Experiment 7

The DC Separately Excited Shunt Generator

OBJECTIVE

- To study the properties of the separately excited DC shunt 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.

DISCUSSION

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. This role is carried out by the commutator and the brushes.

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%, the voltage also increases by 20%.

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 appears at the output. However, 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 which 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.

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!

No Load Characteristics

☐ 1. Because of its constant running speed, the synchronous motor will be used to mechanically drive the DC generator. Using your Power Supply, AC Ammeter and Three-Phase Synchronous Motor/Generator, connect the circuit shown in Figure 7-1.

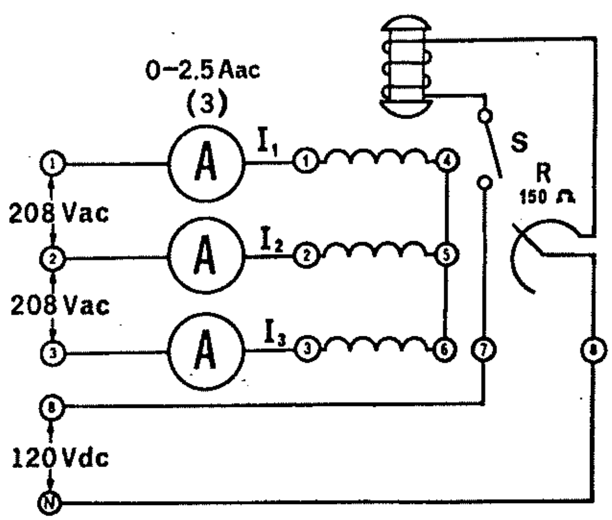

Figure 7-1.

DO NOT APPLY POWER AT THIS TIME!

☐ 2. Terminals 1, 2 and 3 on the power supply provide fixed three-phase power for the three stator windings. (Three-phase power will be covered in later Experiments). 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 (Experiment 1, procedure 6).

☐ 3. a. Using your DC Motor/Generator and DC Voltmeter/Ammeter, connect the circuit shown in Figure 7-2.

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 500 mA meter in series with the positive lead.

c. Connect the 200 V dc 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.

f. Have your instructor check your circuit.

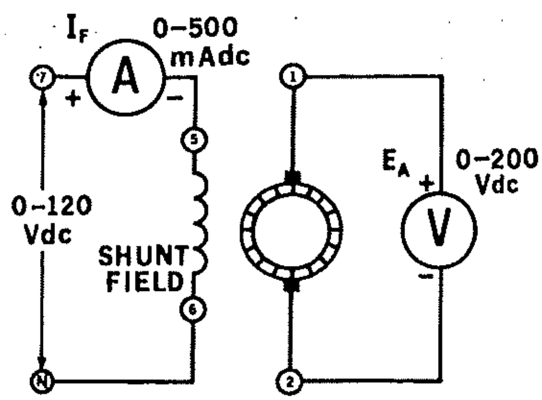

Figure 7-2.

CAUTION!

The switch in the excitation circuit of the synchronous motor should be closed (I) only when the motor is running.

☐ 4. a. Turn on the power supply. The synchronous motor should start running.

b. Close the switch S.

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 V dc meter.

d. Measure and record in Table 7-1 the armature voltage E_A for each of the listed field currents.

I_F (milliamperes)	E_A (volts)
0	
50	
100	
150	
200	
250	
300	
350	
400	

Table 7-1.

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

f. Can you explain why there is an armature voltage even when the field current is zero?

____

____

____

☐ 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 300 mA dc.

c. Did the armature voltage reverse its polarity?

☐ Yes ☐ No

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

☐ 6. a. Interchange the leads to the 200 V dc meter.

b. Turn on the power supply and adjust for a field current I_F of 300 mA dc.

c. Measure and record the armature voltage.

E_A = ______ V dc

d. Is the armature voltage approximately the same as in procedure 4 (at an I_F of 300 mA), except for reversed polarity?

☐ Yes ☐ No

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

☐ 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 I_F of 300 mA dc.

c. Did the armature voltage reverse its polarity?

☐ Yes ☐ No

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

☐ 8. a. Interchange the leads to the 200 V dc meter.

b. Turn on the power supply and adjust for a field current I_F of 300 mA dc.

c. Measure and record the armature voltage.

E_A = ______ V dc

d. Is the armature voltage approximately the same as in procedure 4 (at an I_F of 300 mA), except for reversed polarity?

☐ Yes ☐ No

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

Load Characteristics

☐ 9. Using your Resistive Load, connect the circuit shown in Figure 7-3. Place the resistance switches so that the total load resistance is 120 Ω.

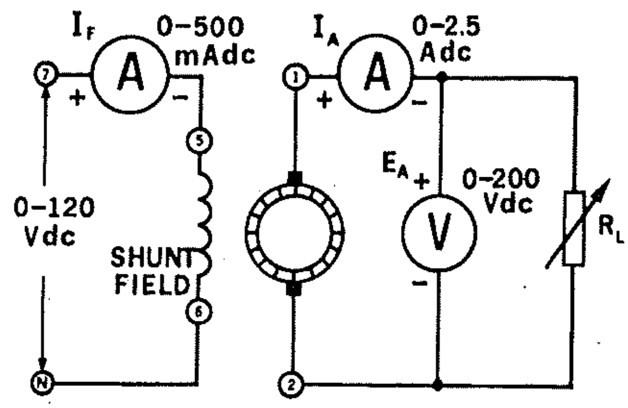

Figure 7-3.

☐ 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 120 V dc. The ammeter I_A should indicate 1 A dc.

c. Record the shunt field current I_F.

I_F = ______ mA

This is the nominal I_F at the rated power output (120 V x 1 A = 120 W) of the DC generator.

☐ 11. a. Adjust the load resistance to obtain each of the values listed in Table 7-2 while maintaining the nominal I_F value found in procedure 10.

b. Measure and record E_A and I_A for each of the resistance values listed in the Table.

Note: *Although the nominal output current rating of the generator is 1 A dc, it may be loaded up to 1.5 A dc (50% overload) without harm.*

R_L (ohms)	I_A (amps)	E_A (volts)	POWER (watts)
∞			
600			
300			
200			
150			
120			
100			
80			
75			

Table 7-2.

☐ 12. a. With the load resistance adjusted for an output current I_A of 1.5 A, turn the field current I_F on and off by removing the connecting lead from terminal 6 to the DC generator.

b. Do you notice that the driving motor is obviously working harder when the generator is delivering power to the load?

☐ Yes ☐ No

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

☐ 13. Calculate and record the power for each of the values listed in Table 7-2.

☐ 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_F is needed to stall the motor?

I_F = ______ mA

f. 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.*

REVIEW QUESTIONS

1. State two ways by which the output polarity of a shunt DC generator can be changed.

____

____

____

2. If a DC generator delivers 180 W to a load, what is the minimum mechanical power (in watts) needed to drive the generator (assume 80% efficiency)?

____

____

____

2. If a DC generator delivers 180 W to a load, what is the minimum hp needed to drive the generator (assume 100% efficiency)?

____

____

____

3. Plot the E_A vs I_F characteristic curve for your DC shunt generator on the graph of Figure 7-4. Use the data from Table 7-1. Note that the curve "bends over" as the field current increases. Can you explain why this happens?

____

____

____

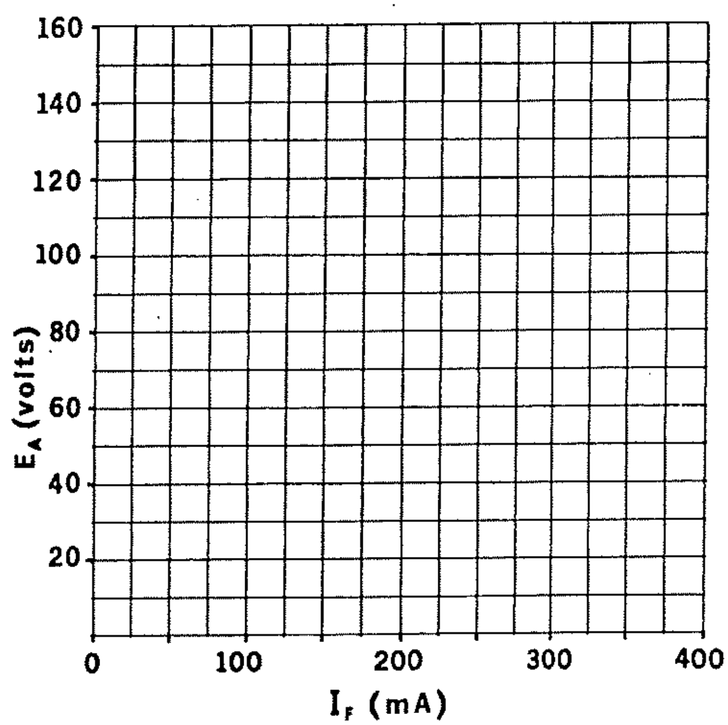

Figure 7-4.

4. Plot the E_A vs I_A regulation curve on the graph of Figure 7-5. Use the data from Table 7-2.

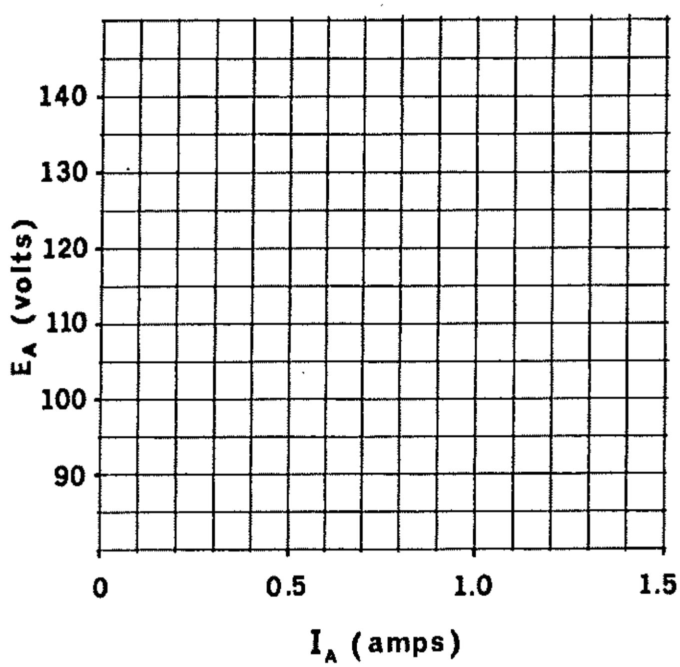

Figure 7-5.

5. Calculate the regulation from no-load to full-load (1 A dc).

____

____

____

Regulation = ______ %

Experiment 8

The DC Self-Excited Shunt Generator

OBJECTIVE

- 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.

DISCUSSION

The separately-excited generator (Experiment 7) 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.

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 Experiment to show these major points.

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. Because of its constant running speed, the synchronous motor will be used to mechanically drive the DC generator. Using your Power Supply, AC Ammeter and Three-Phase Synchronous Motor/Generator, connect the circuit shown in Figure 8-1.

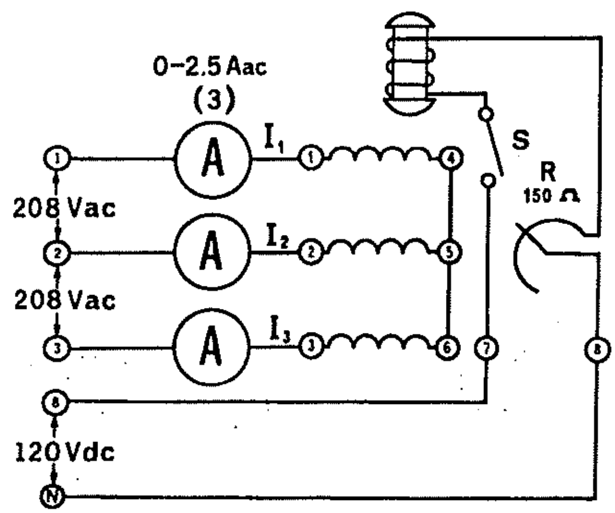

Figure 8-1.

DO NOT APPLY POWER AT THIS TIME!

☐ 2. Terminals 1, 2, and 3 on the power supply provide fixed three-phase power for the three stator windings. (Three-phase power will be covered in later Experiments). 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 (Experiment 1, procedure 6).

☐ 3. a. Using your DC Motor/Generator, DC Voltmeter/Ammeter and Resistive Load, connect the circuit shown in Figure 8-2.

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).

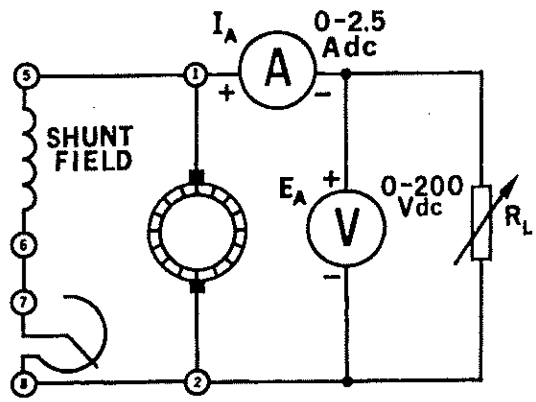

Figure 8-2.

CAUTION!

The switch in the excitation circuit of the synchronous motor should be closed (I) only when the motor is running.

☐ 4. a. Turn on the power supply. The synchronous motor should start running.

b. Close the switch S.

c. Not if voltage E_A builds up.

☐ Yes ☐ No

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.

E_A = ______ V dc

☐ 5. Vary the field rheostat and notice if the armature voltage E_A changes. Explain.

☐ Yes ☐ No

____

____

____

☐ 6. a. Place the resistance switches so that the total load resistance is 120 Ω. Adjust the field rheostat until the generator is delivering an output voltage of 120 V dc. The ammeter I_A should indicate 1 A dc.

b. This is the correct setting of the field rheostat control for the rated power output 120 V x 1 A = 120 W) of the DC generator.

Do not touch the field rheostat control for the remainder of the Experiment!

☐ 7. a. Adjust the load resistance to obtain each of the values listed in Table 8-1.

b. Measure and record E_A and I_A for each of the resistance values listed in the Table.

R_L (ohms)	I_A (amps)	E_A (volts)	POWER (watts)
∞			
600			
300			
200			
150			
120			
100			
80			
75			

Table 8-1.

Note: *Although the nominal output current rating of the generator is 1 A dc, it may be loaded up to 1.5 A dc (50% overload) without harm.*

c. Turn off the power supply.

d. Calculate and record the power for each of the resistance shown in Table 8-1.

☐ 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.

☐ Yes ☐ No

____

____

____

e. Turn off the power supply.

REVIEW QUESTIONS

1. If a self-excited generator has lost all of its residual magnetism, can it build up an output voltage?

   ☐ Yes ☐ No

2. How would you get a generator to work after it had lost all of its residual magnetism?

   ____

   ____

   ____

3. Does a generator slowly lose its residual magnetism with time?

   ☐ Yes ☐ No

4. Plot the E_A vs I_A regulation curve on the graph of Figure 8-3.

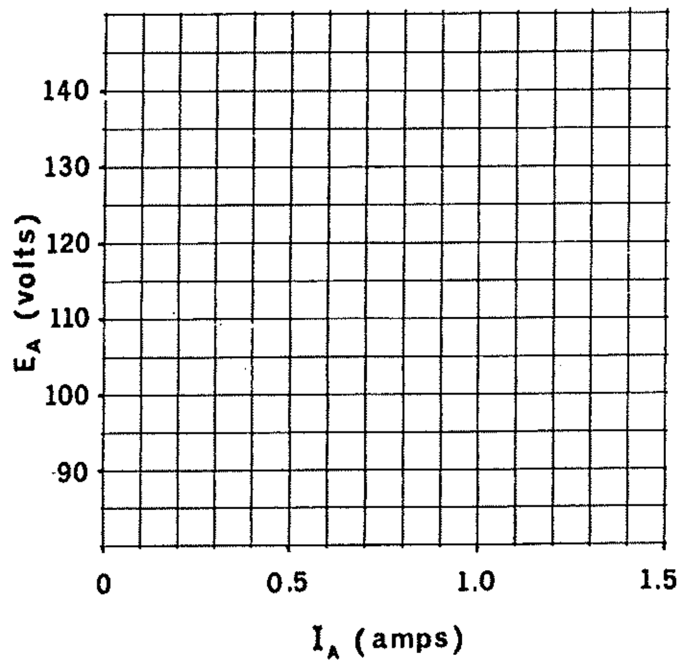

Figure 8-3.

5. Calculate the regulation from no-load to full-load (1 A dc).

____

____

Regulation = ______ %

6. Compare the regulation of the self-excited generator with the regulation of the separately-excited generator (Experiment 7).

____

____

7. Explain why one of the generators has better regulation than the other.

____

____

____

Experiment 9

The DC Compound Generator

OBJECTIVE

- 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.

DISCUSSION

Self-excited shunt generators have the disadvantage in that changes in their load current from no-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 reduces the magnetic field strength, which in turn reduces the armature voltage, etc.

b) The armature voltage drop (I^2 x 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).

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 Experiment to show these major points.

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.

CAUTION!

The switch in the excitation circuit of the synchronous motor should be closed (I) only when the motor is running.

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. Because of its constant running speed, the synchronous motor will be used to mechanically drive the DC generator. Using your Power Supply, AC Ammeter and Three-Phase Synchronous Motor/Generator, connect the circuit shown in Figure 9-1.

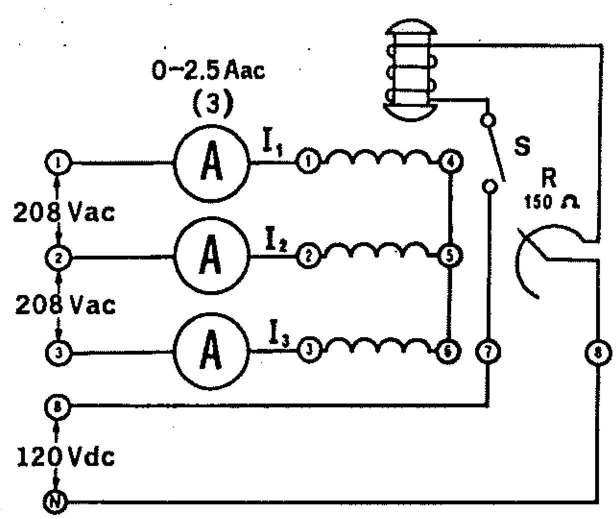

Figure 9-1.

☐ 2. Terminals 1, 2, and 3 on the power supply provide fixed three-phase power for the three stator windings (Three-phase power will be covered in later Experiments). 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 (Experiment 1, procedure 6).

☐ 3. a. Using your DC Motor/Generator, DC Voltmeter/Ammeter and Resistive Load, connect the circuit shown in Figure 9-2.

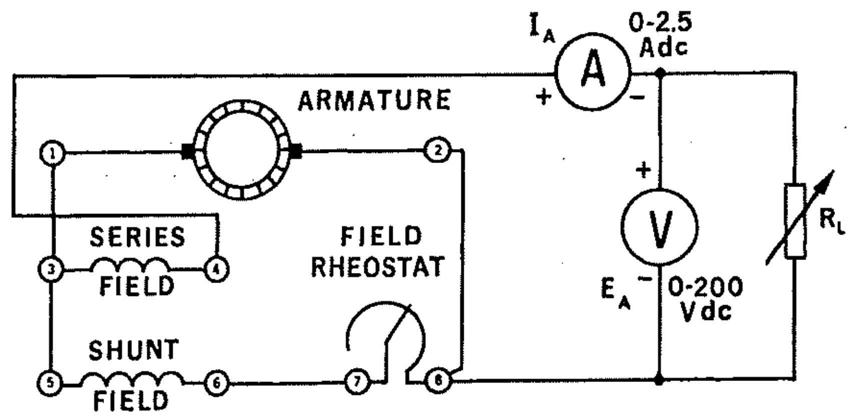

Figure 9-2.

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).

☐ 4. a. Turn on the power supply. The synchronous motor should start running.

b. Close the switch S.

c. Note if voltage E_A builds up.

☐ Yes ☐ No

d. If not, turn off the power supply and interchange any two of the stator connection leads on the synchronous motor.

e. Measure the open circuit armature voltage.

E_A = ______ V dc

☐ 5. Vary the field rheostat and notice if the armature voltage E_A changes. Explain.

☐ Yes ☐ No

____

____

____

☐ 6. Adjust the field rheostat for a no-load current ($I_A = 0$ A) output voltage E_A of 120 V dc.

Do not touch the field rheostat control for the remainder of the Experiment!

☐ 7. a. Adjust the load resistance to obtain each of the values listed in Table 9-1.

b. Measure and record E_A and I_A for each of the resistance values listed in the Table.

> **Note:** *Although the nominal output current rating of the generator is 1 A dc, it may be loaded up to 1.5 A dc (50% overload) without harm.*

c. Turn off the power supply.

d. Calculate and record the power for each of the resistance shown in Table 9-1.

R_L (ohms)	I_A (amps)	E_A (volts)	POWER (watts)
∞			
600			
300			
200			
150			
120			
100			
80			
75			

Table 9-1.

☐ 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 9-3 showing your proposed circuit change.

c. Have your instructor check your circuit and your drawing.

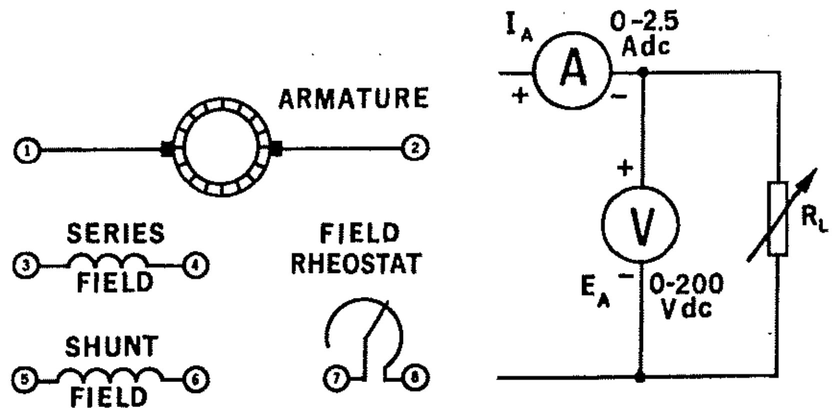

Figure 9-3.

☐ 9. a. Turn on the power supply.

b. Adjust the field rheostat for an E_A of 120 V dc.

c. Do not touch the rheostat after this.

☐ 10. a. Adjust the load resistance to obtain each of the values listed in Table 9-2.

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 9-2.

R_L (ohms)	I_A (amps)	E_A (volts)	POWER (watts)
∞			
600			

300			
200			
150			
120			
100			
80			
75			

Table 9-2.

REVIEW QUESTIONS

1. State which procedure, (7 or 10) is concerned with:

   a) the differential compound generator.

      Procedure ______

   b) the compound generator.

      Procedure ______

2. Plot the E_A vs I_A regulation curve on the graph of Figure 9-4. Use the data from Table 9-2.

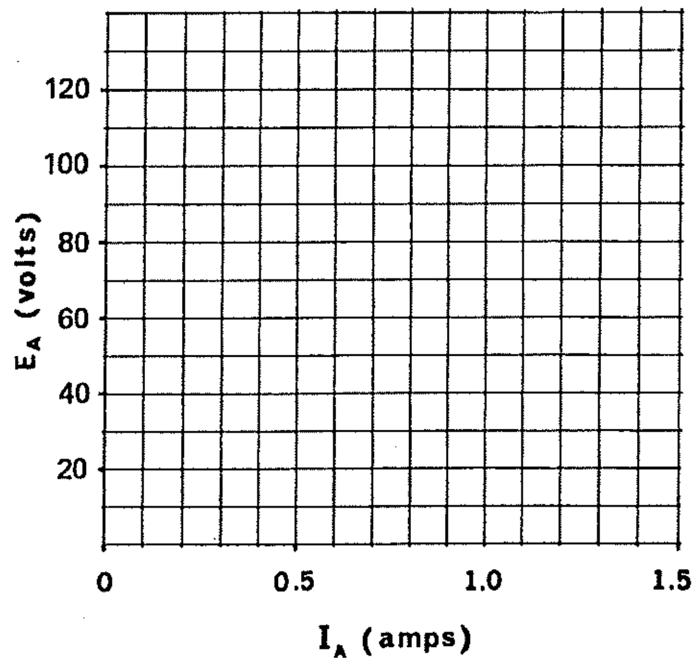

Figure 9-4.

3. Over what voltage range is the armature current nearly constant in the differential compound generator?

   From ______ V dc to ______ V dc

4. Plot the E_A vs I_A regulation curve on the graph of Figure 9-5. Use the data from Table 9-1.

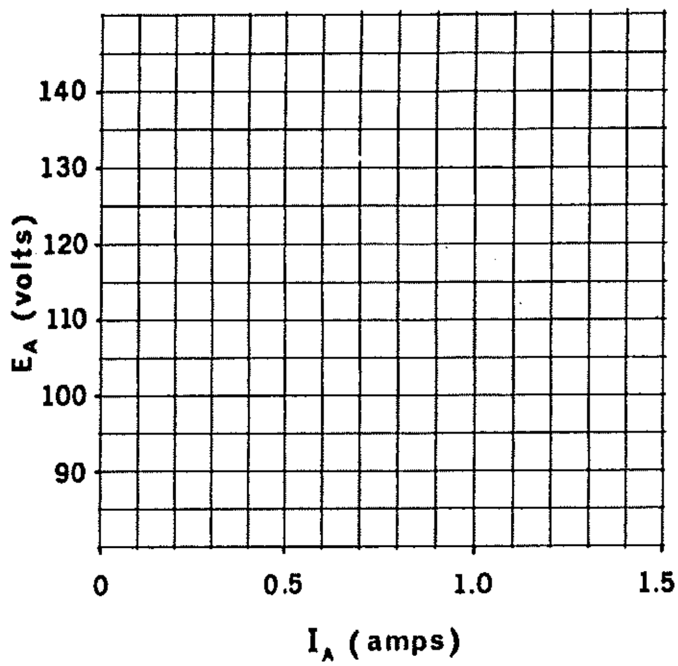

Figure 9-5.

5. Calculate the regulation from no-load to full-load (1 A dc) for the compound generator.

____

____

Regulation = ______ %

6. Compare the regulation of the compound generator with the regulation of the self-excited generator and the separately-excited generator.

____

____

____

____

7. Explain briefly why the voltage does not drop with increasing load for the compound generator.

Experiment 10

DC Motor Starter

OBJECTIVE

- 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.

DISCUSSION

At start-up, the counter-electromotive force of the armature of a DC motor is zero and the armature current is limited only by the armature and brushes resistance. If a DC shunt motor was to be connected directly across a full-voltage source, the inrush current could be as high as 20 to 30 times its nominal current, and the extremely high current could burn the armature winding, damage the commutator or overload the source. For these reasons, appropriate means shall be used to limit this inrush current to a safe value of approximately two times the nominal current of the motor.

In order to reduce the starting current, we normally wire a starting rheostat in series with the armature. This series resistance is then gradually decreased as the motor accelerates and is finally removes from the circuit when the motor reaches its full-load speed. During this operation, the shunt field is generally connected directly across the supply to provide maximum starting torque.

The face-plate starter is commonly used for this purpose; it consists of a series of fixed contacts connected to fixed value resistors as shown on the front face of the Manual DC Motor Starter. When the movable contact, driven by the handle, is first moved from its rest position, all the resistors are placed in series with the armature winding. As the motor speed increases, the handle is moved further so that the total series resistance is decreased. When the handle has been moved all the way, it brings a holding plate across an electromagnet which holds the handle in this position as long as the current flows through the electromagnet; the resistance is also taken out of the circuit.

The Manual DC Motor Starter can also be operated as a 3-point or 4-point starter. If the front switch is placed in the 3-point position, current from the source passes through the electromagnet coil to the shunt field winding of the DC motor. When the starter handle is moved off its rest position, the electromagnet and the shunt field of the motor are energized. In the event of "loss of field", such as an open shunt field circuit or too low a shunt field current, the electromagnet is de-energized and the handle is spring returned to the off position.

When the switch is in the 4-point position, the current to energize the electromagnet is set by the 600 Ω internal resistor placed in series with it. The "loss of field" feature is not provided in this position.

Usually, the 3-point starter is used for shunt or compound motors, while the 4-point starter is used for series motors (the shunt winding being unused).

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. Examine the construction of the Manual DC Motor Starter, paying particular attention to the high wattage fixed resistor equipped with two taps, the movable and fixed contacts, the return spring, the holding plate and the holding electromagnet. Note that a circuit breaker is placed in series with terminal 3 and another one in series with the electromagnet. These are to prevent the burning of the magnet coil or the high wattage resistor in case of overcurrent in the magnet or prolonged use of the starting resistor. The resistor is designed for intermittent use only and the handle should never be left in any intermediate position for an extended period of time. Move the handle gradually from the off position to the holding position. Note that the movable contact is successively connected to the fixed contacts until all of the resistor has been removed from the circuit when the holding plate makes contact with the holding electromagnet. Release the handle; it returns to the off position because the electromagnet is not energized.

☐ 2. a. Using your Power Supply, Manual DC Motor Starter, DC Voltmeter/Ammeter and DC Motor/Generator, connect the circuit shown in Figure 10-1.

b. Place the Manual DC Motor Starter toggle switch to the 3-point position. Turn the rheostat on the DC Motor/Generator fully ccw for maximum resistance; this assures minimum starting torque for the motor, extends the starting period and enhances the demonstration.

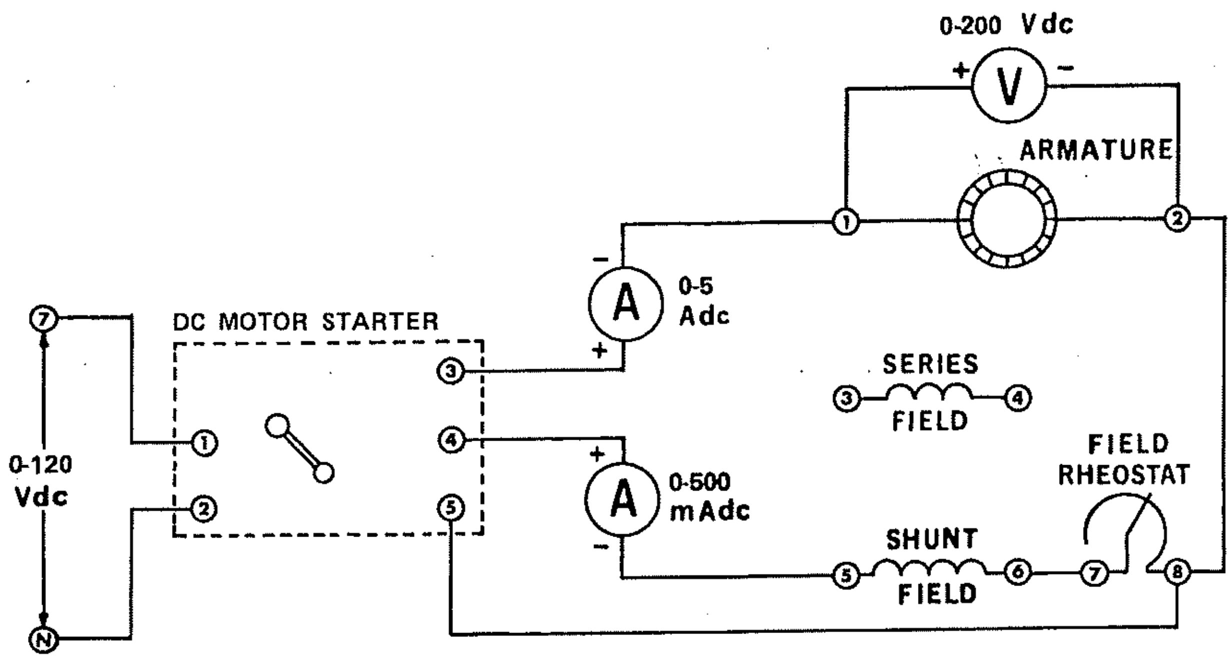

Figure 10-1.

c. Install the electrodynamometer to the right of the motor and couple them together with the timing belt. The electrodynamometer should not be connected to the supply. It is used only to increase the inertia of the system.

☐ 3. Turn on the power supply and adjust for an output voltage of 135 V dc. The motor should not turn. Set the shunt-field rheostat control knob at its full ccw position to provide minimum starting torque and to extend the starting period to an easily measurable value.

☐ 4. a. Move the starter handle slowly until the motor starts turning. Measure the peak armature current. Note that the current decreases thereafter and that the voltage across the armature increases.

I_A = ______ A dc

b. Repeat procedure (a) and measure how long the current remains above the value of 3 A.

Time = ______ s

c. Move the handle slowly the second, third and fourth position and note small jumps in the current at each step.

d. Push the handle as far as it will go and release it. Is it held in place by the electromagnet?

☐ Yes ☐ No

Does the motor keep turning?

☐ Yes ☐ No

e. Force the handle back to the off position. Move the handle rapidly until it reaches the electromagnet. Note that the current goes beyond the full scale range of the current meter. How long does the current stay above 3 A?

Time = ______ s

f. Open momentarily the shunt field circuit by removing the connection lead from one of the shunt field winding terminals (5 or 6). Be extremely careful not to touch any of the terminal connections or any metal part during this procedure.

g. Explain what happened to the 3-point face plate starter and to the motor when the motor lost power to its hunt field.

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☐ 5. a. Move the toggle switch of the Manual DC Motor Starter to the 4-point position and turn the shunt field rheostat to its maximum clockwise position.

b. Move the starter handle slowly and by steps, as in procedure 4 and as far as it will go. Release the handle. Is it held in place by the electromagnet?

☐ Yes ☐ No

Does the motor keep turning?

☐ Yes ☐ No

c. Repeat procedure 4 (f).

d. Explain what happened to the 4-point face starter and to the motor when the motor lost power to its shunt field.

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

DC Motor Starter

REVIEW QUESTIONS

1. Explain why the shunt field rheostat must normally be set for minimum resistance during the starting of a motor with a face plate starter.

2. Why would you prefer a 3-point to a 4-point face plate starter to supply power to a DC motor?

3. What would happen if the motor were heavily loaded and the starter handle were maintained in an intermediate position for too long?

4. Why is the power to the shunt field taken from the first fixed contact of the face plate starter rather than from terminal 3 of the module?

5. What is the purpose of the 600 Ω resistor placed in series with the holding electromagnet of the Manual DC Motor Starter when used as a 4-point starter?

Experiment 11

Thyristor Speed Controllers

EXERCISE OBJECTIVE

- 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;
- You will also learn that thyristor speed controllers offer poor speed stability with varying loads in the open-loop mode of control.

DISCUSSION

In Experiment 3, you saw that the speed of a DC motor can be controlled from zero to maximum by varying the armature voltage while keeping the shunt field voltage constant. Thyristor speed controllers are specially designed for this application.

The Thyristor Speed Controller of your training system contains a thyristor single-phase bridge rectifier. This type of rectifier operates on the same principle as a diode rectifier except that each thyristor begins to conduct only when a current pulse is injected into its gate. Once a thyristor begins to conduct, it continues to conduct until the current flowing through it becomes zero. Since the conduction can be initiated at any angle in the network sinewave between 0 and 180°, the average output voltage and therefore the average current can be varied between 0 and 100%. The resulting output waveform is a pulsated voltage.

By controlling the firing angle of the thyristors, the voltage applied to the armature of the motor can be varied and its speed controlled.

As Figure 11-1 shows, the front panel of the Thyristor Speed Controller shows many important characteristics about its operation:

- Terminals L and N are referred to as the POWER INPUT.
- Q_1, Q_2, D_3 and D_4 make up the thyristor single-phase, full-wave bridge rectifier that converts the fixed AC-voltage into a variable DC-voltage.
- D_1, D_2, D_3 and D_4 make up the diode single-phase, full-wave bridge rectifier that converts the fixed AC-voltage into a fixed DC-voltage.
- D_5 is a free-wheeling diode required to ensure that the circuit can turn off an inductive load like the winding of a motor. Without this diode, when the gate pulses are stopped, the current may never drop to zero and a thyristor may continue to conduct.
- Terminals 1 and 2 are referred to as the variable DC-voltage output. The armature of the DC-motor connects to these terminals. Terminal 1 is positive with respect to terminal 2.

- Terminals 3 and 4 are referred to as the fixed DC-voltage output. The DC motor shunt winding connects to these terminals. Terminal 3 is positive with respect to terminal 4.
- VOLTAGE REFERENCE potentiometer allows for adjustment of the armature voltage.
- VOLTAGE MINIMUM potentiometer allows for adjustment of the voltage reference lower limit.
- RUN selector allows the starting and the stopping of the DC motor.
- REFERENCE INTEGRATOR potentiometer allows for adjustment of the motor acceleration and deceleration.
- CURRENT FEEDBACK potentiometer allows for adjustment of the circuitry that controls the armature voltage to compensate for the voltage loss caused by the armature resistance.
- CURRENT LIMIT potentiometer allows the setting of the armature current maximum value to provide protection against overloads.
- COMPARATOR compares the current feedback to a current limit set by the user with the CURRENT LIMIT potentiometer.
- VOLTAGE FEEDBACK potentiometer allows for adjustment of the voltage feedback amplitude. This makes it possible to use motors having different supply voltages by matching the voltage feedback to the voltage reference. The VOLTAGE FEEDBACK potentiometer is also used to set an upper limit to the armature voltage.
- ERROR DETECTOR compares the voltage feedback signal to the sum of the voltage reference and current feedback signals. The ERROR DETECTOR produces an error signal equal to the difference.
- ERROR INTEGRATOR adjusts the integral gain of the error signal sent by the ERROR DETECTOR. The output signal of the ERROR INTEGRATOR is the control signal of the FIRING CIRCUIT.
- FIRING ANGLE potentiometer allows manual adjustment of the firing angle of the thyristors.
- CLOSED LOOP selector allows selection of open-loop or closed-loop mode of control.
- FIRING CIRCUIT detects when the thyristor voltage becomes positive, and controls the time delay before a current pulse is sent to the thyristor gate.

The Thyristor Speed Controller is designed for both open-loop and closed-loop modes of control.

In the open-loop mode of control, the armature voltage is set manually by controlling the firing angle of the thyristors using the FIRING ANGLE potentiometer.
This allows the control of the motor speed using the FIRING ANGLE potentiometer. In the PROCEDURE of this Experiment, you will observe that the armature voltage decreases rapidly when the load applied to the motor increases, causing the motor speed to decrease. Therefore, the open-loop mode of control is not adequate to control the speed of a motor whose load varies. The decrease in voltage, when the current increases, is a characteristic of the pulsated voltage produced by thyristor rectifiers.

Thyristor Speed Controller

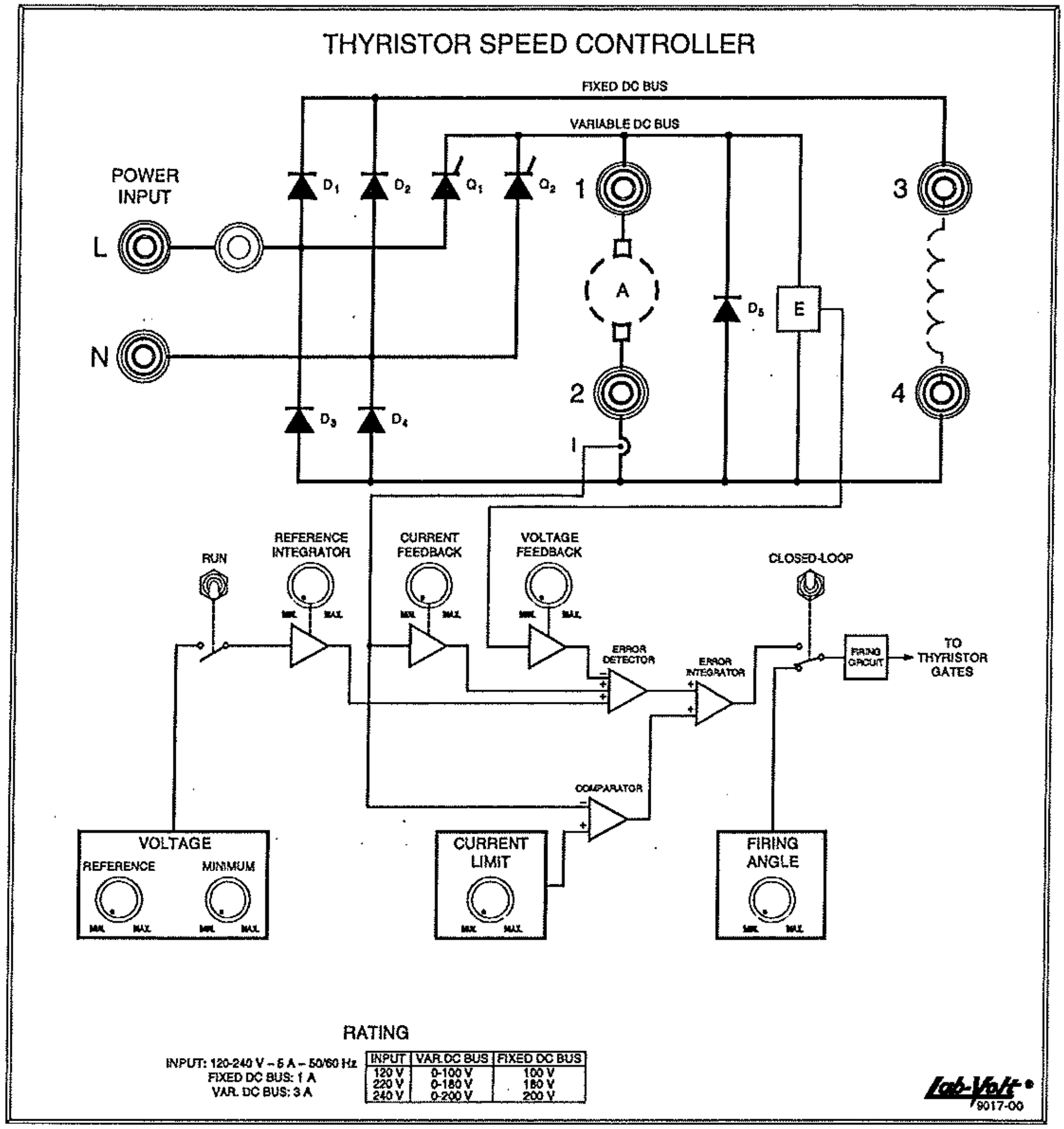

Figure 11-1. Thyristor Speed Controller.

In the closed-loop mode of control, the firing angle of the thyristors is determined by the controller. In this mode of control, the armature voltage is measured and its value is sent back to an error detector to be compared with a voltage reference set by the user. The output signal of the error detector is sent to a firing circuitry to determine the firing angle of the thyristors to produce the correct armature voltage.

However, even if the armature voltage is maintained constant when the load varies, the motor speed will still vary slightly because of the armature resistance. To compensate for the voltage drop produced by the armature resistance, the armature current is also measured. Its value is sent back to the error detector as a voltage corresponding to the armature current (I) multiplied by the armature resistance (R).

The purpose of the closed-loop mode of control is to maintain a constant speed despite the load variations.

Procedure Summary

In the first part of the exercise, *Setting up the Equipment*, you will set up the equipment in the EMS Workstation.

In the second part of the exercise, *Motor Speed Versus Armature Voltage*, you will vary the voltage applied to the armature of the DC Motor/Generator and observe how its speed varies.

In the third part of the exercise, *Motor Speed versus Load*, you will vary the mechanical load applied to the DC Motor/Generator and observe how its speed is affected.

In the last part of the exercise, *Motor Speed versus Load with Constant Armature Voltage*, you will vary the mechanical load applied to the DC Motor/Generator. At each load setting, you will adjust the armature voltage to maintain its value constant and observe how the motor speed is affected.

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. Install the DC Motor/Generator, DC Voltmeter/Ammeter, Power Supply, Electrodynamometer, and Thyristor Speed Controller modules in the EMS Workstation.

☐ 2. On the Power Supply, make sure the main power switch is set to the **O** (off) position, and the voltage control knob is turned fully counterclockwise. Ensure the Power Supply is connected to a three-phase power source.

Do not couple the DC Motor/Generator to the Electrodynamometer with the timing belt now.

☐ 3. Connect the circuit shown in Figure 11-2.

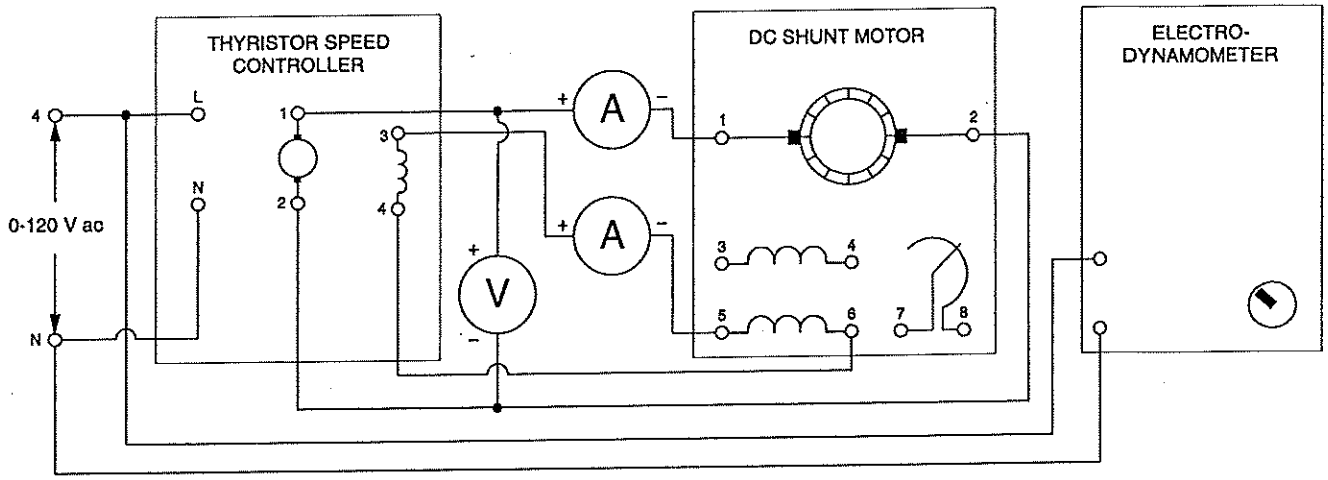

Figure 11-2.

Motor Speed versus Armature Voltage

☐ 4. Set the Thyristor Speed Controller controls as follows:

CLOSED LOOP selector . . . . O
RUN selector . . . . O
FIRING ANGLE . . . . MIN.

☐ 5. On the Power Supply, set the main power switch to the **I** (on) position, and increase the voltage control knob to MAX.

☐ 6. On the Thyristor Speed Controller, adjust the FIRING ANGLE potentiometer so that the armature voltage increases as indicated in the following table.

AC NETWORK VOLTAGE	INCREASE THE ARMATURE VOLTAGE UP TO
120 V	100 V by increments of 10 V
220 V	200 V by increments of 20 V
240 V	200 V by increments of 20 V

For each armature voltage setting, measure and record the armature current I_A, field current I_F, and motor speed in Table 11-1.

E_A (V)	I_A (A)	I_F (mA)	SPEED (r/min)

Table 11-1.

☐ 7. Do your results confirm that the speed of the DC Motor/Generator can be controlled by varying the armature voltage using the Thyristor Speed Controller?

☐ Yes ☐ No

☐ 8. Do your results confirm that the DC Motor/Generator offers a wide speed range when controlling the armature voltage using the Thyristor Speed Controller?

☐ Yes ☐ No

☐ 9. Return the FIRING ANGLE potentiometer at MIN., and turn off the Power Supply.

Motor Speed versus Load

☐ 10. Couple the DC Motor/Generator to the Electrodynamometer with the timing belt.

On the Electrodynamometer, set the dynamometer control knob at its full counterclockwise position for minimum loading.

Turn on the Power Supply.

☐ 11. On the Thyristor Speed Controller, set the FIRING ANGLE potentiometer to obtain the motor speed indicated in the following table.

AC NETWORK VOLTAGE	MOTOR SPEED (r/min)
120 V	1000
220 V	900
240 V	900

☐ 12. Measure and record the armature voltage E_A, armature current I_A, field current I_F, and motor speed in Table 11-2.

On the Electrodynamometer, adjust the dynamometer control knob so that the torque indicated on the module, increases by 0.1 N·m [1.0 lbf·in] increments up to 1.0 N·m [10.0 lbf·in].

For each load setting, record your data in Table 11-2.

LOAD SETTING	E_A (V)	I_A (A)	I_F (mA)	SPEED (r/min)

Table 11-2.

☐ 13. On the Electrodynamometer, set the dynamometer control knob at its full counterclockwise position for minimum loading.

Turn off the Power Supply.

☐ 14. Plot the graph of the *Motor Speed* as a function of *Load* in Figure 11-3.

☐ 15. Do your results confirm that the Thyristor Speed Controller offers poor speed stability with varying loads in the open-loop mode of control?

☐ Yes ☐ No

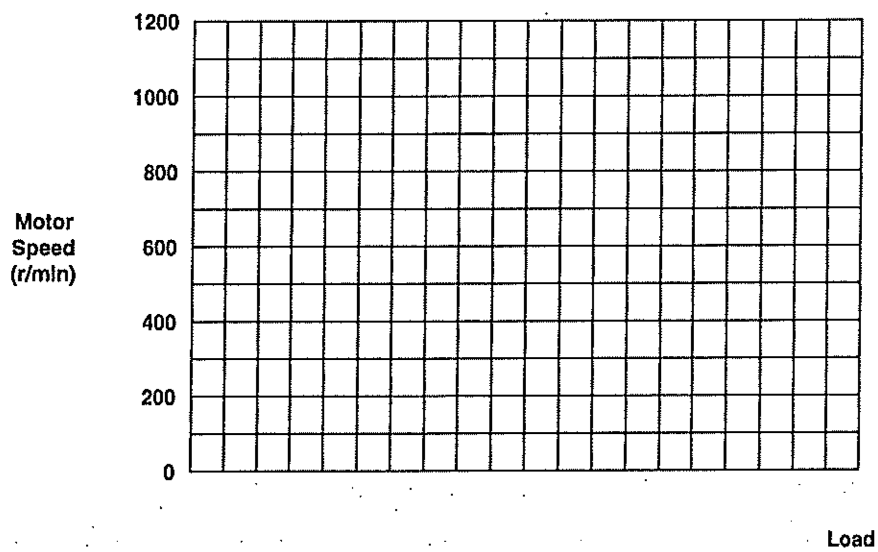

Figure 11-3.

Motor Speed versus Load with Constant Armature Voltage

☐ 16. Turn on the Power Supply.

☐ 17. Make sure that the FIRING ANGLE potentiometer is still set as indicated in step 11. Adjust if necessary.

☐ 18. Record the armature voltage E_A armature current I_A field current I_F, and motor speed in Table 11-3.

On the Electrodynamometer, adjust the dynamometer control knob so taht the torque indicated on the module, increases by 0.1 N·m [1.0 lbf·in] increments up to 1.0 N·m [10.0 lbf·in].

For each load setting, readjust the FIRING ANGLE potentiometer to maintain the armature voltage E_A constant, then record your data in Table 11-3.

LOAD SETTING	E_A (V)	I_A (A)	I_F (mA)	SPEED (r/min)

Table 11-3.

☐ 19. Do your results confirm that by maintaining the armature voltage constant when the load varies, the speed is maintained fairly constant with a small decrease caused by the armature resistance voltage drop?

☐ Yes ☐ No

☐ 20. On the Electrodynamometer, set the dynamometer control knob at its full counterclockwise position for minimum loading.

☐ 21. Turn off the Power Supply.

CONCLUSION

In this exercise, you were introduced to thyristor speed controllers. You learned how to control the speed of a DC motor by varying the firing angle of the thyristors.

You plotted the speed versus load curve of the Thyristor Speed Controller operating in the open-loop mode of control, and observed that it offers poor speed stability with varying loads in this mode.

In the last part of the exercise, you maintained the armature voltage constant when the load varied. You observed that the speed was fairly constant with a small decrease caused by the armature resistance voltage drop.

REVIEW QUESTIONS

1. What is the purpose of the diode single-phase, full-wave bridge rectifier of the Thyristor Speed Controller?

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2. What is the purpose of the thyristor single-phase, full-wave bridge rectifier of the Thyristor Speed Controller?

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3. What is the purpose of the FIRING ANGLE potentiometer on the Thyristor Speed Controller?

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4. Explain why the armature voltage decreases when the load applied to the motor increases in the open-loop mode of control.

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Experiment 12

Thyristor Speed Controllers with Regulation

EXERCISE OBJECTIVE

- 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;

DISCUSSION

You have noticed in the previous Experiment that although the open-loop control of the DC Motor/Generator offered a wide speed range, it had poor speed stability with varying loads. The non-feedback speed controller consisted of a fixed field supply and a manually adjustable armature power supply. Speed regulation was not improved by the controller, when the load changed. However, you saw that by maintaining the armature voltage of the motor constant, it is possible to obtain a motor speed fairly constant even when the load varies.

In this Experiment, you will experiment with the effects of feedback upon motor speed stability. You will learn how feedback, or closed-loop, control systems automatically maintain the armature voltage constant when the current increases.

All feedback systems, where a quantity such as speed, torque, or temperature, is to be kept at a predetermined value, must have a reference level against which the quantity can be compared. The voltage reference level, on the Thyristor Speed Controller, is set using the VOLTAGE REFERENCE potentiometer. It determines the armature voltage which called for a specific motor speed. The lower limit of the voltage reference can be set using the VOLTAGE MINIMUM potentiometer.

The voltage reference signal is sent to an integrator where the time taken by the control signal to be fully applied to the motor can be set using the REFERENCE INTEGRATOR potentiometer. This allows smooth acceleration and deceleration of the motor. The acceleration time of the Thyristor Speed Controller can be set between 0.5 and 8 s, and the deceleration time can be set between 0.06 and 0.8 s. The voltage reference is then sent to the ERROR DETECTOR to be compared with the feedback signals.

In the closed-loop mode of control, the Thyristor Speed Controller senses the armature voltage (voltage feedback) and armature current (current feedback). The controller uses these feedback signals to regulate the motor speed when the load varies.

The voltage feedback signal is sent to the ERROR DETECTOR to be compared with the voltage reference. The difference, or error signal, between the voltage feedback and the voltage reference can then be used to "tell" the FIRING CIRCUIT whether it should increase the armature voltage, or reduce it. Before it is sent to the ERROR DETECTOR, the voltage feedback amplitude is set using the VOLTAGE FEEDBACK potentiometer. The voltage feedback amplifier allows the use of motors having different supply voltages by matching the voltage feedback and the voltage reference. Setting the upper limit of the armature voltage by controlling the gain of this amplifier is also possible.

The current feedback signal is sent to the CURRENT FEEDBACK potentiometer and to the COMPARATOR. The CURRENT FEEDBACK potentiometer allows the setting of the IR compensation that corresponds to the voltage loss caused by the armature resistance. The current feedback is then sent to the ERROR DETECTOR as a voltage corresponding to the armature current (I) multiplied by the armature resistance (R).

The COMPARATOR compares the current feedback to a current limit set by the user with the CURRENT LIMIT potentiometer. The purpose of the current limiter and COMPARATOR is to set an armature current limit to prevent damage to the motor and the controller circuitry, and to limit the torque developed by the motor to prevent damage to the component driven by the motor.

The output signals of the COMPARATOR and ERROR DETECTOR are sent to the ERROR INTEGRATOR before they are sent to the FIRING CIRCUIT.

Procedure Summary

In the first part of the exercise, *Setting up the Equipment*, you will set up the equipment in the EMS Workstation.

In the second part of the exercise, *Maximum Speed Setting*, you will use the VOLTAGE FEEDBACK potentiometer to set the gain of the voltage feedback amplifier to set the upper limit of the motor speed.

In the third part of the exercise, *Minimum Speed Setting*, you will use the VOLTAGE MINIMUM potentiometer to set the lower limit of the motor speed.

In the fourth part of the exercise, *Motor Speed versus Load in Closed Loop, without IR Compensation*, you will determine and plot the speed versus load curve from the data obtained in closed loop without IR compensation. You will compare this curve to the one obtained in the open-loop mode of control.

In the fifth part of the exercise, *Motor Speed versus Load in Closed Loop, with IR Compensation*, you will determine and plot the speed versus load curve from the data obtained in closed loop with IR compensation. You will compare this curve with the one obtained without IR compensation.

In the sixth part of the exercise, *REFERENCE INTEGRATOR Setting*, you will experiment with the acceleration control of the Thyristor Speed Controller.

In the last part of the exercise, *Current Limit*, you will experiment with the current limiter of the Thyristor Speed Controller. You will observe that the torque developed by the DC Motor/Generator can be limited by limiting the armature current.

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. Install the DC Motor/Generator, DC Voltmeter/Ammeter, Power Supply, Electrodynamometer, and Thyristor Speed Controller modules in the EMS Workstation.

☐ 2. On the Power Supply, make sure the main power switch is set to the **O** (off) position, and the voltage control knob is turned fully counterclockwise. Ensure the Power Supply is connected to a three-phase power source.

Couple the DC Motor/Generator to the Electrodynamometer with the timing belt.

☐ 3. Connect the circuit shown in Figure 12-1.

Maximum Speed Setting

☐ 4. On the Electrodynamometer, set the dynamometer control knob at its full counterclockwise position for minimum loading.

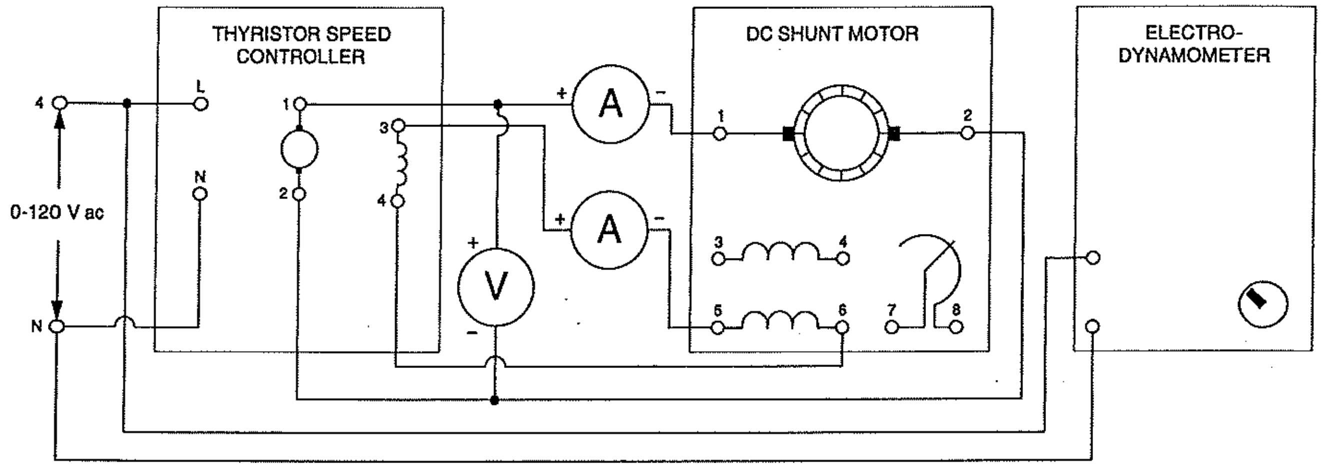

Figure 12-1.

☐ 5. Set the Thyristor Speed Controller controls as follows:

VOLTAGE REFERENCE potentiometer .... MAX.
VOLTAGE MINIMUM potentiometer .... MAX.
RUN selector I
REFERENCE INTEGRATOR potentiometer .... MIN.
CLOSED LOOP selector I
CURRENT FEEDBACK potentiometer .... MIN.
CURRENT LIMIT potentiometer .... MAX.

☐ 6. On the Power Supply, set the main power switch to the I (on) position, and increase the voltage control knob to MAX.

☐ 7. On the Thyristor Speed Controller, set the VOLTAGE FEEDBACK potentiometer to obtain the motor speed indicated in the following table.

AC NETWORK VOLTAGE	MAXIMUM MOTOR SPEED (r/min)
120 V	1100
220 V	1000
240 V	1000

Minimum Speed Setting

☐ 8. On the Thyristor Speed Controller, set the VOLTAGE REFERENCE potentiometer at MIN.

Rotate slowly the VOLTAGE MINIMUM potentiometer counterclockwise until the motor stops.

Note: *The lower speed limit is now set at 0 r/min.*

☐ 9. Vary the VOLTAGE REFERENCE from MIN. to MAX. Measure the motor speed at each of these positions.

Minimum motor speed = ______ r/min

Maximum motor speed = ______ r/min

Note: *It may necessary to readjust the maximum speed setting using the VOLTAGE FEEDBACK potentiometer once the minimum speed setting is completed.*

Motor Speed versus Load in Closed Loop, without IR Compensation

☐ 10. On the Thyristor Speed Controller, set the VOLTAGE REFERENCE potentiometer to obtain the motor speed indicated in the following table.

AC NETWORK VOLTAGE	MOTOR SPEED (r/min)
120 V	1000
220 V	900
240 V	900

☐ 11. Record the armature voltage E_A, armature current I_A, field current I_F, and motor speed in the *Without IR COMP.* columns of Table 12-1.

On the Electrodynamometer, adjust the dynamometer control knob so that the torque indicated on the module, increases by 0.1 N·m [1.0 lbf·in] increments up to 1.0 N·m [10.0 lbf·in].

For each load setting, record your data in Table 12-1.

LOAD SETTING	E_A (V)		I_A (A)		I_F (mA)		SPEED (r/min)	
	Without IR COMP.	With IR COMP.	Without IR COMP.	With IR COMP.	Without IR COMP.	With IR COMP.	Without IR COMP.	With IR COMP.

Table 12-1.

☐ 12. Use your data to plot the graph of the *Motor Speed* as a function of *Load* without IR compensation in Figure 11-3.

☐ 13. Compare the *Motor Speed* versus *Load* curves you plotted in Figure 11-3. Do the curves confirm that the closed-loop control system helps in maintaining the motor speed constant as the load varies?

☐ Yes ☐ No

☐ 14. Compare the armature voltage and speed values with those obtained in the open-loop mode of control when you maintained the armature voltage constant manually (Table 11-2). What can you conclude from your comparison?

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Motor Speed versus Load in Closed Loop, with IR Compensation

IR Compensation Setting

☐ 15. On the Thyristor Speed Controller, set the CURRENT FEEDBACK potentiometer to obtain the motor speed indicated in step 10.

On the Electrodynamometer, set the dynamometer control knob at its full counterclockwise position for minimum loading, then measure the motor speed.

If the motor speed with and without load is different, readjust the current feedback level using the CURRENT FEEDBACK potentiometer to obtain the same speed "with and without" load.

> **Note:** *The IR compensation is now set to compensate for the voltage loss caused by the armature resistance.*

Once the current feedback level is correctly set, adjust the VOLTAGE REFERENCE potentiometer to obtain the motor speed indicated in step 10.

Motor Speed versus Load Characteristics

☐ 16. For each load settings listed in Table 12-1, measure and record the armature voltage E_A, armature current I_A, field current I_F and motor speed in the *With IR COMP.* columns.

☐ 17. Plot the graph of the *Motor Speed* as a function of *Load* with IR compensation in Figure 11-3.

☐ 18. Compare the speed versus load curves you plotted in Figure 11-3 with and without IR compensation. Do the curves confirm that the IR compensation does not affect the speed regulation of the motor?

☐ Yes ☐ No

REFERENCE INTEGRATOR Setting

☐ 19. On the Electrodynamometer, set the dynamometer control knob at its full counterclockwise position for minimum loading.

☐ 20. On the Thyristor Speed Controller, set the VOLTAGE REFERENCE potentiometer at MAX., and position the RUN selector at O.

Ensure that the REFERENCE INTEGRATOR potentiometer is at MIN.

Position the RUN selector at I while observing the time the DC Motor/Generator takes to run at maximum speed.

Note: *The breaker on the Power Supply and/or on the Thyristor Speed Controller may trip when performing this manipulation. Then, turn off the Power Supply, reset the breaker(s). Turn the REFERENCE INTEGRATOR potentiometer clockwise ⅛ of a turn, turn on the Power Supply and continue the manipulation.*

☐ 21. Does the DC Motor/Generator start to run and attain maximum speed very rapidly?

☐ Yes ☐ No

☐ 22. Repeat your observation when the REFERENCE INTEGRATOR potentiometer is set at MAX. To do so, position the RUN selector at O and set the REFERENCE INTEGRATOR potentiometer at MAX.

Position the RUN selector at I while observing the time the DC Motor/Generator takes to run at maximum speed.

☐ 23. Is the acceleration of the motor smooth?

☐ Yes ☐ No

☐ 24. Do your observations confirm that the REFERENCE INTEGRATOR potentiometer allows the control of motor acceleration?

☐ Yes ☐ No

☐ 25. Repeat your observations with different REFERENCE INTEGRATOR potentiometer settings.

Current Limit

☐ 26. Set the Thyristor Speed Controller controls as follows:

RUN selector I
REFERENCE INTEGRATOR potentiometer .... MAX.
CURRENT LIMIT potentiometer .... MIN.

Set the VOLTAGE REFERENCE potentiometer to obtain the motor speed indicated in step 10.

☐ 27. Record the armature voltage E_A, armature current I_A, field current I_F, and motor speed in Table 12-2.

On the Electrodynamometer, adjust the dynamometer control knob so that the torque indicated on the module, increases by 0.1 N·m [1.0 lbf·in] increments up to 1.0 N·m [10.0 lbf·in].

After each load setting, wait 10 s then record your data in Table12-2.

LOAD SETTING	E_A (V)	I_A (A)	I_F (mA)	SPEED (r/min)

Table 12-2.

☐ 28. Were you able to increase the load to the value indicated in the following table?

AC NETWORK VOLTAGE	MOTOR TORQUE
120 V	1 N·m [10 lbf·in]
220 V	1 N·m
240 V	1 N·m

☐ Yes ☐ No

☐ 29. Does this confirm that the torque developed by the DC Motor/Generator can be limited using the current limiter function of the Thyristor Speed Controller?

☐ Yes ☐ No

☐ 30. Repeat your observations with different CURRENT LIMIT potentiometer settings.

☐ 31. Once your observations are completed, set the dynamometer control knob at its full counterclockwise position for minimum loading.

☐ 32. Turn off the Power Supply.

CONCLUSION

In this exercise you were introduced to thyristor speed controllers operating in the closed-loop mode of control. You saw that the Thyristor Speed Controller detects the armature voltage and current to determine the motor speed and torque, and to regulate the speed as the load varies.

You plotted the speed versus load curves from the data measured in closed loop with and without IR compensation, you compared these curves to the one obtained in open-loop mode of control, and observed that the closed-loop mode of control improves speed regulation as the load varies.

You also learned how to control the acceleration, and how to limit the torque developed by the DC Motor/Generator.

REVIEW QUESTIONS

1. Explain how the closed-loop control improves speed regulation as the load varies.

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2. What is the purpose of the VOLTAGE REFERENCE potentiometer on the Thyristor Speed Controller.

3. What is the purpose of the REFERENCE INTEGRATOR of the Thyristor Speed Controller?

4. What is the purpose of the CURRENT LIMIT potentiometer on the Thyristor Speed Controller?

Appendix A

Equipment Utilization Chart

MODEL	EQUIPMENT[1]	ELECTRICAL POWER TECHNOLOGY EXPERIMENT											
		1	2	3	4	5	6	7	8	9	10	11	12
8110	Mobile Workstation	1	1	1	1	1	1	1	1	1	1	1	1
8211	DC Motor/Generator		1	1	1	1	1	1	1	1	1	1	1
8241	Three-Phase Synchronous Motor/Generator	1						1	1	1			
8311	Resistive Load		1	1	1	1	1	1	1	1	1		
8412	DC Voltmeter/Ammeter		1	1	1	1	1	1	1	1	1	1	1
8425	AC Ammeter	1						1	1	1			
8426	AC Voltmeter			1									
8631	Manual DC Motor Starter										1		
8821	Power Supply	1	1	1	1	1	1	1	1	1	1	1	1
8911[2]	Electrodynamometer	1			1	1	1				1	1	1
8920	Digital Tachometer	1		1	1	1	1					1	1
8942	Timing Belt	1			1	1	1	1	1	1	1	1	1
8951	Connection Leads	1	1	1	1	1	1	1	1	1	1	1	1
9017	Thyristor Speed Controller											1	1

[1] The module storage facilities Storage Cabinet have not been included in this chart

[2] The Electrodynamometer Module EMS 8911 may be replaced by a Prony Brake Module EMS 8913.

Appendix B

Impedance Table for the Load Modules

The following table gives impedance values which can be obtained using either the Resistive Load, Model 8311, the Inductive Load, Model 8321, or the Capacitive Load, Model 8331. Figure B-1 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

IMPEDANCE (Ω)			SWITCH POSITIONS FOR LOAD ELEMENTS								
120 V 60 Hz	220 V 50 Hz	240 V 50 Hz	1	2	3	4	5	6	7	8	9
1200	4400	4800	I								
600	2200	2400		I							
300	1100	1200			I						
400	1467	1600	I	I							
240	880	960	I		I						
200	733	800		I	I						
171	629	686	I	I	I						
150	550	600	I			I	I	I			
133	489	533		I		I	I	I			
120	440	480			I		I	I			
109	400	436			I	I	I	I			
100	367	400	I		I	I	I	I			
92	338	369		I	I	I	I	I			
86	314	343	I	I	I	I	I	I			
80	293	320	I			I	I	I	I	I	I
75	275	300		I		I	I	I	I	I	I
71	259	282			I		I	I	I	I	I
67	244	267			I	I	I	I	I	I	I
63	232	253	I		I	I	I	I	I	I	I
60	220	240		I	I	I	I	I	I	I	I
57	210	229	I	I	I	I	I	I	I	I	I

Table B-1. Impedance table for the load modules.

Impedance Table for the Load Modules (cont'd)

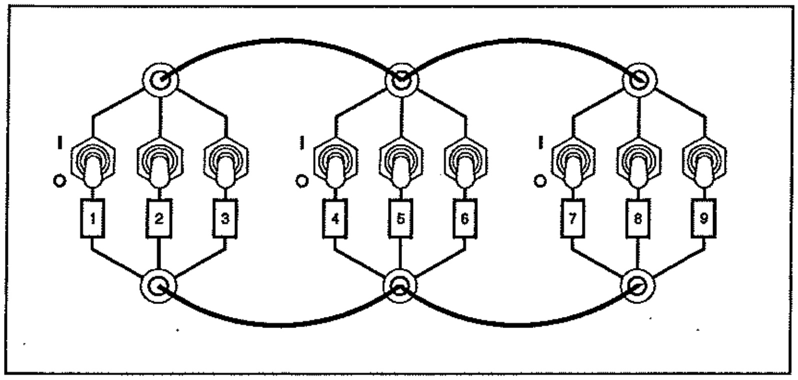

Figure B-1. Location of the load elements.

Appendix C

Performing the Electrical Power Technology Courseware Using the Lab-Volt Data Acquisition and Management System

The exercises in the *Electric Power / Controls* courseware have been designed to be performed using conventional instruments (AC/DC voltmeters and ammeters, power meters, etc). All these exercises can also be carried out using the Lab-Volt Data Acquisition and Management (LVDAM) System.

The LVDAM System consists of the Data Acquisition Interface (DAI) module, model 9062, and the corresponding LVDAM software. The system includes a user manual (p.n. 30328-EX) designed to familiarize users with the operation of the LVDAM System.

The Electrodynamometer (model 8911) and Precision Hand Tachometer (model 8920) are replaced in the LVDAM System by the Prime Mover / Dynamometer module (model 8960). In some exercises, the Prime Mover / Dynamometer module can also replace the Synchronous Motor/Generator (model 8241) to drive rotating machines mechanically. Refer to the manual titled *AC/DC Motors and Generators* (p.n. 30329) to familiarize yourself with the operation of the Prime Mover / Dynamometer module.

When performing the *Electric Power / Controls* courseware with the LVDAM System, the following guidelines should be taken into account:

- The "AC and DC voltmeters" are implemented using the high-voltage inputs E1, E2, and E3 of the DAI module. The voltage values are displayed on meters E1, E2, and E3 in the Metering application of the LVDAM System.

- The "AC and DC ammeters" are implemented using the high-current inputs I1, I2, and I3 of the DAI module. The current values are displayed on meters I1, I2, and I3 in the Metering application of the LVDAM System.

- The "Single-Phase Wattmeter" (model 8431) is implemented using one high-voltage input combined with one high-current input. This can be done using the inputs E1 with I1, E2 with I2, and E3 with I3 of the DAI module. The power values are displayed on meters PQS1, PQS2, and PQS3 in the Metering application of the LVDAM System.

  Note that the voltage and current values used in the power measurements can be displayed on the voltage and current meters in the Metering application of the LVDAM System. This is a useful feature which, in certain cases, can reduce the number of inputs required to measure the various parameters in a circuit. As an example, in a circuit where the line-to-line voltage is measured using input E1, it would be a wise choice to use inputs E1 and I1 to measure single-phase power in this circuit. This would prevent the line-to-line voltage from being measured twice and using two voltage inputs.

- The "Three-Phase Wattmeter" (model 8441) is implemented using two "wattmeters" (each of them being implemented using one high-voltage input combined with one high-current input). This can be done using inputs E1 with I1 to produce P1, E2 with I2 to produce P2, and E3 with I3 to produce P3. The power values are displayed on meters PQS1, PQS2, or PQS3 in the Metering application of the LVDAM System. As an example, using inputs E1 with I1 and E3 with I3, and selecting functions PQS1 and PQS3, allow one to measure W1 and W2 present on the Three-Phase Wattmeter.

EXERCISES WHERE THE NUMBER OF AVAILABLE INPUTS IS EXCEEDED

In some exercises of the *Electric Power / Controls* courseware, four or five high-current inputs are required to perform all current measurements. Unfortunately, only three high-current inputs are available in the LVDAM system.

In the exercises where it is asked to measure the currents I_F, I_A, and the line currents I_1, I_2, and I_3, the number of available inputs is exceeded. Since the line currents are usually measured only to make sure that the motor operation is normal, you may consider measuring only one line current (or all but one at the same time).

In some exercises, the implementation of the Single-Phase Wattmeter, or Three-Phase Wattmeter, using high-voltage and high-current inputs also causes the number of available inputs to be exceeded.

The exercises where the number of available inputs is exceeded are listed below. A solution is also suggested for each case.

- **The DC Separately-Excited Shunt Generator**

  In the circuits of Figures 1, 2 and 3, use input I1 to measure current I_F, input I2 to measure current I_A, and input I3 to measure line current I_3.

- **The DC Self-Excited Shunt Generator**

  In the circuits of Figures 1 and 2, use input I1 to measure current I_A, and inputs I2 and I3 to measure line currents I_2 and I_3.

- **The DC Compound Generator**

  In the circuits of Figures 1 and 2, use input I1 to measure current I_A, and inputs I2 and I3 to measure line currents I_2 and I_3.

- **The DC Series Generator**

  In the circuits of Figures 4 and 5, use input I1 to measure current I_A, and inputs I2 and I3 to measure line currents I_2 and I_3.

Performing the Electrical Power Technology Courseware Using the Lab-Volt Data Acquisition and Management System (cont'd)

- **Transformers in Parallel**

  In the circuit of Figure 1, the implementation of the Single-Phase Wattmeter using one high-voltage input and one high-current input from the LVDAM System increases the number of required high-current inputs to four.

  Use a programmable meter programmed to calculate I1 + I2 to measure the load current I_L ($I_1 + I_2 = I_L$ in this circuit).

- **Frequency Conversion**

  In the circuits of Figures 1 and 2, the implementation of the Three-Phase Wattmeter using two high-voltage inputs and two high-current inputs from the LVDAM system increases the number of required high-current inputs to four.

  Use inputs E1-I1 and E3-I3 to implement the Three-Phase Wattmeter. In step 3d, use temporarily input I3 (currently used in the power measurement circuit) to adjust the DC excitation of the synchronous motor. Once the adjustment is completed, return input I3 in the power measurement circuit.

Appendix D

SCR Speed Control – Part I

OBJECTIVE

- To show the operation of an open-loop electronic variable speed control for a DC motor.

DISCUSSION

In Experiment 3, it was seen that the speed of a DC motor could be controlled from zero to maximum by varying the armature voltage, while keeping the shunt field voltage constant.

Controllers for DC shunt motors often use silicon controlled rectifiers as the controlled element for varying the power applied to the motor. The silicon controlled rectifier (SCR), is a solid state device whose function is analogous to that of the grid controlled thyratron tube. It will pass current in only one direction; hence, it rectifies. In addition, it will turn on and pass current only upon receipt of a trigger signal on a control electrode called the gate. Once turned on, an SCR will continue to conduct until the voltage is removed or the polarity of the voltage across it is reversed.

When an SCR is used to rectify alternating current, the point during the positive half-cycle of the input current at which the rectifier is turned on, can be adjusted by the timing of the application of a trigger signal to the gate. At the end of the positive half-cycle, the SCR will turn off as the polarity of the applied voltage reverses. By controlling the phase relationship of the trigger signal to the zero axis crossing of the positive half-cycle of alternating current, the amount of power transmitted through the SCR can be varied. This is called phase control.

While there are a number of different types of electronic speed controllers for use with DC shunt motors, all of them have in common the conversion of alternating current to pulsating unidirectional current, using half-wave, or full-wave rectification. Both of these currents depart considerably from steady direct current. The measure of the departure of a pulsating, unfiltered, unidirectional current of this nature from a steady direct current is called a *form factor*. Pure direct current has a form factor of one. The form factor of unidirectional currents is determined by the rms value of the current divided by the average value of the current. For half-wave, unfiltered current, the form factor is 1.57; for full-wave, unfiltered current, the form factor is 1.11. Capacitor or inductor-capacitor filters can be used to improve the form factor.

In considering speed controllers for DC shunt motors, the form factor of the DC supplied to the motor is of considerable importance. When operating from rectified power, the increase in motor heating is approximately proportional to the square of the form factor. For example, a motor operating from unfiltered half-wave rectified current with a from factor of 1.57 will have approximately 2 ½ times the heat rise of the same motor operating on unity form factor DC. In addition to the I^2R losses, there are losses in the motor frame and pole pieces, due to pulsating flux produced by intermittent high peak currents.

A second consideration is brush and commutator life. When operating from high form factor current, high peak currents are required to maintain average current input for a given power output, thus accelerating brush and commutator wear.

High form factor adversely affects motor operation at low speeds. The current pulse repetition rate, using half-wave rectification, is 60 pulses per second. Using full-wave rectification, it is 120 pulses per second. At low speeds, these pulsating currents reinforce the motor's tendency to cog (have non-uniform velocity). Therefore, smooth, low-speed operation becomes impractical.

The Thyristor (SCR) Speed Controller has the following features:

a) It will operate from a 120 V, alternating current source.

b) It rectifies the alternating current, changing it to direct current.

c) The DC armature current can be varied by advancing or retarding the firing angle of the SCR. (It also employs a free-wheeling diode circuit to establish a constant magnetic field.)

d) A phase-shift circuit comprising a capacitor ad a variable resistance, permits a change in the SCR firing angle from zero to approximately 150 °.

e) It can be adapted for either "open-loop" (no feedback) or "closed-loop" (with feed-back) control.

Major System Components

It is possible to gain a reasonable understanding of the major parts of the Thyristor (SCR) Speed Controller by referring to the schematic diagram on the face of the module. In moving from left to right, the following reference numbers and components may be identified.

1. Transformer T_1 is an autotransformer which changes the 120 V ac, input (points 2 and 1) to 200 V ac (points 3 and 1). The transformer is center-tapped (point 4) giving 100 V ac between points 4 and 1 or 4 and 3.

2. Capacitor C_1 and Rheostat R_1. As the resistance of R_1 is varied, the phase angle of the voltage between points 4 and 5 changes from zero (R_1 at minimum resistance) to approximately 150 ° lag (R_1 at maximum resistance).

3. Transformer T_2. The voltage between points 4 and 5 is applied to the primary winding of transformer T_2. The stepped-down secondary voltage of T_2 appears between points 7 and 9. As rheostat R_1 is varied, the phase angle of the secondary voltage of T_2 (points 7 and 9) changes from zero to approximately 150 ° with respect to the 200 V output (points 1 and 3) of autotransformer T_1.

4. Diode D_1 and Potentiometer R_2 are part of a DC reference voltage supply. Potentiometer R_2 allows the reference voltage (between points 6 and 1) to be varied from 0 to 140 V dc. This circuit is only required on closed-loop control studies.

5. Reactance X_L is a filter choke to provide smoother operation of the DC motor. It also tends to prevent heavy surges of armature current. The choke is located between points 3 and 10.

6. Silicon controlled Rectifier (SCR). The anode, cathode and gate of the SCR correspond respectively to points 10, 11 and 9. The AC voltage across the secondary of transformer T_2 (points 7 and 9) causes the gate (point 9) of the SCR to trigger the SCR on earlier or later in the cycle, depending upon the phase shift which is controlled by the setting of rheostat R_1. For open-loop control, point 7 is connected to the cathode (point 11) of the SCR.

7. The Armature A. The armature of the DC motor is connected between points 1 and 11. Point 11 is positive with respect to point 1 which is at ground potential.

8. Capacitor C_2 (between points 8 and 1) is an electrolytic filter capacitor that can be connected across the armature winding of the DC motor by joining points 8 and 11. This will result in smoother motor operation because the capacitor will discharge through the armature winding during the periods when the SCR is not conducting. The motor periods when the SCR is not conducting. The motor will vibrate less and run cooler because the capacitor, rather than the armature, will absorb the current peaks during each cycle.

9. Diodes D_2, D_3 and the Shunt Field. The shunt field of the DC motor is connected between points 12 and 1. The action of diodes D_2 and D_3 is such that the field current is kept nearly constant. The DC voltage between points 12 and 1 should be approximately 45% of the AC voltage (points 3 and 1) applied to the free-wheeling circuit.

EQUIPMENT REQUIRED

DESCRIPTION	PART NUMBER
DC Motor/Generator	8211
DC Voltmeter/Ammeter	8412
Power Supply	8821
Electrodynamometer	8911
Digital Tachometer	8920
Timing Belt	8942
Connection Leads	8951
Thyristor (SCR) Speed Controller	9011

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 Thyristor (SCR) Speed Controller, DC Motor/Generator, Electrodynamometer, DC Voltmeter/Ammeter, AC Ammeter and AC Voltmeter, connect the circuit shown in Figure 11-1. The reference numbers appearing on the schematic diagram refer to the numbered points of the SCR speed control unit.

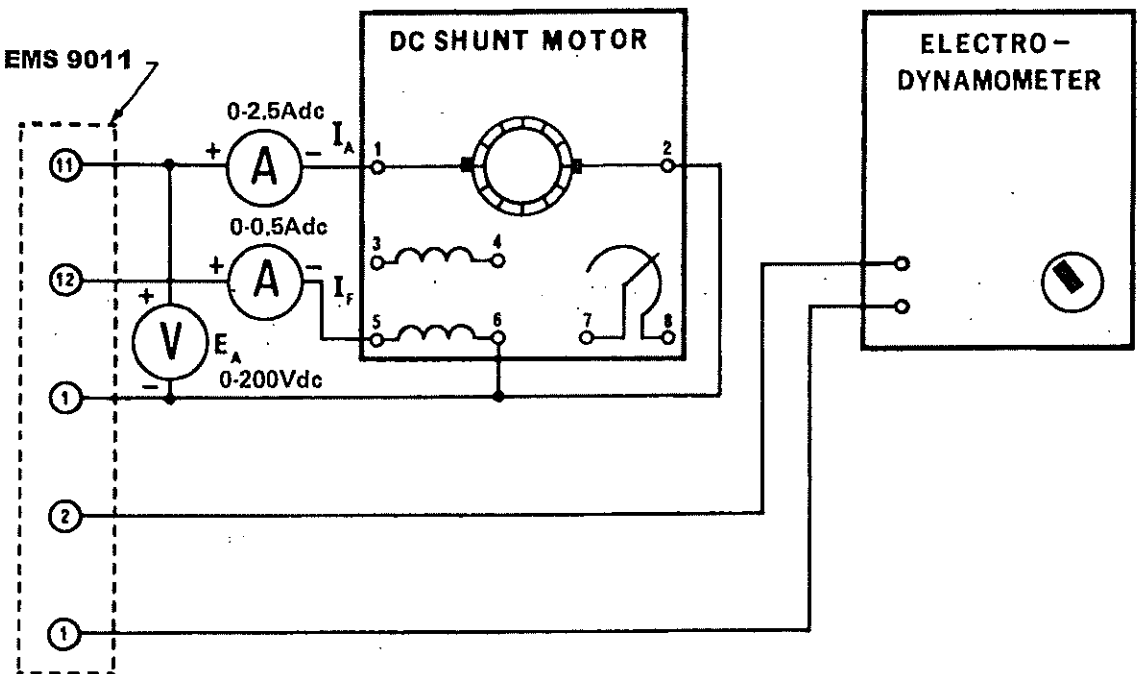

Figure D-1.

a. Connect the armature of the DC motor, in series with the ammeter, to points 11 and 1.

b. Connect the shunt field of the DC motor, in series with the milliammeter, to points 12 and 1.

c. Connect the 0-200 V dc voltmeter across the armature power source, points 11 and 1.

d. Connect points 7 and 11 together so that the triggering signal from the secondary of T_2 can be applied to the gate of the SCR.

e. Set rheostat R_1 at its full ccw position for maximum resistance.

f. Short out reactance X_L by connecting a lead between points 3 and 10.

g. Connect the input of the Thyristor (SCR) Speed Controller to any convenient source of 120 V ac power.

☐ 2. a. Turn on the power; the indicating lamp should light.

b. Vary the position of rheostat R_1 and note the effect upon motor speed and armature voltage.

c. Adjust R_1 until the armature voltage $E_A = 90$ V dc. Measure and record in Table D-1 the armature current, field current and motor speed.

E_A (volts)	I_A (amps)	I_f (amps)	SPEED (r/min)
90			
105			
120			
135			
150			

Table D1.

d. Repeat (c) for each of the armature voltages listed in Table D-1.

e. At low motor speed, does the SCR conduct early or late in the cycle?

____

f. What is the highest motor speed you can attain?

Speed = ______ r/min

g. Turn off the power.

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

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

c. Set rheostat R_1 at its full ccw position for maximum resistance.

d. Turn on the power and adjust the speed control rheostat R_1 and the dynamometer control for a motor speed of 1500 r/min at a load of 0.7 N·m [6 lbf·in].

e. Measure and record the armature voltage, armature current and field current.

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

f. Is there appreciable sparking at the brushes?

☐ Yes ☐ No

g. Is there appreciable motor vibration?

☐ Yes ☐ No

h. What is the frequency of the vibration in Hz?

____

☐ 4. a. Without altering the position of rheostat R_1, reduce the dynamometer loading to its minimum value by turning the control knob to its full ccw position.

b. Measure and record the armature voltage, armature current, field current and motor speed.

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc.

Motor speed = ______ r/min

c. Turn off the power.

d. Is there a large speed change from full-load torque to no-load torque?

☐ Yes ☐ No

e. Might this variation in motor speed be objectionable in some cases? Explain.

☐ Yes ☐ No

____

____

____

☐ 5. You will now repeat procedures 3 and 4, using the LC filter in your SCR speed control unit.

a. To place the filter choke in the circuit, remove the shorting lead between points 3 and 10.

b. To place the filter capacitor in the circuit, connect a lead between points 8 and 11. (The other side of C_2 is permanently connected to point 1).

c. Repeat procedure 3 and record the armature voltage, armature current and field current.

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

d. Is there as much vibration as before?

☐ Yes ☐ No

e. Is there as much sparking at the brushes?

☐ Yes ☐ No

f. Repeat procedure 4 and record the armature voltage, armature current, field current and motor speed.

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

Motor speed = ______ r/min

g. Turn off the power.

REVIEW QUESTIONS

1. Comment on the differences in motor operation with filtered and unfiltered DC power.

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2. Can you comment on one of the faults of open-loop speed control as evidence by performing this Experiment?

____

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3. If C_1 = 2μF, what value of R_1 would be required for a phase shift of 90°?

Appendix E

SCR Speed Control – Part II

OBJECTIVE

- To show the operation of a closed-loop electronic variable speed control for a DC motor.

DISCUSSION

You may have noted that, although the open-loop electronic control of the DC motor of Appendix D offered a wide speed range, it had poor stability with varying loads.

In this Experiment, you will learn the effects of feedback upon motor speed stability. Feedback, or closed-loop, control systems give far better performance than open-loop systems.

The non-feedback speed controller consisted of a field supply and a manually adjustable armature power supply. Speed regulation as the motor load changes is not improved by the controller.

The feedback speed controller can be adjusted to provide the desired motor speed. It is provided with circuitry which senses motor speed and automatically adjusts its output power to maintain motor speed constant as the load varies.

All feedback systems where a quantity such as peed, torque, temperature, etc., is to be kept at a predetermined value, must have a reference against which the quantity can be compared. Thus, if we want to keep the speed of a motor constant, the speed must be compared with a reference. However, it is cumbersome to compare "a speed" with a "reference speed", particularly in systems which are basically electrical. For this reason, we prefer to use an electrical quantity (such as a voltage which is directly related to the speed) and compare it with a reference voltage.

The difference or error between the measured voltage (proportional to the motor speed) and the reference voltage can then be used to "tell" the system whether it should increase the speed or reduce it, in order to bring it back as close as possible to the reference value.

SCR Speed Control – Part II

EQUIPMENT REQUIRED

DESCRIPTION	PART NUMBER
DC Motor/Generator	8211
DC Voltmeter/Ammeter	8412
Power Supply	8821
Electrodynamometer	8911
Digital Tachometer	8920
Timing Belt	8942
Connection Leads	8951
Thyristor (SCR) Speed Controller	9011

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 Thyristor (SCR) Speed Controller, DC Motor/Generator, Electrodynamometer, DC Voltmeter/Ammeter and Power Supply, connect the circuit shown in Figure E-1. (This is the same circuit used in the previous Experiment, where the speed control unit operated without feedback).

SCR Speed Control – Part II

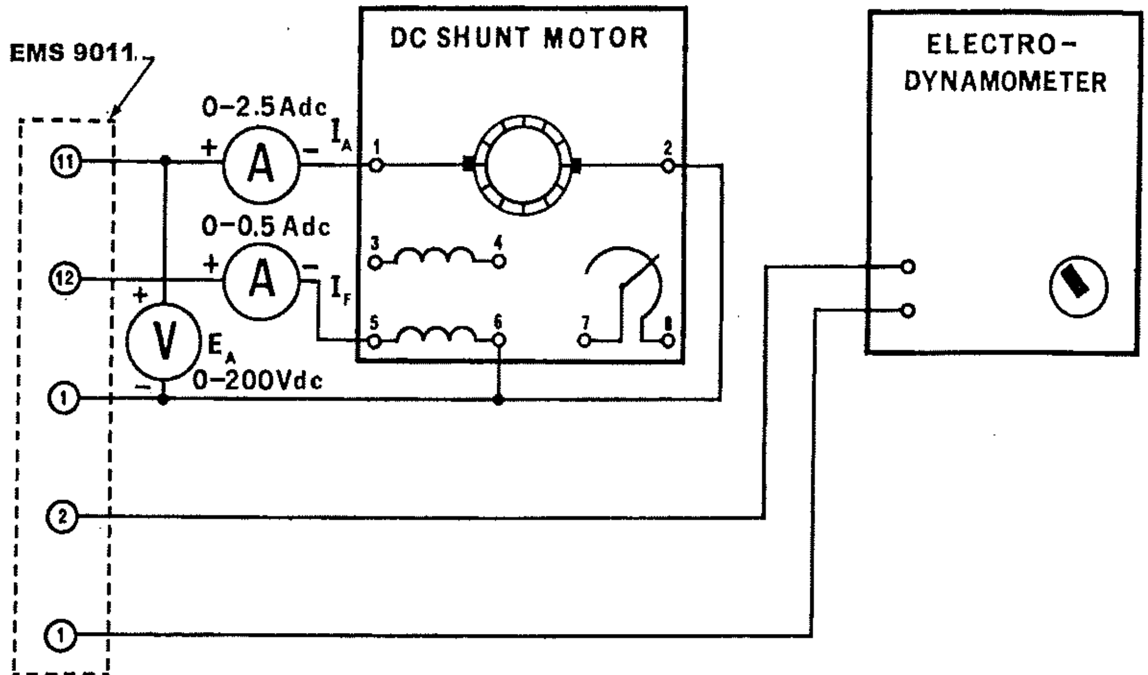

Figure E-1.

☐ 2. a. Connect the armature of the DC motor, in series with the ammeter, to points 11 and 1.

b. Connect the shunt field of the DC motor, in series with the milliammeter, to points 12 and 1.

c. Connect to the 0-200 V DC voltmeter across the armature power source, points 11 and 1.

d. Connect points 7 and 6 together so that the triggering signal from the secondary of T_2 can be applied to the gate of the SCR. (Note that the gate of the SCR is no longer tied to its cathode through the secondary of T_2 as in the open-loop control circuit, but is now tied to a DC voltage reference source).

e. Connect points 8 and 11 together to place the filter capacitor in the circuit.

f. Set rheostat R_1 at its mid-position and leave it there for the remainder of this Experiment.

g. Set potentiometer R_2 at its full ccw position for zero reference voltage between points 6 and 1.

h. Couple the motor to the electrodynamometer with the timing belt.

i. Set the dynamometer control knob at its full ccw position for minimum loading.

☐ 3. a. Turn on the power and adjust the speed control potentiometer R_2 and the dynamometer control for a motor speed of 1000 r/min at a load of 1 N·m [9 lbf·in].

b. Measure and record the armature voltage, armature current and field current.

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

c. Turn the dynamometer control knob to its full ccw position for minimum loading. Do not touch any of the other controls.

d. Measure and record the armature voltage, armature current, field current and motor speed.

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

Motor speed = ______ r/min

e. Does closed-loop control give better speed regulation than open-loop control?

☐ Yes ☐ No

☐ 4. a. Repeat procedure 3 at a motor speed of 1600 r/min and a load of 1 N·m [9 lbf·in].

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

b. At minimum loading:

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

Motor speed = ______ r/min

☐ 5. a. Repeat procedure 3 at a motor speed of 100 r/min and a load of 1 N·m [9 lbf·in].

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

b. At minimum loading:

E_A = ______ V dc, I_A = ______ A dc, I_F = ______ A dc

Motor speed = ______ r/min

c. Turn off the power to the SCR speed control unit.

REVIEW QUESTIONS

1. Explain the relative advantages of closed-loop control.

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2. Explain, if you can, why the armature voltage (between points 11 and 1) can be used as a measure of motor speed.

____

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3. Explain, if you can, what happens to the triggering angle of the SCR when the motor load is increased.

____

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____

4. Explain, if you can, why the motor speed falls when the reference voltage is reduced.

____

____

____

____

ELECTRIC POWER / CONTROSL
DC MACHINES
25987-00
Second Edition: February 2002
Printed: February 2002

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Please take a few minutes to complete this questionnaire. Your answers and comments will enable us to produce better manuals. Return it to the address on the reverse side of this page or ask your instructor to forward it.

How long are the exercises?

☐ Too long ☐ Adequate ☐ Too short

Do the Discussions cover enough information?

☐ Too little ☐ Acceptable ☐ Too much

How easy to follow are the Procedures?

☐ Too difficult ☐ Adequate ☐ Very easy

How useful is the Procedure Summary?

☐ Of little use ☐ Useful ☐ Very useful

How many hours were required per exercise?

☐ 1 ☐ 2 ☐ 3 or more

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Please enclose photocopies of pages where errors were found and indicate the modifications that should be carried out.

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