-phase wattmeter in phase 2. Write your measure at table 3.2.

Step 12: Measure the power consumed in phase 3 using your single-phase wattmeter. Write your measure at table 3.2.

Step 13: Now sum the power values you obtained in steps 10 to 12. Compare your result with the measure of the three-phase wattmeter.

FIGURE 3.9

Question 1: Are the sum close or equal to **the three-phase wattmeter reading? Explain briefly.**

	Y LOAD	Δ LOAD
I_1		
I_2		
I_3		
I_{C1}		
I_{C2}		
I_{C3}		
I_{R1}		
I_{R2}		
I_{R3}		
I_{L1}		
I_{L2}		

I_{L3}		
V_{R1}		
V_{R2}		
V_{R3}		
V_{XL1}		
V_{XL2}		
V_{XL3}		
V_{XC1}		
V_{XC2}		
V_{XC3}		

Table 3.1

	Y LOAD	Δ LOAD	UNBALANCED LOAD
REAL POWER 3Φ			
REACTIVE POWER 3 Φ			
APPARENT POWER 3 Φ			
POWER FACTOR 3Φ			
$W_{\phi 1}$			
$W_{\phi 2}$			
$W_{\phi 3}$			
$W_{\phi 1} + W_{\phi 2} + W_{\phi 3}$			

TABLE 3.2
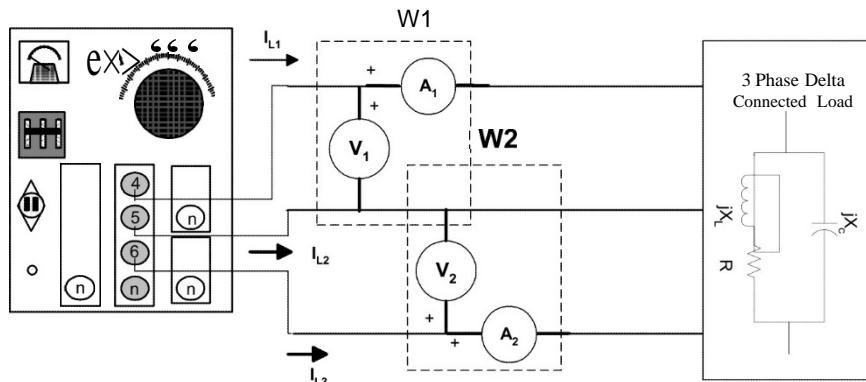
Experiment 3.2   Delta Connected Loads

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Resistance Module	EMS 8311
Inductance Module	EMS 8321
Capacitance Module	EMS 8331
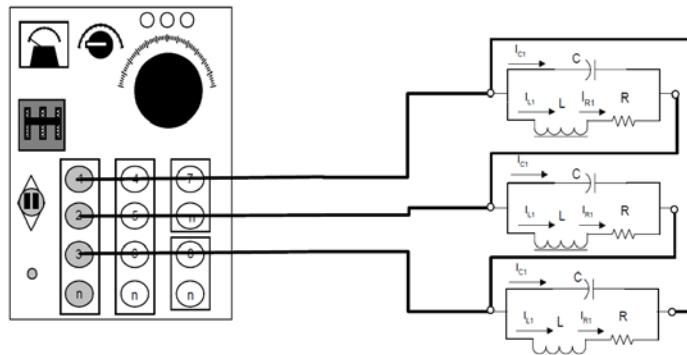
PROCEDURE

Step 1: Connect the circuit shown in Figure 3.10 using R=300Ω X_L= 300Ω, and X,= 400Ω. Use the fixed AC output of the power supply as your power source, terminals 4,5,6.

Step 2: Substitute the AC ammeters (one at a time), as shown in Figure 3.11 to measures currents I , I, and I .

Step 3: Connect the DAI'S TWO-WATTMETER configuration to measure three-phase power consumed by the load.

Step 4: Turn on the power supply and complete the columns marked as "A load" in tables 3.1 and 3.2.

Step 5: Turn off the power supply.

Step 6: Substitute the AC ammeter by the marked leads as shown in figure 3.11 to measure I, , I, , and I, .
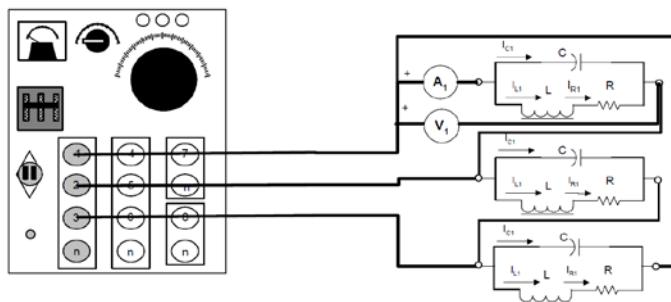
FIGURE 3.10

Step 7: Substitute the AC ammeter as shown in Figure 3.11 to measure I_{Rl}, I_{R2}. and I_{R3} Repeat step 4 and 5.

Step 8: Substitute the AC ammeter as shown in Figure 3.11 to measure I_{L1}, I_{L2}. and I_{L3}. Repeat step 4 but DO NOT TURN THE POWER SUPPLY.

Step 9: Now measure the voltages VR, x_L, and V_{xc} using your ac voltmeter module. Complete Tables 3.1 and 3.2.

FIGUREd.11

Step 10: Now, using your single-phase wattmeter configuration, measure the power in phase 1 as show in the FIGURE 3.12. Notice that the phase-1's currents pass through the current coil, and the voltage coil is in parallel with phase 1. Write your measure at table 3.2.

FIGURE 3.12

Step 11: Now, using the same procedure as step 10, connect the single-phase wattmeter in phase 2. Write your measure at table 3.2.

Step 12: Measure the power consumed in phase 3 using your single-phase wattmeter. Write your measure at table 3.2.

Step 13: Now sum the power values you obtained in steps 10 to 12. Compare your result with the measure of the three-phase wattmeter.

Question 2: Are the sum closed equal **to the three-phase wattmeter reading? Explain Briefly**
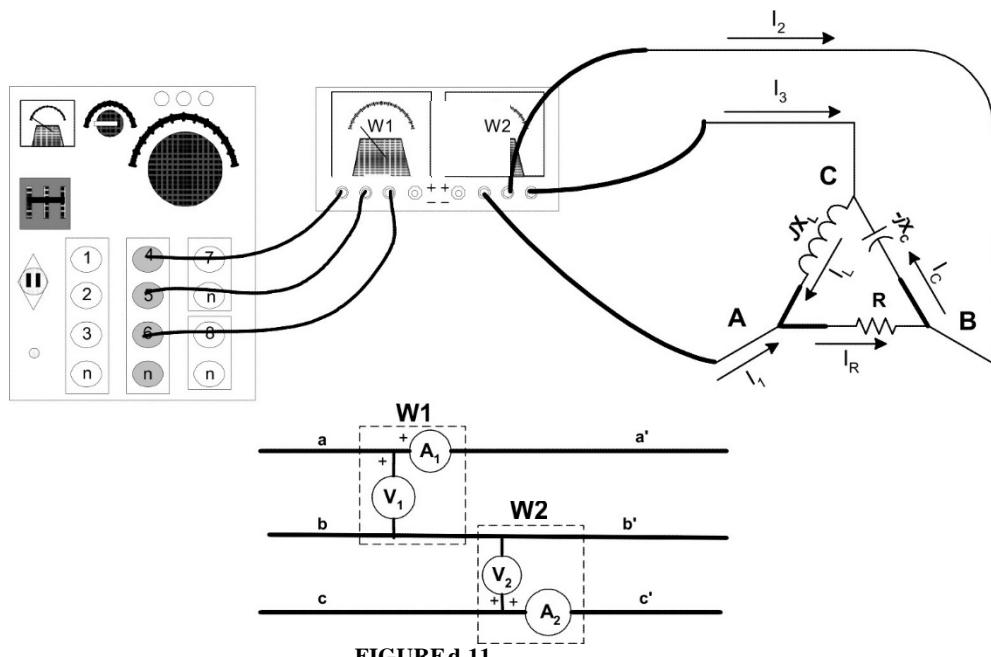
Experiment 3.3   Unbalanced 3-phase loads

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Resistance Module	EMS 8311
Inductance Module	EMS 8321
Capacitance Module	EMS 8331

PROCEDURE

Step 1: Connect the circuit shown in Figure 3.11 using R=300Ω , XL=600Ω, and $X_C = 600\Omega$. Use the variable AC output of the power supply, terminals 4,5and 6, as your power source. The WI and W2 block substitutes the Two wattmeter configuration.

FIGURE d.11

Step 2: Substitute the AC ammeters (one at a time), as shown in Figure 3.11 to measure currents I , If and I,.

Step 3: Connect the three-phase wattmeter to measure the power consumed by the load.

Step 4: Turn on the power supply. Adjust the line-to-line voltage to 120Vac.

Step 5: Complete Tables 3.2 and 3.3.

Step 6: Turn off the power supply.

Step 7: Substitute the AC ammeter by the marked leads as shown in Figure 3.11 to measure IR. I_n and I_L Turn on the power supply and complete Table 3.3.

'The Wl and W2 block substitutes the two wattmeter configuration for three phase power reading. Check Prelab's problem 3 for the internal connection of the W1 and W2 block.

Step 8: Now measure the voltages   Line-Line and Vj using your ac voltmeter module. Complete Table 3.3.

Step 9: Now, using your single-phase wattmeter, measure the power in the R-load phase as you learned in the delta load experiment. Write your measure in Table 3.2 as W .

Step 10: Now, using the same procedure as step 9, connect the single-phase wattmeter in the L-load phase. Write your measure at table 3.2 as W ,.

Step 11: Measure the power consumed in The C-load phase using your single-phase wattmeter. Write your measure at table 3.2 as W .

Step 12: Now sum the power values you obtained in steps 9 to 11. Compare your result with the measure of the three-phase wattmeter.
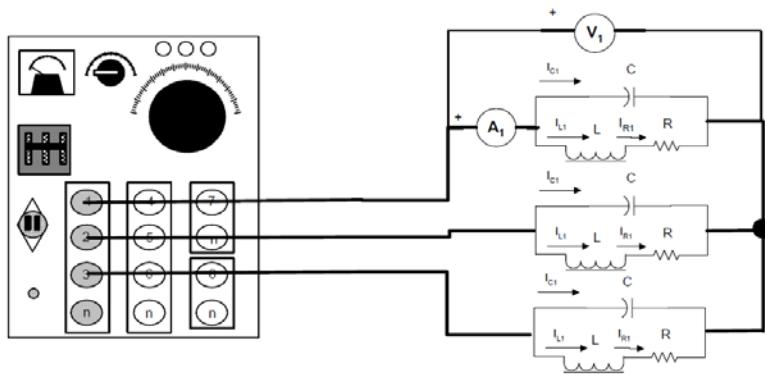
Question 3: Are the Wj, and W ,**readings equal to zero? Explain briefly.**

Question 4: Why **is this connection unbalanced?**

Question 5: If we want **to connect this R-load to the power supply, which are** the correct **values of capacitance and inductance** we need to balance the 3-phase line currents?

UNBALANCED ROAD

I_1	
I_2	
I_3	
I_R	
W_1	

Table 3.2

I_L	
I_C	
$V_{line-line}$	
V_ϕ	
W_2	

Table 3.3

Experiment 3.4   Delta-Wye Parallel Loads

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Resistance Module	EMS 8311
Inductance Module	EMS 8321
Capacitance Module	EMS 8331

PROCEDURE

Step 1: Connect the circuit shown in Figure 3.12. R1=R2=300Ω[7] $X_c = 400\Omega$, and XL=300Ω. Use the variable AC output of the power supply as your power source. Adjust the line voltage to 120Vac.

Step 2: Substitute the AC ammeters to measure the line current, the Z_1 current and the Z_2 current and compare them to the line current.

Step 3: Connect the three-phase wattmeter using the two-wattmeter configuration to measure the power consumed by the load. You need to have consideration of the wattmeter scale, use 750 watts for the scale.

Step 4: Turn on the power supply and complete table 3.4.

Step 5: Turn off the power supply.
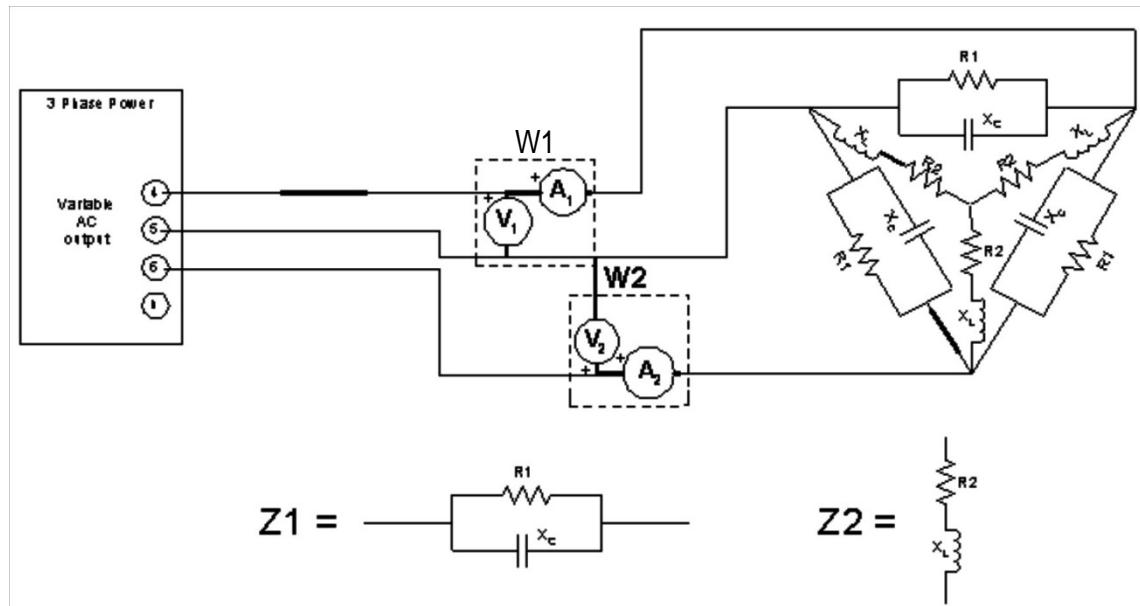
FIGURE 3.12

'Note that you will use two resistance module

I_{LINE}		$I_{Z1}+I_{Z2}$	
I_{Z1}		$\lvert I_{Z1}\rvert + \lvert I_{Z2}\rvert$	
I_{Z2}		W1+W2	

TABLE 3.4

REVIEW QUESTIONS

1. In a balanced wye-connected circuit, the
   a. Line voltages and currents equal the load values.
   b. Line voltage is $\sqrt{3}$ times greater than the phase voltage.
   c. Line voltage is $\sqrt{3}$ times smaller than the phase current.
   d. Line current is $\sqrt{3}$ times greater than the phase current.
2. In a balanced delta connected circuit, the
   a. Line voltages and currents equal the load values.
   b. Line current is $\sqrt{3}$ times smaller than the phase current.
   c. Line current is $\sqrt{3}$ times greater than the phase current.
   d. Line voltage is $\sqrt{3}$ times greater than the phase voltage.
3. What is the line-to-neutral (phase) voltage in a balanced wye-connected circuit when the line-to-line voltage is 346V?
   a. 346V
   b. 600V
   c. 200V
   d. 245V
4. What is the line current in a balanced delta-connected resistive load when the load current through each branch is 10A?
   a. 27.3A
   b. 17.3A
   c. 11.6A
   d. 5.8A
5. In a three-phase balanced circuit, the active power can be determined using two wattmeters connected according to the:
   a. Single-phase wattmeter method
   b. Three-phase wattmeter method
   c. Two-wattmeter method
   d. Apparent power method

REPORT REQUIREMENTS

1) Include the lab session text in full. All tables must be filled with ink. Photocopies won't be acceptable.
2) Compare the line and phase currents in a delta-connected load in a balanced system.
3) Compare the line and phase currents in a wye-connected load in a balanced system.
4) Compare the line and phase voltages in a delta-connected load in a balanced system.
5) Compare the line and phase voltages in a wye-connected load in a balanced system.
6) Use your data of wye load experiment to draw an accurate phasor diagram for the line voltages and currents. Compare your results to theory.
7) For the unbalanced load experiment data, draw the power triangle. Compare your results with a theoretical power triangle.
8) Summarize the 2-wattmeter method, and explain why the wattmeters readings don't have to be equal and sometimes one reading can be negative.

Lab 4: <u>Single-phase transformer operations.</u>

Objective: *to examine the design of single-phase transformers; to study the voltage and current ratios of transformers; to study the voltage regulation of the transformer with varying load.*

Equipment: Power Supply, DAI, Transformer (8341), Variable resistance (8311), Variable inductance (8321), Variable capacitance (8331)

Theory:

Transformers convert one AC voltage to other AC voltage(s). They have a primary winding and one or more secondary winding(s) wrapped around a ferromagnetic core. An important
characteristic of the transformer is its turn ratio:

$$a = \frac{N_p}{N_s} \approx \frac{E_p}{E_s} \approx \frac{I_s}{I_p}$$

Ferromagnetic cores are subject to saturation and losses. Additionally, many factors affect the operation of transformers. The type of load has a significant effect on the transformer regulation. The transformer regulation is determined as:

$$\frac{E_{2,no\,load} - E_{2,full\,load}}{E_{2,full\,load}} 100\,\%$$

Experiment:
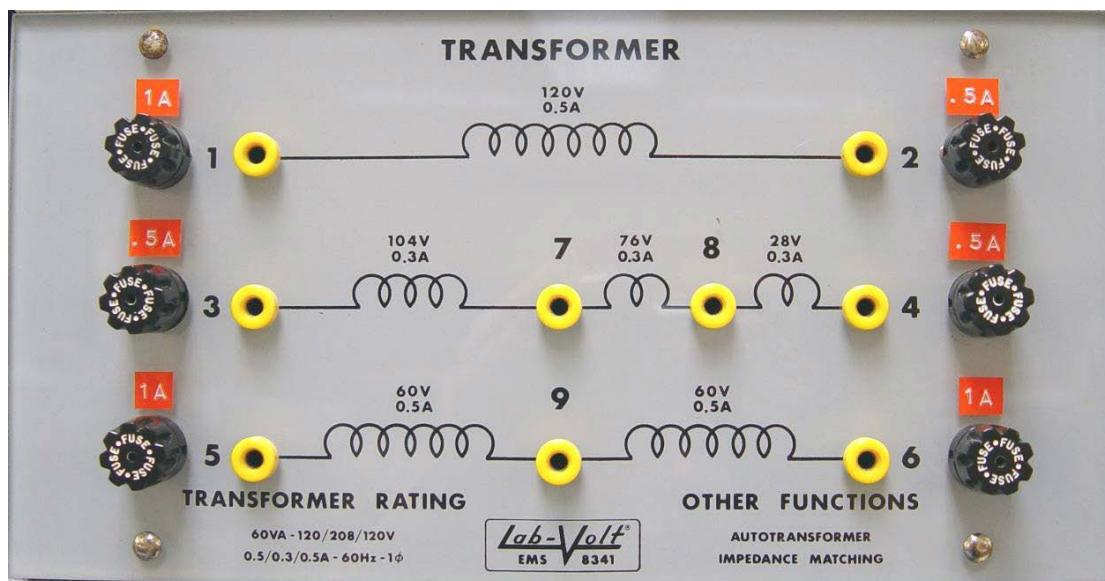
Figure 04-1

Observe that the transformer used in this experiment has three windings: 1-2, 3-4, and 5-6. The rated voltages between the terminals are listed on the front panel of the transformer module.

1) Construct the circuit shown in Figure 04-2:
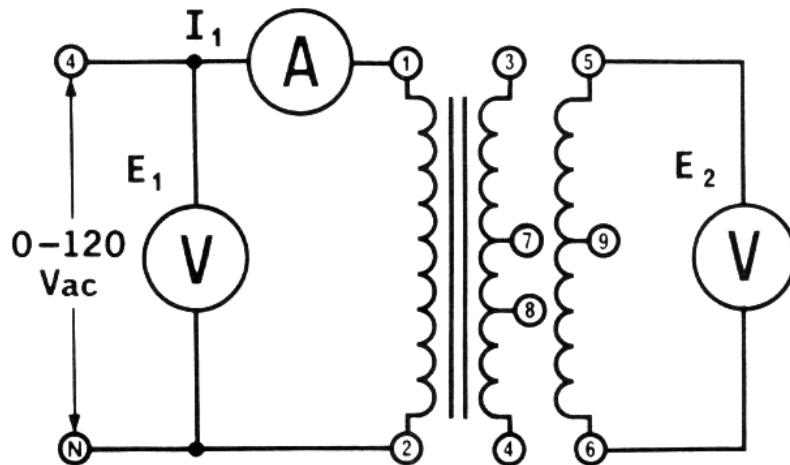
Figure 04-2

After verification of correct wiring, turn ON the PS and adjust the input voltage to 120 V AC. Measure the voltage between the transformer's terminals 5-6. Without turning OFF the power and re-adjusting the input voltage, carefully measure and record voltages between the following terminals: 5-9, 9-6, 3-4, 3-7, 7-8, and 8-4. Are voltages you measured approximately equal to the rated values? If not, report to the instructor.

2) To determine the effect of core saturation, construct the circuit shown in Figure 04-3:

Figure 04-3

Dr. Rad
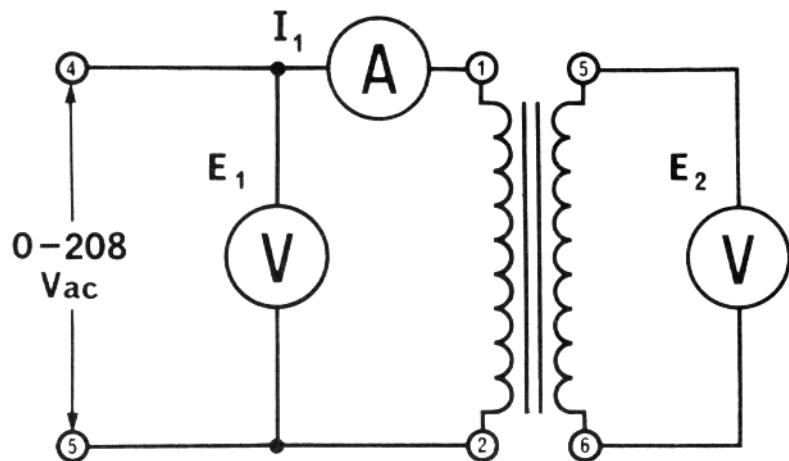
Observe that the primary transformer's winding is connected to different terminals of the PS. Turn ON the PS and adjust the input voltage to 25 V AC. Record the values for primary and secondary voltages and primary current to a Data table. Repeat similar measurements for different input voltages from approximately 50 V to approximately 200 V with steps of approximately 25 V. Record values for each measurement to your Data table.

3) We will study next the importance of polarity of windings. Construct the circuit illustrated in Figure 04-4. Observe that the input voltage is supplied this time to another winding, i.e. 3-4.
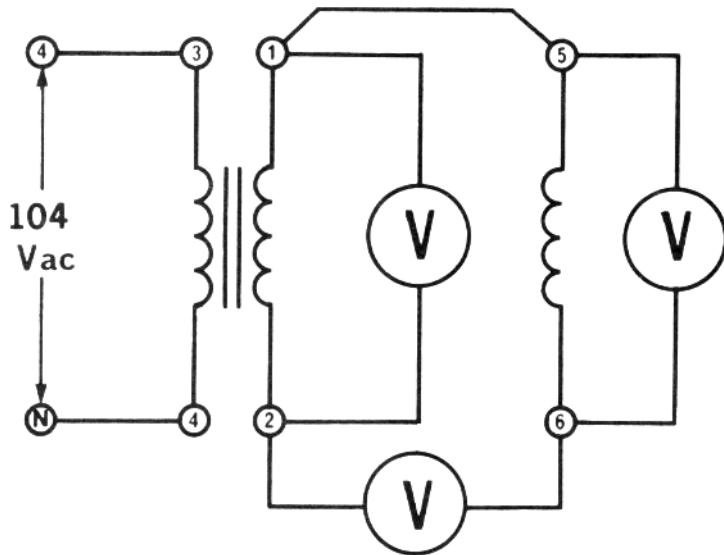
Figure 04-4

Observe that the windings 1-2 and 5-6 are connected in series. After verification of correct wiring, apply an input voltage of approximately 104 V AC. The input voltage can be controlled by the PS voltmeter. Measure and record the voltages across the following terminals: 1-2, 5-6, and 2-6.

Turn OFF the PS and rewire the circuit as shown in Figure 04-5.

Dr. Rad
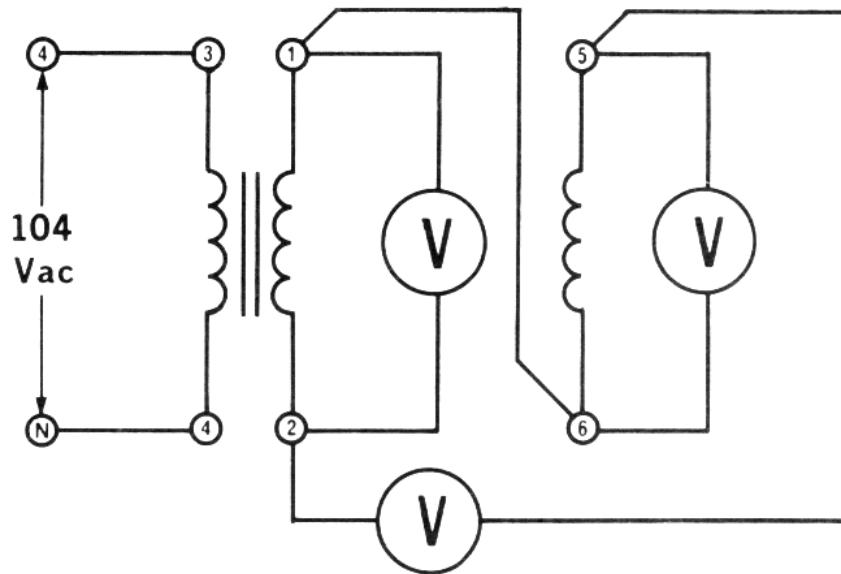
Figure 04-5

After verification of correct wiring, apply an input voltage of approximately 104 V AC. Measure and record the voltages across the following terminals: 1-2, 5-6, and 2-5.

4) To study the transformer regulation, construct the circuit shown in Figure 04-6.
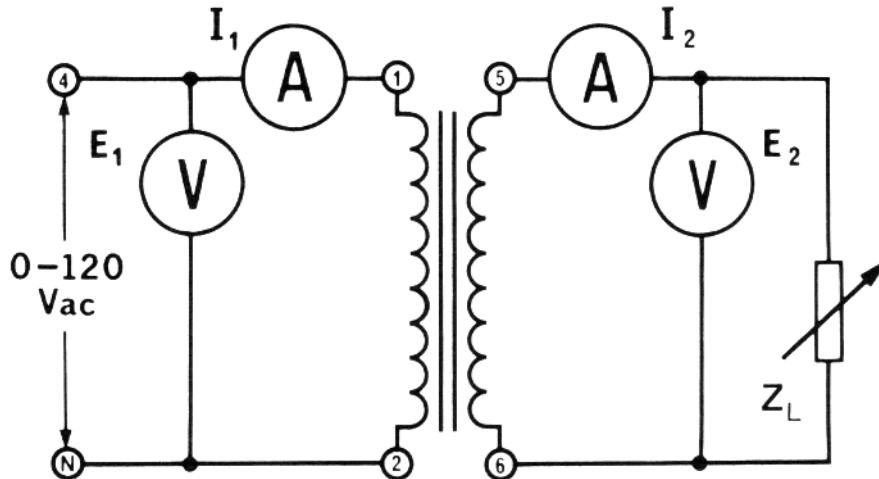
Figure 04-6

Using a resistive load (a Variable resistance module) with all the switches in the OFF position, turn ON the PS and adjust the input voltage to 120 V.

For the following set of load resistances: ∞ (all switches are OFF), 1200 Ω, 600 Ω, 400 Ω (1200 Ω and 600 Ω in parallel), 300 Ω, and 200 Ω (600 Ω and 300 Ω in parallel) measure

primary and secondary voltages and currents. Record the values for each measurement in a Data table.

5) Replace the resistive load by an inductive load (a Variable inductance module). With all the switches in the OFF position, turn ON the PS and adjust the input voltage to 120 V.

For the following set of load reactances: ∞ (all switches are OFF), 1200 Ω, 600 Ω, 400 Ω (1200 Ω and 600 Ω in parallel), 300 Ω, and 200 Ω (600 Ω and 300 Ω in parallel) measure primary and secondary voltages and currents. Record the values for each measurement in another Data table.

6) Replace the inductive load by a capacitive load (a Variable capacitance module). With all the switches in the OFF position, turn ON the PS and adjust the input voltage to 120 V.

For the following set of load reactances: ∞ (all switches are OFF), 1200 Ω, 600 Ω, 400 Ω (1200 Ω and 600 Ω in parallel), 300 Ω, and 200 Ω (600 Ω and 300 Ω in parallel) measure primary and secondary voltages and currents. Record the values for each measurement in another Data table.

In your report:

1. For the voltages you have measured in Part 1, determine the approximate turn ratios between the primary winding 1-2 and the windings 3-4 and 5-6.

   Using the estimated turn ratios and assuming that the primary winding (1-2) has 500 turns, determine turn numbers for the secondary windings 3-4 and 5-6. Comment on accuracy of such estimation. Discuss possible sources of errors associated with this experimental procedure. Please, be more specific than just mentioning "machine accuracy" and "human error"!

2. Import the data you have collected in Part 2 to Matlab and plot a dependence of the primary winding's voltage on the primary current, i.e. E1 vs. I1. Observe that the primary current is a magnetization current. Discuss the graph.

3. For the data collected in Part 3, explain why the voltage with the two winding in series is approximately zero in one case and nearly 120 V in the other. Which terminals have the same polarity?

4. Import the data you have collected in Parts 4, 5, and 6 to Matlab and plot a dependence of the secondary winding's voltage on the secondary current, i.e. E2 vs. I2, on the same axes for all three types of the load. Clearly label each graph. Discuss the graphs you obtained. For each load, calculate the transformer regulation. Is the power in the primary winding equal to the power in the secondary winding? Discuss possible sources for such inequality.

Lab 4-2   SINGLE-PHASE TRANSFORMERS) TESTS, LOADING, EFFICIENCY AND VOLTAGE REGULATION

OBJECTIVES

The main objective of this lab session is to show how to test and connect single-phase transformers for parameter and performance determination.

The specific objectives of this lab session are:

1) To recognize the different parts of single-phase transformers (i.e. core laminations, windings, winding ampacity, etc).
2) To learn how to determine the polarity of a transformer.
3) To learn how to perform short-circuit test on transformers.
4) To learn how to perform open-circuit test on transformers.
5) To determine the voltage regulation of a transformer.
6) To determine the efficiency of a transformer at full load.
7) To modify the single-phase transformer to work as an autotransformer.

REFERENCES

1) Guru, B.S. and Hiziroglu, H.R. *Electric machinery and transformers, 3* ed., Oxford University Press, U.S.A., 2001.

INTRODUCTION

One of the most valuable apparatus in electric systems is the transformer, for it enables us to utilize different voltage levels across the power system for the most economical value. Generation of power at the synchronous machine level is normally at a relatively low voltage, which is most economically desirable. Stepping up this generated voltage is achieved through power transformers to suit the power transmission requirement to minimize losses and increase the transmission capability of the lines. This transmission voltage level is then stepped down in many stages for distribution and utilization purposes. Transformers are used at all levels of the system. Besides voltage transformation, in electronic circuits, transformers are used for impedance matching.

The main uses of electrical transformers are for changing the magnitude of an AC voltage, providing electrical isolation, and matching the load impedance to the source.

The completely self-protecting (CSP see Figure 4.6) distribution transformers are commonly employed in overhead distribution systems. These, as their name implies, are self-protecting from the lightning or line surges, overloads, and short circuits. Lightning arresters mounted directly on the transformer tank (as can be seen in the pole type CSP transformer currently in exhibit in the lab) provide the primary winding (usually the high-voltage winding) against the line and lightning surges. The overload protection is provided by circuit breakers inside the transformer tank.
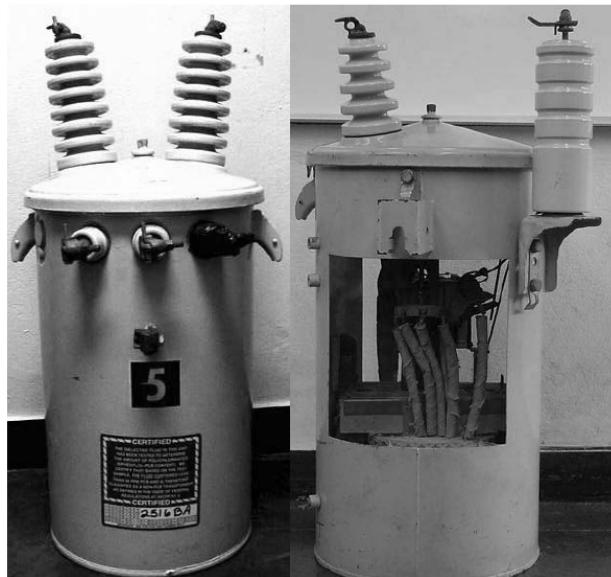
FIGURE 4.6

A transformer is usually considered to be a special form of inductive coupling between two or more coils. They are formed of two or more sets of stationary windings that are magnetically coupled with a high permeability core to maximize the coupling and increase mutual coupling. One of the most useful features of the transformer is its ability to relate the input voltage or current to its output voltage or current respectively (transformation ratio) while maintaining the power relationship the same (i.e. input power = output power).

The conditions of frequency, voltage, current, and volt-amperes product under which a transformer is designed to operate continuously are collectively termed the rating of the transformer.

Tests may be carried out to determine the parameters of the equivalent circuit of the transformer using either winding as the primary, depending upon the potential differences that must be neither very high nor very low. The first is dangerous and the second is inconvenient.

The selection of a proper transformer for a given application involves evaluating certain important performance measures. Two important measures are the voltage regulation and the efficiency. The voltage regulation is a measure of the variation in the secondary voltage when the load is varied from zero to rated value at a constant power factor. The efficiency is a measure of how well power is transferred from the source to the load by the transformer.

The terminals or leads of a transformer are the points to which external electric circuits are connected. In distribution and power transformers, the transformer terminals are marked to show polarity. In transformers, primary and secondary are not identified as such because which is which depends on input and output connections (by

convention, the input AC winding is usually referred to as the primary winding, and the other windings from which output is drawn are referred to as secondary windings). According to NEMA and ASA standards, in distribution transformers, HV or H identifies the high-voltage winding, and LV or X identifies the lower-voltage winding.

The transformer polarity is an indication of the direction of current flowing through the primary leads with respect to the direction of current flow through the secondary leads at any given instant. In other words, the transformer polarity simply refers to the relative direction of induced voltages between the primary and the secondary leads so the dot-marked terminals have the same polarity.
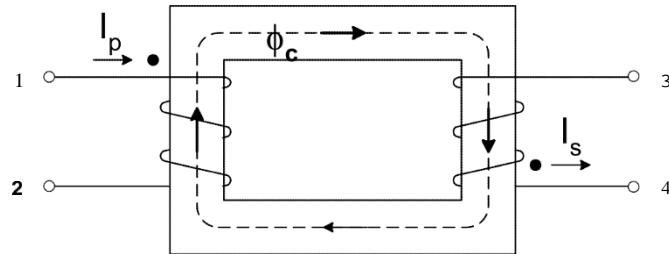
FIGURE 4.7

For example, in Figure 4.7 the terminals 1 and 4 have the same polarity since the primary terminal 1 is positive with respect to terminal 2 at the same time that terminal 4 is positive with respect to 3. The polarity marks in Figure 4.7 could equally well be placed beside terminals 2 and 4 because, as the voltage alternates, they too, become simultaneously positive every half-cycle. Consequently, the polarity marks may be shown beside terminals 1 and 3 or beside 2 and 4. The polarity marking has a direct relation with the right hand rule.
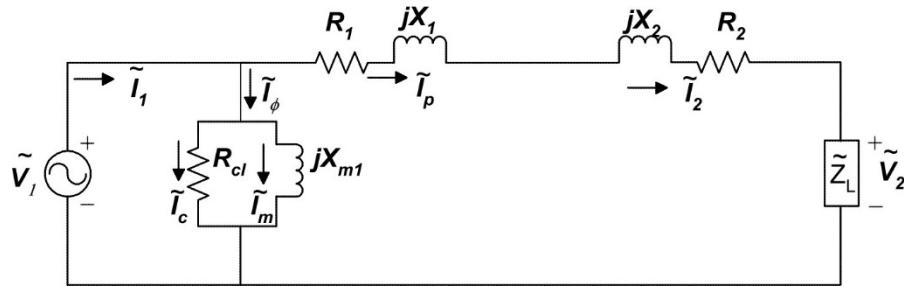
The polarity of a single-phase transformer may be additive or subtractive. A transformer is said to have additive polarity when the primary terminal is diagonally opposite secondary terminal with same polarity. Similarly, a transformer has subtractive polarity when primary dotted terminal is adjacent to secondary dotted terminal. The Figure 4.7 transformer has an additive polarity.

By industry standards, all single-phase transformers 200 KVA and smaller, having high voltages 8660 V and below (winding voltages), have additive polarity. All other single-phase transformers have a subtractive polarity. There are two commonly used methods for polarity determination: the inductive kick test and the alternating voltage test. The inductive kick is a DC test while the other is an AC test.

The open-circuit test gives information regarding the losses in the core, the parameters Rq, X,q, and the turns ratio. Rated voltage is applied at the terminals of one winding while the other winding terminals are open-circuited. Voltage, current and power is measured. The current that flows in the primary winding during this test is called the excitation current. The excitation current component of the primary current is needed to produce the resultant mutual flux. This current has two components: the magnetizing current and the core loss current.

Studying the transformer model in Figure 4.8 we see that he primary and secondary winding resistances are RI, R2. X1 and X2 are the leakage reactances of the resistive windings to account for the magnetic flux, which does not couple all turns. R,q and X,q are the parameters related to core losses and the magnetizing impedance.

The short-circuit test is used to determine the total winding resistance and leakage inductance losses in the windings at full-load current. In this test, one pair of terminals is short-circuited while the voltage of the other winding is raised until full load current flows in the short-circuited, and the voltage, current, and power input are recorded. The voltage that is required for the full-load current in the short-circuit test is determined by the low impedance of the windings and should be equal to 5% of the rated voltage of the winding to which it is applied.

TRANSFORMER EQUIVALENT CIRCUIT MODEL
FIGURE 4.8

Most loads connected to the secondary of a transformer are designed to operate at essentially constant voltage. However, as the current is drawn from the transformer, the load terminal voltage changes because of voltage drop in the internal impedance of the transformer (Figure 4.3). The load terminal voltage may go up or down depending on the nature of the load. The voltage regulation is defined as the change in magnitude of the secondary voltage as the load current changes from the no-load to the loaded condition. The voltage regulation depends on the power factor of the load and it is a maximum when the power factor angle of the load is the same as the negative transformer equivalent impedance angle. The voltage regulation can be formulated as:

$$\%VR = \frac{V_{2noLoad} - V_{2FullLoad}}{V_{2FullLoad}} * 100\%$$

Losses in transformers are small, making transformers highly efficient static devices. The losses in a transformer are the core and copper losses. The core-loss is the sum of the hysteresis and eddy-current losses and manifests itself in the form of heat generated in the core. The copper losses are due to the resistance of the windings.

Single-phase transformers can be rearranged to form an autotransformer as shown in Figure 4.9. This is a special connection of the transformer that raises the VA rating from that of the two-winding configuration. The current remains the same in both arrangements (normal and autotransformer) and therefore, the losses also remain the same. The principle of operation of the autotransformer is the same as that of the two-winding transformer. Autotransformers are generally used when ratio is 3:1 or less. Two disadvantages are the lack of electrical isolation between primary and secondary and the increased short-circuit current over that of the two winding transformer equivalent connection.

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(a) $(V_{1+}V)/V$
step-down
connection

(b) $(V_1+V_2)/V_1$
step-down
connection

(c) $V_2/(V_1+V_2)$
step-up
connection

(d) $V_1/(V_1+V_2)$
step-up
connection
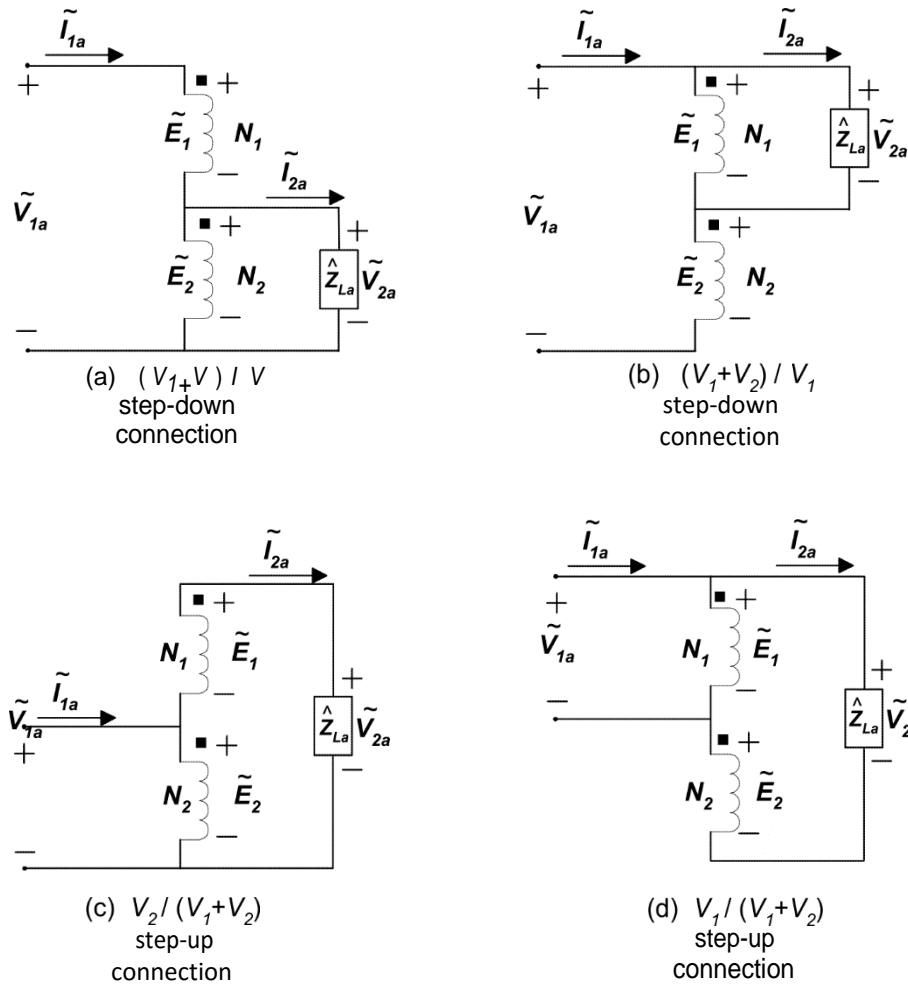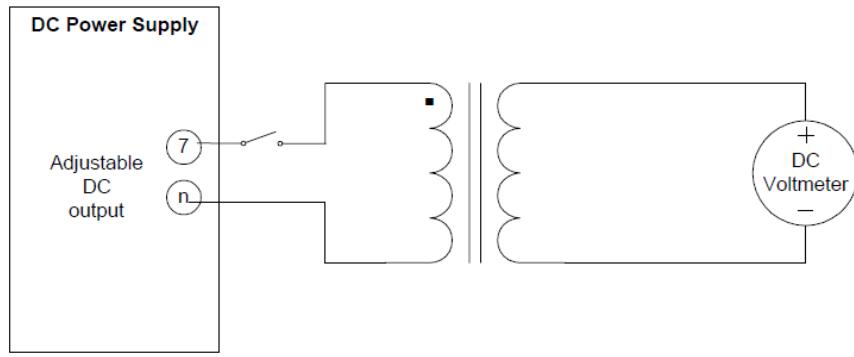
FIGURE 4.9

POLARITY TESTS
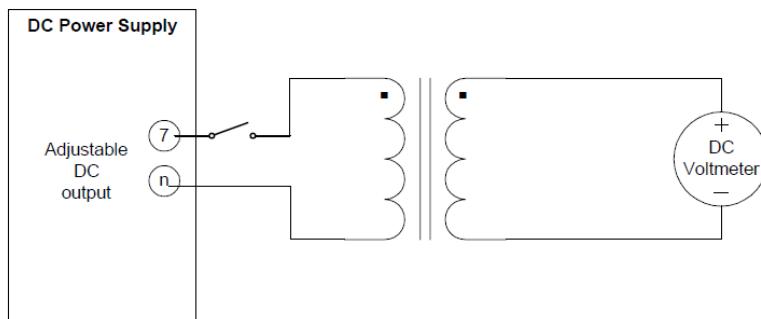
As mentioned previously, the polarity of a transformer is usually determined by using one of these two methods: The inductive kick test and the alternating voltage test.

a) The Inductive Kick Test or DC Test.

This test is a DC test in which a small DC voltage impulse is applied to the primary voltage winding (see Figure 4.9) while we observe if the secondary winding voltage kick is positive or negative. By kick we mean the effect of applying a DC voltage to the primary winding of a transformer will only be seen during the transient period that takes the voltage to go from zero to applied voltage. If the kick is positive, the secondary winding terminal connected to the positive jack of the DC voltmeter has the same polarity of the primary winding terminal connected to the positive output of the power supply, as shown in Figure 4.10. If not positive, these two winding terminals have different polarity.

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FIGURE 4.10

FIGURE 4.11

b) The Alternating Voltage Test

This test is an AC test in which a small AC voltage is applied to the primary winding while primary and secondary are connected as shown in Figure 4.12. If the voltage across the non-connected winding terminals is greater than the applied voltage then the transformer polarity is additive and therefore the jumper wire is connecting different polarity winding terminals. If the voltage across those terminals is less than the input voltage, the polarity is then subtractive and therefore the jumper wire is connecting identical polarity winding terminals.

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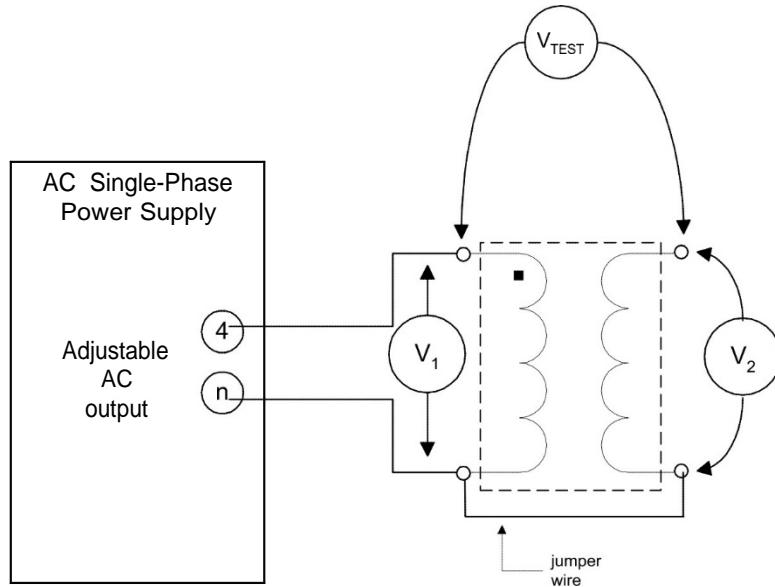
FIGURE 4.11

c) Short-Circuit Test

The set up of the short-circuit test is shown in Figure 4.12. As we can see, the short-circuit is done using an AC ammeter which when placed across any pair of terminal creates a short-circuit between them because of its low internal impedance. This test MUST **be performed quickly** and at very low voltage values since the transformer secondary winding can be burned. The applied test voltage should be approximated prior to performing the test using the DC resistance of the winding and the rated current, sO:

$$Applied\_Test\_Voltage = I_{rated} \times R_{dc}$$
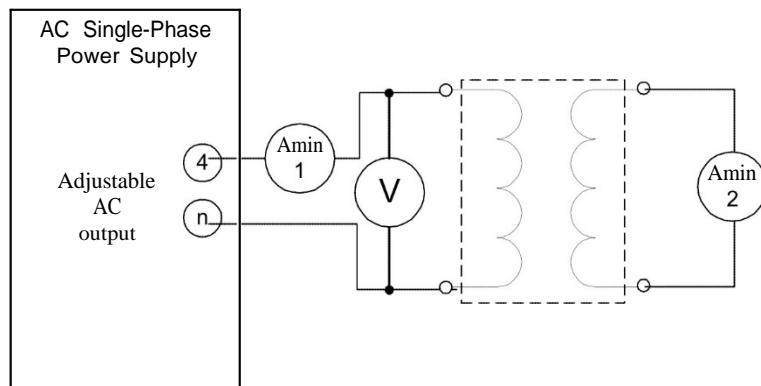
FIGURE 4.12

The transformer we have on the Electric Machines Laboratory has three magnetically coupled windings (Figure 4.13). When the primary winding of this transformer is excited a voltage is simultaneously induced in the other two windings. Any of the three windings can be used as primary or secondary (or be combined to form another winding as in Figure 4. 14 through Figure 4.17).

FIGURE 4.13

Winding 5–9–6:
- 60 V, 0.5 A (5 to 9)
- 60 V, 0.5 A (9 to 6)

Winding 3–7–8–4:
- 104 V, 0.3 A (3 to 7)
- 76 V, 0.3 A (7 to 8)
- 28 V, 0.3 A (8 to 4)

Winding 1–2:
- 120 V, 0.5 A

FIGURE 4.14

AC Single-Phase Power Supply

Fixed 120V AC output

Terminals: 1, n

1:1

Primary (1 to 2): 120 V, 0.5 A

Secondary (5 to 9): 60 V, 0.5 A
Secondary (9 to 6): 60 V, 0.5 A

$\tilde{Z}_L$ V_2

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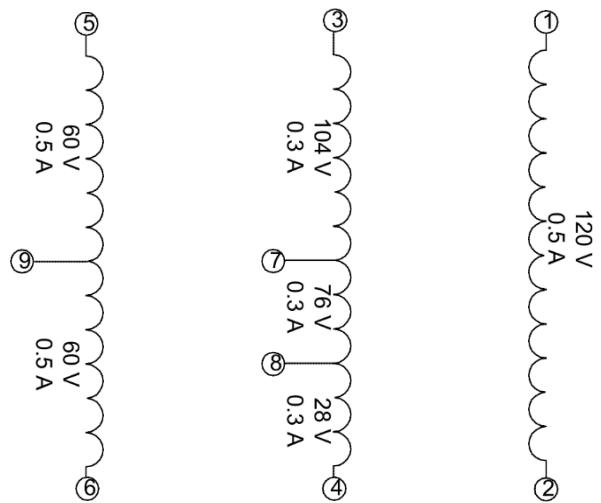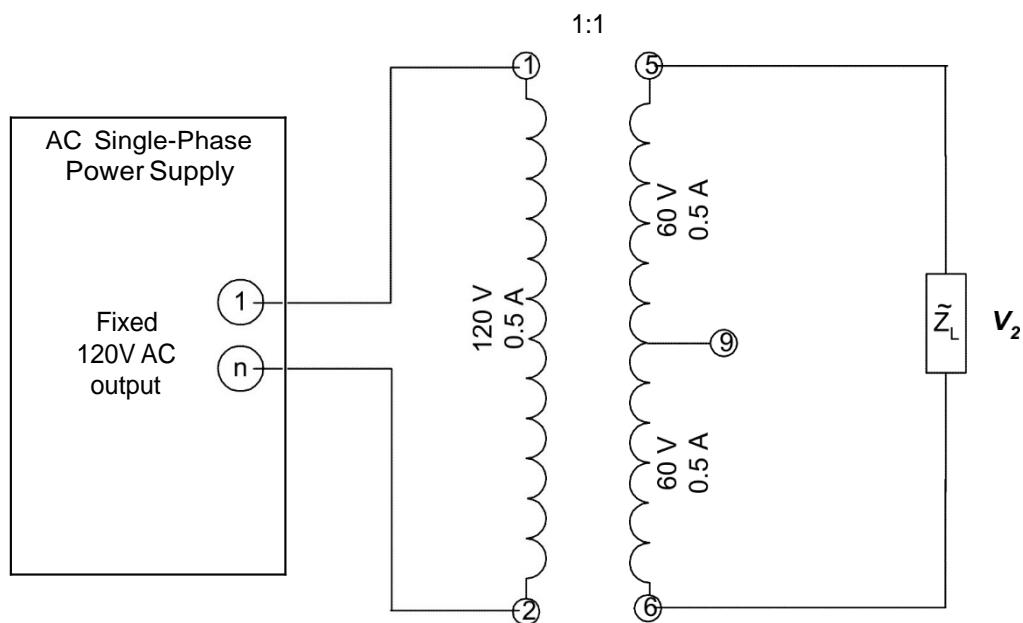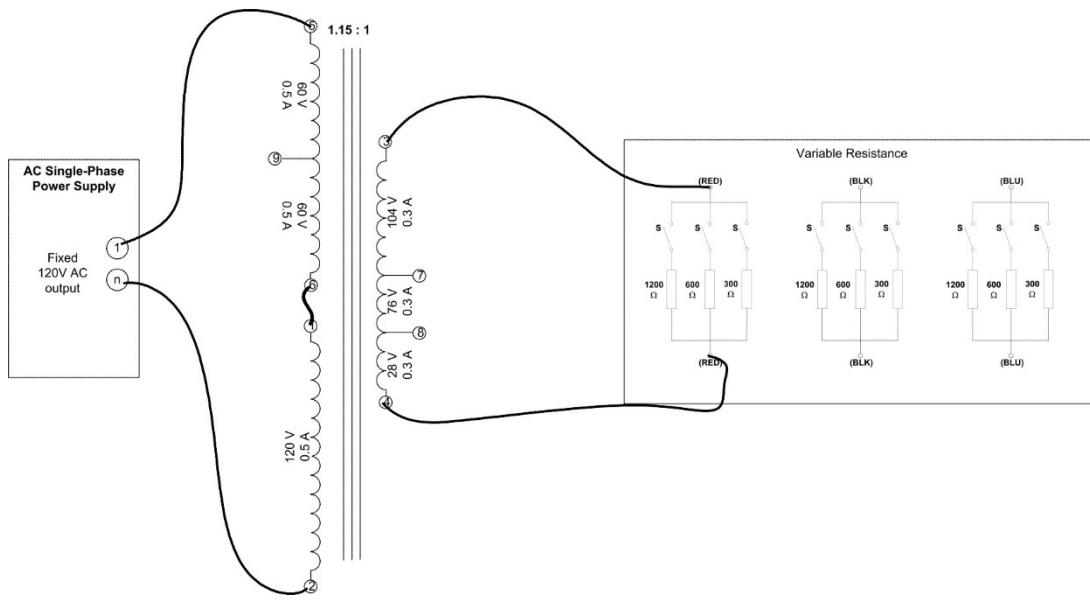
FIGURE 4.15

FIGURE 4.16

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FIGURE 4.17

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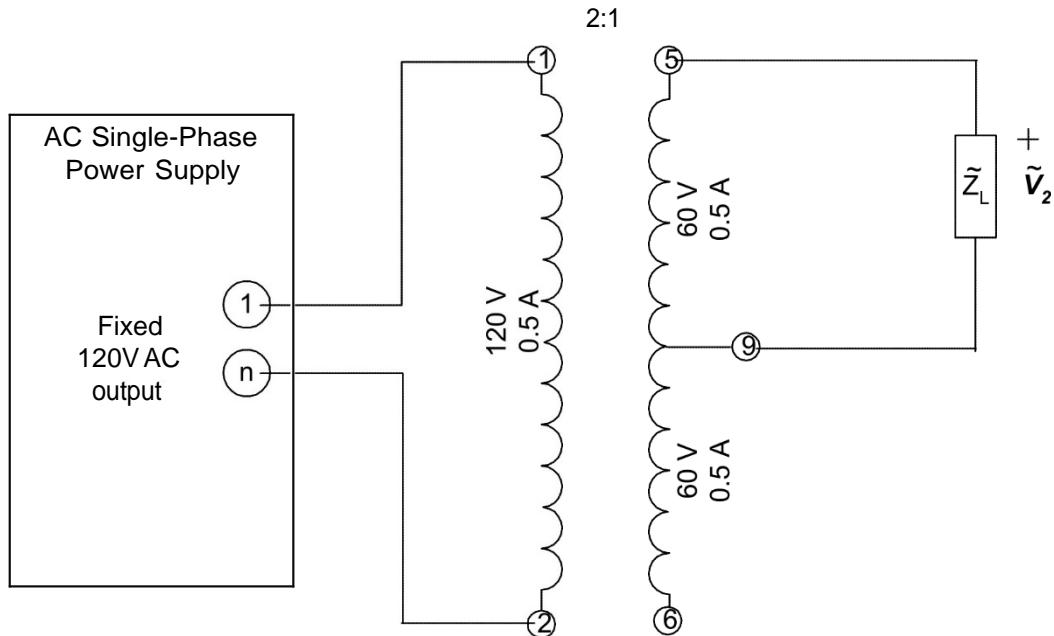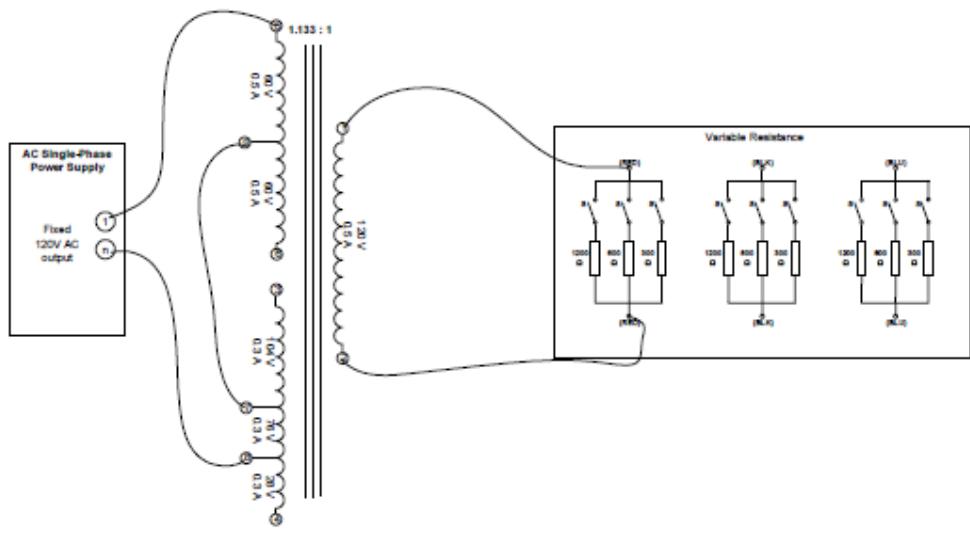
PRELAB

1) The inductive kick method is to be used to determine the polarity of a transformer. Therefore, it is necessary to know what voltage will be used in order not to destroy any of the windings of the transformer by exceeding its current rating. Use the Figure 4.8 model to determine what is the maximum voltage possible for a transformer with the following characteristics:

500 VA, 208/120 volts
$R_{cl} = 500\ \Omega$
$X_m = 9000\ \Omega$
$R_1 = 10\ \Omega$
$R_2 = 5.7\ \Omega$

2) Determine from Figure 4.14 to Figure 4.17 what is:
   a) The primary winding voltage, current and volt-amperes maximum capability.
   b) The secondary winding voltage, current and volt-amperes maximum capability.
   c) The primary winding voltage, current and volt-amperes if Z_L = 600 Ohms.
   d) The secondary winding voltage, current and volt-amperes if Z_L = 600 Ohms.

3) This same transformer has also been tested using the alternating voltage method. It was determined to be additive. If the voltage read in Figure 4.11 was 47 volts:
   a) What was the voltage used for the test?
   b) What will be the voltage reading if the circuit is connected as in Figure 4.17?
   c) What is the maximum voltage that we can use to perform this test on this specific transformer?

4) A short-circuit test was done over the transformer in Figure 4.12. If Vs = 20 V, determine:
   a) The short-circuit current in both windings.
   b) The secondary voltage.
   c) The power dissipated in the test.
   d) If the secondary current was 100 A, what may be happening in the transformer?
   e) If the secondary current was zero, what may be happening in the transformer?

5) After these tests, the transformer has been connected to a resistive load. If:

$R_{LOAD} = 300\ \Omega$
$V_{SOURCE} = 120\angle 0\ V$

   a) Use phasor analysis and the transformer model of Figure 4.12 to determine what is the voltage regulation of this transformer.
   b) Show graphically what is the effect of changing the resistive load (use 5 steps of $100\ \Omega$).
   c) Show graphically what is the effect of changing a reactive (inductive or capacitive) load instead (use 5 steps of $100\ \Omega$ and plot for L and C)).
   d) Plot the efficiency in b) and c).

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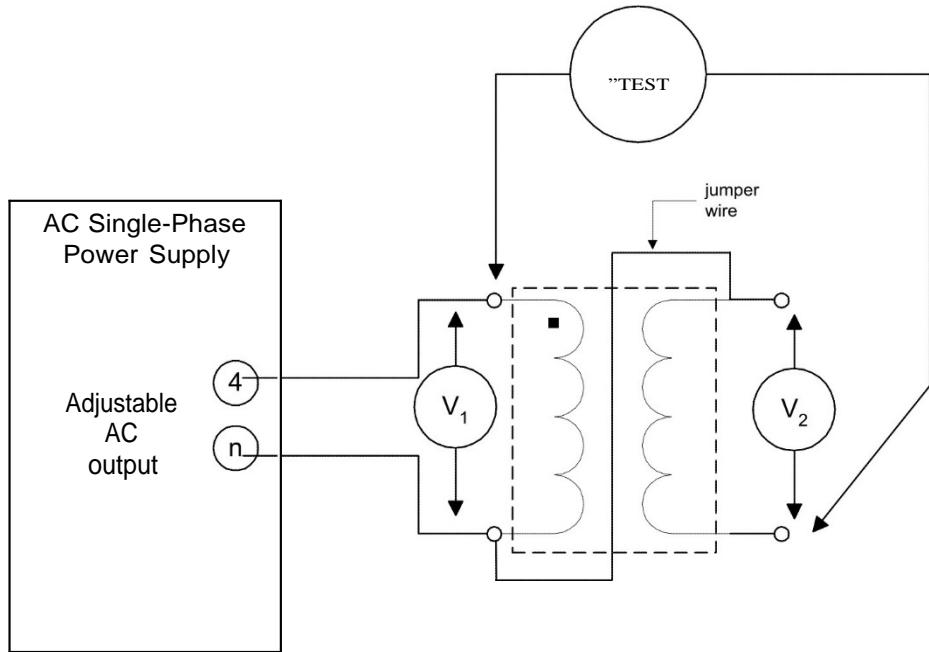
FIGURE 4.18

6) If that transformer is now connected as an autotransformer (Figure 4.9), determine for every case:

$$R_{LOAD} = 300 \ \Omega$$
$$V_{SOURCE} = 120\angle0 \text{ V}$$

a) The windings current.
b) The output voltage and current.
c) The input voltage and current.
d) The maximum power this autotransformer can handle.

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Experiment 4.3 Polarity Tests: Inductive Kick and Alternating Voltage

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Ohmmeter	
Transformer Module	EMS 8341

PROCEDURE

INDUCTIVE KICK

Step 1: Using the digital ohmmeter, determine what is the dc resistance of every winding of the transformer and set the power supply DC adjustable voltage output to have a current of 70% (Approximately 3 volts) of the rated value of the winding.

Step 2: Turn off the power supply without resetting its voltage output.

Step 3: Connect the circuit shown in Figure 4.10. Use the adjustable DC output of the power supply as your power source and realize that the instrumentation is also DC (DO NOT TURN ON THE POWER SUPPLY **YET).** Connect the DC power supply to terminals 1 and 2 and the meter across terminals 3 and 4.

Step 4: To perform the test you must hold the power supply switch and pay attention to the sudden movement the DC voltmeter will do when you turn the power on. TURN ON THE POWER SUPPLY AND IMMEDIATELY TURN IT OFF.

Step 5: Note the deflection of the dc voltmeter at the moment you close the power supply switch.

Question 1: Which to terminals are positive?

ALTERNATING VOLTAGE

Step 1: Adjust the output voltage of the adjustable AC output of the power supply to $15^\%$ of the rated primary voltage for the transformer to be tested. Shut down the power supply without resetting the voltage to zero.

Step 2: Connect the alternating voltage circuit shown in Figure 4.12, first for the case 120/208 volts and later for the 120/120 volts case. Use the adjustable AC output of the power supply as your power source. (DO NOT turn on the power supply yet).

Step 3: To perform the test you must turn on the power supply switch and compare the reading of the voltmeter labeled "test voltmeter" with the sum of the primary and secondary winding voltages (this test will be performed using the 120 V winding as the primary). Record your readings in Table 4.1.

Step 4: Draw a schematic of the transformer showing the winding polarities. Use the dot convention to represent the instantaneous positive terminals.

	120/208 VOLTS		120/120 VOLTS	
	TERMINALS	VOLTAGE	TERMINALS	VOLTAGE
PRIMARY WINDING				
SECONDARY WINDING				
TEST VOLTMETER				

TABLE4.1

Experiment 4.4   Short-Circuit Test

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Ohmmeter	
Transformer Module	EMS 8341

PROCEDURE

Step 1: Connect the circuit shown in Figure 4.12. The terminals short-circuited are terminals 1 and 2, and the adjusted AC output of the power supply connected to terminals 3 and 4.

Step 2: Verify the rated current listed in the front panel of the transformer for each winding. Calculate the maximum voltage to be applied at the input using the values of resistance of the windings of the transformer to be tested, without exceeding the 70% of rated current of any winding, (Approximated 3 volts).

Step 3: Set the adjustable ac control knob to its minimum value without turning on the power supply. Turn on the power supply and slowly increase the supply voltage until 70% of rated current is flowing in the winding. It is important to maintain the voltage less or equal to the calculated maximum voltage at Step 2. **THIS TEST MUST BE PERFORMED QUICKLY TO** AVOID DAMAGING THE TRANSFORMER.

Step 4: Record quickly power, voltage and currents in Table 4.2. Turn off the power supply immediately when finished.

PRIMARY WINDING CURRENT	AMPS
SECONDARY WINDING CURRENT	**AMPS**
PRIMARY VOLTAGE	**VOLTS**
P **(COPPER)**	**WATTS**

Table 4.2

Experiment 4.5   Open-Circuit Test

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Transformer Module	EMS 8341

PROCEDURE

Step 1: Turn on the power supply and adjust the AC output to 120 V.

Step 2: Turn off the power supply without resetting.

Step 3: Connect the circuit shown in Figure 4.19 using the 120V winding (terminal 1 and 2) as your primary winding.
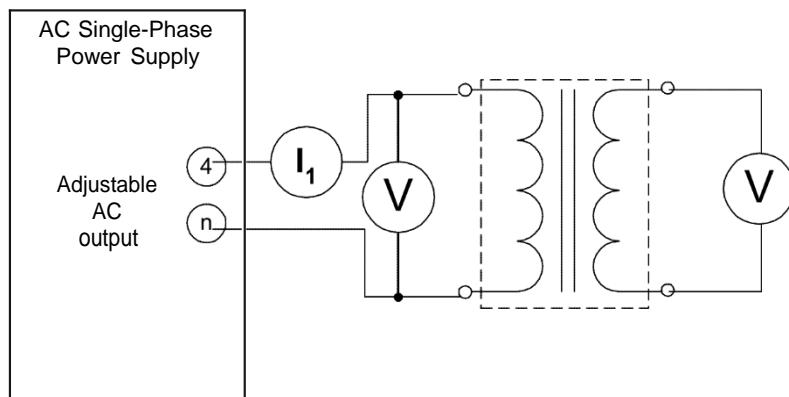
FIGURE 4.19

Step 4: Turn on the power supply and measure the voltage across every winding. Record your measurements in Table 4.3a.

Step 5: Record also the rated current, and voltage of every winding in Table 4.3b.

Step 6: Turn off the power supply.

Step 7: Calculate some different transformation ratios possible with this transformer (table 4.4).

V_{IN}	H_N	P_{CORE}

Table 4.3a

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WINDINGS	MEASURED	RATED	
	VOLTAGE	CURRENT	VOLTAGE
1-2			
3-7			
7-8			
8-4			
5-9			
9-6			
3-4			
7-4			
6-5			

Table 4.3b

WINDING / WINDING	TRANSFORMER RATIO
1-2 / 3-7	
1-2/7-8	
1-2/8-4	
1-2 / 5-9	
1-2/9-6	
1-2 / 3-8	
1-2 / 3-4	
1-2/4-7	
1-2/4-8	
1-2 / 5-6	

WINDING / FINDING	TRANSFORMER RATIO
3-7 / 5-6	
3-7 / 9-6	
8-7 / 5-9	
8-7 / 5-6	
8-7 / 9-6	
8-4 / 5-9	
4-8 / 5-6	
7-4 / 9-6	
8-3 / 5-9	

Table 4.4

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Experiment 4.6 Transformer Loading: Efficiency and Voltage Regulation

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Transformer Module	EMS 8341
Resistance Module	EMS 8311
Inductance Module	EMS 8321
Capacitance Module	EMS 8331

PROCEDURE

Step 1: Without placing any load, Connect the circuit shown in Figure 4.20. Set the power supply to 120 Vac.
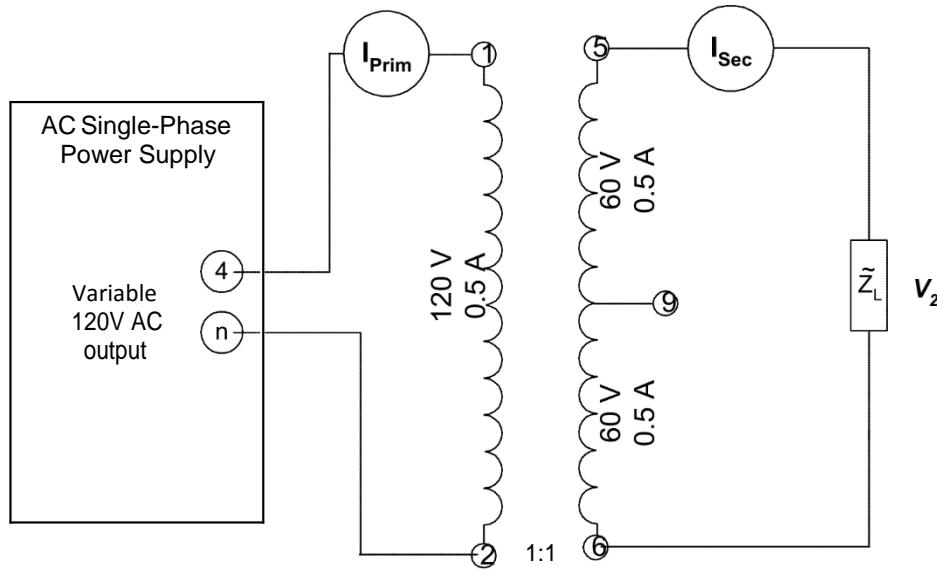
FIGURE 4.20

Step 2: Measure and record in Table 4.5 the secondary voltage at no load and the windings currents.

Step 3: Adjust the load resistance to 240Ω and measure the secondary voltage at full load and the windings currents.

Step 4: Turn off the power supply and readjust the primary voltage to 120V. Connect now the inductance module and repeat Step 3.

Step S. Turn off the power supply and readjust the primary voltage to 120 V. Connect now the capacitive module and repeat Step 3.

Step 6: Calculate the voltage regulation for each load type, and record your calculations in table 4.5.

Step 7: Reduce the voltage to zero and turn off the power supply.

Step 8: Connect the circuit shown in Figure 4.21. Notice that the three types of load are paralleled connected.

Step 9: Complete the table 4.6

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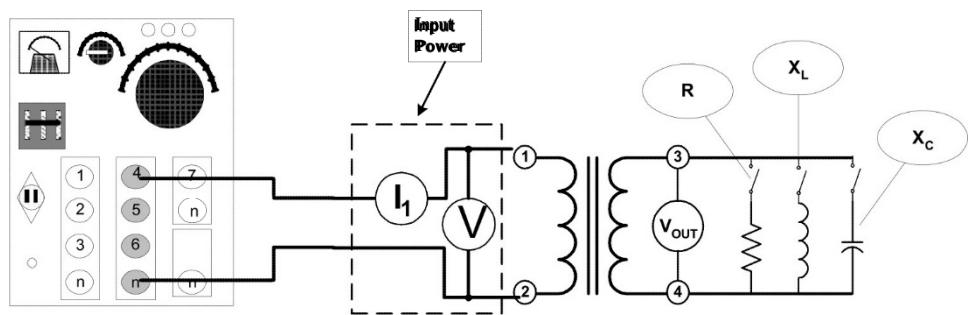
FIGURE 4.21

Load Type	V Sec no-load	V Sec full-load	I Prim no-load	I Prim full load	I Sec no-load	I Sec. full load	VOLTAGE REG.
Resistive							
Inductive							
Capacitive							

Table 4.5

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RESISTANCE	REACTANCE	INPUT POWER	V_{OUTPUT}	OUTPUT POWER	EFFICIENCY
1200Ω	None				
600Ω	None				
400Ω	None				
300Ω	None				
240Ω	None				
1200Ω	X_L=1200Ω				
1200Ω	X_L=600Ω				
1200Ω	X_L=400Ω				
1200Ω	X_L=300Ω				
1200Ω	X_C=1200Ω				
1200Ω	X_C=600Ω				
1200Ω	X_C=400Ω				
1200Ω	X_C=300Ω				
600Ω	X_L=1200Ω				
600Ω	X_L=600Ω				
400Ω	X_L=400Ω				
600Ω	X_C=1200Ω				
600Ω	X_C=600Ω				
400Ω	X_C=400Ω				
None	X_L=240Ω				
None	X_C=240Ω				

Table 4.6

Experiment 4.7   The Autotransformer

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Transformer Module	EMS 8341
Resistance Module	EMS 8311

PROCEDURE

STEP-UP TRANSFORMER

Step 1: Set up the autotransformer shown in Figure 4.22.

Question 2: If it is necessary to obtain 120 Vac at the output, what is the necessary **input voltage?**

Step 2: Use the adjustable AC power output of the power supply and set it to the correct answer of

Question 3. It is necessary **to obtain an output of 120** Vac since this is the **maximum rated voltage at tht? Rjoad•**

Step 3: Turn off the power supply without resetting.

Step 4: Connect the instrumentation to measure the power, voltage, and current in the circuit as in Figure 4.23.

Step 5: Turn on the power supply and record your measurements in table 4.7.

Step 6: Turn off the power supply.
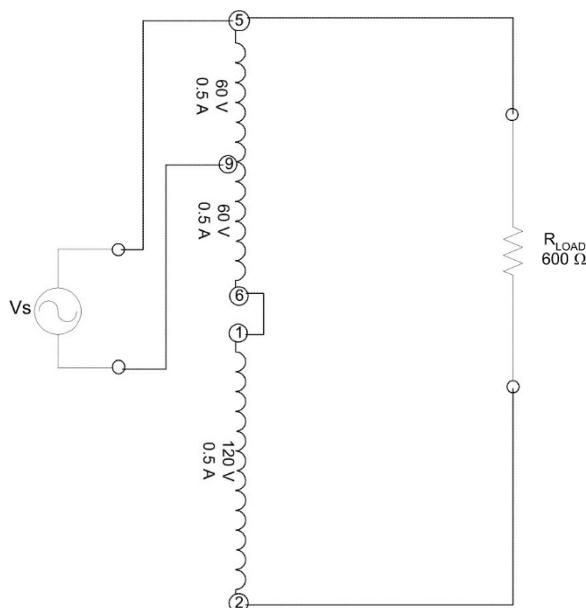
FIGURE 4.22
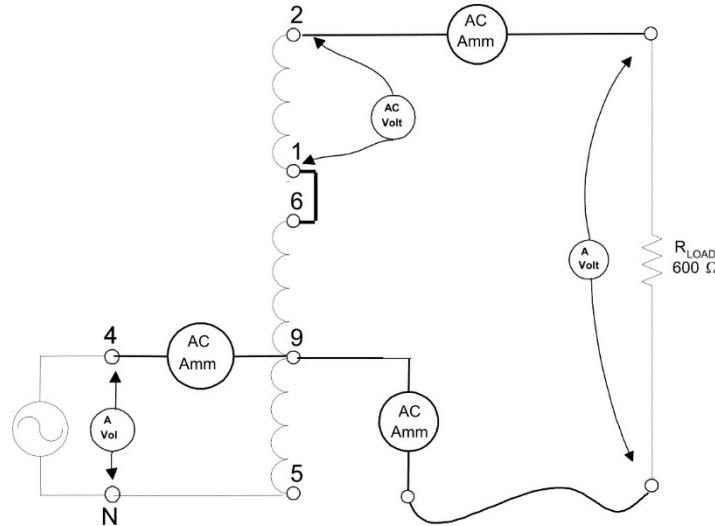
FIGURE 4.23

STEP-DOWN TRANSFORMER

Step 1: Set up the autotransformer shown in Figure 4.24.

Step 2: Use the adjustable AC power output of the power supply and set it to 150 Vac.

Question 4: What **is the theoretical output voltage at the load?**

Step 3: Turn off the power supply without resetting.

Step 4: Connect the instrumentation to measure the power, voltage and current in the circuit as in Figure 4. 21. THE INPUT VOLTAGE MUST BE ADJUSTED TO **150** V SINCE THIS IS THE MAXIMUM RATED VOLTAGE AT THE WATTMETER.

Step 5: Turn on the power supply and record your measurements in table 4.7.

Step 6: Turn off the power supply.
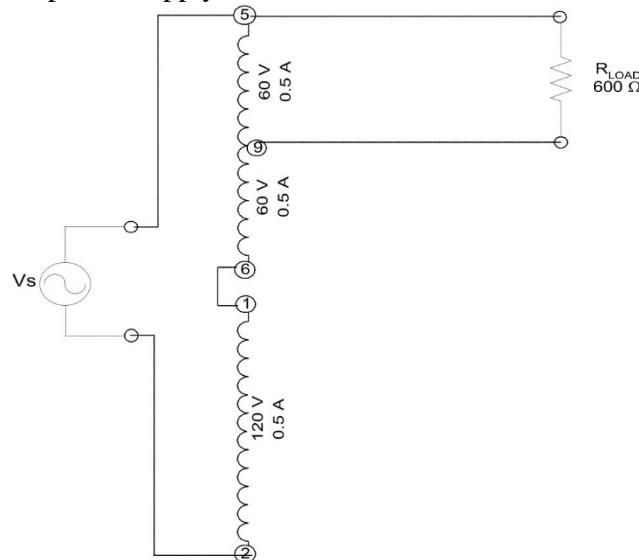
FIGURE 4.24

FIGURE 4. 25

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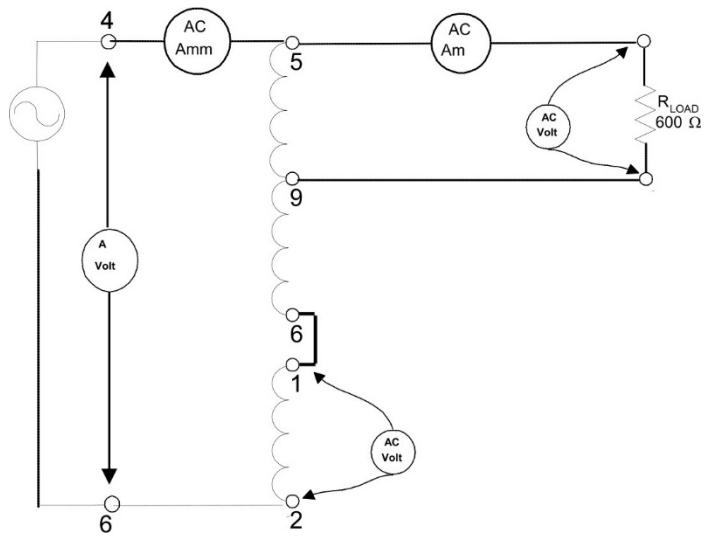
	STEP-UP Figure 4.22	STEP-DOWN Figure 4.24
SECONDARY WINDING TERMINALS		
PRIMARY WINDING TERMINALS		
SECONDARY FINDING VOLTAGE		
PRIMARY VI/INDING VOLTAGE		
SOURCE VOLTAGE		
ROAD VOLTAGE		
SECONDARY WINDING CURRENT		
PRIMARY FINDING **CURRENT**		
SOURCE CURRENT		
LOAD CURRENT		
OEAL INPUT **POWER**		
OEAL OUTPUT POWER		
PRIMARY WINDING APPARENT POWER		
SECONDARY WINDING APPARENT POWER		
APPARENT **INPUT POWER**		
APPARENT **OUTPUT POWER**		
AUTOTRANSFORMER CURRENT IIATIO		
AUTOTRANSFORMER VOLTAGE IIATIO		
% EFFICIENCY OF AUTOTRANSFORMER		
CALCULATED MAXIMUM AUTOTRANSFORMER APPARENT POWER		

Table 4.7

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REPORT REQUIREMENTS

1) Include the lab session text in full. All tables must be filled with ink. Photocopies won't be acceptable.
2) Determine the internal parameters of the single-phase transformer tested in the lab. The parameters to be calculated are the copper impedance and the core impedance. Look up your textbook if you need help. Draw the transformer equivalent circuit model with the calculated values.
3) Using the transformer equivalent circuit, calculate the voltage regulation and efficiency of experiment 4.6.
4) Use the lab data from table 4.7 to compare the step-up autotransformer to the original single-phase transformer.
5) Use the lab data from table 4.7 to compare the step-down autotransformer to the original single-phase transformer.
6) Use the lab data from table 4.7 to compare the step-up and step-down autotransformers.

Lab 5: <u>Transformers in parallel and 3-phase transformers</u>.

Objective: *to learn how to connect transformers in parallel; to determine the efficiency of parallel connected transformers; to connect transformers in delta and Y configurations; to study the voltage and current relationships.*

Equipment: Power Supply, DAI, two Transformer modules (8341), 3-phase transformer (8348), Variable resistance (8311)

Theory:

In an ideal transformer, the power in the secondary windings is exactly equal to the power in the primary windings. This is true for transformers with a coefficient of coupling of 1.0 (complete coupling) and no internal losses. In real transformers, however, losses lead to secondary power being less than the primary power. The degree to which a real transformer approaches the ideal conditions is called the efficiency of the transformer:

$$Efficiency\ (\%) = \frac{P_{out}}{P_{in}} \cdot 100\%$$

where *P_{out}* and *P_{in}* are the real output and the input powers. Apparent and reactive powers are not used in efficiency calculations.

Transformers may be connected in parallel to supply currents greater than rated for each transformer. Two requirements must be satisfied:

1) The windings to be connected in parallel must have identical output ratings;
2) The windings to be connected in parallel must have identical

polarities. Severe damage may be made to circuitry if these requirements are not satisfied.

Single-phase transformers can be connected to form 3-phase transformer banks for 3-phase power systems. Four common methods of connecting three transformers for 3-phase circuits are Δ-Δ, Y-Y, Y-Δ, and Δ-Y connections. An advantage of Δ-Δ connection is that if one of the transformers fails or is removed from the circuit, the remaining two can operate in the open-Δ or V connection. This way, the bank still delivers 3-phase currents and voltages in their correct phase relationship. However, the capacity of the bank is reduced to 57.7 % $(1/\sqrt{3})$ of its original value.

In the Y-Y connection, only 57.7% of the line voltage is applied to each winding but full line current flows in each winding. The Y-Y connection is rarely used.

The Δ-Y connection is used for stepping up voltages since the voltage is increased by the transformer ratio multiplied by $\sqrt{3}$. The Y-Δ connection may be used for stepping down voltages.

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The four connection types are shown in Figure 05-1.
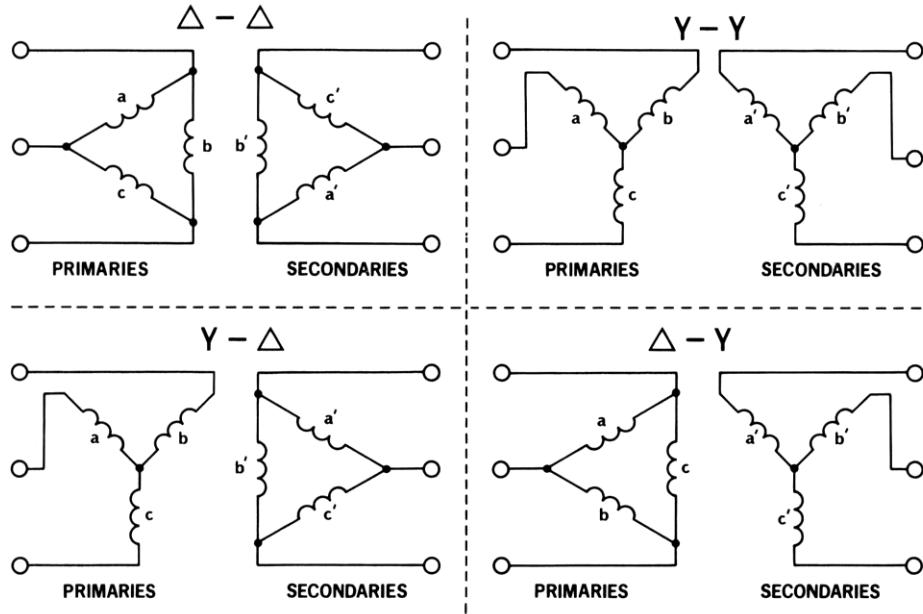
Figure 05-1.

Regardless of the connection method, the windings must be connected in the proper phase relationships. To determine these in a Y-connected secondary winding, the voltage is measured across two windings as shown in Figure 05-2. The voltage A to B should be equal to $\sqrt{3}$ times the voltage across either winding. If the voltage is equal to that across either winding, then one of the windings must be reversed. The third winding c is then connected and the voltage C to A or B should also equal $\sqrt{3}$ times the voltage across any one winding. If not, the winding c must be reversed.
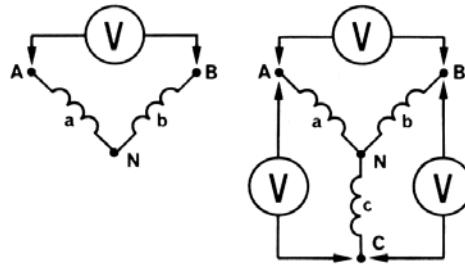
Figure 05-2.

To determine the proper phase relationships in a Δ-connected secondary winding, the voltage is again measured across two windings as shown in Figure 05-3. The voltage A to C should equal the voltage across either winding. If not, one of the windings must be reversed. The winding c is then connected as shown, and the voltage C^1 to C should equal zero. If not, winding c must be reversed and open ends can be joined after that to form the Δ-connection.

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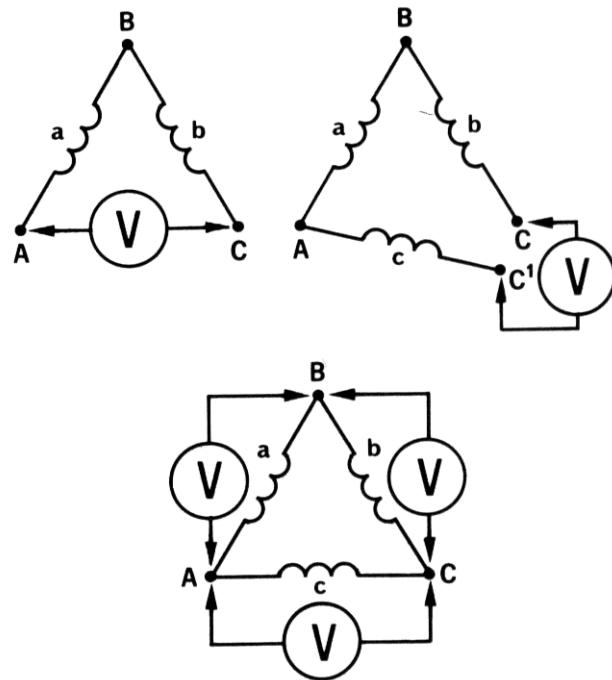
Figure 05-3.

Note: the Δ-connection should never be closed until the test is first made to verify that the voltage within the Δ is zero. Otherwise, severe damage may be made!

Experiment:

1) Using two identical Transformer modules and a Variable resistance module, construct the circuit shown in Figure 06-4. Start the Metering window and make active the channels **E1, E2, I1, I2,** and **I3**. *Note: all meters must be in the AC mode.*

Figure 05-4.

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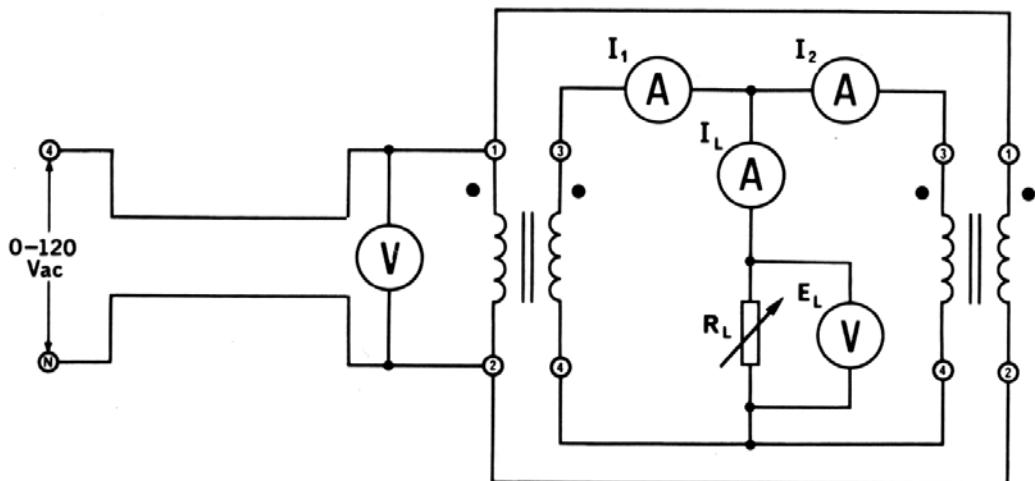
While wiring your transformers, pay specific attention to the polarity of the windings. Tip: use the DAI channel **E1** as the input voltmeter. Place all the resistance switches to their OFF positions first for zero load current. Before turning ON the power, have your instructor to verify the correct wiring.

2) Once the correct wiring has been verified, turn ON the PS and slowly adjust the input voltage to approximately 30-40 V. If the windings are properly wired, load and secondary currents must be approximately zero. By closing the appropriate switch on the Variable resistance module, make the load resistance to be 1200 Ω. Observe that the ammeters **I1** and **I2** read approximately equal currents. If not, consult with your instructor.

3) Turn OFF the PS and modify your circuit as shown in Figure 06-5. Tip: use the DAI channel **I1** to measure the input current. *Caution:* high voltages will be present in the circuit since step up transformers are used!
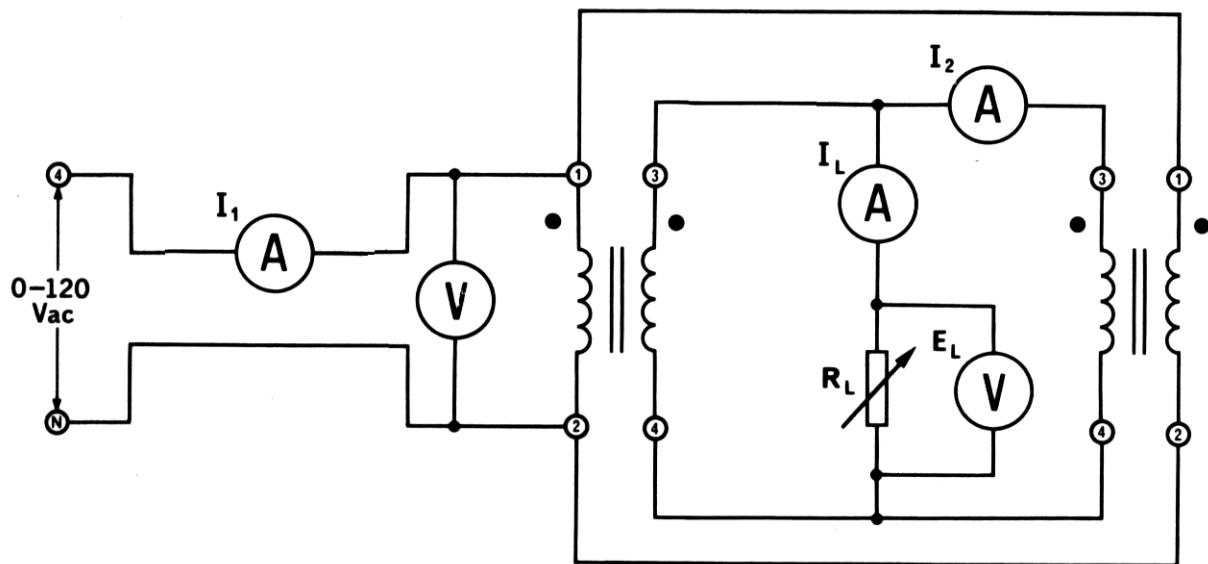
Figure 05-5.

Turn ON the wattmeter **P1** and set it to measure the real input power (for meters **E1** and **I1**). Turn ON the PS and slowly increase the input voltage to 120 V. Set the load resistance to 400 Ω (1200 Ω and 600 Ω connected in parallel). The load current should be approximately 0.5 A. Record (as quickly as possible!) the values read by the meters to a Data table. Without readjusting the input voltage, turn OFF the PS.

4) Rewire your circuit to make it as indicated by Figure 06-4 again. Turn ON the PS. Note: the input voltage must be the same as in Part 3. If it slightly differs, adjust the input voltage to make it equal to one in Part 3. For the same load resistance as in Part 3, record (as quickly as possible!) the voltages and currents to your Data table.

5) Using the 3-phase transformer module, construct the 3-phase transformer shown in Figure

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06-7.
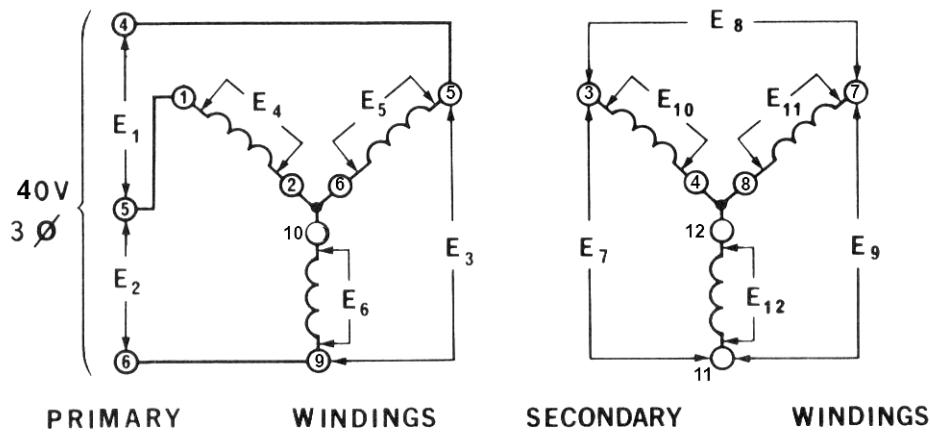
Figure 05-6.

Figure 05-7.

Turn ON the PS and adjust the input voltage to approximately 40 V. Measure and record to a new Data table the input voltages **E1, E2, E3, E4, E5,** and **E6** and the output voltages **E7, E8, E9, E10, E11,** and **E12.** Tip: in order to save results of 4 measurements, your Data table should contain 4 records. Make sure to remember the order in which the voltages are saved. *Note: since the voltages are relatively low, you may connect voltmeters (one wire at a time) while power is ON.*

Start the Harmonic analyzer and observe harmonics of voltage across any secondary winding. Save the Harmonic analyzer's screen by printing it to a pdf-file.

Start the oscilloscope and observe the voltage across any secondary winding. Save the oscilloscope data to a txt-file.

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Ground the primary winding's neutral: i.e. connect the transformer's terminal *2* to the PS terminal *N*. Save the Harmonic analyzer's screen by printing it to another pdf-file. Save the oscilloscope data to another txt-file.

Turn OFF the PS.

6) Construct the 3-phase transformer shown in Figure 05-8.
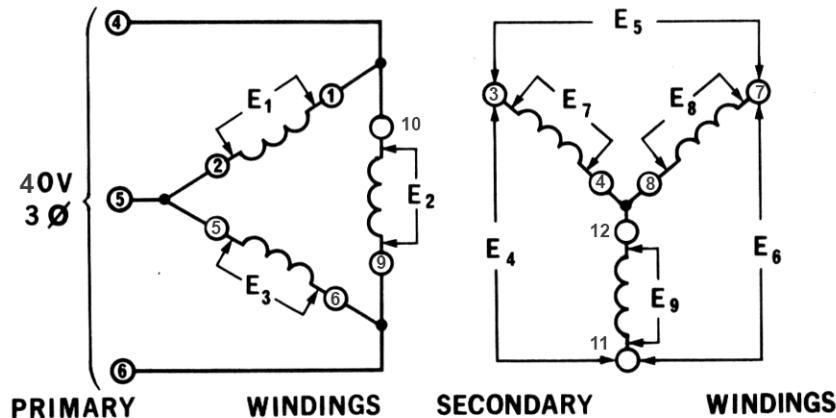
Figure 05-8.

Turn ON the PS and adjust the input voltage to approximately 40 V. Measure and record to the Data table the input voltages **E1, E2, E3, E4, E5,** and **E6** and the output voltages **E7, E8,** and **E9.** Make sure to remember the order in which the voltages are saved. *Note: you may connect voltmeters (one wire at a time) while power is ON.*

Observe harmonics of voltage across any secondary winding. Save the Harmonic analyzer's screen by printing it to another pdf-file.

Turn OFF the PS.

7) Construct the 3-phase transformer shown in Figure 05-9.
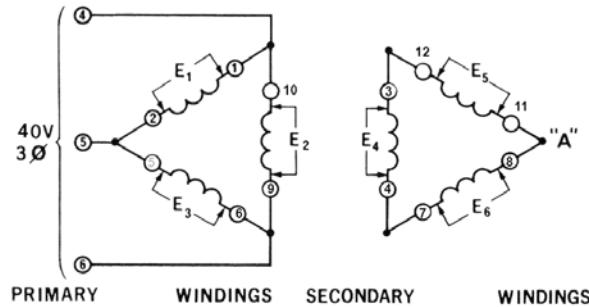
Figure 05-9.

Caution: before finalizing the connection on the secondary windings, you need to verify that the voltage within Δ is indeed zero as discussed in the "Theory"! Open the circuit at the point "A" and place a voltmeter across the opening. Turn On the PS and slowly increase the voltage to approximately 40 V. the voltmeter at the point "A" should read approximately zero volts. Return the input voltage to zero and turn OFF the PS. Remove the voltmeter and finalize the connection at the point "A". Turn ON the PS and adjust the input voltage to approximately 40 V. Measure and record to the Data table the input voltages **E1, E2,** and **E3** and the output voltages **E4, E5,** and **E6.** Make sure to remember the order in which the voltages are saved. *Note: you may connect voltmeters (one wire at a time) while power is ON.*

Observe harmonics of voltage across any secondary winding. Save the Harmonic analyzer's screen by printing it to another pdf-file.

8) Construct the 3-phase transformer shown in Figure 05-10.
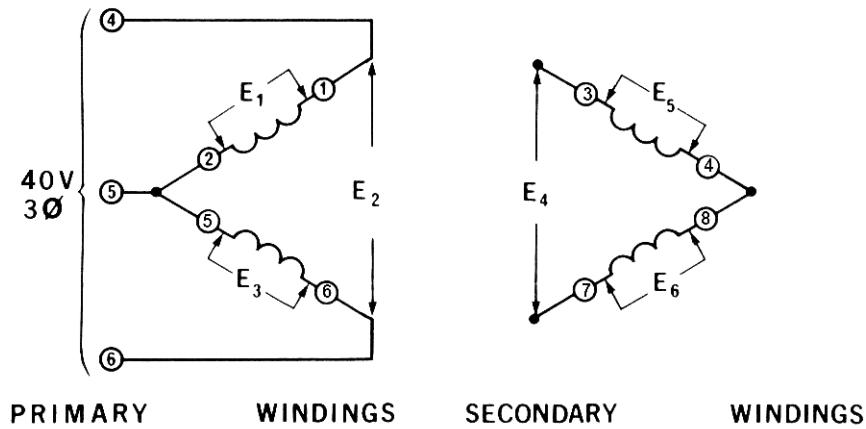
Figure 05-10.

Turn ON the PS and adjust the input voltage to approximately 40 V. Measure and record to the Data table the input voltages **E1, E2,** and **E3** and the output voltages **E4, E5,** and **E6.** Make sure to remember the order in which the voltages are saved. *Note: you may connect voltmeters (one wire at a time) while power is ON.*

Turn OFF the PS and disassemble your circuit.

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In your report:

1) For the voltages, currents, and the input power you have measured in Part 3 and Part 4, determine and report:
   1. The load power;
   2. The circuit efficiency;
   3. The transformer losses;
   4. The power delivered by the transformer 1;
   5. The power delivered by the transformer 2.

2) Is the load reasonably distributed between the two transformers? Explain. Discuss the possible advantages of parallel connection of transformers.

3) For the experiment in Part 5, determine the type of transformers' connection first. For the input voltage of 40 V, predict the values for the voltages **E1** through **E12**. Explain your computations. Are these values compatible with the values you have measured? Discuss possible sources of discrepancy.

4) For the experiment in Part 6, determine the type of transformers' connection first. For the input voltage of 40 V, predict the values for the voltages **E1** through **E9**. Explain your computations. Are these values compatible with the values you have measured? Discuss possible sources of discrepancy.

5) For the experiment in Part 7, determine the type of transformers' connection first. For the input voltage of 40 V, predict the values for the voltages **E1** through **E6**. 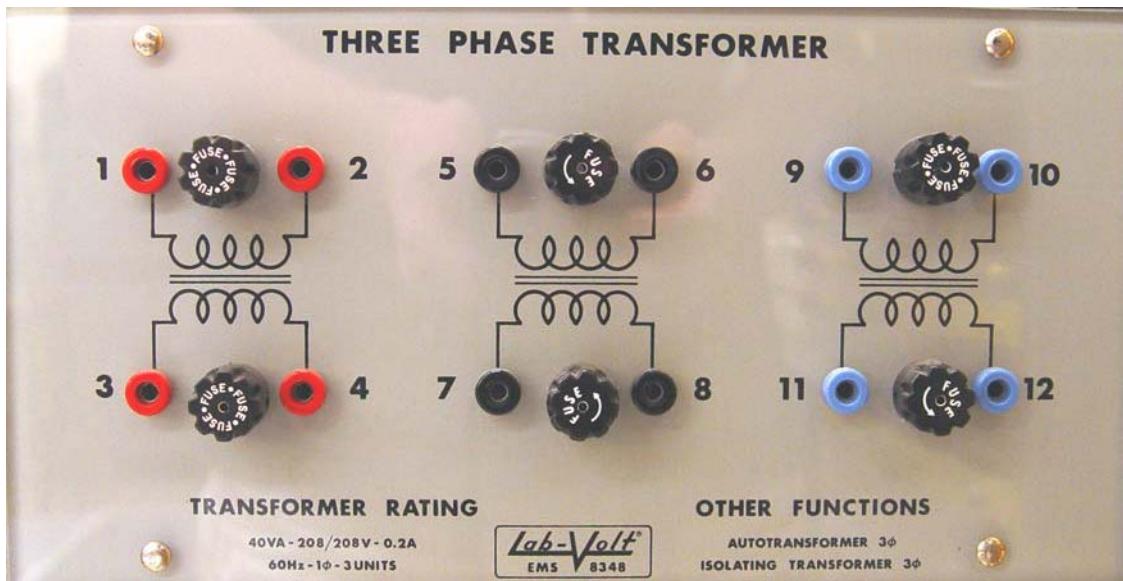Explain your computations. Are these values compatible with the values you have measured? Discuss possible sources of discrepancy.

6) For the experiment in Part 8, determine the type of transformers' connection first. For the input voltage of 40 V, predict the values for the voltages **E1** through **E6**. Explain your computations. Are these values compatible with the values you have measured? Discuss possible sources of discrepancy. What do you conclude regarding the turn ratio of the 3- phase transformer you used?

7) Report the screenshots you collected by Harmonic analyzer in Parts 5, 6, and 7. Describe your observations. Did you observe any effects of grounding of the primary neutral in Part 5? Import to Matlab the oscilloscope data recorded in Part 5 with and without grounded neutral. On the same axes, plot these two voltages as functions of time. Describe the differences between two plots. Based on your observations, which connection type(s) would you recommend as most advantageous?

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Lab 6: <u>Split-phase induction motor.</u>

Objective: *to examine the construction of the split-phase motor; to learn its wiring connections; to observe its starting and running operations; to measure its starting and operating characteristics under load and no-load conditions.*

Equipment: Power Supply, DAI, Split-phase/Capacitor start motor (8251), Electrodynamometer
(8960),
timing belt.

Theory:

Some means must be provided for getting two phases from the standard single-phase power sup- plied to homes if we need to start and run an AC motor. The process of deriving two phases from one is known as phase-splitting and is usually built into the stator circuit of the AC motor.
2-phase power creates the rotating
magnetic field.

One method is a special auxiliary winding built into the stator called the start (auxiliary) winding to differentiate it from the actual run (main) winding of the stator. In split-phase AC motors, the start winding is used only for starting the motor and has a high resistance and low inductive reac- tance. The run winding has low resistance and high reactance. When power is first applied, both windings are energized. Because of their different inductive reactances, the run winding current lags the start winding current, creating a phase difference between the two. Ideally, the phase difference should be 90 degrees; but in practical motors, it is much less. Nevertheless, the windings develop fields that are out of phase, which creates a rotating magnetic field in the stator. This applies torque to the rotor, starting the motor.

When the motor gets up to operating speed, the rotor is able to follow the alternations of the magnetic field created by the run winding without the field of the start winding. The start winding is then switched out of the circuit by a mechanical device called a centrifugal switch, because it is operated by the centrifugal force created by the rotor revolutions. The direction of a split-phase rotating field can be reversed by reversing the connections to the start winding. This changes the direction of the initial phase shift, creating a -magnetic field rotating in the opposite direction.

The motor speed depends essentially upon the AC power line frequency and the number of poles on the stator.

When power is applied to a split-phase induction motor, both the running *(main)*

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and the starting *(auxiliary)* windings draw about 4-*5* times their normal full load current. This means that the heat loss in these windings is from *16* to *25* times higher than normal. As a result, the starting period must be kept short to prevent overheating of the windings.

The high starting currents also produce a proportionally high current in the squirrel-cage rotor, so that the entire motor heats up very quickly during start-up.

The smaller diameter wire employed in the auxiliary winding of split-phase motors is particularly susceptible to overheating and will burn out if it is not disconnected from the power line within 4

to 6 seconds.

The starting current of a split-phase motor is usually 4-5 times normal full-load current. This produces two effects: 1) the motor heats very rapidly during start up; and 2) the high starting current can cause a large line voltage drop so that the starting torque may be seriously reduced.

The no-load current is usually *60%* to *80%* of the full-load current, which is high compared to three-phase motors. Most of the no-load current is used to produce the magnetic field in the motor, and only a small portion is used to overcome the mechanical friction and the copper and iron losses. Because of the large magnetizing current, the power factor of these motors is rarely more than 60%, even at full-load.

The split-phase motor, like all single-phase induction motors, vibrates mechanically at twice the power line frequency. Split-phase motors tend to be much noisier than their 3-phase counterparts, because of the inherent *120 Hz* mechanical vibration. This vibration can be reduced by using resilient rubber mounting supports.

The **power output** (in horsepower) of the motor delivered to the load is defined as follows:

$$P_{out,hp} = \frac{1.4 \cdot \omega_{rpm} \cdot T_{Nm}}{10\ 000} \qquad (6\text{-}1)$$

where ω_{rpm} is the motor speed in revolutions per minute, T_{Nm} is its torque in Newton-meters. Keep in mind that one horsepower equals approximately to 746 W. The **reactive power** [var] can be computed as:

$$Q = \sqrt{S^2 - P^2} \qquad (6\text{-}2)$$

where *S* is the apparent power [VA], *P* is the real power [W] consumed by the motor. The **efficiency of the motor** is:

$$efficiency = \frac{P_{out,W}}{P} \cdot 100\ \% \qquad (6\text{-}3)$$

where $P_{out,W}$ is the output power delivered to the load in Watts. The **motor losses,** therefore, are estimated as:

$$Losses = P - P_{out,W} \qquad (6\text{-}4)$$

Experiment:

1) Examine the construction of the Split-phase/Capacitor start motor module (Figure 6-1). Identify the main stator winding that is composed of many turns of larger diameter wire. Identify the auxiliary stator winding – wound inside the main stator winding – that is composed of fewer turns of smaller diameter wire. Note that there are four main stator poles and four auxiliary poles. Observe the centrifugal switch mechanism mounted on the

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rear of the motor. *Note: the module is equipped with a capacitor that is used when the motor is wired as the capacitor start motor and, thus, will be disconnected in this experiment.*
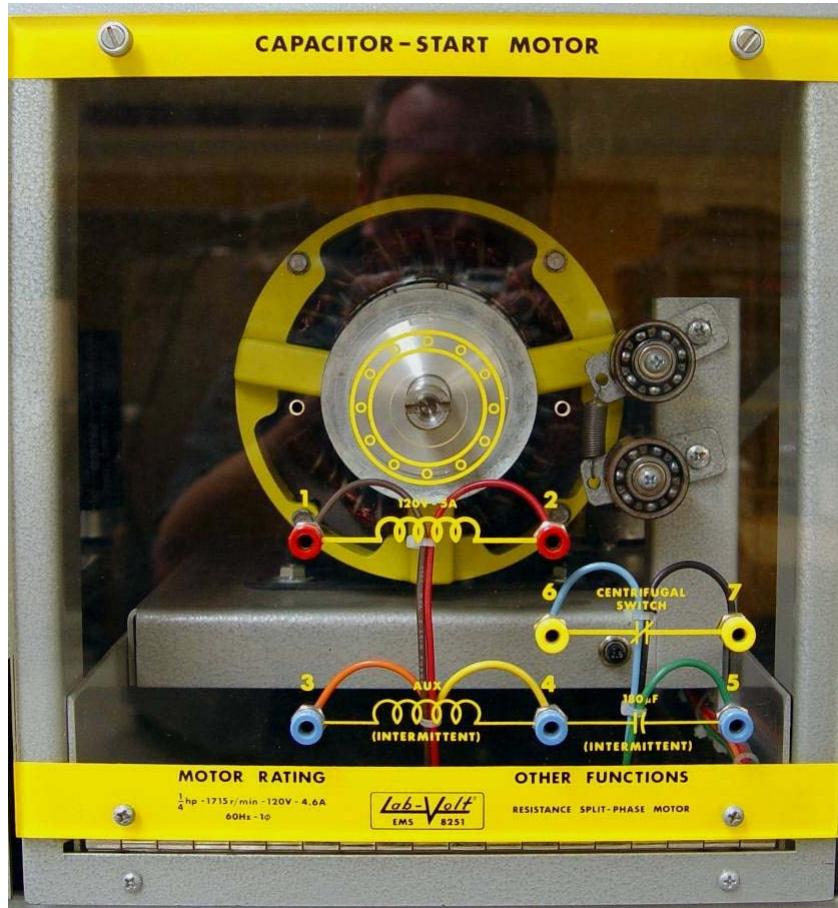
Figure 6-1

2) Couple your motor with the dynamometer by a timing belt. Connect the dynamometer to the fixed low voltage AC source by the grey cable. Using thin red wires, connect the "torque" and "speed" outputs of the dynamometer to the "T" and "N" terminals of the DAI; connect "ground" terminals of dynamometer ("4") and DAI. Set the "MODE" switch of the dynamometer to the "DYN" position and the dynamometer load control switch to the "MAN" position. Set the dynamometer control knob to the utmost counter-clockwise position for the minimum load. Connect the circuit as indicated in Figure 6-2.
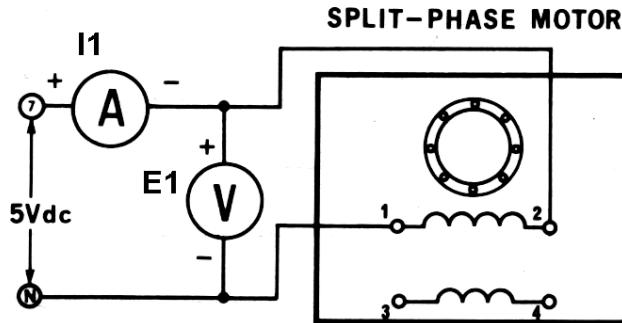
Figure 6-2

Open the Metering window and turn ON the meters to measure a DC voltage E_1, a DC current I_1, the impedance (resistance) based on E_1, and I_1, torque, and speed. Make sure that the voltage adjustment knob on the PS is in its utmost counter-clockwise position for the lowest voltage. Turn ON the PS and adjust for approximately 5 V DC. Record the values of voltage, main winding current, and the main winding resistance to a Data table. Return the voltage to zero and turn OFF the PS.

3) Connect the circuit as indicated in Figure 6-3.
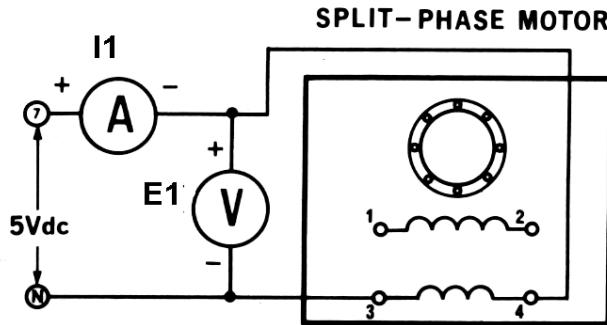
Figure 6-3

Notice that this time the voltage is applied to the auxiliary winding. Turn ON the PS and adjust for approximately 5 V DC. Record the values of voltage, auxiliary winding current, and the auxiliary winding resistance to a Data table. Return the voltage to zero and turn OFF the PS.

4) Disconnect all wires from the PS and from the motor. Connect an AC voltmeter across the PS terminals *4* and *N*. Turn ON the PS and adjust for an output voltage of 100 V as indicated by your voltmeter. **Do not readjust the setting on the PS unless otherwise instructed!** Turn OFF the PS.

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5) Connect the motor's main winding (terminals *1* and *2*) to the pre-adjusted 100 V AC output of the PS (terminals *4* and *N*). Turn ON the PS **for no longer than 3 seconds**. Did the motor growl? Did the motor turn?

6) Disconnect the main winding (terminals *1* and *2*) from the PS. Connect the auxiliary winding (terminals *3* and *4*) to the pre-adjusted 100 V AC output of the PS (terminals *4* and *N*). Turn ON the PS **for no longer than 3 seconds**. Did the motor growl? Did the motor turn?

7) Connect the main winding (terminals *1* and *2*) in parallel to the auxiliary winding (terminals *3* and *4*) and to the pre-adjusted 100 V AC output of the PS (terminals *4* and *N*). Turn ON the PS **for no longer than 3 seconds**. Did the motor start? Was the motor noisy? What was the direction of rotation?

8) Interchange the leads connecting two windings in parallel. Turn ON the PS **for no longer than 3 seconds**. What was the direction of rotation this time?

9) Connect the circuit as shown in Figure 6-4. Observe that the centrifugal switch is connected in series with the auxiliary winding and both windings are connected in parallel to the 100 V AC.
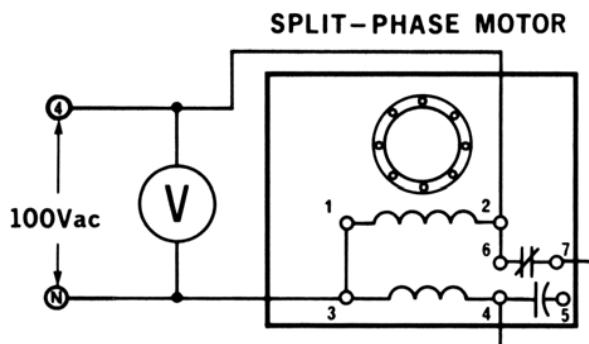
Figure 6-4

Turn ON the PS. The voltmeter should read approximately 100 V. Did the motor start? Did the centrifugal switch operate (you may judge from a clicking sound coming from the motor)? Record the motor speed as measured by the tachometer. Reduce the voltage to approximately 80 V as indicated by the voltmeter. Record the motor speed as measured by the tachometer. Increase the voltage to approximately 120 V as indicated by the voltmeter. Record the motor speed as measured by the tachometer. Return the voltage to 100 V and turn OFF the PS.

10) Connect the circuit as shown in Figure 6-5. Observe that both windings are connected in parallel to the 100 V AC and the centrifugal switch is connected in series with both windings.

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SPLIT-PHASE MOTOR
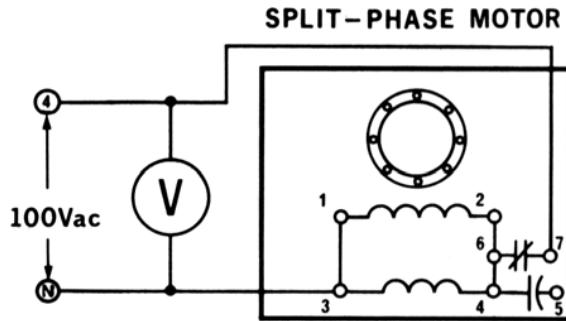
Figure 6-5

Turn ON the PS and observe what happens. Measure and record the approximate speed at which the centrifugal switch closes. Return the voltage to zero and turn OFF the PS.

11) Connect the circuit as shown in Figure 6-6.

SPLIT-PHASE MOTOR
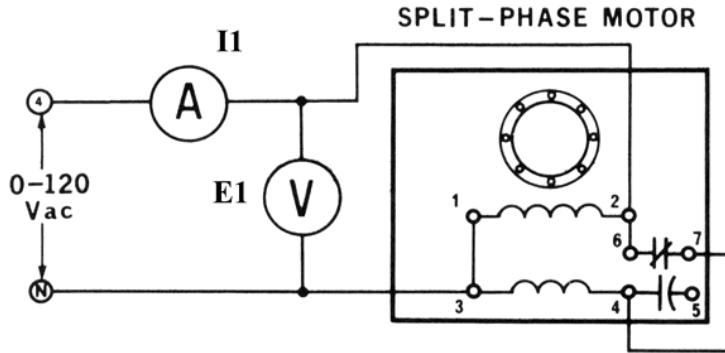
Figure 6-6

In your Metering window, set the following meters: E_1 (AC), I_1 (AC), torque, speed, apparent AC power S_1 between E_1 and I_1 [VA]. Also set the two additional programmable meters: **A** – to measure a real AC power P_1 between E_1 and I_1 [W] and **B** – to measure the power factor between E_1 and I_1.

12) Turn ON the PS and adjust the motor voltage to 120 V as indicated by the voltmeter. Record to a new Data table the values of the line voltage, current, apparent and real powers, the power factor, and the motor speed. Repeat the same measurements (while recording the data to your Data table) for the following values of the (decreased) input voltage: 90 V, 60 V, and 30 V.

13) Adjust the voltage to 120 V and keep it unchanged. Record to a new Data table the values of the line current, apparent and real powers, the power factor, the motor speed, and the load torque. Perform these measurements for the output torques of 0, 0.2, 0.4, 0.6, 0.8,

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1.0, 1.2, and 1.4 Nm. *Note: perform measurements for the torque of 1.2 and 1.4 Nm as quickly as possible.*

14) For the no-load applied to your motor, decrease the input voltage to approximately 50 V.

Start the Oscilloscope and observe both the input voltage and the line current applied to the motor. Save the oscilloscope data in a txt-file. Turn OFF the PS and disassemble your circuit.

In your report:

1) Report and compare the resistances of the main and auxiliary windings you have measured in Parts 2 and 3. What can you conclude based on these values and on your observations of these windings wound by wires of different diameter?

2) From your observations in Parts 5, 6, and 7, what do you conclude about the purpose of the main and the auxiliary windings?

3) From your observations in Parts 7 and 8, what do you conclude about reversing the direction of a split-phase motor?

4) From your observations in Part 9, would you conclude that the speed of the split-phase induction motor depends on the voltage? Support your conclusion by your results.

5) From your observations in Part 10, at what speed the centrifugal switch operates? Explain in details the behavior of the motor as seen in Part 10.

6) Using Matlab and the data recorded in Part 12, plot the dependence of the real power consumed by the motor on the voltage input to the motor. On separate axes, plot the motor speed as a function of the input voltage under the *no-load conditions*. Does this graph support your previous conclusion? On separate axes, plot the power factor as a function of the input voltage for the split-phase induction motor.

7) Using Matlab and the data recorded in Part 13, plot the dependence of the real power on the load torque. On separate axes, plot the motor speed and power factor as functions of the motor load.

8) For the data collected in Part 13 for the full-load operation (1.0 Nm), compute and report the power delivered by the motor, its efficiency, and the motor losses. Compare the efficiency of the split-phase induction motor to the efficiency of the synchronous motor.

9) Load the oscilloscope data you have collected in Part 14 to Matlab. Plot on the same axes both the line voltage and the line current as functions of time (the way the oscilloscope shows signals). Judging from your graphs, would you conclude that the line current passing through motor windings is sinusoidal? *Hint: you may*

decide to scale one of the plots for better representation.

LABORATORY SESSION V

THREE-PHASE TRANSFORMERS: VOLTAGE AND CURRENT RELATIONSHIPS, AND
CONNECTIONS

OBJECTIVES
The main purposes of this laboratory session are to connect a set of three single-phase transformers to form the different three-phase transformer connections and to study the current and voltage relationships of these connections.
The specific objectives of this lab session are:
1) To understand how to connect three single-phase transformers to form a three-phase transformer according to known standards.
2) To learn different types of connections of three-phase transformer banks.
3) To learn the advantages and disadvantages of the different types of connections of three-phase transformers.
4) To learn how to relate the three-phase systems voltage and current characteristics to that of three-phase transformers.
5) To learn the effects of unbalanced three-phase loads.

REFERENCES
1) Guru, B.S. and Hiziroglu, H.R. *Electric machinery and transformers,* ^{Ord} md., Oxford University Press, U.S.A., 2001.
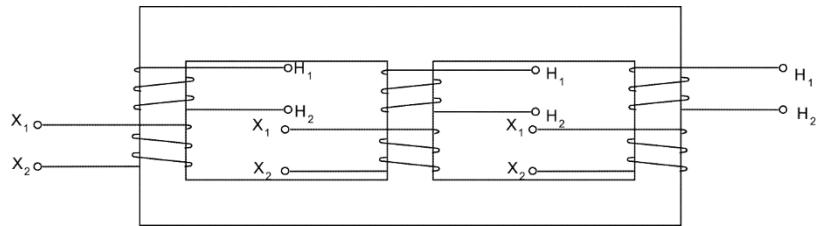
INTRODUCTION
For reasons of efficiency and economy in the use of copper, the generation, transmission, and distribution of electric power takes place on a three-phase basis rather than single-phase. Three-phase transformers are required to step-up or step-down voltages in the various stages of power transmission.
A three-phase transformer can be built in one of two ways: by suitably connecting a bank of three identical single-phase transformers or by constructing a three-phase transformer on a common magnetic core as in Figure 5.1.
Any type of three-phase connection can be carried out on both sides of the transformer bank, such as Y/Y, Y/Δ, Δ/Y and Δ/Δ. Each transformer carries one third of the three-phase load under balanced conditions. However, it is possible to obtain three-phase connections with two transformers, for example the case of open delta connection (V) with a reduced capacity of the bank.
The major benefit of using a Y-connected winding in a transformer is that it provides a neutral point. Mainly, Δ-connected windings are used to suppress third harmonic currents in transformers; a major disadvantage of a Δ-winding in a transformer is that both ends of individual windings are connected to the lines. Consequently, both terminals of the winding may experience over voltages that occur in the system. Therefore, Δ-windings need more expensive insulation as compared to Y-windings. To maintain the same flux density in the core, the mml requirements for Y- and Δ-connected transformers must be equal. This requires the volt-per-turn ratio to be held constant. Therefore, a Δ-connected transformer requires times as many tums for each of its phases as are needed for a Y-connected transformer.

The single unit three-phase transformer consists of a three-legged construction with each leg carrying the primary and secondary coils of one phase as shown in Figure 5.1. When compared to three single-phase transformers equipped to deal with the same volt-amperes, the single three-phase unit is lighter, cheaper, requires less space, and is slightly more efficient. Some cost-conscious installations prefer them because of the smaller initial investment. However a selection in favor of the three single-phase transformers has some notable advantages. The larger total surface area, for example, makes for better cooling and greater ease of repair. Moreover, in the initial development of a power system, it may be entirely possible to operate with just two of the transformers. The third unit can be added at some future date when the full capacity of the system is needed. Also, if a reserve unit is needed to meet emergency conditions, only a smaller unit is often sufficient to have on hand as compared to the need to have a complete single unit three-phase transformer.

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One aspect of three-phase electric power systems is the control of the third harmonic component of the exciting current. This third harmonic component may produce undesirable effects in three-phase transformer operation, particularly in the case of the wye-wye connection.

THE A-A CONNECTION

When connecting three single transformers for three-phase operation, care must be taken in order to ensure that the secondary terminals provide a balanced system of voltages. The primary coils may be arbitrarily connected. To illustrate the point, refer to the arrangement depicted in Figure 5.2a. The objective is to arrange the secondary coil connections so that the line voltages will be balanced and no circulating current takes place in the secondary coils. In Figure 5.2, the voltages supplied to the primary windings are assuming to be balanced.

It is helpful to be aware that although the primary voltages are the same, they differ in phase. The same applies for the secondary voltages. Therefore, when closing the secondary windings in delta, the voltage sum around the loop must equal zero before closing it. Consequently, when a voltmeter is placed across the open terminal AC in the manner illustrated in 5.2b, the reading will indicate if the connection is safe. In case of Figure 5.2b, the delta must not be closed since the voltmeter reading isn't equal to zero. In that case, T must be reversed as show in Figure 5.2c, which is safe connected.
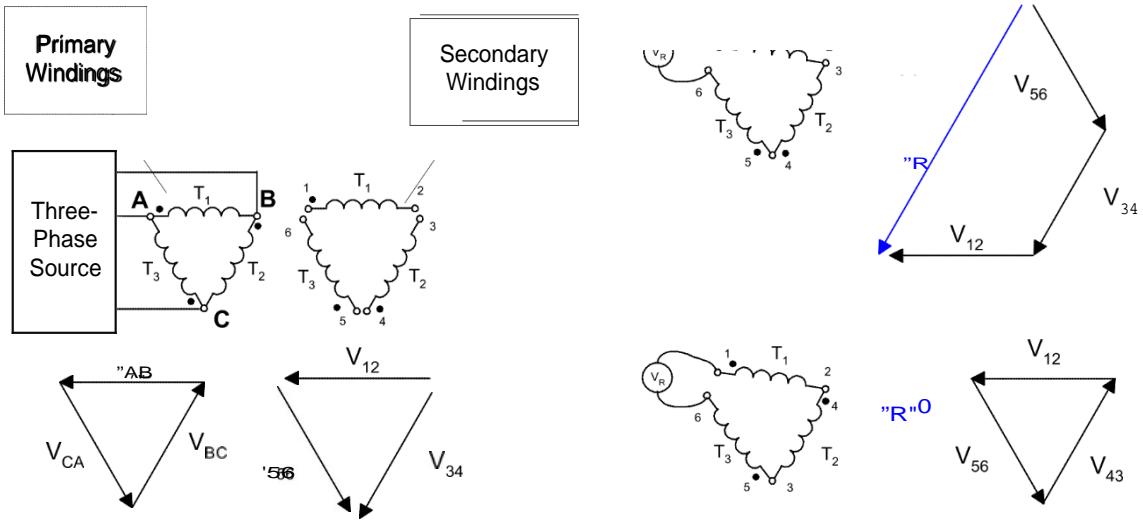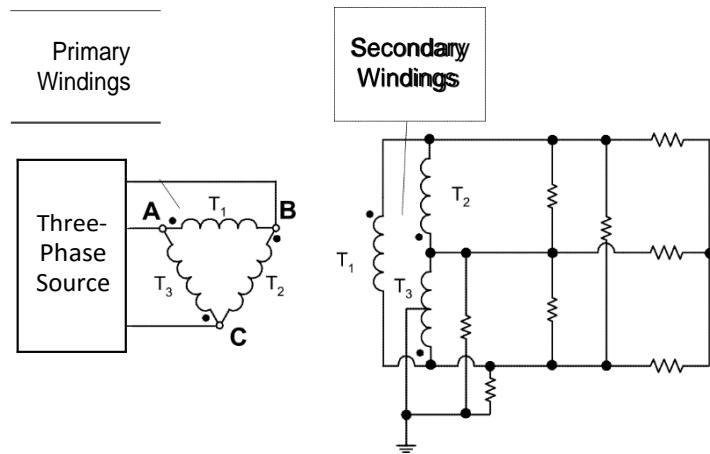
FIGURE 5.2

The A-A connection is often used to supply a small single-phase lighting load and three-phase power simultaneously. To provide this type of service the mid-tap of the secondary winding of one of the transformers is grounded and connected to the secondary neutral conductor, as shown in Figure 5.3.

The A-A connection is the most flexible of the various connections forms. One of the advantages of this connection is that if one transformer becomes damaged or is removed from service, the remaining two can be operated in what is known as the open A or V connection.

A/A Transformer with Single-Phase, A and Y Loads

FIGURE 5.3

THE A-Y CONNECTION

The delta-wye arrangement of transformers is commonly found at the transmitting end of transmission lines as well as at the distribution end. At the transmitting end, the delta-wye connection offers the advantage of an increased step-up ratio beyond that associated with the individual transformers. At the distribution end the inclusion of a neutral wire allows a choice of two voltages for the customer's use. A popular combination that is available from the electric power companies to homes and commercial establishments is the 208/120-V system.

As in the delta-delta connection, the primary coils can be wired arbitrarily in a closed delta arrangement. However, the phasing procedure for a delta-wye connection proceeds differently from the delta-delta one. Now, since the secondary windings will be connected in Y, the secondary line-to-line voltages must be balanced. Other aspect to consider is that there is a phase-shift between primary line-to-line voltages and the secondary ones.

American standards require that when A-Y or Y-A transformers phasing is completed, VAN Phase A primary to ground voltage) lead in 30 degreés Van (Phase a secondary to ground voltage). So, whenever a A/Y or Y/A **transformer,** care must be taken in order to obey standards and provide a balanced system of voltages.
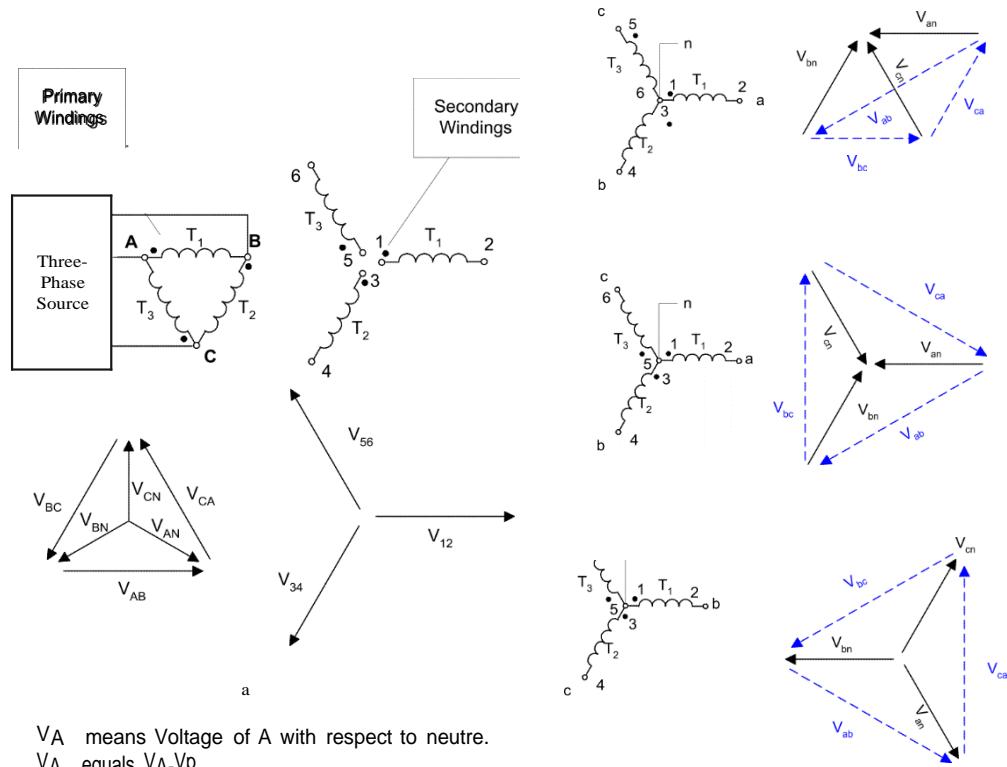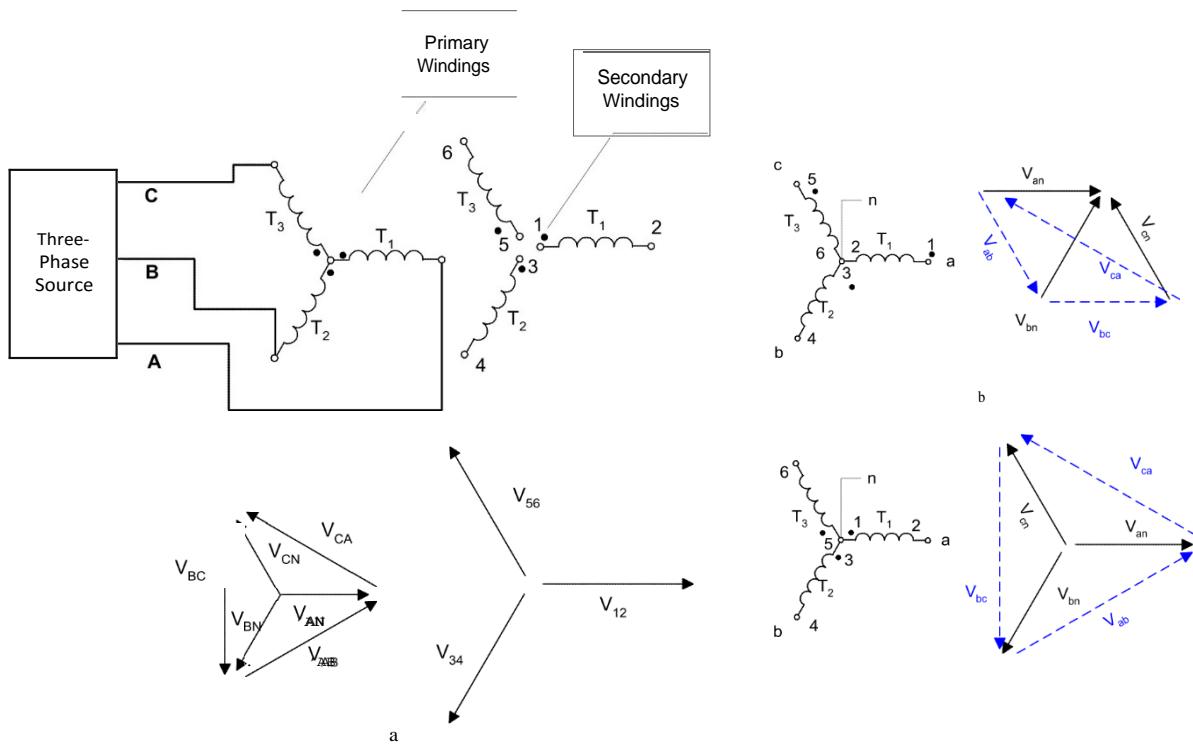
FIGURE 5.4

Figure 5.4 shows three examples of possible A/Y connections. Figure 5.4b and Figure 5.4c are incorrect and Figure 5.4d is correct. Can you explain the reasons?

THE Y-Y CONNECTION

When equipped with a primary and secondary neutral, the wye-wye connection offers two advantages: (1) it provides a choice of two voltages at the secondary side; and (2) transformers need to be specified for an insulation that guards against the magnitude of the line-to-phase voltage rather than line-to-line voltage.

The Y-Y connection (Figure 5.5) is very rare because it creates serious disturbances in communication circuits in their immediate vicinity (e.g. telephone interference). The exciting current and induced third harmonic voltages mainly cause these problems when the neutral connection of the primary winding to the source neutral is lost.
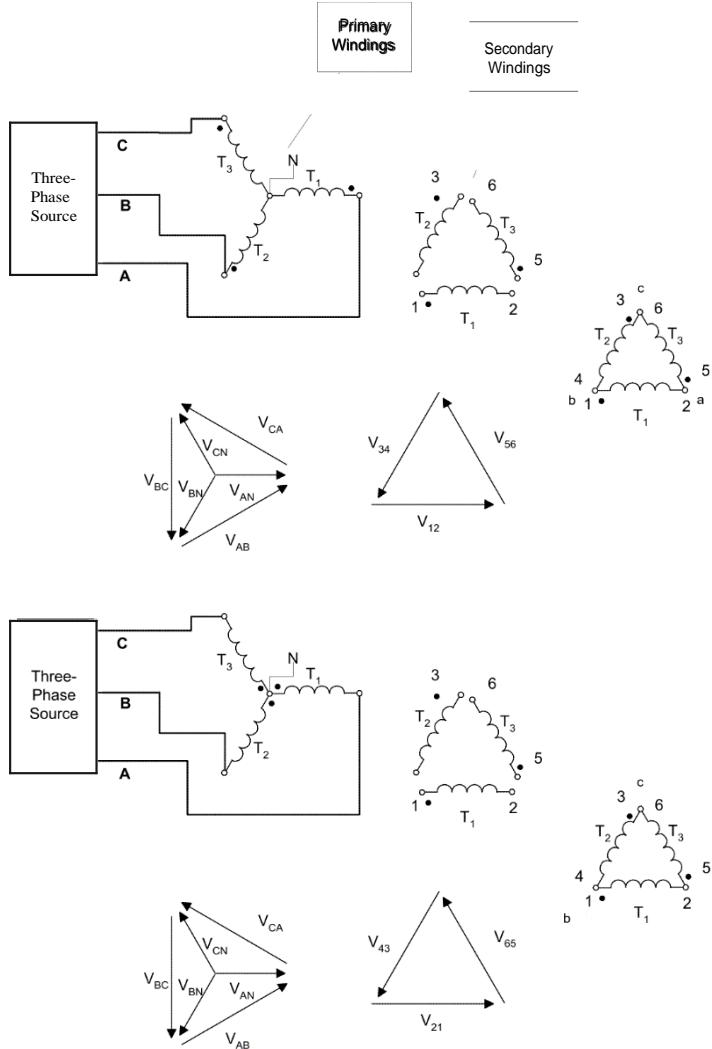
V_{AN} means Voltage of A with respect to neutre.
V_A equals V_A-V

FIGURE 5.5

Like with A/A connection, the electrician must connect the windings so the system voltage keeps balanced. Figure 5.5 shows some examples of some possible Y-Y connections, however just one is correct. Which figure (Figure 5.5b or Figure 5.5c) is right connected so the voltage system is balanced? Explain

THE Y-Δ CONNECTION

FIGURE 5.6
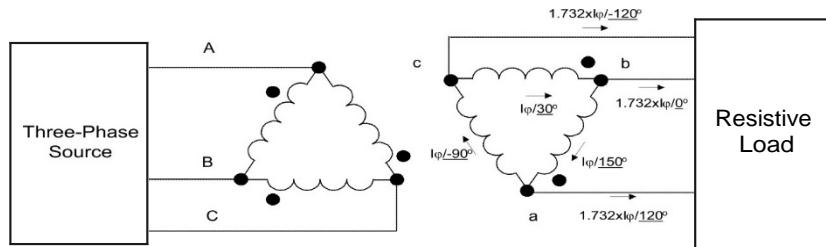
The wye-delta arrangement of single-phase transformers is often found at the receiving end of a transmission line. The reason is that it provides a large step-down voltage ratio from primary line voltage to secondary line voltage. Like the delta wye connection, whoever connects the transformer must balance the voltage system and must obey the American standard discussed before.

As when **closing the delta windings in the delta-delta connection, before closing the delta loop the voltage sum across the loop must be equal to** zero before closing
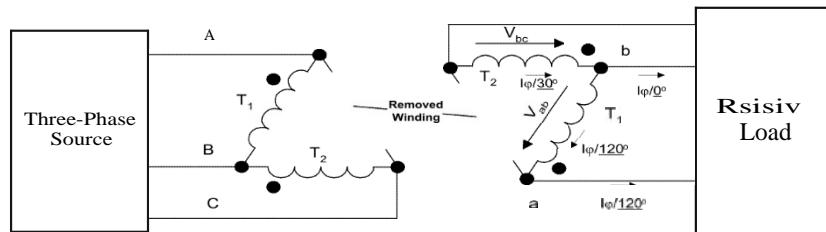
Figure 5.6 shows two examples of some possible Y-Δ connections. Which one (Figure 5.6a or Figure 5.6b) is agreed with the American standards?

OPEN DELTA CONNECTION

In some situations a full transformer bank may not be used to accomplish three-phase transformation. For example, suppose that a A-A transformer bank composed of separate transformers has a damaged phase that must be removed for repair. The resulting situation is shown in Figure 5.7b. If the two remaining secondary voltages an a' 0' and $V_{ab'}$ 0' and $V_b = V$ 120', then the voltage across the gap where the third transformer used to be is given by:

a) Delta-Delta Bank

b) Open Delta Bank

FIGURE 5.7

$$V_{ab} + V_{bc} + V_{ca} = 0$$
$$V_{ca} = -V_{ab} - V_{bc}$$
$$= -V \; 0' - V \; 120' = V \quad 120'V$$

This is exactly the same voltage that would be present if the third transformer were still there. Thus, the open-delta connection lets a transformer bank get by with only two transformers, allowing some power flow to continue even with a damaged phase removed.

However, the maximum apparent power that can be delivered is reduced. At first, it seems that it could supply two-thirds of its rated apparent power, since two thirds of the transformers are still present, but not.

The Figure 5.7a shows the transformer bank in normal operation connected to a resistive load. If the rated voltage of one transformer bank is Vp and the rated current is If, then the maximum power that can be supplied to the load is:

$$P = 3VpI, \cos 8$$

The angle between the voltage Vp and If in each phase is 0', so the total power supplied by the transformer is:

$$P = 3V_\varphi I_\varphi \cos 0' = 3V_\varphi I_\varphi$$

The open-delta transformer is shown in Figure 5.7b. It is important to note the angles on the voltages and currents in this transformer bank. Because one of the transformer phases is missing, the transmission line current is now equal to the phase current in each transformer, and the currents and voltages in the transformer bank differ in angle by 30' Since the current and voltage angles differ in each of the two transformers, it is necessary to examine each transformer individually to determine the maximum power it can supply. For transformer 1, the voltage is at an angle of 150' and the current is at an angle of 120', so the expression for the maximum power in transformer 1 is:

$$P_1 = V_\varphi I_\varphi \cos(150' - 120')$$

$$= V_\varphi I_\varphi \cos 30°$$

$$= \frac{\sqrt{3}}{2} V_\varphi I_\varphi$$

For transformer 2, the voltage is at an angle of 30' and the current is at an angle of 60', so its maximum power is:

$$P_2 = V_\varphi I_\varphi \cos(30' - 60')$$

$$= V_\varphi I_\varphi \cos(-30°)$$

$$= \frac{\sqrt{3}}{2} V_\varphi I_\varphi$$

Therefore, the total maximum power of the open-delta bank is given by:

$$= \frac{\sqrt{3}}{2} V_\varphi I_\varphi + \frac{\sqrt{3}}{2} V_\varphi I_\varphi$$

$$= \sqrt{3} V_\varphi I_\varphi$$

The rated current is the same in each transformer whether there are two or three of them, and the voltage is the same on each transformer; so the ratio of the output power available from the open-delta bank to the output power available from the normal three-phase bank is:

$$\frac{P_{open-\Delta}}{P_{3-phase}} \equiv \frac{\sqrt{3} V_\varphi I_\varphi}{3 V_\varphi I_\varphi} \equiv \frac{1}{\sqrt{3}} = 57.7\%$$

The available power out or the open-delta bank is only 57.7 percent of the original bank's rating.

What happens to the rest of open-delta bank's rating? To find out, examine the reactive power of the open-delta bank. The reactive power of Transformer 1 is:

$$Q_1 = V_\varphi I_\varphi \sin(150' - 120')$$

$$= V_\varphi I_\varphi \sin 30°$$

$$= 0.5 V_\varphi I_\varphi$$

The reactive power of transformer 2 is:

$$Q, = V \: I \: \sin(30' - 60')$$
$$= V_\varphi I_\varphi \sin\left(-30°\right)$$
$$= -0.5 V_\varphi I_\varphi$$

Thus one transformer is producing reactive power, which the other one is consuming. It is this exchange of energy between the two transformers that limits the power output to 57.7 percent of the original bank's rating instead of the otherwise expected 66.7 percent.

In these experiments the student is introduced to the three-phase transformer bank built from three single-phase transformers.

PRELAB

1) Analyze the circuit shown in Figure 5.8 (refer to Figure 5.5 to see how the transformer bank is connected internally) assuming that the transformer ratio of every single-phase transformer is 1:1 and

   R1 = R2 = R3 = 771.4 II

   a) Find the line and phase currents in both primary and secondary sides of the transformer bank if Vs = 120 V.
   b) Calculate the line voltages at both primary and secondary sides of the transformer bank
   c) Calculate the phase load voltage.
   d) Determine the three-phase power delivered by the power source.
   e) Determine the power consumption of each load.
   I) What is the power factor of the load?
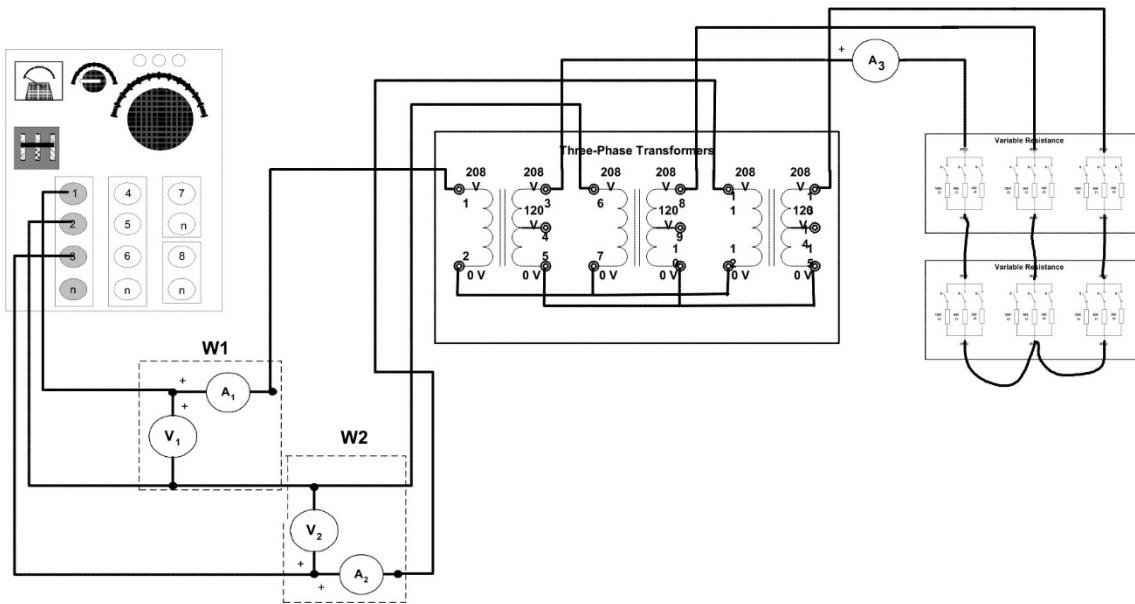
FIGURE 5.8

2) Analyze the circuit shown in Figure 5.9 assuming that the transformer ratio of every single-phase transformer is 1:f3 (that is, the 120 V winding is the primary and the 208 V winding is the secondary).

$$R1 = R2 = R3 = 771.4 \text{ } £1$$
$$L1 = L2 = L3 = 300 \text{ } II$$

a) Find the line and phase currents in both primary and secondary sides of the transformer bank if Vs = 120 V.
b) Calculate the line voltages at both primary and secondary sides of the transformer bank.
c) Calculate the phase load voltage.
d) Determine the three-phase power delivered by the power source.
e) Determine the power consumption of each load.
b   What is the power factor of the load?
g) What is the ratio of the line-to-line voltage at the load side to that at the source?
h) Change the load for an unbalanced load as in Figure 5.10 and repeat all steps above.
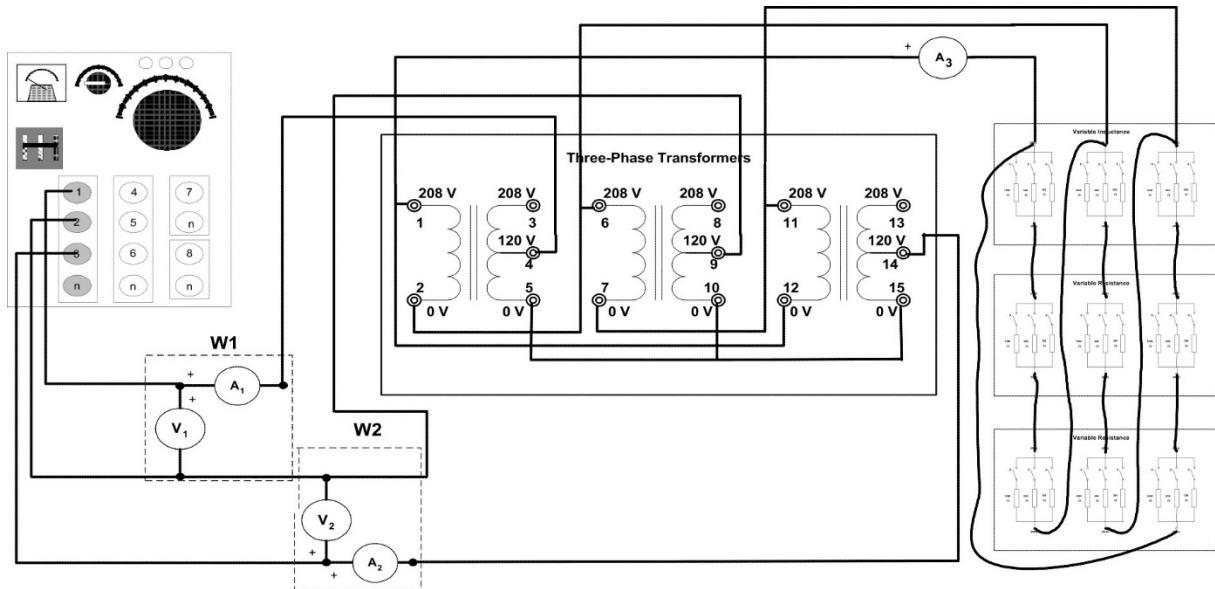
FIGURE 5.9
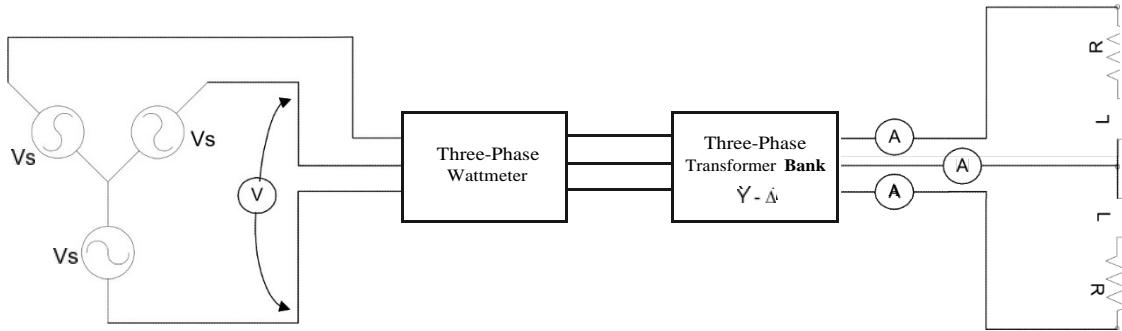
FIGURE 5.10

3) Analyze the balanced circuit shown in Figure 5.11 assuming that the transformer ratio of every single-phase transformer is 93 : 1 (that is, the 208 V winding is the primary and the 120 V winding is the secondary).

> Vs = 120 V
> W1 = 70 W (W1 & W2 are the lectures of the two-wattmeter set, check appendix A)
> W2 = 150 W
> PF = 0.85

a) Find the line and phase currents in both primary and secondary sides of the transformer bank if Vs = 120 V.
b) Calculate the line voltages at both primary and secondary sides of the transformer bank.
c) Calculate the phase load voltage.
d) Calculate the three-phase real, apparent and reactive power delivered by the power source.
e) Determine the power consumption of each load.
f) What is the ratio of the line-to-line voltage at the load side to that at the source?
g) Find the phase impedance.
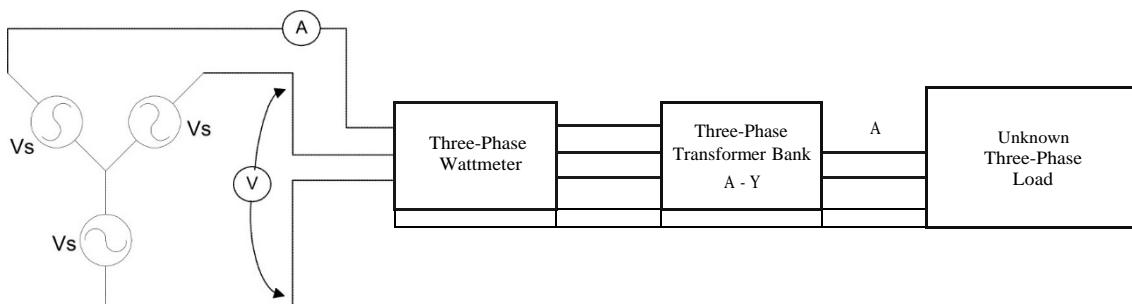
FIGURE 5.11

4) Analyze the circuit shown in Figure 5.12 assuming that the transformer ratio of every single-phase transformer is f3:1 (that is, the 208 V winding is the primary and the 120 V winding is the secondary).

    R1 = R2 = R3 = 85.7 II

a) Find the line and phase currents in both primary and secondary sides of the transformer bank if Vs = 120 V.

b) Calculate the line voltages at both primary and secondary sides of the transformer bank.

c) Calculate the phase load voltage.

d) Determine the three-phase power delivered by the power source.

e) Determine the power consumption for each load.

f) What is the power factor of the load?

g) What is the ratio of the line-to-line voltage at the load side to that at the source?

h) Remove one of the transformers from the bank (Open delta connection) and connect the other two transformers as in Figure 5.13. Repeat all steps above.

i) Calculate the maximum power available from the open delta configuration.
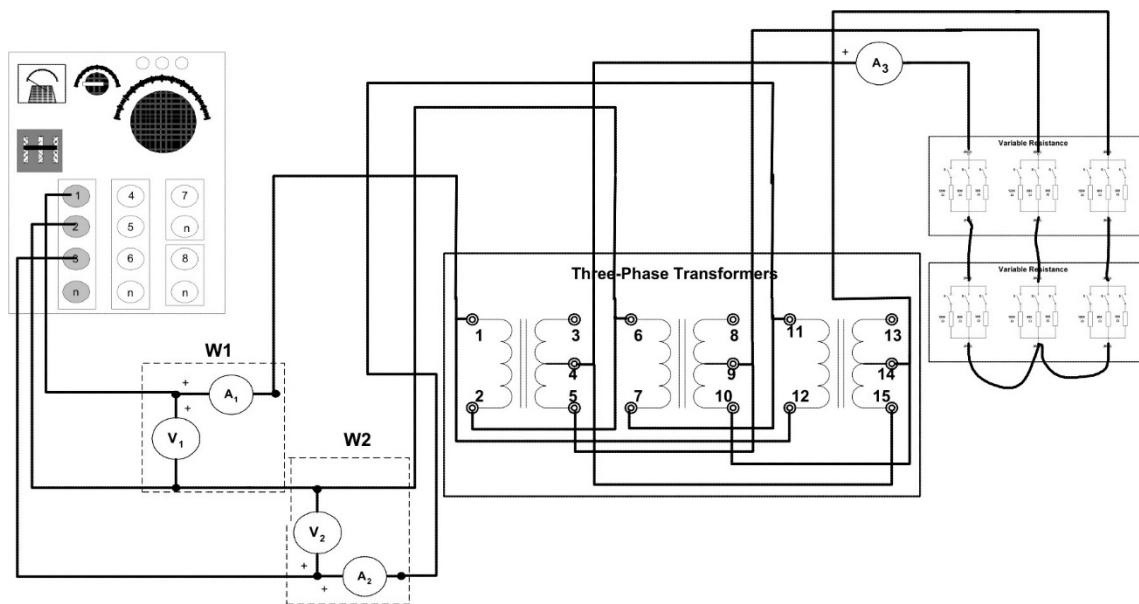
FIGURE 5.12
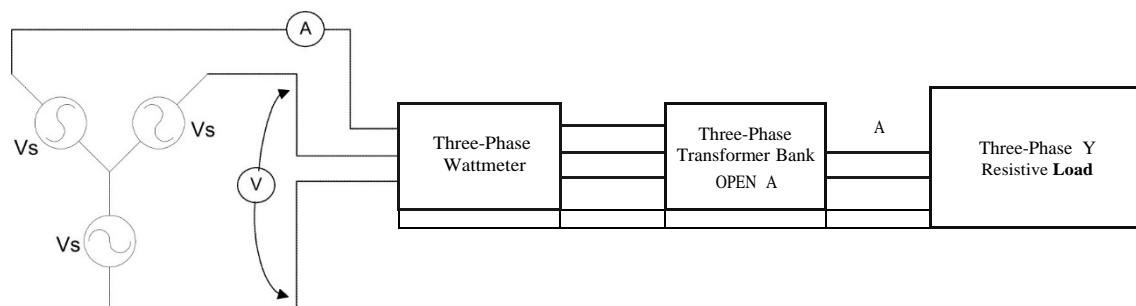
FIGURE 5.13

Experiment 5.1   The Wye-Wye **Three-Phase Transformer Bank**

1 EQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Three-Phase Transformer Module	EMS 8348
Resistance Module	EMS 8311

PROCEDURE

Step 1: Connect the circuit shown in Figure 5.8. Neutral connection will not be used. Use the fixed output of the power supply as your power source. The single-phase transformer ratio to be used is 1:1.

Step 2: Find out both phase and line currents at primary's and secondary's windings.

Step 3: Connect the AC voltmeters according to the measurements you need to make.

Step 4: Turn on the power supply and complete the columns marked as Y-Y in the Table 5.1.

Step 5: Turn off the power supply.

Question 1: In case of Figure 5.2b, Figure 5.2 c, which is safe, connected.

Question 2: Figure 5.4b and Figure 5.4c are **incorrect and Figure 5.4d is** correct. **Can you explain the reasons?**

Question 3: Which Figure (Figure 5.5b or Figure 5.5c) is right connected so the voltage system **is balanced? Explain**

Question 4: Which one (Figure 5.6a or Figure 5.6b) is agreed with the American standards?

	Y-Y	Y-Δ	Δ-Y	Δ-Δ	OPEN Δ
SINGLE TRANSFORMER VLL RATIO					
TRANSFORMER BANK VLL RATIO					
W2					
Q					
S					
PF					
SECONDARY WINDING'S VLL					
SECONDARY WINDING'S VQ					
SECONDARY WINDING'S I					
SECONDARY WINDING'S IQ					
PRIMARY WINDING'S VLL					
PRIMARY WINDING'S Vϕ					
PRIMARY WINDING'S Ir					
PRIMARY WINDING'S Iϕ					
MAXIMUM 3 ϕ POWER					

Table 5.1

Experiment 5.2   The Wye-Delta Three-Phase Transformer Bank

REQUIRED EQUIPMENT

Power Supply Module   EMS 8821
Connection Lead Set   EMS 8941
Three-Phase Transformer Module   EMS 8348
Resistance Module   EMS 8311

PROCEDURE

Step 1: Connect the circuit shown in Figure 5.9. Neutral connection will not be used. Use the fixed output of the power supply as your power source. The single-phase transformer ratio to be used is 1:f3. The 120v winding is the primary and the 208v winding is the secondary.

Caution: The delta should never be closed until a test is first made to determine that the voltage within the delta is zero. If not, and the delta is closed on itself, the resulting current will be of short-circuit magnitude, with resulting damage to the transformers.

Step 2: Substitute the AC ammeters by the marked leads (one at a time).

Step 3: Connect the AC voltmeters according to the measurements you need to make.

Step 4: Turn on the power supply and complete the columns marked as Y-Δ in the Table 5.1.

Step 5: Turn off the power supply.

Experiment 5.3 The Delta-Wye Three-Phase Transformer Bank

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Three-Phase Transformer Module	EMS 8348
Resistance Module	EMS 8311

PROCEDURE

Step 1: Connect the circuit shown in Figure 5.14. Neutral connection will not be used. Use the variable output of the power supply as your power source. The single-phase transformer ratio to be used is #3: 1. Adjust the power supply line-to-line voltage to 120 V. R=771.4D and L=300D
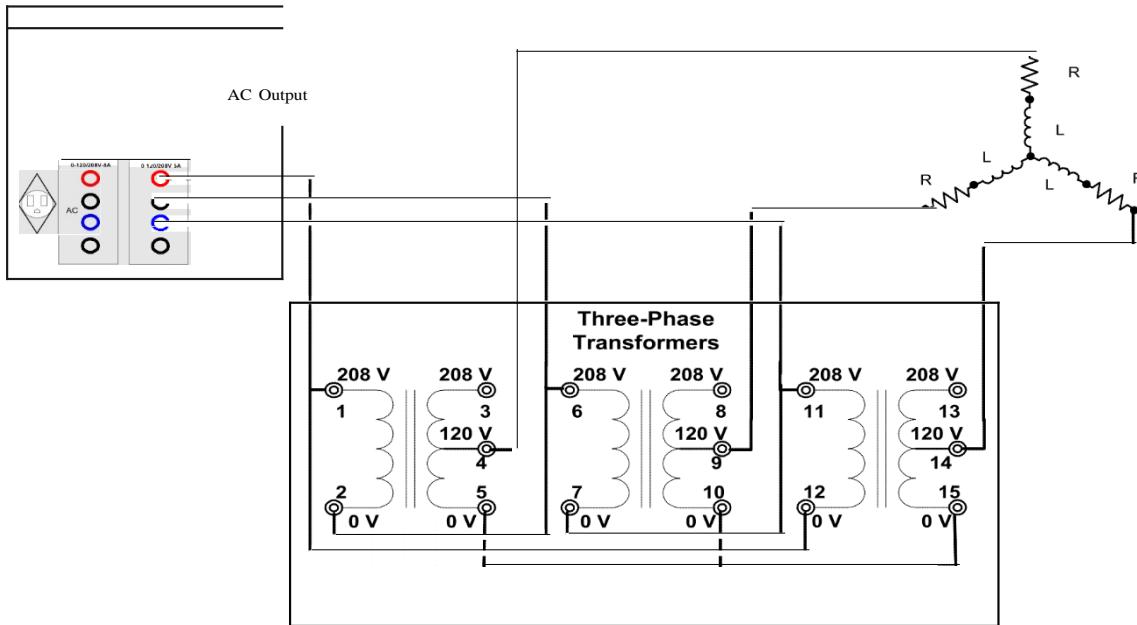
FIGURE 5.14

Step 2: Measure the secondary winding's line and phase currents. Also, measure the primary winding's line and phase currents.

Step 3: Connect the AC voltmeters according to the measurements you need to make.

Step 4: Turn on the power supply and complete the columns marked as A-Y in the Table 5.1.

Step 5: Turn off the power supply.

Experiment 5.4   **The Delta-Delta Three-Phase Transformer Bank**

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Three-Phase Transformer Module	EMS 8348
Resistance Module	EMS 8311

PROCEDURE

Step 1: Connect the circuit shown in Figure 5.12. Neutral connection will not be used. Use the fixed output of the power supply as your power source. The single-phase transformer ratio to be used is 3:1.

Caution: The delta should never be closed until a test is first made to determine that the voltage within the delta is zero. If not, and the delta is closed on itself, the resulting current will be of short-circuit magnitude, with resulting damage to the transformers.

Step 2: Substitute the AC ammeters by the marked leads (one at a time).

Step 3: Connect the AC voltmeters according to the measurements you need to make.

Step 4: Turn on the power supply and complete the columns marked as A-A in the Table 5.1.

Step 5: Turn off the power supply.

Experiment 5.5 The Open Delta Three-Phase Transformer Bank

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Three-Phase Transformer Module	EMS 8348
Resistance Module	EMS 8311

PROCEDURE

Step 1: Remove one of the transformers from the previous configuration conserving the same load. Neutral connection will not be used. Use the fixed output of the power supply as your power source. The single-phase transformer ratio to be used is 3:1.

Step 2: Substitute the AC ammeters by the marked leads (one at a time). Use the appendix A to understand how does the AC ammeter works.

Step 3: Connect the AC voltmeters according to the measurements you need to make.

Step 4: Turn on the power supply and complete the columns marked as open A in the Table 5.1.

Step 5: Turn off the power supply.

REPORT REQUIREMENTS

1) Include the lab session text in completely. All tables must be filled with ink. Photocopies won't be acceptable.

2) Compare the differences and similarities of all different three-phase transformer connections. You can consult any reference you have.

3) Determine the $\dfrac{LL}{V_{ll}}$ ratio (primary-secondary line to line voltage ratio) for each three-phase transformer connection in terms of n (single-phase transformer ratio). Determine the ratio of line currents too for each one. Use some lab data to support your expressions.

4) Find out about harmonics and the effect of them in the power systems. Explain why is so important to eliminate the third harmonic and why three-phase delta connected transformers eliminate the i^{rd} harmonic.

LABORATORY SESSION VI

THREE PHASE INDUCTION MOTOR; NO-ROAD, **SPEED-CURRENT** AND **SPEED-TORQUE CHARACTERISTICS**

OBJECTIVES

The main purposes of this laboratory session are to study the operation and characteristics of three-phase induction motors.

The specific objectives of this lab session are:

1) To determine the phase sequence of a three phase power line and its effect on motor operation.
2) To examine the construction of the three-phase wound rotor induction motor.
3) To understand exciting current, synchronous speed and slip in a three-phase induction motor.
4) To observe the effect of the revolving field and rotor speed upon the voltage induced in the rotor.
5) To determine the starting characteristics of the wound rotor induction motor (WRIM).
6) To observe the rotor and stator currents at different rotor speeds.
7) To observe the characteristics of the wound rotor induction motor at no load and at full load.
8) To observe speed control using an external variable resistance in a wound rotor induction motor.
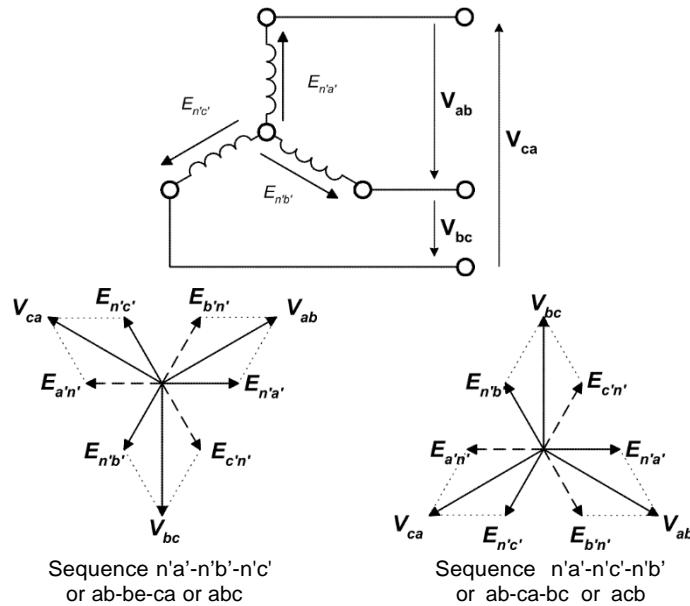
INTRODUCTION

A balanced three-phase voltage set consists of three sinusoidal voltages that have identical amplitudes and frequency but are out of phase with each other by exactly 120' In discussing three-phase circuits, it is standard practice to refer to the three phases as A, B, and C. The three voltages that comprise the three-phase set are referred to as the A-phase voltage, the B-phase voltage, and the C-phase voltage. The order in which the voltages, A, B, and C, succeed one another is called the phase sequence or the rotation of the voltages. This sequence is determined at the power generating station by the direction of rotation of the generators.

It is extremely important to know the phase sequence when connecting three phase motors to the power line, as their direction of rotation depends upon the phasing. Merely interchanging any two of the three power lines may change the sequence, and therefore, the rotation. Consider, for example, the connecting of a 4,000-hp motor, which may take an electrician two days of soldering and taping the three heavy leads. If the phase sequence is not determined in advance, the motor has one chance in two of turning in the wrong direction.

Refer to Figure 6.1 and consider the generated voltages Eq'a' Eg b and E, , as forming a balanced system of phase voltages. Either the sequence of these voltages will bé Eg a E, b -E, , as shown in the left hand vector diagram or it will be E, ,-E, , -E, b as shown in the right hand vector diagram. If wye-connected, these individual phase voltages will combine to form the line to line generated voltages Eb'a' E9 b and Ea'« Which in turn

define the time-phase sequence of the line to line voltage drops t_{ab}, l_{bs}, and p_a- An inspection of the vector diagrams of Figure 6.1 will show that generated voltage phase sequence n'a'-n'b'-n'c' yields ab-bc-ca sequence of line to line voltage drops, while generated voltage phase sequence n'a'-n'c'-n'b' yields ab-ca-be sequence of line to line voltages. Thus the sequence of the line-to-line voltages depends upon whether $E_{n'b'}$ lags Of l dS $E_{p'a'}$. BOth conditions may, of course, exist, and the one which actually does exist in a particular case, depends upon the relative positions of the three individual windings of the altemator[8] and the direction of motion of the rotating field.

Sequence n'a'-n'b'-n'c'
or ab-be-ca or abc

Sequence n'a'-n'c'-n'b'
or ab-ca-bc or acb

Illustrating the manner in which the generator phase sequence En'a', En'b', En'c' gives rise to line-to-line voltage sequence Vab, Vbc, Vca; also the manner in which generator phase sequence En'a', En'c'. En'b' gives rise to line-to-line voltage sequence Vab, Vca, Vbc.

FIGURE 6.1
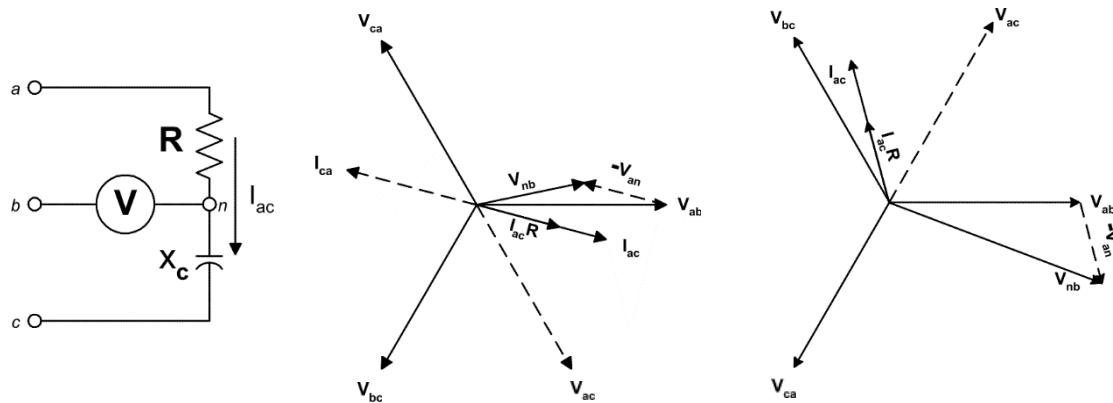
Given a three-wire, three-phase system of voltages, which are approximately balanced, the problem is to predict whether the sequence of voltages is abcabc or acbacb . The lines may be arbitrarily labeled a, b, and c. Phase sequence can be determined with the aid of various types of unbalanced loads, which have been analyzed so that the effects peculiar to a particular phase sequence are known. Upon observation of these effects the phase sequence can then be specified.

Three common methods of checking phase sequence will be analyzed briefly and then the correspondence of the results will be checked experimentally.

---

[8] Later, in chapter x, We'll describe the synchronous generator.
'Note that the sequence bac is the same as acb, which is the same as cba.

Method 1: Resistance-Capacitance Method.

Sequence V_{ab}, V_{bc}, V_{ca} exists if $(V=V_{nb})<V_{line}$; sequence V_{ac}, V_{ca}, V_{bc} exists if $(V=Vnb)>V_{line}$

Figure 6.2

First label the three lines a, b, and c. Place a resistor and condenser in series across terminals marked a and c as shown in Figure 6.2, that is, with the resistance connected to the a $_{line'}$[0] Then connect a voltmeter between the b line and the junction of the resistor and condenser as shown. If the voltmeter shown in Figure 6.2 is assumed to take a negligibly small amount of current as compared with the current flowing from a to c through R and Xc then the analysis may be carried out as shown in the accompanying vector diagrams. If R is roughly equal in magnitude to Xc then lac is approximately 45 degrees ahead of Vac for either sequence. In either case the voltmeter reading will be the magnitude of Vnb=Vab-Van because Vab=Van Vnb. Therefore the voltmeter reading will be the magnitude of:

$$V_{nb}= V_{ab}-V_{bn}=V_{ab}-I_{ac}R$$

An inspection of the two vector diagrams will show that the voltmeter reading Vnb is much smaller than the line voltages in one case and much larger in the other. Therefore, if the line voltages are approximately balanced:

                            abcabc sequence is indicated by   nb< [inc

And

                            acbacb sequence is indicated If   nb> ine

Method 2: Resistance-Inductance Method:

If Xc of Figure 6.2 is replaced with an inductive reactance XL. as shown in Figure 6.3, an analysis similar to that outlined above will show that:

                            abcabc sequence is indicated If   nb> [inc

and

                            acbacb sequence is indicated If   nb< ine

---

The opposite connection could be used equally well to determine the phase sequence, but, since the following analysis is based upon the connections shown in Figure 6.2, those connections must be employed if the results of the present analysis are to be used.
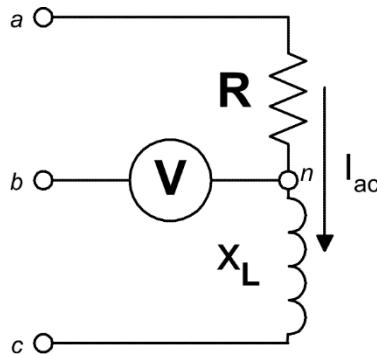
Figure 6.3 - Sequence ab-bc-ca exists if $(V=V_{nb})>V_{line}$, sequence ab-ca-bc exits if ('"nb)'"line"
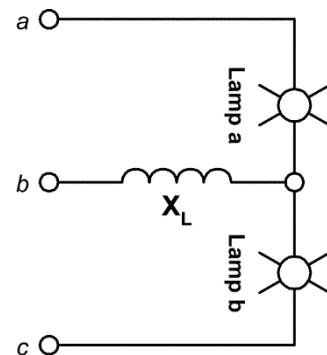
Figure 6.4 - Sequence ab-bc-ca exists if lamp a is brighter than la in p c ; seq u e n ce a b- ca - bc exits if lamp c is brighter than a .

Method 3: Two- lamps Inductance Method

If two lamps and inductance coil are connected in wye and the combination connected to the terminals a, b, and c as shown in Figure 6.4:

abcabc sequence is indicated if lamp a is brighter than lamp b

And

acbacb sequence is indicated if lamp b is brighter than lamp a.

For satisfactory results, the ohmic value of X_L should be comparable in magnitude to the resistance of one lamp, and similar lamps should be used.

Method 4: **Two Lamps-Capacitance Method**

As the two-lamps inductance method, you can insert a capacitor instead of the inductor in Figure 6.4. However, the sequence indication will be:

abcabc if lamp b is brighter than lamp a

And

acbacb if lamp a is brighter than lamp b.

The Three-Phase Induction Motor

The induction machine is the most rugged and the most widely used machine in industry. In the induction machine both stator winding and rotor winding carry alternating currents. The alternating current is supplied to the stator winding directly and to the rotor winding by induction, hence the name of induction machine.

The induction motor is used in various sizes. Large three-phase induction motors are used in pumps, fans, compressors, paper mills, textile mills and so forth.

As induction motor, a rotating magnetic field is generated in a magnetic core (see Figure 6. 5). This core, the stator, induces a voltage in other magnetic element called rotor. Both magnetic elements, one fixed or immobile (stator) and the other capable of

rotation (rotor), are separated by a narrow annular airgap. Each element carries windings arranged axially along the gap and a mutual magnetic flux crosses the gap to link them when the stator of a three-phase motor is connected to a three-phase source. Rotation of the rotor results in e.m.f. induction and in electromechanical energy conversion through interaction and alignment torque.

The synchronous speed of an induction motor is the speed at which its magnetic field revolves. It depends upon the number of poles for which the stator is wound and the frequency of the three-phase power source. The electric power companies accurately maintain the frequency of electric power systems; therefore, the synchronous speed of the stator field remains constant. The synchronous speed can be formulated as:

Cross Sectional View	Front View

MAGNETIC FLUX

ROTOR

AIRGAP

ESTATOR
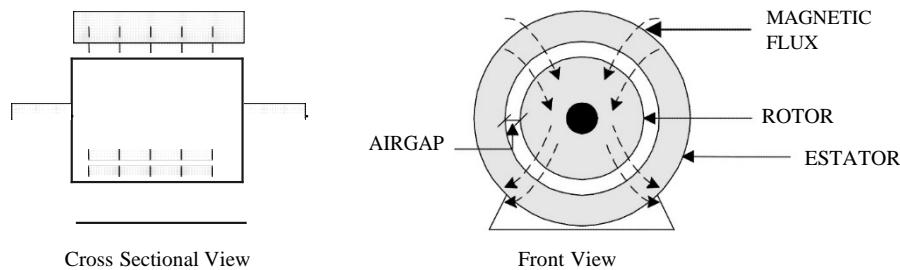
FIGURE 6.5

$$Sync\_Speed = \frac{120 \times f}{P}$$

The slip of an induction motor is the ratio of the difference between the rotating magnetic-field speed and it is expressed as a percent of the synchronous speed:

$$\%slip = \frac{100 * (\text{use}\_Speed - actual\_\text{speed})}{Sync\ Speed}$$

The power delivered by a rotor is formulated as:

$$P - Torque \times rotor\ speed - \frac{lbf.in\ x\ (r/\min)\ x\ 1.5867}{100,000}\ \textbf{[hp]}$$

The wound rotor consists of a rotor core with three windings in place of the conducting bars of the squirrel cage rotor. In this case, currents are induced in the windings just as they would be in winding shorted tums. However, the advantage of using windings is that the wires can be brought out through slip rings so that resistance can be inserted to the rotor and, therefore, the current through this winding can be controlled.

As an induction motor, the induced voltage in the rotor is proportional to the relative speed of the magnetic field and the rotor, in other words, the induced voltage is proportional to the slip. The rotating stator field induces an alternating voltage in each winding of the rotor. If the rotor windings are open, there are not rotor currents. The stator current will be equal to the exciting current and the rotor will stay standstill.
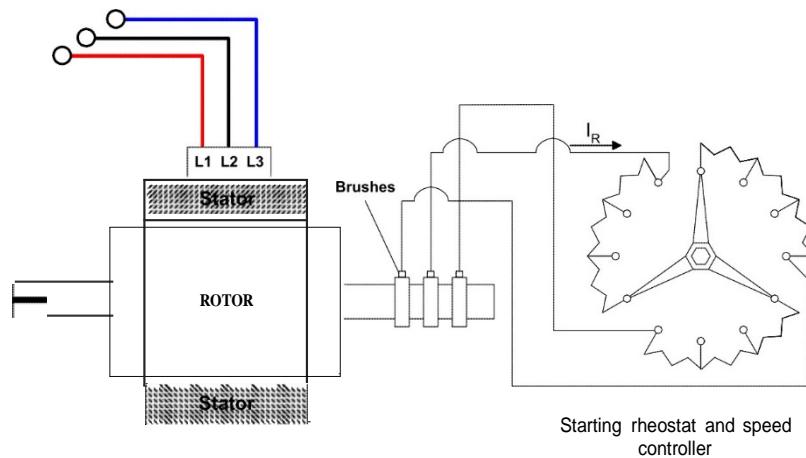
When the rotor is at standstill, the frequency of the induced rotor voltage is equal to that of the power source. If the rotor is now rotated by some external means (prime mover) in the same direction as the rotating stator field, the rate at which the magnetic flux cuts the rotor windings will diminish. The induced voltage and its frequency will

drop. When the rotor revolves at the same speed and in the same direction as the rotating stator field, the induced voltage as well as its frequency will drop to zero.

If the rotor windings are short-circuited, the induced voltage will cause large circulating currents in the windings. To supply this rotor current, the stator current must increase in value above its ordinary exciting current level. The power consumed (VA) in the rotor windings (and associated circuitry) must be supplied by the stator windings. Therefore, we should expect the following:

   a) At standstill, or at low speed, the rotor currents, stator currents and torque will be high.
   b) At synchronous speed, the rotor current and torque will be zero, and the stator will only carry the exciting current.
   c) At any other motor speed, the currents and the developed torque will be between the above extremes.

The Wound Rotor Three-Phase Induction Motor

Starting rheostat and speed controller

FIGURE 6.6 **EXTERNAL RESISTORS CONNECTED TO THE THREE** SUP-RINGS OF A **WOUND-ROTOR** INDUCTION MOTOR.
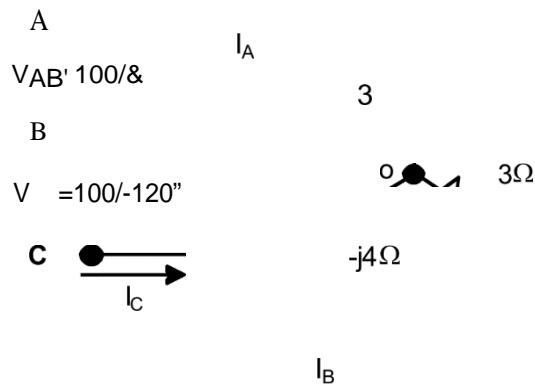
The three ends of the three-phase rotor windings are brought out to three slip rings mounted on the rotor shaft (Figure 6. 6). The brushes bearing on the slip rings play an important role in realizing maximum advantage from the wound rotor motor. By connecting the brushes through rheostats, it becomes possible to develop a higher starting torque than is possible with a squirrel cage motor. On starting, the full resistance of the rheostats is maintained in the rotor circuit, thus providing the very maximum starting torque.

As the motor approaches normal operating speed, the rheostat resistance is gradually reduced until it is out of the circuit entirely at full speed. Although the starting torque of the wound rotor is higher, it is not efficient.

A special feature of the wound rotor motor is its variable speed capability. By varying the rheostat resistance, it is possible to vary the percentage of slip and thus, vary the motor speed. In such cases, below full speed operation means the motor is running at reduced efficiency and horsepower, the motor is made more susceptible to variation in speed as the load changes.

PRELAB

1) The circuit shown in Figure 6.3 indicates a three-phase load. Use circuit analysis and calculate:

A

V_{AB}' 100/& I_A

3

B

V =100/-120" $\circ$ 3Ω

C $\bullet$ -j4Ω

I_C

I_B

FIGURE 6.3

a) The line currents: I_A. I_B and I_{ce}
b) Phase voltages: V_{AO}. Bo and V_{co} Compare these values each other.
c) Draw a phasor voltage diagrams showing the line and phase voltages.
d) Determine the phase sequence in this problem. What will happen with the line to neutral if the sequence would be different?

2) A 7.5-hp three-phase induction motor has 6 poles, a nominal speed of 1140-rpm, a power factor of 0.9 and an efficiency of 84. ^{0} . Calculate:

a) The synchronous speed in RPM and in rad/seg and slip of this motor.
b) The output torque in 1bf*ft in 1bf*in, and in N*m.
c) The current drawn by the motor at nominal speed and load.
d) The apparent power and reactive power.
e) The losses.

Experiment 6.1   Phase Sequence Determination

1 **EQUIRED EQUIPMENT**

Power Supply Module (0-120/208 V) (Three-phase)	EMS 8821
Connection Leads	EMS 8941
Inductance module	EMS 8321
Capacitance module	EMS 8331

PROCEDURE

Step 1: Connect the circuit shown in Figure 6.7, and realize that the resistance, the capacitor and the voltmeter are connected in wye to the variable 0-120/208V output of the power supply.
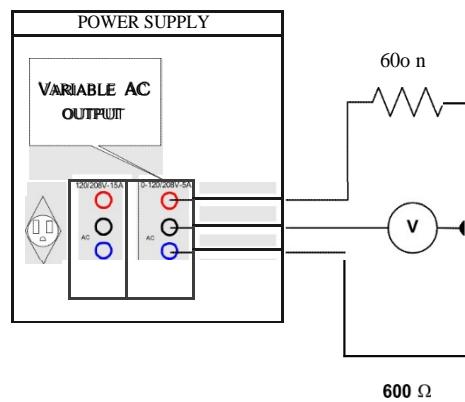
FIGURE 6.7

Step 2: Adjust the capacitance module for a reactance Xc of 600 ohm.
Step 3: Turn on the power supply and adjust to 50 Vac as indicated by the power supply ac voltmeter.
Step 4: Determine the phase sequence from the voltmeter reading (456456 or 465465), and complete the table 1 with the correct sequence below the title "Sequence Step 3". Remember connect a line voltmeter to measure the line voltage.
Step 5: Return the voltage to zero and turn off the power supply.
Step 6: Now, interchange any two leads to the power supply.
Step 7: Turn on the power supply and adjust to 50 V as indicated by the power supply ac voltmeter. Determine the phase sequence.
Question 1: Is the phase sequence the same (456456) as step 3?
Step 8: Complete the table 6.1 with the correct phase sequence below sequence step 6.
Step 9: Using your EMS Inductance Module, replace the capacitance with an inductance of 600 ohm, without disturbing any of your circuit wiring.
Step 10: Turn the power supply and adjust to 50 Vac as indicated by the power voltmeter. Determine the sequence as indicated by the resistance-inductance method discussed in the introduction.
Step 11: Complete the table 1 below "step 9".
Step 12: Turn off the power supply, and compare the results of steps 3 and 6.
Question 2: Are **the results equal?**

SEQUENCE STEP 3	SEQUENCE STEP 6	SEQUENCE STEP 9

Table 6.1

EXPERIMENT 6.2 WRIM CONNECTION AND EFFECT OF THE REVOLVING FIELD UPON THE INDUCED VOLTAGE

REQUIRED EQUIPMENT

Power Supply Module   (208, 3-phase, 0-120dc)   EMS 8821
Connection Lead Set   EMS 8941
Wound Rotor Induction Motor Module   EMS 8231
Electrodynamometer   EMS 8911
Timing Belt   EMS 8942

PROCEDURE

Step 1: Examine the construction (structure) of the wound-rotor induction motor module.
Step 2: Identify the three rotor slip rings and brushes.
Question 3: How many brushes have?
Question 4: Can the brushes be moved?
Step 3: Identify the stator windings and rotor windings. Note the small spacing of air gap between the rotor and the stator.
Question 5: Why should the spacing between the rotor and the stator be **small?** Explain **it in terms of "reluctance".**
 Step 4: Examine the front face of the module.
Question 6: To which numbers are the stator terminals connected
Question 7: What is the rated current **of the stator winding?**
Question 8: What is the rated voltage of the stator winding?
Question 9: The three rotor windings are (wye or delta) connected?
Question 10: To which numbers are the rotor terminals connected?
Question 11: What is the rated voltage of the rotor windings?
Question 12: What is the rated current of the rotor windings?
Question 13: What are the rated speed, voltage, current, frequency and horsepower of the motor?
Now you will see the effect of the revolving field and rotor speed upon the rotor induced voltage.
Step 5: Connect the circuit shown in Figure 6.. Couple the wound rotor to the dynamometer with a timing belt. See appendix to see how the dynamometer works. ASx **vOrR INSTRUCTOR FOR HELP IF YOU NEED IT.**

     Note: the prime mover is connected **to the variable dc terminals of the power supply; the stator of the wound rotor is connected to the** l"ixed ac **output of** the power supply.
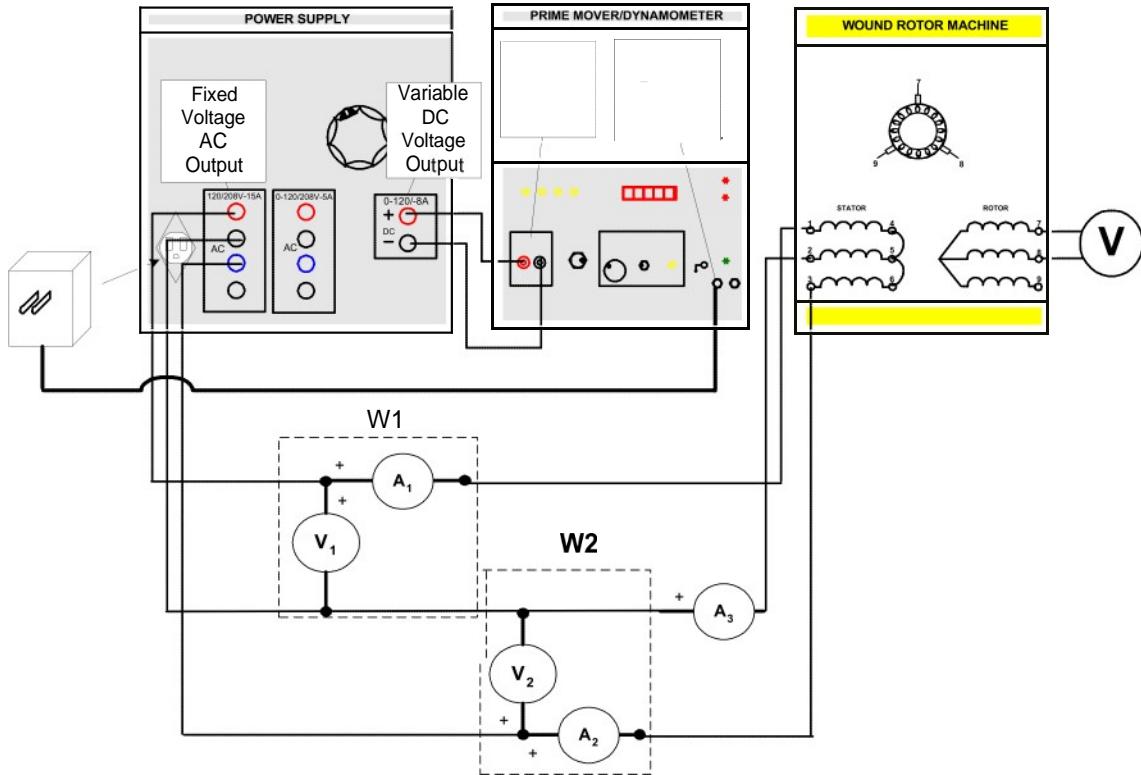
FIGURE 6.8

Question 14: How is **connected the wound rotor's stator** (wye or **delta**)**?**

Step 6: After you couple the wound rotor and the prime mover/ dynamometer, complete the first column in table 6.2 (zero speed rotor).

Step 7: The speed at the prime mover is controlled by the variable dc source. Increase, the dc voltage until you read 900 rpm, if, the value of V2 at 900 rpm is greater than at zero speed, turn off the power supply and interchange any two of the three-stator leads.

Step 8: Complete table 6.2 at 900 RPM.

Step 9: Increase the speed to 1200 rpm, complete table 6.2.

Step 10: Repeat step 9, but at 1800 rpm.

Step 11: Calculate the following for each case in table 6.2, and complete Table 6.3 with these results.

      a) Apparent power
      b) Real power
      c) Power factor
      d) Reactive power.

Question 15: Is the rotor being turned with or **against the rotating stator** field? Does the rotor **voltage is proportional to speed? Explain:**

Question 16: Using this experience, how many poles are in the WRIM? (Clue: the speed **of the magnetic field is equal to the** speed **when the induced voltage in** the rotor was zero.)

	11 (amps)	I2 (amps)	13 (amps)	El (volts) Stator	E2 (volts) Rotor	WI (watts)	W2 (watts)
0 rpm							
900 rpm							
1200 rpm							
1800 rpm							

Table 6.2

	S3ϕ	**P3ϕ**	Pf	**Q3ϕ**
0 rpm				
900 rpm				
1200 rpm				
1800 rpm				

Table 6.3

Experiment 6.3 WRIM Speed-Torque Characteristics

REQUIRED EQUIPMENT

Power Supply Module	EMS 8821
Connection Lead Set	EMS 8941
Wound-Rotor Induction Machine	EMS-8231
Speed Control Rheostat Module	EMS-8731
120/24 AC Adapter	

PROCEDURE

Step 1: Connect the circuit shown in Figure 6. Since the dynamometer and not the prime mover is needed, use the 120/24 AC Adapter and connect the output to the dynamometer's low power input.

Step 2: Couple the dynamometer to the motor with the timing belt and set the dynamometer control knob at its full cw position (to provide a maximum starting load for the motor).
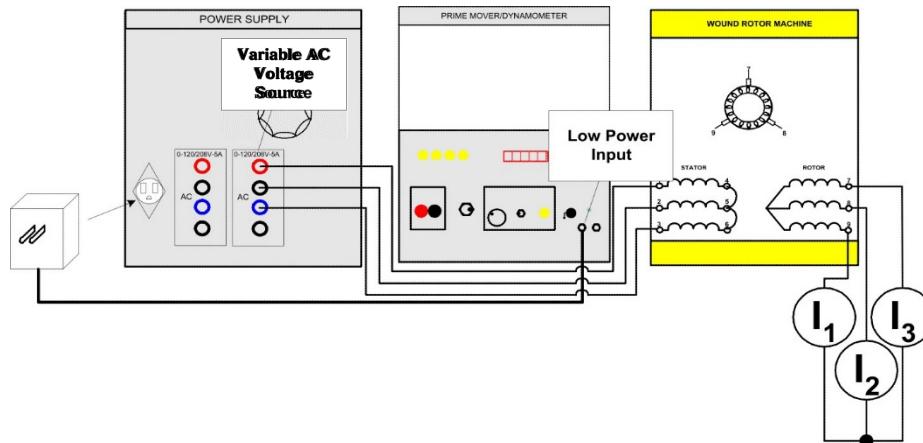
FIGURE 6.9

Step 3: Turn on the power supply and adjust the voltage from line to neutral of 100 Vac at the stator windings. Connect Van and measure 100V.

Step 4: Measure the three rotor currents and the developed torque. Record this data at table 6.4.

Question 17: Are the three rotor currents **approximately equal?**

Step 5: Gradually, reduce the load on the motor by slowly adjusting the dynamometer control knob. As the load is reduced the motor speed will increase.

Question 18: Do the three rotor currents **remain approximately equal** between **them?**

Question 19: Do the three rotor currents decrease as the motor speeds up?

Step 6: Measure and record in table 6.4 the rotor currents at a torque of 1 lbf.in.

Step 7 Return the stator voltage to zero and turn off the power supply.

Step 8: Connect the circuit shown in Figure 6. 10.
Note that the fixed 3-phase output of the power supply, terminals 1, 2, and 3 are now being used.
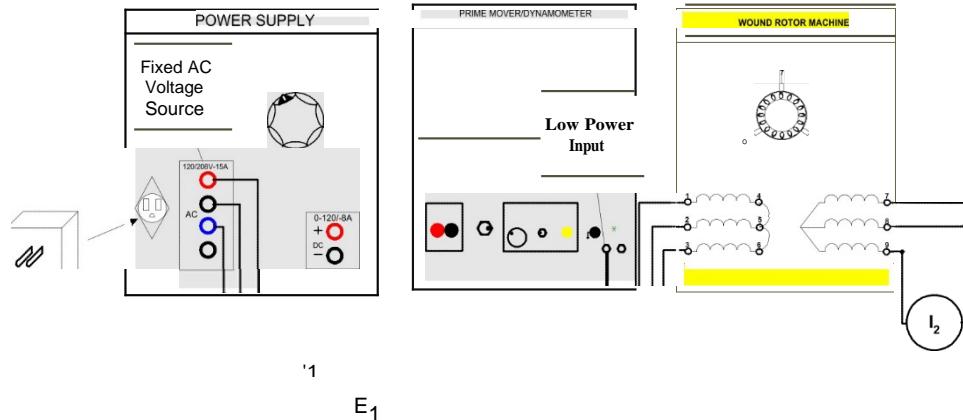
FIGURE 6. 10

Step 9: Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the motor).

Step 10: Turn on the power supply and quickly measure El, Il, I2 and the developed starting torque.

Step 11: Turn off the power supply.

Step 12: Fill the table 6.5 with your measures and calculate the apparent power to the motor at starting torque.

Step 13: Now you will experiment with the wound rotor with external resistances connected to it. See how the speed control rheostat module works in the appendix

Step 14: Connect the circuit shown if Figure 6.4. Do not couple the motor to the electrodynamometer at this time!

Step 15: Set the speed control rheostat knob at its full ccw position for zero resistance. Turn on the power supply and adjust the line-to-line voltage in the power supply to 208 Vac. The motor should be running.

Step 16: Measure and record in Table 6.6, the three line currents, the two-wattmeter indications (remember, to observe the polarities) and the motor speed using the hand tachometer.

Step 17: Return the voltage to zero and turn off the power supply.

Step 18: Couple the motor to the electrodynamometer with the timing belt.

Step 19: Set the dynamometer control knob at its full ccw position, and repeat the step 16 to for each of the torques listed in Table 6.6 maintaining the input voltage at 208 Vac.

Step 20: Turn the voltage to zero and turn off the power supply.

Step 21: Set the speed control rheostat knob at its full cw position for maximum resistance. Uncouple the motor form the electrodynamometer.

Step 22: Turn on the power supply and adjust the line-to-line voltage to 208 Vac. The motor should be running.

Step 23 Measure and record in table 6.7, the three line currents, the two-wattmeter indications and the motor speed using the hand tachometer.

Step 24 Return the voltage to zero and turn off the power supply.
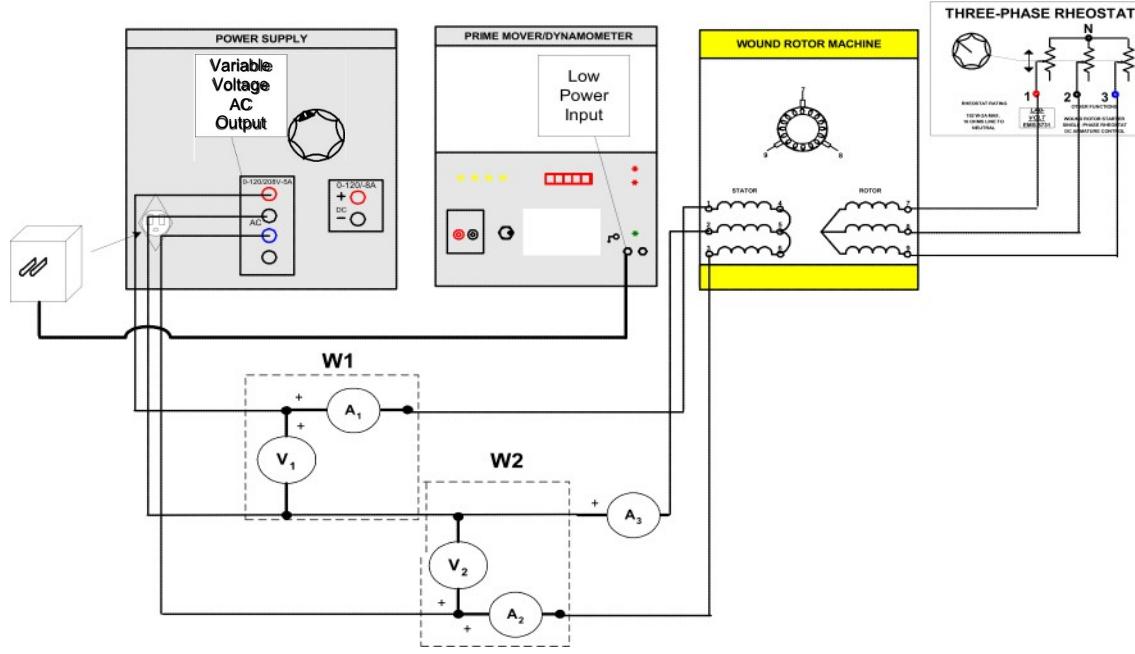
FIGURE 6.4

Step 25: Couple the motor to the electrodynamometer with the timing belt. Set the dynamometer control knob at its full ccw position.

Step 26: Repeat steps 23 to 24 for each torques listed in table 6.7, maintaining the input voltage at 208 Vac.

Question 20: With a developed torque of 9 **lbf.in, rotate the** speed control rheostat **knob from full** cw **to full** ccw. Does **the motor** speed change? Does the developed torque change?
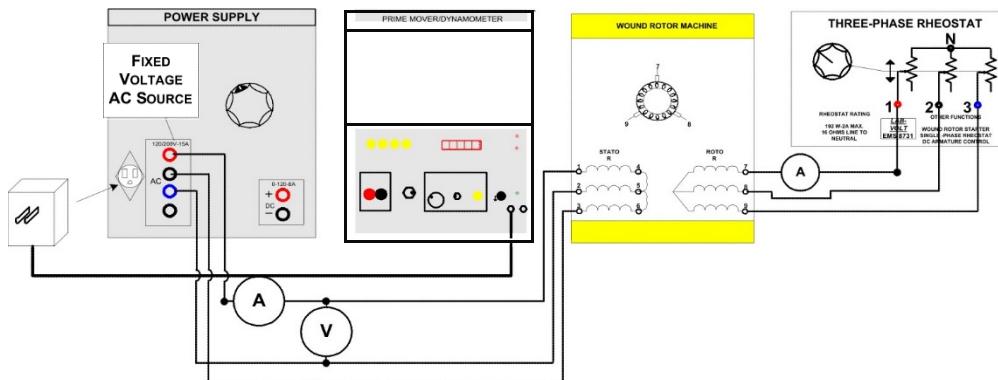
FIGURE 6.5

Step 27: Return the voltage to zero and turn off the power supply.

Step 28: Connect the circuit shown in Figure 6.5. Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the motor).

Step 29: Set the speed control rheostat knob at its full cw position (to provide maximum resistance).

Step 30: Turn on the power supply and quickly measure the line to neutral voltage at the power supply, the line current, the current at the rotor, and the developed starting torque.

Step 31 Turn off the power supply.

Step 32: Calculate the apparent power to the motor at starting torque and complete the Table 6.8.

Question 17: Are the three rotor currents **approximately equal?**

Question 18: Do the three rotor currents **remain approximately equal between** them?

Question 19: Do the three rotor currents decrease as the motor speeds **up?**

Question 20: With a developed torque of 9 **lbf.in, rotate the** speed control rheostat **knob from full** cw **to full** ccw. Does the motor speed change? Does the developed torque change?

TORQUE	II	12	I3
Full load			
1 **lbf.in**			

Table 6.4

Torque (lbf.in)	11	I2	EI	S (VA)

Table 6.5

Torque Lbf.in	I, Amps	If Amps	I, Amps	Wi Watts	Wk Watts	Speed r/min
0						
6						
9						
12						

Table 6.6

Torque Lbf.in	I; Amps	12 Amps	I Amps	Wj Watts	2 Watts	Speed r/min
0						
6						
9						
12						

Table 6.7

Three-Phase Induction Motor, No Load, Speed-Current and Speed-Torque Characteristics

I₁	I₂	V	Torque

Table 6.8

OEPORT REQUIREMENTS

1) Draw a phasor diagram explaining the two lamps and an inductor method for determining the phase sequence.
2) Name the principal components of an induction motor.
3) Name the different types of induction rotors and describe them briefly.
4) Why does the rotor of an induction motor turn slower than the stator-revolving field?
5) Why does the voltage induced in the rotor of an induction motor decrease as the rotor speeds up?
6) Calculate the ratio between starting currents and nominal currents.
7) Calculate the ratio between starting torque and nominal torque output.
8) What is the effect of changing the phase sequence in an induction motor?
9) How do the rotor and stator currents vary at different rotor speeds?

LABORATORY SESSION **VII**

SQUIRREL CAGE INDUCTION MOTOR AND INDUCTION MOTOR CONTROL

OBJECTIVES

In this laboratory session we will study the squirrel-cage induction motor and use it for motor control. The main purpose of this laboratory session is to become familiar with various components and the terminology used in the controls program and to examine the difference between the squirrel-cage induction motor and the wound rotor. Also, we are interested in using two starting methods for induction motors.

The specific objectives of this lab session are:

1) To examine the construction of the three-phase squirrel cage induction motor.
2) To explain the important terminology used in conjunction with motor controls.
3) To show the graphic symbols and device designations that will be used in the manual.
4) To realize the advantages of reduced voltage starting.
5) To learn the principle of wye-delta starting.
6) To construct a wye-delta starter.
7) To perform various timing operation using the time delay relay.
8) To construct a delayed start 3$ magnetic starter.
9) To use the inertia wheel to represent a high inertia starting loads.
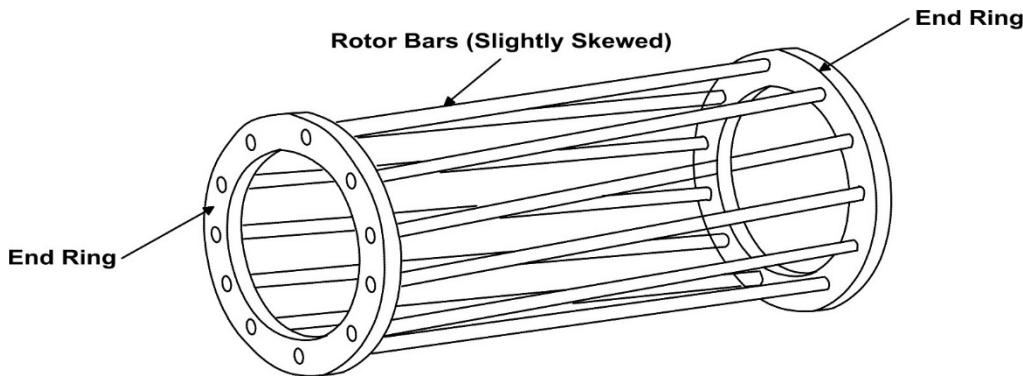
IIEFERENCES
1) Wildi/Devito, *Control of Industrial Motors and transformers,* 2 ed., Buck Engineering Co. Inc. Farmingdale, New Jersey. (In Canada: Lab-volt Limited, Montreal Quebec), 1972.

INTRODUCTION

THE SQUIRREL CAGE THREE PHASE INDUCTION MOTOR

The simplest and most widely used rotor for induction motors is   the   so-called squirrel cage rotor, from which the squirrel cage induction motor gets its name. The squirrel cage rotor consists of a laminated iron core, which is slotted lengthwise around its periphery. Solid bars of copper of coppers or aluminum are tightly pressed or embedded into the rotor slots (Figure 7. 1). At both ends of the rotor, short-circuiting rings are welded or brazed to the bars to make a solid structure. The short-circuited bars, because their resistance is much less than the core, do not have to be specially insulated from the core. In some rotors the bars and end rings are cast as a single integral structure for placement on the core. The short-circuiting elements actually form shorted turns that have high currents induced in them by stator field flux.

Sketch of Squirrel Cage
Winding
FIGURE 7.1

Compared to the intricately wound and arranged wound rotor or the armature of the DC motor, the squirrel cage rotor is relatively simple. It is easy to manufacture and is essentially trouble-free in actual service. In an assembled squirrel cage induction motor, the periphery of the rotor is separated from the stator by a very small air gap. The width of this air gap, in fact, is as small as mechanical clearance needs will permit. This insures that the strongest possible electromagnetic induction action will take place.

When power is applied to the stator of a practical induction motor, a rotating magnetic field is created. As field begins to revolve, its flux lines cut the shorted turns embedded around the surface of the squirrel cage rotor and generate voltages in them by electromagnetic induction. Because these turns are short-circuits with very low resistance, the induced voltages cause high currents to circulate in the rotor bars. The circulating rotor currents then produce their own strong magnetic fields. These local rotor flux fields produce their own magnetic poles, which are attracted to the rotating field. Thus, the rotor revolves with the main field.

The starting torque of the basic squirrel-cage induction motor is low, because at rest the rotor has a relatively large inductive reactance (X_{LI} with respect to its resistance (R). Under these conditions we would expect the rotor currents to lag rotor voltage by 90 degrees. We thus say that the power factor in the circuit is low and cannot derive really useful energy for its operation from the power source.

Despite the inefficiency, torque is developed and the motor begins to turn. As it starts turning, the difference in speed between rotor and rotating field, or slip, goes form a maximum of 100 percent to some intermediate value, say 50 percent. As the slip decreases in this manner, the frequency of the voltages induced in the rotor decreases, because the rotating field cuts conductors at a decreased rate; this, in turn, causes the overall inductive reactance decreases, the power factor begins to increase. This improvement is reflected as an increase in torque and a subsequent increase in speed.

When the slip drops to some value between 2 and 10 percent, the motor speed stabilizes. This stabilization occurs because every tendency for the motor speed to increase to where slip will drop below 2 percent is naturally offset by the fact that, as the rotor approaches within 2 percent of the synchronous speed, the effects of reduced induction overcome the previous tendency to increase torque as the motor is speeded up from start. Thus, the motor exhibits an automatic speed control characteristic similar to that of the DC shunt motor.

STANDARD CONTROL-CIRCUIT SYMBOLS AND DIAGRAMS

All trades and professions have a certain language that enables the rapid and efficient transfer of information and ideas. This language may include symbols, drawings or diagrams, words, phrases, or abbreviations. Line (ladder) diagrams use industrial electrical symbols to provide the information necessary to understand the operation of any electrical control system. Industrial electrical symbols illustrate the electrical devices within a circuit.

A line (ladder) diagram is a diagram that shows, with single lines and symbols, the logic of an electrical circuit or system of circuits and components. A line diagram indicates the location of electrical devices within a circuit. A line diagram shows the power source and how current flows through the various parts of the circuit, such as pushbuttons, contacts, coils, and overloads. A line diagram shows the circuitry necessary for the operation of the controller. A line diagram is not intended to show the physical relationship of the various devices in the controller.

In a line diagram, the symbols are basic representations of the electrical functions occurring in the circuit. The graphic symbols shown conform to *NATIONAL ELECTRICAL MANUFACTURERS ASSOCIA TION* (NEMA), *AMERICAN NATIONAL STANDARDS INSTITUTE* (ANSI), and *INSTITUTE OF ELECTRICAL AND ELECTRONIC ENGINEERS* (IEEE) standards. Review the appendix C so you can get familiar with the symbols.

MANUAL CONTROL CIRCUITS

A manual control circuit is any circuit that requires a person to initiate an action for the circuit to operate. A line diagram may be used to illustrate a manual control circuit of a pushbutton controlling a pilot light (Figure 7.2).

Momentary Contact
Pushbutton

Pilot Light 1

L_1 L_2

PB1   PU

Power Circuit
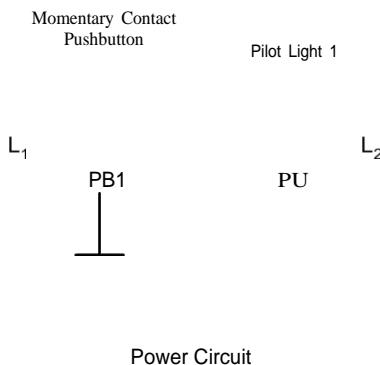
FIGURE 7.2

Line diagrams are read from left (L) to right (Lt). In the circuit of Figure 7.2, pressing pushbutton 1 (PBI) allows current to pass through the closed contacts of PB1, through pilot light 1 (PLI) and on to L2. This forms a complete circuit, which activates PU. Releasing PB1 opens contacts PB1, stopping the current flow to the pilot light. This tums OFF the pilot light.

Squirrel Cage Induction Motor and Induction Motor Control

AUTOMATIC CONTROL CIRCUITS

Automatically controlled devices have replaced many jobs that were once performed manually. As a part of automation, control circuits are designed to replace manual devices. Any manual control circuit may be converted to automatic operation. For example, an electric motor on a sump pump can be turned ON and OFF automatically by adding an automatic control circuit device such as a float switch (See Figure 7.3). This control circuit is used in basements to control sump pump to prevent flooding. The float switch senses the change in water level and automatically starts the pump, which removes the water when it reaches a predetermined level.

Line Diagram

Picto±al Drawing

Circuit Application
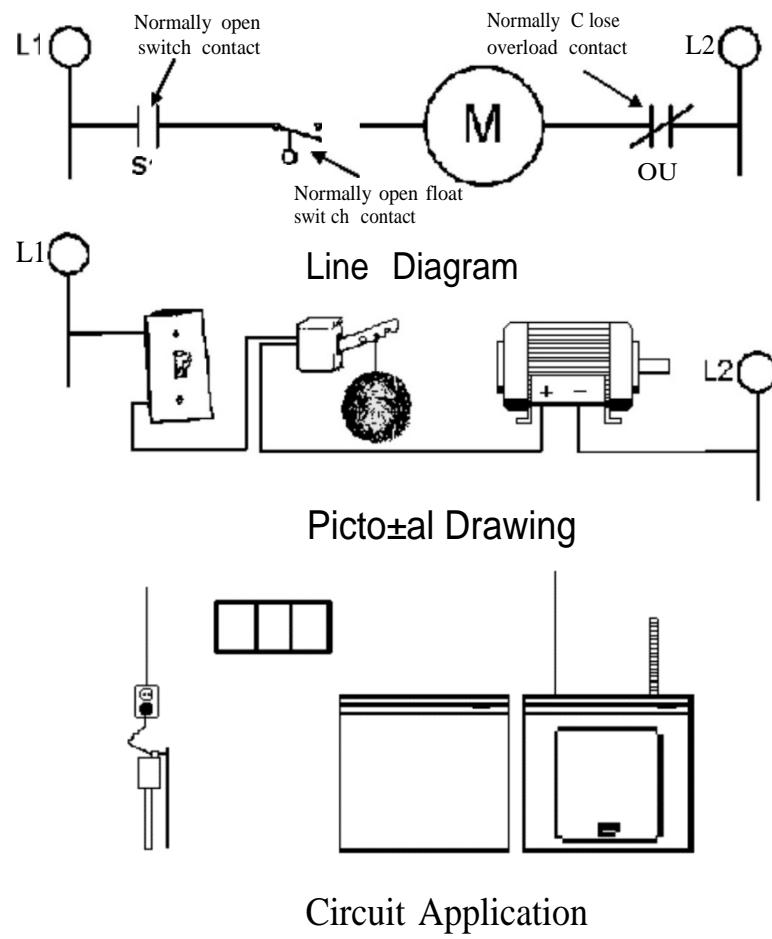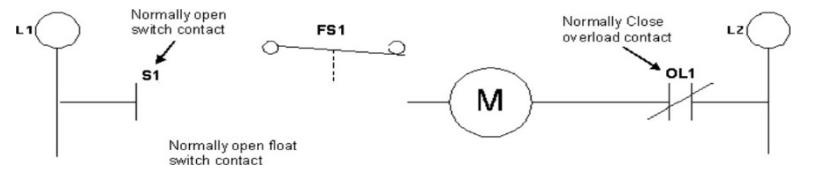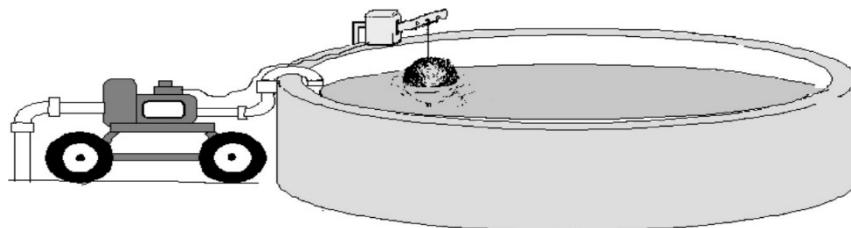
FIGURE 7.3

In the circuit of Figure 7.3, float switch contacts FS1 determine if current passes through the circuit when switch contacts S1 are closed manually. Current passes through contacts SI, FS1, the motor, its overload, and on to L2 when the float switch contacts FSI are closed. This starts the pump motor. The pump motor pumps water until the water level drops enough to open contacts FSI and shut OFF the pump motor. A motor overload, power failure, or the manual opening of contacts SI stops the pump motor for automatically pumping water when it reaches the predetermined level.

Line Diagram

Circuit Application

FIGURE 7.4

Control devices, such as float switches, are normally designed with NO (normally open) and NC (normally closed) contacts. For example, variations in the application of the float switch are possible because the NO and NC contacts can close or open contacts when changes in liquid level occur. As shown in Figure 7.4, the NC contacts of the float switch may be used for pump operation to maintain certain levels of water in a livestock water tank. The NC contacts close and start the pump motor when the water level drops, due to evaporation or drinking. The float opens the NC contacts, shutting the pump motor OFF when the water level rises to a predetermined level.

DELAYED START OF A 3$ INDUCTION MOTOR
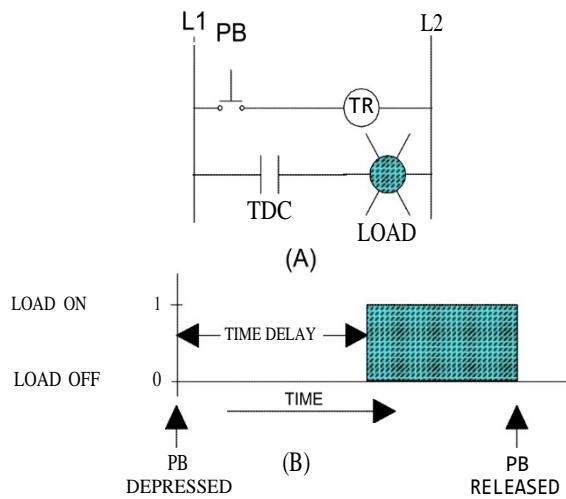
FIGURE 7.5

During this Laboratory Experiment we will examine five different timing functions that can be performed using the same time delay relay. For each of the following circuits, assume that L1 and L2 are connected to and appropriate power source and that the pilot lamp represents the load.

Examine the simple timing circuit shown in Figure 7.5a, due to the normally open contacts, both the operating coils, initiating the start of the timing function. After a preset time interval the normally open TDC contacts close, completing the load circuit. Releasing the pushbutton de-energizes the operating coil, causing the TDC contacts to open immediately, and disconnecting the load circuit. This sequence of events is shown in Figure 7.5b.
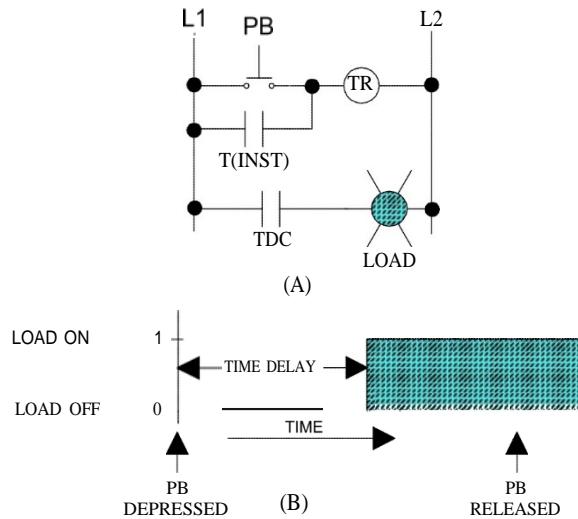
FIGURE 7.6

The circuit of Figure 7.6a shows how the load can be kept on when the pushbutton is released. This is accomplished by adding a holding contact in parallel with the pushbutton. Because an instantaneous operating contact is used, the pushbutton can be released immediately without disturbing the sequence of events shown in Figure 7.6b.
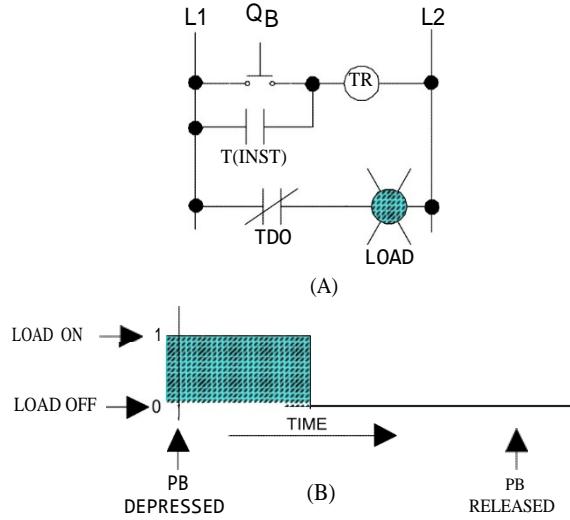
FIGURE 7.7

A new sequence of events can be obtained by changing the time-delay-closing TDC contact to a time delay opening TDO contact as shown in Figure 7.7a. The load is normally on prior to depressing the pushbutton as shown in Figure 7.7b.
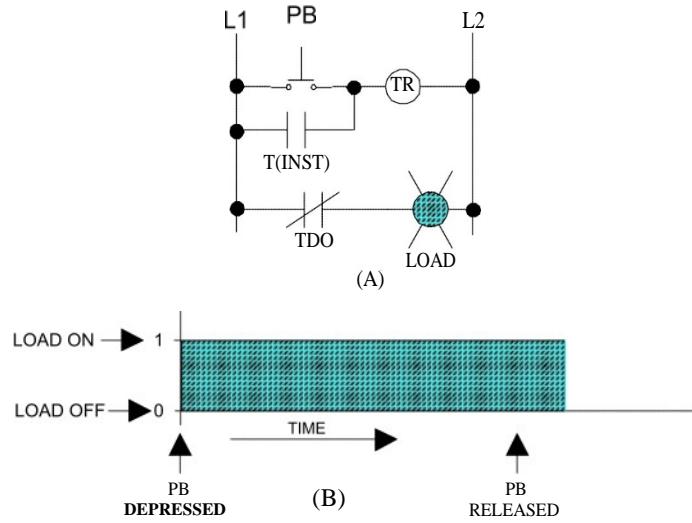
FIGURE 7.8

The circuit of Figure 7.8a shows how the load can come on at once for a definite time interval. The pushbutton, once depressed, has no further control over the load. This is graphically represented in Figure 7.8b.
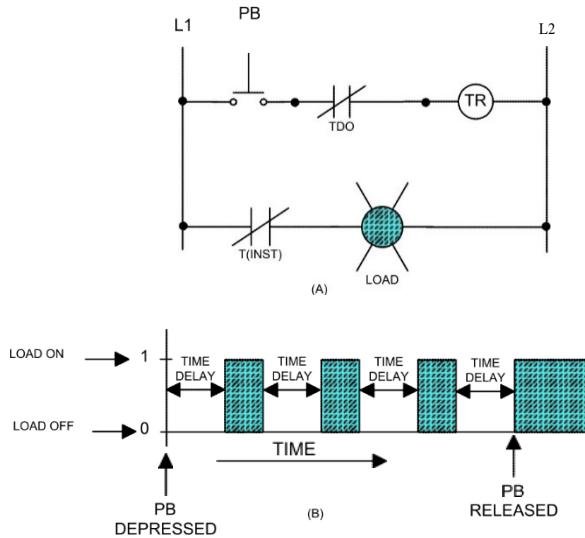
FIGURE 7.9

The load is normally on in the circuit shown in Figure 7.9a. When the pushbutton is depressed the load is turned off for a definite time interval and then comes on again. This cycle repeats as long as the pushbutton is depressed. Upon release, the load returns to its on state in Figure 7.9b.

When starting up complex mechanical loads such as those found in steel mills, newspaper printing presses, etc., it is often desirable, for operator safety, to precede the actual drive motor starting by a warning signal. This can be done automatically by

having the motor starting control activate the warning signal, which can be a bell, buzzer or lamp, while delaying the start of the motor for some predetermined time interval.

To accelerate a load, the drive motor must develop torque in excess of the load torque. This excess torque accelerates the moving mass of the driven load to full speed, depends on its inertia. The EMS Inertia Wheel, Model 9126, simulates a high inertia load that allows drive motor acceleration and deceleration properties to be observed.

PRELAB

1. A three-phase 125hp 440V 60Hz eight-pole induction motor has a starting current of 581A and a starting torque of 497 N*m when direct connected to full voltage to its terminals. Calculate the starting torque and starting current when the motor is started at a reduced voltage of 254V.

2. A 208V 60 Hz. three-phase induction motor has a nominal torque of 2,290 lbf*ft at 1710 rpm. Calculate:
   a) The nominal output power of the motor in Hp and KW.
   b) If the motor has to be started with a load of 1,000 lbf*ft, which is the minimum voltage permissible for starting the motor with a reduced voltage starter.

Experiment 7.1   The Squirrel Cage **Induction Motor**

REQUIRED EQUIPMENT

Power Supply Module (0-120/208)	EMS 8821
Connection Lead Set	EMS 8941
Squirrel Cage Induction Motor Module	EMS 8221
Electrodynamometer Module	EMS 8911
Hand Tachometer	EMS 8920
Timing Belt	EMS 8942
Connection Leads	EMS 8941

PROCEDURE

Step 1: Examine the construction of the Squirrel Induction Motor, paying particular attention to the motor, connection terminals and the wiring.

Step 2: a) Identify the stator windings. Note that they consist of many turns of small diameter wire evenly spaced around the stator. (The stator windings are identical to that of the wound rotor induction motor.)

b) Identify the cooling fan.

c) Identify the end rings of the squirrel cage rotor.

d) Note the length of the air gap between the stator and the rotor.

Question 1: Is there any electrical connection between the rotor and any other part of the motor like in the WRIM?

Step 3: Look at the front face of the module:

Question 2: The three separate **stator windings** are connected to which **terminals?**

Question 3: What is the rated current of the stator windings?

Question 4: What is the rated voltage of the stator windings?

Question 5: What is the rated speed and horsepower **of the motor?**

Step 4: a) Connect the circuit shown in Figure 7.10. Do not couple the motor to the dynamometer at this time!

b) Turn on the power supply and adjust the line-to-line voltage of the power supply to 208 Vac. The motor should be running.

Step 5: a) Measure and record in Table 7.1, the three line currents, the two-wattmeter indications and the motor speed.

b) Return to zero and turn off the power supply.

Step 6: a) Couple the motor to the electrodynamometer with the timing belt.

b) Set the dynamometer control knob at its full ccw position.

c) Repeat step 5 for each of the torques listed in Table 7.1

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

Step 7. a) Connect the circuit shown in Figure 7.11.

b) Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the motor).
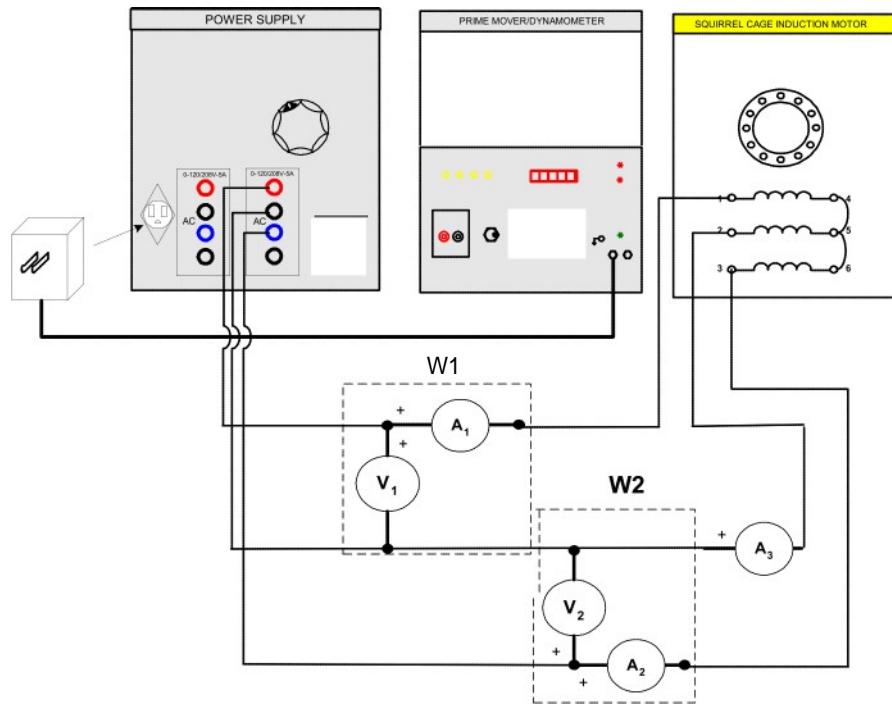
FIGURE 7.10

Step 9: a) Calculate the apparent power to the motor at starting torque.
b) Complete Table 7.2.
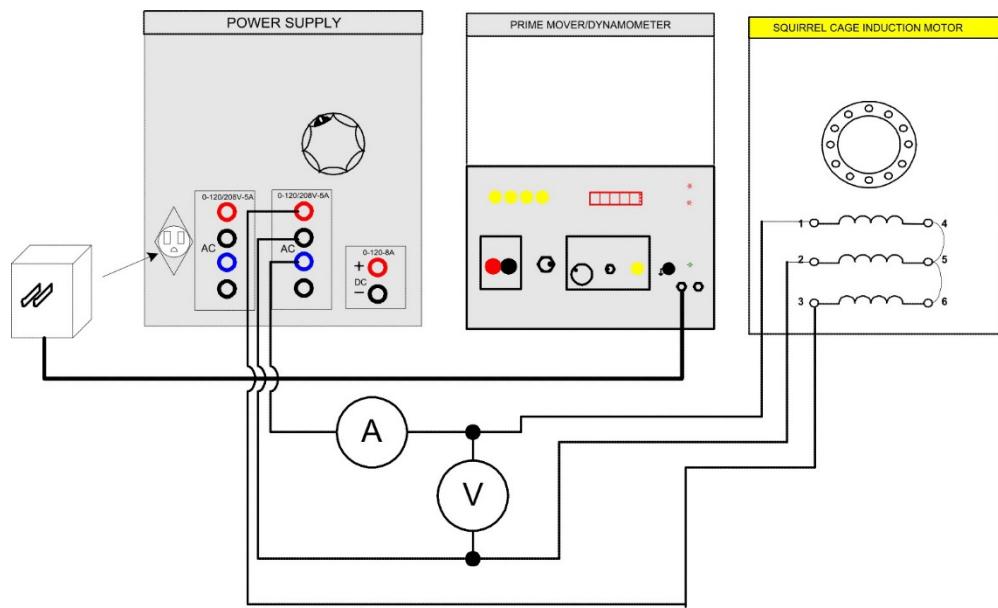
FIGURE 7.11

Torque Lbf.in	I, Amps	If Amps	I Amps	Wj Watts	J2 Watts	Speed r/min
0						
6						
9						
12						

Table 7.1

V	I	Torque	S

Table 7.2

Experiment 7.2   Delayed Start of a 3$ induction Motor.

1EQUIRED EQUIPMENT

Power Supply Module (120/208V 3B)	EMS 8821
Connection Lead Set	EMS 8941
Pushbutton, Red	EMS 9102
Pushbutton, Black	EMS 9103
Electromagnetic Contactor	EMS 9106
Time Delay Relay	EMS 9107
Overload Relay	EMS 9109
Circuit Breaker	EMS 9110
Pilot Lamp, Red	EMS 9120
Pilot Lamp, Green	EMS 9121
Inertia Wheel	EMS 9126
Component Panel (2)	EMS 9127
Connection Leads	EMS 9128
Squirrel-Cage Induction Motor Module (3$)	EMS 8221
Control Transformer	EMS 9123
Test Buzzer	EMS 9124
Electrodynamometer Module	
Timing Belt	

PROCEDURE
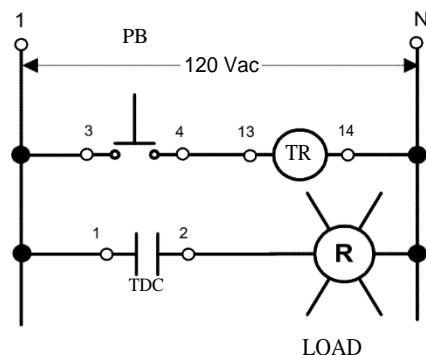
FIGURE 7.12

Step 1:a) Set up the circuit shown in Figure 7.12. Note that the circuit input is connected to the fixed 120Vac output for the power supply, terminals 1 and N.

b) Adjust for a time delay of five seconds.

c) Turn on the power supply. Operate the pushbutton while observing the behavior of the pilot lamp.

Question 1: Does the lamp come on after the push button is held in the depressed **condition** for five seconds?

Question 2: Does the lamp go off **when the pushbutton is released?**

Question 3: Does repeated **short time operation of the pushbutton activate the lamp? Explain**

Step 2: Turn off the power supply.
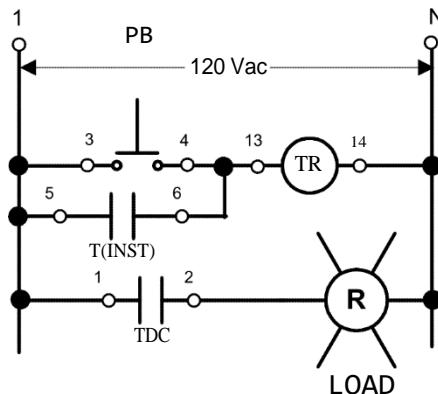
FIGURE 7.13

Step 3: a) Add a holding contact to your circuit as shown in Figure 7.13.
   b)   Turn on the power supply.
   c)   Operate the pushbutton while observing the behavior of the pilot lamp.
Question 4: Does the lamp come one when pushbutton is depressed?
Question 5: Does the **lamp** go off when the pushbutton is released?
Question 6: What must be done to turn the lamp off?
Question 7: Does the lamp eventually come on even **if the pushbutton is** released **prior to the five-second-delay time? Explain**
   d) Turn off the power supply.
Step 4: a) Change the TDC contact to a TDO contact as shown in Figure 7.14.
   b)   Turn on the power supply.
   c)   Operate the pushbutton while observing the behavior of the pilot lamp.
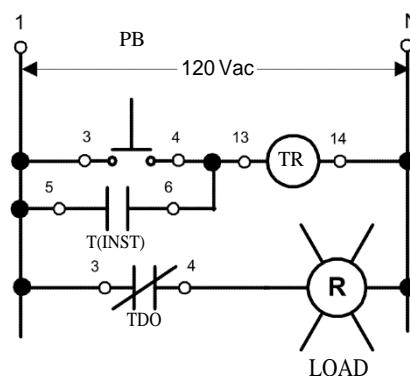
FIGURE 7.14

Question 8: Does **the lamp go off when the pushbutton is** depressed?
Question 9: Does the lamp go off l"ive **seconds after the pushbutton has been** depressed?
Question 10: Can the pushbutton be used to turn the lamp on?
Step 5: Turn off the power supply.
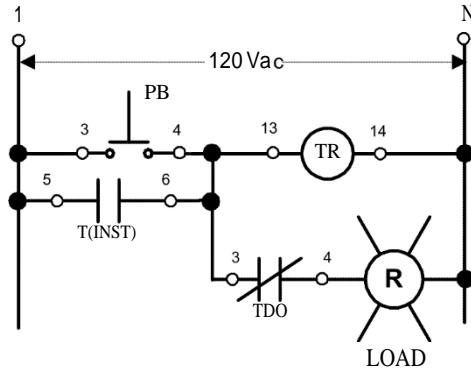
FIGURE 7.15

Step 6: a) Change the connection to terminal 3 of the TDO contact as shown in Figure 7.15.

b) Turn on the power supply. Operate the pushbutton while observing the behavior of the lamp.

Question 11: Does the lamp come on **when the pushbutton is depressed?**

Question 12: Does the lamp go off **when the pushbutton is released?**

Question 13: What does determines the on time of the lamp?

Question 14: Does **the pushbutton control the lamp, once the lamp has gone through an on-off cycle? Explain.**
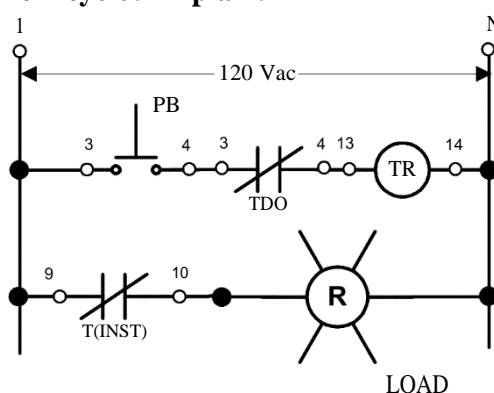
FIGURE 7.16

Step 7: Turn off the power supply.

Step 8: a) Connect the circuit shown in Figure 7.16.

b) Turn on the power supply.

Step 9: a) Operate the pushbutton while observing the behavior of the pilot lamp.

Question 15: Does the lamp go off **when the pushbutton is** depressed?

Question 16: Does it remain off while the pushbutton is held in the depressed state?

Question 17: When the pushbutton is held in the depressed **condition, what determines the on time?**

Question 18: Could this circuit be called a relay oscillator circuit? Explain.

Step 10: Turn off the power supply.

Step 11 Examine the circuit shown in Figure 7.17.

Question 19: Is this an across-the-line magnetic starter circuit?
Question 20: Which operating coil will be energized when the start button is
    depressed?
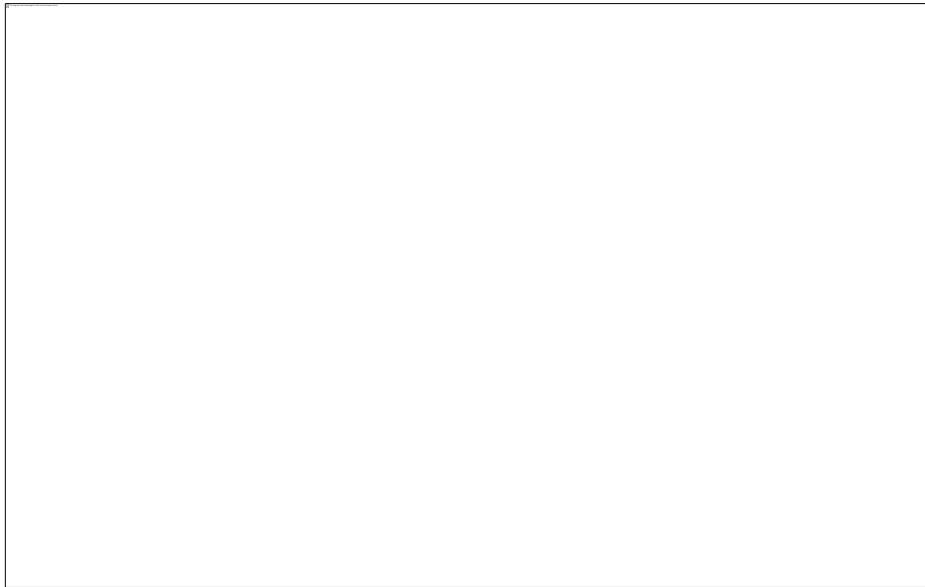
FIGURE 7.17

Question 21: When will the M contacts close?
Question 22: Will the buzzer sound when these **contacts close? Explain**
Question 23: Will the red pilot lamp indicate when the **motor is on?**
Step 12: a) Set up the circuit shown in Figure 7.17. Connect the three squirrel cage
    motor terminals (4, 5, and 6) together (wye connection). Adjust for a time
    delay of ten seconds.
    b) Close the disconnect switch and turn on the power supply.
    c) Depress the start pushbutton and observe the operation of the motor.
    d) Depress the stop pushbutton. Repeat the start and stop depression several
    times.
Question 24: Does **the circuit perform** as expected?
    e) Turn off the power supply and open the disconnect switch.
Step 13: We will now measure the time it takes for an unloaded motor to reach full
    speed when started (acceleration) and the time it takes for it to come to a stop
    (deceleration) from full speed. We will then repeat these measurements while
    the motor is driving a high inertia load. A motor draws maximum current at
    the instant of starting. As the motor accelerates, the starting current drops.
    The current stabilizes at some value when the motor reaches full speed.
    a) Remove the buzzer test set from your circuit.
    b) Insert an ac current meter, set on the 2.SA range, in series with one of the
    input leads to the overload relay.
    c) Adjust for zero time delay.
Step 14: a) Close the disconnect switch and turn on the power supply.

b) Using a timer to monitor the acceleration time, depress the start button while observing the current meter.

$T_{acceleration}$ '_____ S

c) Depress the stop button and measure the deceleration time.

$T_{deceleration}$ '_____

d) Repeat acceleration and deceleration steps three times and record your measurements in the Table 7.3 as unloaded.

e) Turn off the power supply and open the disconnect switch.

Step 15: a) Couple the electrodynamometer to the squirrel cage motor with the timing belt. The dc motor/generator will serve as a passive load for the squirrel cage motor and is not to be connected electrically.
We will use the inertia wheel to simulate a high inertia-starting load.

b) Make sure the locking screw is retracted into the wheel hub. Slide the inertia wheel onto the shaft of the squirrel cage motor until the short hub-extension touches the timing pulley.

c) Fasten the wheel to the motor shaft by turning the locking control knob clockwise.

d) Change the range of the current meter to 8 Aac. Close the disconnect switch and turn on the power supply.

e) Using a timer, measure the acceleration and deceleration time for the loaded motor. Record your results in the table as loaded.

Caution: Remember, never attempt to stop the inertia wheel by hand. Wait until it comes to rest by itself.

Step 16: a) Turn off the power supply and open the disconnect switch.

b) Examine the results shown in the table.

Question 25: Is there an appreciable difference between the loaded and unloaded **measurements? Explain.**

$T_{acceleration}$'_____ S   TJeceleration ⊂ _____ S

	ACCELERATION TIME		DECELERATION TIME	
TRIAL	UNLOADED	LOADED	UNLOADED	LOADED
No. 1				
No. 2				
No. 3				

Table 7.3

REPORT REQUIREMENTS

1) Which is the main difference between squirrel cage and wound rotors?
2) What are the reasons for using reduced-voltage starting?
3) What is the difference in starting torque between full-voltage starting and reduced-voltage starting?
4) Look up in your textbooks and write about other starting methods for induction motors.
5) When is recommended to used delayed starting method in motors?
6) What is meant by "normally-open" and "normally-closed" contacts?
7) Design a circuit so that the motor will start as soon as the start button is depressed, and automatically will be disconnected after 15 seconds. Draw the schematic diagram.

LABORATORY SESSION **VIII**

SINGLE PHASE INDUCTION MOTORS

OBJECTIVES

The main purpose of this session is demonstrate that a single-phase induction motor requires some auxiliary means for starting and then demonstrate the qualitative difference between manual starting, resistance split phase starting, and capacitor starting. Also, the authors are interested in showing the different characteristics when operating a universal motor in AC and DC.

The specific objectives of this lab session are:
1) To examine the construction of a split-phase motor.
2) To measure the resistance of its windings.
3) To learn the basic motor wiring connections.
4) To observe the starting and running operation of the split-phase motor.
5) To measure the starting and operating characteristics of the capacitor-start motor.
6) To examine the construction of the capacitor run motor.
7) To determine the capacitor run motor running and starting characteristics.
8) To compare the split-phase, the capacitor start, and the capacitor run motors' running and starting performances.
9) To examine the construction of the universal motor.
10) To determine the universal motor's no-load and full-load characteristics while operating on alternating current and while operating on direct current.
11) To compare the starting torque on both AC and DC.
12) To observe the effects of removing the compensating winding.
13) To provide the motor with inductive compensation.

REFERENCES
1) Wildi, Theodore. and De Vito, Michael. *Investigations in Electric Power Technology,* 2 ed., Buck Engineering Co. Inc. Farmingdale, New Jersey (In Canada: Lab—Volt Limited Montreal, Quebec. 1971.

INTRODUCTION

The single-phase induction motor is, perhaps, the most widely used electromechanical device. Garbage disposals, washers, dryers, furnace fans, etc., are but a few of the many applications of fractional-horsepower single-phase induction motor. However, the single phase induction motor's windings produces oppositely rotating air gap minds of equal amplitude. If the single-phase induction motor is stalléd r'0, and if sinusoidal current is applied to the stator winding, the rotor will not move if there isn't some auxiliary mean for starting. This device for itself does not develop a starting torque. Why? Well, the rotor cannot follow either of the rotating minds since it develops as much torque to go with one as it does to go with the other. If, however, you manually turn the rotor in either direction, it will accelerate in that direction and operate normally. Although single-phase induction motors normally operate with only one stator winding, it is
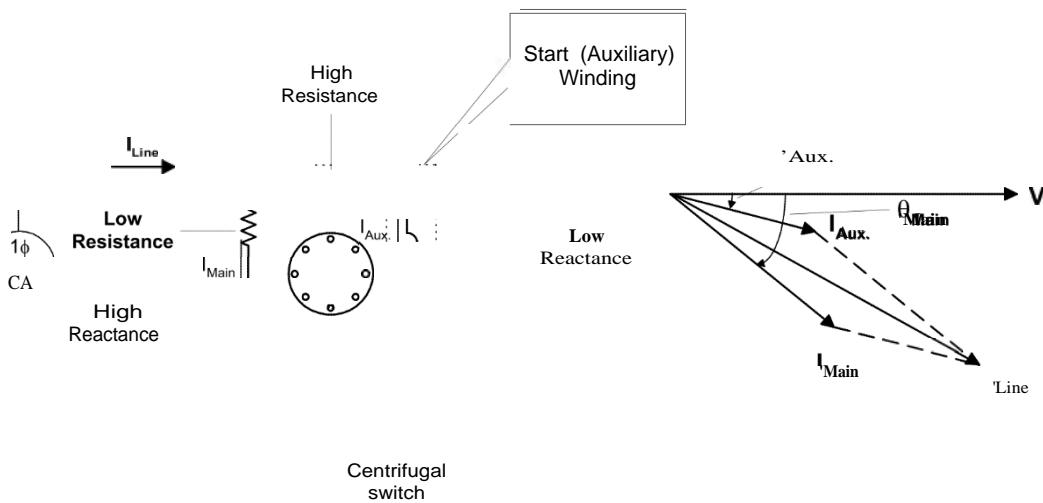
necessary to use a second stator winding to start the device. Actually, the single-phase induction motors we use in our homes are two-phase induction motors with provisions to switch out one of the windings once the motor accelerates to between 60 and 80 percent of synchronous speed.

The next question is how do we get two-phase voltages from a single-phase household supply? Well, we do not actually develop a two-phase supply, but we approximate one. We will see different methods of doing it.

SPLIT PHASE INDUCTION MOTOR

Some means must be provided for getting two phases from the standard single-phase power supplied to homes if it is to be used to start and run a single-phase ac motor. The process of deriving two phases from one is known as *p?iiise splitting* and is usually built into the stator circuit of the ac motor. Two-phase power creates the rotating magnetic field.

One method is a special auxiliary winding built into the stator called the *start (auxiliary) winding* to differentiate it from the actual *run (main) winding* of the stator. In split-phase AC motors, the start winding is used only for starting the motor and has a high resistance and low inductive reactance. The run winding has low resistance and high reactance (see Figure 8. 1). When power is first applied, both windings are energized. Because of their different inductive reactances, the run winding current lags the start winding current, creating a phase difference between the two. Ideally, the phase difference should be *90 degrees,* but in practical motors, it is much less. Nevertheless, the windings develop fields that are out of phase, which creates a rotating magnetic field in the stator. This applies torque to the rotor, starting the motor.

FiGuR£ 8.1

When the motor gets up to operating speed, the rotor is able to follow the alternations of the magnetic field created by the run winding without the field of the start winding. The start winding is then switched out of the circuit by a mechanical device called a *centrifugal switch,* because it is operated by the centrifugal force created by the rotor revolutions. *Reversing the connections to the start winding can reverse the direction of*

a split-phase-rotating field. This changes the direction of the initial phase shift, creating a magnetic field rotating in the opposite direction.

The motor speed depends essentially upon the AC power line frequency and the number of poles on the stator.

The split-phase motor, like all single-phase induction motors, vibrates mechanically at twice the power line frequency.

When power is applied to a split-phase induction motor, both the running (main) and the starting (auxiliary) windings draw from 4 to 5 times their normal full load current. This means that the heat loss in these windings is from 16 to 25 times higher than normal. As a result, the starting period must be kept short to prevent overheating of the windings.

The high starting currents also produce a proportionally high current in the squirrel-cage rotor, so that the entire motor heats up very quickly during start-up. The starting current can also cause a large line voltage drop so that the starting torque may be seriously reduced.

The smaller diameter wlre employed in the auxlllary winding of split-phase motors 1s particularly susceptible to overheating and wlll burn out if it is not disconnected from the power llne wlthin 4 to 6 seconds.

The no load current is usually 60° to 80% of the full-load current, which is high compared to three-phase motors. Most of the no-load current is used to produce the magnetic field in the motor, and only a small portion is used to overcome the mechanical friction and the copper and iron losses. Because of the large magnetizing current, the power factor of these motors is rarely more than 60° even at full-load.

Split-phase motors tend to be much noisier than their three-phase counterparts, because of the inherent 120 cycle mechanical vibration. Using resilient rubber mounting supports can reduce this vibration.

CAPACITOR START MOTOR

When the split-phase-rotating field was described, it was pointed out that the phase difference between start and run winding currents falls far short of *90 degrees.* The starting torque developed in a motor that uses a split-phase stator also falls far short of the maximum that can be attained at an ideal *90 degrees* phase difference.

A phase shift closer to the ideal 90 degrees is possible through the capacitor-start system for creating a rotating stator field. This system, a modification of the split-phase system, uses a low reactance capacitor placed in series with the start winding of the stator to provide a phase shift of approximately 90 degrees for the start current resulting in greatly improved starting torque over the standard split-phase system (see Figure 8.2). Capacitor start motors have the same running characteristics as their split-phase counterparts.
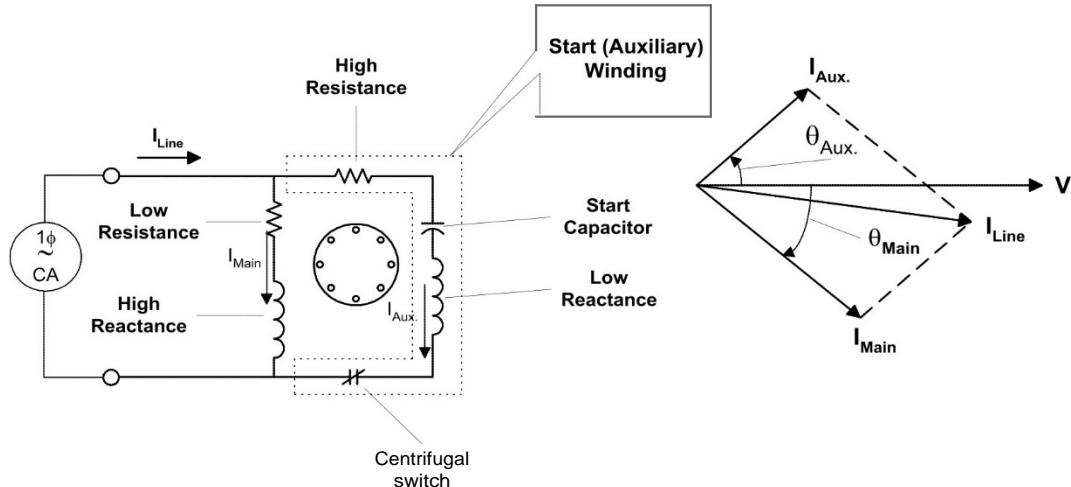
FIGURE 8.2

A centrifugal switch, just as in the case of the standard split-phase motor disconnects the capacitor and the start winding. Reversing the direction of rotation of a capacitor start motor is the same as in the case of the split-phase motor, that is, reverse the connections to the start or to the running winding leads.

CAPACITOR RUN MOTOR

Single-phase motors are all rather noisy because they vibrate at 120Hz when operated on a 60Hz-power line. Various attempts to reduce this noise, such as resilient rubber mounting, are never totally effective in eliminating this vibration, particularly when the motor is directly coupled to a large resonant-prone fan.

The capacitor run motor is very useful in this type of application, because the motor can be designed to have low vibration under full-load. The capacitor serves to shift the phase on one of the windings so that the voltage across the winding is at 90' from the other winding, thus making the capacitor run motor a truly two-phase machine at its rated load (see Figure 8.3). Because the capacitor remains in the circuit at all times no centrifugal switch is required.
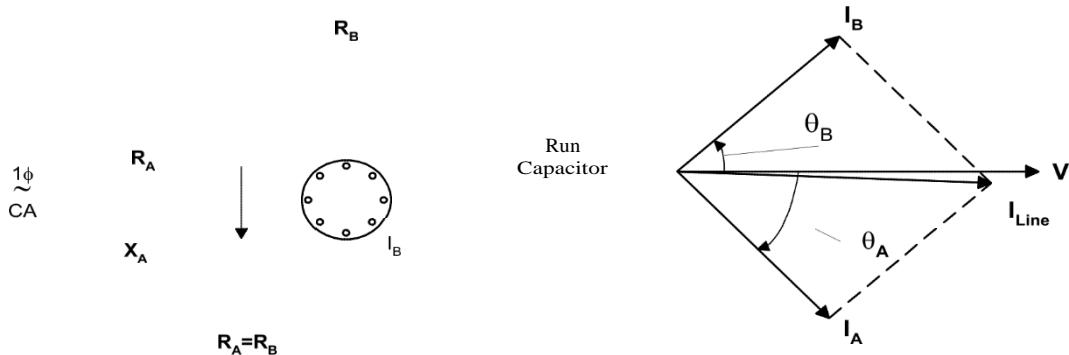
FIGURE 8.3

When running at no-load the motor is always noisier than at full-load, because only under full-load does it run as a true two-phase machine. If the proper value of capacitance is chosen, the currents through each of the two equal stator windings, under full-load, can be made such that the power factor is close to 100%. However, the starting torque is quite low and the capacitor-run motor is not recommended for severe starting conditions.

THE UNIVERSAL MOTOR.
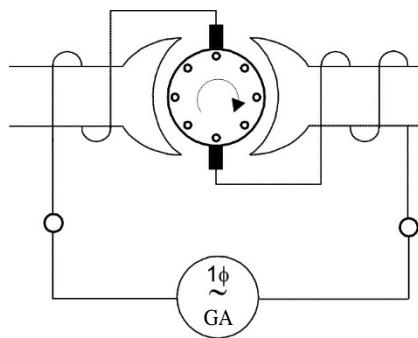
FIGURE 8.4

The AC/DC universal motor is found in portable tools such as electric drills, saws, sanders, etc., and in home appliances such as vacuum cleaners, electric mixers, blenders, etc., where high speed, power and small size are an advantage.

The universal motor is closer in concept to the DC motor than to the AC motor and has some inherent disadvantages, which can be avoided in purely AC induction motors; chiefly, the need for commutation and brushes.

The universal motor is basically a series DC motor that is specially designed to operate on AC as well as on DC. A standard DC series motor has very poor characteristics when operated on AC, mainly due to two reasons:

a) The high reactance of both the armature and field windings limits AC current to a much lower value than DC current (for the same line voltage).

b) If solid steel is used for the stator frame, AC flux will produce large eddy currents in the frame with consequent heating.

Placing a compensating winding on the stator so that the fluxes oppose or "cancel" each other can lower the reactance of the armature winding. This same compensating winding can be connected in series with the armature winding. In this case, the motor is said to be *conductively compensated.* Under these conditions, the universal motor will have similar operating characteristics whether on AC or DC power.

The compensating winding may be simply shorted upon itself, so that it behaves like a short-circuited secondary of a transformer (the armature winding acting as the primary). The induced AC current in the compensating winding again opposes or "bucks" the armature current and the motor is said to be *inductively compensated.* The reactance of the field winding can be kept low by limiting the number of turns.

The current that flows through the armature and field windings determines the starting torque of a universal motor. Due to the inductive reactance of these windings the AC starting current will always be less than the DC starting current (with equal supply voltages). Consequently, the starting torque on AC power will be lower than the

starting torque on DC power. The compensating winding has the important role of reducing the overall reactance of the motor. However, it also has an equally important part in opposing armature reaction, thereby improving commutation. An uncompensated universal motor will lose most of its power. Sparking at the brushes will also be markedly worse.

In appendix D, there is a summary of the AC motors discussed so far. It includes a comparison with three-phase motors.

PRELAB

1. A 6-pole single-phase motor is connected to a 60 Hz. Source. What is its synchronous speed?
2. Referring to a split single phase induction motor, the effective impedances of the main and auxiliary windings are:

	Effective Resistance	Effective Reactance
Main Winding	4£I	7.5Ω
Auxiliary Winding	7.SSI	4Ω

   If the line voltage is 119 V, calculate the following:
   a. The magnitude Of IAu× and Ijjjain
   b. The phase angle between them
   c. The line current IL. and
   d. The power factor of the motor.
3. A single-phase induction motor has a main winding impedance of 6/ °f2 and an auxiliary winding impedance of 10/5'D.
   a. What capacitor value is needed in series with the starting winding to produce a 90° phase shift between winding currents at startup?
   b. With this added capacitor, what are the winding currents and line current at starting? The line voltage is 120 V.

Experiment 8.1 The Split-Phase **Induction Motor**

REQUIRED EQUIPMENT

Split-Phase/Capacitor Start Motor Module	EMS 8251
Power Supply Module	EMS 8821
Electrodynamometer Module	EMS 8911
Hand Tachometer	EMS 8920
Connection Leads	EMS 8941
Timing Belt	EMS 8942
Ohmmeter	

PROCEDURE

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!**

Step 1: Examine the construction of the Split-Phase/Capacitor Start Motor Module EMS 8251, paying particular attention to the motor, centrifugal switch, connection terminals and the wiring.
THE CAPACITOR, MOUNTED IN THE REAR OF THE MODULE, IS USED ONLY WHEN THE MODULE IS CONNECTED AS A CAPACITOR-START MOTOR.

Step 2: Viewing the motor from the front of the module:
The main stator winding is composed of many turns of large diameter wire. Identify the main winding.
The auxiliary stator winding, wound inside the main stator winding, is composed of fewer tums of smaller diameter wire. Identify the auxiliary winding.

Question 1: Does **the auxiliary winding exactly straddle the main winding? Explain.**

Question 2: How many main stator poles are there?

Question 3: How many auxiliary poles are there?

Step 3: a) Note that there are a number of slots distributed in each pole.
b) Note the construction of the rotor.
c) Note the rotor aluminum end ring.
d) Note that the fan is integrally cast with the end ring.
e) Note the air gap separating the rotor and the stator.
I) Estimate the air gap distance in thousandths of an inch. _____

Step 4: Viewing the motor from the rear of the module:
a) Identify the centrifugal switch mechanism mounted on the shaft.
b) Pull outward on the centrifugal weights and note the action of the insulated sleeve.
c) Note that the stationary electrical contacts open when the weights are pulled out.

Question 4: If the coiled springs on the centrifugal switch were stiffer, would the electrical contacts open at a lower **or higher shaft speed?**

Step 5: Viewing the front face of the module:

      a) The main winding (many turns of heavy wire) is connected to terminals _____and _____

      b) The auxiliary winding (fewer turns of finer wire) is connected to terminals _____and _____

      c) The centrifugal switch contacts are connected to terminals_____and _____

      d) The capacitor (not used in the split-phase motor wiring) is connected to terminals_____and _____

      e) Note that the current rating for the main winding is marked 5 amperes while the auxiliary winding is marked "intermittent"

      NOTE: The circuit breaker **protecting the auxiliary winding will trip if the winding is left across the input line (120V)** for longer than a few **seconds. Caution:** Always **connect the centrifugal switch in** series with the **auxiliary winding and the input line, unless you** are instructed not to do

Step 6: Using your ohmmeter measure and record the resistance of the:

<div align="center">

Main winding   _____ G

Aw.r. minding —_____ G

</div>

Step 7: Using the Power Supply, the Data Acquisition Interface (DAI) modules in the EMS workstation and Split-Phase Motor Modules, connect the circuit shown in Figure 8.5.

Step 8: Turn on the power supply and adjust for exactly 5Vdc as indicated by the voltmeter across the main winding (terminals 1 and 2).

<div align="center">

$I_{main\ winding.} =$ *A dc*

$R_{jjjain\ winding}$ **'E/I** _____ Ω

</div>
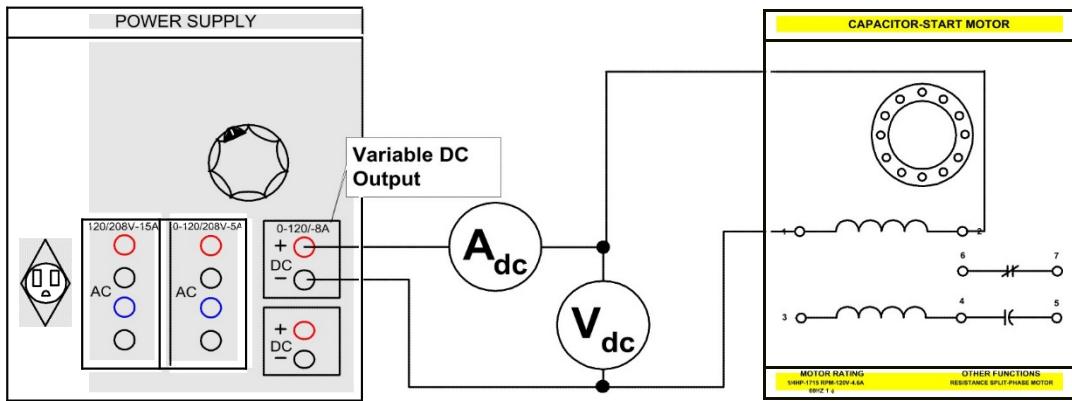
FIGURE 8.5

Step 9. Return the voltage to zero and turn off the power supply. Connect the circuit shown in Figure 8.6.
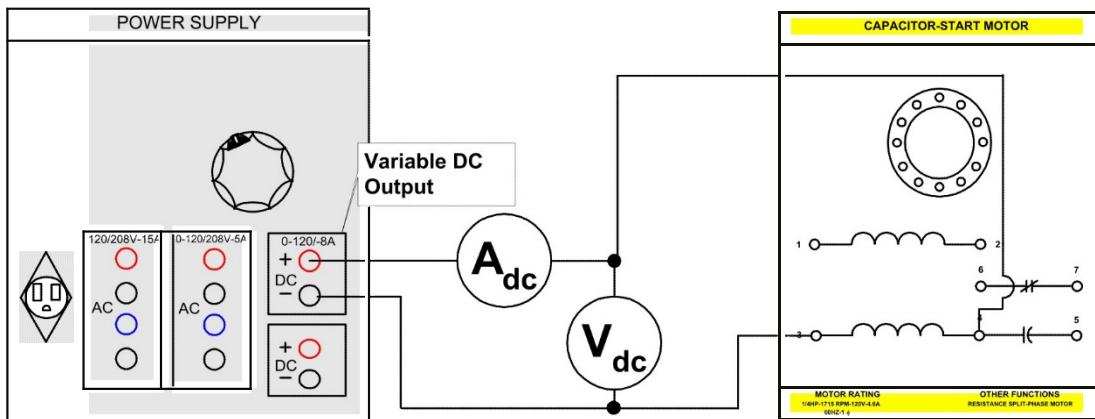
FIGURE 8.6

Step 10: Turn on the power supply and adjust for exactly 5Vdc as indicated by the voltmeter across the auxiliary winding (terminals 3 and 4).

Iaux winding   ——————————————————Add

Raux winding 'E$I ▾ ——————————————— Ω

Step 11: Return the voltage to zero and turn off the power supply.

Step 12: Compare the results of Step 6 with the results of Step 8 and 10.

Step 13: Note that although the main winding has many more tums of wire than the auxiliary winding, its resistance is lower. Explain.

Step 14: Connect an AC voltmeter across the variable ac power supply terminals 4 and N. Turn on the power supply and adjust for an output of 100 Vac as indicated by the voltmeter. Do not **touch the voltage output control** for the remainder of this **Laboratory Experiment unless told to do** so.

Step 15: Turn off the power supply.

Step 16: Connect the main winding of the split-phase motor, terminals 1 and 2, to the pre-adjusted 100Vac output of the power supply, terminals 4 and N. Close the power supply switch for no longer than 3 seconds.

Question 5: Did the motor growl (rumble)?

Question 6: Did the motor turn?

Step 17: a) Lower the front face of the module and carefullv reach in behind the front face of the module so that you may give the motor shaft a quick turn by hand at the moment of power supply switch closure.

b) Close the power supply switch for no longer than 3 seconds.

Question 7: Did the motor turn?

Question 8: What determined the direction of rotation of the motor?

c) Return the front face of the module to its normal position and turn off the power supply.

Step 18: a) Disconnect the main winding, terminals 1 and 2, from the power supply.

b) Connect the auxiliary winding, terminals 3 and 4, to the pre-adjusted 100Vac output of the power supply terminals 4 and N.

c) Close the power supply switch for no longer than 3 seconds.

Question 9: Did the motor growl?

Question 10: Did the motor turn?

Step 19: a) Connect the main winding, terminals 1 and 2, in parallel with the auxiliary winding, terminals3 and 4.

b) Connect the paralleled windings to the pre-adjusted 100 Vac output of the power supply.

c) Close the power supply switch for no longer than 3 seconds.

Question 11: Did the motor start?

Question 12: Was the motor noisy?

d) Note the direction of rotation. _____

Step 20: a) Interchange the leads connecting the two windings in parallel.

b) Close the power supply switch for no longer than 3 seconds.

c) Note the direction of rotation. _____

d) Give a rule for reversing the rotation of a split-phase motor.

Step 21: Connect the circuit shown in Figure 8.7. The centrifugal switch is connected in series with the auxiliary winding and both windings are connected in parallel across the 100Vac power source terminals 4 and N. Note that the capacitor, connected between terminals 4 and 5, is not used when the module is operated as a split-phase motor.
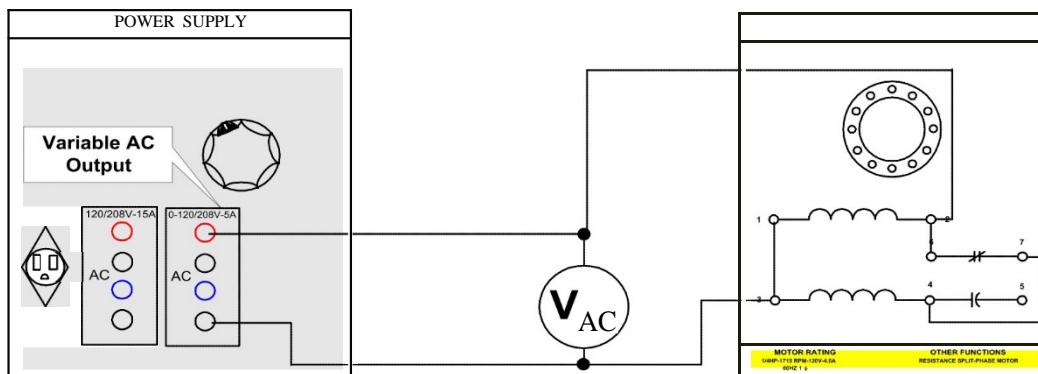
FIGURE 8.7

Step 22: a) Close the power supply switch. The output voltage control should remain at its 100 V setting.

Question 13: Did the motor start?

Question 14: Did the centrifugal switch operate?

b) Estimate the starting time_____s

c) Using your hand tachometer measure the running speed._____*r'min*

d) Reduce the input voltage to 80 Vac as indicated by the voltmeter and measure the running speed_____r/min

e) Return the voltage to 100 Vac and turn off the power supply.

Step 23: Connect the circuit shown in Figure 8.8. Note that both windings are connected in parallel and that the centrifugal switch is in series with the parallel connected motor windings and the 100 Vac power supply terminals 4 and N.

Step 24: Before applying power to the motor answer the following questions:

Question 15: Will current flow through both windings?

Question 16: Will a starting torque be developed?

Question 17: Will the motor start to turn?
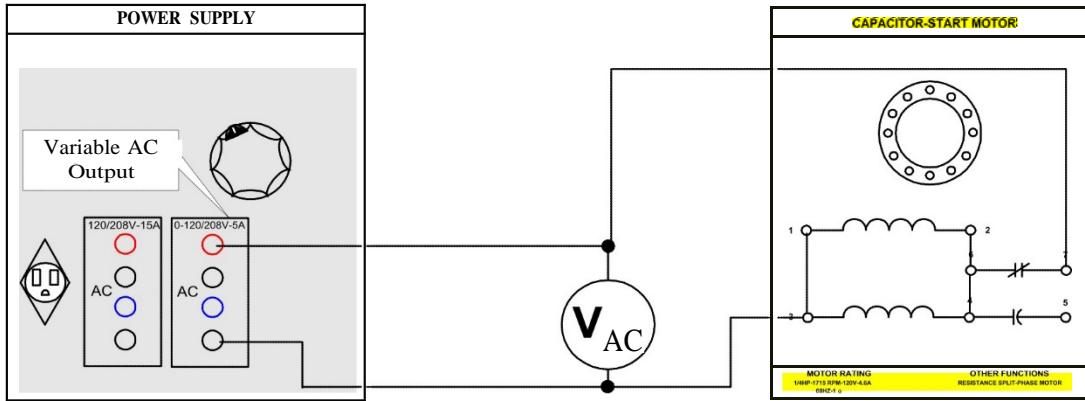
FIGURE 8.8

Question 18: What will eventually happen?
Step 25: a) Close the power supply switch and note what happens.
      b) Observe the operation of the centrifugal switch.
Question 19: At approximately what speed does **the centrifugal switch close?**
      c) Return the voltage to zero and turn off the power supply.
Step 26: Using your EMS Split-Phase/Capacitor Start Motor, Power Supply and the Data
      Acquisition Interface (DAI) modules in the EMS workstation connect the circuit
      shown in Figure 8.9.
      Note that the fixed 120 Vac output of the power supply is being used.

FIGURE 8.9

Step 27: Close the power supply switch and measure the current through the main
      winding as quickly as possible within 3 seconds.

      main winding _____ *AOS*
Step 28: a) Disconnect your leads from the main winding and connect them to the
      auxiliary winding, terminals 3 and 4 as shown in Figure 8.10.
      b) Repeat step 26. Remember to take your measurement as quickly as
      possible.

      $I_{auxiliary\ winding}$ _____ *Aac*
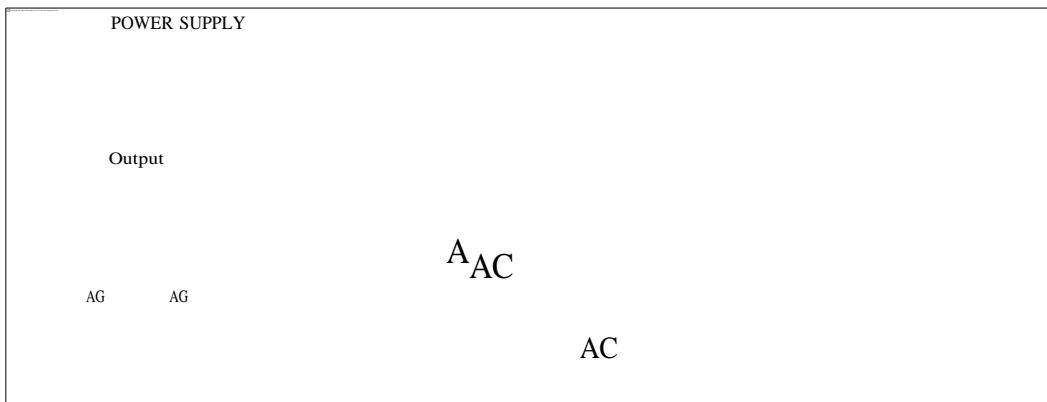
FIGURE8.!0

Step 29. a) Connect both windings in parallel, terminals 1 to 3 and 2 to 4 as shown in Figure 8.11.

b) Couple the electrodynamometer to the split-phase motor with the timing belt.

c) Connect the electrodynamometer's low input terminal to the 120Vac outlet of the power supply, using the 120Vac/24Vac transformer.

d) Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the split-phase motor).

e) Close the power supply switch and measure the starting current as quickly as possible within 3 seconds.

s tasting _____ *Aac*
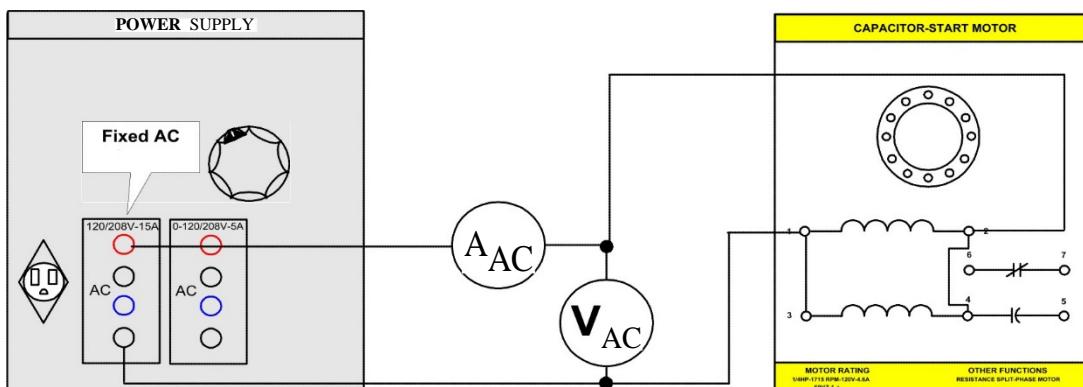
FIGURE 8.11

NO-LOAD OPERATION

Step 30: Using your Data Acquisition Interface (DAI) modules in the EMS workstation, connect the circuit shown in Figure 8.12.

Note that the module is wired as a standard split-phase motor.

Step 31: a) Turn on the power supply and adjust for 120Vac as indicated by the voltmeter across the motor.

b) Measure and record in Table 8.1 the line current, the power and motor speed. Note and record the relative motor vibration.

c) Repeat (b) for each of the input voltages listed in the Table 8.1.

d) Return the voltage to zero and turn off the power supply.
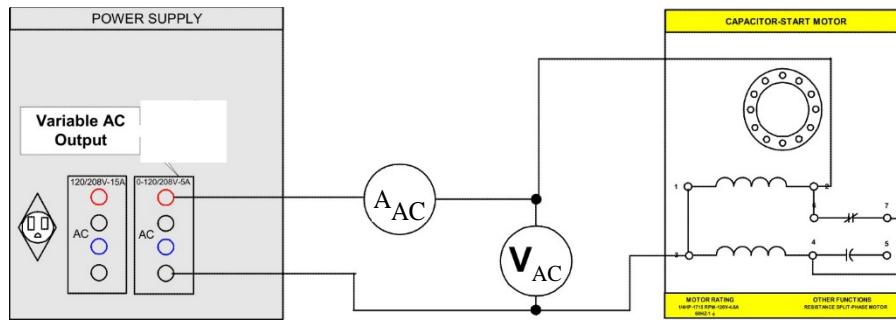
FIGURE 8.12

FULL-LOAD OPERATION

Step 32: a) Couple the electrodynamometer to the split-phase motor with the timing belt.

b) Connect the low input terminals of the electrodynamometer to the 120 Vac outlet of the power supply using the 120Vac/24Vac transformer.

c) Set the dynamometer control knob at its full ccw position (to provide a minimum-starting load for the split-phase motor).

Step 33: a) Turn on the power supply.

b) Measure and record in Table 8.2 the line current, the power and motor speed.

c) Repeat (b) for each of the torques listed in the Table 8.2, maintaining the input voltage at 120 Vac.

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

Step 34: a) Calculate and record in the Table 8.2, the apparent power delivered to the motor for each of the listed torques.

b) Calculate and record in the Table 8.2, the developed horsepower for each of the listed torques. Use the formula:

$$Hp = \frac{1.59 \text{ fr/min) (torque)}}{100,000}$$

Step 35: You will now determine the maximum starting torque developed by the split-phase motor.

a) Disconnect the DAI from your circuit.

b) Connect the input of your split-phase motor to terminals 2 and $\wedge\!\!\!/$ of the power supply (fixed 120Vac).

c) Set the dynamometer control knob at its full cw position (for maximum loading).

d) Close the power supply switch and quickly measure the developed torque on the dynamometer scale. Open the power supply switch.

Starting Torque =_____lbf*in

E (Volts)	I (Amps)	P (Watts)	SPEED (R/MIN)	VIBRATION
120				
90				
60				
30				

Table 8.1

TORQUE (LBF * IN)	I (AMPS)	VA	P (WATTS)	SPEED (r/min)	**HP**
0					
6					
12					

Table 8.2

SINGLE PHASE INDUCTION MOTORS

Experiment 8.2 The Capacitor Start Motor

REQUIRED EQUIPMENT

Split-Phase/Capacitor Start Motor Module	EMS 8251
Power Supply Module	EMS 8821
Electrodynamometer Module	EMS 8911
Single-Phase Wattmeter Module	EMS 8431
Hand Tachometer	EMS 8920
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1: Connect the circuit shown in Figure 8.13.
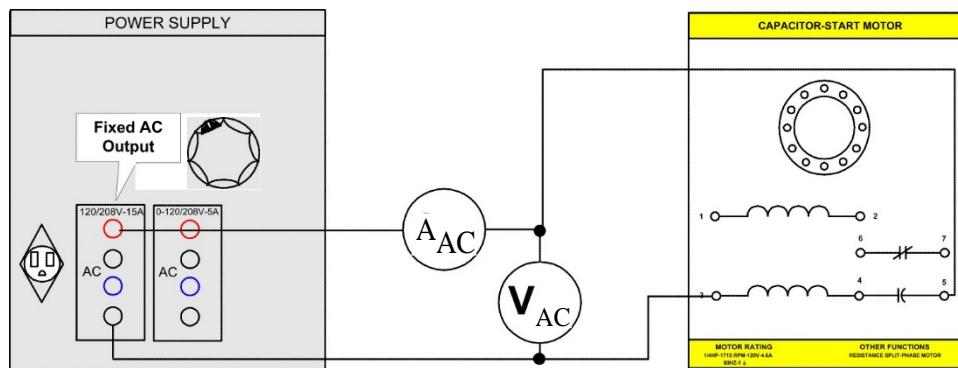
FIGURE 8.13

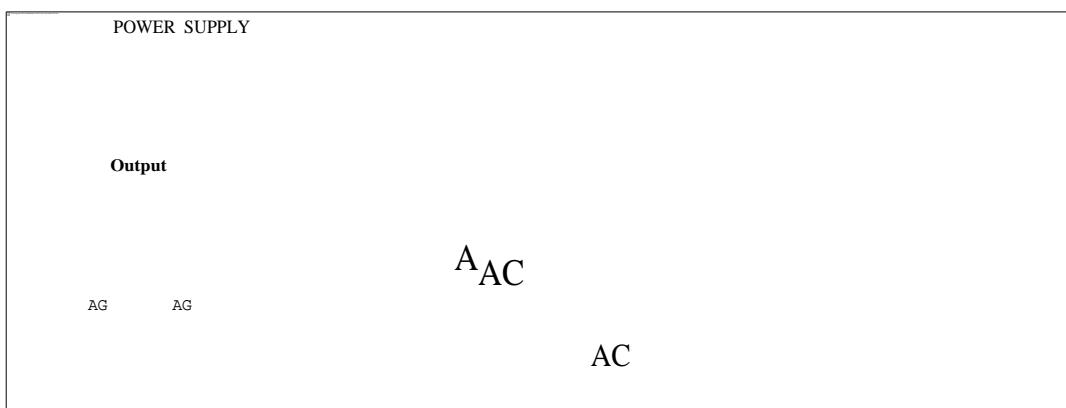Step 2: Close the power supply switch and measure the current through the auxiliary winding as quickly as possible within 3 seconds.

auxiliary winding _____ *Aac*

Step 3:a) Connect both main and auxiliary windings in parallel as shown in Figure 8.14.

b) Couple the electrodynamometer to the capacitor-start motor with the timing belt.

c) Connect the low input terminals of the electrodynamometer to the 120Vac outlet of the power supply using the 120Vac/24Vac.

d) Set the dynamometer control knob at its full cw position to provide a maximum starting load for the capacitor-start motor.

e/ Close the power supply switch and measure the starting current as quickly as possible within 3 seconds.

starting _____ AU

Step 4: Compare your results from steps 2, 3 and 4 with the results from step 27 and 28 of Lab Session 8.1.

Question 1: What inference can you make about the main winding currents for a **capacitor-start motor and the split-phase one?** Are they the same?

Question 2: What conclusions can you make about the auxiliary winding currents?

Question 3: What conclusions can you make about the starting current for each **type of motor?**

FIGURE 8.14

Step 5: Using your Data Acquisition Interface (DAI) modules in the EMS workstation, and Electrodynamometer, connect the circuit shown in Figure 8.15.

FIGURE 8.15

Note that the module is wired as a standard capacitor start motor.

Step 6: Set the dynamometer control knob at its full ccw position to provide minimum starting torque for the capacitor start motor.

Step 7: a) Turn on the power supply and adjust for 120Vac.

b) Measure and record in table 8.3, the line current, the power and motor speed.

c) Repeat (b) for each of the torques listed in the table 8.3.

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

Step 8: a) Calculate and record in the Table 8.3, the apparent power delivered to the motor for each of the listed torques.

b) Calculate and record in the Table 8.3, the developed horsepower for each of the listed torques.

Step 9: You will now determine the maximum starting torque developed by the capacitor start motor.

a) Disconnect the wattmeter and metering modules from your circuit.

b) Connect the input of your capacitor start motor to terminals 2 and *N* of the power supply (fixed 120Vac).

c) Set the dynamometer control knob to its full cw position (for maximum loading).

d) Close the power supply switch and quickly measure the developed torque on the dynamometer scale. Open the power supply switch.

Starting Torque =_____lbf in

TORQUE LBF * IN	I (amps)	VA	P (watts)	SPEED	Hp
0					
3					
6					
9					
12					

Table 8.3

Experiment 8.3   **Capacitor-Run Induction Motor**

REQUIRED EQUIPMENT

Capacitor Run Motor Module	EMS 8253
Power Supply Module (120Vac, 0-120Vac)	EMS 8821
Electrodynamometer Module	EMS 8911
Hand Tachometer	EMS 8920
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1:Examine the construction of the Capacitor Run Motor Module EMS 8253, paying particular attention to the motor, capacitor, connection terminals and the wiring.

Step 2: Viewing the motor from the front of the module:

a) Both stator windings are composed of many turns of wire. Identify the stator windings.

Question 1: Do the stator windings appear to be identical?

Question 2: Do the windings exactly straddle each other? Explain

Question 3: How many poles are **there? (Hint: use the nominal** speed) **Explain**

b) This is a_____pole motor.

c) Note that there are a number of slots distributed in each pole.

d) Note the construction of the rotor.

e) Note the rotor aluminum end ring.

fl Note that the fan is integrally cast with the end ring.

Step 3: Viewing the motor from the rear of the module:

a) Note the capacitor and its rating.

Question 4: Is this capacitor an electrolytic (polarized capacitor)? Explain.

Step 4: Viewing the front face of the module:

a) Note the two-stator windings.

b) One winding is connected to terminals_____and _____

c) The other winding is connected to terminals_____and _____

d) Note that the voltage and current ratings for each winding are identical.

e) The capacitor is connected to terminals_____and _____

Step 5: Using your EMS Capacitor Run Motor, Power Supply, Data Acquisition Interface (DAI) modules in the EMS workstation and Electrodynamometer, connect the circuit shown in Figure 8.16.

FIGURE 8.16

Step 6:a)Couple the electrodynamometer to the capacitor run motor with the timing belt.

b) Connect the low input terminals of the electrodynamometer to the 120Vac outlet of the power supply using the 120Vac/24Vac transformer.

c) Set the dynamometer control knob at its full ccw position (to provide a minimum-starting load for the capacitor run motor).

Step 7: a) Turn on the power supply and adjust for 120 Vac.

b) Measure and record in Table 8.4 the line current, the power and motor speed.

c) Repeat (b) for each of the torques listed in the table 8.4, maintaining the input voltage at 120 Vac.

Question 5: Was there a **noticeable** difference in the level **of motor vibration between no-load and full- load?**

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

Step 8: a) Calculate and record in the Table 8.4, the apparent power delivered to the motor for each of the listed torques.

b) Calculate and record in the Table 8.4 the developed horsepower for each of the listed torques. Use the formula:

$$Hp = \frac{1.59 \text{ tr/min) (torqueJ}}{100,000}$$

Step 9: You will now determine the maximum starting torque developed by the capacitor run motor and its starting current.

a) Disconnect the wattmeter and metering modules from your circuit and change the range of the ammeter from 8 /o *25A,*

b) Connect the input of your capacitor run motor to terminals 2 *and N* of the power supply *(fixed 120 Vac).*

c) Set the dynamometer control knob to its full cw position (for maximum loading).

d) Close the power supply switch and quickly measure the developed torque on the dynamometer scale and the starting current. Open the power supply switch.

Starting Torque —_____*lbf in*

Starting Current _____*Aac*

TORQUE LBF * IN	I (amps)	VA	P (watts)	SPEED	Hp
0					
6					
9					
12					

Table 8.4

Single Phase Induction Motors

Experiment 8.4 The Universal Motor

1 **EQUIRED EQUIPMENT**

Universal Motor Module	EMS 8254
Power Supply Module	EMS 8821
Electrodynamometer Module	EMS 8911
Hand Tachometer	
Connection- Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE
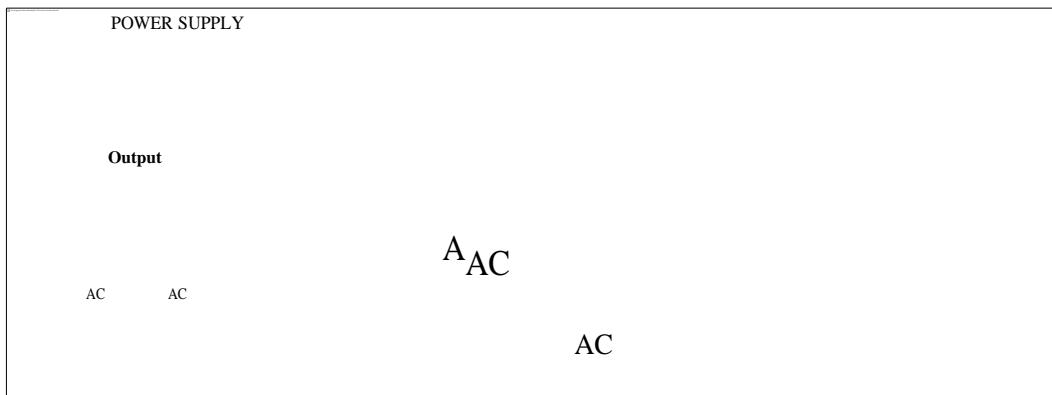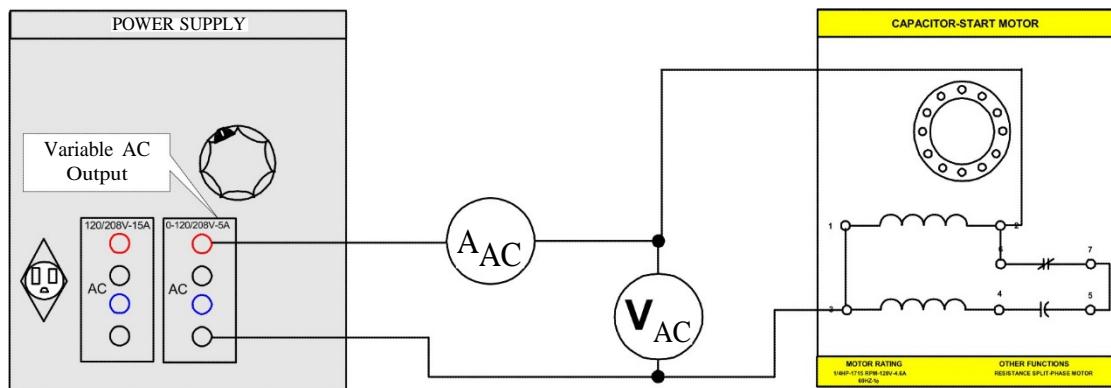
Step 1: Examine the construction of the Universal Motor Module EMS 8254, paying particular attention to the motor, brushes, connection terminals and wiring.

Step 2: Viewing the motor from the rear of the module:
   a) Identify the armature winding.
   b) Identify the stator.
   c) Identify the main series winding.
   d) Identify the compensating winding.

Step 3: Viewing the motor from the front of the module:
   a) Identify the commutator.
   b) Identify the brushes.
   c) A red line marked on the motor housing indicates the neutral position of the brushes. Identify it.
   d) The brushes can be positioned on the commutator by moving the lever to the right or left of the red line. Move the lever both ways and then return it to its neutral position.

Step 4: Viewing the front face of the module:
   a)   The main series winding is connected to terminals_____and _____
   b)   The compensating winding is connected to terminals_____and _____
   c)   The brushes (commutator and armature winding) are connected to terminals _____and _____

FINDING THE NEUTRAL

Step 5: You will now determine the neutral brush position for your motor by using alternating current. Using your EMS Power Supply, Data Acquisition Interface (DAI) modules in the EMS workstation a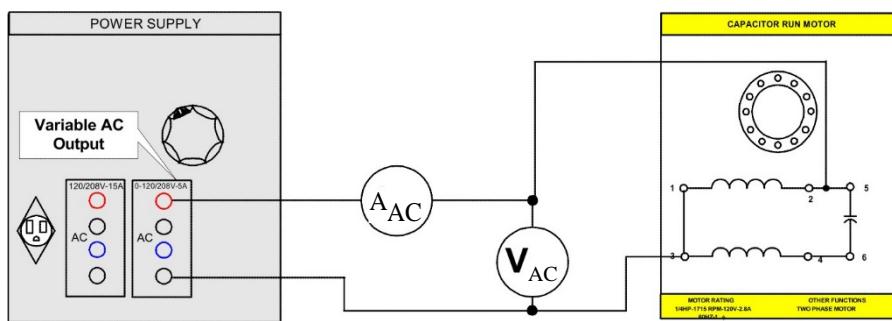nd Motor Modules, connect the circuit shown in Figure 8. 17. Terminals 4 and N on the power supply will furnish variable 0-120Vac as the voltage output control is advanced.

DO NOT APPLY POWER AT THIS TIME!
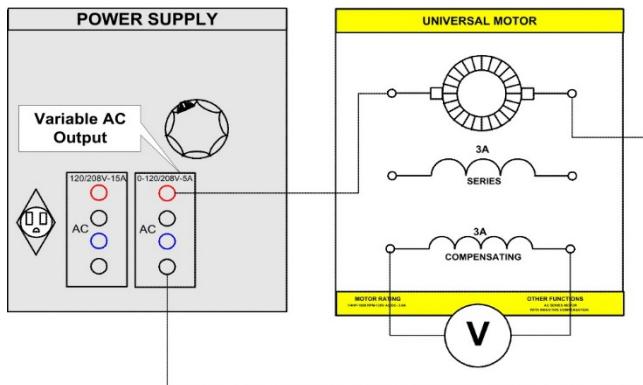
FIGURE 8.17

Step 6: a) Unlock the Universal Motor Module and move it forward approximately 4 inches.
b) Reach in behind the front face of the module and move the brush-positioning lever to its maximum cw position. Do not slide the module back in place (you will later move the brushes again).

Step 7: a) Turn on the power supply and adjust the output control until approximately 60 volts Vac is applied to the armature. The ac voltage that appears across the compensating winding is induced by the ac current through the armature.

Step 8: a) Carefully reach in behind the front face of the module (preferably keeping one hand in your pocket) and move the brushes from one extreme position to another. You will notice that the induced voltage across the compensating winding increases and then drops again as you approach the other extreme position.
b) Leave the brushes at the position where the induced voltage is maximum. This is the neutral point of your Universal Motor. Each time you use the Universal Motor the brushes should be set at the neutral position.
c) Return the voltage to zero and turn off the power supply. Slide your Universal Motor Module back in place.
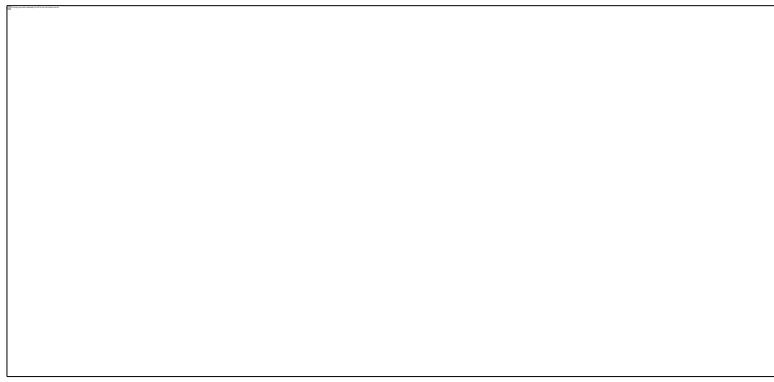
FIGURE 8.18

Step 9: Connect the armature and compensating windings in series, across the 0-120Vac output of the power supply as shown in Figure 8.18.

Steps 10:a) Turn on the power supply and adjust for 30 Vac.

b) If the line current is less than 1 Aac with 30Vac applied, the compensating winding is producing a flux in the same direction as the armature thereby increasing the inductance (and reactance). If this occurs, interchange the leads to the armature or to the compensating winding.

c) Measure and record the line current.
$$I = \underline{\hspace{3cm}} Aac$$

NOTE: If the armature revolves, the brushes are not exactly **at the neutral position.**

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

Step 11: Using your Data Acquisition Interface (DAI) modules in the EMS workstation and Electrodynamometer Modules, connect the circuit shown in Figure 8.19. (Remember to keep the armature and the compensating winding connections as in Step 10).

A_{AC}
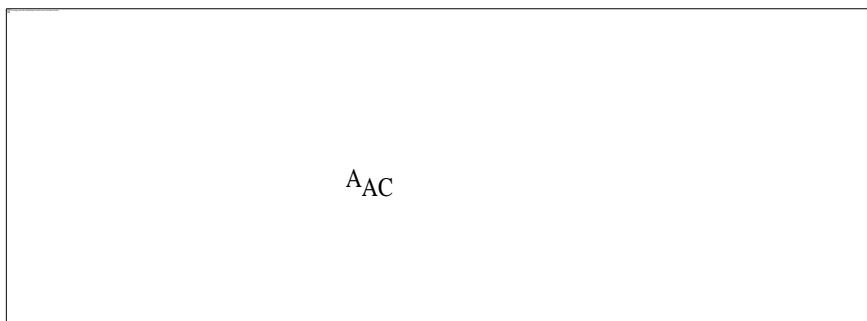
FIGURE 8.19

Step 12:a) Couple the electrodynamometer to the universal motor with the timing belt.

b) Connect the Low input terminals of the electrodynamometer to the 12OVac outlet of the power supply with the 120Vac/24Vac transformer.

c) Set the dynamometer control knob at its full ccw position (to provide a minimum-starting load for the universal motor).

Steps 13:a) Turn on the power supply and adjust for 120 Vac.

b) Measure and record in Table 8.5, the line current, the power and motor speed. Note that there is very little sparking at the brushes.

c) Repeat (b) for each of the torques listed in the Table, maintaining the input voltage at 120Vac.

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

Step 14:a) Calculate and record in the Table the apparent power delivered to the motor for each of the listed torques.

b) Calculate and record in the Table the developed horsepower for each of the listed torques.

Step 15: Replace the AC meters with DC meters and connect the input to the variable DC output, terminals 7 and N, of the power supply as shown in Figure 8.20.

Step 16: Repeat steps 13 and 14 using DC power instead of AC power and complete Table 8.6.

Step 17: Remember to keep the armature and compensating winding connections as in Step 10.

a) Couple the electrodynamometer to the universal motor with the timing belt.

b) Connect the low input terminal of the electrodynamometer to the 120Vac outlet using the 120/24 Vac transformer.

c) Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the universal motor).

d) Make sure the brushes on the universal motor are set at their neutral position.
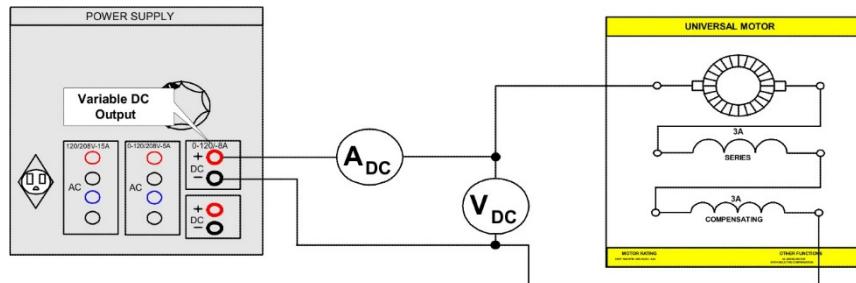
FIGURE 8.20

Step 18: a) Turn on the power supply and adjust for 30Vdc as indicated by the voltmeter across the motor windings.

b) Measure and record the motor current and the torque developed.

$$I — \underline{\hspace{4cm}} Adc$$
$$Torque \; – \underline{\hspace{4cm}} lbf.in$$

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

Step 19: Reconnect your circuit for AC operation as shown in Figure 8.21.
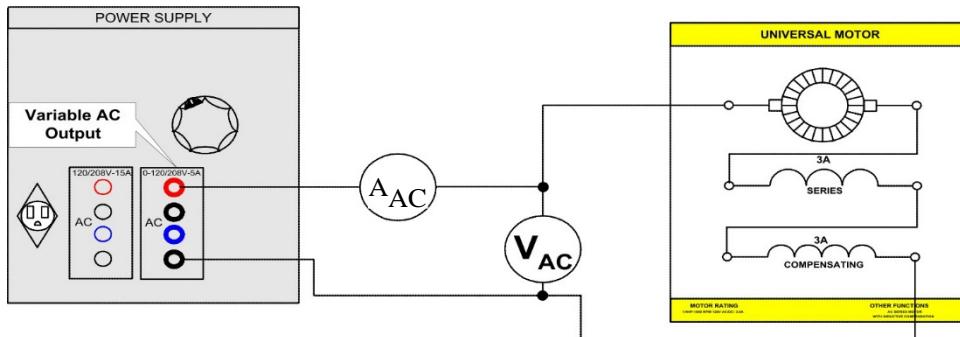
FIGURE 8.21

Step 20: a) Turn on the power supply and adjust for 30Vac as indicated by the voltmeter across the motor windings.

b) Measure and record the motor current and the torque developed.

$$I = \underline{\hspace{3cm}} Aac$$
$$Torque \underline{\hspace{3cm}} \frac{lbf}{in}$$

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

Step 21: Explain the results of steps 18 and 20.

UNCOMPENSATED OPERATION

Single Phase Induction Motors

Step 22: Eliminate the compensating coil winding by reconnecting your circuit as shown in Figure 8.22.
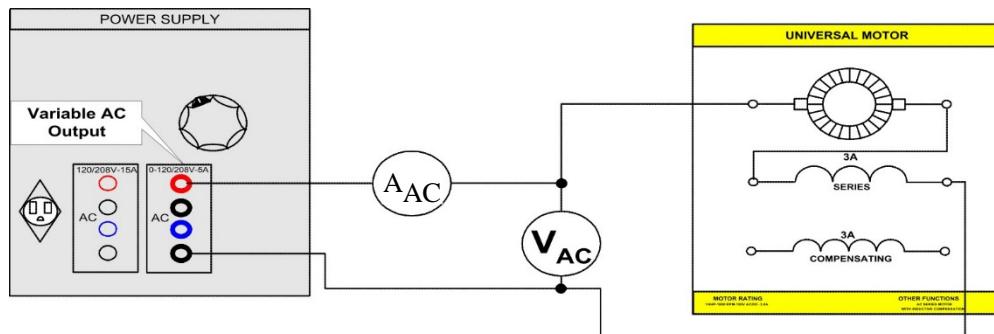
FIGURE 8.22

Step 23: a) Set the dynamometer control knob at its full ccw position (to provide a minimum-starting load).

 b) Turn on the power supply and adjust for 120 Vac.

 c) Carefully increase the dynamometer loading to 3 lbf in of torque.

 d) Measure and record the motor current and speed.

$$I = \underline{\hspace{5cm}} Aac$$
$$AC\ speed = \underline{\hspace{4cm}} r/min$$

 f) Note the sparking at the brushes.

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

Step 24: a) Compare the above results with the results from Table 8.5.

 Question 1: Is the sparking at the brushes worse than when using the compensated **windings?**
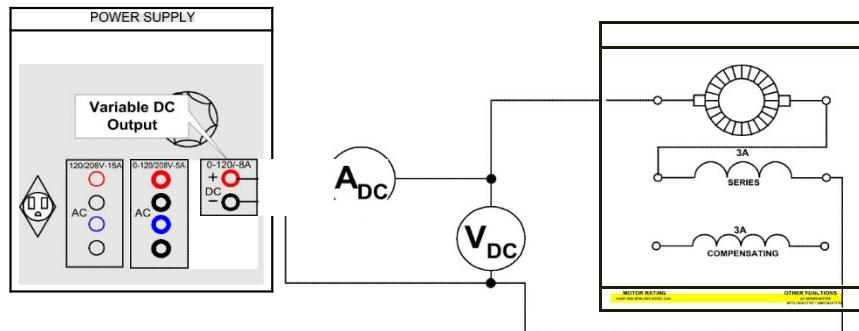
FIGURE 8.23

Step 25: Reconnect your circuit for DC operation as shown in Figure 8.23.

Step 26. Repeat step 23.

$$I= \text{-----------------------} Adc$$
$$DC\ speed = \text{--------------------------} r/min$$

Step 28:a) Compare the above results with the results from Table 8.6.

 Question 2: Is the **sparking at the** brushes worse than when **connecting the motor** with the ac power supply and **using the compensating coil?**

INDUCTIVE COMPENSATION

Single Phase Induction Motors

Step 29:a) You will now observe the effect of using inductive compensation while the motor is operating on AC.

b) Reconnect your circuit for AC operation as shown in Figure 8.22. Short out the compensating coil by connecting a lead directly across its terminals.

c) Turn on the power supply and adjust for 120 Vac.

d) Load the motor to 9 lbf in torque.

e) Measure and record the motor current, motor speed and developed torque.

$$I \underline{\hspace{5cm}} Aac$$
$$AC\ speed = \underline{\hspace{5cm}} rev/min$$
$$AC\ torque = \underline{\hspace{5cm}} lbf\ in$$

Question 3: **Is the sparking at the brushes about the same** as was observed when the motor was **conductively compensated?**

fl While the motor is operating, remove the short across the compensating coil.

Caution: Hold the shorting lead by the insulated connectors; do not touch the exposed **terminals!**

g) Explain what happened.

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

Step 30:a) Reconnect your circuit for DC operation as shown in Figure 8.23.

b) Repeat Step 29.

$$I = \underline{\hspace{5cm}} Adc$$
$$De\ speed = \underline{\hspace{5cm}} r/min$$
$$DC\ torque = \underline{\hspace{5cm}} lbf\ in$$

Question 4: Was there any change when the short was removed?

Question 5: Does the inductively compensated motor work as well on DC as on AC?

AC OPERATION

TORQUE (lbf.in)	I (Amps)	VA	P (Watts)	SPEED r/min	Hp
0					
6					
9					

Table 8.5

DC OPERATION

TORQUE (lbf.in)	I (Amps)	VA	P (Watts)	SPEED r/min	Hp
0					
6					
9					

Table 8.6

REPORT REQUIREMENTS

1. What is the purpose of the auxiliary winding in a single-phase induction motor? How can we change the rotation of such a motor?
2. Explain the differences between:
    a) Split phase induction motor and capacitor start motor
    b) Capacitor start motor and capacitor run motor
3. List some of the properties and advantages of a universal motor. Why is it called "universal"?
4. Why are some single-phase motors equipped with a resilient mounting? Is such a mounting necessary on 3-phase motors?
5. Calculate the efficiency of each single-phase motor and compare them with three-phase motor. Are any of them more efficient than the other? Which single-phase motor does have the best pf? Show your conclusions with any calculations proving them.

LABORATORY SESSION IX

SYNCHRONOUS MOTOR OPERATION AND CONTROL

OBJECTIVES

The main purposes of this laboratory session are to connect and operate a wound-rotor polyphase synchronous motor, to vary its field excitation while operating at various output powers, and to learn the principle of "loss of synchronism" control of a 3$ synchronous motor.

The specific objectives of this lab session are:

1) To examine the construction of the 3$ synchronous motor.
2) To obtain the starting characteristics of the 3$ synchronous motor.
3) To observe how a synchronous motor can act as a variable inductance or capacitance.
4) To obtain the dc current vs. ac current characteristics curve for the synchronous motor.
5) To determine the full load characteristics of the synchronous motor.

IIEFERENCES

1) Wildi, Theodore. and De Vito, Michael. *Investigations in Electric Power Technology,* 2 ed., Buck Engineering Co. Inc. Farmingdale, New Jersey (In Canada: Lab —Volt Limited, Montreal, Quebec. 1971.
2) Wildi, Theodore. and De Vito, Michael. *Control ofIndustrial Motors,* 2 ed., Buck Engineering Co. Inc. Farmingdale, New Jersey (In Canada: Lab —Volt Limited, Montreal, Quebec., 1971.

INTRODUCTION

The synchronous motor gets its name from the term synchronous speed, which is the natural speed of the rotating magnetic field of the stator. As you have learned, the number of pole pairs and the frequency of the applied power control this natural speed of rotation strictly. Like the induction motor, the synchronous motor makes use of the rotating magnetic field. Unlike the induction motor, however, the torque developed does not depend on the induction currents in the rotor. Briefly, the principle of operation of the synchronous motor is as follows: A multiphase source of ac is applied to the stator windings and a rotating magnetic field is produced. A direct current is applied to the rotor windings and a fixed magnetic field is produced. The motor is so constructed that these two magnetic fields react upon each other causing the rotor to rotate at the same speed as the rotating magnetic field. If a load is applied to the rotor shaft, the rotor will momentarily fall behind the rotating field but will continue to rotate at the same synchronous speed.

The falling behind is analogous to the rotor being tied to the rotating field with a rubber band. Heavier loads will cause stretching of the band so the rotor position lags the stator field but the rotor continues at the same speed. If the load is made too large, the rotor will pull out of synchronism with the rotating field and, as a result, will no longer rotate at the same speed. The motor is then said to be overloaded.

The synchronous motor is not a self-starting motor. The rotor is heavy and, from a dead stop, it is not possible to bring the rotor into magnetic lock with the rotating magnetic field. For this reason, all synchronous motors have some kind of starting device. A simple starter is another motor that brings the rotor up to approximately 90 percent of its synchronous speed. The starting motor is then disconnected and the rotor locks in step with the rotating field. The more commonly used starting method is to have the rotor include a squirrel cage induction winding. This induction winding brings the rotor almost to synchronous speed as an induction motor. The squirrel cage is also useful even after the motor has attained synchronous speed, because it tends to dampen rotor oscillations caused by sudden changes in loading. Your synchronous motor/generator module contains a squirrel cage type rotor.

The starting characteristics of synchronous motors with squirrel-cage windings are essentially the same as those of squirrel-cage induction motors. Starting torque and starting current depend largely upon the resistance of the squirrel-cage winding. A low resistance squirrel-cage produces low torque during starting but high torque at near synchronous speed, resulting in a low slip at which the motor pulls into synchronism. A low resistance squirrel cage is also more effective as a damper winding in suppressing torque oscillations. A high resistance squirrel-cage produces opposite effects.

If the power system permits, synchronous motors can be started by applying full voltage to the stator terminals in the same manner as across-the line starting of squirrel-cage motors. If the system requirements demand a reduction in starting current, reduced-voltage starting may be used, as for squirrel-cage motors.

After the motor has attained synchronous speed, the squirrel-cage winding does not carry current except when it acts as a damper winding, as when the axis of the rotor flux shifts with respect to the axis of the stator flux under the impact of sudden load changes. Squirrel-cage windings are not designed to carry starting current continuously. Precautions must be taken to prevent overheating of the squirrel-cage winding in the event the motor should fail to synchronize and attempt to run as an induction motor for a prolonged period of time.

While the motor is accelerating, the revolving stator flux cuts across the field winding of the rotor. Because the field winding consists of a large number of turns, high voltages might be induced if it were left open-circuited. However, short-circuiting of the field winding results in a reduction of the available starting torque. Thus, during the starting period, the field winding should be connected to an external resistance. The voltage across the field terminals is thereby limited to the product of induced field current and resistance.

After the synchronous motor has been started and accelerated to the maximum speed it can attain as an induction motor (about 95° to 97° of synchronous speed), field excitation is applied by connecting the field winding to a source of direct current. A synchronizing torque is then developed which must overcome the load torque and accelerate the motor and load the motor, the slip must not exceed a certain value, otherwise the motor will fail to synchronize.

You have learned that positive reactive power is needed to create the magnetic field in an alternating current motor. This reactive power has the disadvantage of producing a low power factor. Low power factors are undesirable for several reasons. Generators, transformers, and supply circuits are limited in ratings by their current carrying

capacities. This means that the kilowatt load that they can deliver is directly proportional to the power factor of the loads that they supply. For example, a system can deliver only 70 percent of the kilowatt load at 0.7 power factor that it can deliver at unity power factor. The synchronous motor requires considerable reactive power when it operates at no load without any dc excitation to the rotor. It acts like a three-phase inductance load on the power line. When the rotor is excited, it will produce some of the magnetism in the motor with the result that the stator has to supply less, and the reactive power drawn from the power line decreases. If the rotor is excited until it produces all the magnetism, the power line will only have to supply real power to the stator, and the power factor will be unity. As far as the power line is concerned, the synchronous motor now looks like a three-phase resistance load. If the rotor is excited still further, tending to create more magnetism than the motor needs, then the power line starts supplying negative reactive power to the stator in its attempt to keep the total flux constant. But negative reactive power corresponds to a capacitor, and the synchronous motor now looks like a three-phase capacitance load to the power line. At no load, the synchronous motor has the property of acting like a variable inductor/variable capacitor, the value of reactance (X_L or X_c) being determined by the amount of dc current flowing in the rotor. A synchronous motor when used on the same power system with induction motors improves the overall system power factor.

Just as it was possible to vary the power factor of the synchronous motor at no load, it is possible to vary it under full load conditions. Although the power factor is normally held close to 100 percent, the synchronous motor may be overexcited with direct current so as to improve the overall power factor of a large electrical system. When operated on the same electrical power system with induction motors or other devices that operate at lagging power factors, the leading reactive kilovars, supplied by the synchronous motors compensate for the lagging reactive kilovars, of the induction motors or other devices, resulting in an improvement in the overall electrical system's power factor. Synchronous motors, like induction motors, may be temporarily overloaded. However, unlike the induction motor, the synchronous motor will maintain constant speed under overload conditions up to a certain point. This maximum overload point depends on the dc rotor excitation. Beyond this overload point the rotor poles will "unlock" from the revolving stator field and the rotor will fall out of synchronism. This overload point is called the pullout torque of the motor. If it were not for the squirrel cage windings, it would cease to develop any torque at all, and consequently, come to a quick stop. A synchronous motor that has been pulled out of synchronism should be disconnected from the power line as quickly as possible.

Basically, synchronous motor starters differ from induction motor starters by the addition of control devices, which apply DC excitation to the field winding of the synchronous motor at exactly the right instant to achieve synchronization. Timing is essential to maximize the motor's synchronous effort, and to minimize any oscillatory power disturbances in the power lines while the motor is locking into step.

To accomplish the synchronization operation successfully, the DC excitation current must be applied only when the stator poles and rotor poles are in favorable relationship. Successfully synchronizing dictates that the starter apply excitation current to the field winding only when the following two conditions are met simultaneously:

1. The rotor must have accelerated to the maximum speed possible on the squirrel-cage winding. This approximately 97% of synchronous speed.
2. Each rotor pole must be lagging slightly behind a stator pole of opposite polarity.

To fulfill the first requirement, we must measure the speed of the rotor. Since it is impractical to make such a measurement directly, the rotor speed must be determined indirectly from the time span of one-half cycle of induced voltage (or current) in the rotor field, during start-up. When the rotor is at 97% synchronous speed, the speed

difference (or slip) is 3%. Since 3% of 60 Hz. (synchronous speed) is $\frac{r}{.8}$ .555s.

Therefore, the time for one half cycle is approximately 0.28s. The synchronizing control must keep the DC excitation off the field winding until the rotor has accelerated to at least 97% of its synchronous speed. Consequently, we need a sensing element that will only produce an output signal when the proper induced rotor frequency has been reached. This frequency is attained when the time span of one-half cycle of the induced voltage lengthens to 0.28s.

Other requirement for proper synchronization dictates that each rotor pole should be lagging slightly behind a stator pole of opposite polarity. When this condition exists, the voltage induced in the field winding will be in the negative half-cycle, and this will be the proper time for DC excitation to be applied to the field.

FIELD CURRENT LOSS

If dc voltage is available for the field winding of the motor, but no current flows when FC closes, the motor can never synchronize. If the motor continues running with no dc field, the already above- normal stator currents can overheat and damage the motor.

FIELD VOLTAGE LOSS

Here, additional protection is provided to prevent starting the motor if the dc supply voltage is not present. This method does not apply when a direct-connected exciter is used to provide synchronous field excitation.

OPEN FIELD CIRCUIT
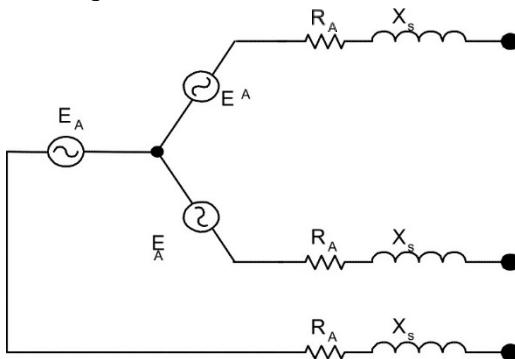
If a synchronous motor is started without connecting the field to the discharge resistor, a high voltage will appear across the field terminals during start-up. Furthermore, if the start button is pushed the motor will start as an induction motor, but since dc can never be applied, the motor will not synchronize.

The most common cause of such an open circuit is the slip ring brush assembly of the motor. Maintenance men may lift the brushes to clean the rings and forget to replace the brushes. The basic protection, then, is to provide a means of detecting an open field circuit automatically. When this condition is sensed, protective devices prevent the motor from starting.

In appendix D, there is a summary of the AC motors discussed so far. It includes a comparison with single-phase and three-phase induction motors.

PRELAB

1. What is the synchronous speed of a 12-pole 460 V 60Hz synchronous motor? At what speed will it run when the full load is reduced to 50 %? What is the speed if the supply voltage is 380 V?

2. A 60 Hz. 10 hp 208 V synchronous motor with a nominal pf of 0.8 leading and wye connected has synchronous impedance (X) of 2.7CI. The windage-friction and iron losses are equal to 400 W and to 250 W respectively. Calculate using the Figure 9. 1 and Figure 9.2:

   a. The apparent power

   e. The nominal excitation current

   b. The line current

   f. The motor efficiency

   c. The value of E_A

   d. The nominal rotor torque

FiGuR£ 9.1
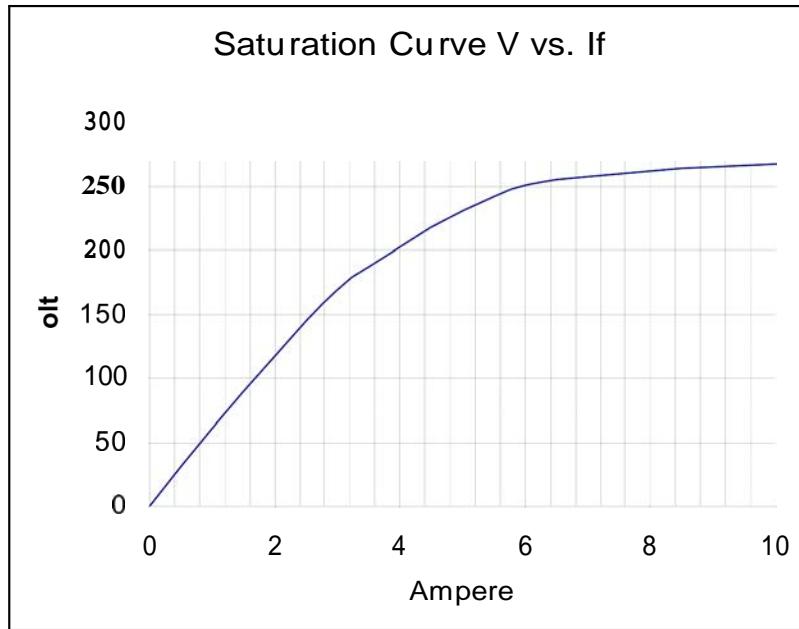
FIGURE 9.2

EXPERIMENT 9.1   SYNCHRONOUS MOTOR OPERATION UNDER LOAD

REQUIRED EQUIPMENT

Synchronous Motor/Generator Module   *EMS 8241*
Electrodynamometer Module   *EMS 8960-10*
Power Supply Module   *EMS 8821*
Synchronizing Switch Module   *EMS 8621*
Hand Tachometer   *EMS 8920*
Connection Leads   *EMS 8941*
Timing Belt   *EMS 8942*

PROCEDURE

Step 1: Examine the construction of the Synchronous Motor/Generator Module EMS **8241,** paying particular attention to the motor, slip rings, rheostat, connection terminals and the wiring.

Step 2: Viewing the motor from the rear of the module:

a) Identify the two slip rings and brushes.

Question 1: Can the brushes be moved?

b) Note that the two rotor windings are brought out to the two slip rings via a slot in the rotor shaft.

c) Identify the dc damper windings on the rotor. (Although there are only two windings, they are connected so that their magneto motive forces act in opposition, thus, creating four poles).

d) Identify the four salient poles just beneath the damper windings.

e) Identify the stator winding and note that it is identical to that of the three-phase squirrel cage and wound rotor motors.

Step 3: Viewing the front face of the module:

a) The three separate stator windings are connected to terminals _____ and _____ and _____.

Question 2: What is the rated voltage of the stator windings?

Question 3: What is the rated current of the stator windings?

The rotor winding is connected through the 150 D rheostat (and a toggle switch S) to terminals_____ and _____.

Question 4: What is the rated voltage **of the rotor winding?**

Question 5: What is the rated speed and horsepower of the motor (in r/min and **hp**)?

STARTING CHARACTERISTICS

Step 4: Using your EMS Synchronous Machine, Power Supply and Data Acquisition Interface (DAI) modules in the EMS workstation, connect the circuit shown in Figure 9.3. Note that the three-stator windings are wye connected to the fixed 208V 3$ output of the power supply, terminals 1, 2 and 3.

Step 5: a) Turn on the power supply. Note that the motor starts smoothly and continues to run as an ordinary induction motor.

b) Note the direction of rotation.
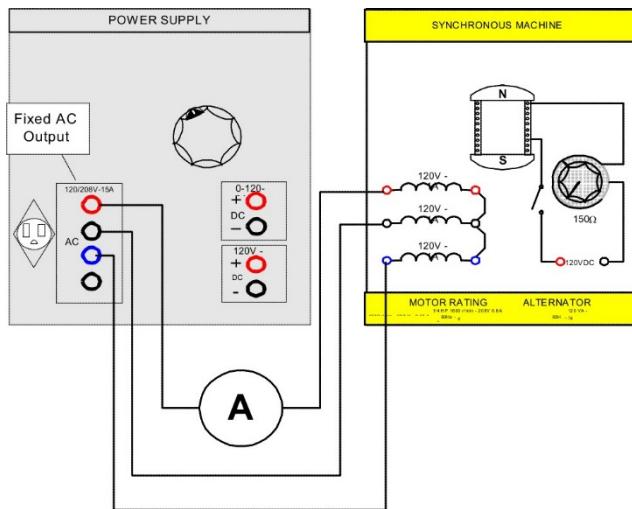
FIGURE 9.3

     c) Turn off the power supply and interchange any two of the leads from the power supply.

     d) Turn on the power supply and note the direction of rotation.

            Rotation   _____, I   _____*Aac*

     e) Turn off the power supply.

Step 6: Using your EMS Electrodynamometer and Synchronizing Switch Modules, connect the circuit shown in Figure 9.4. Couple the motor to the electro-dynamometer with the timing belt.
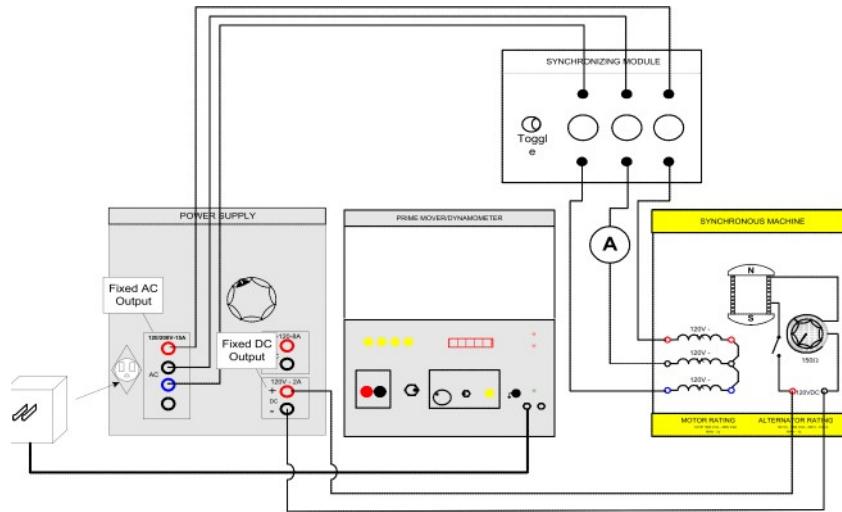
FIGURE 9.4

Step 7: a) The synchronizing switch module will be used as an on-off switch for the 3$ power to the stator windings. Set the switch in its off position.

     b) The electrodynamometer is connected to the fixed 120Vac outlet of the power supply using the 120/24 Vac adapters. Set the dynamometer control knob for approximately 40 percent excitation.

$ynchronous Motor Operation And Control

c) The rotor of the synchronous motor is connected to the fixed 120Vdc output of the power supply, terminals 8 and N. Set the field rheostat for zero resistance (control knob turned fully cw).

d) If the synchronous motor has switch S, close it at this time.

Step 8: a) Turn on the power supply. Then apply 3$ power by closing the synchronizing switch and observe what happens. Do NOT LEAVE THE POWER ON FOR LONGER THAN 105.

b) Describe what happened

Question 6: What did the ammeter indicate?

Question 7: Should a synchronous motor, under load, be started **with dc excitation** on its l"ield?

Step 9: a) Connect the rotor of the synchronous motor to the variable 0-120Vdc outputs of the power supply, terminals 7 and *N.* Do not disturb any of the other connections or change any control settings.

b) With the variable output voltage control at zero, turn on the power supply. Apply 3$ power by closing the synchronizing switch and observe what happens.

c) Describe what happened

Question 8: Is your motor operating as an induction motor?

d) Carefully adjust the power supply output to 120Vdc as indicated on the power supply meter.

e) Describe what happened

Question 9: Is your motor operating as a **synchronous motor?**

fJ Return the voltage to zero and turn off the power supply.

Step 10: a) Connect the circuit shown in Figure 9.5. Note that the synchronous motor is wired in its normal starting configuration (as a three-phase squirrel cage induction motor).

b) Set the dynamometer control knob at its full cw position (to provide a maximum starting load for the synchronous motor).

c) If the synchronous motor has switch S, close it at this time.

Step 11: a) Turn on the power supply and quickly measure *EI, E2,* II and the developed starting torque. Turn off the power supply.

E_1 _____ Vac, E _____ Vac, I _____ Aac

Starting torque = _____ Lbf.in

b) Calculate the apparent power to the motor at starting torque.

Apparent power = _____ VA

c) Calculate the full load torque corresponding to '74 hp at 1800 r/min.

Full load torque = _____ lbf.in

d) Calculate the ratio of starting torque to full load torque.

Ratio _____
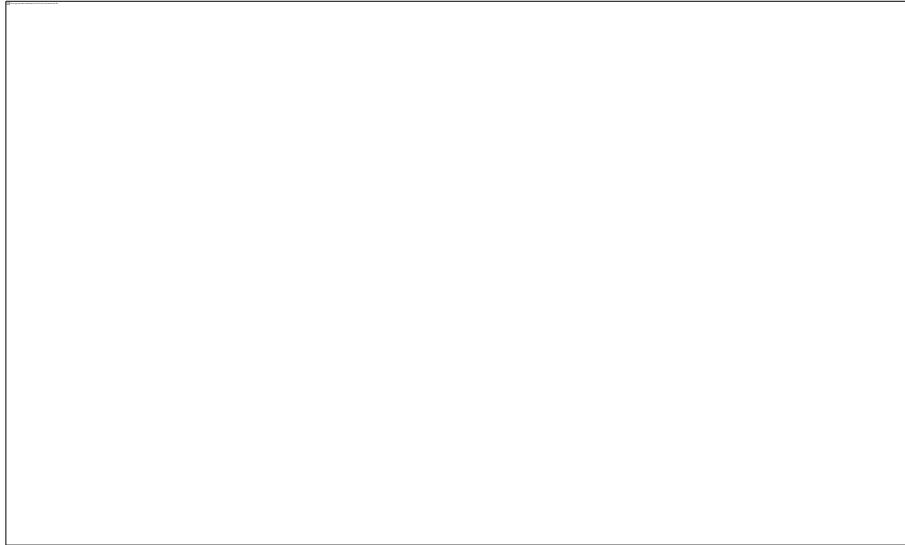
FIGURE 9.5

e) Explain why a large ac voltage E2 was induced in the rotor windings.

Step 12: With your circuit unchanged, turn on the power supply and slowly turn the dynamometer control knob ccw to reduce the loading. The motor will come up to full speed and run as a squirrel cage induction motor. Note the effect upon the induced voltage E2.

Question 10: Why does E2 decrease as the motor speed increases?

Step 13: a) Using your EMS Synchronous Machine, Power Supply and Data Acquisition Interface (DAI) modules in the EMS workstation, connect the circuit shown in figure 9.6. Note that the stator windings are connected, through the wattmeter, to the fixed 208V 3$ output of the power supply, terminals 1, 2 and 3. The rotor winding is connected, through the ammeter, to the variable 0-120Vdc output of the power supply, terminals 7 and N. The voltage adjust control knob should be at zero.

b) If the motor is equipped with switch S, open it at this time.

c) Set the field rheostat for zero resistance (knob turned fully cw).
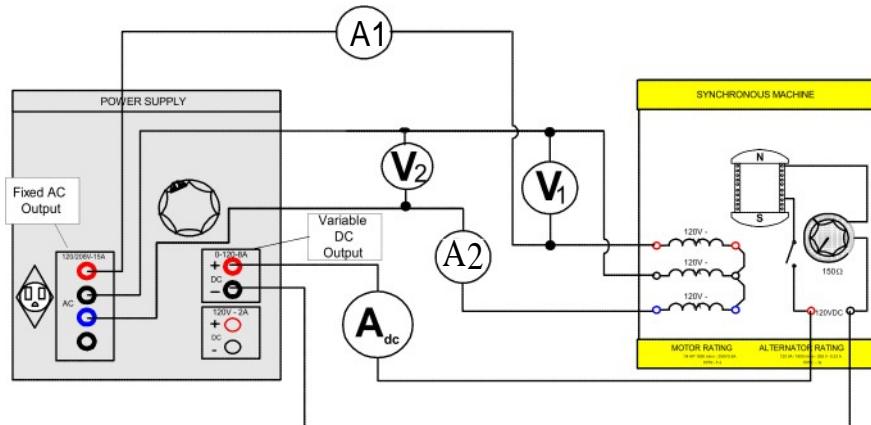
FIGURE 9.6

Step 14: a) Turn on the power supply; the motor should be running. Note the value of ac current I . The motor is drawing positive reactive power from the power supply at zero dc excitation and looks like an inductor.

b) If the motor is equipped with switch S, close it at this time.

c) Gradually increase the dc excitation until the ac current I is at its minimum value. Both wattmeters should have equal positive indications, and, as far as the power supply is concerned, the motor looks like a resistor.

d) Note I , If, W , and W,.

$$I = \text{----------} \text{ Aac} \qquad I,= \text{----------} \text{ Adc },$$
$$W_1 = \text{----------W} \qquad \mathbf{W_2 =} \text{ ----------W}$$

e) Increase the dc excitation and note that the ac current I begins to increase again. The motor is drawing negative reactive power from the power supply and looks like a capacitor.

Step 15: a) With the dc excitation at zero, measure and record El, I1, W1 and W2 in Table 9-1.

b) Repeat for each of the dc current values listed in Table 9.1. TAKE YOUR MEASUREMENTS AS QUICKLY AS POSSIBLE WHEN THE EXCITATION EXCEEDS 0.6 Adc. Remember to note the polarity of the wattmeter indications.

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

Step 16: Complete Table 91 by calculating the apparent power (remember to multiply by 1.73) real power and power factor for each of the dc currents listed.

Step 17: a) From the results of Table 9.1, calculate the reactive power at zero dc rotor current = _____Var

Question 11: Is the power factor leading or lagging?

Step 18: a) From the results of Table 9.1, calculate the reactive power at maximum dc rotor current. _____ver

Question 12: Is the power factor leading or lagging?

I_2 DC (amps)	E_1 (Volts)	I_1 (Amps)	POWER (VA)	W_1	W_2	POWER (Watts)	PF
0							
0.1							
0.2							
0.3							
0.4							
0.5							
0.6							
0.7							
0.8							
0.9							

Table 9.1

Report Recommendations

1. How does the synchronous motor must be started? Can it start as a synchronous motor? Find out the different starting methods of a synchronous motor in your textbook and explain them briefly in your report.
2. What is a synchronous capacitor? How can the power factor of a synchronous motor be changed?
3. Plot the synchronous motor curve line current vs. field current. Divide the curve, according to the input power factor, in three regions: lagging, unity power factor, and leading.

LABORATORY SESSION X

THREE PHASE SYNCHRONOUS GENERATOR

OBJECTIVES

The main objectives of this lab session are to show the characteristics in open circuit and short circuit configurations of the three-phase alternator. Also we are interested in demonstrating the effects of various power factor loads on the voltage regulation.

The specific objectives of this lab session are:
 1) To obtain the no load saturation curve of the alternator.
 2) To obtain the short-circuit characteristics of the alternator.
 3) To determine the voltage regulation characteristics of the alternator with resistive, capacitive and inductive loading.
 4) To observe the effect of unbalanced loads on the output voltage.
 5) By observing the direction of rotation of the rotor, compare how the phase sequence of a three phase synchronous generator changes.

REFERENCES
 1) Wildi, Theodore. and De Vito, Michael. *Investigations in Electric Power Technology,* 2 ed., Buck Engineering Co. Inc. Farmingdale, New Jersey (In Canada: Lab —Volt Limited, Montreal, Quebec. 1971.

INTRODUCTION

OPEN AND SHORT **CIRCUIT CHARACTERISTICS**

The terms alternating current generator, synchronous generator, synchronous alternator, and alternator are commonly used interchangeably in engineering literature. Because synchronous generators are so much more commonly used than induction generators, the term alternator, as often used, and as used here, applies only to synchronous generators.

Alternators are, by far, the most important source of electric energy. Alternators generate an ac voltage whose frequency depends entirely upon the speed of rotation. The generated voltage value depends upon the speed, the dc field excitation and the power factor of the load.

As the dc field excitation of an alternator is increased, its speed being held constant, the magnetic flux, and hence, the output voltage, will also increase in direct proportion to the current. However, with progressive increases in dc field current, the flux will eventually reach a high enough value to saturate the iron in the alternator.

Saturation in the iron means that there will be a smaller increase in flux for a given increase in dc field current. Because the generated voltage is directly related to the magnetic flux intensity, it can be used as a measure of the degree of saturation.

The three phases of the alternator are mechanically spaced at equal intervals from each other, and therefore, the respective generated voltages are not in phase, but are displaced from each other by 120 electrical degrees.

When an alternator delivering full rated output voltage is suddenly subjected to a short circuit, very large currents will initially flow. However, these large short-circuit currents drop off rapidly to safe values if the short-circuit is maintained.

Voltage Regulation

The output voltage of an alternator depends essentially upon the total flux in the air-gap. At no load, this flux is established and determined exclusively by the dc field excitation. Under load, however, the ampere-tums of the rotor and the ampere-turns of the stator determine the air-gap flux. The latter may aid or oppose the MMF (magneto motive force) of the rotor depending upon the power factor of the load. Leading power factors assist the rotor, and lagging power factors oppose it. Because the stator MMF has such an important effect upon the magnetic flux, the voltage regulation of alternators is quite poor, and the dc field current must continuously be adjusted to keep the voltage constant under variable load conditions. If one phase of a three-phase alternator is heavily loaded, its voltage will decrease due to the $I*R$ and $I*X_L$ drops in the stator winding. Modifying the dc field current because the voltages of the other two phases will also be changed cannot compensate this voltage drop. Therefore, it is essential that three-phase alternators do not have loads that are badly unbalanced.
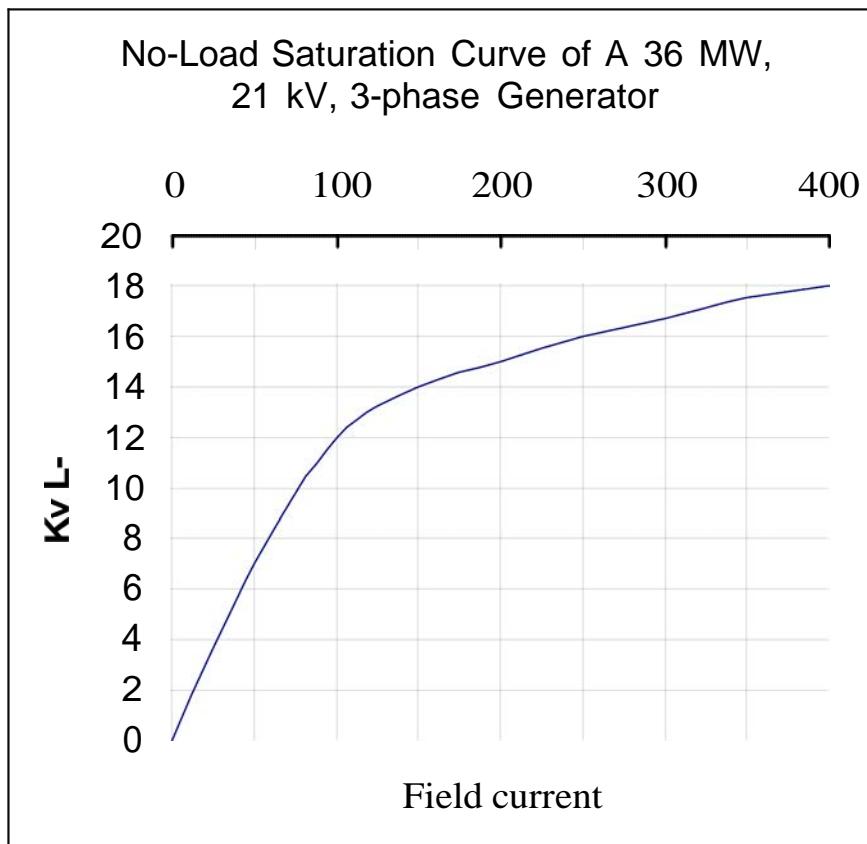
Phase Sequence of a Three Phase Synchronous Generator.

You should know by now the importance of the phase voltages sequence in electric power systems. The voltage sequence in an alternator is quite important for parallel connection between generators or when connecting a generator to the power line. Therefore, the phase sequence must be determined before the connection or the generator(s) would be destroyed as a consequence of high currents flowing through its (theirs) stator's windings.

For this experiment, we will use the method of the two lamps-capacitive method taught on LABORATORY SESSION VI. Review this method before working in this experiment.

Three Phase Synchronous Generator

PRELAB

1. If a three-phase 1800 r/min, 38 kV synchronous generator's field current is kept constant, calculate the no-load voltage and frequency if the speed is
   a. 1000 r/min   b. 5 r/min
2. The Figure 10.1 is a no load saturation curve of an alternator, calculate   the exciting current needed to generate a no load line voltage of:
   a. 24.2 kV   b. 12.1 kV
3. If the no load saturation curve of Figure 10.1 is at nominal speed, (1200 rpm), calculate the terminal voltage for an excitation current   of   150A   and   a   speed   of 1800 RPM.
4. A 15kVA, 1.5 kV, three-phase Y connected generator has a winding resistance of 1.3 D and a synchronous reactance of 5.6 D on a per phase basis. Determine its voltage regulation when the power factor is:
   a. 65% lagging   c. 65^0 leading
   b. Unity

No-Load Saturation Curve of A 36 MW, 21 kV, 3-phase Generator

FIGURE]0.I

EXPERIMENT 10.1 OPEN CIRCUIT AND SHORT-CIRCUIT CHARACTERISTIC OF THE THREE-PHASE SYNCHRONOUS GENERATOR

IIEQUIRED EQUIPMENT

Synchronous Motor/Generator Module   EMS 8241

Three Phase Synchronous Generator

Squirrel Cage Induction Motor Module	EMS 8221
Synchronizing Switch Module	EMS 8621
Power Supply Module	EMS 8821
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1: Using your EMS Synchronous Motor/Generator, Squirrel Cage Motor, Power Supply and Data Acquisition Interface (DAI) modules in the EMS workstation, connect the circuit shown in Figure 10.2. The squirrel cage motor will be used to drive the synchronous motor/generator as an alternator. Its speed will be assumed constant during this Laboratory Experiment. Note that the squirrel cage motor is connected to the fixed 208 V 3 / outputs of the power supply, terminals 1, 2 and 3. The rotor of the alternator is connected to the variable 0-120Vdc outputs of the power supply, terminals 7 , N.

FIGURE 10.2

Step 2: a) Couple the squirrel cage motor to the alternator with the timing belt.
   b) Set the alternator field rheostat at its full cw position (for zero resistance). Open Switch S.
   c) Set the power supply voltage control at its full ccw position (for zero dc voltage).
Step 3: a) Turn on the power supply. The motor should be running.
   b) What is the rotor speed?
   c) With zero dc excitation measure and record E , E, and Ed.
      E —_____Vac, E, _____Vac, E —_____Vac
   d) Explain why there is an ac voltage generated in the absence of dc excitation.
Step 4: a) If the motor has switch S, close it at this time.
   b) Gradually increase the dc excitation from zero to 0.lAdc.
   c) Measure and record in Table 10.1 the three generated voltages E , E, and E .
   d) Repeat (b) for each of the dc currents listed in Table 10.1.
   e) Return the voltage to zero and turn off the power supply.
Step 5: Calculate and record in Table 10.1 the average output voltage of the alternator for each of the listed dc currents.
Step 6: a) Turn on the power supply and adjust the dc excitation until El = *208 Vac*. Measure and record E2 and E3-

Three Phase Synchronous Generator

E = <u>208 Vac</u>, E,=_____Vac, E =_____Vac.

b) Turn off the power supply without touching the voltage adjust control.

c) Reconnect the three-ac voltmeters so they will measure the voltages across each of the three-stator windings.

d) Turn on the power supply. Measure and record the generated voltages across each of the wye connected stator windings.

E 1 to 4 =_____Vac   E   2   to   5

_____Vac

E 3 to 6 =_____Vac

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

Question 1: Compare the results of (a) and (d). Do the results correspond to what you would expect **to find coming from a normal three-phase** power supply?

Step 7: Using your EMS Synchronizing Switch, connect the circuit shown in Figure 10.3. The dynamometer/prime mover will be connected as a <u>prime mover</u> Note that the switch is wired to present a dead short across the alternator windings when it is closed.

Step 8: a) Set the synchronizing switch to its open position. Adjust the speed to 1800 RPM by adjusting the variable dc input of the prime mover.

b) Turn the power supply and adjust the dc excitation until E=208 Vac. The motor should be running and the three lamps on the synchronizing module should be illuminated.

c) Measure and record the dc exciting current I .

I,   _____A dc

FIGURE 10.3

d) Apply a short-circuit to your alternator by closing the synchronizing switch and note the behavior of the ac current I .

Question 2: To what approximate peak value did If increase?

Question 3: What is the final steady-state value of **If and I,?**

e) Return the voltage to zero and turn off the power supply

I_1 (Amps)	E_1 (Volts)	E_2 (Volts)	E_3 (Volts)	E_{ac} (Avg.)
0				
0.1				
0.2				
0.3				
0.4				
0.5				
0.6				
0.7				
0.8				
0.9				

Table 10.1

EXPERIMENT 10.2 VOLTAGE REGULATION OF THE THREE-PHASE SYNC. GEN.

1 **EQUIRED EQUIPMENT**

Synchronous Motor/Generator Module	EMS 8241
Electrodynamometer	EMS 8960-10
Resistance Module	EMS 8311
Capacitance Module	EMS 8331
Inductance Module	EMS 8321
Power Supply Module	EMS 8821
Hand Tachometer	EMS 8920
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1: Using your EMS Synchronous Motor/Generator, Prime Mover/Dynamometer (PMD), Resistance, Power Supply and Data Acquisition Interface (DAI) modules in the EMS workstation, connect the circuit shown in Figure 10.4. Note that the balanced resistive load is wye connected to the three-phase output of the alternator. The alternator rotor is connected to the fixed 120Vdc output of the power supply, terminals 8 and N. The prime mover dynamometer is connected to the variable 0-120Vdc outputs of the power supply, terminals 7 and N.
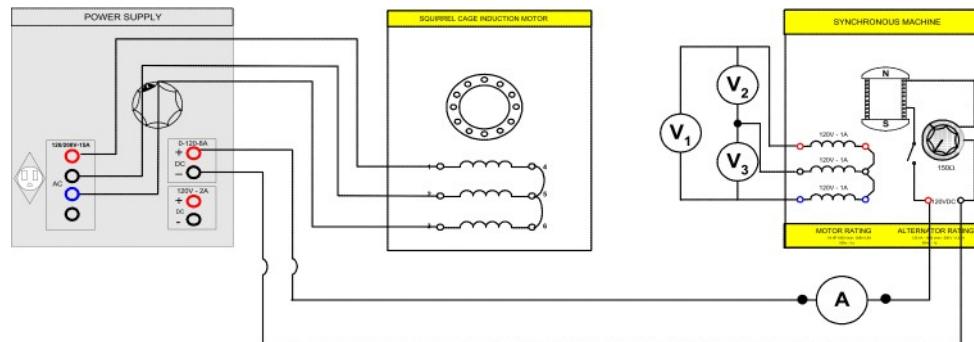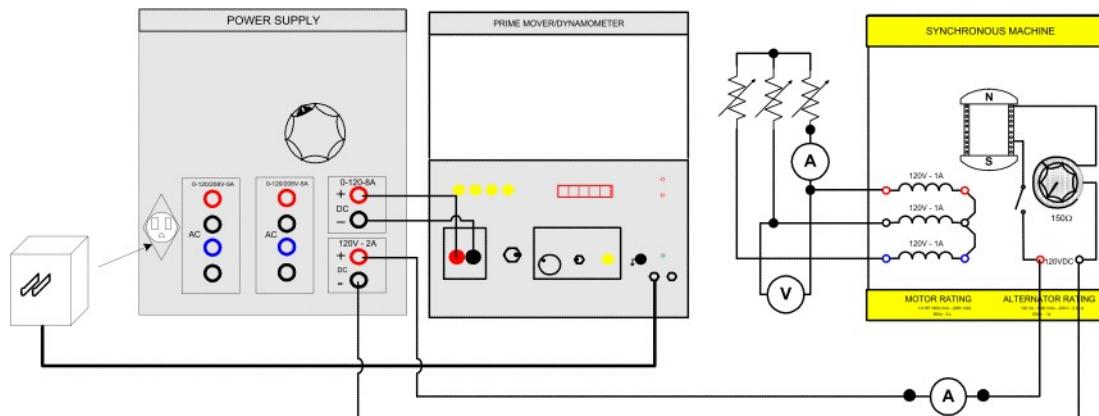

FIGURE 10.4

Step 2. a) Couple the prime mover/dynamometer (PMD) to the alternator with the timing belt.

b) Toggle the PMD mode switch to prime mover.

c) Set the alternator field rheostat at its full ccw position (for maximum resistance).

d) Adjust each resistance section for a resistance of 300D.

Step 3: a) Turn on the power supply and, using your PMD display, adjust the de motor rheostat for a motor speed of 1800 r/min. Note: This speed must be kept constant for the remainder of this Laboratory Experiment!

b) If the synchronous motor has switch S, close it at this time.

c) Adjust the dc excitation of the alternator until the output voltage E = 208Vac. Measure and record the full load I and I,.

I =_____Aac, I =_____Adc

d) Open the three resistance load switches for no load on the alternator and measure and record the no load E and I,. REMEMBER TO CHECK THE MOTOR SPEED AND READJUST **TO 1800** R/MIN IF REQUIRED.

E —_____Vac   I, =_____Adc

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

fl Calculate the alternator regulation with resistive loading.

$$^0 \text{ Regulation} = \underline{\text{NL volts - FL volts}} \times 100^0$$
$$\text{FL volts}$$

_____

Step 4: a) Using your EMS Inductance module, replace the resistive load with an inductive load.

b) Adjust each inductance section for a reactance X_L of 300D.

c) Repeat step 3 and record the full load values of I , and I .

I _____Aac,   I _____Adc

d) Measure and record the no load values of E_l «nd If.

E _____Vac, I _____Adc

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

I) Calculate the alternator regulation with inductive loading.

_____

Question 1: With an inductive load, does the stator MMF aid or oppose the rotor MMF?

Step 5: a) Using your EMS Capacitance Module, replace the inductive load with a capacitive load.

b) Adjust each capacitance section for a reactance Xc of 300 1.

c) Repeat Step 3 and record the full- load value of I and I .

I _____Aac   I _____Adc

d) Measure and record the no load values of E_d and I .

E _____Vac   I _____Adc

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

fl Calculate the alternator regulation with capacitive loading =_____

Question 2: With capacitive loading does the stator MMF aid or oppose the rotor MMF?

Step 6: a) With a capacitive reactance load of 1200 t2 per phase, turn on the power supply and adjust for a motor speed of 1800 r/min.

b) Adjust the dc excitation of the alternator until the output voltage E = 208Vac.

c) Increase the capacitive loading by placing an additional reactance of 600V in parallel with each of the 1200 sections and observes what happens.

d) Increase the capacitive loading further by placing an additional reactance of 300f1 across each section and observe what happens.

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

f) Explain, the phenomenon you have just observed.

Step 7: a) Connect the circuit shown in Figure 10.5. Note that only one of the alternator phases has a load.

b) Turn on the power supply and adjust the dc motor rheostat for a motor speed of 1800 r/min.

c) Adjust the dc excitation of the alternator until the voltage across the 600V load E = 208 Vac.

d) Measure and record the two other phase voltages E and Ed.

$E_2 = $ _____ Vac, E_3 _____ Vac
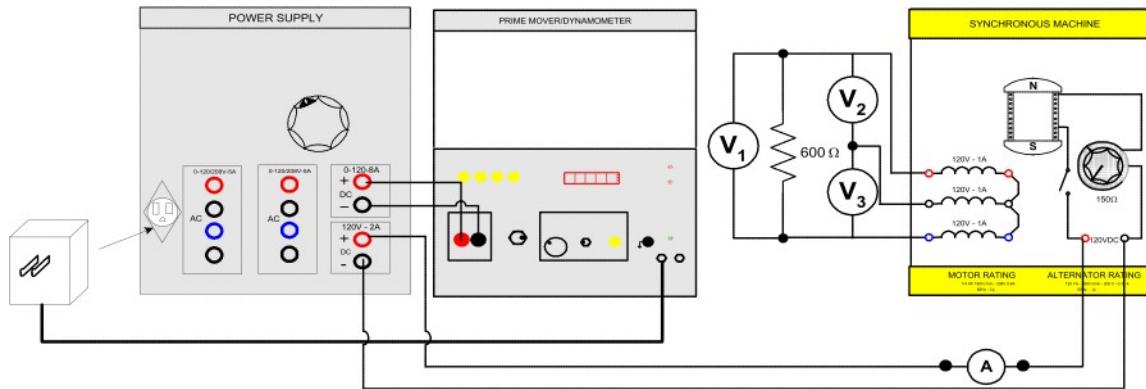
FIGURE 10.5

e) Turn off the power supply without touching any of the variable controls.

I) Reconnect the three-ac voltmeters so they will measure the voltages across each of the three-stator windings.

g) Turn on the power supply. Measure and record the voltages across each of the alternator windings.

E 1 to 4 = _____ Vac

E 2 to 5 _____ Vac   E 3 to 6 = _____ Vac

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

Question 3: Did the single-phase load produce a large unbalance?
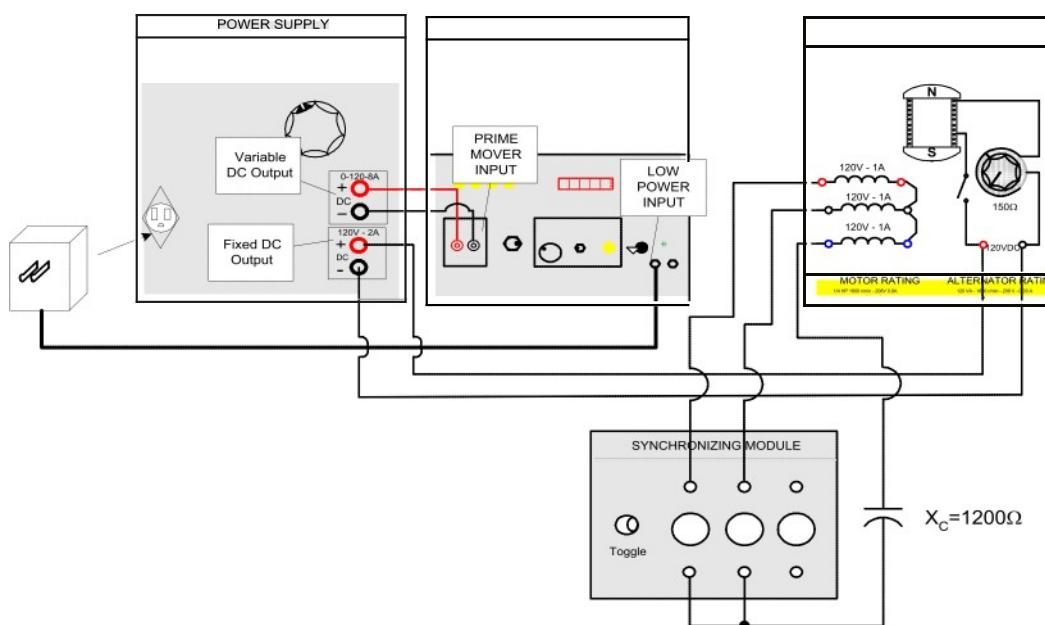
EXPERIMENT 10.3 THREE PHASE GENERATOR VOLTAGE SEQUENCE DETERMINATION

REQUIRED EQUIPMENT

Synchronous Motor/Generator Module	EMS 8241
Synchronizing Switch Module	EMS 8621
Capacitance Module	EMS 8331
Power Supply Module	EMS 8821
Connection Leads	EMS 8941
Timing Belt	EMS 8942
Connection leads	

PROCEDURE

Step 1: Using your Synchronizing Switch, Capacitance, power supply and Synchronous Generator, connect the circuit shown in Figure 10.6.

FIGURE 10.6

Step 2: Place the synchronizing switch in its open position. Do not close the switch, it will cause a short across the generator!

Step 3: Connect the variable dc output's positive terminal to the red terminal of the prime mover input and the negative, to the black one.

Step 4: a) Couple the prime mover/dynamometer (PMD) to the alternator with the timing belt.
b) Toggle the PMD mode switch to prime mover.

Step 5: Turn on the power supply and adjust the speed of the PMD to 1800 RPM by increasing or decreasing the dc voltage applied to the prime mover input. Close the switch of the field winding.

Step 6: Determine the voltage sequence of the generator.

Step 7: Turn off the power supply. Now, interchange the leads connected to the prime mover input so the negative terminal of dc variable output source is connected to the red terminal of the prime mover output and the positive, to the black one. The prime mover should turn to the opposite direction when turning on the power supply again.

Step 8: Determine now the voltage sequence of the generator.

Step 9: Does the sequence is the same of that obtained in step 6?   Explain.
    Is the sequence determined by the rotation of the rotor?

REPORT REQUIREMENTS

1. Draw the saturation curve of the synchronous alternator. Be sure of specifying the speed at which you did the experiment.
2. Can you determine the internal impedance with the short circuit characteristic of the alternator? Calculate the synchronous impedance of the three phase synchronous alternator in case of affirmative response.
3. Show the voltage regulation results you obtain in the experiment. Specify when the regulation is for lagging, unity or leading power factor loads.
4. Look up in your textbook and write in your report the conditions necessary to connect various generators in parallel.
5. What instruments are needed to check the conditions necessary to connect generators in parallel? Described them briefly.

LABORATORY SESSION XI

DIRECT CURRENT MOTOR OPERATION AND CONTROL

OBJECTIVES

The main purpose of this laboratory session is to observe the variable speed range of the different dc motors and to produce the load-speed characteristic curves of each one. Furthermore, we are interested in calculate the efficiencies of the different dc motors, to connect, operate, and understand the necessity for a direct current motor starter switch, and to observe the circuit changes necessary to reverse a dc motor.

The specific objectives of this lab session are:

1) To study the torque vs. speed characteristics of shunt wound, series, and compound dc motors.
2) To calculate the efficiency of shunt wound, series, and compound dc motors.

REFERENCES

1) Guru, B.S. and Hiziroglu, H.R. *€ec/mc machinery and transformers,* 3 ed., Oxford University Press, U.S.A., 2001.

INTRODUCTION
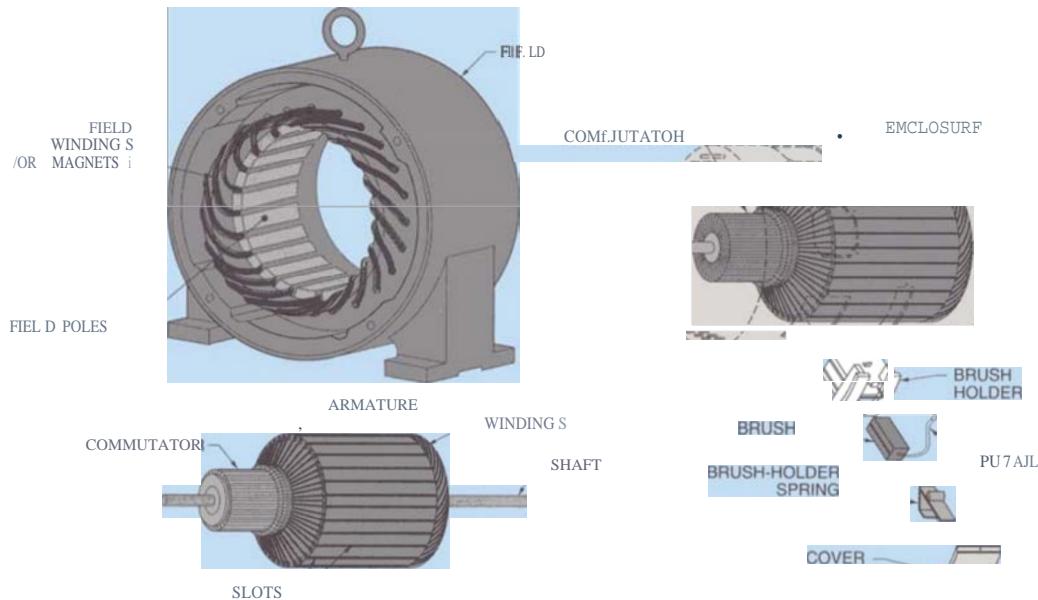
FIGURE 11.1 CONSTRUCTION OF A DC MOTOR (FROM THE BOOK OF ELECTRICAL MOTOR CONTROL WRITTEN BY GARY ROCKIS AND GLEN MAZUR)

Direct current motors are unsurpassed for adjustable-speed applications, and for applications with severe torque requirements. Uncounted millions of fractional horsepower DC motors are used by the transportation industries in automobiles, trains and aircraft where they drive fans and blowers for air conditioners, heaters and defrosters; they operate windshield wipers and raise and lower seats and windows. One of their most useful functions is starting of gasoline and diesel and boats.

The DC motor contains a stator and a rotor, the latter being more commonly called an armature. The stator contains one or more windings per pole, all of which are designed to carry direct current, thereby setting up a magnetic field.

The armature and its winding are located in the path of this magnetic field, and when the winding also carries a current, a torque is developed, causing the motor to turn.

A commutator associated with the armature winding is actually a mechanical device, to assure that the armature current under any given stator pole will always circulate in the same direction irrespective of position. If a commutator were not used, the motor could not make more than a fraction of mm, before coming to halt.

In order for a DC motor to run, current must flow in the armature winding. The stator must develop a magnetic field (flux), either by means of a shunt winding or a series winding (or both).

The torque developed by a DC motor is directly proportional to the armature current and the stator flux. On the other hand, the armature voltage and the stator flux mainly determine motor speed. Motor speed increases when the voltage applied to the armature increases. Motor speed will also increase when the stator flux is reduced. As a matter of fact, the speed can attain dangerous proportions if, accidentally, there is a complete loss of the stator field. However, your DC motor has been carefully designed to withstand possible over speed conditions.

De Shunt Motor

The speed of any dc motor depends mainly upon its armature voltage and the strength of the magnetic field. In a shunt motor, the field winding, as well as the armature winding, is connected in parallel (shunt) directly to the dc supply lines. If the dc line voltage is constant, then the armature voltage and the field will be constant. It is, therefore, apparent that the shunt motor should run at a reasonably constant speed.

The speed does tend to drop with an increasing load on the motor. This drop in speed is mainly due to the resistance of the armamre winding. Shunt motors with low armamre windings resistance run at nearly constant speeds.
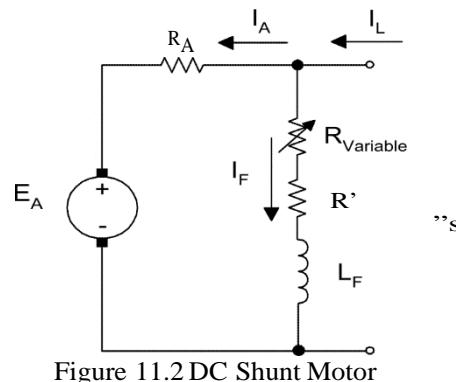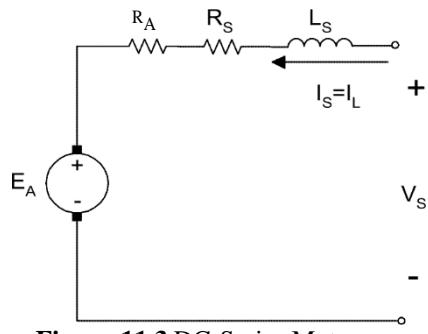
Figure 11.2 DC Shunt Motor

Just like most energy conversion devices, the dc shunt motor is not 100% efficient. In order words, all of the electric power, which is supplied to the motor, is not converted into mechanical power. The power difference between the input and output is dissipated in the form of heat, and constitutes what are known as the "losses" of the machine. These losses increase with load; with the result that the motor gets hot as it delivers mechanical power.

De Series Motor

The shunt wound dc motor was seen to have almost constant speed because its armature voltage and magnetic field remained substantially unchanged from no-load to full-load. The series motor behaves quite differently.

In the series dc motor, the magnetic field is produced by the current, which flows through the armature winding, with the result that the magnetic field is weak when the motor load is light (the armature winding draws minimum current). The magnetic field is strong when the load is heavy (the armature winding draws maximum current). The armature voltage is nearly equal to the supply line voltage (just as in the shunt wound motor if we neglect the small drop in the series field). Consequently, the speed of the series wound motor is entirely determined by the load current. The speed is low at heavy loads, and very high at no load. In fact, many series motors will, if operated at no load, run so fast that they destroy themselves. The high forces, associated with high speeds, cause the rotor to fly apart, often with disastrous results to people and property nearby.

Figure 11.3 DC Series Motor

The torque of any dc motor depends upon the product of the armature current and the magnetic field. For the series wound motor this relationship implies that the torque will be very large for high armature currents, such as occur during start-up. The series wound motor is, therefore, well adapted to start large heavy-inertia loads, and is particularly useful as a drive motor in electric buses, trains and heavy-duty traction applications.

The DC Compound Motor

The high torque capability of the series wound dc motor is somewhat compromised by its tendency to over speed at light loads. This disadvantage can be overcome by adding a shunt field; the motor then becomes a cumulative compound machine. Again, in special applications where dc motors are used in conjunction with flywheels, the constant speed characteristic of the shunt wound motor is not entirely satisfactory, because it does not permit the flywheel to give up its kinetic energy by an appropriate drop in motor speed. This kind of application (which is found in punch-press work), requires a motor with a "drooping" speed characteristic, that is, the motor speed should drop significantly with an increase in load. The cumulative compound wound dc motor is well adapted for this type of work.
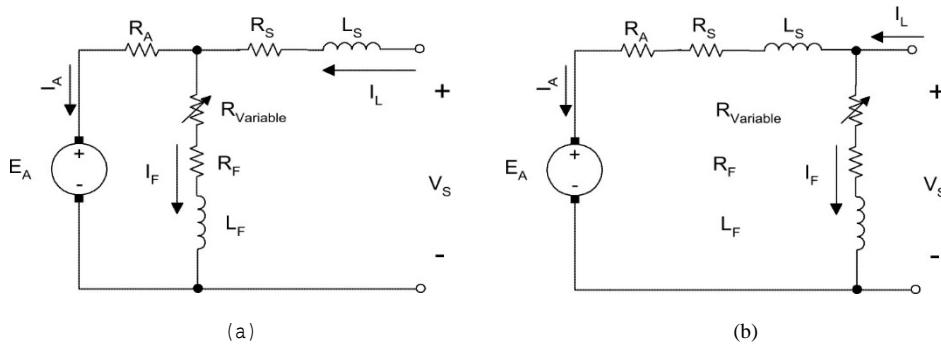
FIGURE 11.4 DC COMPOUND MOTORS (A) SHORT

The series field can also be connected so that it produces a magnetic field opposing that of the shunt field. This produces a differential compound motor, which has very limited application, principally because it tends to be unstable.

Thus, as the load increases, the armature current increases, which increases the strength of the series field. Since it acts in opposition to the shunt winding, the total flux is reduced, with the result that the speed increases. An increase in speed will generally further increase the load which raises the speed still more and could cause the motor to run away.

Differential compound motors are sometimes made with weak series fields that compensate somewhat for the normal slowing of a shunt motor under load and, hence, have more constant speed. Differential compound motors are not used very often.

CAM-Switch Control of a DC Motor

Starting

If a dc motor were connected directly to a power line, the armature inrush current would be from ten to twenty times the normal full-load motor current. Since torque is directly proportional to armature current, the starting torque could be twenty times normal and the initial heating of the motor would be 400 times normal. Except for small machines, neither motor, driven machine, nor power line would stand this punishment. The voltage across the motor must therefore be reduced in some way, and the simplest and most usual method is to connect a resistor in series with the armature. The resistor should allow more than full-load current to flow, so that the torque will be sufficient to accelerate the rated load. A usual starting resistor will allow 150% to 300% of normal full-load current to flow.

Acceleration

When the motor starts to turn, it will accelerate as long as its torque is greater than that required by the load. As the motor accelerates, its counter voltage (CEMF) increases, with a corresponding drop in torque. To maintain full-load torque it is necessary to reduce the starting resistance, as the motor speed increases. Figure 11.5 is the elementary diagram of a shunt-motor starting circuit with three steps of starting resistance and three accelerating contacts. Such a starter is called a four-step starter. On the first step, line contactor M closes and the motor armamre is connected to the line with all starting resistance in series. On steps 2, 3, and 4, accelerating contacts IA, 2A, and 3A close in sequence with intervals between steps, as governed by the

characteristics of the control system chosen for the starter. The contacts may be operated manually or electromechanically.
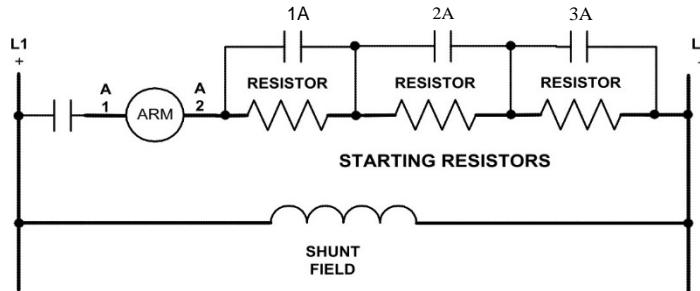
FIGURE **11.5**

SPEED

The speed of a dc shunt motor may be reduced below normal by reducing the voltage across the armature or by increasing the strength of the shunt field. Since the field winding is generally across the power line, there is no practical way to   increase   its strength. Lowering the source voltage may reduce the voltage to the armature, but a resistance in series with the armature can be used to obtain speeds below normal. Although it gives poor speed regulation it has the merit of simplicity.

REVERSING

Reversing either the armature or the field connections but not both may reverse a dc motor. It is customary to reverse the armature connections because the high inductance of the field windings makes them relatively hard to open (due to contact arcing) and slow in response. Reversing the field also produces severe armature current peaks. Motors are often plugged for quick reversal, which means opening the armature circuit and immediately reconnecting it in the reverse direction before the motor has stopped.

DYNAMIC BRAKING

The purpose of dynamic braking is to obtain a quick stop. The armature is disconnected from the line, and a braking resistance is connected across it as shown in Figure 11.6. The field remains on the line. Since the motor is turning, it   acts   as   a generator and forces current around the loop formed by the armature and the braking resistance. Knowing the braking torque desired, the designer can calculate the braking current, and hence the value of the braking resistor. Braking current is usually set at 150% of normal armature current, but where very quick stopping is desired, the current may be allowed to go as high as 300^0 of normal. As the   motor   slows   down,   the generated voltage falls; consequently the braking current and braking torque are reduced. At zero speed there is no braking effect at all. For very quick stopping the braking resistance is sometimes cut out in two or more steps as the voltage falls, thus keeping the braking current high. It is not unusual to stop a large machine in one second or less.
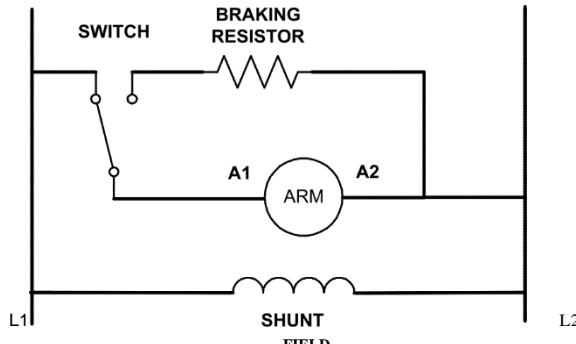
FIGURE 11.6

PRELAB

1. A 12 kW, 100 V, 1000 RPM dc shunt motor has armature resistance R_A 0.1 CI, shunt field winding resistancé R_{shunt} '80 t2, and Nf=1200 tums per pole. The rated field current is 1 ampere. The magnetization characteristic" at l000rpm is shown in Figure 11.7. The machine is operated as a shunt dc motor. Calculate the rotor speed when the shunt resistance is increased to 100 D at rated voltage and nominal load. The brushes drop is 6V.

2. A 10 hp 230V dc compound motor has an armature resistance of 0.2512, a series winding resistance of 0.25D and a brush voltage drop of SV. The shunt winding resistance is 230 I, the no-load terminal current is 4A with a speed of 1810 RPM and at full load demand the current drawn to the source is 50A. Calculate:
   a. The no load armamre voltage
   b. The full load armature voltage
   c. The speed at full load demand
   d. The motor efficiency at nominal load"
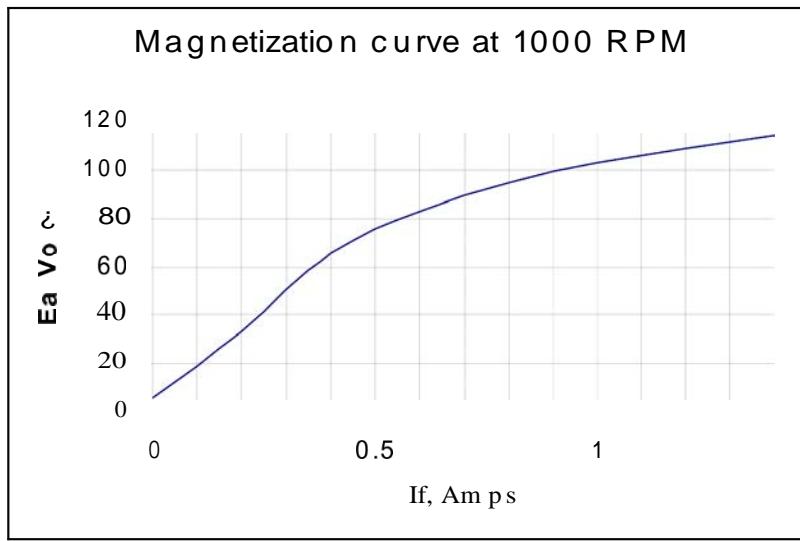
FIGURE 11.7

" Remember that the magnetization curve is done at no load operation when the motor is connected as an independent excited generator.
" Consider linearity and neglect armature reaction.

EXPERIMENT **11.1 DC** SHUNT MOTOR

REQUIRED EQUIPMENT

Power Supply Module (120Vac, 0-120Vdc)	EMS 8821
DC Motor/Generator Module	EMS 8211
Electrodynamometer Module	EMS 8911
Hand Tachometer	EMS 8920
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1: Using your EMS Power Supply, DC Motor/ Generator, the Data Acquisition Interface (DAI) modules in the EMS workstation and Electrodynamometer Modules, connect the circuit shown in Figure 11.8.
DO NOT APPLY **POWER AT THIS TIME!**
   Notice that the motor is wired for shunt field operation and is connected to the variable dc output of the power supply (terminals 7 *and N).* The electrodynamometer is connected to the fixed 120 V ac output of the power supply.
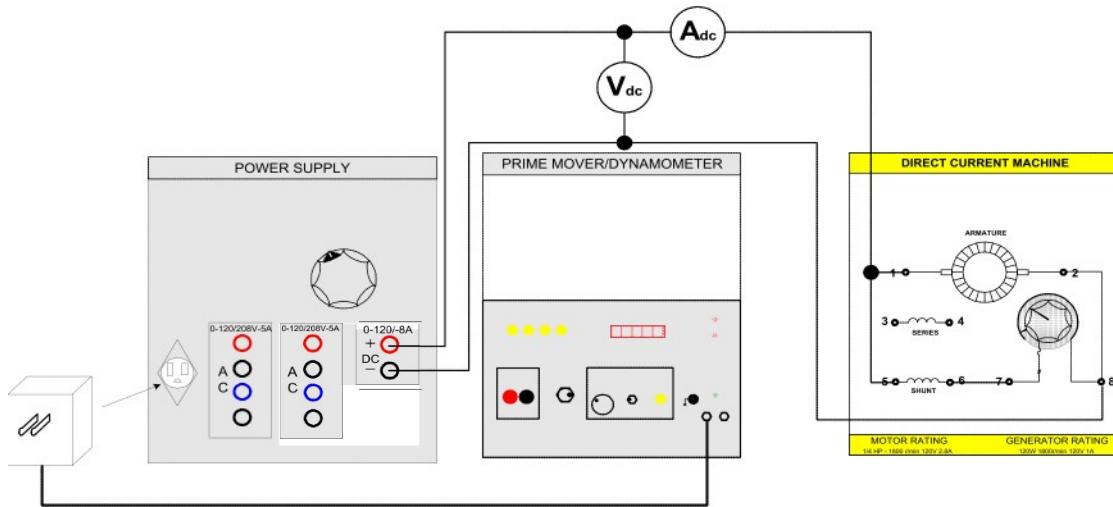
FIGURE 11.8

   Couple the dynamometer to the dc motor/generator with the timing belt as shown in the Figure.

Step 2: Set the shunt field rheostat control knob at its full cw position (for maximum shunt field excitation). Make sure the brushes are in their neutral position.

Step 3: Set the dynamometer control knob at its full ccw position (to provide a minimum-starting load for the dc motor).

Step 4: Turn on the power supply. Adjust the variable output voltage to 120dc as indicated by the meter. Note the direction of rotation; if it is not clockwise, turn off the power supply and interchange the shunt field connections.

Step 5: a) Adjust the shunt field rheostat for a *no-load* motor speed of *7800* r/min as indicated on your hand tachometer. (Make sure that the voltmeter, connected across the input of your circuit, indicates exactly 120Vdc).

> **NOTE: Do not** change the field rheostat **adjustment for** the **remainder** of the experiment.

b) Measure the line current, as indicated by the ammeter, for a motor speed of 1800 *r/min.* Record this value in Table 11-1.

> **NOTE: For an exact torque of 0lbf.in, uncouple the motor** from the dynamometer.

Step 6: a) Apply a load to your dc motor by varying the dynamometer control knob until the scale marked on the stator housing indicates 3lbf.in. (Readjust the power supply, if necessary, to maintain exactly 120Vdc/.

b) Measure the line current and motor speed. Record these values in Table 11-1.

c) Repeat for each of the torque values listed in the Table, while maintaining a constant 120Vdc input.

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

Step 7: a) Plot the recorded motor speed values from *Table 11-1* on the graph of FIGURE 11.9.

b) Draw a smooth curve through your plotted points.

c) The completed graph represents the *speed ve. Torque* characteristics of a typical dc shunt-wound motor. Similar graphs for series wound and compound wound dc motors will be constructed in the following two Laboratory Experiments. The *speed vs. Torque* characteristics for each type of motor will then be compared and evaluated.

Step 8: Calculate the *speed vs. Torque* regulation *(full load — 9lbf ini* using the equation:

$$Regulation - \frac{(no \quad load \quad speed) - (\ [ull \quad load\_speed \ )}{(full \quad load \quad speed)} \times 100$$

Step 9: Set the dynamometer control knob at its full cw position (to provide the maximum starting load for the shunt-wound motor).

Step 10: a) Turn on the power supply and gradually increase the dc voltage until the motor is drawing 3 amperes of line current. The motor should turn very slowly or not at all.

b) Measure and record the dc voltage and the torque developed.

E =_____V   torque_____lbf in

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

Step 11: a) The line current in step 10 is limited only by the equivalent dc resistance of the shunt-wound motor.

b) Calculate the value of the starting current if the full line voltage (120Vdc.) were applied to the shunt-wound dc motor.

Starting current =_____A

E	I	SPEED	TORQUE
(Volts)	(Amps)	(R/min)	(Lbf,in)
120			0
120			3
120			6
120			9
120			12

TABLE 11-1

Torque (lbf¼n)
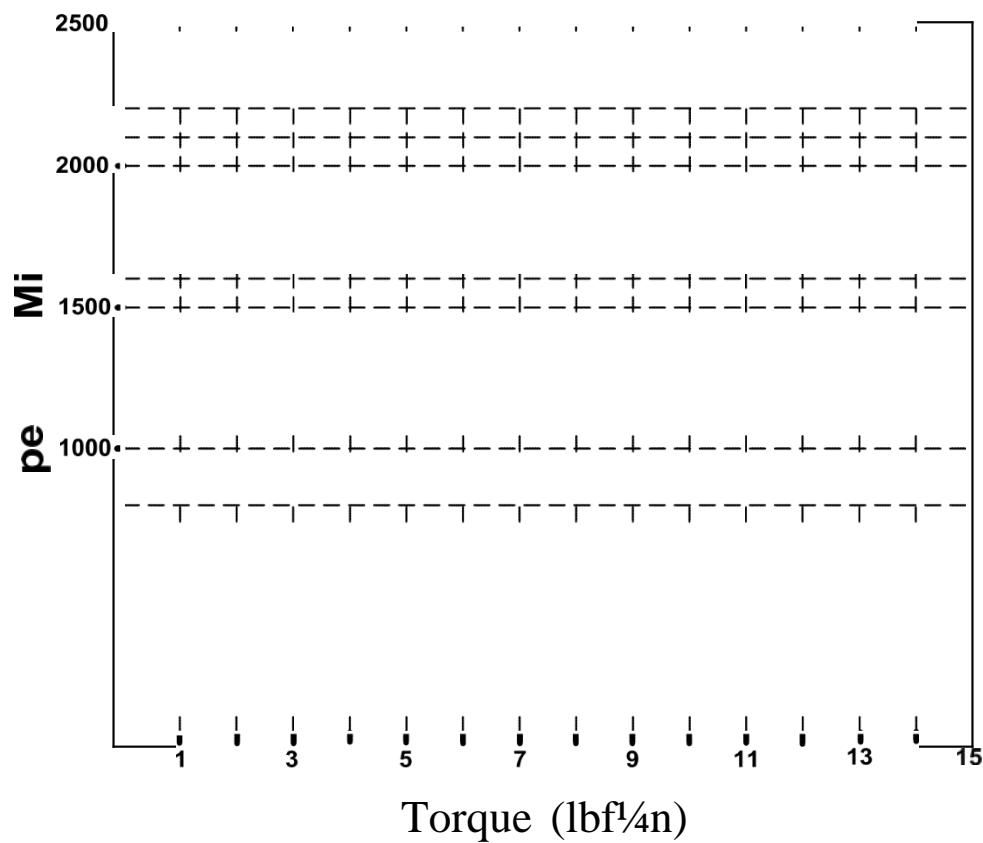
Figure 11.9

EXPERIMENT **11.2 DC** SERIES MOTOR

REQUIRED EQUIPMENT

Power Supply Module (120Vac, 0-120Vdc)	EMS 8821
DC Motor/Generator Module	EMS 8211
Electrodynamometer Module	EMS 8911
Hand Tachometer	EMS 8920
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1: Using your EMS Power Supply, DC Motor/ Generator, the Data Acquisition Interface (DAI) modules in the EMS workstation and Electrodynamometer Modules, connect the circuit shown in Figure 11.10.

DO NOT APPLY **POWER AT THIS TIME!**

FIGURE 11.Ill

Notice that the motor is wired for *series* operation *bthe shunt field winding and the rheostat are not used)* and is connected to the variable dc output of the power supply (terminals 7 *and NI.* The electrodynamometer is connected to the fixed 120 V ac output of the power supply. Couple the dynamometer to the dc motor/generator with the timing belt as shown in the figure.

Step 2: Set the dynamometer control knob at its mid-range position (to provide a starting load for the dc motor).

Step 3: a) Turn on the power supply. Gradually increase the dc voltage until the motor starts to turn. Note the direction of rotation. If it is not cw, turn off the power and interchange the series field connections.

b) Adjust the variable voltage for exactly 120Vdc as indicated by the meter.

Step 4: a) Adjust the loading of your dc series wound motor by varying the dynamometer control knob until the scale marked on the stator housing

indicates *l2lbf in.* (Readjust the power supply, if necessary, to maintain exactly *120 Vdc).*

b) Measure the line current and motor speed (use your hand tachometer). Record these values in Table 11-2.

c) Repeat for each of the torque values listed in the *Table,* while maintaining a constant *120Vdc* input.

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

NOTE: For an exact **torque of 0lbf.in, uncouple the motor from the** dynamometer.

Step 5: a) Plot the recorded motor speed values from Table 11-2 on the graph of Figure 11.11.

b) Draw a smooth curve through your plotted points.

c) The completed graph represents the speed vs. Torque characteristics of a typical dc series wound motor. A similar graph for the compound wound dc motor will be constructed in the next Laboratory Experiment. The speed vs. Torque characteristics for each type of motor will then be compared and evaluated.

Step 6: Calculate the speed vs. Torque regulation (full load = 9lbf in) using the equation:

$$Regulation - \frac{(no\_load\_speed) - (full\_load\_speed)}{(full\ load\ speed)} * 100$$

Step 7: Set the dynamometer control knob at its full cw position (to provide the maximum starting load for the series wound motor).

Step 8: a) Turn on the power supply and gradually increase the dc voltage until the motor is drawing 3 amperes of line current. The motor should turn slowly.

b) Measure and record the dc voltage and the torque developed.

E=_____V   torque_____in

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

Step 9:a) The line current in step 8 is limited only by the equivalent dc resistance of the series-wound motor.

b) Calculate the value of the starting current if the full line voltage (120Vdc.) were applied to the shunt-wound dc motor.

Starting current =_____A

E (Volts)	I (Amps)	SPEED (R/min)	TORQUE (Lbf.in)
120			0
120			3
120			6
120			9
120			12

TABLE 11-2
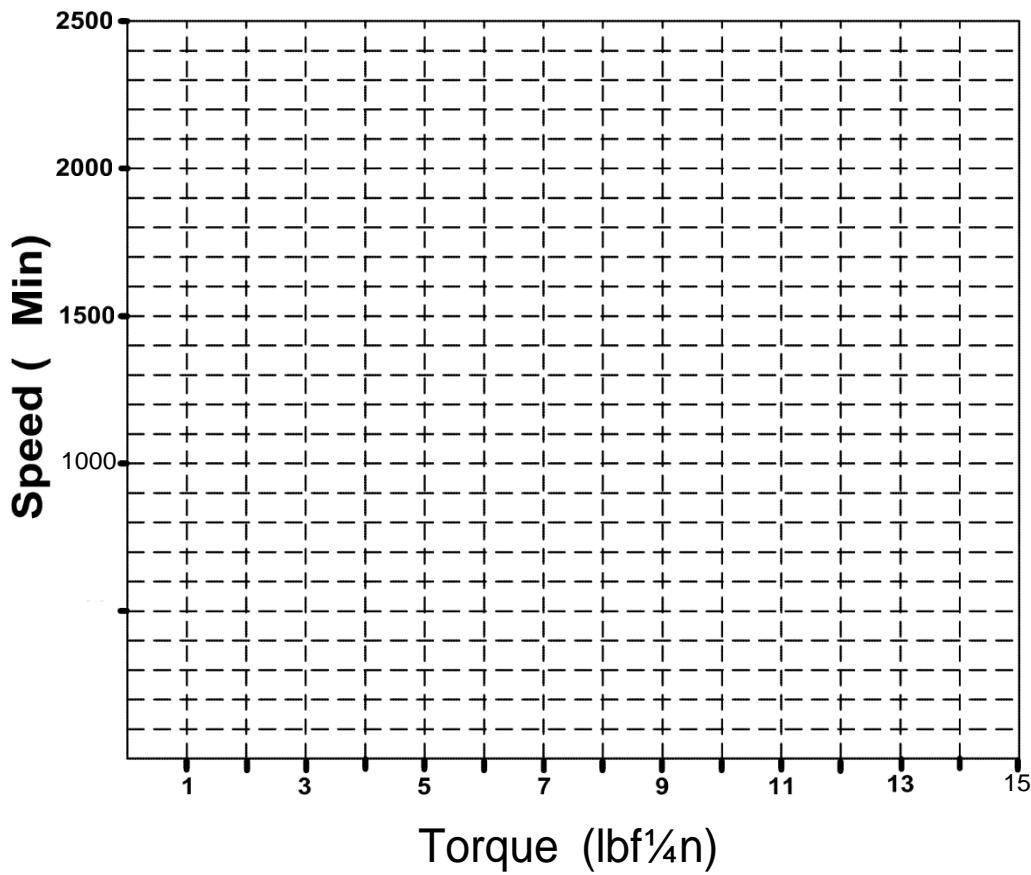
FIGURE II.11

EXPERIMENT 11.3 DC COMPOUND MOTOR

REQUIRED EQUIPMENT

Power Supply Module (120Vac, 0-120Vdc)	EMS 8821
DC Motor/Generator Module	EMS 8211
Electrodynamometer Module	EMS 8911
Hand Tachometer	EMS 8920
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1: Using your EMS Power Supply, DC Motor/ Generator, the Data Acquisition Interface (DAI) modules in the EMS workstation and Electrodynamometer Modules, connect the circuit shown in Figure 11.12.
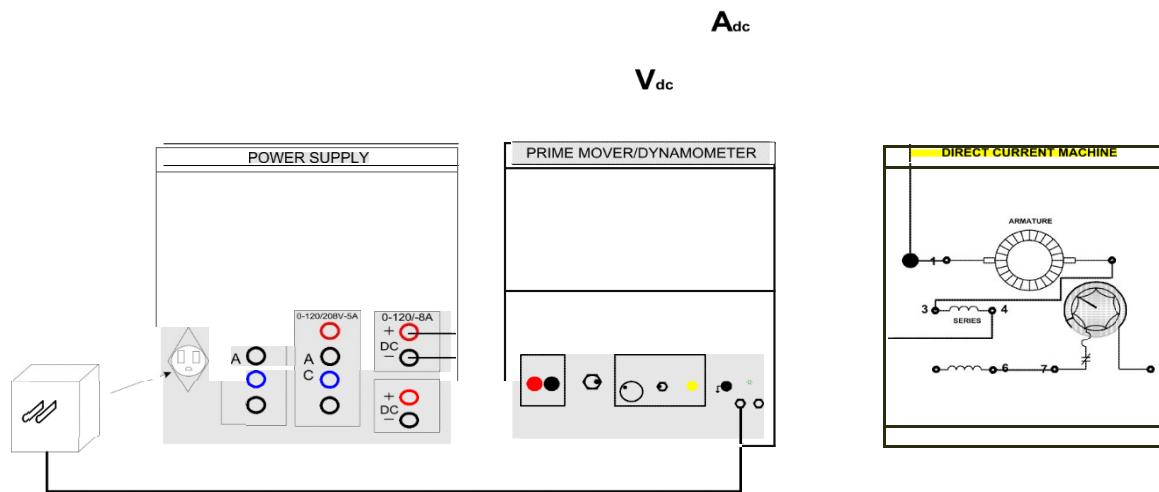
FiGURE 11.12
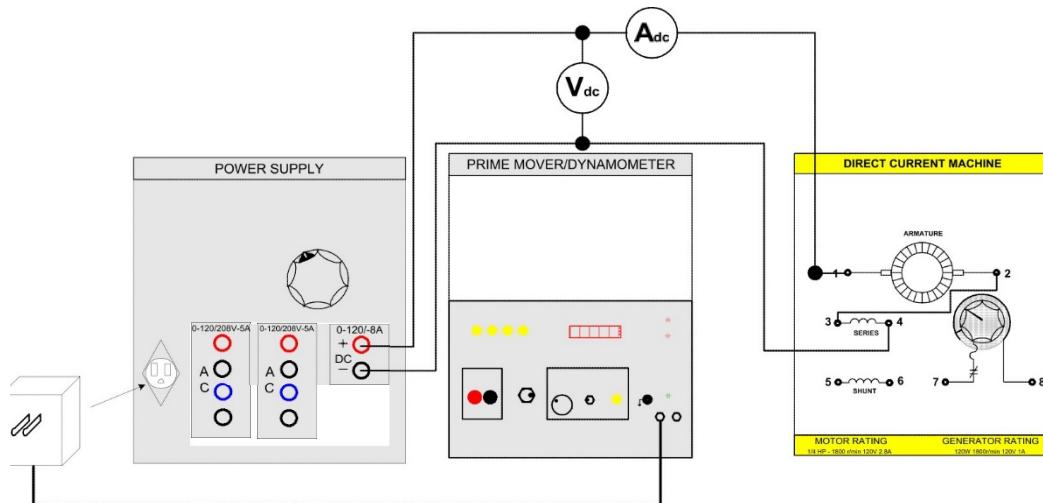
DO NOT APPLY **POWER AT THIS TIME!**

Notice that the motor is wired for series operation (the shunt field winding and the rheostat not in the circuit as yet), and is connected to the variable dc output of the power supply (terminals 7 and N). The electrodynamometer is connected to the fixed 120Vac output of the power supply (terminals 1 and N).

Couple the dynamometer to the dc motor/generator with the timing belt as shown in the figure.

Step 2: Set the shunt field rheostat control knob at its full cw position (for maximum shunt field excitation). Make sure the brushes are in their neutral position.

Step 3: a) Turn on the power supply. Gradually increase the dc voltage until the motor starts to turn. Note the direction of rotation. If it is not cw turn off the power and interchange the series field connections.

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

Step 4: Connect the shunt field, in series with the rheostat, to terminals 1 and 4 as shown in Figure 11.13.

Direct Current Motor Operation and Control
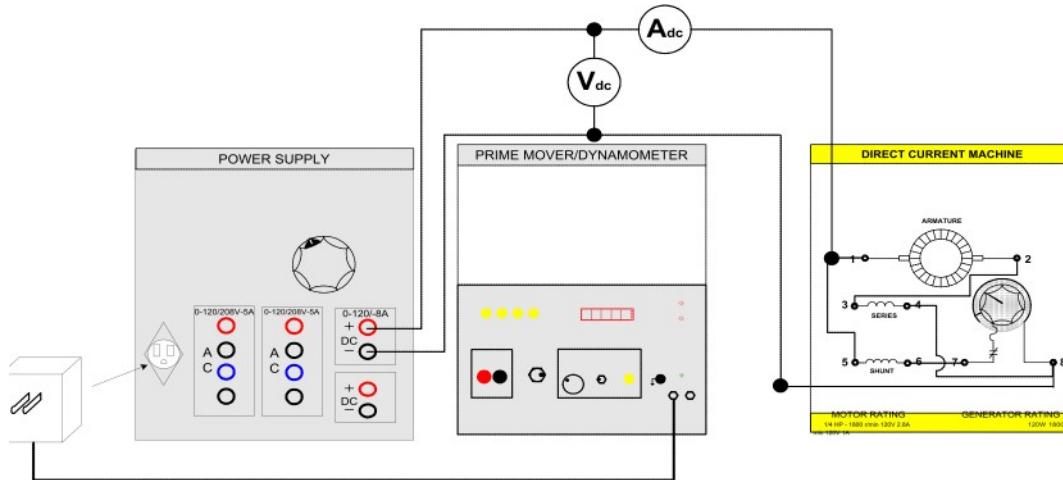
FIGURE 11.13

Step 5: Turn on the power supply. Adjust the voltage for 120Vdc. as indicated by the meter. If the motor is running at an excessively high speed then it is in the differential-compound mode. If this is the case, return the voltage to zero and turn off the power supply. Interchange the shunt field connections to terminals 1 and 4 to obtain the cumulative-compound mode of operation.

Step 6: With the input at exactly 120Vdc adjust the shunt field rheostat for a no-load motor speed of 1800 r/min as indicated by your hand tachometer.

> **NOTE: Do not** change the field rheostat adjustment for the remainder of the experiment.

Step 7: a) Apply a load to your dc motor by varying the dynamometer control knob until the scale marked on the stator housing indicates 3lbf in. (Readjust the power supply, if necessary, to maintain exactly 120Vdc/.

   b) Measure the line current and motor speed. Record these values in Table 11-3.

   c) Repeat for each of the torque values listed in the Table, while maintaining a constant 120Vdc input.

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

> **NOTE: For** an exact **torque of 0lbf.in, uncouple** the motor from the dynamometer.

Step 8: a) Plot the recorded motor speed values from Table 11-3 on the graph of Figure 11.14.

   b) Draw a smooth curve through your plotted points.

   c) The completed graph represents the speed vs. torque characteristics of a typical dc compound wound motor.

Step 9: Calculate the *speed ve. torque* regulation (full load = 9lbf in) using the

equation: $regulation - \dfrac{(no\ load\ speed) - (full\ load\ speed)}{(full\ load\ speed)} \times 100$

Step 10: Set the dynamometer control knob at its full cw position (to provide the maximum starting load for the compound wound motor).

Step 11: a) Turn on the power supply and gradually increase the dc voltage until the motor is drawing 3 amperes of line current. The motor should turn very slowly or not at all.

b) Measure and record the dc voltage and the torque developed.

E=_____V   torque =_____Lbf in

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

Step 12: a) The line current in step 10 is limited only by the equivalent dc resistance of the equivalent dc resistance of the compound wound motor.

b) Calculate the value of the starting current if the full line voltage (120Vdc.) were applied to the shunt-wound dc motor.

Starting current =_____A

E (Volts)	I (Amps)	SPEED (R/min)	TORQUE (Lbf.in)
120			0
120			3
120			6
120			9
120			12

Table **11-3**
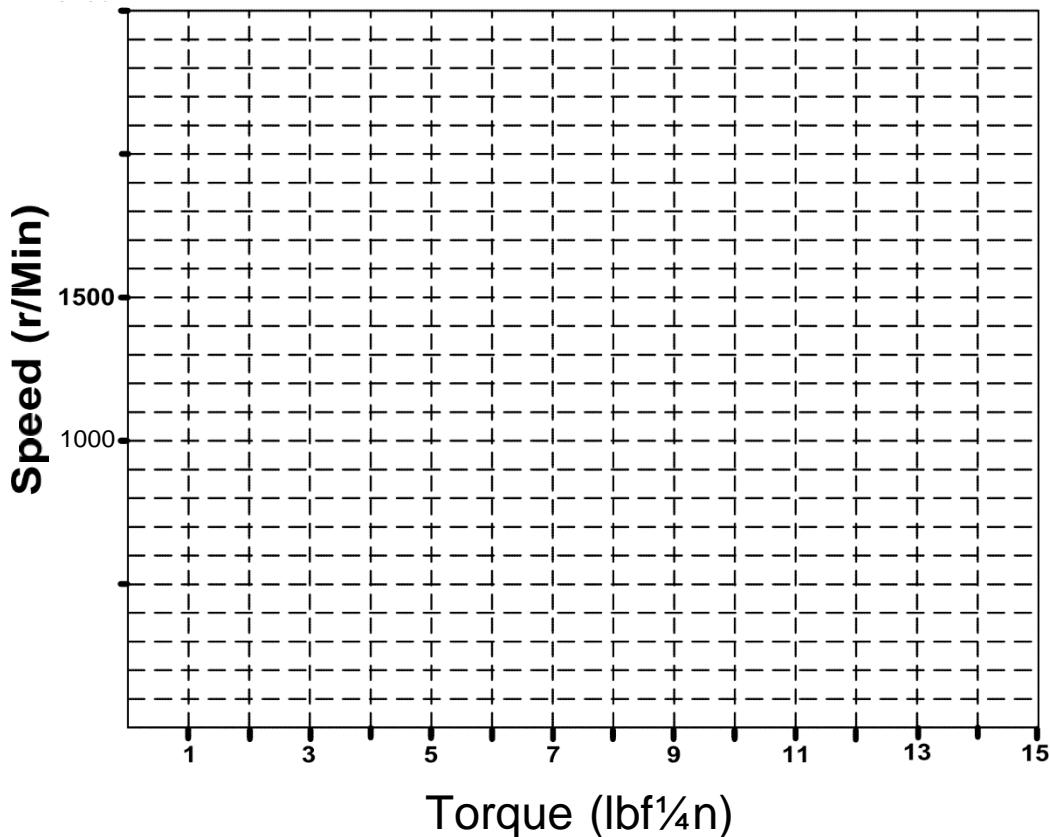
FiCURE 11.14

Report Recommendation

1. Calculate the maximum starting current that would appear in each motor from your data. Show your calculations
2. Plot the load speed characteristic of all motors in a single graph. Do not suppress the zero in the graph.
3. Relate briefly the relationship between speeds, power and back e.m.f.
4. Which motor is the most efficient at full load? Show the calculations that prove your response. Explain why it is the most efficient by a brief analysis.
5. Compare the series motor with the universal. List all the advantages and disadvantages of the series dc motor with respect of the single-phase universal motor. Look up in your textbook if necessary when doing this comparison.

LABORATORY SESSION XII

DIRECT CURRENT GENERATORS

OBJECTIVES

The main purpose of this laboratory session is to observe the saturation curve of dc generators, to observe their characteristics curves (terminal voltage vs. load current) in different types of connection and to learn how to connect the different dc generators configurations.

The specific objectives of this lab session are:
1) To study the properties of the separately excited, the shunt, the series, the differential compound, and additive compound dc generators under no-load and full-load condition.
2) To obtain the saturation curve of the generator.
3) To learn how to connect the different dc generators.
4) To obtain the armature voltage vs. armature current load curve of the dc generators.

REFERENCES
1) Guru, B.S. and Hiziroglu, H.R. *Electric machinery and transformers,* 3 ed. Oxford University Press, 2001.

INTRODUCTION

DC Separately Excited Generator

A DC machine can run either as a motor or as a generator. A motor converts electrical power into mechanical power while a generator converts mechanical power into electrical power. A generator must, therefore, be mechanically driven in order that it may produce electricity.

Since the field winding is an electromagnet, current must flow through it to produce a magnetic field. This current is called the excitation current, and can be supplied to the field winding in one of two ways; it can come from a separate, external dc source, in which case the generator is called a separately excited generator; or it can come from the generator's own output, in which case the generator is called a self-excited generator.

Assume that the shunt field is excited by a dc current, thereby setting up a magnetic flux in the generator. If the rotor (or more correctly, the armature) is rotated by applying mechanical effort to the shaft, the armature coils will cut the magnetic flux, and a voltage will be induced in them. This voltage is ac and in order to get dc out of the generator, a rectifier must be employed. The commutator and the brushes carry out this role.

The voltage induced in the coils (and, therefore, the dc voltage at the brushes) depends only upon two things-the speed of rotation and the strength of the magnetic field. If the speed is doubled, the voltage doubles. If the field strength is increased by 20^0 o, the voltage also increases by 20%.
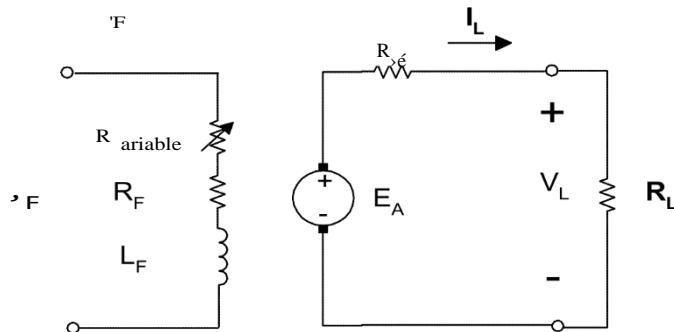
FIGURE 12.1

Although separate excitation requires a separate dc power source, it is useful in cases where a generator must respond quickly and precisely to an external control source, or when the output voltage must be varied over a wide range.

With no electrical load connected to the generator, no current flows and only a voltage appear at the output. But if a resistance load is connected across the output, current will flow and the generator will begin to deliver electric power to the load.

The machine that drives the generator must then furnish additional mechanical power to the generator. This is often accompanied by increased noise and vibration of the motor and the generator, together with a drop in speed.

DC Shunt Generator

The separately excited generator has many applications. However, it does have the disadvantage that a separate direct current power source is needed to excite the shunt field. This is costly and sometimes inconvenient; and the self-excited dc generator is often more suitable.

In a self-excited generator, the field winding is connected to the generator output. It may be connected across the output, in series with the output, or a combination of the two. The way in which the field is connected (shunt, series or compound) determines many of the generator's characteristics.
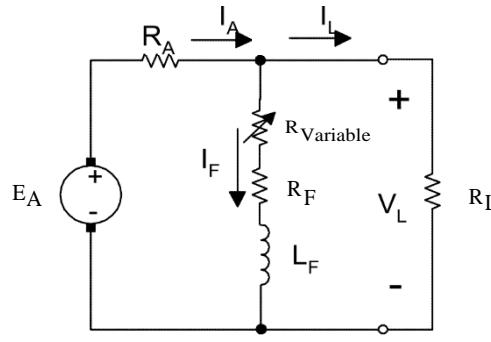
FIGURE 12.2

All of the above generators can have identical construction. Self-excitation is possible because of the residual magnetism in the stator pole pieces. As the armature rotates a small voltage is induced across its windings. When the field winding is connected in

parallel (shunt) with the armature a small field current will flow. If this small field current is flowing in the proper direction, the residual magnetism will be reinforced which further increases the armature voltage and thus, a rapid voltage build- up occurs.

If the field current flows in the wrong direction, the residual magnetism will be reduced and voltage build-up cannot occur. In this case, interchanging the shunt field leads will correct the situation. It is the purpose of this Laboratory Experiment to show these major points.

De Series Generator

When the field winding is connected in series with the armature winding, the generator is called a series generator. The exciting current through the field winding of a series generator is the same current the generator delivers to the load. See Figure 12.3

If the load has high resistance only a minimum output voltage can be generated because of the minimum field current. On an open circuit, the generator will only have a minimum output voltage due to its residual magnetism. If the load draws current, the excitation current increases, the magnetic field becomes stronger and the generator delivers an output voltage.
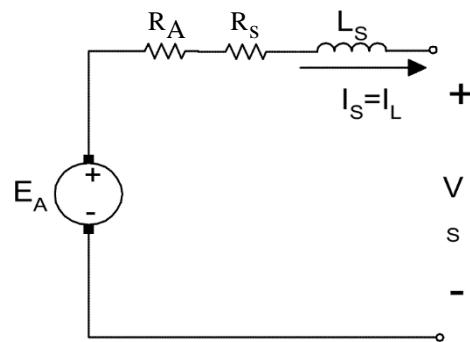
FIGURE 12.3

You can see then that in a series generator, changes in load current greatly affect the generator output voltage. A series generator has very poor voltage regulation and is not recommended for use as a power source.

Series generators have been used on DC distribution systems as line voltage boosters. Consider for example, the circuit shown in Figure 12.4 in which a power source furnishes DC power to the load RL over a transmission line having resistance R .
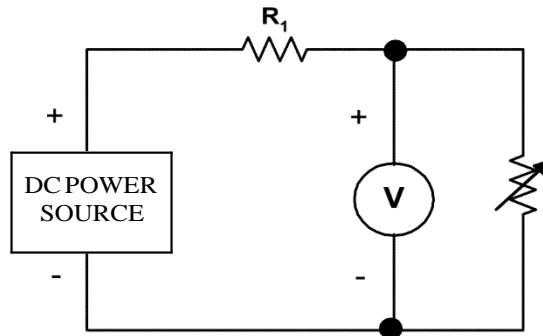
FIGURE 12.4

The load voltage will fluctuate according to whether the line current is large or small. This fluctuating load voltage can be corrected by inserting a series generator in the line as shown in Figure 12.5. As the load current increases, the generator voltage VG increases, compensating for the voltage drop across the transmission line resistance RI, thereby maintaining a relatively constant voltage across the varying loads.
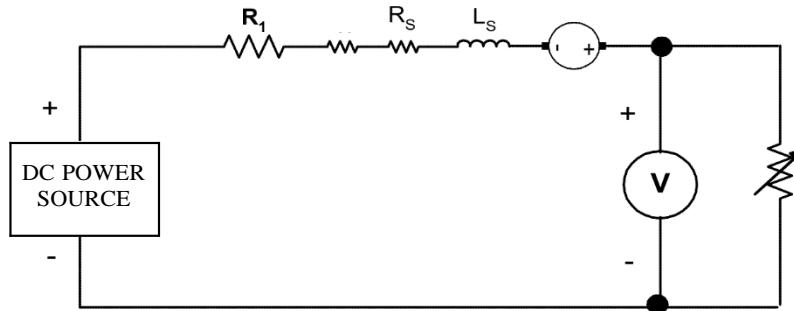
FIGURE 12.5

De Compound Generator

Self-excited shunt generators have the disadvantage in that changes in their load current from no-load to full-load cause their output voltage to change also. Their poor voltage regulation is due to three factors:

a) The magnetic field strength drops as the armature voltage drops, which further reduce the magnetic field strength, which in turn reduces the armature voltage etc.

b) The armature voltage drop (I'R losses) from no-load to full-load.

c) The running speed of the driving motor may change with load. (This is particularly true of internal combustion engines and induction motors).

(a)   (b)
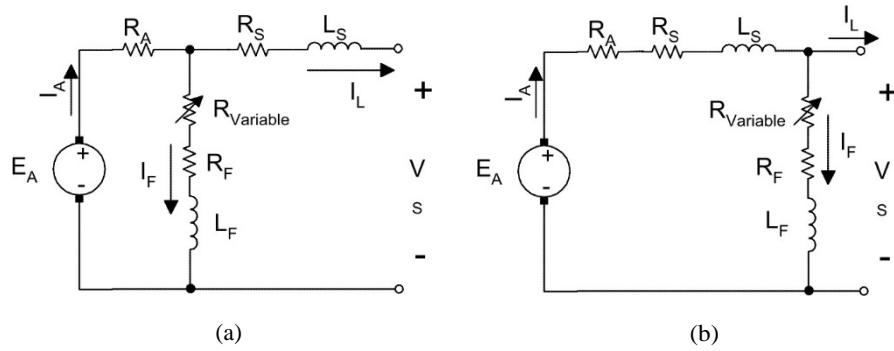
FIGURE 12.6

The two field windings (shunt and series) on the compound generator are connected so that their magnetic fields aid each other. Thus, when the load current increases, the current through the shunt field winding decreases, reducing the strength of the magnetic field. But, if the same increase in load current is made to flow through the series field winding, it will increase the strength of the magnetic field. With the proper number of turns in the series winding, the increase in magnetic strength will compensate for the decrease caused by the shunt winding. The combined magnetic field strength remains almost unchanged and little change in output voltage will take place as the load goes

from no-load to full-load. If the series field is connected so that the armature current flows in such a direction as to oppose the shunt field, we obtain a differential compound generator. This type of generator has poor regulation, but is useful in applications such as welding and arc lights where maintaining a constant output current is more important than a constant output voltage. It is the purpose of this Laboratory Experiment to show these major points.

PRELAB

1. If the no-load voltage of a separately excited generator is 125V at 900 rpm, what will be the voltage if the speed is increased to 1200 r/min.
2. Figure 12.7 shows the no-load saturation curve of a separately excited dc generator when revolves at 1500 rpm. Calculate the exciting current needed to generate 120 V at 1300 rpm.

Saturation Curve of a DC Generator
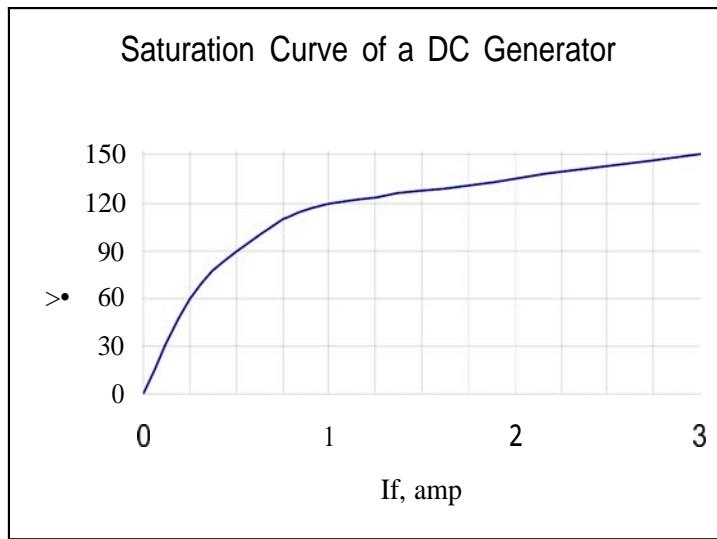
FIGURE 12.7

3. If the generator of problem 2 has a shunt field resistance of 60 ohms and the rated current of SA, calculate at a speed of 1400 rpm and rated voltage:
   a. The rated armature current when connected as a shunt generator.
   b. The voltage induced in the armature.
   c. The output power and torque developed neglecting the windage and fiction losses.

EXPERIMENT **12.1 DC** SEPARATELY EXCITED GENERATOR

REQUIRED EQUIPMENT

Power Supply Module
    (120/208V 3$, 120 Vdc, 0-120Vdc)   EMS 8821
DC Motor/Generator Module   EMS 8211
Synchronous Motor/Generator Module   EMS 8241
Resistance Module   EMS 8311
Connection Leads   EMS 8941
Timing Belt   EMS 8942

PROCEDURE

NO LOAD CHARACTERISTICS

Step 1: Because of its constant running speed, the synchronous motor will be used to mechanically drive the dc generator. Using your EMS Power Supply, the Data Acquisition Interface (DAI) modules in the EMS workstation and Synchronous Motor Modules, connect the circuit shown in Figure 12.8.

DO NOT APPLY POWER AT THIS TIME!
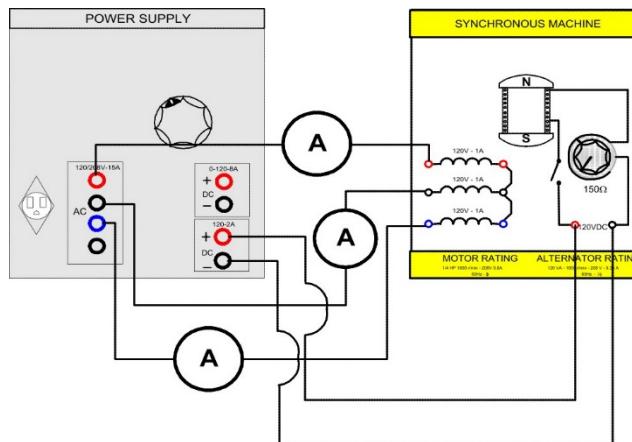
FIGURE 12.8

Step 2: Terminals 1, 2 and 3 on the power supply provide fixed three-phase power for the three-stator windings. Terminals 8 and N on the power supply provide fixed dc power for the rotor winding. Set the rheostat control knob to its proper position for normal excitation. The normal position of the rheostat is that by controlling the DC excitation, the stator currents are at their minimum values.

Step 3: a) Using your EMS DC Motor/Generator and the Data Acquisition Interface (DAI) modules in the EMS workstation, connect the circuit shown in Figure 12.9.
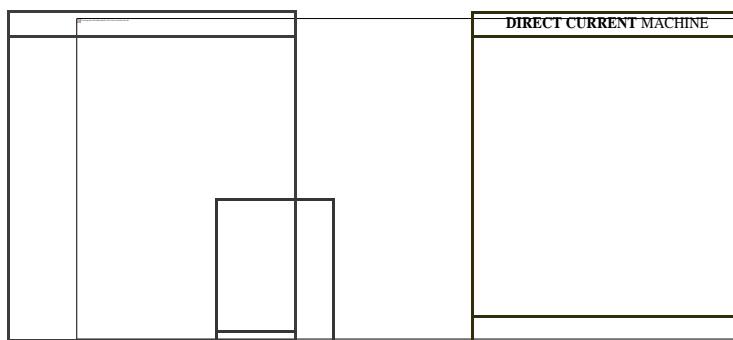
FIGURE 12.9

b) Connect the shunt field of the generator, terminals 5 and 6, to the variable dc output of the power supply, terminals 7 and N, while connecting the 500mA meter in series with the positive lead.

c) Connect the 200Vdc meter across the generator output (armature terminals 1 and 2).

d) Couple the synchronous motor and the dc generator with the timing belt.

e) Make sure the brushes are in their neutral position.

I) Have your instructor check your circuit.

Caution: The switch in the excitation circuit of the synchronous motor should be closed (up position) only when the **motor is running.**

Step 4: a) Turn on the power supply. The synchronous motor should start running.

b) If the synchronous motor has switch S, close it at this time.

c) Vary the shunt field current I_F by rotating the voltage control knob on the power supply. Note the effect on the generator output (armature voltage) E_A as indicated by the 200 Vdc meter.

d) Measure and record in Table 12-1 the armature voltage E_A for each of the listed field currents.

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

II Can you explain why there is an armature voltage even when the field current is zero?

Step 5: a) Reverse the polarity of the shunt field by interchanging the leads to terminals 5 and 6 on the dc generator.

b) Turn on the power supply and adjust for a field current I_F of 300mAdc.

c) Did the armature voltage reverse its polarity?

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

Step 6: a) Interchange the leads to the 200Vdc meter.

b) Turn on the power supply and adjust for a field current I_F of 300mAdc.

c) Measure and record the armature voltage.

$$E_A=\underline{\hspace{3cm}}Vdc$$

d) Is the armature voltage approximately the same as in Procedure 4 (at an I_F of 300mA), except for reversed polarity?

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

Step 7: a) Reverse the rotation of the driving motor by interchanging any two of the stator lead connections (terminals 1, 2 or 3) to the synchronous motor.

b) Turn on the power supply and adjust for a field current IF of 300mAdc,

c) Did the armature voltage reverse its polarity?

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

Step 8: a) Interchange the leads to the 200Vdc meter.

b) Turn on the power supply and adjust for a field current I_F of 300mAdc.

c) Measure and record the armature voltage.

E_A _____ Vdc

d) Is the armature voltage approximately the same as in Procedure 4 (at an I_F of 300mA), except for reversed polarity?

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

LOAD CHARACTERISTICS

Step 9: Using your EMS Resistance Module, connect the circuit shown in Figure 12.10. Place the resistance switches so that the total load resistance is 120 ohms.
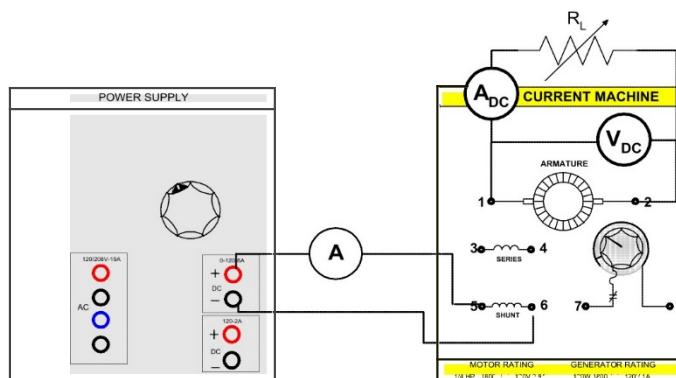
FIGURE 12.10

Step 10: a) Turn on the power supply. The synchronous motor should start running.

b) Adjust the shunt field current I_F until the generator is delivering an output voltage of 120Vdc. The ammeter I_A should indicate lAdc.

c) Record the shunt field current

I _____ mA.

This is the nominal I_F at the rated power output (120V x IA = 120W) of the dc generator.

Step 11: a) Adjust the load resistance to obtain each of the values listed in Table 12-2 while maintaining the nominal I_F ×alue found in step 10.

b) Measure and record E_A «nd I_A for each of the resistance values listed in the Table 12-2.

NOTE: **Although the nominal, output current rating of the** generator is lAdc, it **may be loaded up to 1.5Adc (50% overload) without harm.**

Step 12: a) With the load resistance adjusted for an output current I_A of 1.EA, turn the field current I_F on and off by removing the connecting lead from terminal 6 of the dc generator.

b) Do you notice that the driving motor is obviously working harder when the generator is delivering power to the load?

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

Step 13: Calculate and record the power for each of the values listed in Table 12-2

Step 14: a) Place a dead short across the armature (terminals 1 and 2).

b) Make sure that the power supply voltage control knob is turned down for zero field current.

c) Turn on the power supply.

d) Gradually increase the field current I_F until the motor stalls.

Caution: Do not leave the motor in the stalled condition for more than a couple of seconds.

e) What value of shunt field current I, is needed to stall the motor?

I_F _____

I) Turn off the power supply.

NOTE: With a short-circuit across the armature, its current becomes very **large; this produces** a strong braking effect sufficient to **stall the driving motor.**

Can you explain why there is an armature voltage even when the field current is zero?

Record the armature voltage. E_A _____Vdc

Is the armature voltage approximately the same as in Procedure 4 (at an I_F of 300mA), except for reversed polarity?

Did the armature voltage reverse its polarity?

Record the shunt field current I_F _____ A.

What value of shunt field current I_F is needed to stall the motor? I, _____mA

If (Milliamperes)	E_A (Volts)
0	
50	
100	
150	
200	
250	
300	
350	
400	

TABLE 12-1

R (Ohms)	I$_A$ (Amps)	E$_A$ (Volts)	Power (Watts)
600			
300			
200			
150			
120			
100			
80			
75			

Table 12-2

EXPERIMENT **12.2 DC** SHUNT GENERATOR

REQUIRED EQUIPMENT

Power Supply Module (120/208V 3$, 120Vdc, 0-120Vdc).	EMS 8821
DC Motor/Generator Module	EMS 8211
Synchronous Motor/Generator Module	EMS 8241
Resistance Module	EMS 8311
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Step 1: Because of its constant running speed, the synchronous motor will be used to mechanically drive the dc generator. Using your EMS Power Supply, the Data Acquisition Interface (DAI) modules in the EMS workstation and Synchronous Motor Modules, connect the circuit shown in Figure 12.8. **DO NOT APPLY POWER AT THIS TIME!**

Step 2: Terminals 1, 2, *and* 3 on the power supply provide fixed three-phase power for the three-stator windings. Terminals 8 and N on the power supply provide fixed dc power for the rotor winding.

Set the rheostat control knob to its proper position for normal excitation.

Step 3: a) Using your EMS DC Motor/Generator, the Data Acquisition Interface (DAI) modules in the EMS workstation and Resistance Modules, connect the circuit shown in Figure 12.11.

FiGURE 12.11

b) Couple the synchronous motor and the dc generator with the timing belt.

c) Turn the dc generator field rheostat control knob full cw for minimum resistance.

d) Make sure the brushes are in their neutral position.

e) Place the resistance switches for no-load (all switches open).

Step 4: a) Turn on the power supply. The synchronous motor should start running.

b) If the synchronous motor has switch S, close it at this time.

c) Note if voltage E_A builds up.

d) If not, turn off the power supply and interchange the shunt field leads at terminals 5 and 6.

e) Measure the open circuit armature voltage.

EA'_____Vdc

Step 5: Vary the field rheostat and notice if the armature voltage E_A changes. Explain

Step 6: a) Place the resistance switches so that the total load resistance is 120 ohms. Adjust the field rheostat until the generator is delivering an output voltage of 120Vdc. The ammeter I_A should indicate lAdc.

b) This is the correct setting of the field rheostat control for the rated power output (120 V x 1A = 120W) of the dc generator.

Do not touch the field **rheostat control for** the remainder of the Laboratory Experiment!

Step 7: a) Adjust the load resistance to obtain each of the values listed in Table 12-3.

b) Measure and record E_A «nd I_A for each of the resistance values listed in the Table 12-3.

NOTE: **Although the nominal output current rating of the generator is** 1 Adc, it **may be loaded up to lAdc (50% overload) without** harm.

c) Turn off the power supply.

d) Calculate and record the power for each of the resistances shown in Table 12-3.

Step 8: a) Reverse the rotation of the driving motor by interchanging any two of the stator lead connections (terminals 1, 2, or 3) to the synchronous motor.

b) Remove the generator load by opening all of the resistance switches.

c) Turn on the power supply.

d) Does the generator voltage build up? Explain

e) Turn off the power supply.

Record the open circuit armature voltage. E_A _____Vdc

Explain why varying the field rheostat the armature voltage E_A changes.

RL (OHMS)	IA (AMPS)	EA (VOLTS)	POWER (WATTS)
600			
300			
200			
150			
120			
100			
80			
75			

Table **12-3**

EXPERIMENT 12.3 DC SERIES GENERATOR

REQUIRED EQUIPMENT

Power Supply Module
    (120/208V, 3$, 120Vdc, 0-120Vdc)   EMS 8821
DC Motor/Generator Module   EMS 8211
Synchronous Motor/Generator Module   EMS 8241
Resistance Module (2)   EMS 8311
Connection Leads   EMS 8941
Timing Belt   EMS 8942

PROCEDURE

Step 1: Because of its constant running speed, the synchronous motor will be used to mechanically drive the dc generator. Using your EMS Power Supply, the Data Acquisition Interface (DAI) modules in the EMS workstation and Synchronous Motor Modules, connect the circuit shown in Figure 12.8.
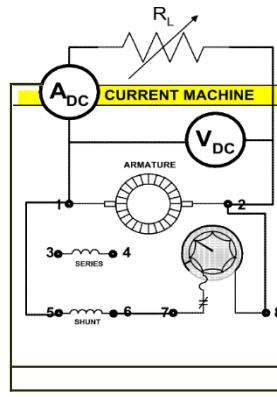
DO NOT APPLY POWER AT THIS TIME!

Step 2: Terminals 1, 2, and 3 on the power supply provide fixed three-phase power for the three-stator windings. Terminals 8 and N on the power supply provide fixed dc power for the rotor winding.

Set the rheostat control knob to its proper position for normal excitation.

Step 3: a) Using your EMS DC Motor/Generator, DC Metering and Resistance Modules, connect the circuit shown in Figure 12.12.
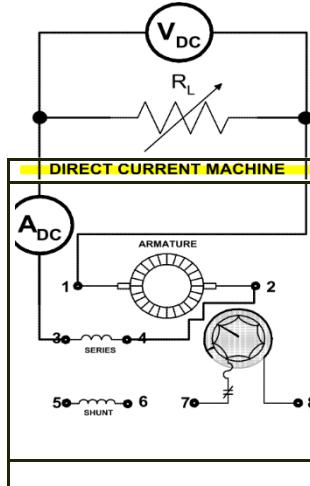
FiGURE 12.12

b) Couple the synchronous motor and the dc generator with the timing belt.
c) Make sure the brushes are in their neutral position.
d) Place the resistance switches for no-load (all switches open).

Caution: The switch in the excitation circuit of the synchronous motor should be closed (up position) only when the motor **is running.**

Step 4: a) Turn on the power supply. The synchronous motor should be running.
b) If the synchronous motor has switch S, close it at this time.
c) Measure the generator output voltage across the open load circuit.

E_A _____ Vdc

d) To what do you attribute this open circuit voltage?

Step 5: a) Place a 28.5ohm load in the circuit by closing all of the resistance switches on both resistance modules and note whether E_A increases.
b) If not, turn off the power supply and interchange the series field leads at terminals 3 and 4.

Step 6 a) Adjust the load resistance to obtain each of the values listed in *Table* 12-4. (Use the Parallel Equivalent Resistance Table on Appendix F, remembering that you now has two resistance modules in parallel).
b) Measure and record E_A and I_A for each of the resistance values listed in the Table 12.4.

NOTE: Although the nominal output current rating of the **generator is** I Adc, it may be loaded up to I.5Adc **(50% overload) without harm.**

c) Turn off the power supply.
d) Calculate and record the power for each of the resistances shown in Table 12-4.

OPTIONAL EXPERIMENT

NOTE: If time permits, the following experiment on the use of a series generator as a voltage regulator, may be performed. You will have to borrow another Resistance Module from your neighbor.

Step 7: a) Connect the circuit shown in Figure 12.13. (Disconnect the synchronous motor from the power supply but do not uncouple the motor from the generator).
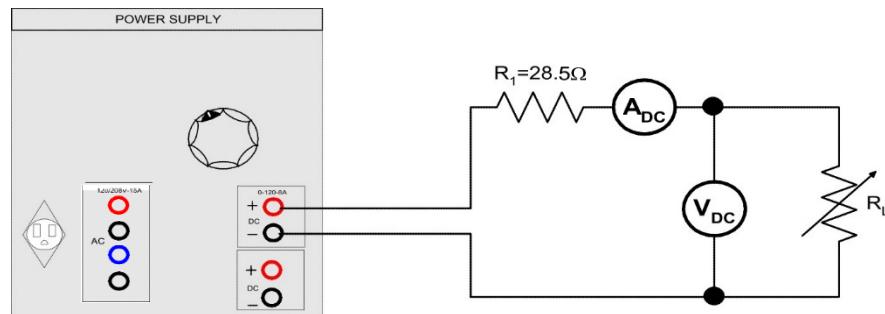
FICURE **12.13**

b) Adjust R1 (which represents the transmission line resistance) to 28.5 ohms by closing all of the switches on the paralleled resistance modules.

Step 8: a) Turn on the power supply and adjust for 120Vdc as indicated by the voltmeter V1

b) Adjust the load resistance R_L þthe third resistance module) to obtain each of the values listed in Table 12-5.

c) Measure and record V2 and I for each of the values listed in the Table.

Be sure to check your 120Vdc input voltage prior to each measurement.

d) Return the voltage to zero and turn off the power supply

Step 9: What are your comments about the voltage regulation at the load R_U

Step 10: a) Connect your series generator in the circuit as shown in Figure 12.14.

b) Connect the synchronous motor to the power supply.
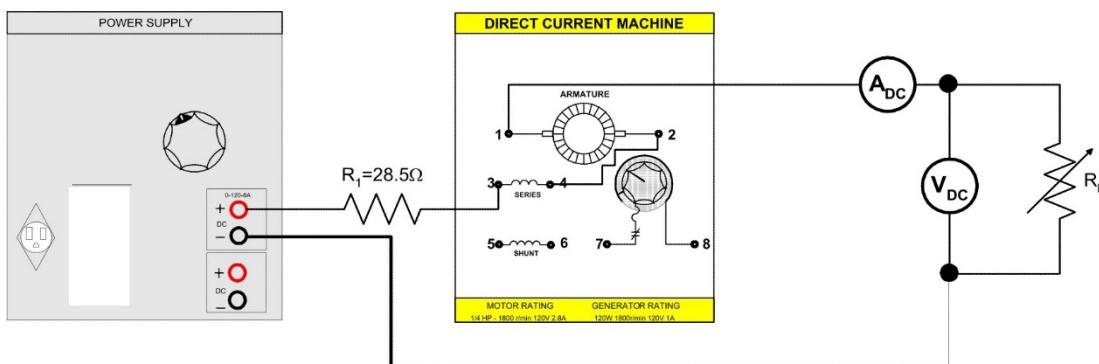
FICURE 12.14

Step 11: a) Turn on the power supply. The motor should be running.

b) Adjust the supply voltage V   so that the load voltage V2 is equal to 120Vdc at no load.

c) Repeat step 8 but enter your results in Table 12-6. Be sure that the supply voltage Vi remains the same prior to each measurement.

NOTE: If the change in load voltage V   is greater than in step 8, turn **off the power supply and interchange the connections to the** series l"ield **winding (terminals** 3 and 4).

Step 12: Compare the voltage regulation with and without the addition of the series generator.

Record the generator output voltage across the open load circuit.

E_A _____Vdc

To what do you attribute this open circuit voltage?

What are your comments about the voltage regulation at the load R_U

Compare the voltage regulation with and without the addition of the series generator.

R_L (Ohms)	I_A (Amps)	E_A (Volts)	Power (Watts)
40			
37.5			
35.3			
31.5			
30.0			
28.5			

TABLE 12-4

R_L (Ohms)	I_A (Amps)	V_2 (Volts)
600		
240		
150		
100		
80		

TABLE 12-5

R_L (Ohms)	I_A (Amps)	V_2 (Volts)
600		
240		
150		
100		
80		

TABLE 12-6

Direct Current Generators

EXPERIMENT **12.4 DC** COMPOUND GENERATOR

REQUIRED EQUIPMENT

Power Supply Module	
(120/208V, 3$, 120Vdc, 0-120Vdc)	EMS 8821
DC Motor/Generator Module	EMS 8211
Synchronous Motor/Generator Module	EMS 8241
Resistance Module	EMS 8311
Connection Leads	EMS 8941
Timing Belt	EMS 8942

PROCEDURE

Caution: The switch in the excitation circuit of the synchronous motor should be closed (up position) only when the motor **is running.**

Step 1: Because of its constant running speed, the synchronous motor will be used to mechanically drive the dc generator. Using your EMS Power Supply, the Data Acquisition Interface (DAI) modules in the EMS workstation and Synchronous Motor Modules, connect the circuit shown in Figure 12.8.

Step 2: Terminals 1, 2, and 3 on the power supply provide fixed three-phase power for the three-stator windings. Terminals 8 and N on the power supply provide fixed dc power for the rotor winding. Set the rheostat control knob to its proper position for normal excitation.

Step 3: a) Using your EMS DC Motor/Generator, the Data Acquisition Interface (DAI) modules in the EMS workstation and Resistance Modules, connect the circuit shown in Figure 12.15.
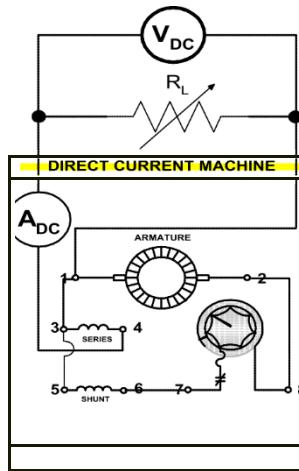
FIGURE 12.15

b) Couple the synchronous motor and the dc generator with the timing belt.

c) Turn the dc generator field rheostat control knob full cw for minimum resistance.

d) Make sure the brushes are in their neutral position.

e) Place the resistance switches for no-load (all switches open).

Step 4: a) Turn on the power supply. The synchronous motor should start running.

b) If the synchronous motor has switch S, close it at this time.

c) Note if voltage E_A builds up.

d) If not, turn off the power supply and exchange any two of the stator connection leads on the synchronous motor.

e) Measure the open circuit armature voltage. E_A _____ Vdc

Step 5: Vary the field rheostat and notice if the armature voltage E_A «hanges. Explain

Step 6: Adjust the field rheostat for a no-load current ($I_A = 0A$) output voltage E_A of 120Vdc.

Do not touch the field **rheostat control for** the remainder of **the Laboratory Experiment!**

Step 7: a) Adjust the load resistance to obtain each of the values listed in Table 12-6.

b) Measure and record E_A «nd I_A for each of the resistance values listed in the Table.

NOTE: Although the nominal output current rating of the **generator is** lAdc, it may be loaded up to I.5Adc **(50% overload) without harm.**

c) Turn off the power supply.

d) Calculate and record the power for each of the resistances shown in Table 12-6.

Step 8: a) Change the connections to the series field only, so that the armature current flows through it in the opposite direction.

b) Complete the drawing shown in Figure 12.16 showing your proposed circuit change.

c) Have your instructor check your circuit and your drawing.
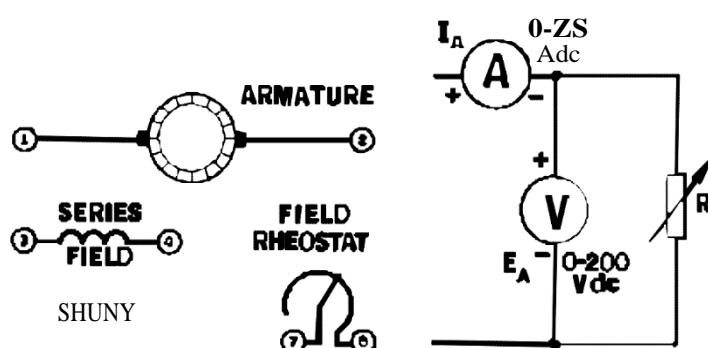
FIGURE 12.16

Step 9: a) Turn on the power supply

b) Adjust the field rheostat for an EA of 120 Vdc.

c) Do not touch the rheostat after this.

Step 10: a) Adjust the load resistance to obtain each of the values listed in Table 12-7.

b) Measure and record E_A and I_A for each of the resistance values listed in the Table.

c) Turn off the power supply.

d) Calculate and record the power for each of the resistances shown in Table 12-7.

Record the open circuit armature voltage. E_A _____ Vdc

Explain why varying the field rheostat the armature voltage E_A «hanges.

R (Ohms)	I_A (Amps)	E_A (Volts)	Power (Watts)
600			
300			
200			
150			
120			
100			
80			
75			

TABLE 12-6

R (Ohms)	I_A (Amps)	E_A (Volts)	Power (Watts)
600			
300			
200			
150			
120			
100			
80			
75			

TABLE 12-7

Reports Recommendations:

1. Sketch the main components of a dc generator.
2. How do we adjust the voltage of a dc generator?
3. Explain the difference between separately excited, shunt, compound, differential compound and series dc generator.
4. Explain why the output voltage of series generator increases but the shunt generator's voltage is reduced when increasing load.
5. Look in your textbook for the parallel dc generator conditions and write them in your report.
6. Plot the generator characteristics curves (armature voltage vs. armature current) of all the dc-generators experimented in the same graph. Discuss the reasons for the shape of the curves.

LABORATORY SESSION XIII

INDUCTION MACHINE FED OPERATION FROM PWM SOURCES

OBJECTIVES

In this laboratory session we will study the behavior of an induction machine when operated with a variable frequency, pulse width modulated (PWM) source.

The specific objectives of this lab session are:

1) To study the control of an adjustable-speed induction motor drive (using V/f control) and observe various motor waveforms.
2) To determine motor torque-speed characteristics (with fixed V/f) at different frequencies.

REFERENCES

1) Daniel W. Hart, *Introduction to Power Electronics,* Prentice Hall, 1997.
2) Guru and Hiziroglu, *Electric Machinery & Transformers* 3rd edition, Oxford University Press, 2001.
3) Vincent del Toro, *Basic Electric Machines,* Prentice Hall, 1990.

INTRODUCTION

An induction machine is normally operated on the linear region of the speed torque curve. This region is near the synchronous speed of the machine so, with a constant frequency source, the machine can be thought of as operating at a constant speed.

Some of the methods for speed control of induction motors are:

CHANGING **THE STATOR POLES**

This method is quite suitable for an induction motor with a squirrel-cage rotor. In this case, the stator can be wound with two or more entirely independent windings. Each winding corresponds to a different number of poles and therefore different synchronous speed. At any time, only one winding is in operation. All other windings are disconnected. This method of speed control is very simple, provides good speed regulation, and ensures high efficiency at either speed setting. Such a machine is called *multispeed motor.*

Unfortunately once a particular speed is selected there is no further control available. Speed control in this instance occurs in a discrete fashion. For example, an induction motor wound for 4 and 6 poles at a frequency of 60 Hz. can operate either close at a synchronous speed of 1800 RPM or close at 1200 RPM by the action of a switch. If the speed control is desired between 1800 and 1200, it cannot be achieved with the multispeed squirrel-cage induction motor.

The use of multispeed motors has been made in the design of traction motors, elevator motors, and small motor driving machine tools.

ROTOR RESISTANCE CONTROL

We have already discussed on Laboratory Session 6 the effect of changes in the rotor resistance on the speed-torque characteristics of an induction motor. This method of speed control is suitable only for wound-rotor induction motors. Adding external resistance in the rotor circuit can decrease the operating speed of the motor. However, an increase in the rotor resistance causes (a) an increase in the rotor copper loss, (b) an increase in the operating temperature of the motor, and (c) a reduction in the motor efficiency.

In essence, this method of speed control can be used only for short periods.

APPLIED STATOR VOLTAGE

This method involves reducing the applied line voltage. The student may remember that in an induction motor that torque is proportional to the square of the applied voltage. In this way, some degree of speed control is obtained as can be seen on Figure 13.1. The operating point is denoted by a, which is at rated stator voltage and rated torque output. A reduction of 30% in the applied voltage causes the operating point for the constant-load torque to move from a to b and from a to c for the variable-torque load. Note that this scheme may allow increasing or decreasing not quite an appreciable amount of speed
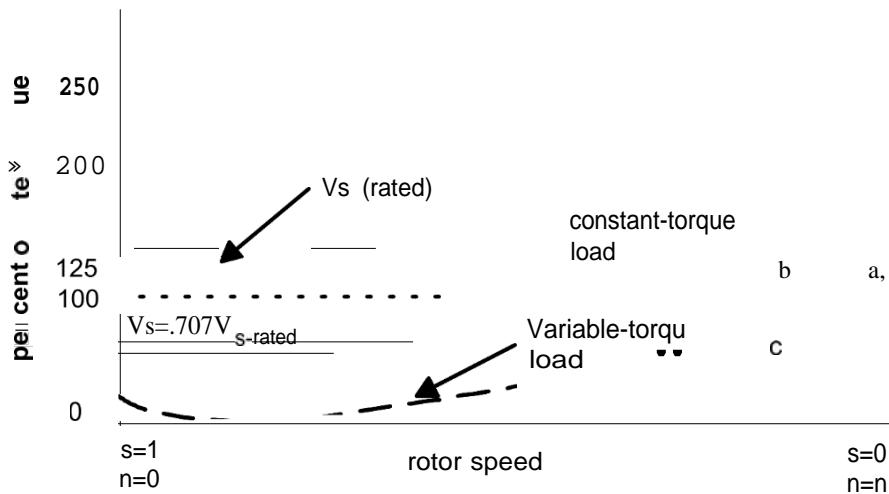
FIGURE 13.1

This speed control is expensive. Variable three-phase voltage is obtained efficiently through the employment of a motor-generator set or a three-phase variacs" having ratings at least as large as the motor being controlled. Second, when the motor is operating at reduced voltage, its reserve capacity is dangerously reduced. If an attempt were made to operate the motor over the full range at the reduced voltage, a glance at Figure 13.1 would make it clear that only the variable-torque load can be so operated. At reduced voltage the motor's starting torque may be insufficient to move the constant-torque load

---

the Electrical machine lab's power supply (EMS-8821), use variacs for its variable voltage terminals. The variacs are cilindrical variable transformers and your lab instructor may show you one if you ask.

Induction Machine Fed Operation from PWM Sources
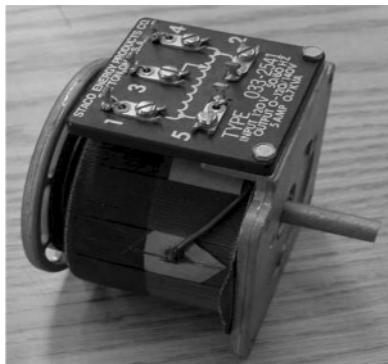
FIGURE 13.2 A VARIAC USED IN THE LABARATORY

INJECTING AN EMF IN THE ROTOR CIRCUIT

   Injecting an EMF in the rotor circuit instead of resistors can also change the speed of a wound-rotor. For proper operation, the frequency of the injected EMF must be equal to the rotor frequency. However, there is no restriction on the phase of the injected EMF. If the injected EMF is in phase with the induced e.m.f. of the rotor, the rotor current increases. In this case, the rotor circuit manifests itself as if it has a low resistance. On the other hand, if the injected e.m.f. is in phase opposition to the induced EMF in the rotor circuit, the rotor current decreases. The decrease in the rotor current is analogous to the increase in the rotor resistance. The change in the rotor resistance is accompanied by the change in the operating speed of the motor. Further control speed can also be achieved by varying the magnitude of the injected e.m.f.

VARIABLE FREQUENCY DRIVES

   Adjusting the frequency of the applied voltage can control the speed of an induction motor. This method enables us to obtain a wide variation in the operating speed of an induction motor. The only requirement is that we must have a variable-frequency supply.
   On Laboratory Session 6 theory, we learned that the synchronous speed and rotor speed in RPM are defined by:

$$Ns - \frac{120 f}{}, \text{ and} \qquad Nr = (1 - slip) * Ns$$

   Therefore, if the applied electrical frequency is changed, the motor will change proportionally. However, if the applied voltage is held constant when the frequency is lowered, the magnetic flux is in the air gap will increase to the point of saturation. It is desirable to keep the air-gap flux constant and equal to its rated value. This is accomplished by varying the applied voltage proportionally with frequency. The ratio of applied voltage to applied frequency may be constant:

or may have an expression which rule such dependency as for example:

$$v = A \ f' + k$$

Induction Machine Fed Operation from PWM Sources

The term volts/hertz control is often used for this situation. The induction motor torque speed curves Figure 13.3 are for different frequencies and constant volts/hertz.
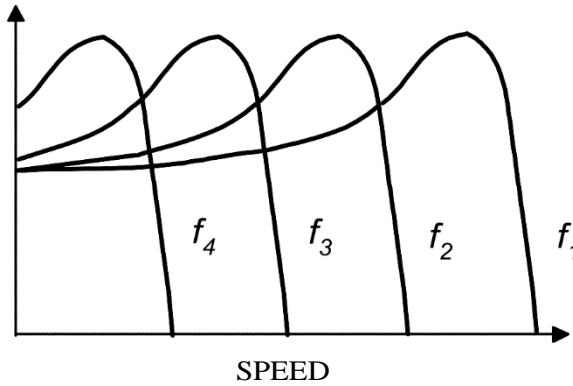
SPEED

FIGCR£ 13.3 **INDUCTION MOTOR TORQUE-SPEED RELATIONSHIPS FOR VARIOUS FREQUENCIES.**

One of the possible solution projects for obtaining variable frequency sources is the use of dc motor and synchronous generator set. Unfortunately, this solution projects its own shortcomings such as the need for a suitable dc supply, the need to purchase two additional machines, a reduced efficiency, etc.

A better solution lies in the use of an inverter, which can be made to change a dc source into a variable frequency source. Because the dc power is not readily available, it becomes necessary to generate it through the use of suitable *rectifier* circuits. Figure 13.4 is classified as an ac-ac converter with a dc link (a low pass LC filter) between the two-ac voltages.

The adjustable frequency drive shown on Figure 13.4 operates by first rectifying the 3-phase line voltage creating a dc voltage. To generate the adjustable frequencies, power semiconductor devices are used to switch this dc voltage. The line voltages can be switched to have either a positive, negative, or zero value. To approximate a sine wave the voltages are switched to positive voltages during the positive half cycle. The average value of the voltage is adjusted by setting the output voltage to zero for various lengths of time. This type of voltage control is called pulse width modulation (PWM). An example of PWM inverter output line to neutral voltage is shown in Figure 13.5.
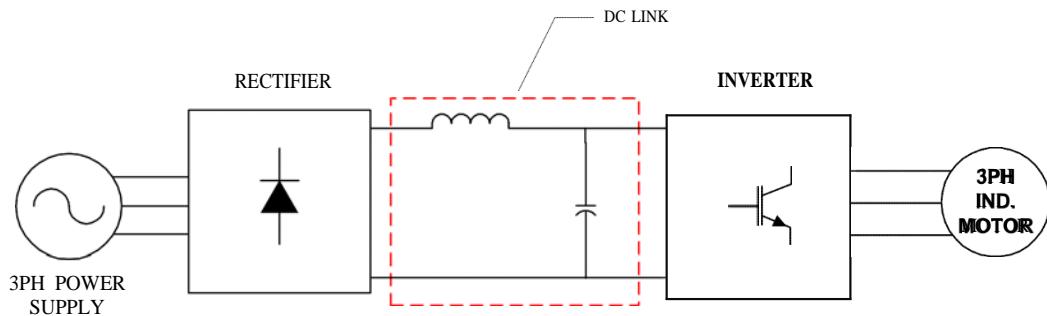
FIGURE 13.4 BLOCK DIAGRAM TO ILLUSTRATE THE PRINCIPAL EQUIPMENT NEEDED IN THE ELECTRONIC SPEED CONTROL OF A SQUIRREL-CAGE THREE-PHASE INDUCTION MOTOR

Induction Machine Fed Operation from PWM Sources
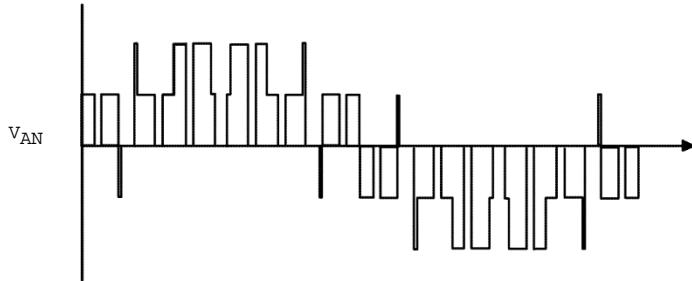
FIGURE 13.5

Because PWM does not produce exact sinusoids there are considerable harmonics generated. These harmonics can add losses to the machine reducing the machines total performance.

ACX **SERIES AC MOTOR CONTROLLERS**

The ACX, Figure 13.6, is a general purpose AC micro-controller that provides adjustable speed control of conventional AC motors in applications exhibiting a variety of load characteristics. The controller converts the fixed frequency and voltage of the AC line power source to a pulse width modulated adjustable voltage and frequency output. The power section utilizes Insulated-Gate Bipolar Transistors (IGBT's) operating at a fixed carrier frequency. The design features and programming functions of the ACX, along with its available options, enable the controller to be applied to numerous industrial applications. Boston Gear builds this controller model%.
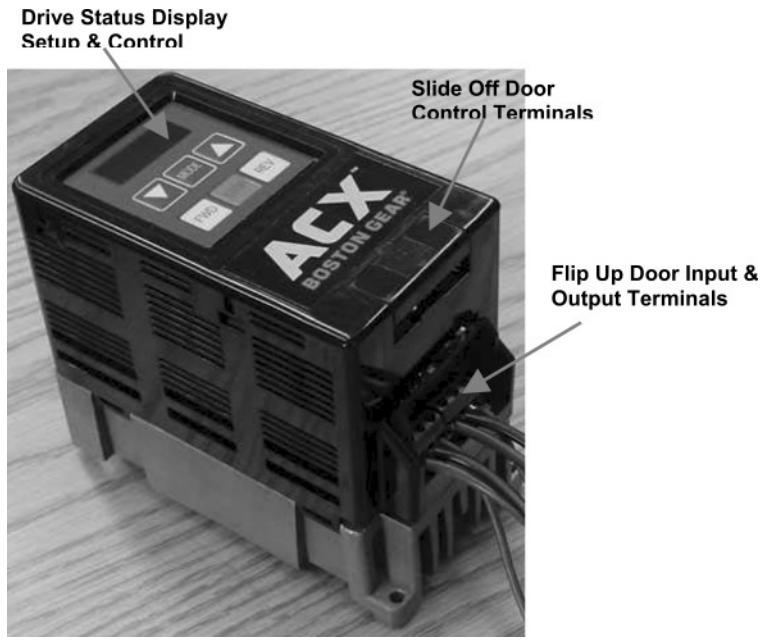
FIGURE 13.6

Terminals are located under the flip up door (see Figure 13.6). Terminals legend is located on Figure 13.7

```
  R     S     T     U     V     W
  L1    L2    L3    T1    T2    T3
```
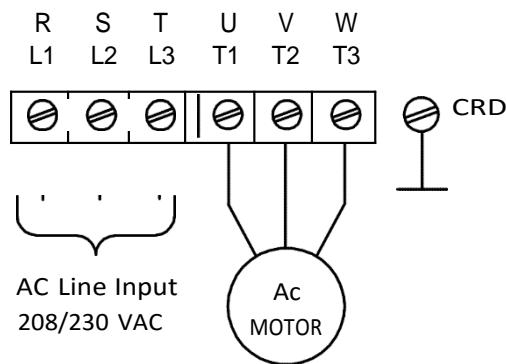
FIGURE 13.7

The membrane keypad consists of 6 buttons and a 3 digit LED display. The buttons are used for changing operating modes, parameters values and running the motor.

switches b&ween the run and parameter inodw.

LED display to inonitor motor sped. Additienally, it display paramete• numbe•s and values when in the param#er moda

Decrease motor speed, scrolls down Oirough parameter liséngs and decreases parameter sewings.

Increase motor speed, scrolls up through parametu lisangs and increases parameter seténgs.

Run in forward direcaon.

Run in revwse direction.

Stops the in otor and also acts as a drive resd:.

FIGURE 13.8

Induction Machine Fed Operation from PWM Sources

The most commonly used parameters are:

Parameter		Unit	Range		Factory Preset
No.	NAME		MINIMUM	MAXIMUM	
P01	**Run** Speed Command	%	**0.00**	**100**	**0.00**
P02	**Minimum** speed	%	**0.00**	**75.0**	**0.00**
P03	**Maximum** Speed	%	**50.0**	**100**	**100**
P04	**Acceleration** Time	**Seconds**	**00.1**	**999**	**10.0**
P05	**Deceleration** Time	**Seconds**	**00.1**	**999**	**10.0**
P06	**Motor Full** Load Amps.	**Amps**	**0.60**	**3.98**	**3.60**
P07	**Nominal Line Voltage**	**Volts**	**190**	**230**	**230**
P08	Save Parameters	___	**0**	**1**	**0**
P28	Reverse Enable	___	**0**	**1**	**0**
P31	Keypad Speed **Adjust**	___	**0**	**1**	**1**
P33	**Line Starting**	___	**0**	**1**	**0**
P96	Factory Preset	___	**0**	**1**	**0**

PRELAB
No prelab will be given for this experiment

Experiment 13.1 The Squirrel Cage Induction Motor

REQUIRED EQUIPMENT

Power Supply Module (0-120/208)	EMS 8821
Connection Lead Set	EMS 8941
Squirrel Cage Induction Motor Module	EMS 8221
Electrodynamometer Module	EMS 8911
DAI Module	EMS 9061
Hand Tachometer	EMS 8920
Timing Belt	EMS 8942
AC Motor PWM controller	ACX Series, BOSTON GEAR

PROCEDURE

Step 1: Install the Power Supply, Prime Mover/Dynamometer, the Squirrel-Cage induction Motor, the Motor controller and, the Data Acquisition Interface (DAI) modules in the EMS workstation.

Step 2: Connect the induction machine as shown in Figure 13.9. Don't connect the neutral terminal.

FIGURE 13.9

Step 3: Turn on the power supply. The keypad's LED display of the PWM drive should turn on.

    a) By pressing the MODE button, select the parameter value P96 (Factory Preset) by using the arrow buttons'[4] Change the parameter value to 1. Press the MODE button to accept this value.

    b) Now, you will set the nominal line voltage and full load current of the motor. Select the parameters P06 (Motor Full Load Amps parameter) by

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[14] f you need help, review the Appendix E. If you still need more help, ask your instructor for it.

Induction Machine Fed Operation from PWM Sources

using again the arrow buttons. Change the parameter value to the nominal current value that appears on the front panel of the motor. Press again the MODE button to accept this value.

c) After this, select the parameter P07 (nominal line voltage) and make the parameter value equal to the nominal line voltage of the motor, which appears on the front panel of the motor. Press the Mode button to accept this value.

d) Finally, save the parameter values by setting the P08 parameter value equal to 1.

Step 4: Run the motor in the forward direction by pressing the FWD button. Adjust the speed of the motor to its maximum value using the arrow buttons (up side arrow to increase the speed). The maximum speed will appear on **the LED display** as 100%.

Step 5: Couple the motor to the electrodynamometer with the timing belt. Set the control knob of the dynamometer to its maximum CCW position to get the lowest torque.

Step 6: Start the Metering application. Select the DAI's Scope and measure the fundamental frequency of the voltage applied to the motor. This frequency should be very close to 60 Hz.

Step 7: Measure and complete the Table 13.1. Keep the drive's output voltage frequency constant.

QUESTION 1: Why the line voltage and the phase voltage ratio is not equal to   ? Explain.

Step 8: Repeat step 7 for each of the torque listed in Table 13.1.

Step 9: Using your harmonic analyzer, write down on Table 13.2 the five (5) highest harmonics of the motor current and applied stator line and phase voltages when the motor is fully loaded. Write it down at which frequencies they occur also.

Step 10: Adjust the drive's output frequency to 50 Hz (check the frequency on the digital scope). Load the dynamometer and complete Table 13.3 for each of the torque listed.

Step 11: Repeat Step 9 and write down the results on Table 13.4.

Step 12: Adjust the drive's output frequency to 40 Hz (check the frequency on the digital scope). Load the dynamometer and complete Table 13.5 for each of the torque listed.

Step 13: Repeat Step 9 and write down the results on Table 13.6.

Step 14: Turn off the power supply.

Warning: Wait at least 5 minutes before accessing the unit after AC power has been disconnected from the controller. **Failure** to do this could cause electric shock that can result in **personal injury** or loss of life.

QUESTION 1: Why the line voltage and the phase voltage ratio is not equal to   ? Explain.

f=60Hz								
Torque Lbf*in	$I_{sine\ line}$[15]	I_{line}[16]	V_{line}[17]	Vph[18]	**W1**	**W2**	**W3ph**	**Speed RPM**
0								
3								
6								
9								
12								

TABLE 13.1

	Frequency	I_{line}	V_{line}	Vph
1				
2				
3				
4				
5				

TABLE 13.2

Power supply Line Current
[6] Motor Line current
[7] Motor Line Voltage
"   Motor Phase Voltage

Induction Machine Fed Operation from PWM Sources

f=50Hz							
Torque Lbf*in	$I_{sine\ line}$	I_{line}	V_{line}	Vph	W1	W2	W3ph	Speed RPM
0							
3							
6							
9							
12							

TABLE 13.3

	Frequency	I_{line}	V_{line}	Vph
1				
2				
3				
4				
5				

TABLE 13.4

Induction Machine Fed Operation from PWM Sources

f=40Hz								
Torque Lbf*in	$I_{sine\ line}$	I_{line}	V_{line}	Vph	W1	W2	W3ph	Speed RPM
0								
3								
6								
9								
12								

TABLE 13.5

	Frequency	I_{line}	V_{line}	Vph
1				
2				
3				
4				
5				

TAB[E13.6

Induction Machine Fed Operation from PWM Sources

REPORT REQUIREMENTS

1) Include the lab session text in full. All tables must be filled with ink. Photocopies won't be acceptable.
2) On the same graph, draw the speed torque characteristics of the induction machine at the three frequencies tested.
3) Calculate the efficiency of the motor at full load conditions for all the three frequencies. Compare the results with the 60 Hz sine wave source efficiency on Experiment 7.1.s
4) Comment on the terminal voltage versus frequency. Plot the voltage versus frequency of the drive at no load conditions. Suggest a control law equation (curve fitting) using these three data points.
5) Comment on the harmonics generated.
6) Make any additional comments relevant to the experiment.

APPENDIX A

The Student Guide

This student guide was conceived to help the lab student to keep a safe working environment during the lab sessions and to help him/her to make a good lab report. If followed, these guidelines given here will help you to get the most out of the Electric Machines Laboratory.

A.1.1 SAFETY IN THE LABORATORY

There are three main types of risk the student could be exposed to when working in the electrical machinery laboratory, which are electric shock, mechanical injure and burn risk. These are, however, avoidable risks and do usually happen when the student fails in follow the instructions given by the laboratory manual by the lab instructor.

Caution: High voltages are present in these laboratory experiments!

In order to make safety a priority in the laboratory, the following are the rules every laboratory instructor must enforce:

1) Drinking, eating and smoking are prohibited in the lab.
2) You must wear cloths that can protect you against scratches and falling objects.
3) You must not talk to students of other groups during the lab experiments.
4) Check your circuit before energizing (your instructor must always check the connections after you).
5) If any device or instrumentation equipment is burning or smells like it, turn off the power supply and DO NOT touch anything, some equipment or cables could be burning hot. Call your instructor to check the circuit again.
6) Don't be a clown in the lab and don't ever allow yourself to be distracted while performing an experiment.
7) Be careful when moving around your experiment workbench. Always think first what is it you want to do.
8) Prior and after the circuit is energized work only with one hand at a time. A current between two hands crosses your heart and can be more lethal than any other electric shock your body may be subjected to.
9) After using a passive loads (especially resistance modules) do not touch them inside while moving them because they could be burning hot.
10) If you don't know or don't remember a procedure ASK YOUR INSTRUCTOR.
11) Always check that the power is off when making connections in the circuit.
12) The power should be turned off after completing each individual measurement.

A.1.2 CONNECTING THINGS AROUND.

To maximize the safety and the instructor's time in checking your circuits you MUST ALWAYS follow these guidelines:

1) The circuit will be connected with NO instrumentation first. This will give you the certainty that your circuit has been connected correctly.
2) You will choose the line in which current will be measured and then substitute that line with the ammeter with the necessary connection leads. This will prevent you from causing short-circuits which could challenge your safety or could damage the equipment.

3) Voltmeters will be connected last. This will simplify the connections for you since voltmeters are always connected in parallel to measurement points.
4) The wattmeter is to be connected between the circuit and the power supply

A.1.3 THE MAKING OF THE LAB REPORT

Communication skills are as important for engineers as the technical knowledge since both written and oral communications are essential to get the job done. The development of such skills isn't achieved overnight. As everything in life, it takes some effort and a lot of practice.

An important characteristic of technical reports is that you must perform an experiment, have data recorded and make observations prior to complete the report. With that in mind, you should begin each experiment with a clear idea of the purpose of the experiment and the theory behind the experiment. Therefore, preparation before coming to the laboratory is an important part of experimental work. You should prepare in advance for every experiment by reading the objectives, the introductory discussion and the reading assignment, and by making the prelab section corresponding to that experiment. It is also helpful to have the expected results plotted (or know what the result must be like). Sampling range and connection diagrams are also to be identified before the experiment is done. In short, the technical reports are intended to train lab students to keep complete and accurate record of their experimental work so they can do appropriately in their professional work field.

A very important part of a technical report is plotting the results obtained. In many cases, the curves will be the parts of the report actually studied. Usually the supporting text and figures will be read through to determine the validity and applicability of the report. Once satisfied, the curves become the focus of our attention. They must be self-sufficient and complete. The curves must be legible, neat, and logically composed.

The following information should be included in the lab report:

1) RUM cover sheet for the Electrical Machinery Laboratory (use the model given at the end of this appendix).
   The cover sheet must have, in this same order, the following:

   a) Electrical and Computer Engineering Department
   b) Electric Machines Laboratory
   c) The lab session name (right in the middle of the page)
   d) The date the experiment was performed (e.g. Wednesday, Oct 3)
   e) Laboratory students with their ID #s
   f) Calendar year

2) Table of contents (with page numbers).
3) Descriptive title and date of the performed laboratory session in every page.
4) Presentation of each experiment in the same order as performed.

5) Purpose of the experiment(s). Give a statement of what you intend to determine as a result of the investigation.
6) The answered pre-lab.
7) Circuit diagrams, including the measurement connections (include only the performed experiment diagram).
8) Graphs of the data obtained (use the report Requirements).
9) Any observations made during the experiment that might be interesting.
10) Sample calculations. Give the formulas that you applied to the raw data to transform them to processed data.
11) Discussion of the results and Conclusions. The conclusion is a specific statement supported by the experimental data. It should be related to the objectives of the performed experiment(s) (avoid mentioning that this or that objective was met, support the theory from the experimentation instead).
12) Prelab, Review questions, Instructors assignment and questions and the Report Requirements.

It is worth to remember that you MUST follow these guidelines when preparing your technical laboratory report:

a) The completed laboratory report may be either neatly handwritten in ink (black or blue) or typewritten. It is important to remember that both neatness and legibility are important.
b) Use standard white paper size (8 '?› by 11). If handwritten you may use lined paper.
c) Label all pages, figures, and tables.
d) Report should be written in the past tense and in the third person.
e) Schematics must be placed within the procedures (i.e. you should not put them at the end of the report and away from the referenced procedure).
I) Show only sample calculations when required.
g) Keep a logical order when writing your report.

A.1.4 CURVE PLOTTING
The first step in plotting the results of an experiment is to identify which item was the controlled variable (independent variable) and which one was the dependent variable. Conventionally, the independent variable is placed in the abscissa or horizontal scale and the dependent variable is placed as the ordinate or vertical scale.

Data range must be determined next. This depends very much on the specific case treated. Use good judgment when doing so.

When multiple plots are to be placed in the same graph, it is usually more convenient to use normalized Iper unit) plots instead of different scaling. In this case you choose a base value for each plot and normalize all your data points corresponding to that same plot by dividing each per this base value. This way to present complex graphs has the advantage to simplify the comparison of different plots even when they refer to different variables. However, the method lacks in that no significant information beyond that of the comparison can be retrieved directly from the graph.
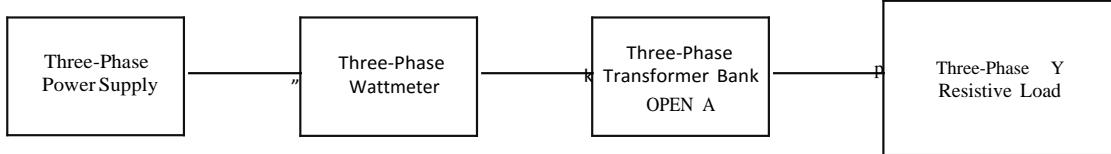
A.1.5 DIAGRAMS

Electrical drawings showing circuit diagrams normally accompany electrical equipment. There are basically 4 types of diagrams we are going to use in the Electric Machines Lab:

1) One-line diagrams.

A one-line diagram links the different parts of a system by a single line and has the power flow direction. It is important to remember that the power flow is from the power supply to the load when the load is passive. If the load is active or reactive, power flow could be either direction it will depend on the operation characteristic of the load.

In the one-line diagrams it is much easier to see which device output is the input for another device.
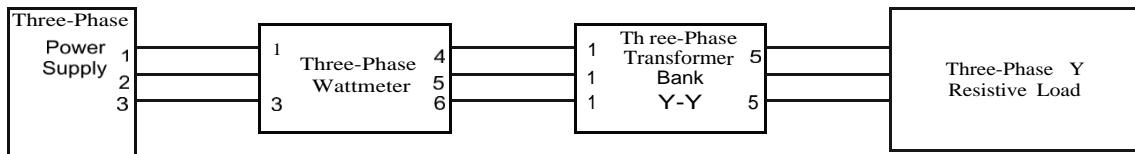

ONE-LINE **DIAGRAM**
FIGURE A.1

2) Connection diagrams.

A connection diagram gives very specific indications on how to interconnect two devices. However, these diagrams don't show the device internal connections.
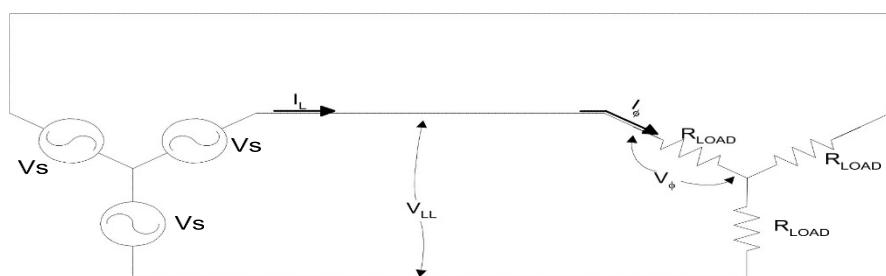

CONNECTION DIAGRAM
FIGURE A.2

3) Schematic diagrams.

These diagrams show all necessary circuit information so that a complete circuit may be traced and understood. Little or no resemblance to the actual physical layout of the devices is a typical characteristic of these diagrams.
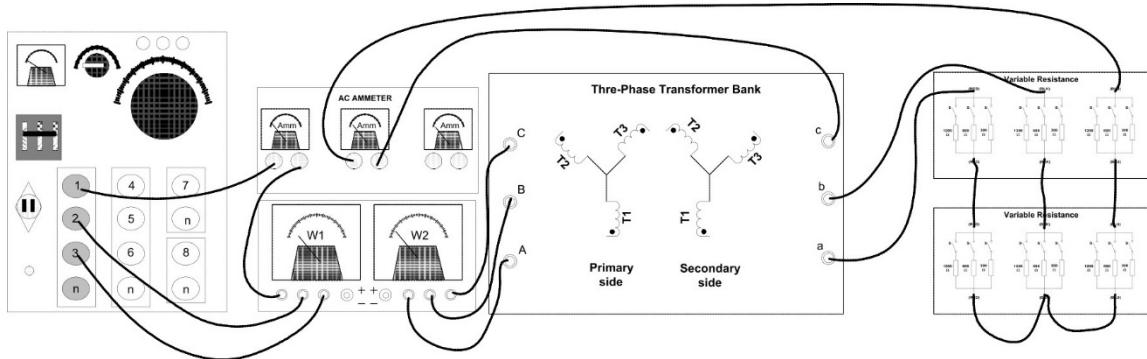

SICHEMATIC **DIAGRAM**
FIGURE A.3

2

4) Wiring diagrams

This type of diagram permits the location of a circuit point by its physical appearance.

WIRING DIAGRAM
FIGURE A.4

Accepted approach for report writing

Summary: A brief statement of the purpose or objective of the tests, the mayor findings, and what was deduced from them.

Objective or purpose: A more detailed statement of purpose or objective, plus other pertinent background data.

Equipment setup: A list of the equipment and materials used for the tests, and a description and illustration of how the equipment is interconnected. (If there is a series of tests requiring different equipment configurations, a full list of equipment and materials should appear here. A description and illustration of each setup should then be inserted at the beginning of each test description.)

Method: A step-by-step detailed description of each test.

Results: A statement of the test results or findings evolving from the test.

Analysis: A detailed analysis of the results or findings, their implications, and what can be learned or interpreted from them.

Conclusions: A brief statement describing how the tests, findings and resulting analysis have met the objective stated in the objective or purpose compartment.

Data (attachments): A separate sheet (or sheets) containing data derived during the tests, such as detailed calculations, measurements, weights, stresses, and sound levels.
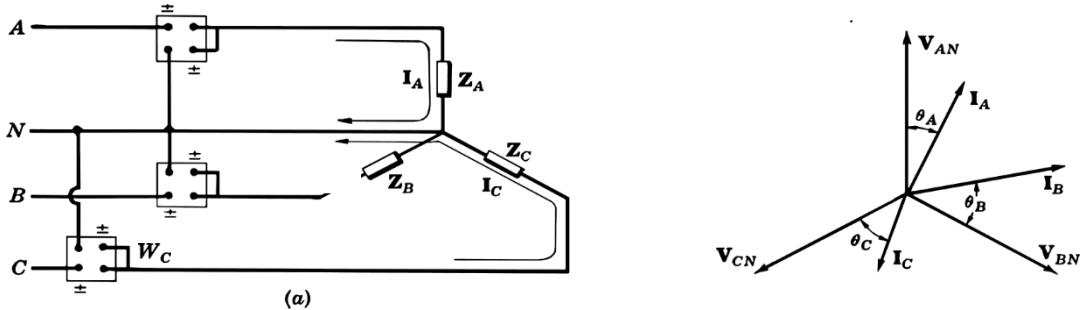
A few pointers for efficient report writing may be given at this point:

1) Identify the purpose: Always check that you have clearly identified the purpose of your report before you start writing. On a separate sheet write the words "The purpose of my report is..." and complete in a single sentence.
2) Present facts clearly and in logical sequence. You should write briefly, directly, and forthrightly.
3) Write in the first person since writing of reports in the third person seems afraid to display the writer involvement in the order of components, the data survey, the report submission, and the recommendation.
4) Use the active voice. Sentences written in the active voice are generally shorter and more emphatic than sentences written in the passive voice.
5) Use simple words and removes words of low information content.

APPENDIX B

WATTMETERS AND FOUR-WIRE WYE LOADS

The wattmeter is an instrument with a potential coil and a current coil so arranged that its deflection is proportional to $U/\cos\theta$ where θ is the angle between the voltage and current. A four-wire, wye connected load requires three wattmeters with one meter in each line as shown in Figure B-1 (a).

FIGURE B-1

The phasor diagram in Figure B-1 (b) assumes a lagging current in Phase A and leading currents in Phases B and C with phase angles θ_A θ_B and θ_C respectively. Then the wattmeter readings are:

$$W_A = V_{AN}I_A \cos\angle_A^{AN}, \qquad W_B = V_{BN}I_B \cos\angle_B^{BN} \qquad W_C = V_{CN}I_C \cos\angle_C^{CN}$$

Where E^{AN} indicates the angle between V_{AN} and I_A Wattmeter W_A reads the power in phase A and wattmeters W_B and W_C the power in phases B and C respectively. The total power is:

$$P_T = W_A + W_B + W_C$$

THE TWO-WATTMETER METHOD

The total power in a three-phase, three-wired load is given by the sum of the readings on two wattmeters connected in any two lines with their potential coils connected to the
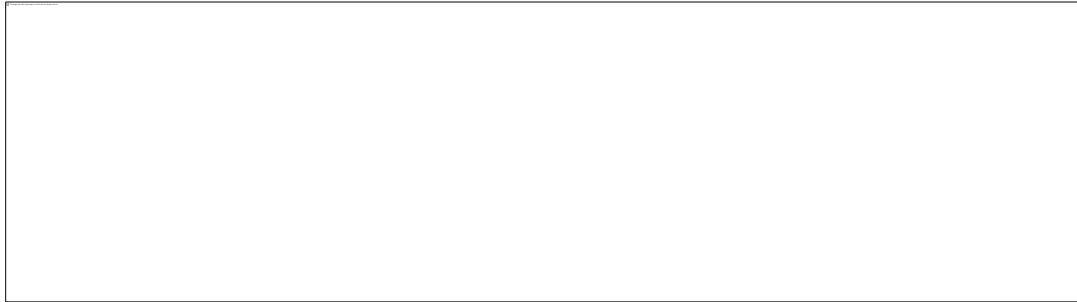

Figure B-2   Figure B-3

$$W_A = V_{AB}I_A \cos \angle_A^{AB} \qquad \text{and} \qquad W_C = V_{CB}I_C \cos \angle_C^{CB} \qquad (1)$$

Applying Kirchhoffs current law to junctions A and C of the delta load, we obtain:

$$I_A = I_{AB} + I_{AC} \qquad \text{and} \qquad I_C = I_{CA} + I_{CB} \qquad (2)$$

Substituting the expressions for IA and Ic siven in (2) into the wattmeters equations (1), we obtain:

$$\times A = V_{AB}I_{AB} \text{ GOs } _{AB}^{AB} + V_{AB}I_{AC} \cos \angle_{AC}^{AB}$$

$$W_C = V_{CB}I_{CA} \cos \angle_{CA}^{CB} + V_{CB}I_{CB} \cos \angle_{CB}^{CB} \qquad (3)$$

The terms $V_{AB}I_{AB}$ •os TAB and $_{C}BI_{CB}$ °° PCB are immediately recognized as the power in AB and CB of the load. The two remaining terms contain $V_{AB}I_{Ac}$ and $V_{c}BI_{CA}$ which can now be written $V_L I_{Ac}$ since VAB and VcB are line voltages and IAC ICA To identify these two terms, construct the phasor diagram of Figure B-3 above where current IA« is assumed to lag VAc by 8.

From the phasor diagram:

$$TAB = 60' + 8 \qquad \text{and} \qquad \$B = 60'— 8 \qquad (4)$$

Now add the two remaining wattmeter terms from (3) and substitute $60' + 8$ and $60'— 8$ for V_{AB} and /B respectively.

$$*_L I_{AC} \text{ Gos}(60' + 8) + V_L I_{AC} \text{ Gos}(60'— 8) \qquad (5)$$

Since $\cos(x'y) = \cos x \cos \;\; + \sin x \sin y$, we write:

$$V_L I_{AC} t\cos 60' \; \cos 8 — \sin 60' \; \sin 8 + \cos 60' \; \cos 8 + \sin 60' \; \sin 8) \qquad (6)$$

or $\qquad$ VLlACcos8

Which is the power in the remaining phase of the load, phase AC. Thus we find that two wattmeters indicate the total power in delta-connected load.

$$P_T = W_A + W_C$$

The two-wattmeter method for a wye-connected load is left as an exercise for the reader.

APPENDIX C

Control Devices Used in the Machine Lab.

As with any technical subject, the terminology used in conjunction with motor controls is quite important. In the following discussion, most of the explanation of the control terms is directly related to the various EMS control components, which will be used in this laboratory session.

CONTACTS

A contact consists of conducting parts that co-act to complete or interrupt an electrical circuit. A *nag/e-brca/‹* contact has one fixed element mounted on a conducting arm. A *double-break* contact has two fixed elements mounted on an insulated base and one movable conducting element mounted on an insulated arm   the movable element acts as a jumper across the two contacts. See Fig. I-1.

A contact is either open or closed in the normal state and is referred to as being *normally open* (NO) or *normally closed* (NC). In the *normal* state occurs when   the operating coil is deenergized.

A contact is never complete unto itself. Some means must be provided to open or close the contact. One of the simplest means is a switch.
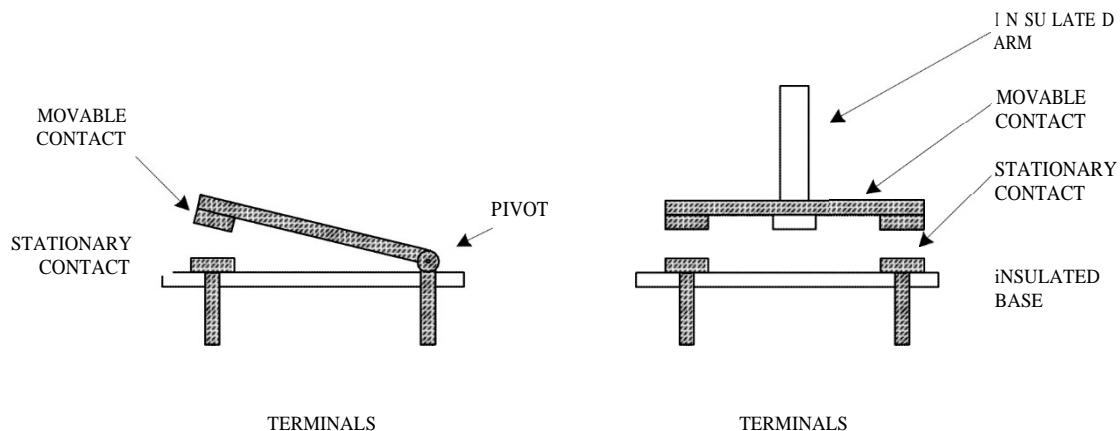
SWITCHES

Figure I-1

A switch is a device for making, breaking or changing the connections in an electric circuit. All switches contain one or more poles. A pole consists of one complete set of contacts that opens or closes one electric circuit. Thus a *nag/c po/e* switch would be used where only one circuit was involved. A *double pole* switch would be used for two circuits, etc.

PUSHBUTTON SWITCHES

Pushbuttons are the most commonly used *p//o/* devices in the field of motor control. By way of definition, we can say that a pushbutton is a manually-operated switch employed to make and/or break one or more control circuits. These circuits can operate

120V CONTACT RATINGS

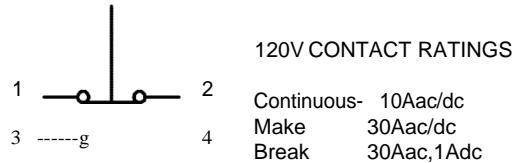|	
Continuous-	10Aac/dc
Make	30Aac/dc
Break	30Aac,1Adc

Fig I-2

magnetic control devices such as starters, contactors, and relay.

The EMS Pushbuttons, models 9102 (red), and 9103 (black) are two circuit-switching devices. They have double-break contacts connected to a plunger, which when depressed, break a normally closed circuit and make a normally open circuit. When the pushbutton is released, a spring returns the contacts to their normal position. This is *called momentary action. See* Fig. I-2.

ELECTROMAGNETIC CONTACTORS

Contactors are devices for *repeatedly* establishing and interrupting an electric power-type relay with heavy-duty contacts for switching industrial loads. The magnet design of an ac contactor consists of a stationary core and a movable armature. The magnet, made of laminated high permeability steel, provides the path for the magnetic field established by the coil current. This field pulls the armature towards the core. Movable contacts carried by the armature *make* against stationary contacts, completing an electrical circuit. When the coil current is interrupted, the magnetic field collapses, and gravity or springs return the armature to its original position, thereby disengaging the contacts. Contactors may have auxiliary contacts for operating indicator lamps, relays, other contactors, and for holding or interlocking purposes.

CONTACT RATINGS

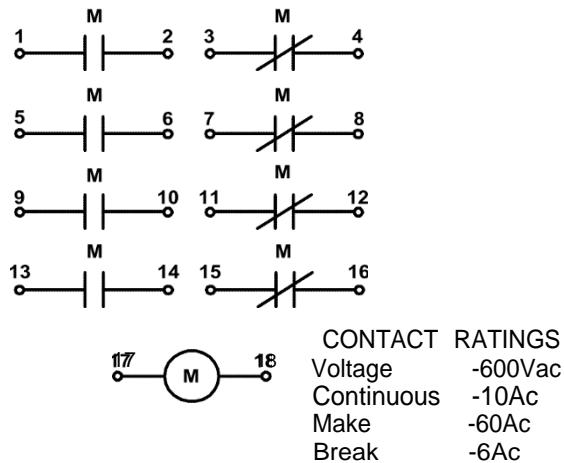|	
Voltage	-600Vac
Continuous	-10Ac
Make	-60Ac
Break	-6Ac

Figure I-3

The EMS Electromagnetic Contactor, Model 9106, is a power-type *universal* four-pole relay that provides a variety of open and closed contact arrangements. Each universal pole consists of two stationary pairs of heavy-duty solid silver double-break contacts. One pair is normally open. The magnet coil (solenoid) is rated for 120Vac operation. See Fig. I-3.

TIMING RELAY

CONTACT RATINGS
Voltage   -300Vac
Continuous   -10Ac, 1.1Adc
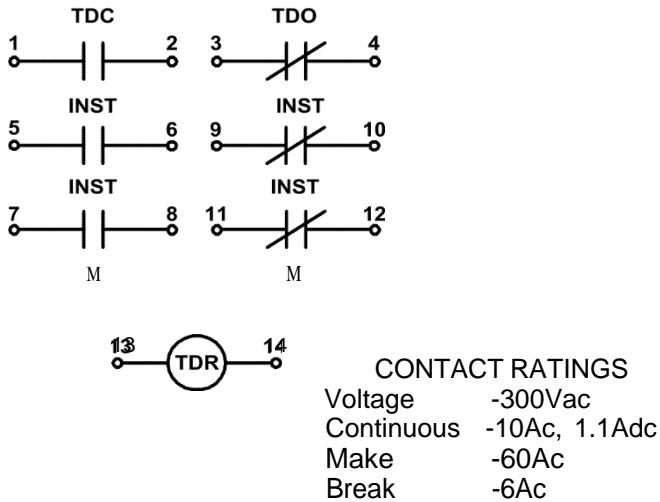Make   -60Ac
Break   -6Ac

Figure I-4

A timing relay is a control circuit device that provides a switching function based on the passage of time. There are many types of timing relays such as: motor driven, hydraulic, magnetic flux-decay, capacitor discharge and electronic. However, construction and performance features of the pneumatic timer make it suitable for the majority of industrial control operations. A *pnenma//c* timing relay is a rcse/ device that utilizes the escape of a fluid or air through and adjustable orifice. Reset timers that allow a delay before the load is energized is called *delay* timers.

The EMS Time Delay, Model 9107, consists of an operating coil, a pneumatic timing head and two sets of contact assemblies. The four-pole, lower set of double-break solid silver contacts (two normally closed and two normally open) is actuated instantaneously by energizing the 120Vac-operating coil. The upper pair of contacts (one normally closed and one normally open) opens or closes with a time delay after the coil has been energized. By turning the adjustment wheel, repeatable (within 15%) time delays of 0.2 and 60 seconds can be obtained. The two timing head contacts have the same rating as the lower four main relay contacts. See fig. I-4.

THE OVERLOAD RELAY

ELEMENT RATINGS

Adjustable   -1.1 to 2.1A
Maximum Overload   -6A

CONTACT RATINGS

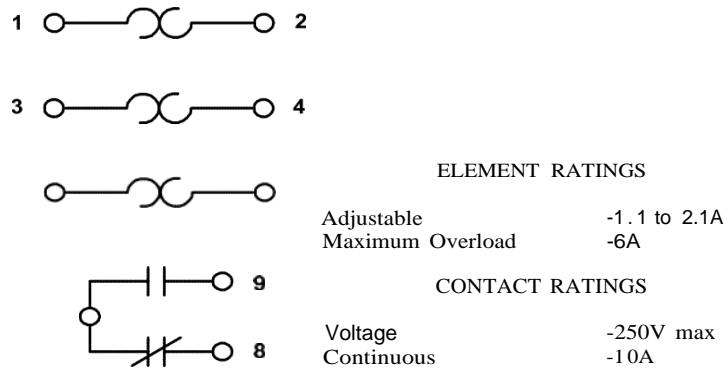Voltage   -250V max
Continuous   -10A

Figure I-5

The overload relay is a control circuit device to protect a motor against excessively heavy loads. Current sensitive thermal or magnetic elements are connected in series with the motor line conductors when some predetermined value of overload current is drawn, the overload relay will trip and de-energize the starting controls thereby stopping the motor. A manual or automatic reset button is provided for restoring control circuit operation.

The EMS Overload Relay, Model 9109, is a three element bimetallic device that actuates a built in SPDT switch when any one of the elements is overheated. The relay can be easily adjusted to trip within a range of 1.1 to 2.1 amperes by turning the calibrated dial on top of the unit. The bimetallic elements have a built in time delay function preventing nuisance tripping during motor starting. A cooling off period is required after tripping, before the relay will reset itself. The SPDT contacts are rated for 10 amperes continuous duty. See Fig. I-5.

CIRCUIT BREAKER

The circuit breaker is a device designed to open and close a circuit by non-automatic means, and to open the circuit automatically on a pre-determined overload of current, without injury to itself when properly applied within its rating.

The EMS Circuit Breaker, Model 9110, is a three-pole magnetic control circuit device that provides the following functions:
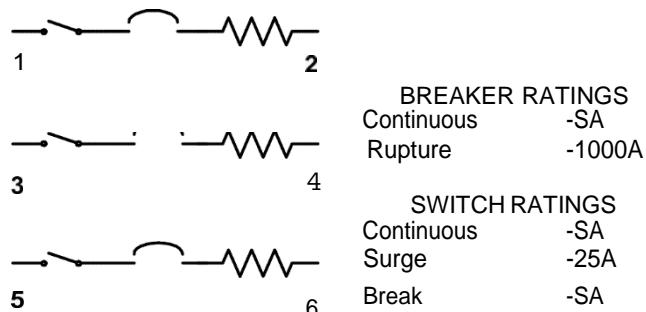

BREAKER RATINGS
Continuous   -SA
Rupture   -1000A

SWITCH RATINGS
Continuous   -SA
Surge   -25A
Break   -SA

Figure I-6

Disconnect Switch -. It provides a means where by the conductors of a circuit can be isolated from their source of power. A single toggle handle operates all three poles. When used in this manner it may also be called a *safey* or *isolating switch.*

Circuit Protector.- It provides reliable circuit overload protection. The structure consists of three single poles, each rated at five amperes, assembled with an internal mechanical interlock, which actuates all units simultaneously, opening each line conductor. The single toggle handle moves to the off position on overload, and cannot be forced to close until the overload is removed. It is said to be "trip-free".

Manual Control Switch -. Its special time-delay series tripping characteristics, and high rupturing current capacity, make it useful as a direct motor on-off control switch, when used within its ratings. It may also be called a motor-circuit switch.

INDICATOR LAMPS

Indicator lamps are pilot devices generally mounted in or near the pushbutton switching station. They serve to show a particular motor operation condition such as forward, fast, slow, raise, lower, overload, etc. Although they are usually red or green, other colors such as amber, blue or white may be used.

EMS 9120   EMS 9121

Figure I-7

The EMS Pilot lamp, Models 9120 (red) and 9121 (green) are incandescent lamps that operate on 120Vac or dc. They have built in current limiting resistors that protect the lamps from high voltage surges. See Fig. I-7.

CONTROL TRANSFORMER

Control transformers are devices specially designed to provide a safe, reasonably constant, low voltage (usually 120 V) source, for relays, contactors and other electro-magnetic devices. Control circuit faults, breakage, careless wiring, and so on, may subject the operator to a shock, which could be serious with higher voltages (such as 440 V). Besides the safety factor, another reason for limiting control circuits to 120 volts, is the cost of pilot devices, control relays, contactors and the like for operation on high voltage.
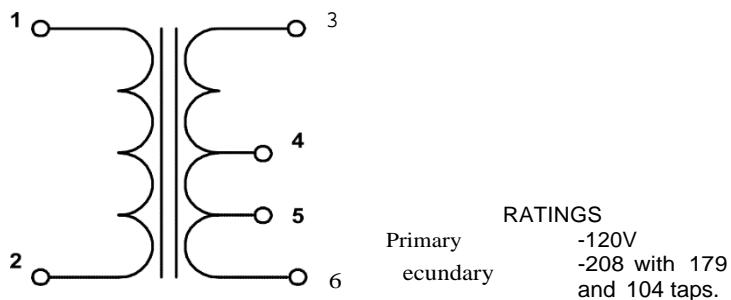
Figure I-8

The EMS Control Transformer, Model 9123, is a two-winding transformer with a 120V primary winding (terminal 1 and 2) and a 208 V secondary winding (terminals 3 and 6). The secondary winding is tapped at 50% of the turns (terminal 4) and at 86^0 of tums (terminal 5) for use in autotransformer and other applications. See Fig. I-8.

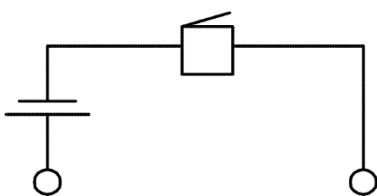## THE TEST BUZZER

BUZZER

Figure I-9

The test buzzer is an audible-signaling device used by electricians to identify wires and terminals that are directly interconnected. It determines whether switch contacts are open or closed, or whether wiring is short-circuited. Unlike an ohmmeter, the buzzer will not indicate circuit continuity if any appreciable resistance is present.

The EMS Test Buzzer, model 9124, is a self contained, low voltage and battery-operated device. Like all test instruments, it should be checked before using. A buzzing sound should be heard when a patch cord is plugged into the two polarized jacks thus completing the external circuit. A faint buzz (or no sound at all) indicates a weak or dead battery. See Fig. I-9.

FLYWHEELS

A flywheel is a relatively heavy wheel attached to a driven shaft. Its purpose is to smooth out sudden changes in shaft speed cause by periodic load fluctuations such as found in punch presses, piston type air compressors and water pumps. It provides *inertia* to keep the shaft turning smoothly during the peak cyclic loading periods. The flywheel absorbs wer y from the driving motor as it comes up to full speed and releases energy when the speed tends to decrease.

```
                         SPECIFICATIONS
                    Rim Diameter      -9 in OD
                    Rim Diameter      -6 in ID
                    Rim Mean Radius -3.75 in
                    Wheel Weight      -11.5 lbs
INERTIA WHEEL       Rim Weight        -10.3 lbs
                    Stored Energy     -ISO ftlbs (1800r/min)
```

Figure I-10

Small electric motors possess inertia, which are proportionally much smaller than those of large machines, with the result that they come up to speed much faster. We must therefore add inertia to make these small machines behave like the large ones do, and this is the purpose of the EMS Inertia Wheel.
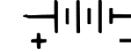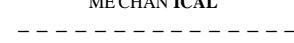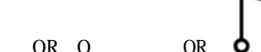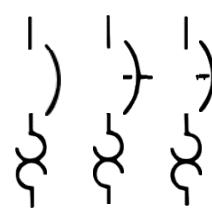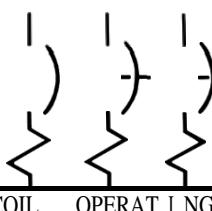
The EMS Inertia Wheel, Model 9126, is a flywheel designed to store 550 foot-pounds of energy when revolves at 1800 revolutions per minute. The driving motor during its acceleration from standstill to full speed must furnish this total energy. By using the wheel as a simulated high inertia load, motor-starting characteristics can be observed and measured. The inertia wheel is fastened to the motor shaft by turning the locking control knob clockwise until the brass-tipped rod makes contact with the shaft. Hand tightening is adequate for all of the experiments. See Fig. 1-10.
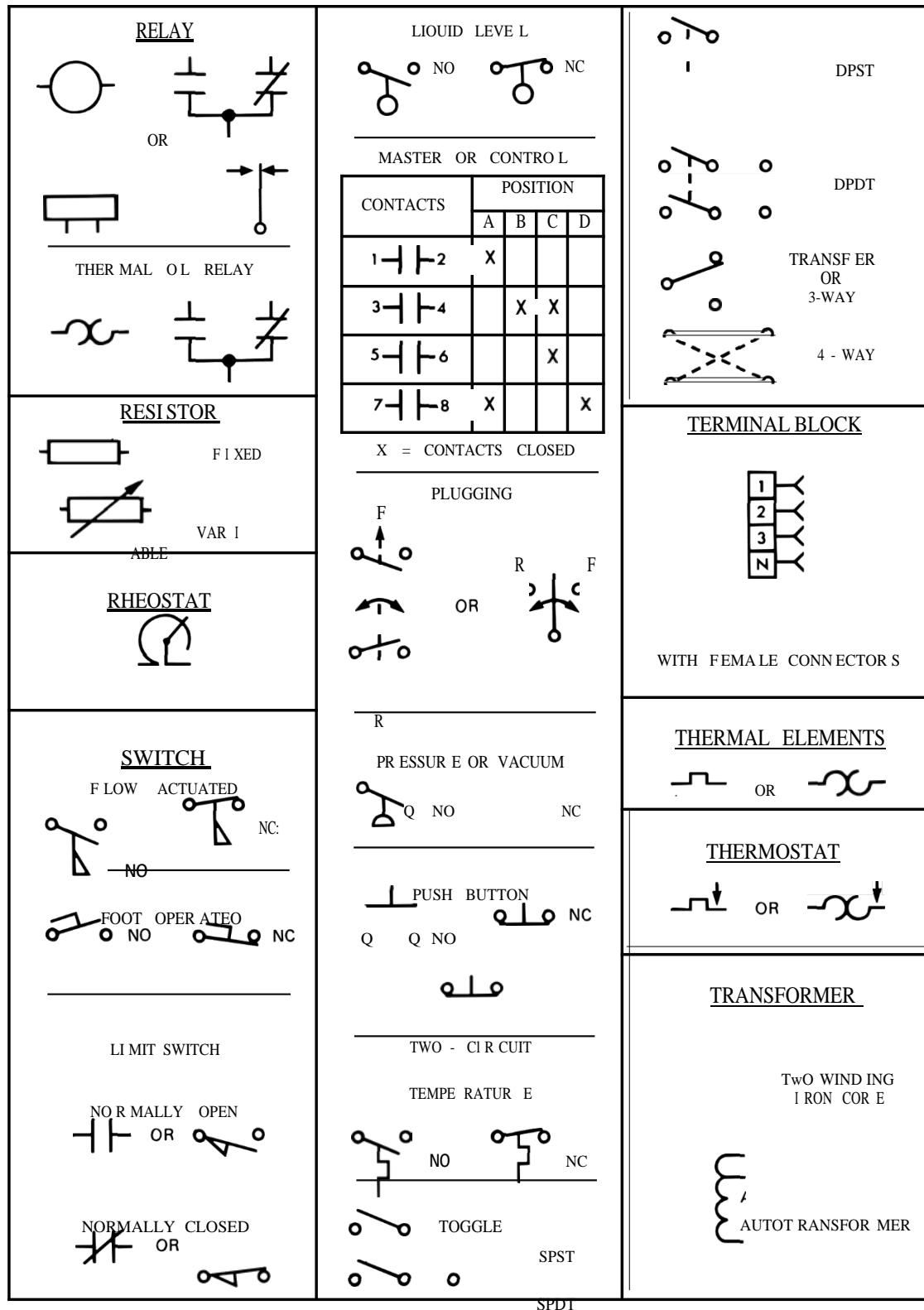
Caution: never attempt to stop the **inertia** wheel by hand. Wait until it comes to rest **by itself when moving.**

COMPONENT PANEL

The EMS Component Panel, Model 9127, provides a convenient method of assembling the snap-on control devices when performing the experiments listed in the student manual. The two panels mount vertically in the console module openings. Locking leaf springs hold the panels in place. The panels also provide a grounding path for the metal framework of each control device. This path is through the metal track to the grounding terminal located at the lower left-hand corner. During each experiment, this terminal should be connected, with a path cord, to one of "N" terminals of the power supply, which in turn is internally connected to the ground wire of the input power cord.

GRAPHIC SYMBOLS FOR ELECTRICAL MOTOR CONTROL

BATTERY

SINGLE CELL   MULTI CELL

BRAKE COIL

BUZZER

CAPACITOR

OR

POLARIZED

CIRCUIT BREAKER

3 POLE THERMAL

3 POLE MAGNETIC

COIL, OPERATING

OR

CONDUCTORS

CROSSING   CONNECTED

CONNECTORS

ELECTRICAL

MALE   FEMALE

MECHANICAL

CONTACTS

OR   OR

NORMALLY CLOSED

OR   OR

NORMALLY OPEN

TDO

TIME DELAY OPENING

TDC

OR

TIME DELAY CLOSING

DIODE

DISCONNECT SWITCH

3 POLE

METERS

AMMETER   VOLTMETER

MOTORS

DC MOTOR OR GENERATOR

ARM   ARMATURE

SHUNT FIELD

SERIES FIELD

TI

T2   SINGLE PHASE

TI

T2   SQUIRREL CACE 36

T3

WOUND ROTOR 34'

TI   M1

T2   M2

T3   M3

TI

T2

T3

RECTIFIERS

HALF WAVE

FULL WAVE BRIDCE

APPENDIX C

RELAY

OR

THERMAL O L RELAY

RESISTOR

F I XED

VAR I ABLE

RHEOSTAT

SWITCH

F LOW   ACTUATED

NC:

NO

FOOT OPER ATEO   NO   NC

LI MIT SWITCH

NO R MALLY   OPEN

OR

NORMALLY CLOSED

OR

LIOUID LEVE L

NO   NC

MASTER OR CONTRO L

CONTACTS	POSITION			
	A	B	C	D
1 ⊣ ⊢ 2	X			
3 ⊣ ⊢ 4		X	X	
5 ⊣ ⊢ 6			X	
7 ⊣ ⊢ 8	X			X

X = CONTACTS CLOSED

PLUGGING

F

R   F

OR

R

PR ESSUR E OR VACUUM

Q NO   NC

PUSH BUTTON

NC

Q   Q NO

TWO - CI R CUIT

TEMPE RATUR E

NO   NC

TOGGLE

SPST

SPDT

DPST

DPDT

TRANSF ER
OR
3-WAY

4 - WAY

TERMINAL BLOCK

1
2
3
N

WITH F EMA LE CONN ECTOR S

THERMAL ELEMENTS

OR

THERMOSTAT

OR

TRANSFORMER

TwO WIND ING
I RON COR E

AUTOT RANSFOR MER

APPENDIX D

MOTOR CHARACTERISTICS

	Motor Type	Starting Abilit	Speed Range RPM	cost'9	Typical Uses
1 φ	Shaded-Pole	Very Low 50^0 o to 100^0	Fixed 900, 1200, 1800, 3600	Very Low 75% to 85^0	Light-duty applications such as small fans, hair dryers, blowers, and computers.
	Split-phase	Low 75^0 to 200^0 o of full load	Fixed 900, 1200, 1800, 3600	Low 85% to 95%	Low-torque applications such as pumps, blowers, fans, and machine tools.
	Capacitor Start	High 200% to 350% of full load	Fixed 900, 1200, 1800	Low 90^0 to 110^0 o	Hard-to-start loads such as refrigerators, air compressors, and power tools.
	Capacitor Run	Very low 50^0 to 100^0 o of full load	Fixed 900, 1200, 1800	Low 100^0 o to 110^0 o	Applications that require a high running torque such as pumps and conveyors.
	Squirrel Cage Rotor I.M."	Low 100^0 o to 175 of full load	Fixed 900, 1200, 3600	Low 100%	Most industrial applications.
3 φ	Wound Rotor I.M."	High 200^0 o to 300% of full load	Varies by changing resistance in rotor or with variable ac frequency drives	Very high 250% to 350^0 o	Applications that require high torque at different speeds such as cranes and elevators.
	Synchronous	é LOW 40^0 o to 100^0 o of full load	Exact constant speed when used with fixed frequency voltage sources. The eed may be changed by changing the applied stator frequency	High 200^0 to 250^0	Applications that require very low speeds and correct power factors.

Based on Standard 3) Squirrel Cage Induction Motor

" Induction Motor

" Induction Motor

DC AND **UNIVERSAL MOTOR CHARACTERISTICS**

Motor Type	Starting Ability	Speed Range (RPM)	Cost[22]	Typical Uses
DC Series	Very high 400^0 o to 450^0 o of full load	Varies 0 to full speed	High 175^0 to 225^0	Applications that require very high torque such as hoists and bridges.
Shunt	Low 125^0 o to 250% of full load	Fixed or adjustable below full speed	High 175^0 o to 225^0	Applications that require better speed control than a series motor such as woodworking machines.
Compound	High 300^0 to 400% of full load	Fixed or adjustable	High 175^0 o to 225^0	Applications that require high torque and speed control as printing presses, conveyors, and hoists.
AC/DC Universal	High 300% to 400% of full load	Fixed 900, 1200, 1800	High 175^0 to 225^0 o	Most portable tools such as drills, routers, mixers, and vacuum cleaners.

" Based on Standard 3) Squirrel Cage Induction Motor

APPENDIX E

PARAMETER DESCRIPTIONS FOR THE ACX **INDUCTION MOTOR CONTROLLER**

P01: RUN SPEED COMMAND, Setting Range 0.00-1.00, Factory Setting 0.00
> Sets the digital speed command when the drive is in the Run mode. The controller is factory preset to use Parameter P01 as the speed command source.

P02: MINIMUM SPEED, Setting Range 0.00-75.0, Factory Setting 0.00
> Sets minimum speed.
> Note: if the minimum speed parameter P02 is set higher than the Maximum Speed Parameter (P03), the value in Parameter P03 will limit motor speed.

P03: MAXIMUM SPEED, Setting Range 50.0-100, Factory Setting 100
> Sets maximum speed.

P04: **ACCELERATION TIME,** Setting Range 00.1-999, Factory Setting 10.0
> Sets the amount of time it takes the drive to accelerate from zero speed to motor rated speed. This parameter also controls the rate at which the speed will change when using the keypad to increase motor speed.

P05: DECELERATION TIME, Setting Range 00.1-999, Factory Setting 10.0
> Sets the amount of time it takes the drive to decelerate from motor rated speed to zero speed. This parameter also controls the rate at which the speed will change when using the keypad to decrease motor speed.

P06: MOTOR FULL LOAD Avi s, Setting Range 0.60-3.98, Factory Setting 3.60
> Enter the motor nameplate current rating.

P07: **NOMINAL LINE VOLTAGE,** Setting Range 190-230, Factory Setting 230.
> Sets the nominal line voltage.

P08: SAVE **PARAMETERS,** Setting Range 0 or 1, Factory Setting 0
> Setting Parameter P08=1, saves all parameter settings. If parameter P08 is not set to 1, changed parameter values will be lost when AC power is removed.

P28: **REVERSE ENABLE:,** Setting Range 0 or 1, Factory Setting 0
> Enables the drive to operate in the reverse direction.
> 0= Disables operation in the reverse direction
> 1= Enables operation in the reverse direction.

P31: KEYPAD SPEED ADJUST, Setting Range 1 or 0, Factory Setting 1
> Allows the Up and Down arrow keys on the keypad to adjust motor speed when in the monitor mode.
> 0= Disables keypad speed adjust
> 1= Enables keypad speed adjust.

P33: **LINE STARTING,** Setting Range 1 or 0,m Factory Setting 0
> Allows the drive to be started when AC line power is applied to the drive.
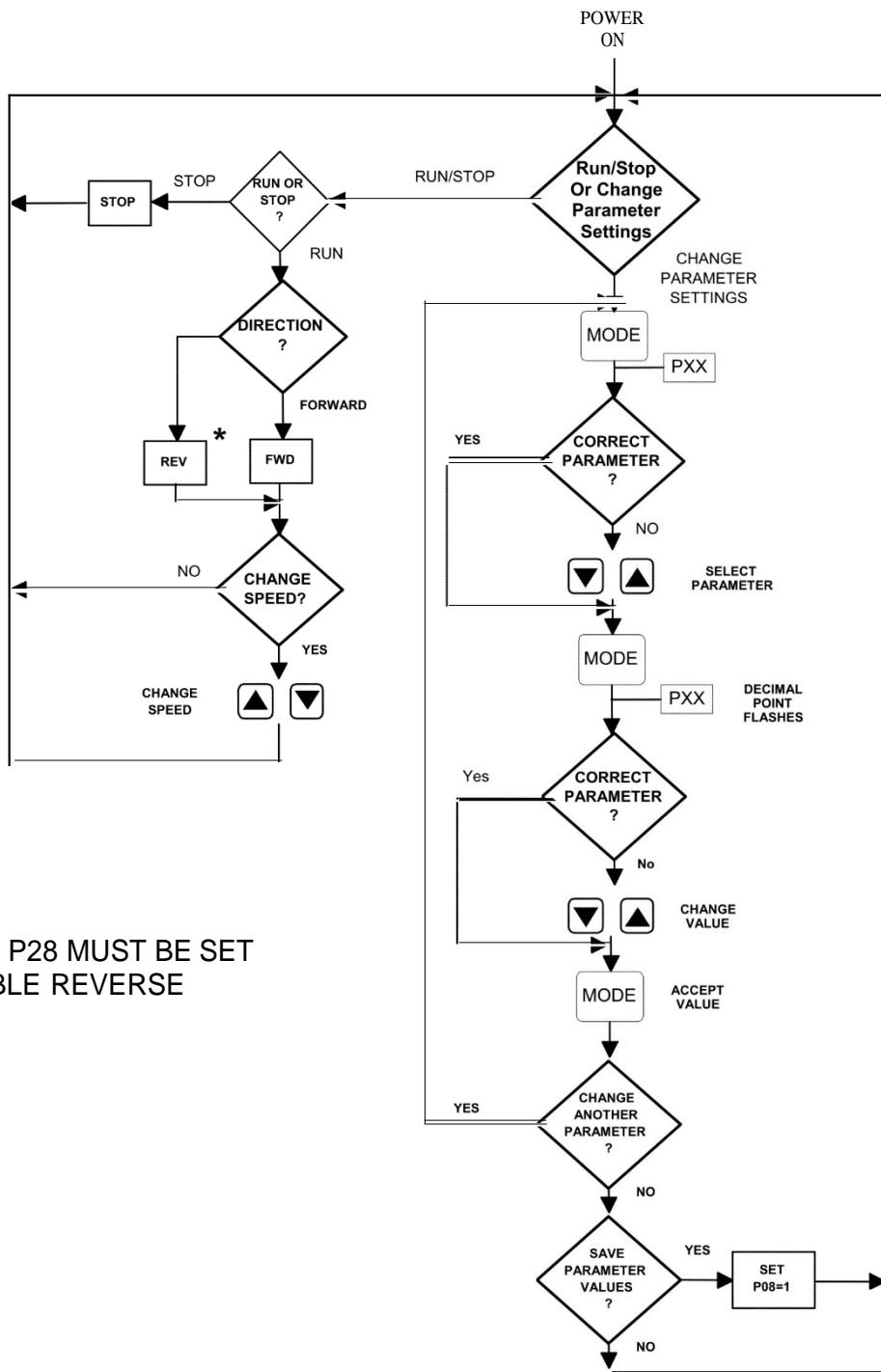> 0=Disables line starting
> 1= Enables line starting.
> When Parameter P33=1, a jumper must be placed between terminals 1 and 4 (forward) or 1 and 5 (reverse).

P96: **FACTORY PRESET,** Setting Range 1 or 0, Factory Setting 0.
> Setting Parameter P96=1 loads all parameters with the factory preset values.

FUNCTIONAL FLOW CHART OF THE ACX MODEL PWM DRIVE

"PARAMETER P28 MUST BE SET TO 1 TO ENABLE REVERSE FUNCTION

FIGURE E.1

APPENDIX F

TOTAL PARALLEL EQUIVALENT IIESISTANCE / REACTANCE
OBTAINABLE FROM EMS MODULES 8311, 8321 AND 8331 @ 60Hz

EQUIVALENT RESISTANCES REACTANCE VALUES	FIRST SECTION CLOSED SWITCHES	SECOND SECTION CLOSED SWITCHES	THIRD SECTION CLOSED SWITCHES
1200	**1200**	None	None
600	**600**	None	None
300	**300**	None	None
400	**1200&600**	None	None
240	**1200&300**	None	None
200	**600&300**	None	None
171.4	**1200&600&300**	None	None
150	**1200**	**1200&600&300**	None
133.3	**600**	**1200&600&300**	None
120	300	**600&300**	None
109.1	300	**1200&600&300**	None
100	**1200&300**	**1200&600&300**	None
92.3	**600&300**	**1200&600&300**	None
85.7	**1200&600&300**	**1200&600&300**	None
80	**1200**	**1200&600&300**	**1200&600&300**
75	**600**	**1200&600&300**	**1200&600&300**
70.6	**300**	**600&300**	**1200&600&300**
66.7	**300**	**1200&600&300**	**1200&600&300**
63.1	**1200&300**	**1200&600&300**	**1200&600&300**
60	**600&300**	**1200&600&300**	**1200&600&300**
57.1	**1200&600&300**	**1200&600&300**	**1200&600&300**

TABLE F.1