Electricity and New Energy

Investigations in Electric Power Technology

Modularized Systems - Volumes 1 to 4

Courseware Sample

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By the staff of Festo Didactic

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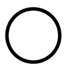
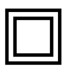
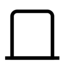
Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger
	Caution, lifting hazard
	Caution, hand entanglement hazard
	Notice, non-ionizing radiation
⎓	Direct current
∿	Alternating current
⏦	Both direct and alternating current
3∿	Three-phase alternating current
⏚	Earth (ground) terminal

Safety and Common Symbols

Symbol	Description
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

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Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

Table of Contents

Introduction

The Lab-Volt 0.2-kW Electromechanical Training System (EMS), Model 8001, is a modern modular instructional program. It represents a new approach to teaching electric power technology by providing new opportunities for laboratory observations. The program, presented in four subsystems and special applications, deals with the different techniques associated with the generation and use of electrical energy. The subsystems cover the common machines, and each subsystem is offered with its courseware presented in a student manual. The special applications deal with less common machines, and the courseware is available in individual leaflet form for each application.

Each subsystem is available as a package that consists of the equipment necessary to perform the laboratory exercises presented in the correlated student manual. This modular instructional program gives the instructor complete versatility in selecting a program adapted to students' specific career objectives.

The EMS System was developed by educators to satisfy educational requirements that include industrial applications of electric power technology. The design objective was to develop a low-power educational system with equipment that operates like industrial equipment. Through careful attention to engineering detail, the Lab-Volt EMS System meets this objective, and in so doing, provides laboratory results that are easy to understand, with data values that are easily observed.

Student manuals guide students step-by-step through the experiments and provide the necessary theoretical background to successfully complete the educational objectives. These manuals contain experiments that correlate with the training equipment for "hands-on" involvement with the subject matter. The instructor can select the experiments that will satisfy the objectives of technical courses or university programs.

The flexibility of this system allows students to use their own initiative during the laboratory sessions. Under the direction of an instructor, students can gain the required competencies for successful employment.

Courseware Outline

POWER CIRCUITS

Experiment 1 Series and Parallel Equivalent Resistances

To calculate the single resistance which is equivalent to a group of resistors connected in series. To calculate the single resistance which is equivalent to a group of resistors connected in parallel.

Experiment 2 Resistances in Parallel

To become physically acquainted with the Resistive Load Module EMS 8311. To learn the operational functions of the Resistive Load. To become familiar with the operation of an ohmmeter. To measure the equivalent resistance of resistors connected in parallel. To learn how to hook-up simple electrical circuits from a schematic diagram.

Experiment 3 Resistances in Series and in Series-Parallel

To measure the equivalent resistance of resistors connected in series. To calculate and measure the equivalent resistance of resistors connected in series-parallel. To learn how to hook-up more complex electrical circuits from a schematic diagram.

Experiment 4 Safety and the Power Supply

To learn the simple rules of safety. To learn how to use the AC/DC power supply.

Experiment 5 Ohm's Law

To demonstrate Ohm's Law and to show its various forms. To become familiar with DC voltmeters and ammeters.

Experiment 6 Circuit Solution – Part I

To calculate the voltages and currents in series and in parallel circuits.

Experiment 7 Circuit Solution – Part II

To verify experimentally, the theoretical calculations performed in Experiment 6.

Experiment 8 Power in DC Circuits – Part I

To calculate the power dissipated in a direct current circuit. To show that the power dissipated in a load is equal to the power supplied by the source.

Courseware Outline

POWER CIRCUITS

Experiment 9 Power in DC Circuits – Part II

To calculate the power dissipated in a resistive DC circuit. To show that this power can be found by using any one of three methods.

Experiment 10 The Transmission Line

To study the characteristics of a transmission line at no-load, full-load and overload conditions. To learn the meaning of transmission line "voltage drop". To learn the effects of a short circuit on a transmission line.

Experiment 11 AC Voltage and Current – Part I

To study a sine wave of alternating voltage and current. To understand frequency, cycle, period. To study instantaneous and average power. To learn about effective values of alternating voltage and current.

Experiment 12 AC Voltage and Current – Part II

To measure the effective value of an alternating voltage. To learn the use of AC voltmeters and ammeters. To verify Ohm's Law for AC circuits. To calculate power in AC circuit.

Experiment 13 The Wattmeter

To learn how to use a wattmeter. To become familiar with active and apparent power in AC circuits.

Experiment 14 Phase Angle, Active, and Apparent Power

To study the meaning of phase angle. To study the relationship between active and apparent power.

Experiment 15 Capacitive Reactance

To study the behavior of the capacitor in AC circuits. To become familiar with the meaning of capacitive reactive power.

Experiment 16 Inductive Reactance

To study the behavior of the inductor in AC circuits. To become familiar with the meaning of inductive reactive power.

Courseware Outline

POWER CIRCUITS

Experiment 17 Watt, Var, Volt-Ampere, and Power Factor

To study the relationship among watt, var and volt-ampere. To determine the apparent, active and reactive power of an inductive load. To improve the power factor of an inductive load.

Experiment 18 Vectors and Phasors – Series Circuit

To study the behavior of complex AC circuits by the use of vector graphics.

Experiment 19 Vectors and Phasors – Parallel Circuits

To study the behavior of complex AC circuits by the use of vector graphics.

Experiment 20 Impedance

To learn Ohm's Law for AC circuits. To solve complex AC circuits by the use of impedance equations.

Experiment 21 Three-Phase Circuits

To study the relationship between voltage and current in three-phase circuits. To learn how to make delta and wye connections. To calculate the power in three-phase circuits.

Experiment 22 Three-Phase Watts, Vars, and Volt-Amperes

To determine the apparent, active and reactive power in three-phase circuits. To calculate the power factor in three-phase circuits.

Experiment 23 Three-Phase Power Measurement

To measure power in a three-phase circuit using the two wattmeter method. To determine the active and reactive power, and the power factor of a three-phase system.

Experiment 24 Phase Sequence

To determine the phase sequence of a three-phase power line.

Appendices A Equipment Utilization Chart
B Impedance Table for the Load Modules
C Performing the Electrical Power Technology Courseware Using the Lab-Volt Data Acquisition and Management System

Courseware Outline

DC MACHINES

Experiment 1 Prime Mover and Torque Measurement

To learn how to connect a three-phase synchronous motor. To learn how to connect the electrodynamometer. To learn how to use the Prony brake.

Experiment 2 The Direct Current Motor – Part I

To examine the construction of a DC motor/generator. To measure the resistance of its windings. To study the nominal current capabilities of the various winding.

Experiment 3 The Direct Current Motor – Part II

To locate the neutral brush position. To learn the basic motor wiring connections. To observe the operating characteristics of series and shunt connected motors.

Experiment 4 The DC Shunt Motor

To study the torque vs speed characteristics of a shunt wound DC motor. To calculate the efficiency of the shunt wound DC motor.

Experiment 5 The DC Series Motor

To study the torque vs speed characteristics of a series wound DC motor. To calculate the efficiency of the series wound DC motor.

Experiment 6 The DC Compound Motor

To study the toque vs speed characteristics of a compound wound DC motor. To calculate the efficiency of the compound wound DC motor.

Experiment 7 The DC Separately Excited Shunt Generator

To study the properties of the separately excited DC shund generator under no-load and full-load conditions. To obtain the saturation curve of the generator. To obtain the armature voltage vs armature current load curve of the generator.

Experiment 8 The DC Self Excited Shunt Generator

To study the properties of the self-excited DC shunt generator under no-load and full-load conditions. To learn how to connect the self-excited generator. To obtain the armature voltage vs armature current load curve of the generator.

Courseware Outline

DC MACHINES

Experiment 9 The DC Compound Generator

To study the properties of compound DC generators under no-load and full-load conditions. To learn how to connect both the compound and the differential compound generators. To obtain the armature voltage vs armature current load curves for both generators.

Experiment 10 DC Motor Starter

To examine the construction of a DC motor starter. To observe the operation of a 3-point DC starter. To observe the operation of a 4-point DC starter.

Experiment 11 Thyristor Speed Controller

Completing this exercise will give you an introduction to thyristor speed controllers. You will learn how to control the speed of a DC motor by varying the armature voltage using a thyristor speed controller.

Experiment 12 Thyristor Speed Controller with Regulation

In this exercise, you will be introduced to thyristor speed controllers operating in the closed-loop mode of control. You will learn how the closed-loop mode of control regulates the motor speed by detecting the armature voltage and current. You will learn how to control the acceleration of the DC Motor/Generator. You will also learn how to limit the current and the torque of the DC Motor/Generator.

Appendices

A Equipment Utilization Chart
B Impedance Table for the Load Modules
C Performing the Electrical Power Technology Courseware Using the Lab-Volt Data Acquisition and Management System
D SCR Speed Control – Part I
E SCR Speed Control – Part II

Courseware Outline

SINGLE-PHASE TRANSFORMERS AND AC MACHINES

Experiment 1 The Single-Phase Transformer

To study the voltage and current ratios of a transformer. To learn about transformer exciting currents, volt-ampere capacity and short-circuit currents.

Experiment 2 Transformer Polarity

To determine the polarity of transformer windings. To learn how to connect transformer windings in series aiding. To learn how to connect transformer windings in series opposing.

Experiment 3 Transformer Regulation

To study the voltage regulation of the transformer with varying loads. To study transformer regulation with inductive and capacitive loading.

Experiment 4 The Autotransformer

To study the voltage and current relationship of an autotransformer. To learn how to connect a standard transformer as an autotransformer.

Experiment 5 Transformers in Parallel

To learn how to connect transformers in parallel. To determine the efficiency of parallel connected transformers.

Experiment 6 The Distribution Transformer

To understand the standard distribution transformer with a 120/220 V secondary winding.

Experiment 7 Prime Mover and Torque Measurement

To learn how to connect a split-phase induction motor. To learn how to connect the electrodynamometer. To learn how to use the Prony brake.

Experiment 8 The Split-Phase Inductor Motor – Part I

To examine the construction of a split-phase motor. To measure the resistance of its windings.

Experiment 9 The Split-Phase Inductor Motor – Part II

To learn the basic motor wiring connections. To observe the starting and running operation of the split-phase motor.

Courseware Outline

SINGLE-PHASE TRANSFORMERS AND AC MACHINES

Courseware Outline

THREE-PHASE TRANSFORMERS AND AC MACHINES

Experiment 1 Three-Phase Transformer Connections

To connect transformers in delta and wye configurations. To study the current and voltage relationships.

Experiment 2 Prime Mover and Torque Measurement

To learn how to connect a direct current shunt motor. To learn how to connect the electrodynamometer. To learn how to use the Prony Brake.

Experiment 3 The Wound-Rotor Induction Motor – Part I

To examine the construction of the three-phase wound-rotor induction motor. To understand exciting current, synchronous speed and slip in a three-phase induction motor. To observe the effect of the revolving field and rotor speed upon the voltage induced in the rotor.

Experiment 4 The Wound-Rotor Induction Motor – Part II

To determine the starting characteristics of the wound-rotor induction motor. To observe the rotor and stator currents at different motor speeds.

Experiment 5 The Wound-Rotor Induction Motor – Part III

To observe the characteristics of the wound rotor induction motor at no-load and full-load. To observe speed control using an external variable resistance.

Experiment 6 The Squirrel-Cage Induction Motor

To examine the construction of the three-phase squirrel-cage motor. To determine its starting, no-load and full-load characteristics.

Experiment 7 The Synchronous Motor – Part I

To examine the construction of the 3ϕ synchronous motor. To obtain the starting characteristics of the 3ϕ synchronous motor.

Experiment 8 The Synchronous Motor – Part II

To observe how a synchronous motor can act as a variable inductance or capacitance. To obtain the DC current vs AC current characteristics curve for the synchronous motor.

Courseware Outline

THREE-PHASE TRANSFORMERS AND AC MACHINES

Experiment 9 The Synchronous Motor – Part III

To determine the full-load characteristics of the synchronous motor. To determine the pull-out torque of the synchronous motor.

Experiment 10 The Three-Phase Alternator

To obtain the no-load saturation curve of the alternator. To obtain the short-circuit characteristics of the alternator.

Experiment 11 The Alternator Under Load

To determine the voltage regulation characteristics of the alternator with resistive, capacitive and inductive loading. To observe the effect of unbalanced loads on the output voltage.

Experiment 12 Alternator Synchronization

To learn how to synchronize an alternator to the electric power utility system. To observe the effects of improper phase conditions upon the synchronizing process.

Experiment 13 Alternator Power

To observe the effect of DC excitation upon the power delivered by an alternator. To observe the effect of power delivered by an alternator upon the torque of the prime mover.

Experiment 14 Three-Phase Motor Starter

To examine the construction of a three-phase magnetic starter and to study its operation. To examine the construction of an automatic synchronous motor starter and evaluate its performance.

Experiment 15 Frequency Conversion

To observe the no-load and full-load characteristics of a rotary frequency converter. To operate a three-phase squirrel-cage motor from a 120 Hz power source.

Experiment 16 Reactance and Frequency

To show that inductive reactance is doubled when the frequency is doubled. To show that capacitive reactance is halved when the frequency is doubled.

Courseware Outline

Sample Exercise

Extracted from

Power Circuits

Experiment 14

Phase Angle, Active, and Apparent Power

OBJECTIVE

- To study the meaning of phase angle.
- To study the relationship between active and apparent power.

DISCUSSION

In a DC circuit, with a resistance load, as the voltage across the resistor increases, the current through the resistor increases. This is also true in an AC circuit with a resistance load. If a sinusoidal voltage e is applied across a resistor R, the instantaneous variations of current i through R follow exactly the instantaneous changes in voltage e. Thus, at the instant e is going through zero, i is going through zero. When e is at maximum, i is at maximum. When the voltage and current are "in step" with each other, they are said to be in phase. This relationship is shown graphically in Figure 14-1. However, it only occurs when the circuit load is a pure resistance.

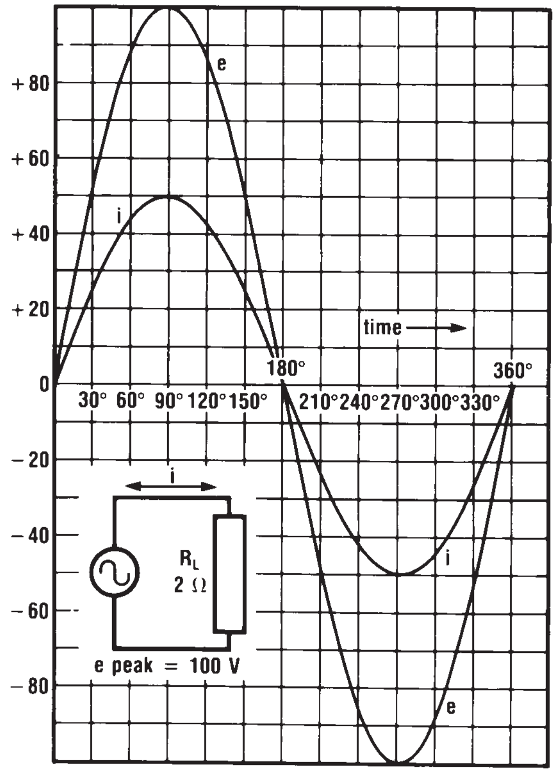
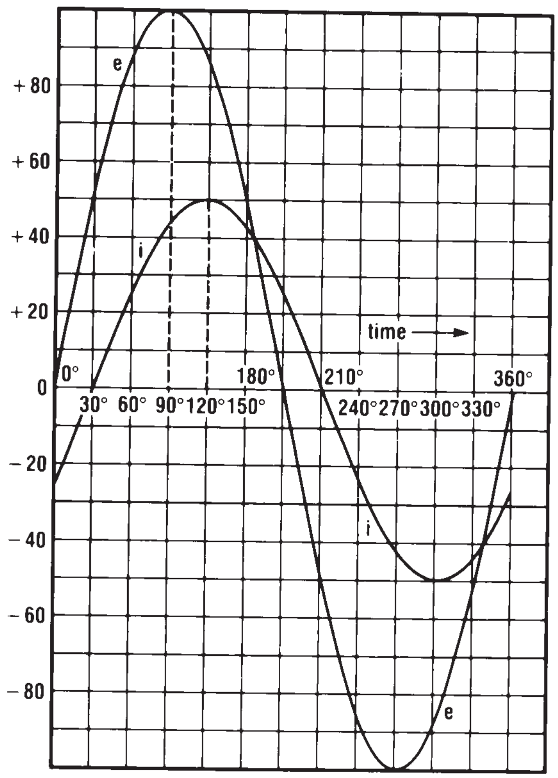


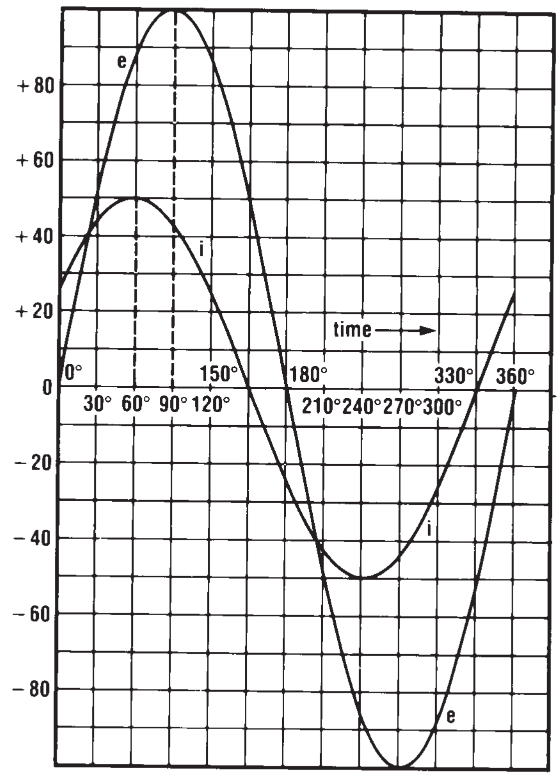
Figure 14-1.

There are conditions under which the current is not "in phase" with the voltage. Such a condition is shown in Figure 14-2 (a) where the current attains its maximum value some 30 electrical degrees after the voltage. The current is said to "lag" behind the voltage by 30°.

On the other hand, the current waveform shown in Figure 14-2 (b) attains its maximum value 30° ahead of the voltage. The current is said to "lead" the voltage by 30°.



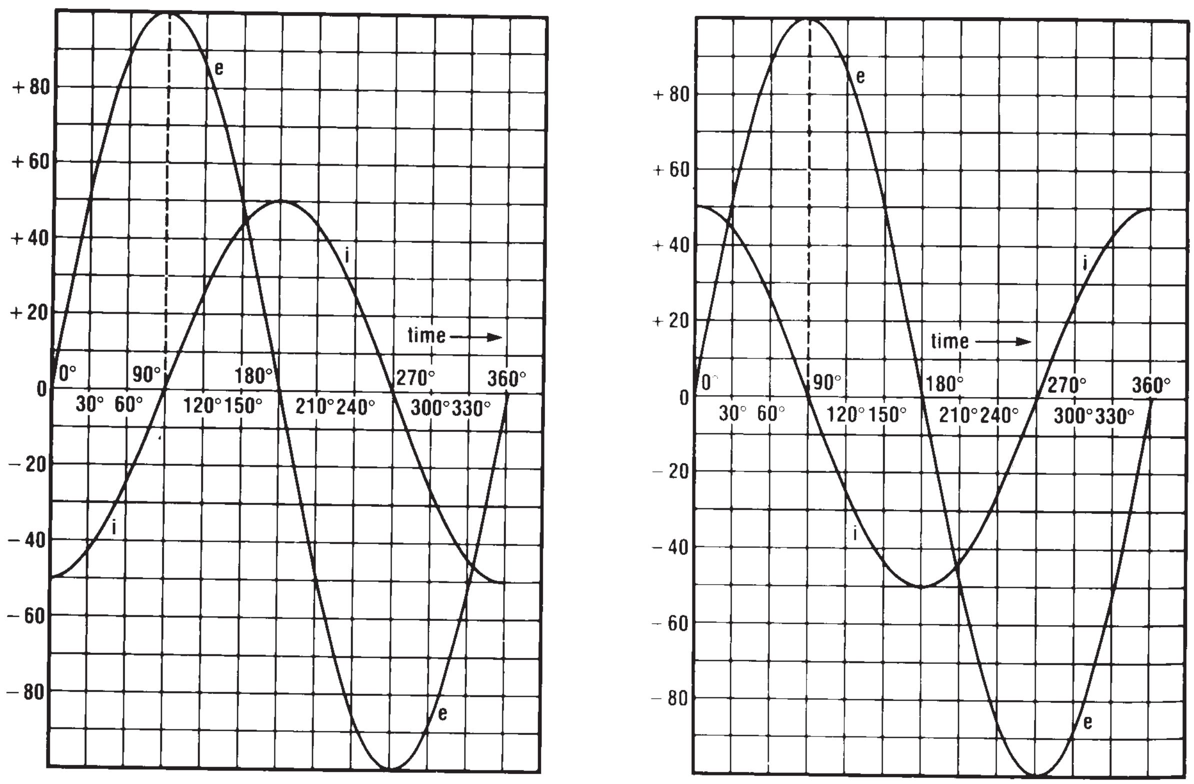
(a)



(b)

Figure 14-2.

To complete the picture, the current in Figure 14-3 (a) lags behind the voltage by 90°. (we would also be correct in stating that the voltage leads the current by 90°). In Figure 14-3 (b), the current leads the voltage by 90°. (We could also say that the voltage "lags" the current by 90°). Here we find the interesting condition where the current is zero at the instant when the voltage is maximum and vice-versa.



(a) (b)

Figure 14-3.

Although this would appear quite improbable because we have been told up until this point that the voltage causes the current. How then can we have maximum current when the voltage is zero? It occurs when a load (such as on containing an inductor or capacitor) which is capable of storing energy is connected to an AC source. The load absorbs energy during part of the cycle and, depending upon how much resistance is in the circuit, returns part of the energy during another part of the cycle. This absorbing and returning of energy shows up (among other ways) by the voltage and current being out of phase. If the load is purely inductive or capacitive, with no resistance, all of the energy absorbed during two quarters of the cycle is returned during the remaining two. The active power is zero. The voltage and current will be 90° out of phase with this type of load.

Assume that the peak voltage value is 100 V and the peak current value is 50 A in every example shown in Figures 14-1 to 14-3. An AC voltmeter would indicate (70.7 V) and an AC ammeter would likewise indicate a current of 35.3 A. But there must be a difference somewhere to account for the phase angle between E ans I. There is indeed, and as we shall see, this difference is manifested in the amount of active power associated with each of the examples shown.

Phase Angle, Active, and Apparent Power

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

☐ 1. The load for the circuit shown in Figure 14-4, is resistive. The AC current meter indicates 35.3 A (rms) and the AC voltmeter indicates 70.7 V (rms).

Calculate the power being supplied by the source.

E ______ x I ______ = ______ VA

Is the power “active” or “apparent”?

____

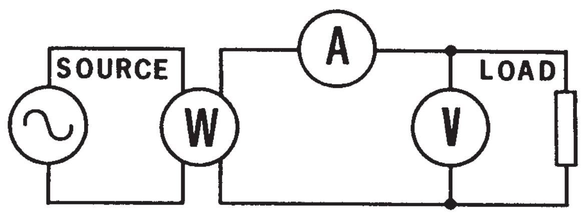


Figure 14-4.

Does the wattmeter indicate this power?

____

Are the voltage and current waveforms in phase?

____

☐ 2. The voltage and current waveforms, for the circuit of Figure 14-4, are shown on the graph of Figure 14-5.

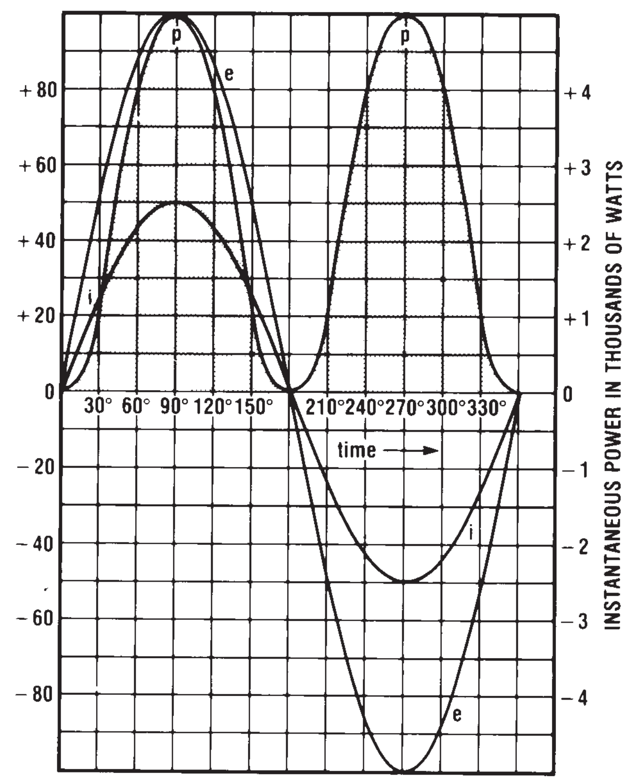


Figure 14-5.

The instantaneous power curve has also been plotted on the graph. Note that the instantaneous power curve p is sinusoidal and goes through two complete cycles during one cycle (360°) of the voltage or current.

a. Does the power curve ever go negative when the circuit load is resistive?

☐ Yes ☐ No

b. Is this power "active"?

☐ Yes ☐ No

c. Can you visually determine if the average power for one cycle (360°) is actually ½ of the peak power?

____

d. What is the average power? ______ W

☐ 3. The load for the circuit shown in Figure 14-6 is capacitive. With a capacitance load the current leads the voltage by 90°. (The current has exactly the same wave shape as in procedures 1 and 2, but is simply shifted by 90° to the left). The AC current meter indicates 35.3 A (rms) and the AC voltmeter indicates 70.7 V (rms).

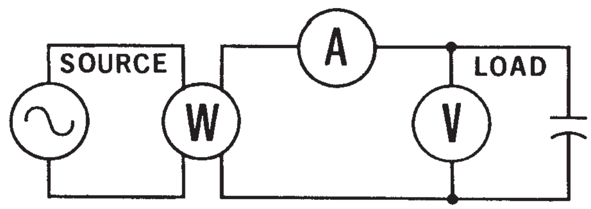


Figure 14-6.

Calculate the power being supplied by the source.

E ______ x I ______ = ______ VA

Is this power "active" or "apparent"?

____

Does the wattmeter indicate this power?

____

☐ 4. The voltage and current waveforms for the circuit of Figure 14-6 are shown on the graph of the Figure 14-7.

Note that when the instantaneous voltage e is at its maximum value, the instantaneous current i is at zero. Conversely, when the instantaneous current i is at its maximum value, the instantaneous voltage e is at zero.

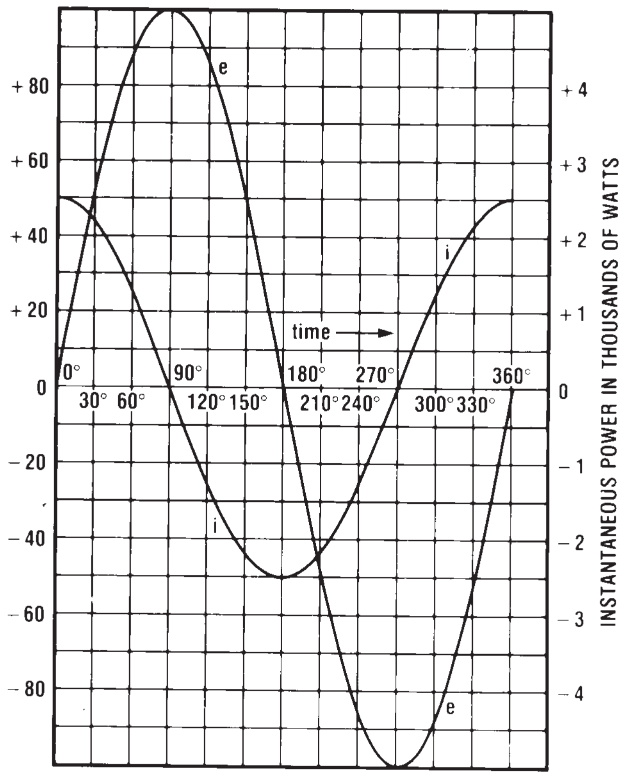


Figure 14-7.

☐ 5. The instantaneous current and voltage values for each 45° interval are shown in Table 14-1.

Calculate the instantaneous power values for each 45° interval and complete Table 14-1.

°	0	45	90	135	180	225	270	315	360
e	0	70.7	100	70.7	0	−70.7	−100	−70.7	0
i	50	35.3	0	−35.3	−50	−35.3	0	35.3	50
p									

Table14-1.

☐ 6. Plot your calculated 45° interval power values on the graph of Figure 14-7, and draw the power curve through these points. Remember, that the power curve is sinusoidal and goes through two complete cycles for every single cycle (360°) of the voltage or current.

☐ 7. From your plotted power curve determine the following:

a. Peak power = ______ W

b. Peak power occurs at ______ °

c. Does the instantaneous power ever go negative?

☐ Yes ☐ No

d. Are all of the poser curve peaks of equal magnitude?

☐ Yes ☐ No

e. Is the enclosed area under the positive power curve the same as the enclosed area under the negative power curve?

☐ Yes ☐ No

f. The average (apparent) power for one complete cycle (360°) in volt-amperes = ______ VA.

g. The average (active) power for one complete cycle (360°) in watts = ______ W.

☐ 8. The load for the circuit shown in Figure 14-8 is inductive. With an inductive load the current lags the voltage by 90°. (The current has exactly the same wave shape as in procedures 1 and 2, but is simply shifted by 90° to the right). The AC current meter indicates 35.3 A and the AC voltmeter indicates 70.7 V.

Calculate the power being supplied by the source.

E______ x I ______ = ______ VA

Is this power “active” or “apparent”?

____

Does the wattmeter indicate this power?

____

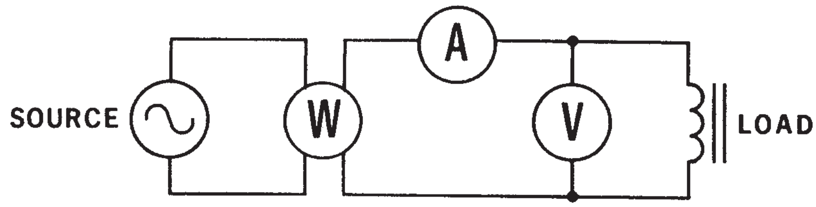


Figure 14-8.

☐ 9. The voltage and current waveforms, for the circuit of Figure 14-8 are shown on the graph of Figure 14-9.

Note that when the instantaneous voltage e is at its maximum value, the instantaneous current i is at zero. Conversely, when the instantaneous current i is at its maximum value, the instantaneous voltage e is at zero.

☐ 10. The instantaneous current and voltage values for each 45° interval are shown in Table 14-2.

°	0	45	90	135	180	225	270	315	360
e	0	70.7	100	70.7	0	−70,7	−100	−70.7	0
i	−50	−35.3	0	35.3	50	35.3	0	−35.3	−50
p									

Table 14-2.

Calculate the instantaneous power values for each 45° interval and complete Table 14-2.

☐ 11. Plot your calculated 45° interval power values on the graph of Figure 14-9, and draw the power curve through these points. Remember that the power curve is sinusoidal and goes through two complete cycles for every single cycle (360°) of the voltage or current.

Phase Angle, Active, and Apparent Power

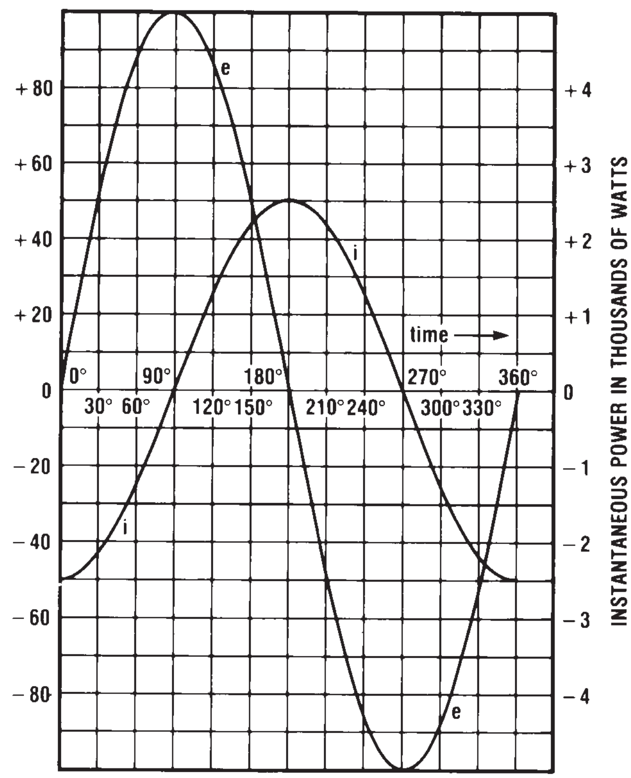


Figure 14-9.

☐ 12. From your plotted power curve determine the following:

a. Peak power = ______ W

b. Peak power occurs at ______ °

c. Does the instantaneous power ever go negative?

☐ Yes ☐ No

d. Are all the power curve peaks of equal magnitude?

☐ Yes ☐ No

e. Is the enclosed area under positive power curve the same as the enclosed area under the negative power curve?

☐ Yes ☐ No

f. The average (apparent) power for one complete cycle (360°) in volt-amperes = ______ VA

g. The average (active) power for one complete cycle (360°) in watts = ______ W

REVIEW QUESTIONS

1. If, in one cycle (360°), all of the instantaneous power falls under positive loops (no negative loops), the load must be:

   a) a resistor; b) an inductor or capacitor.

   Explain:

   ____

   ____

2. Draw, in the spaces provided, rough sketches showing the following:

   a) A current which lags the voltage by 60°.

   b) A current which leads the voltage by 60°.

c) A current which lags the voltage by 180°.

3. A wattmeter will indicate zero when the current lags (or leads) the voltage by 90°. Explain.

____

____

4. Assuming a 60 Hz system, how much time - in seconds - is the peak positive current behind the peak positive voltage when the current lags the voltage by:

a) 90° ______________________________________

______________________________ = __________ s

b) 0° ______________________________________

______________________________ = __________ s

c) 60° ______________________________________

______________________________ = __________ s

Sample Exercise

Extracted from

DC Machines

Experiment 3

The Direct Current Motor – Part II

OBJECTIVE

- To locate the neutral brush position.
- To learn the basic motor wiring connections.
- To observe the operating characteristics of series and shunt connected motors.

DISCUSSION

In order of 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, motor speed is mainly determined by the armature voltage and the stator flux. 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. DC motors have been known to fly apart under these overspeed conditions. However, your DC motor has been carefully designed to withstand possible overspeed condition.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

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

Finding the Neutral

☐ 1. You will now determine the neutral brush position for your DC motor by using alternating current. Using your Power Supply, AC Voltmeter and DC Motor/Generator, connect the circuit shown in Figure 3-1. Terminals 4 and N on the power supply will furnish variable 0-120 V ac as the voltage output control is advanced.

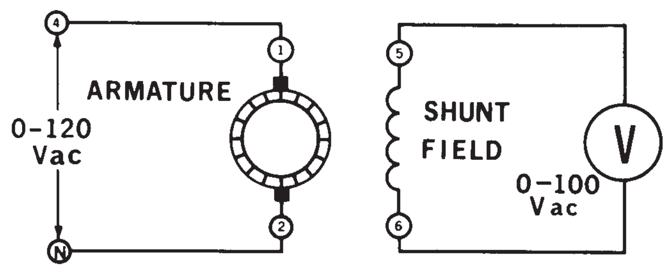


Figure 3-1.

DO NOT APPLY POWER AT THIS TIME!

☐ 2. Unlock the DC Motor/Generator and move it forward approximately 10 cm [4 in]. Reach behind the front face of the module and move the brush positioning lever to its maximum clockwise position. Do not slide the module back in place (you will later move the brushes again).

☐ 3. Turn on the power supply. Place the power supply voltmeter switch to its 4-N position. Slowly advance the voltage output control until the AC voltmeter connected across the shunt field winding indicates approximately 80 V ac. (The AC voltage across the shunt field is induced by the AC current through the armature. This will be covered in a later Experiment).

☐ 4. a. Carefully reach 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 AC voltage across the field drops to zero and then increases again as you approach the other extreme counter-clockwise position.

b. Leave the brushes at the position where the induced voltage is zero. This is the neutral point of your DC Motor/Generator.

Each time you use the DC Motor/Generator the brushes should be set at the neutral position.

c. Return the voltage to zero and turn off the power supply. Slide your DC Motor/Generator back in place and disconnect your circuit.

Series Motor Connections

☐ 5. Using your Power Supply, DC Voltmeter/Ammeter and DC Motor/Generator, connect the circuit shown in Figure 3-2. Notice that the armature is connected in series with the series field winding, across the input voltage.

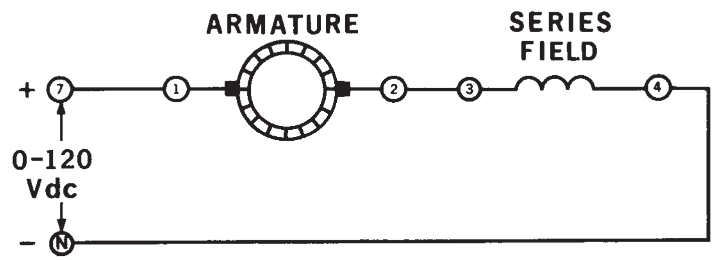


Figure 3-2.

☐ 6. Turn on the power supply. Place the power supply voltmeter switch to its 7-N position. Adjust the output voltage to 120 V dc.

☐ 7. a. Does the motor turn fast?

☐ Yes ☐ No

b. Using your hand tachometer, measure the motor speed in revolutions per minute.

Series speed = ______ r/min

Note: *The operating instructions are enclosed within the tachometer container.*

☐ 8. a. Reduce the power supply voltage and note the effect on motor speed. Comments:

____

b. Reduce the voltage until you can determine the direction of rotation (clockwise or counterclockwise).

Rotation = ______

c. Reduce the voltage to zero and turn off the power supply.

☐ 9. Reconnect your circuit as shown in Figure 3-3. (The only change made to the circuit of Figure 3-2 is that the connections to the armature have been reversed).

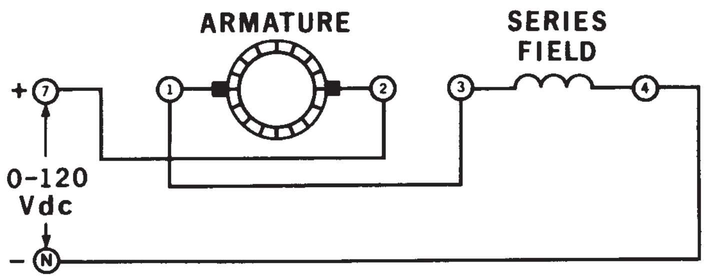


Figure 3-3.

☐ 10. Repeat procedures 6 through 8 (using the reversed armature connections shown in Figure 3-3).

Series speed$_{(reversed)}$ = ______ r/min

Rotation = ______

☐ 11. State a rule for changing the direction of rotation of a series connected DC motor.

____

Shunt Motor Connections

☐ 12. Connect the circuit shown in Figure 3-4. Notice that the rheostat is in series with the shunt field, and that this combination is in parallel with the armature, across the input voltage.

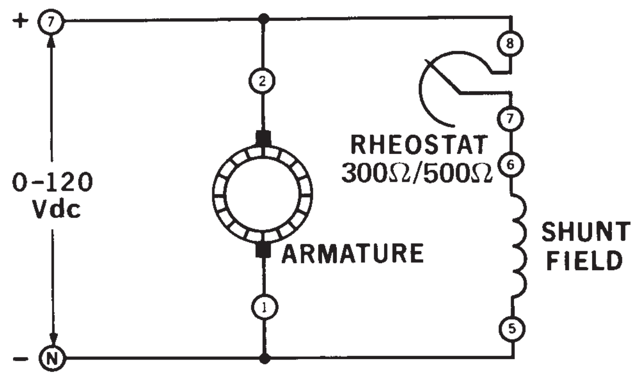


Figure 3-4.

☐ 13. a. Adjust the rheostat for minimum resistance (approximately 0 Ω, when turned fully clockwise).

b. Turn on your power supply and adjust for 120 V dc.

c. Using your tachometer measure the motor speed.

Shunt speed$_{\text{(zero ohms)}}$ = ______ r/min

d. Adjust the rheostat for maximum resistance (approximately 500 Ω).

e. Determine the direction of rotation.

Rotation = ______

☐ 14. a. Return the voltage to zero and turn off the power supply.

b. Reverse the polarity of the input voltage by interchanging the power supply connection leads only.

☐ 15. Repeat procedure 13 and compare your results:

a. Did the rotation change direction?

☐ Yes ☐ No

b. Did the speed change?

☐ Yes ☐ No

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

☐ 16. Interchange the connection leads to the power supply. Your circuit should be the same as the one shown in Figure 3-4. Now reverse the connections to the armature only.

☐ 17. Repeat procedure 13 and compare the direction of rotation to that found in procedure 13.

Rotation = ______

☐ 18. a. While the motor is still running, momentarily open the shunt field circuit by removing the connection lead from one of the terminals of the shunt field winding (5 or 6). Be extremely careful not to touch any of the other terminal connections or any metal during this procedure. Be prepared to immediately cut power to the motor by turning off the power supply.

b. Explain what happens when a DC motor loses power to its shunt field.

____

____

c. Could the same thing occur in a series field connected DC motor? Explain.

☐ Yes ☐ No

____

____

☐ 19. Connect the circuit shown in Figure 3-5. Note that the armature is connected to the variable 0-120 V dc output (terminals 7 and N) while the shunt field is now connected to the fixed 120 V dc output (terminals 8 and N).

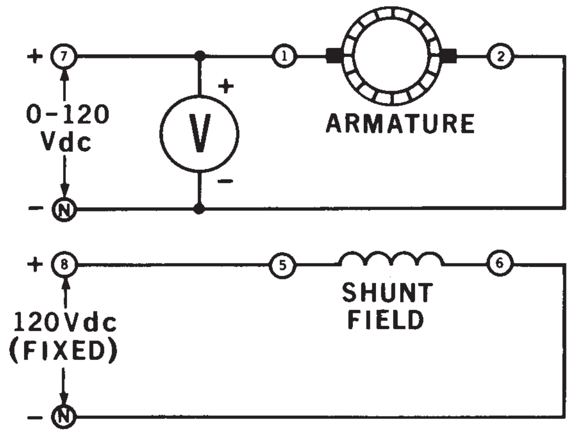


Figure 3-5.

☐ 20. a. Turn on the power supply. Adjust the armature voltage to 30 V dc as indicated by the meter.

b. Use your hand tachometer and measure the motor speed. Record your speed measurement in Table 3-1. (Wait until the motor speed stabilizes before you take your measurement).

c. Repeat (b) for each of the voltage values listed in the Table. Return voltage to zero and turn off the power supply.

E (volts)	0	30	60	90	120
SPEED (r/min)	0				

Table 3-1.

d. Plot each of the points from Table 3-1 on the graph shown in Figure 3-6. Draw a smooth curve through your plotted points.

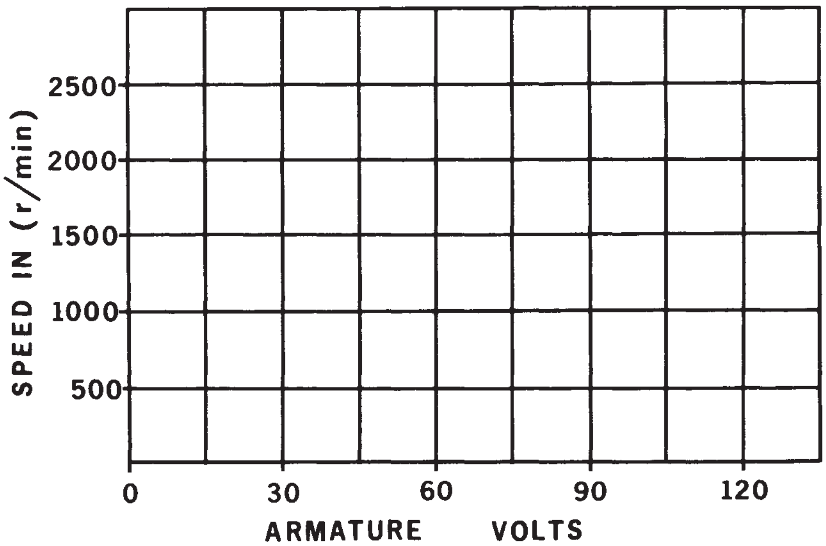


Figure 3-6.

e. Does varying the armature voltage (with the shunt field voltage held constant) offer a good method of speed control?

☐ Yes ☐ No

REVIEW QUESTIONS

1. Explain how to locate the neutral brush position in a DC motor.

____

2. Would the motor turn if only the armature were excited (had voltage applied across it)?

☐ Yes ☐ No

3. Why is it dangerous to supply power to an unloaded series connected DC motor?

____

4. In what two ways may the rotation of a shunt connected DC motor be reversed?

____

5. Why are field loss detectors necessary in large DC motors?

____

6. In procedure 20:

   a) Does the motor speed double when the armature voltage is doubled? Explain.

      ☐ Yes ☐ No

      ____

   b) Would it be correct to say “with a fixed field voltage, the speed of a shunt motor is proportional to its armature voltage?” Explain.

      ☐ Yes ☐ No

      ____

7. Draw a circuit showing how you would connect:

   a) a shunt motor to a DC supply.

b) a shunt motor to a DC supply, using a field rheostat.

c) a series motor to a DC supply.

8. In what two ways can the speed of DC motor be varied?

a) ______________________________

b) ______________________________

9. Of the two methods given in (8):

    a) which method gives the greatest speed range? ______

    b) which method is the most economical (uses fewer parts)? ______

Sample Exercise

Extracted from

Single-Phase Transformers

and AC Machines

Experiment 11

The Capacitor-Start Motor

OBJECTIVE

- To measure the starting and operating characteristics of the capacitor-start motor.
- To compare its starting and running performance with the split-phase motor.

DISCUSSION

When the split-phase rotating field was described, it was stated that the different resistance-reactance ratio of the two windings was designed to give the difference in time phase of the currents in the windings necessary to produce a rotating magnetic field.

In two-phase machines, where the windings are identical but displaced in space by 90°, the ideal time phase displacement of the winding currents is 90°.

For both two-phase and split-phase motors the torque developed at starting can be calculated using the relationship:

$$T = k\, I_1 I_2 \sin \alpha$$

where k is a machine constant, I_1 and I_2 are the currents in the windings, and α is the angle between the currents.

Because of the small magnitude of α in the split-phase machine the developed torque is relatively low. It is possible to increase α by adding capacitance in series with the auxiliary winding. If too much capacitance is added, the impedance of the winding is increased to the point that there is an unacceptable reduction in the current which more than offsets the benefit gained from increasing α.

The optimum value of C is that where the product of the sine of α and the auxiliary winding current is a maximum.

The capacitor and the start winding are disconnected by a centrifugal switch, just as in the case of the standard split-phase motor. 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.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

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

☐ 1. Using your Capacitor-Start Motor, Power Supply, and AC Ammeter, connect the circuit shown in Figure 11-1. Note that the fixed 120 V ac output of the power supply, terminals 1 and N are being used.

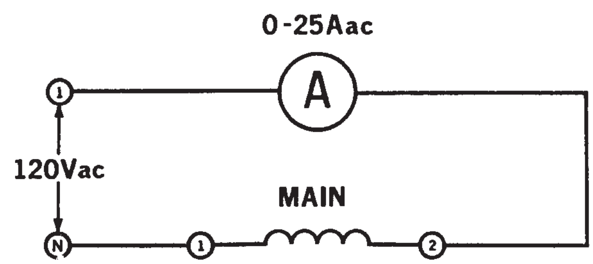


Figure 11-1.

☐ 2. Close the power supply switch and measure the current through the main winding as quickly as possible - within 3 seconds.

$I_{main\ winding}$ = ______ A ac

☐ 3. a. Disconnect the leads from the main winding and connect them to the auxiliary winding and capacitor, as shown in Figure 11-2.

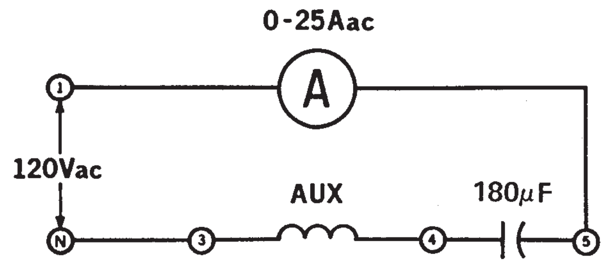


Figure 11-2.

b. Repeat procedure 2.

Note: *Remember to take your measurement as quickly as possible.*

$I_{auxiliary\ winding}$ = _______ A ac

☐ 4. a. Connect both windings in parallel, terminals 1 to 3 and 2 to 5, as shown in Figure 11-3.

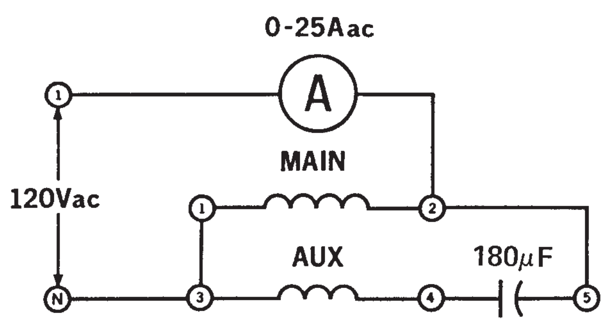


Figure 11-3.

b. Couple the electrodynamometer to the capacitor-start motor with the timing belt.

c. Connect the input terminals of the electrodynamometer to the fixed 120 V ac output of the power supply, terminals 1 and N.

d. Set the electrodynamometer 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.

$I_{starting}$ = _______ A ac

☐ 5. Compare your results from procedures 2, 3 and 4 with the results from procedures 2, 3 and 4 of Experiment 10.

a. What conclusions can you make about the main winding currents?

____

____

b. What conclusions can you make about the auxiliary winding currents?

____

____

____

c. What conclusions can you make about the starting current for each type of motor?

____

____

☐ 6. Using your Single-Phase Wattmeter, Electrodynamometer, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 11-4.

Note that the module is wired as a standard capacitor-start motor.

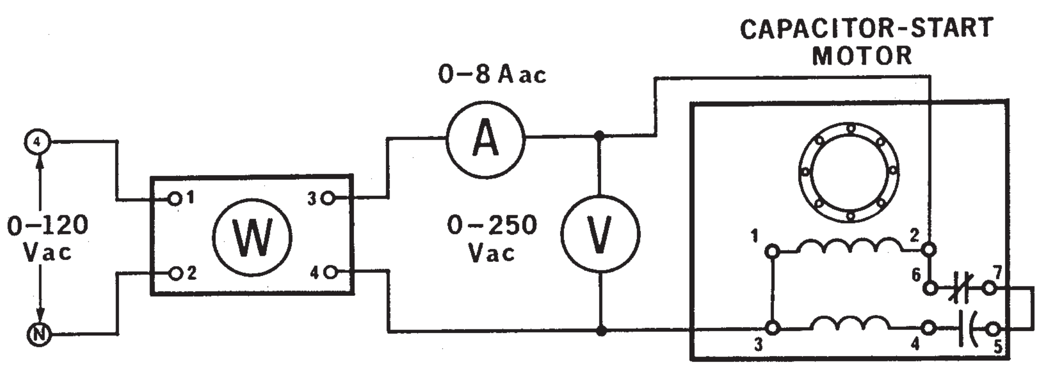


Figure 11-4.

☐ 7. Set the electrodynamometer control knob at its full ccw position to provide minimum starting torque for the capacitor-start motor.

☐ 8. a. Turn on the power supply and adjust for 120 V ac.

b. Measure and record in Table 11-1, the line current, the power and motor speed.

c. Repeat (b) for each of the torques listed in the Table.

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

TORQUE (N·m)	I (amps)	VA	P_{in} (watts)	SPEED (r/min)	P_{out} (watts)
0					
0.3					
0.6					
0.9					
1.2					

Table 11-1.

TORQUE (lbf·in)	I (amps)	VA	P (watts)	SPEED (r/min)	P_{out} (hp)
0					
3					
6					
9					
12					

Table 11-1.

☐ 9. a. Calculate and record in the Table 11-1, the apparent power delivered to the motor for each of the listed torques.

b. Calculate and record in the Table 11-1, the developed power (P_{out}) [horsepower] for each of the listed torques.

☐ 10. Your will now determine the maximum starting torque developed by the capacitor-start motor. This torque is too high to be measured directly by your electrodynamometer. However, you can calculate it by measuring the torque developed when the motor is supplied with a lower voltage, 60 V ac, which is half the rated voltage.

a. Disconnect the Single-Phase Wattmeter, AC Ammeter and AC Voltmeter from your circuit.

b. Set the electrodynamometer control knob to its full cw position (for maximum loading).

c. Turn on the power supply switch and adjust the voltage applied to the motor to 60 V ac. Measure the developed torque on the electrodynamometer scale. Open the power supply switch.

Starting Torque (60 V ac) = ______ N·m [lbf·in]

d. Calculate the starting torque developed by the motor when supplied with 120 V ac. The starting torque is nearly proportional to the square of the applied voltage; thus the starting torque obtained at 120 would be four times greater than at 60 V.

Starting Torque (120 V ac) = ______ N·m [lbf·in]

REVIEW QUESTIONS

1. From Table 11-1 state the no-load (0 N·m [lbf·in] torque):

a) apparent power = ______ VA

b) active power = ______ W

c) reactive power = ______var

d) power factor = ______

2. From Table 11-1 state the full-load (1.2 N·m [9 lbf·in] torque):

a) apparent power = ______ VA

b) active power = ______ W

c) reactive power = ______ var

d) power factor = ______

e) power delivered = ______ W [hp]

electrical equivalent = ______ W

f) efficiency of the motor = ______ %

g) motor losses = ______ W

3. What is the approximate full-load current of your capacitor-start motor?

   I = ______ A ac

4. How much larger is the starting current than the full-load operating current?

   ____

5. Compare these results with those found for the split-phase motor (Experiment 10).

   ____
   ____
   ____
   ____
   ____

Sample Exercise

Extracted from

Three-Phase Transformers

and AC Machines

Experiment 5

The Wound-Rotor Induction Motor – Part III

OBJECTIVE

- To observe the characteristics of the wound-rotor induction motor at no-load and full-load.
- To observe speed control using an external variable resistance.

DISCUSSION

The three ends of the three-phase rotor windings are brought out to three slip rings mounted on the rotor shaft. 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 motor is higher, it is not as efficient as the squirrel cage motor at full speed, because the resistance of the rotor windings is always more than that of a squirrel cage motor.

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 mechanical output power. In addition, because of a high rotor resistance, the motor is made more susceptible to variation in speed as the load changes.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart, in Appendix A of this manual, to obtain the list of equipment required to perform this exercise.

PROCEDURE

CAUTION!

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

☐ 1. a. Examine the construction of the Three-Phase Rheostat, paying particular attention to the circuit schematic diagramed on the face of the module.

b. Note that the arms of the three rheostats are separately brought out to terminals 1, 2 and 3. The remaining ends of the rheostats are wired together internally and brought out to the N terminal.

c. Note that the three rheostats are ganged together and that their individual resistances ca be varied simultaneously by turning the single control knob.

d. When the control knob is fully ccw the resistance of each rheostat is 0 Ω. When the control knob is fully cw the resistance of each rheostat is 16 Ω.

☐ 2. Using your Three-Phase Wound-Rotor Induction Motor, Electrodynamometer, Single-Phase Wattmeter, Three-Phase Rheostat, Power Supply, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 5-1. Do not couple the motor to the electrodynamometer at this time!

☐ 3. a. Set the speed control rheostat knob at its full ccw position for zero resistance.

b. Turn on the power supply and adjust E_1 to 208 V ac. The motor should be running.

c. Measure and record in Table 5-1, the three line currents, the two wattmeter indications (remember, to observe the polarities) and the motor speed.

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

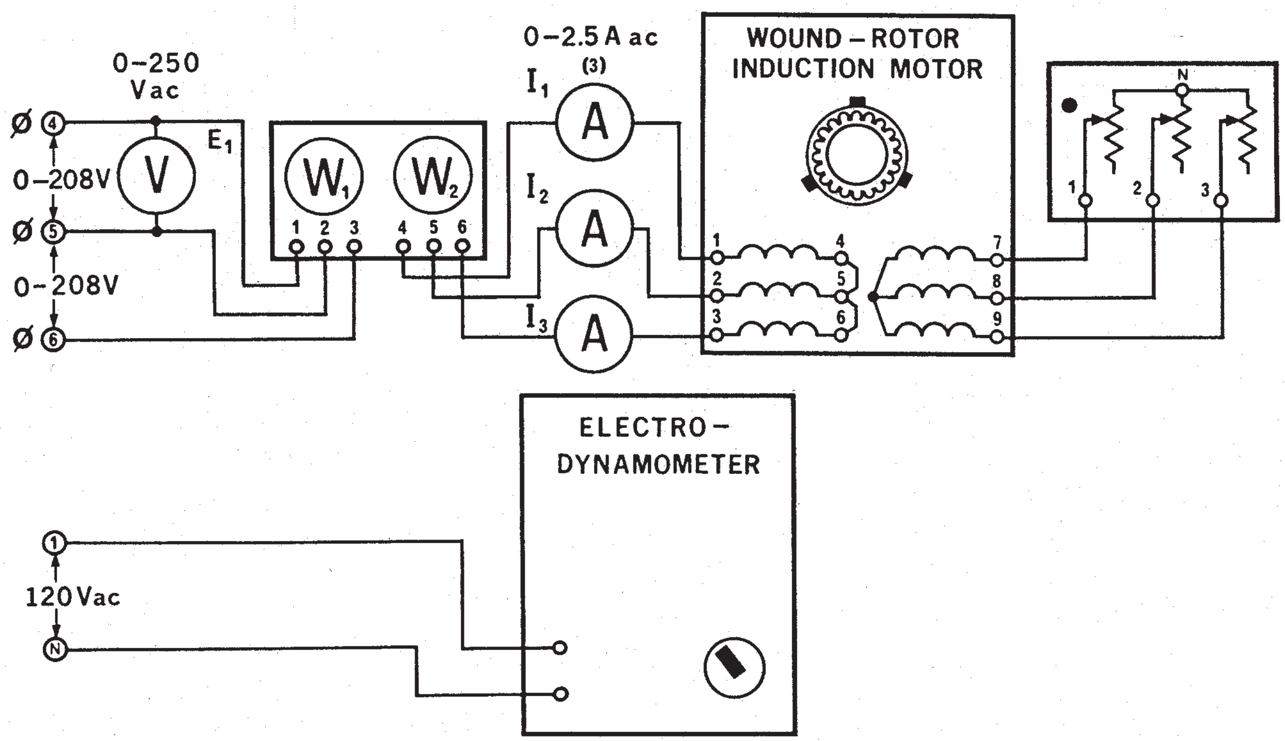


Figure 5-1.

☐ 4. a. Couple the motor to the electrodynamometer with the timing belt.

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

c. Repeat procedures 3 for each of the torques listed in Table 5-1, maintaining the input voltage at 208 V ac.

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

TORQUE (N·m)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
0.3						
0.6						
0.9						
1.2						

Table 5-1.

TORQUE (lbf·in)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
3						
6						
9						
12						

Table 5-1.

☐ 5. a. Set the speed control rheostat knob at its full cw position for maximum resistance.

b. Uncouple the motor from the electrodynamometer.

☐ 6. a. Turn on the power supply and adjust E_1 to 208 V ac. The motor should be running.

b. Measure and record in Table 5-2, the three line currents, the two wattmeter indications and the motor speed.

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

TORQUE (N·m)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
0.3						
0.6						
0.9						
1.2						

Table 5-2.

TORQUE (lbf·in)	I_1 (amps)	I_2 (amps)	I_3 (amps)	W_1 (watts)	W_2 (watts)	SPEED (r/min)
0						
3						
6						
9						
12						

Table 5-2.

☐ 7. a. Couple the motor to the electrodynamometer with the timing belt.

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

c. Repeat procedure 6 for each of the torques listed in Table 5-2, maintaining the input voltage at 208 V ac.

d. With a developed torque of 0.9 N·m [9 lbf·in], rotate the speed control rheostat knob from full cw to full ccw.

e. Does the motor speed change?

☐ Yes ☐ No

f. Does the developed torque change?

☐ Yes ☐ No

g. Return the voltage to zero and turn off the poser supply.

☐ 8. a. Connect the circuit shown in Figure 5-2. Note that the fixed 3ϕ output of the power supply, terminals 1, 2 and 3 are now being used.

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

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

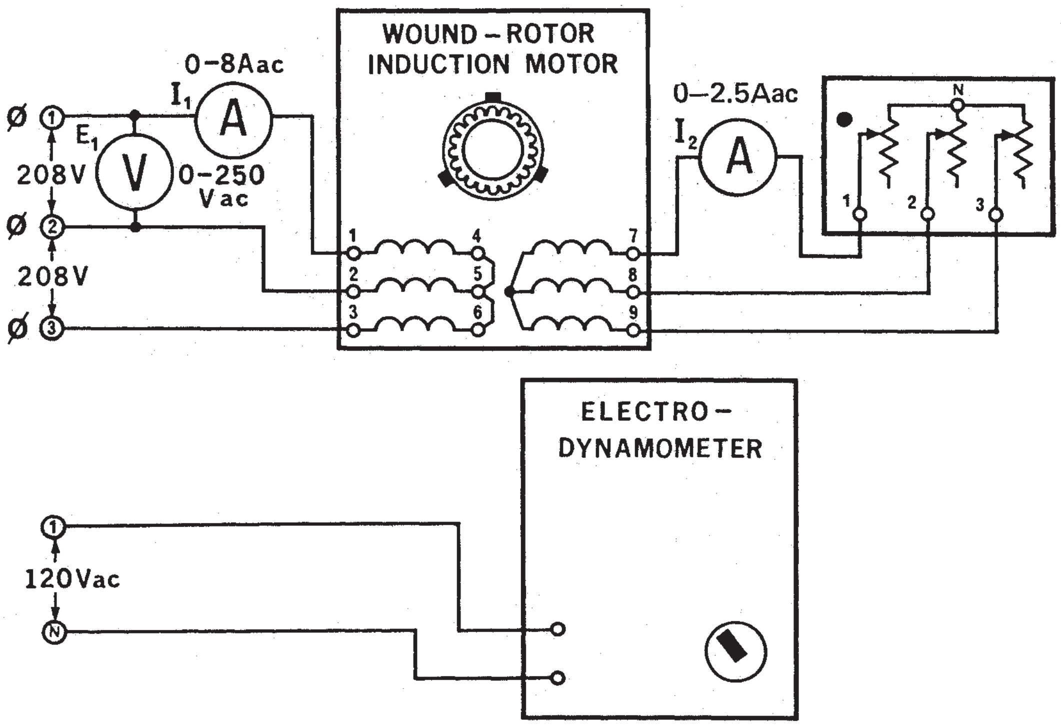


Figure 5-2.

☐ 9. a. Turn on the power supply and quickly measure E_1, I_1, I_2 and the developed starting torque. Turn off the power supply.

I_1 = ______ A ac, I_2 = ______ A ac

E_1 = ______ V ac, Torque = ______ N·m [lbf·in]

b. Calculate the apparent power to the motor at starting torque.

Apparent power = ______ VA

REVIEW QUESTIONS

1. Using the results of Table 5-1, calculate the no-load characteristics of the wound-rotor motor.

   a) average current

   ____

   ______________________________ = __________ A ac

b) apparent power

____

_______________________________ = ____________ VA

c) active power

____

_______________________________ = ____________ W

d) reactive power

____

_______________________________ = ____________ var

e) power factor

____

_______________________________ = ____________

2. Using the results of Table 5-1, calculate the 0.9 N·m [9 lbf·in] characteristics of the wound-rotor motor (with 0 Ω external rotor resistance).

a) average current

____

_______________________________ = ____________ A ac

b) apparent power

____

_______________________________ = ____________ VA

c) active power

____

_______________________________ = ____________ W

d) reactive power

____

______________________________ = __________ var

e) power factor

____

______________________________ = ____________

f) mechanical output power

____

______________________________ = ________ W [hp]

g) efficiency

____

______________________________ = __________ %

3. Using the results of Table 5-2, calculate the 0.9 N·m [9 lbf·in] characteristics of the wound-rotor motor (with 16 Ω external rotor resistance).

a) average current

____

______________________________ = _________ A ac

b) apparent power

____

______________________________ = __________ VA

c) active power

____

______________________________ = __________ W

d) reactive power

____

______________________________ = ____________ var

e) power factor

____

______________________________ = ______________

f) mechanical output power

____

______________________________ = __________ W [hp]

g) efficiency

____

______________________________ = ____________ %

4. Using the results of procedure 9 and Table 5-2, make the following ratio calculations (use the 0.9 N·m [9 lbf·in] characteristics for the full-load values).

a) starting current to full-load current

____

______________________________ = ___________ A ac

b) starting torque to full-load torque

____

____________________________ = __________ N·m [lbf·in]

c) full load current to no-load current

____

______________________________ = ___________ A ac

5. The efficiency of the motor is much lower when the external resistance is in the motor circuit. Explain.

6. The power factor improves with loading. Explain.