DC Motors and Generators

When you have completed this unit, you will be able to use the DC Motor/Generator module to demonstrate and explain the operation of dc motors and generators

Operating principle of dc motors

As stated in Unit 1, motors turn because of the interaction between two magnetic fields. This unit will discuss how these magnetic fields are produced in dc motors, and how magnetic fields induce voltage in dc generators.

The basic principle of a dc motor is the creation of a rotating magnet inside the mobile part of the motor, the rotor. This is accomplished by a device called the **commutator** which is found on all dc machines. The commutator produces the alternating currents necessary for the creation of the rotating magnet from dc power provided by an external source. Figure 2-1 illustrates a typical dc motor rotor with its main parts. This figure shows that the electrical contact between the segments of the commutator and the external dc source is made through brushes. Note that the rotor of a dc motor is also referred to as the armature.
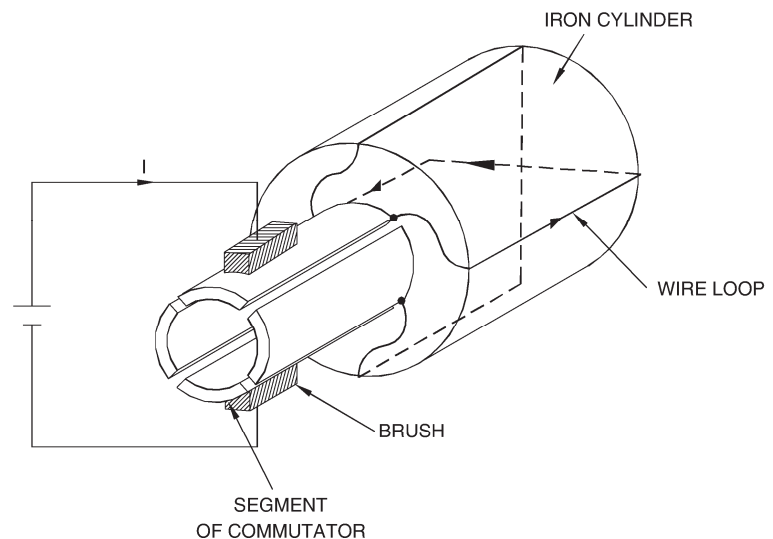

Figure 2-1. The main parts of a dc motor rotor (armature).

In Figure 2-2a, the brushes make contact with segments A and B of the commutator and current flows in wire loop A-B. No current flows in the other wire loop (C-D). This creates an electromagnet A-B with north and south poles as shown in Figure 2-2a.

If the rotor is turned clockwise a little as shown in Figure 2-2b, current still flows in wire loop A-B and the magnetic north and south poles rotate clockwise.
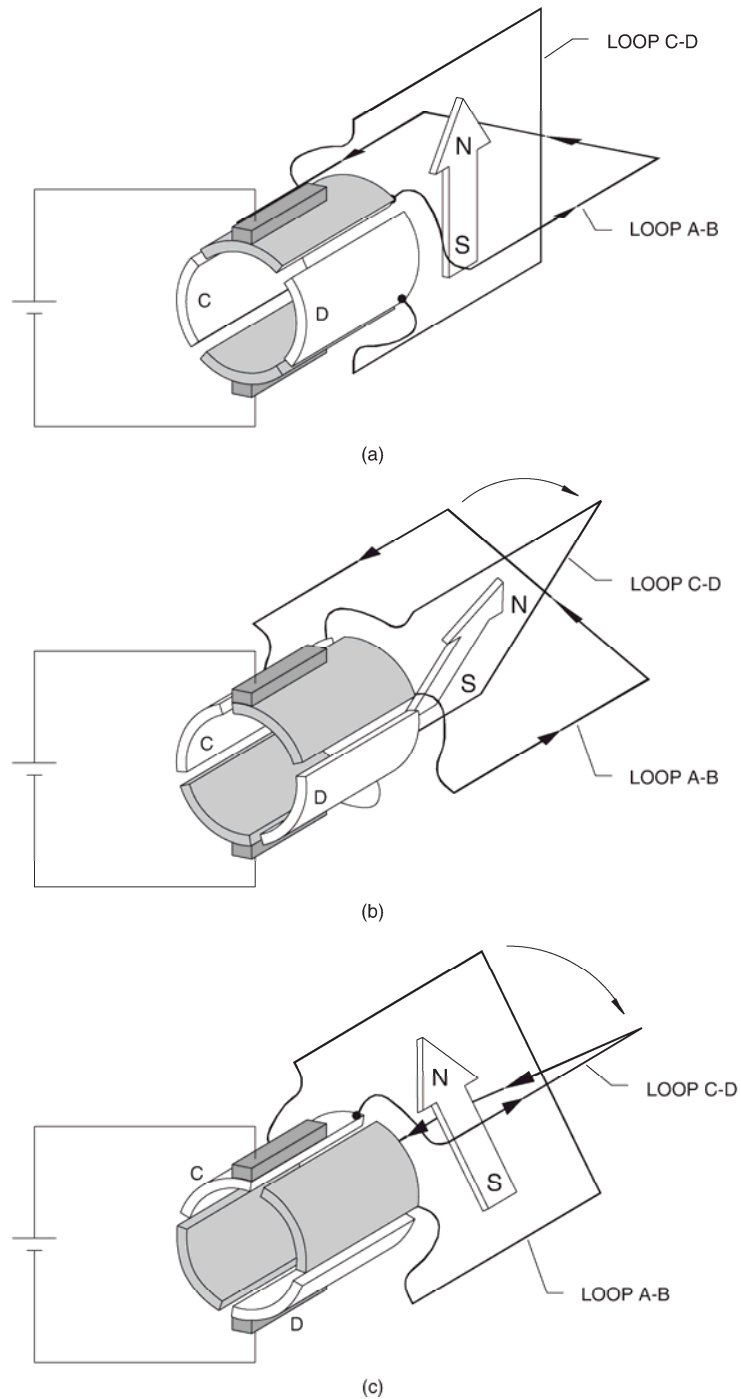

(a)

(b)

(c)

Figure 2-2. Operation of the commutator.

As the rotor continues to rotate clockwise, a time comes where a commutation occurs, i.e., the brushes make contact with segments C and D instead of segments A and B, as shown in Figure 2-2c. As a result, current now flows in wire loop C-D instead of flowing in wire loop A-B. This creates an electromagnet C-D with north and south poles as shown in Figure 2-2c.
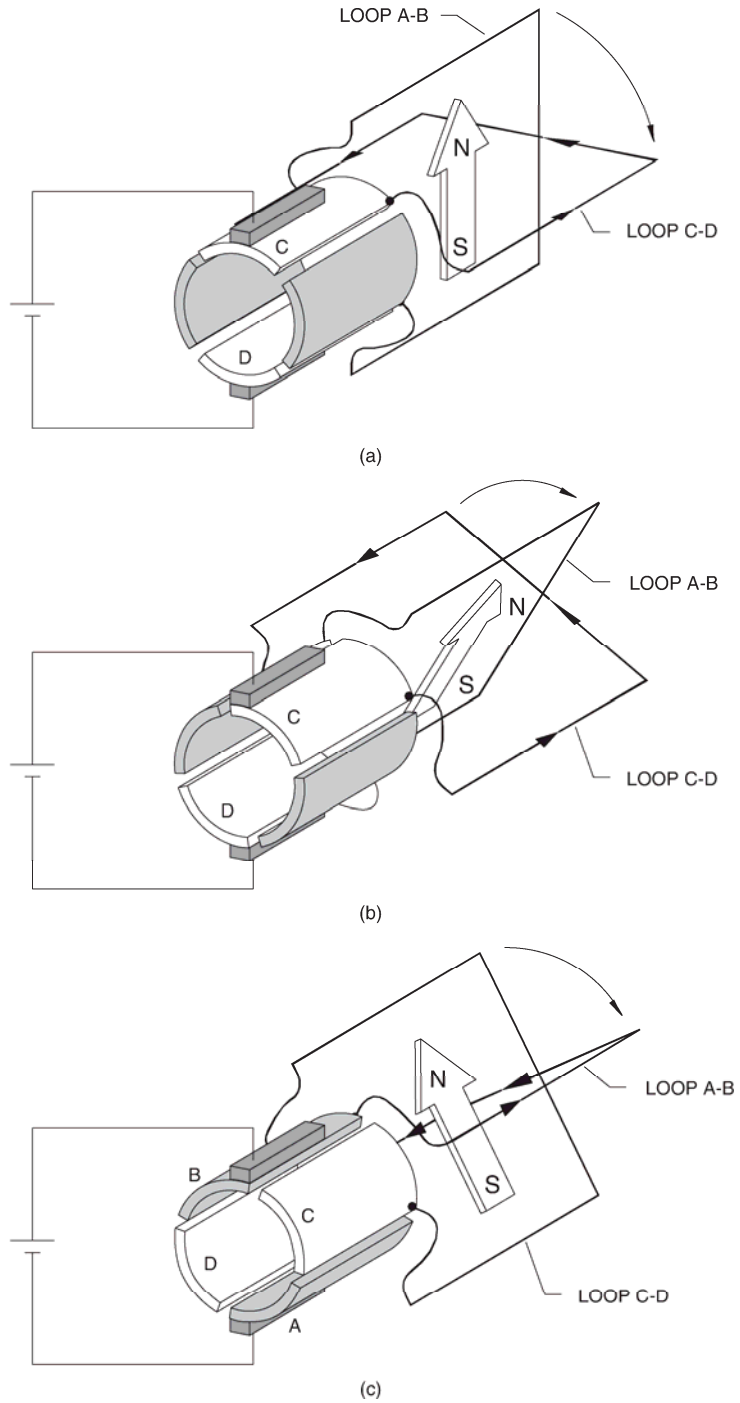
(a)

(b)

(c)

Figure 2-3. Operation of the commutator (continued).

By comparing Figure 2-2b and Figure 2-2c, you can see that the magnetic north and south poles rotate 90° counterclockwise at the commutation. As the rotor continues to rotate clockwise, the same phenomenon repeats every 90° angle of rotation, as shown in Figure 2-3a, Figure 2-3b, and Figure 2-3c.

In brief, as the rotor turns, the north and south poles of the electromagnet go back and forth (oscillate) over a 90° angle, as shown in Figure 2-4. In other words, the north and south poles are stationary, i.e., they do not rotate as the rotor turns. This is equivalent to having an electromagnet in the rotor that rotates at the same speed as the rotor but in the opposite direction. The higher the number of segments on the commutator, the lower the angle of rotation between each commutation, and the lower the angle over which the north and south poles oscillate. For example, the north and south poles would oscillate over an angle of only 11.25° if the commutator in Figure 2-2, Figure 2-3, and Figure 2-4 were having 32 segments.
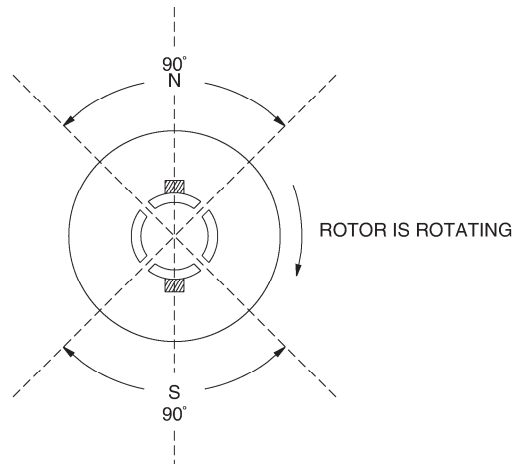

Figure 2-4. The north and south poles oscillate around a fixed position.

If this rotor is placed next to a fixed permanent magnet stator as shown in Figure 2-5, the magnetic poles of opposite polarity attract each other (in order to align) and the rotor starts to turn. After the rotor has turned by a certain angle, a commutation occurs and the north and south poles of the electromagnet go back. Once again, the magnetic poles of opposite polarity attract each other, and the rotor continues to rotate in the same direction so as to align the magnetic poles of opposite polarity. However, another commutation occurs a little after and the north and south poles of the electromagnet go back once again. This cycle repeats over and over. The force that results from the interaction of the two magnetic fields always acts in the same direction, and the rotor turns continually. Thus, a converter of electrical-to-mechanical energy, i.e., an electric motor, has been achieved. The direction of rotation depends on the polarity of the voltage applied to the brushes of the rotor.
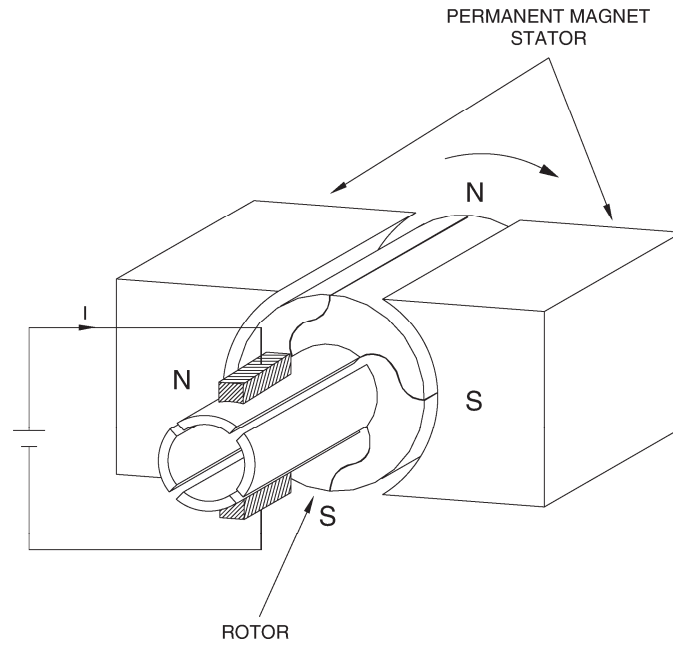
Figure 2-5. Rotation resulting from interaction of magnetic fields in the stator and the rotor.

Operating principle of dc generators

Previously, we saw that the variation of magnetic flux in a coil of wire caused a voltage to be induced between the ends of the coil of wire. If a wire loop is placed between two magnets and rotated as shown in Figure 2-6, magnetic lines of force are cut and a voltage "e" is induced in the loop. The polarity of the induced voltage "e" depends on the direction in which the wire loop moves as it cuts the magnetic lines of force. Since the wire loop cuts magnetic lines of force in both directions within a full revolution, the induced voltage is an ac voltage similar to that shown in Figure 2-6.

If a commutator such as that shown in Figure 2-1 is used, it will act as a **rectifier** and convert the induced ac voltage into a dc voltage (with ripple), as shown in Figure 2-6. Direct current will therefore be produced at the output of the generator. The faster the rotor turns, the more lines of force that are cut and the higher the output voltage. Also, the stronger the stator magnet, the more lines of force that are present, and therefore, the higher the output voltage.
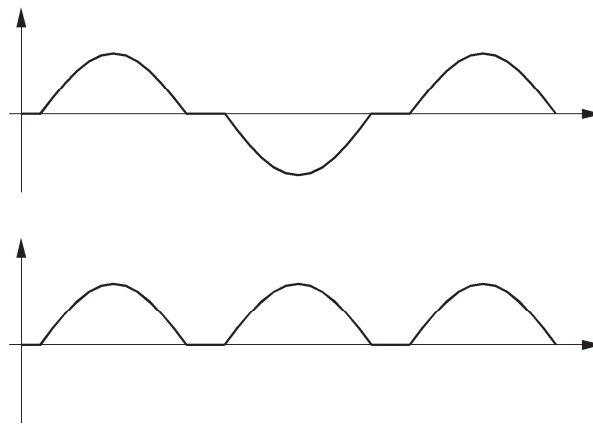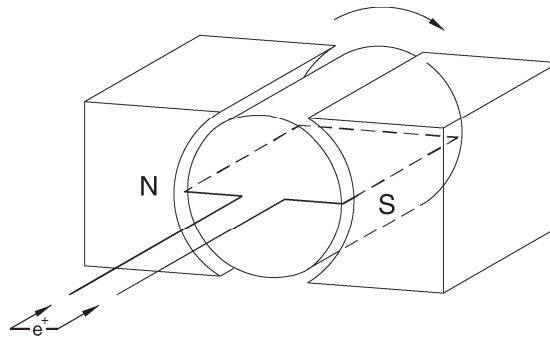
Figure 2-6. A coil rotating in a magnetic field results in an induced voltage.

The Separately-Excited DC Motor

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the main operating characteristics of a separately-excited dc motor using the DC Motor/Generator module.

DISCUSSION

Previously, you saw that a dc motor is made up basically of a fixed magnet (stator) and a rotating magnet (rotor). Many dc motors use an electromagnet for the stator, as illustrated in Figure 2-7.
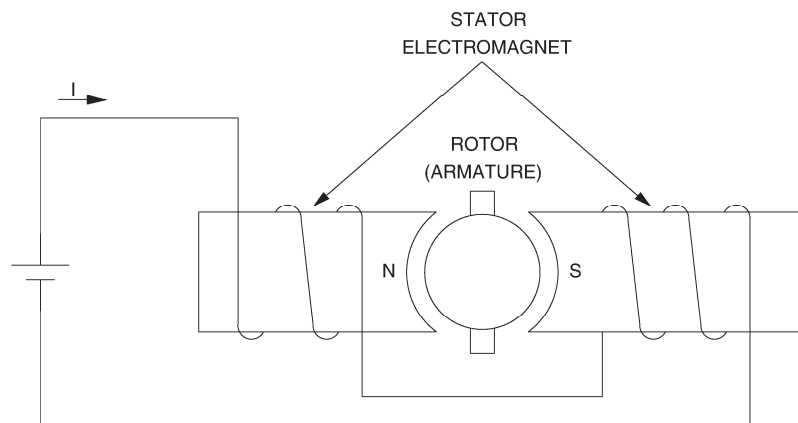
Figure 2-7. Simplified dc motor with an electromagnet as stator.

When power for the stator electromagnet is supplied by a separate dc source, either fixed or variable, the motor is known as a separately-excited dc motor. Sometimes the term independent-field dc motor is also used. The current flowing in the stator electromagnet is often called **field current** because it is used to create a fixed magnetic field. The electrical and mechanical behaviour of the dc motor can be understood by examining its simplified equivalent electric circuit shown in Figure 2-8.

Figure 2-8. Simplified equivalent circuit of a dc motor.

In the circuit, E_A is the voltage applied to the motor brushes, I_A is the current flowing through the brushes, and R_A is the resistance between the brushes.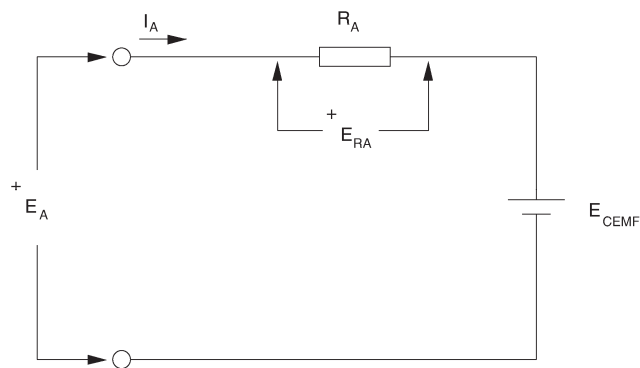 Note that E_A, I_A, and R_A are usually referred to as the armature voltage, current, and resistance, respectively. E_{RA} is the voltage drop across the armature resistor. When the motor turns, an induced voltage E_{CEMF} proportional to the speed of the motor is produced. This induced voltage is represented by a dc source in the simplified equivalent circuit of Figure 2-8. The motor also develops a torque T proportional to the armature current I_A flowing in the motor. The motor behaviour is based on the two equations given below. The first relates motor speed n and the induced voltage E_{CEMF}, and the second relates the motor torque T and the armature current I_A.

$$n = K_1 \times E_{CEMF} \quad \text{and} \ T = K_2 \times I_A$$

where K_1 is a constant expressed in units of $\mathrm{r/min} / \mathrm{V}$.

           K_2 is a constant expressed in units of $\mathrm{N \cdot m} / \mathrm{A}$ or $\mathrm{lbf \cdot in} / \mathrm{A}$.

When a voltage E_A is applied to the armature of a dc motor with no mechanical load, the armature current I_A flowing in the equivalent circuit of Figure 2-8 is constant and has a very low value. As a result, the voltage drop E_{RA} across the armature resistor is so low that it can be neglected, and E_{CEMF} can be considered to be equal to the armature voltage E_A. Therefore, the relationship between the motor speed n and the armature voltage E_A is a straight line because E_{CEMF} is proportional to the motor speed n. This linear relationship is illustrated in Figure 2-9, and the slope of the straight line equals constant K_1.
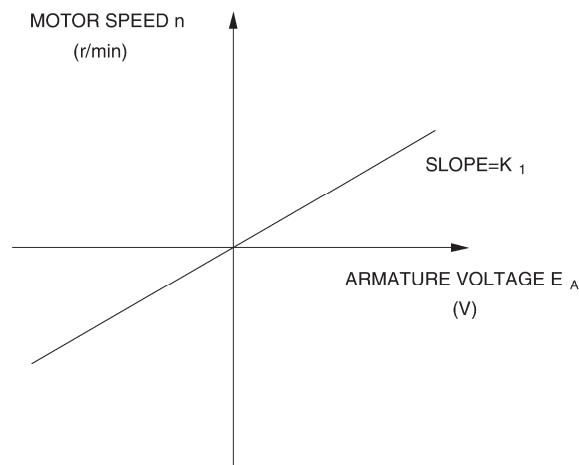

Figure 2-9. Linear relationship between the motor speed and the armature voltage.

Since the relationship between voltage E_A and speed n is linear, a dc motor can be considered to be a linear voltage-to-speed converter, as shown in Figure 2-10.
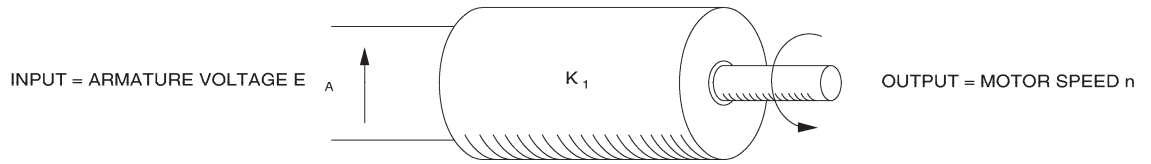
Figure 2-10. DC motor as a voltage-to-speed converter.

The same type of relationship exists between the motor torque T and the armature current I_A, so that a dc motor can also be considered as a linear current-to-torque converter. Figure 2-11 illustrates the linear relationship between the motor torque T and the armature current I_A. Constant K_2 is the slope of the line relating the two. Figure 2-12 shows the linear current-to-torque converter.
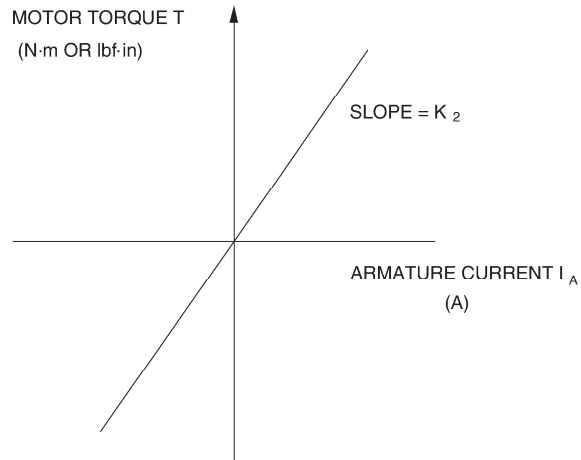
Figure 2-11. Linear relationship between the motor torque and the armature current.
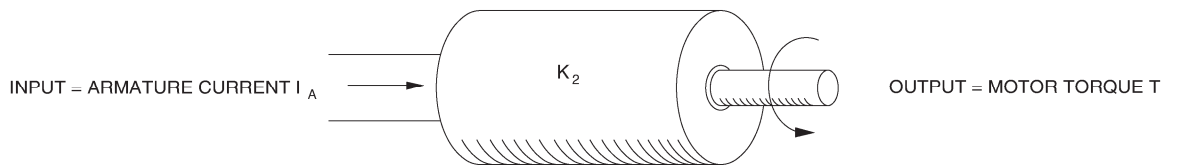
Figure 2-12. DC motor as a current-to-torque converter.

When the armature current I_A increases, the voltage drop E_{RA} ($R_A \times I_A$) across the armature resistor also increases and can no longer be neglected. As a result, the armature voltage E_A can no longer be considered to be equal to E_{CEMF}, but rather the sum of E_{CEMF} and E_{RA}, as indicated in the following equation:

$$E_A = E_{CEMF} + E_{RA}$$

Therefore, when a fixed armature voltage E_A is applied to a dc motor, the voltage drop E_{RA} across the armature resistor increases as the armature current I_A increases, and thereby, causes E_{CEMF} to decrease. This also causes the motor speed n to decrease because it is proportional to E_{CEMF}. This is shown in Figure 2-13, which is a graph of the motor speed n versus the armature current I_A for a fixed armature voltage E_A.

Figure 2-13. Motor speed drop as the armature current increases (fixed armature voltage E_A).

Procedure summary

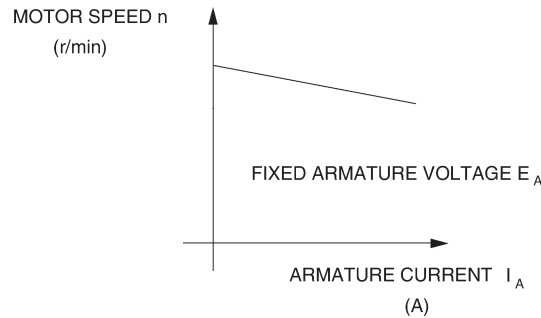In the first part of the exercise, you will set up the equipment in the Workstation, connect the equipment as shown in Figure 2-14, and make the appropriate settings on the equipment.

In the second part of the exercise, you will measure the armature resistance R_A of the DC Motor/Generator. It is not possible to measure the armature resistance R_A directly with a conventional ohmmeter because the non-linear characteristic of the motor brushes causes incorrect results when I_A is too small. The general method used to determine the armature resistance R_A consists in connecting a dc power source to the motor armature and measuring the voltage required to produce nominal current flow in the armature windings. Power is not connected to the stator electromagnet to ensure that the motor does not turn. Therefore, E_{CEMF} equals zero. The ratio of the armature voltage E_A to the armature current I_A yields the armature resistance R_A directly.

The motor will not start to rotate because it is mechanically loaded.

In the third part of the exercise, you will measure data and plot a graph of the motor speed n versus the armature voltage E_A to demonstrate that the speed of the separately-excited dc motor is proportional to the armature voltage E_A under no-load conditions.

In the fourth part of the exercise, you will measure data and plot a graph of the motor torque T versus the armature current I_A to demonstrate that the torque of the separately-excited dc motor is proportional to the armature current I_A.

In the fifth part of the exercise, you will demonstrate that when the armature voltage E_A is set to a fixed value, the speed of the separately-excited dc motor decreases with increasing armature current or torque because of the increasing voltage drop across the armature resistor.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart in Appendix C to obtain the list of equipment required for this exercise.

PROCEDURE

⚠ WARNING

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

Setting up the equipment

1. Install the equipment required in the EMS workstation

If you are performing the exercise using the EMS system, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect an ac power source (terminals 4 and N of the Power Supply) to the armature of the DC Motor/Generator (terminals 1 and 2) through CURRENT INPUT I1 of the data acquisition module. Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to VOLTAGE INPUT E1 of the data acquisition module. Start the Metering application and open setup configuration file ACMOTOR1.DAI. Turn the Power Supply on and set the voltage control knob so that an ac current (indicated by meter I line 1) equal to half the nominal value of the armature current flows in the armature of the DC Motor/Generator. Adjust the brush adjustment lever on the DC Motor/Generator so that the voltage across the shunt winding (indicated by meter E line 1) is minimum. Turn the Power Supply off, exit the Metering application, and disconnect all leads and cable.

Mechanically couple the prime mover/dynamometer module to the DC Motor/Generator using a timing belt.

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.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, connect its POWER INPUT to a wall receptacle.

3. Ensure that the data acquisition module is connected to a USB port of the computer.

Connect the POWER INPUT of the data acquisition module to the 24 V - AC output of the Power Supply.

If you are using the Prime Mover/Dynamometer, Model 8960-1, connect its LOW POWER INPUT to the 24 V - AC output of the Power Supply.

On the Power Supply, set the 24 V - AC power switch to the I (on) position.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it on by setting its POWER INPUT switch to the I (on) position. Press and hold the FUNCTION button 3 seconds to have uncorrected torque values on the display of the Four-Quadrant Dynamometer/Power Supply. The indication "NC" appears next to the function name on the display to indicate that the torque values are uncorrected.

4. Start the Data Acquisition software (LVDAC or LVDAM). Open setup configuration file DCMOTOR1.DAI.

If you are using LVSIM-EMS in LVVL, you must use the IMPORT option in the File menu to open the configuration file.

In the Metering window, select layout 2. Make sure that the continuous refresh mode is selected.

5. Set up the separately-excited dc motor circuit shown in Figure 2-14. Leave the circuit open at points A and B shown in the figure.

6. Set the Four-Quadrant Dynamometer/Power Supply or the Prime Mover/Dynamometer to operate as a brake, then set the torque control to maximum (knob turned fully clockwise). To do this, refer to Exercise 1-1 or Exercise 1-2 if necessary.

If you are performing the exercise using LVSIM®-EMS, you can zoom in on the Prime Mover/Dynamometer module before setting the controls in order to see additional front panel markings related to these controls.
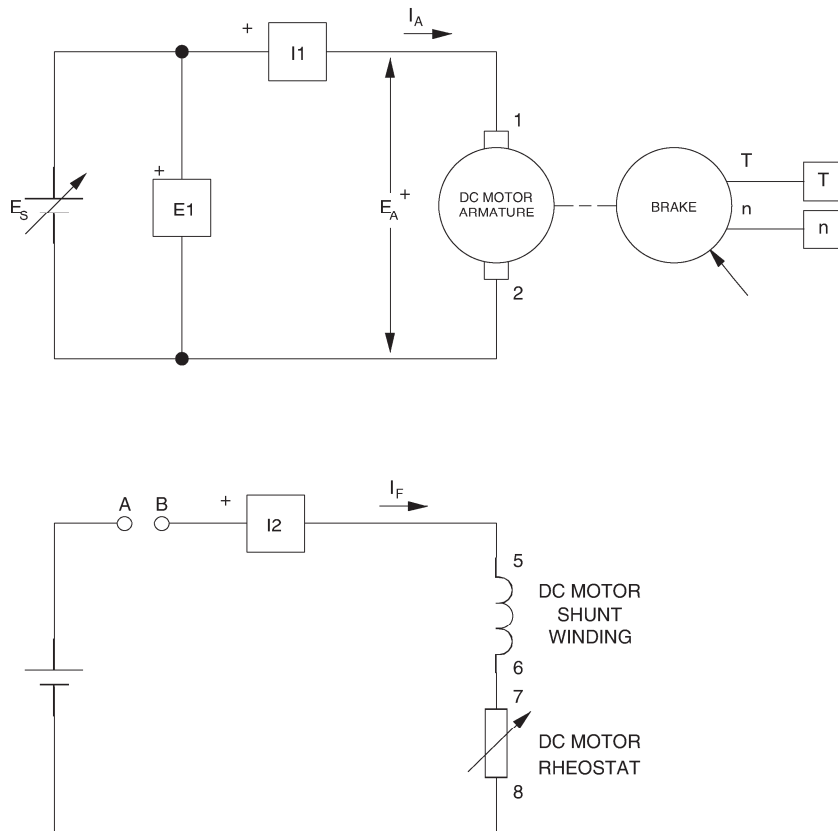
Figure 2-14. Separately-excited dc motor coupled to a brake.

Determining the armature resistance

7. Turn the Power Supply on by setting its main power switch to the I (on) position, and set the voltage control knob so that the rated armature current flows in the DC Motor/Generator. The armature current is indicated by meter I arm. (I_A) in the Metering window.

The rating of any of the machines is indicated in the lower left corner of the module front panel.

Record the value of armature resistance R_A indicated by meter $R_A = E_A/I_A$.

$$R_A = \underline{\qquad} \ \Omega$$

8. Turn the voltage control knob fully counterclockwise and turn the Power Supply off.

Interconnect points A and B shown in the circuit of Figure 2-14.

Motor speed versus armature voltage

9. Turn the Power Supply on.

On the brake, set the torque control to minimum (knob turned fully counterclockwise).

On the DC Motor/Generator, set the FIELD RHEOSTAT so that the field current I_f indicated by meter I field in the Metering window is equal to the value given in Table 2-1.

Table 2-1. DC motor field current.

Local ac power network		I_f (mA)
Voltage (V)	Frequency (Hz)	
120	60	300
220	50	190
220	60	190
240	50	210

10. In the Metering window, make sure that the torque correction function of the Torque meter is enabled. The Torque meter now indicates the dc motor output torque. Record the armature voltage, armature current, field current, output torque, and speed in the Data Table. These parameters are indicated by meters E arm. (E_A), I arm. (I_A), I field (I_f), Torque, and Speed, respectively.

On the Power Supply, set the voltage control knob to 10%, 20%, 30% etc. up to 100% in order to increase the armature voltage E_A by steps. For each voltage setting, wait until the motor speed stabilizes, and then record the data in the Data Table.

11. When all data has been recorded, turn the voltage control knob fully counterclockwise and turn the Power Supply off.

In the Data Table window, confirm that the data has been stored, entitle the Data Table as DT211, and print the Data Table.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to edit, entitle, and print a Data Table.

12. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed n (obtained from the Speed meter) as a function of the armature voltage E_A [(obtained from meter E arm. (E_A)]. Entitle the graph as G211, name the x-axis as Armature voltage, name the y-axis as DC motor speed, and print the graph.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to use the Graph window of the Metering application to obtain a graph, entitle a graph, name the axes of a graph, and print a graph.

What kind of relationship exists between the armature voltage E_A and the dc motor speed n?

_____

Does this graph confirm that the separately-excited dc motor is equivalent to a linear voltage-to-speed converter, with higher voltage producing greater speed?

❑ Yes   ❑ No

13. Use the two end points to calculate the slope K_1 of the relationship obtained in graph G211. The values of these points are indicated in Data Table DT211.

$$K_1 = \frac{n_2 - n_1}{E_2 - E_1} = \frac{-}{-} = \underline{\quad} \ \frac{\text{r/min}}{\text{V}}$$

In the Data Table window, clear the recorded data.

Motor torque versus armature current

14. Turn the Power Supply on.

On the DC Motor/Generator, slightly readjust the FIELD RHEOSTAT so that the field current I_f indicated by meter I field (I_f) still equals the value given in Table 2-1 (if necessary).

On the Power Supply, set the voltage control knob so that the dc motor speed is 1500 r/min. Note the value of the armature voltage E_A in the following blank space.

$E_A = \underline{\quad}$ V $(n = 1500 \ \text{r/min})$

15. Record the dc motor armature voltage E_A, armature current I_A, field current I_f, output torque T, and speed n in the Data Table.

On the brake, set the torque control so that the torque indicated by the Torque meter in the Metering window increases by 0.2 N·m (2.0 lbf·in) increments up to about 2.3 N·m (about 20.4 lbf·in). For each torque setting, readjust the voltage control knob of the Power Supply so that the armature voltage E_A remains equal to the value recorded in the previous step, then record the data in the Data Table.

The armature current may exceed the rated value while performing this manipulation. It is, therefore, suggested to complete the manipulation within a time interval of 5 minutes or less.

16. When all data has been recorded, set the torque control on the brake to minimum (knob turned fully counterclockwise), turn the voltage control knob fully counterclockwise, and turn the Power Supply off.

In the Data Table window, confirm that the data has been stored, entitle the Data Table as DT212, and print the Data Table.

17. In the Graph window, make the appropriate settings to obtain a graph of the dc motor torque (obtained from the Torque meter) as a function of the armature current I_A [obtained from meter I arm. (I_A)]. Entitle the graph as G212, name the x-axis as Armature current, name the y-axis as DC motor torque, and print the graph.

What kind of relationship exists between the armature current I_A and the dc motor torque T as long as the armature current does not exceed the nominal value?

_____

Does this graph confirm that the separately-excited dc motor is equivalent to a linear current-to-torque converter (when the armature current does not exceed the nominal value), with higher current producing greater torque?

❑ Yes   ❑ No

The torque versus current relationship is no longer linear when the armature current exceeds the nominal value because of a phenomenon called armature reaction. This phenomenon is described in the next unit of this manual.

18. Use the two end points of the linear portion of the relationship obtained in graph G212 to calculate the slope K_2. The values of these points are indicated in Data Table DT212.

$$K_2 = \frac{T_2 - T_1}{I_2 - I_1} = \frac{-}{-} = \underline{\quad} \frac{N \cdot m \, (lbf \cdot in)}{A}$$

Speed decrease versus armature current

19. Using the armature resistance R_A and the constant K_1 determined previously in this exercise, the armature voltage E_A measured in step 14, and the set of equations given below, determine the dc motor speed n for each of the three armature currents I_A given in Table 2-2.

$$E_{RA} = I_A \times R_A$$

$$E_{CEMF} = E_A - E_{RA}$$

$$n = E_{CEMF} \times K_1$$

Table 2-2. DC motor armature currents.

Local ac power network		Armature current I_A (A)	Armature current I_A (A)	Armature current I_A (A)
Voltage (V)	Frequency (Hz)			
120	60	1.0	2.0	3.0
220	50	0.5	1.0	1.5
220	60	0.5	1.0	1.5
240	50	0.5	1.0	1.5

When $I_A =$ _____ A:

$E_{RA} =$ _____ V

$E_{CEMF} =$ _____ V

$n =$ _____ r/min

When $I_A =$ _____ A:

$E_{RA} =$ _____ V

$E_{CEMF} =$ _____ V

$n =$ _____ r/min

When I_A = _____ A:

E_{RA} = _____ V

E_{CEMF} = _____ V

n = _____ r/min

Based on your results, how should the dc motor induced voltage E_{CEMF} and speed n vary when the armature current I_A is increased?

_____

_____

_____

20. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed (obtained from the Speed meter) as a function of the armature current I_A [obtained from meter I arm. (I_A)], using the data recorded previously in the Data Table (DT212). Entitle the graph as G212-1, name the x-axis as Armature current, name the y-axis as DC motor speed, and print the graph.

Does graph G212-1 confirm the prediction you made in the previous step about the variation of the dc motor speed as a function of the armature current I_A?

❑ Yes   ❑ No

Briefly explain what causes the dc motor speed to decrease when the armature voltage E_A is fixed and the armature current I_A increases.

_____

_____

_____

21. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed (obtained from the Speed meter) as a function of the dc motor torque T (obtained from the Torque meter), using the data recorded previously in the Data Table (DT212). Entitle the graph as G212-2, name the x-axis as Separately-excited dc motor Torque, name the y-axis as Separately-excited dc motor speed, and print the graph. This graph will be used in the next exercise of this unit.

22. On the Power Supply, set the 24 V - AC power switch to the O (off) position.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it off by setting its POWER INPUT switch to the O (off position).

Remove all leads and cables.

Additional experiments

DC motor speed-versus-armature voltage graph and torque-versus-armature current graph for reversed armature connections

You can obtain graphs of the dc motor speed n versus the armature voltage E_A, and dc motor torque T versus the armature current I_A, with reversed armature connections. To do so, make sure the Power Supply is turned off and reverse the connection of the leads at terminals 7 and N of the Power Supply. Refer to steps 6 to 17 of this exercise to record the necessary data and obtain the graphs. This will allow you to verify that the linear relationships between the speed and armature voltage, and the torque and armature current, are valid regardless of the polarity of the armature voltage. Recalculating constants K_1 and K_2 will show you that their values are independent of the armature voltage polarity.

CONCLUSION

In this exercise, you have learned how to measure the armature resistance of a dc motor. You have seen that the speed of a separately-excited dc motor is proportional to the armature voltage applied to the motor. You saw that the torque produced by a dc motor is proportional to the armature current. You observed that the dc motor speed decreases with increasing armature current when the armature voltage is fixed. You demonstrated that this speed decrease is caused by the increasing voltage drop across the armature resistor as the armature current increases.

If you have performed the additional experiments, you observed that the speed versus voltage and torque versus current relationships are not affected by the polarity of the armature voltage. You also observed that the direction of rotation is reversed when the polarity of the armature voltage is reversed.

REVIEW QUESTIONS

1. What kind of relationship exists between the speed and armature voltage of a separately-excited dc motor?

   a. A linear relationship
   b. A parabolic relationship.
   c. An exponential relationship.
   d. The speed of the motor is independent of the applied voltage.

2. What kind of relationship exists between the torque and armature current of a separately-excited dc motor as long as the armature current does not exceed the nominal value?

   a. A linear relationship.
   b. A parabolic relationship.
   c. An exponential relationship.
   d. The motor torque is independent of the current.

3. Connecting a dc source to the armature of a dc motor that operates without field current and measuring the voltage that produces nominal current flow in the armature allows which parameter of the dc motor to be determined?

   a. The nominal armature current.
   b. The nominal armature voltage.
   c. The armature resistance.
   d. The resistance of the field winding.

4. Does the speed of a separately-excited dc motor increase or decrease when the armature current increases?

   a. It increases.
   b. It decreases.
   c. It stays the same because speed is independent of motor current.
   d. The speed will oscillate around the previous value.

5. The armature resistance R_A and constant K_1 of a dc motor are 0.5 Ω and 5 r/min/V, respectively. A voltage of 200 V is applied to this motor. The no-load armature current is 2 A. At full load, the armature current increases to 50 A. What are the no-load and full-load speeds of the motor?

   a. $n_{NO\ LOAD}$ = 1005 r/min, $n_{FULL\ LOAD}$ = 880 r/min
   b. $n_{NO\ LOAD}$ = 995 r/min, $n_{FULL\ LOAD}$ = 875 r/min
   c. $n_{NO\ LOAD}$ = 1000 r/min, $n_{FULL\ LOAD}$ = 875 r/min
   d. The speeds cannot be calculated without constant K_2.

Separately-Excited, Series, Shunt, and Compound DC Motors

EXERCISE OBJECTIVE   When you have completed this exercise, you will be able to demonstrate how the field current affects the characteristics of a separately-excited dc motor using the DC Motor/Generator module. You will also be able to demonstrate the main operating characteristics of series, shunt, and compound motors.

DISCUSSION

Separately-excited dc motor

It is possible to change the characteristics of a separately-excited dc motor by changing the strength of the fixed magnetic field produced by the stator electromagnet. This can be carried out by changing the current that flows in the stator electromagnet. This current is usually referred to as the field current (I_f) because it is used to produce the fixed magnetic field in the dc motor. A rheostat connected in series with the electromagnet winding can be used to vary the field current.

Figure 2-15 illustrates how the speed versus armature voltage and torque versus armature current relationships of a separately-excited dc motor are affected when the field current is decreased below its nominal value. Constant K_1 becomes greater and constant K_2 becomes smaller. This means that the motor can rotate at higher speeds without exceeding the nominal armature voltage. However, the torque which the motor can develop, without exceeding the nominal armature current, is reduced.
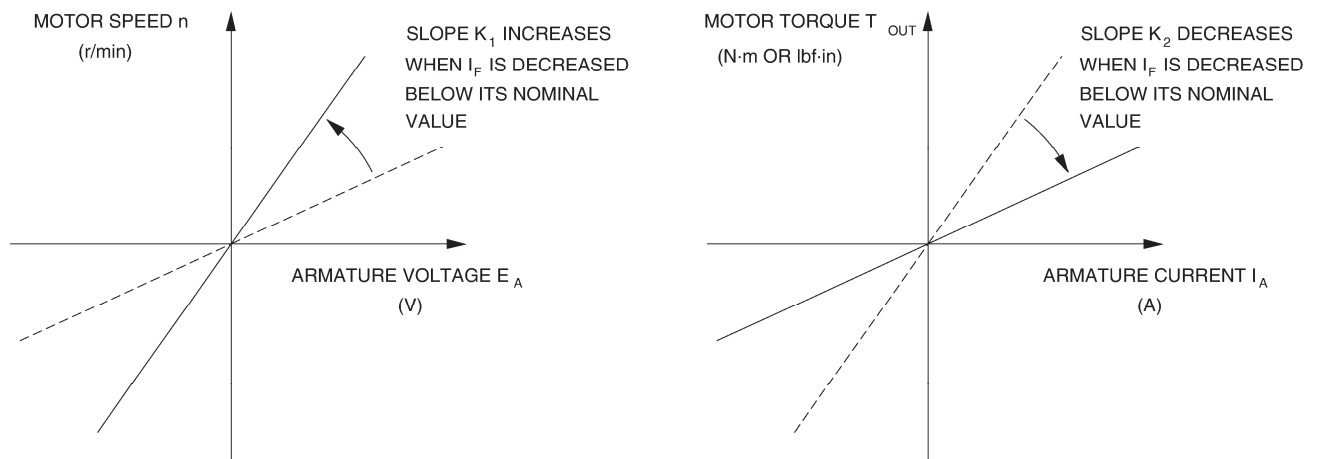
Figure 2-15. Decreasing current I_f below its nominal value affects constants K_1 and K_2.

It is also possible to set the field current of a separately-excited dc motor above its nominal value for short time intervals. The effect on the speed versus armature voltage and torque versus armature current relationships is reversed, i.e., constant K_1 becomes smaller and constant K_2 becomes higher. As a result, the motor can develop a higher torque during these time intervals but the speed at which the motor can rotate, without exceeding the nominal armature voltage, is reduced. Increasing the field current of a separately-excited dc motor when it is starting improves the motor torque, and thereby, provides faster acceleration.

The strength of the fixed magnetic field in a dc motor can also be changed by changing the way the stator electromagnet is implemented. The stator electromagnet, or field electromagnet, can be a shunt winding connected directly to a dc voltage source, as in the separately-excited dc motor. A shunt winding can also be connected in parallel with the armature of the dc motor. The field electromagnet can also be a series winding, a coil consisting of a few loops of heavy-gage wire, connected in series with the armature. A combination of the shunt and series windings can also be used to implement the field electromagnet.

Various electromagnet implementations have been used so far to build several types of dc motors having different characteristics when powered by a fixed-voltage dc source. This was necessary at the time the first dc motors were in used, because variable-voltage dc sources were not still available. These dc motors, which are used less and less today, are briefly described in the following sections of this discussion.

Series motor

The series motor is a motor in which the field electromagnet is a series winding connected in series with the armature as shown in Figure 2-16. The strength of the field electromagnet, therefore, varies as the armature current varies. As a result, K_1 and K_2 vary when the armature current varies. Figure 2-16 shows the speed versus torque characteristic of a series motor when the armature voltage is fixed. This characteristic shows that the speed decreases non linearly as the torque increases, i.e., as the armature current increases.
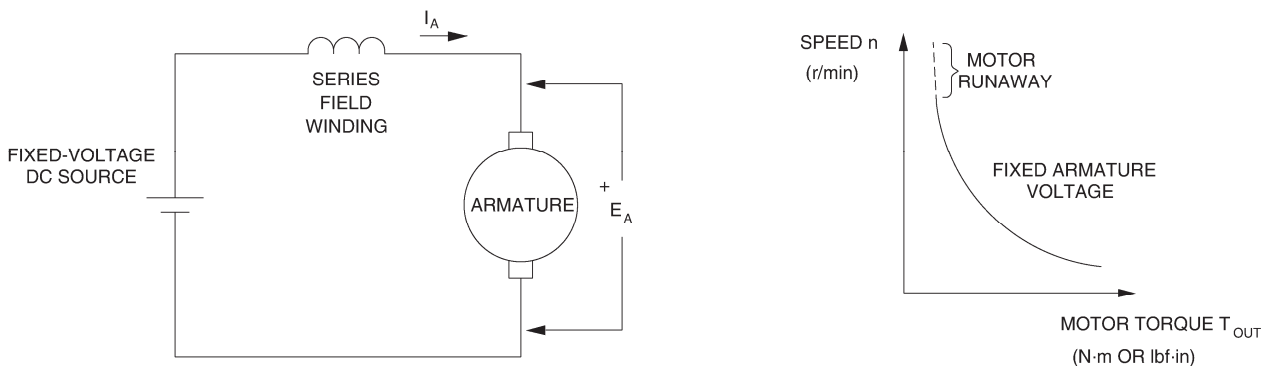

Figure 2-16. Series motor and its speed versus torque characteristic.

The series motor provides a strong starting torque and a wide range of operating speeds when it is supplied by a fixed-voltage dc source. However, the speed, torque, and armature current depend on the mechanical load applied to the motor. Also, the series motor has non-linear operating characteristics as suggested by the speed versus torque relationship in Figure 2-16. As a result, it is difficult to operate a series motor at a constant speed when the mechanical load fluctuates. Furthermore, the armature current must be limited to prevent damage to the motor when it is starting (when power is applied to the motor). Finally, a series motor must never run without mechanical load because the speed increases to a very-high value which can damage the motor (motor runaway).

Today, series motors can operate with fixed-voltage power sources, for example, automobile starting motors; or with variable-voltage power sources, for example, traction systems.

Shunt motor

The shunt motor is a motor in which the field electromagnet is a shunt winding connected in parallel with the armature, both being connected to the same dc voltage source as shown in Figure 2-17. For a fixed armature voltage, constants K_1 and K_2 are fixed, and the speed versus torque characteristic is very similar to that obtained with a separately-excited dc motor powered by a fixed-voltage dc source, as shown in Figure 2-17. As in a separately-excited dc motor, the characteristics (K_1 and K_2) of a shunt motor can be changed by varying the field current with a rheostat. However, it is difficult to change the speed of a shunt motor by changing the armature voltage, because this changes the field current, and thereby, the motor characteristics, in a way that opposes speed change.
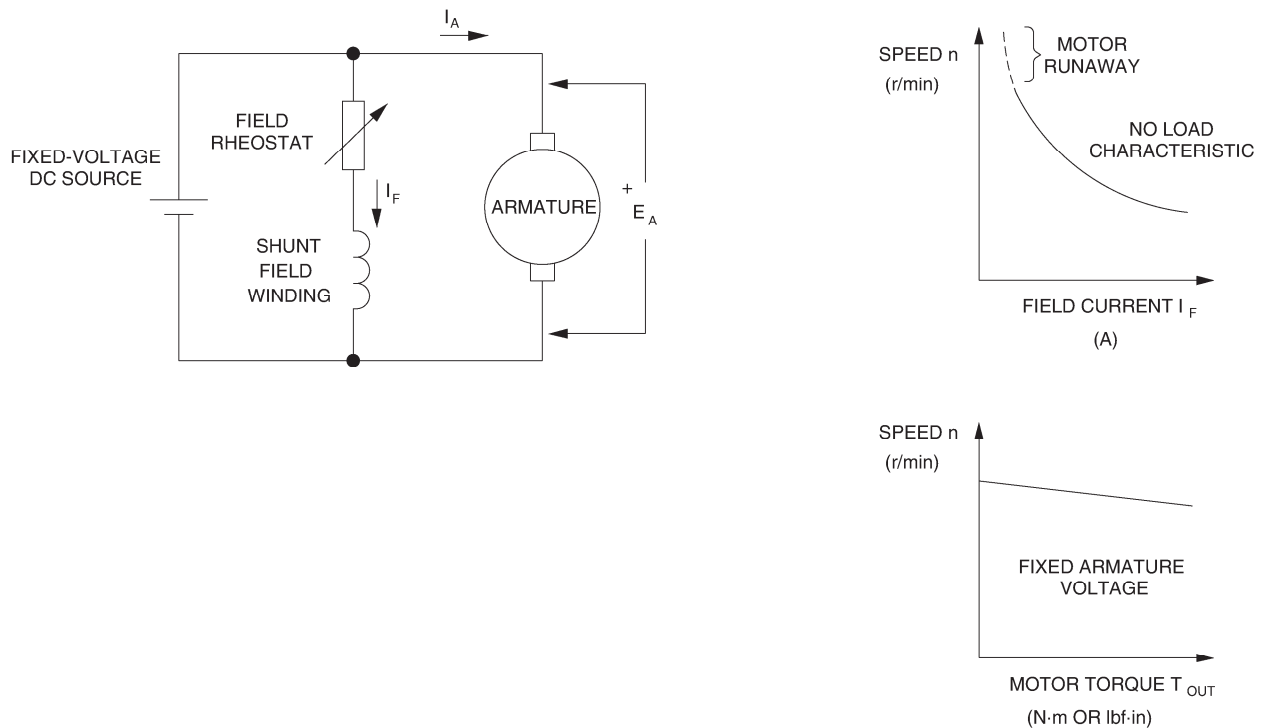

Figure 2-17. Shunt motor and its characteristics.

The main advantage of a shunt motor is the fact that only a single fixed-voltage dc source is required to supply power to both the armature and the shunt winding. Also, speed varies little as the mechanical load varies. However, a shunt motor has a limited speed range because speed cannot be easily varied by varying the armature voltage. Furthermore, the armature current must be limited to prevent damage to the motor when it is starting (when power is applied to the motor). Finally, when the shunt winding opens accidentally, the field current I_f becomes zero, the motor speed increases rapidly, and motor runaway occurs as suggested by the speed versus field current characteristic shown in Figure 2-17.

Compound motor

It is possible to combine shunt and series windings to obtain a particular speed versus torque characteristic. For example, to obtain the characteristic of decreasing speed when the motor torque increases, a series winding can be connected in series with the armature so that the magnetic flux it produces adds with the magnetic flux produced by a shunt winding. As a result, the magnetic flux increases automatically with increasing armature current. This type of dc motor is referred to as a cumulative compound motor because the magnetic fluxes produced by the series and shunt windings add together. Shunt and series windings can also be connected so that the magnetic fluxes subtract from each other. This connection produces a differential-compound motor, which is rarely used because the motor becomes unstable when the armature current increases. Figure 2-18 shows a compound motor and its speed versus torque characteristic (cumulative compound).
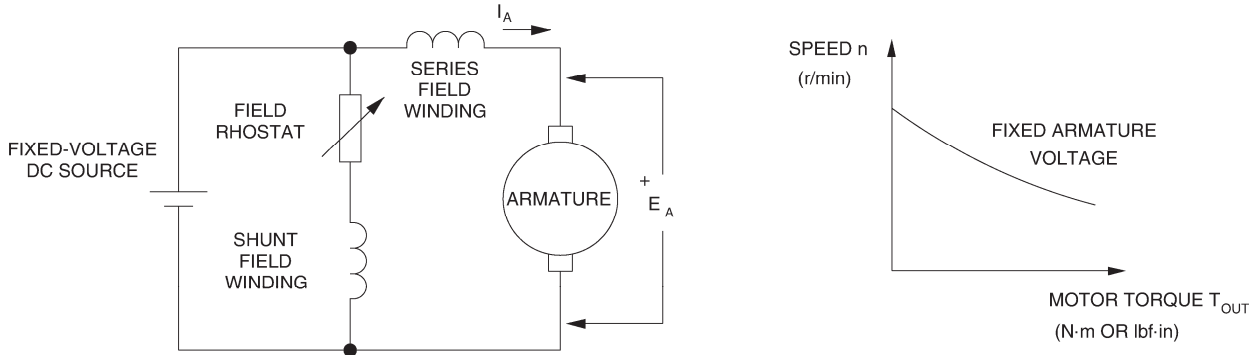

Figure 2-18. Compound motor and its speed versus torque characteristic.

Figure 2-19 is a graph that shows the speed versus torque characteristics of the various types of dc motors discussed so far. As can be seen, the separately-excited dc motor and the shunt motor have very similar characteristics. The main feature of these characteristics is that the motor speed varies little and linearly as the torque varies. On the other hand, the series motor characteristic is nonlinear and shows that the motor speed varies a lot (wide range of operating speed) as the torque varies. Finally, the characteristic of a cumulative compound motor is a compromise of the series and shunt motor characteristics. It provides the compound motor with a fairly wide range of operating speed, but the speed does not vary linearly as the torque varies.
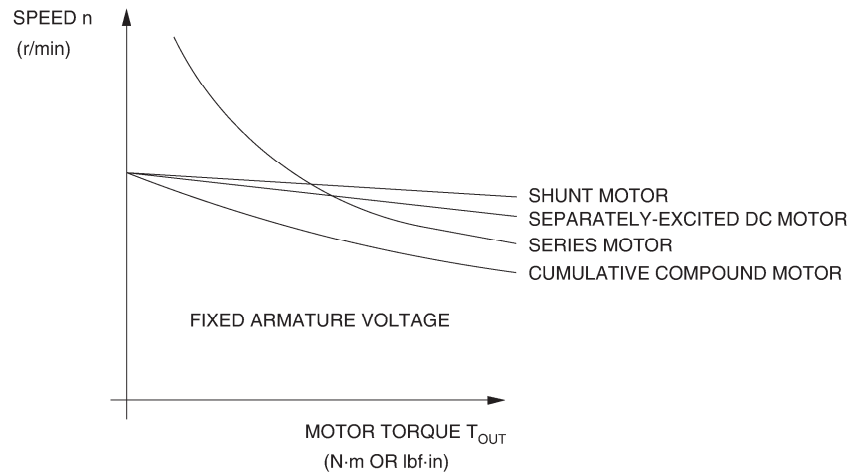
SPEED n
(r/min)

SHUNT MOTOR
SEPARATELY-EXCITED DC MOTOR
SERIES MOTOR
CUMULATIVE COMPOUND MOTOR

FIXED ARMATURE VOLTAGE

MOTOR TORQUE T$_{OUT}$
(N·m OR lbf·in)

Figure 2-19. Speed versus torque characteristics of various dc motors.

Procedure summary

In the first part of the exercise, you will set up the equipment in the Workstation, connect the equipment as shown in Figure 2-20, and make the appropriate settings on the equipment.

In the second part of the exercise, you will set the field current of the separately-excited dc motor to a lower value than in the previous exercise (below the nominal value). You will measure data and plot a graph of the motor speed n versus the armature voltage E_A. You will calculate constant K_1. You will compare constant K_1 and the graph with those obtained in the previous exercise to determine how decreasing the field current affects these characteristics.

In the third part of the exercise, you will measure data and plot a graph of the motor torque T versus the armature current I_A. You will calculate constant K_2. You will compare constant K_2 and the graph with those obtained in the previous exercise to determine how decreasing the field current affects these characteristics.

In the fourth part of the exercise, you will connect the DC Motor/Generator as a series motor (see setup in Figure 2-21). You will measure data and plot a graph of the motor speed n versus the motor torque T. You will compare the speed versus torque characteristic of the series motor to that of the separately-excited dc motor obtained in the previous exercise.

EQUIPMENT REQUIRED

Refer to the Equipment Utilization Chart in Appendix C to obtain the list of equipment required for this exercise.

PROCEDURE

⚠ **WARNING**

High voltages are present in this laboratory exercise. Do not make or modify any banana jack connections with the power on unless otherwise specified.

Setting up the equipment

1. Install the equipment required in the EMS workstation

If you are performing the exercise using the EMS system, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect an ac power source (terminals 4 and N of the Power Supply) to the armature of the DC Motor/Generator (terminals 1 and 2) through CURRENT INPUT I1 of the data acquisition module. Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to VOLTAGE INPUT E1 of the data acquisition module. Start the Metering application and open setup configuration file ACMOTOR1.DAI. Turn the Power Supply on and set the voltage control knob so that an ac current (indicated by meter I line 1) equal to half the nominal value of the armature current flows in the armature of the DC Motor/Generator. Adjust the brush adjustment lever on the DC Motor/Generator so that the voltage across the shunt winding (indicated by meter E line 1) is minimum. Turn the Power Supply off, exit the Metering application, and disconnect all leads and cable.

Mechanically couple the prime mover/dynamometer module to the DC Motor/Generator using a timing belt.

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.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, connect its POWER INPUT to a wall receptacle.

3. Ensure that the data acquisition module is connected to a USB port of the computer.

Connect the POWER INPUT of the data acquisition module to the 24 V - AC output of the Power Supply.

If you are using the Prime Mover/Dynamometer, Model 8960-1, connect its LOW POWER INPUT to the 24 V - AC output of the Power Supply.

On the Power Supply, set the 24 V - AC power switch to the I (on) position.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it on by setting its POWER INPUT switch to the I (on) position. Press and hold the FUNCTION button 3 seconds to have uncorrected torque values on the display of the Four-Quadrant Dynamometer/Power Supply. The indication "NC" appears next to the function name on the display to indicate that the torque values are uncorrected.

4. Start the Data Acquisition software (LVDAC or LVDAM). Open setup configuration file DCMOTOR1.DAI.

If you are using LVSIM-EMS in LVVL, you must use the IMPORT option in the File menu to open the configuration file.

In the Metering window, select layout 1. Make sure that the continuous refresh mode is selected.

5. Set up the separately-excited dc motor circuit shown in Figure 2-20. Note that this setup is the same as that used in the previous exercise.

If you are performing the exercise with a line voltage of 220 V, use the Resistive Load module to connect a 880-Ω resistor in series with the rheostat of the DC Motor/Generator. If you are performing the exercise with a line voltage of 240 V, connect a 960-Ω resistor in series with the rheostat.
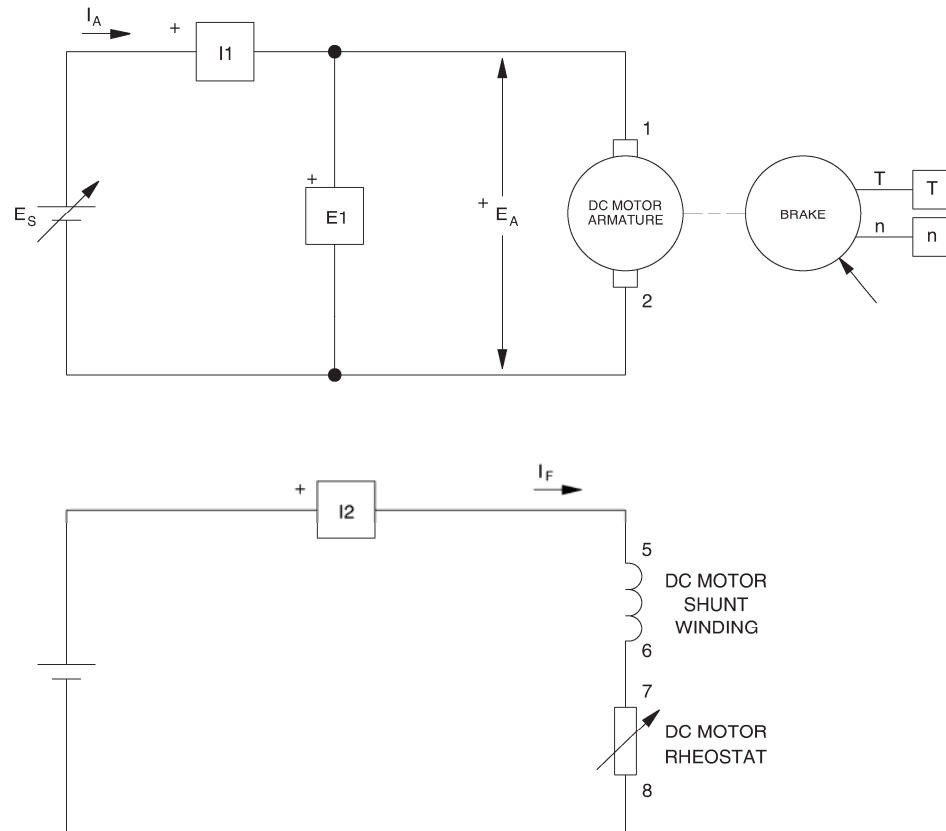
Figure 2-20. Separately-excited dc motor coupled to a brake.

6. Set the Four-Quadrant Dynamometer/Power Supply or the Prime Mover/Dynamometer to operate as a brake, then set the torque control to minimum (knob turned fully counterclockwise). To do this, refer to Exercise 1-1 or Exercise 1-2 if necessary.

If you are performing the exercise using LVSIM®-EMS, you can zoom in on the Prime Mover/Dynamometer before setting the controls in order to see additional front panel markings related to these controls.

Speed versus armature voltage characteristic of a separately-excited dc motor

7. Turn the Power Supply on.

On the DC Motor/Generator, set the FIELD RHEOSTAT so that the field current I_f indicated by meter I field (I_f) in the Metering window is equal to the value given in Table 2-3:

Table 2-3. Field current of the separately-excited dc motor.

Local ac power network		I_f (mA)
Voltage (V)	Frequency (Hz)	
120	60	200
220	50	125
220	60	125
240	50	140

8. In the Metering window, make sure that the torque correction function of the Torque meter is enabled. The Torque meter now indicates the dc motor output torque. Record the armature voltage, armature current, field current, output torque, and speed in the Data Table. These parameters are indicated by meters E arm. (E_A), I arm. (I_A), I field (I_f), Torque, and Speed respectively.

On the Power Supply, set the voltage control knob to 10%, 20%, 30%, etc. up to 100% in order to increase the armature voltage E_A by steps. For each voltage setting, wait until the motor speed stabilizes, and then record the data in the Data Table.

9. When all data has been recorded, turn the voltage control knob fully counterclockwise and turn the Power Supply off.

In the Data Table window, confirm that the data has been stored, entitle the Data Table as DT221, and print the Data Table.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to edit, entitle, and print a Data Table.

10. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed n (obtained from the Speed meter) as a function of the armature voltage E_A [obtained from meter E arm. (E_A)]. Entitle the graph as G221, name the x-axis as Armature voltage, name the y-axis as DC motor speed, and print the graph.

Refer to the user guide dealing with the computer-based instruments for EMS to know how to use the Graph window of the Metering application to obtain a graph, entitle a graph, name the axes of a graph, and print a graph.

11. Use the two end points to calculate the slope K_1 of the relationship obtained in graph G221. The values of these points are indicated in Data Table DT221.

$$K_1 = \frac{n_2 - n_1}{E_2 - E_1} = \frac{-}{-} = \frac{}{} \; \frac{r/\text{min}}{V}$$

Compare graph G221 and constant K_1 obtained in this exercise with graph G211 and constant K_1 obtained in the previous exercise. How does decreasing the field current I_f affect the speed versus voltage characteristic and constant K_1 of a separately-excited dc motor?

_____

_____

_____

In the Data Table window, clear the recorded data.

Torque versus armature current characteristic of a separately-excited dc motor

12. Turn the Power Supply on.

On the DC Motor/Generator, slightly readjust the FIELD RHEOSTAT so that the field current I_f indicated by meter I field (I_f) still equals the value given in Table 2-3 (if necessary).

On the Power Supply, set the voltage control knob so that the dc motor speed is 1500 r/min. Note the value of the armature voltage E_A in the following blank space.

E_A = _____ V $[n = 1500 \text{ r/min}]$

13. In the Metering window, make sure that the torque correction function of the Torque meter is enabled. Record the dc motor armature voltage E_A, armature current I_A, field current I_f, output torque T, and speed n in the Data Table.

On the brake, set the torque control so that the torque indicated by the Torque meter increases by 0.2 N·m (2 lbf·in) increments up to about 1.5 N·m (about 14.0 lbf·in). For each torque setting, readjust the voltage control knob of the Power Supply so that the armature voltage E_A remains equal to the value recorded in the previous step, then record the data in the Data Table.

The armature current may exceed the rated value while performing this manipulation. It is therefore suggested to complete the manipulation within a time interval of 5 minutes or less.

14. When all data has been recorded, set the torque on the brake to minimum (turned fully counterclockwise), turn the voltage control knob fully counterclockwise, and turn the Power Supply off.

In the Data Table window, confirm that the data has been stored, entitle the Data Table as DT222, and print the Data Table.

15. In the Graph window, make the appropriate settings to obtain a graph of the dc motor torque (obtained from the Torque meter) as a function of the armature current I_A [(obtained from meter I arm. (I_A)]. Entitle the graph as G222, name the x-axis as Armature current, name the y-axis as DC motor torque, and print the graph.

The torque versus current relationship is no longer linear when the armature current exceeds the nominal value because of a phenomenon called armature reaction. This phenomenon is described in the next unit of this manual.

16. Use the two end points of the linear portion of the relationship obtained in graph G222 to calculate the slope K_2. The values of these points are indicated in Data Table DT222.

Use the two end points of the linear portion of the relationship obtained in graph G222 to calculate the slope K_2. The values of these points are indicated in Data Table DT222.

$$K_1 = \frac{T_2 - T_1}{I_2 - I_1} = \frac{-}{-} = \underline{\quad} \; \frac{N \cdot m \; (lbf \cdot in)}{A}$$

Compare graph G222 and constant K_2 obtained in this exercise with graph G212 and constant K_2 obtained in the previous exercise. Describe how does decreasing the field current I_f affect the torque versus current characteristic and constant K_2 of a separately-excited dc motor.

_____

_____

_____

In the Data Table window, clear the recorded data.

Speed versus torque characteristic of a series motor

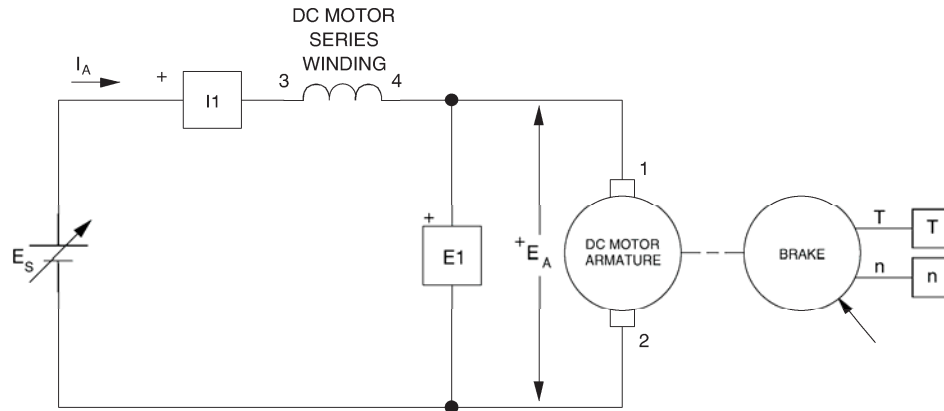**17.** Modify the connections so as to obtain the series motor circuit shown in Figure 2-21.

Figure 2-21. Series motor coupled to a brake.

18. Turn the Power Supply on and set the voltage control knob so that the armature voltage E_A indicated by meter E arm. (E_A) is equal to the value recorded in step 14 of the previous exercise. The series motor should start to rotate.

19. In the Metering window, make sure that the torque correction function of the Torque meter is enabled. Record the dc motor armature voltage E_A, armature current I_A, output torque T, and speed n in the Data Table.

On the dynamometer, set the torque control so that the torque indicated by the Torque meter increases by 0.2 N·m (2 lbf·in) increments up to about 2.3 N·m (about 20.3 lbf·in). For each torque setting, readjust the voltage control knob of the Power Supply so that the armature voltage E_A remains equal to the value set in the previous step, wait until the motor speed stabilizes, and then record the data in the Data Table.

It may not be possible to maintain the armature voltage to its original value as the torque is increased. The armature current may exceed the rated value while performing this manipulation. It is, therefore, suggested to complete the manipulation within a time interval of 5 minutes or less.

20. When all data has been recorded, set the torque control on the brake to minimum (fully counterclockwise), turn the voltage control knob fully counterclockwise, and turn the Power Supply off.

In the Data Table window, confirm that the data has been stored, entitle the Data Table as DT223, and print the Data Table.

21. In the Graph window, make the appropriate settings to obtain a graph of the series motor speed (obtained from the Speed meter) as a function of the series motor torque (obtained from the Torque meter). Entitle the graph as G223, name the x-axis as Series motor torque, name the y-axis as Series motor speed, and print the graph.

Briefly describe how the speed varies as the mechanical load applied to the series motor increases, i.e., as the motor torque increases.

_____

_____

Compare the speed versus torque characteristic of the series motor (graph G223) to that of the separately-excited dc motor (graph G212-2 obtained in the previous exercise).

_____

_____

_____

22. On the Power Supply, set the 24 V - AC power switch to the O (off) position.

If you are using the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, turn it off by setting its POWER INPUT switch to the O (off) position.

Remove all leads and cables.

Additional experiments

Speed versus torque characteristic of a shunt motor

You can obtain the speed versus torque characteristic of a shunt motor and compare it to those obtained for the separately-excited dc motor and series motor. To do so, make sure the Power Supply is turned off and set up the shunt motor circuit shown in Figure 2-22. (If you are using the Four-Quadrant Power Supply/Dynamometer, make sure to press and hold the FUNCTION button 3 seconds to have uncorrected values on this module's display). Make sure the torque control on the brake is set to minimum (fully counterclockwise). Turn the Power Supply on, set the armature voltage E_A to the value recorded in step 14 of the previous exercise. Set the FIELD RHEOSTAT on the DC Motor/Generator so that the field current I_f is equal to the value indicated in Table 2-1. Clear the data recorded in the Data Table. Refer to steps 19 to 21 of this exercise to record the necessary data and obtain the graph. Entitle the Data Table and graph as DT224 and G224, respectively. Compare the speed versus torque characteristic of the shunt motor (graph G224) to those of the separately-excited dc motor (graph G212-2 obtained in the previous exercise) and series motor (graph G223).
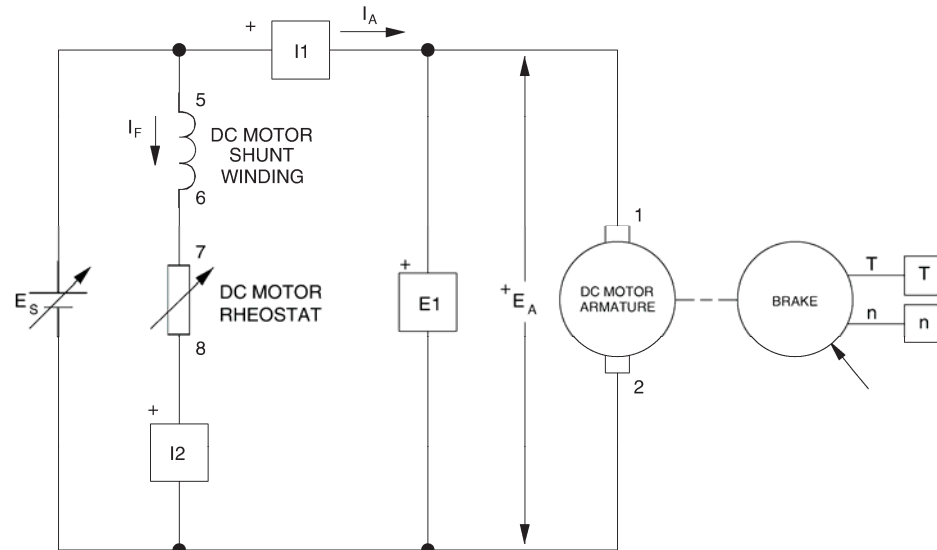

Figure 2-22. Shunt motor circuit.

Speed versus torque characteristic of a cumulative compound motor

You can obtain the speed versus torque characteristic of a cumulative compound motor and compare it to those obtained for the other dc motors. To do so, make sure the Power Supply is turned off and set up the cumulative compound motor circuit shown in Figure 2-23. (If you are using the Four-Quadrant Power Supply/Dynamometer, make sure to press and hold the FUNCTION button 3 seconds to have uncorrected values on this module's display). Make sure the torque control on the brake is set to minimum (fully counterclockwise). Turn the Power Supply on, set the armature voltage E_A to the value recorded in step 14 of the previous exercise. Set the FIELD RHEOSTAT on the DC Motor/Generator so that the current in the shunt winding I_f is equal to the value indicated in Table 2-1. Clear the data recorded in the Data Table. Refer to steps 19 to 21 of this exercise to record the necessary data and obtain the graph. Entitle the Data Table and graph as DT225 and G225, respectively. Compare the speed versus torque characteristic of the cumulative compound motor (graph G225) to those of the other dc motors (graphs G212-2, G223, and G224).
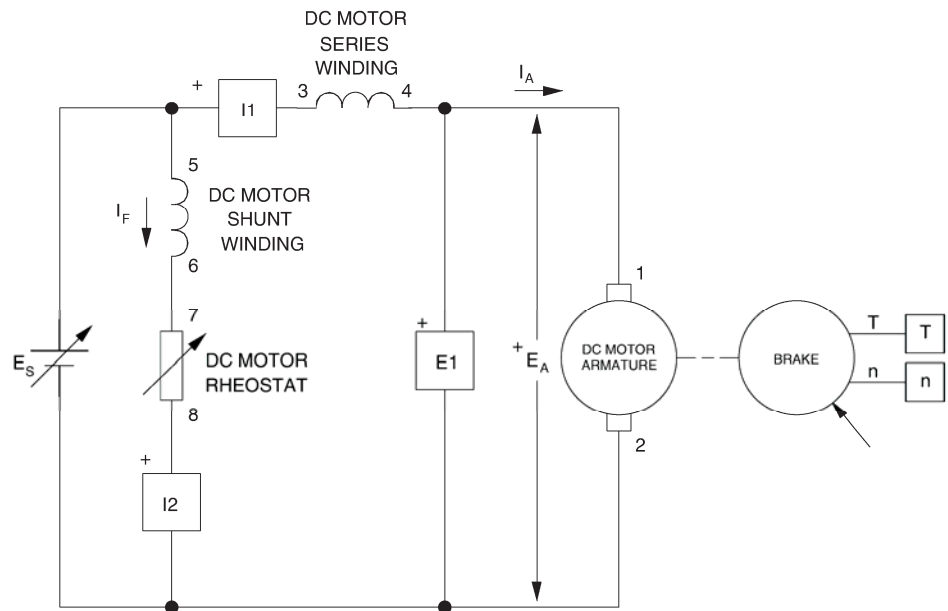

Figure 2-23. Cumulative compound motor circuit.

CONCLUSION

In this exercise, you observed that decreasing the field current of a separately-excited dc motor below its nominal value increases constant K_1 but decreases constant K_2. You saw that this allows the motor to rotate at higher speeds without exceeding the nominal armature voltage but reduces the torque which the motor can develop without exceeding the nominal armature current. You also saw that it is possible to increase the field current above its nominal value for short time intervals to improve the starting torque. You plotted a graph of the speed versus torque characteristic of a series motor and compared it to that obtained in the previous exercise with a separately-excited dc motor. You observed that the speed of a series motor decreases more rapidly than that of the separately-excited dc motor as the torque increases. Furthermore, you observed that the speed versus torque characteristic of the separately-excited dc motor is linear whereas that of the series motor is non linear.

If you have performed the additional experiments, you plotted graphs of the speed versus torque characteristic for a shunt motor and a cumulative compound motor. You compared these characteristics to those obtained with the separately-excited dc motor and the series motor. You found that the characteristic of a shunt motor is very similar to that of a separately-excited dc motor. You saw that the characteristic of a cumulative compound motor is a compromise of the characteristics of the separately-excited dc motor and series motor.

REVIEW QUESTIONS

1. What effect does decreasing the field current below its nominal value have on the speed versus voltage characteristic of a separately-excited dc motor?

    a. Constant K_1 increases.
    b. Constant K_2 increases.
    c. Constant K_1 decreases.
    d. Constant K_2 decreases.

2. What effect does decreasing the field current below its nominal value have on the torque-current characteristic of a separately-excited dc motor?

    a. Constant K_1 increases.
    b. Constant K_2 increases.
    c. Constant K_1 decreases.
    d. Constant K_2 decreases.

3. What is the advantage of increasing the field current above its nominal value for a short time interval when starting a separately-excited dc motor?

    a. This prevents damage to the motor.
    b. This allows the motor to reach a higher speed.
    c. This increases the armature voltage.
    d. This increases the starting torque.

4. Does the speed of a shunt motor increase or decrease when the armature current increases?

    a. It increases.
    b. It decreases.
    c. It oscillates around the previous value.
    d. It does not change because speed is independent of the armature current.

5. What is the advantage of decreasing the field current of a separately-excited dc motor below its nominal value?

    a. This allows the motor to develop a higher torque without exceeding the nominal armature voltage.
    b. This allows the motor to develop a higher torque without exceeding the nominal armature current.
    c. This allows the motor to rotate at a higher speed without exceeding the nominal armature voltage.
    d. This has no advantage.