Germany
Festo Didactic SE
Rechbergstr. 3
73770 Denkendorf
Tel.: +49 711 3467-0
Fax: +49 711 347-54-88500
did@festo.com

United States
Festo Didactic Inc.
607 Industrial Way West
Eatontown, NJ 07724
Tel.: +1 732 938-2000
Toll Free: +1-800-522-8658
Fax: +1 732 774-8573
services.didactic@festo.com

Canada
Festo Didactic Ltée/Ltd
675, rue du Carbone
Québec (Québec) G2N 2K7
Tel.: +1 418 849-1000
Toll Free: +1-800-522-8658
Fax: +1 418 849-1666
services.didactic@festo.com

www.festo-didactic.com

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Conventional DC Machines and Universal Motor

Student Manual

Conventional DC Machines and Universal Motor

Electricity and New Energy

LabVolt Series

Student Manual

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Electricity and New Energy

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Student Manual

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Internet: www.festo-didactic.com
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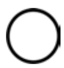
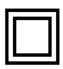
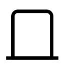
Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

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

Safety and Common Symbols

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

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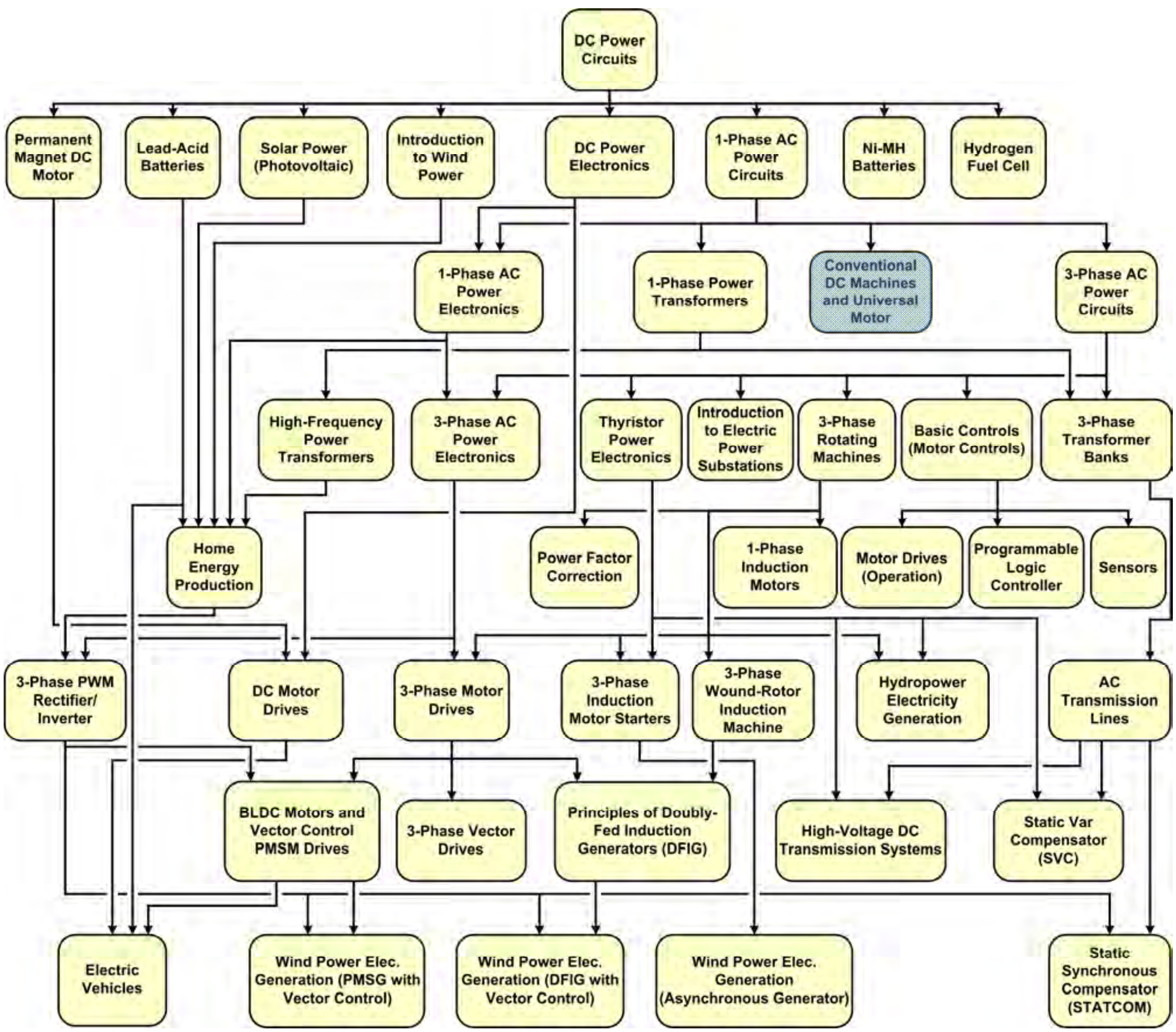
Preface

The production of energy using renewable natural resources such as wind, sunlight, rain, tides, geothermal heat, etc., has gained much importance in recent years as it is an effective means of reducing greenhouse gas (GHG) emissions. The need for innovative technologies to make the grid smarter has recently emerged as a major trend, as the increase in electrical power demand observed worldwide makes it harder for the actual grid in many countries to keep up with demand. Furthermore, electric vehicles (from bicycles to cars) are developed and marketed with more and more success in many countries all over the world.

To answer the increasingly diversified needs for training in the wide field of electrical energy, the Electric Power Technology Training Program was developed as a modular study program for technical institutes, colleges, and universities. The program is shown below as a flow chart, with each box in the flow chart representing a course.



The Electric Power Technology Training Program.

Preface

The program starts with a variety of courses providing in-depth coverage of basic topics related to the field of electrical energy such as ac and dc power circuits, power transformers, rotating machines, ac power transmission lines, and power electronics. The program then builds on the knowledge gained by the student through these basic courses to provide training in more advanced subjects such as home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, large-scale electricity production from wind power (doubly-fed induction generator [DFIG], synchronous generator, and asynchronous generator technologies), smart-grid technologies (SVC, STATCOM, HVDC transmission, etc.), storage of electrical energy in batteries, and drive systems for small electric vehicles and cars.

Do you have suggestions or criticism regarding this manual?

If so, send us an e-mail at did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

This course, *Conventional DC Machines and Universal Motor*, first describes the operation of the prime mover and brake used throughout the hands-on exercises. The student learns how to determine the polarity of the speed, torque, and mechanical power measured for a machine operating as either a motor or a generator. The course then introduces the student to the operation and characteristics of the following rotating machines: separately-excited, shunt, series, and compound dc motors, separately-excited, shunt, and compound dc generators, and universal motor. These machines, although still in use in numerous applications today, are less common in modern battery-powered applications (e.g., electric bicycles, mobility scooters, etc.) where power efficiency is at a premium.

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Prerequisite

As a prerequisite to this course, you should have read the manuals titled *DC Power Circuits*, part number 86350 and *Single-Phase AC power Circuits*, part number 86358.

Systems of units

Units are expressed using the International System of Units (SI) followed by the units expressed in the U.S. customary system of units (between parentheses).

Fundamentals of Rotating Machines

UNIT OBJECTIVE

When you have completed this unit, you will be familiar with the basic operation of motors and generators. You will know how to calculate the work, torque, and power produced in a system. You will also be familiar with the basic functions of the Four-Quadrant Dynamometer/Power module used in this manual. You will be able to determine the polarity of the speed, torque, and mechanical power measured for a machine operating as either a motor or a generator.

DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Basic motor operation
- The rotating electromagnet principle
- The generator principle
- Work, torque, and power
  Work. Torque. Power.
- Electric motor efficiency

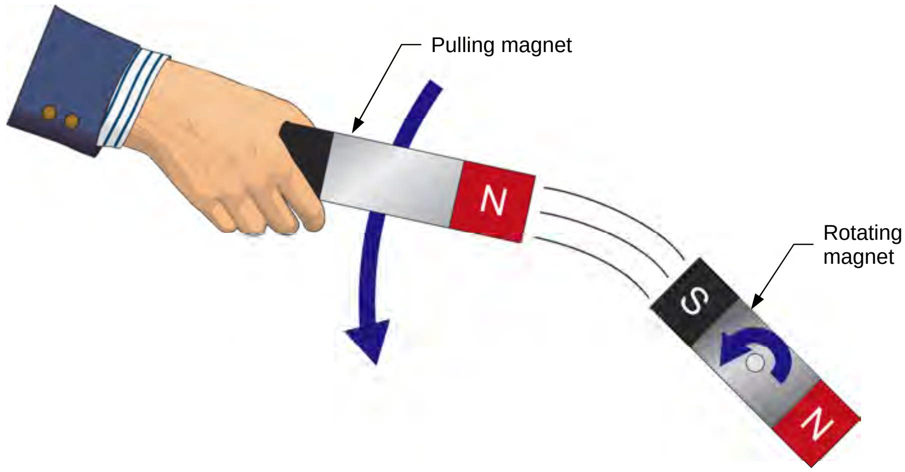
DISCUSSION OF FUNDAMENTALS

Basic motor operation

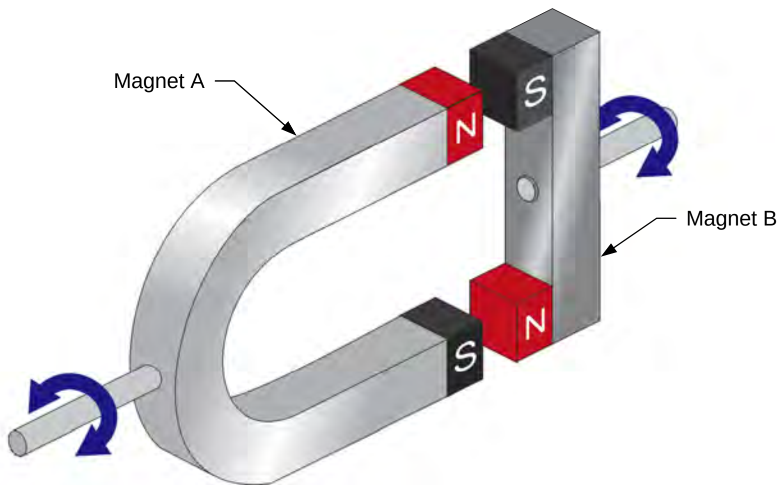
Everyone is familiar with some type of **electric motor** or another, whether it is the tiny **dc motor** in battery-operated toys, the dc starter motor in automobiles, or the **ac motor** in washing machines and clothes dryers. Electric motors are also used in fans, electric drills, pumps and many other familiar devices. But how and why do these motors work, and why do they turn? The answer is surprisingly simple: it is due to the interaction between two magnetic fields.

If you take two magnets and fix one of them on a shaft so that it can rotate, and then move the second magnet (pulling magnet) in a circle around the first, the rotating magnet will be pulled along by the **magnetic force** of attraction between the two, as shown in Figure 1-1a. As a result, the rotating magnet will rotate in synchronization with the pulling magnet.

The interaction between two magnets is shown more realistically in Figure 1-1b. In the figure, magnets A and B can both rotate freely on the same axis. When magnet A is turned, magnet B follows, and vice-versa, due to the magnetic attraction between the two.



(a) Rotating magnet pulled along as another magnet rotates around it



(b) Interaction between two rotating magnets

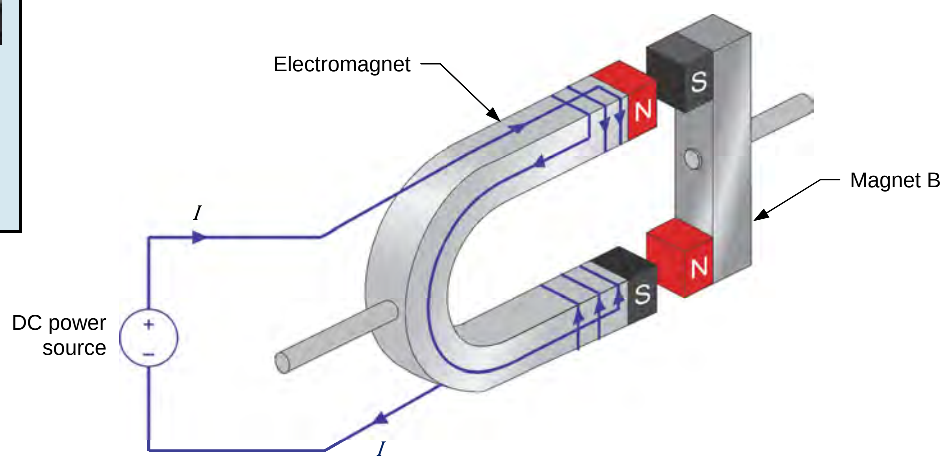
Figure 1-1. Interacting magnetic forces cause magnet rotation.

The rotating electromagnet principle

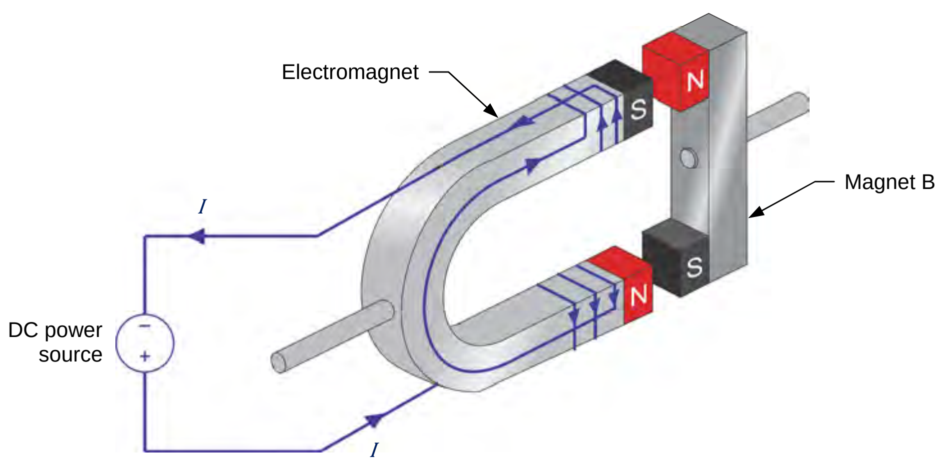
Figure 1-3a shows how magnet A from Figure 1-1b can be used to make an **electromagnet**. First, a coil of wire is wrapped around the iron core of the magnet. The ends of the coil are then connected to a dc power source in order to make current flow in the coil, thus producing a north and a south **magnetic poles**. Due to these induced magnetic poles, magnet A has become an electromagnet.

When the electromagnet in Figure 1-3 is rotated manually, it causes magnet B to rotate, like the two magnets in Figure 1-1. At first glance, this setup offers no advantage because a first object (the electromagnet) must still be rotated in order to cause a second object (magnet B) to rotate. Furthermore, to prevent the leads interconnecting the dc power source and the electromagnet from twisting, the source would have to rotate with the electromagnet, which would not be convenient.

Figure 1-2. Physicist Michael Faraday is generally credited with the discovery of electromagnetic induction.



(a)



(b)

Figure 1-3. Electric current flow produces an electromagnet.

However, if the polarity of the dc power source is reversed as in Figure 1-3b, the positions of the north and south poles on the electromagnet are interchanged, causing magnet B to rotate one half turn. As you can see, reversing the direction of current flow in the electromagnet causes magnet B to rotate without having to rotate the electromagnet. By combining two electromagnets, two dc power sources, and continually reversing the voltage and polarity of the dc power sources, it is thus possible to make magnet B rotate in a given direction without having to move the electromagnet.

Figure 1-4 shows how the electromagnet of Figure 1-3 can be modified to achieve this. When the currents I_1 and I_2 that flow in the two electromagnets alternate as shown in Figure 1-4, the magnetic poles created in the electromagnets continually reverse polarity. The resulting sequence of attraction and repulsion between the magnets makes the rotating magnet rotate in the clockwise direction. Current switching thus results in the electrical equivalent of a rotating magnet. This is the operating principle of all motors.

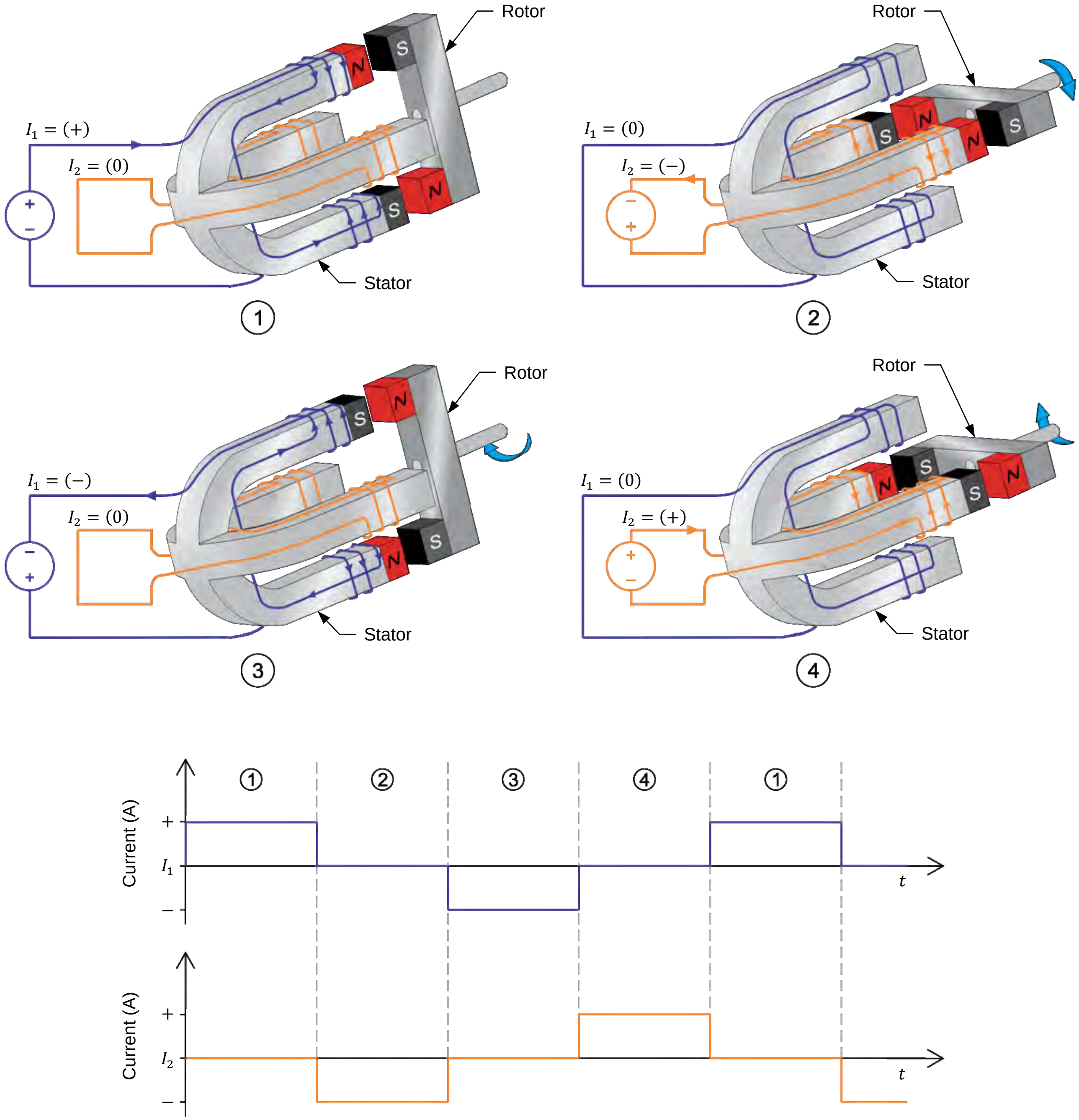


Figure 1-4. Electromagnet causing a magnet to rotate in the clockwise direction and graphs of the currents flowing in the electromagnet at each instant.

The direction of rotation of the rotating magnet can be reversed by interchanging currents I_1 and I_2, as Figure 1-5 shows.

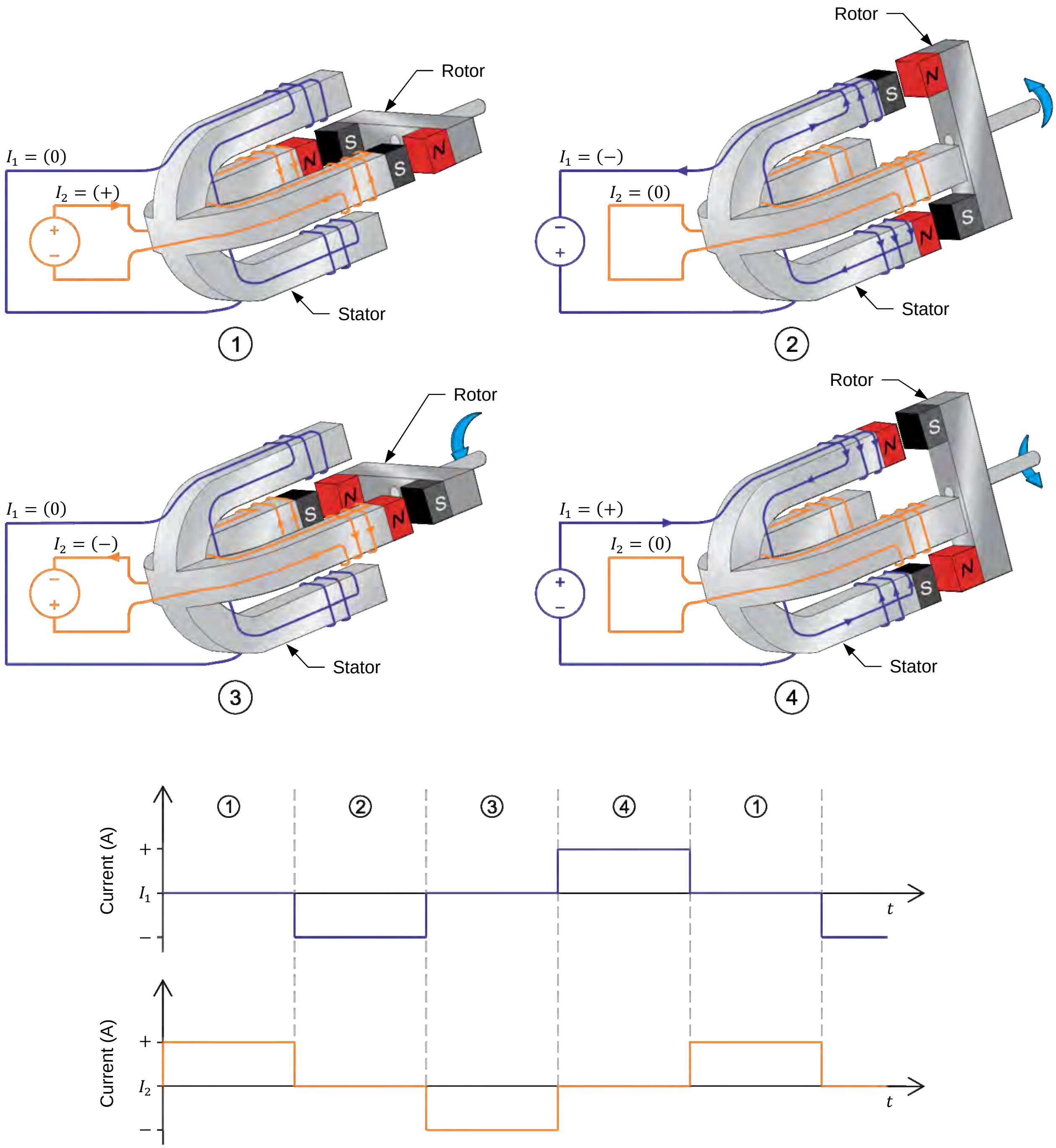


Figure 1-5. Electromagnet causing a magnet to rotate in the counterclockwise direction and graphs of the currents flowing in the electromagnet at each instant.

The machine shown in Figure 1-4 and Figure 1-5 converts electrical energy (i.e., the energy produced by the dc power source) into mechanical energy (i.e., the energy of the rotating magnet) and is called a motor.

A motor basically consists of two main components: a **stator** (the electromagnet) and a **rotor** (the rotating magnet). The stator is the motor component producing the electromagnetic field. As its name implies, a stator does not move in relation to the other motor components. The rotor, on the other hand, is the motor component that rotates along or inside the stator, thus producing mechanical work. In real dc motors, the rotor is made up of several wire loops, as Figure 1-6 shows.

Figure 1-6. In real dc motors, the rotor is made up of several wire loops.

The generator principle

The operation of **electric generator** (or alternator) is based on Faraday's law of **electromagnetic induction**, which states the following:

1. A voltage is induced between the terminals of a wire loop if the magnetic flux passing through the loop varies as a function of time.

2. The value of the induced voltage is proportional to the rate of change of the magnetic flux.

The voltage induced between the terminals of a wire loop when the magnetic flux passing through the loop varies can be calculated using the following equation:

In Equation 1-1, the polarity of the induced voltage is not taken into account as it is not important for the purpose of this discussion.

$$E = N_{Turns} \cdot \frac{\Delta\phi}{\Delta t} \tag{1-1}$$

where E is the voltage induced across the terminals of the wire loop, expressed in volts (V).
N_{Turns} is the number of turns of wire in the loop.
$\Delta\phi$ is the variation in intensity of the magnetic flux passing through the wire loop, expressed in Webers (Wb).
Δt is the time interval during which the magnetic flux variation occurs, expressed in seconds (s).

Figure 1-7 gives an example of the voltage induced in a wire loop that is exposed to a magnetic flux varying in intensity.

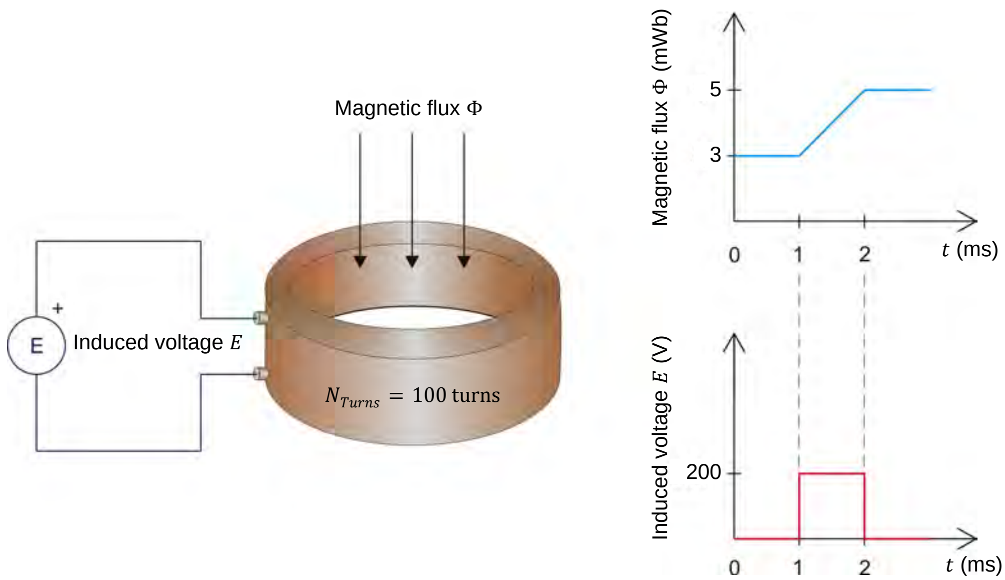


Figure 1-7. Voltage induced in a wire loop that is exposed to a magnetic flux varying in intensity.

Using the values given in Figure 1-7, the voltage E induced in the coil is equal to:

$$E = N_{Turns} \cdot \frac{\Delta\phi}{\Delta t} = 100 \text{ turns } \cdot \frac{0.005 \text{ Wb} - 0.003 \text{ Wb}}{0.001 \text{ s}} = 200 \text{ V}$$

The principle of operation of a generator can be illustrated using the electromagnet and the rotating magnet of Figure 1-4 and Figure 1-5. If the rotating magnet (i.e., the rotor) is turned manually, a magnetic field variation is created in the electromagnet (i.e., the stator). Following Faraday's law of electromagnetic induction, this magnetic field variation will induce a variable voltage in the conductors wound around the stator, as shown in Figure 1-8.

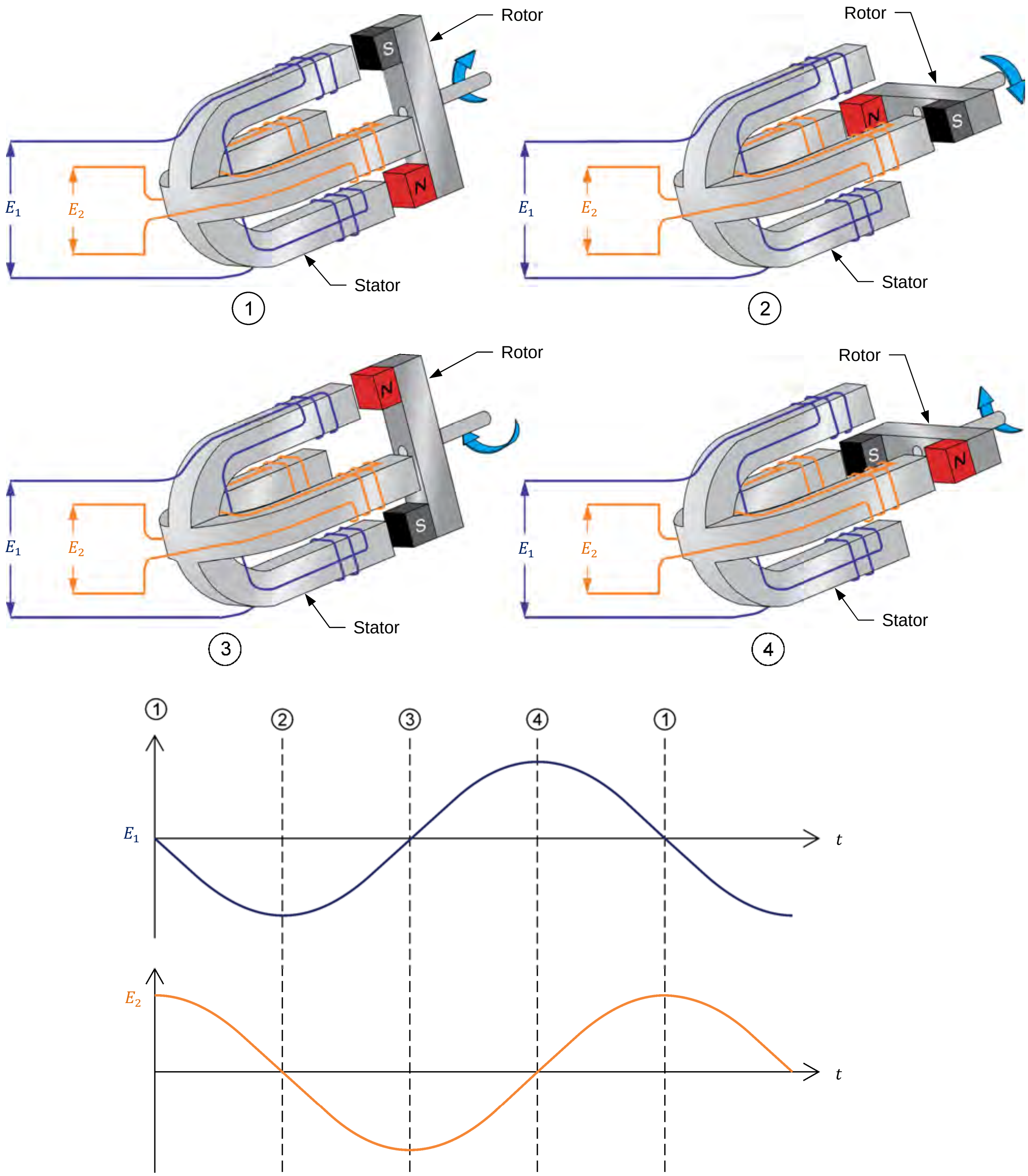


Figure 1-8. Generator operation and resulting voltage waveforms induced across the stator windings at each instant.

The machine shown in Figure 1-8 converts mechanical energy (i.e., the energy of the rotating magnet) into electrical energy (i.e., the energy of the voltage induced across the stator conductors) and is called a generator (or alternator).

Figure 1-9. Most of the electricity worldwide is produced by three-phase synchronous generators. The above picture shows the Three-Gorges Dam hydropower plant, on the Yangtze River, in China. It contains thirty 700 MW three-phase synchronous generators, each weighing about 6 000 000 kg (about 6000 tons).

Work, torque, and power

Work

The mechanical work W that is done when a force F moves an object over a distance d can be calculated using the following equation:

$$W = F \cdot d \quad (1\text{-}2)$$

where W is the mechanical work done by the force, expressed in joules (J) or in pound-force inches (lbf·in).
F is the magnitude of the force moving the object, expressed in newtons (N) or in pound-forces (lbf).
d is the distance over which the force moves the object, expressed in meters (m) or in inches (in).

Figure 1-10 shows the example of a block that is moved over a distance d of 1 m (39.4 in) by a force F of 1 N (0.22 lbf). Using Equation (1-2), it can be calculated that a mechanical work W of 1 J (8.85 lbf·in) has been done.

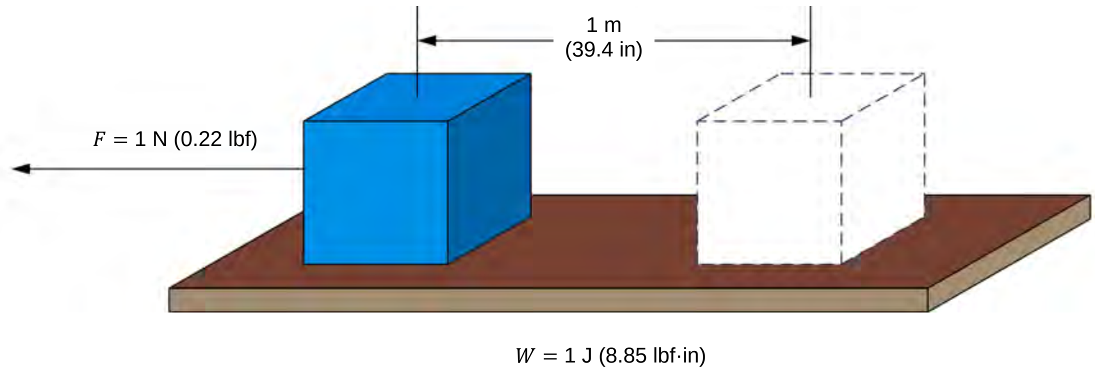


Figure 1-10. Work required to a move a block.

Torque

Consider now that the block in Figure 1-10 is moved over the same distance using a pulley that has a radius r, as Figure 1-11 shows.

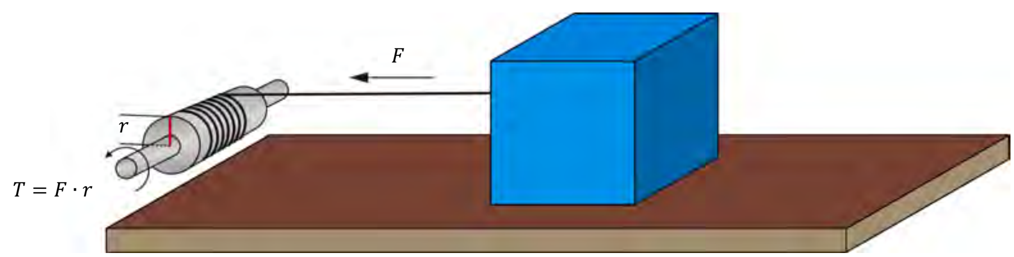


Figure 1-11. Moving a block using a pulley.

A twisting force must be applied on the pulley shaft to make it rotate so that the rope wound around the pulley shaft pulls the block with a force F. This twisting force is known as the **torque** T and is defined by the following equation:

$$T = F \cdot r \tag{1-3}$$

where T is the torque exerted on the pulley shaft, expressed in newton-meters (N·m) or in pound-force inches (lbf·in).
F is the magnitude of the force acting on the pulley shaft, expressed in newtons (N) or in pound forces (lbf).
r is the radius of the pulley, expressed in meters (m) or in inches (in).

At the end of each complete rotation of the pulley, the block has been pulled a distance of $(2\pi \cdot r)$ m or in, meaning that $(2\pi \cdot r \cdot F)$ J or lbf·in of work has been done. Since $T = F \cdot r$, the amount of work W done in one revolution can be expressed as $(2\pi \cdot T)$ J or lbf·in.

Power

power P is defined as the rate of doing work, and it is calculated using the following equation when work W is expressed in joules.

$$P = \frac{W}{t} \tag{1-4}$$

where P is the power of the device doing the work, expressed in watts (W).
W is the amount of work done, expressed in joules (J).
t is the time taken to do the work, expressed in seconds (s).

In Equation (1-5) and Equation (1-7), the term $1/8.85$ is used to convert the work W, expressed in pound-force inches (lbf·in), into a work W, expressed in joules (J).

When work W is expressed in pound-force inches (lbf·in), the following equation must be used to calculate the power :

$$P = \frac{W}{t} \cdot \frac{1}{8.85} = \frac{W}{8.85 \cdot t} \tag{1-5}$$

where W is the amount of work done, expressed in pound-force inches (lbf·in).

In Equation (1-6) and Equation (1-7), the term $1/60\ \mathrm{s}$ is used to convert the rotation speed n, expressed in revolutions per minute (r/min), into a rotation speed n expressed in revolutions per second (r/s).

Since power is work done per unit of time, the power P of a motor turning at a **rotation speed n** can be found using the following equation when the torque T is expressed in newton-meters (N·m).

$$P = n \cdot \frac{1\ \mathrm{min}}{60\ \mathrm{s}} \cdot 2\pi T = n \cdot \frac{1\ \mathrm{min}}{9.55\ \mathrm{s}} \cdot T = \frac{n \cdot T}{9.55} \tag{1-6}$$

where n is the rotation speed of the motor, expressed in revolutions per minute (r/min).

When torque T is expressed in pound-force inches (lbf·in), the power P of the motor can be found using the following equation:

$$P = n \cdot \frac{1\ \mathrm{min}}{60\ \mathrm{s}} \cdot 2\pi T \cdot \frac{1}{8.85} = n \cdot T \cdot \frac{1\ \mathrm{min}}{84.5\ \mathrm{s}} = \frac{n \cdot T}{84.5} \tag{1-7}$$

It is possible to obtain the power P, expressed in horsepower (hp), for any given power P, expressed in watts (W), by dividing the power value in watts by 746.

Electric motor efficiency

Electric **motor efficiency** is the ratio of the **mechanical power** P_m produced by a motor to the electrical power P_{in} supplied to the motor. In equation form:

$$\text{Electric motor efficiency (\%)} = \frac{P_m}{P_{in}} \cdot 100\% \tag{1-8}$$

The mechanical power P_m of a motor depends on its speed and torque, and can be determined using one of the two formulas given in the previous section of this discussion [i.e., Equation (1-6) or Equation (1-7),], depending on whether torque is expressed in newton-meters (N·m) or pound-force inches (lbf·in).

The efficiency of an electric motor is usually represented in the form of a graph showing efficiency versus mechanical output power. For example, Figure 1-12 shows an example of the typical efficiency-versus-mechanical output power curve (in blue) for a 10-kW dc motor. Notice that electric motor efficiency is sometimes specified by a numerical value at the nominal power rating instead of a graph.

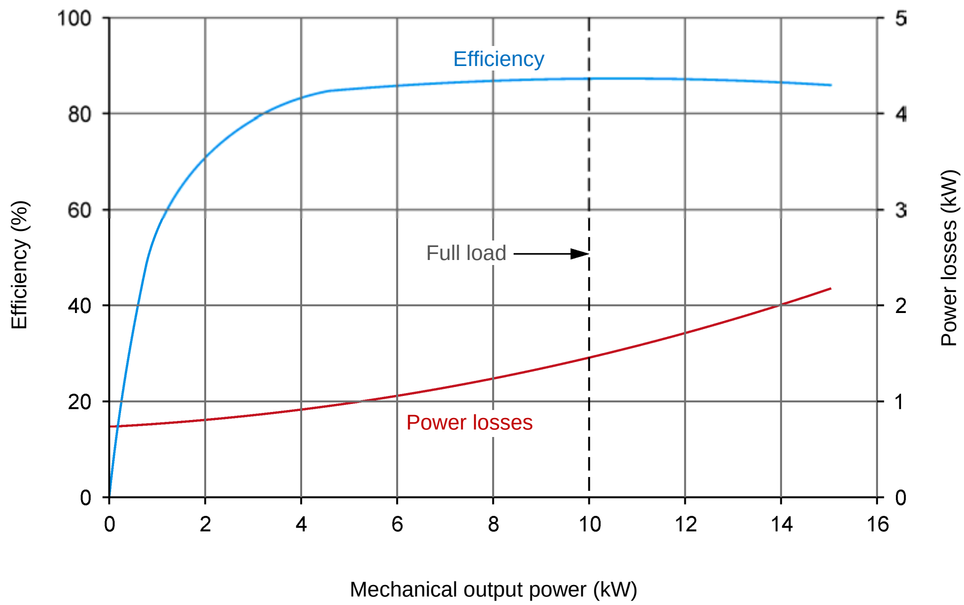


Figure 1-12. Typical relationship between the losses and efficiency of a 10-kW dc motor as a function of mechanical output power.

There are two types of power losses in rotating machines: mechanical losses and electrical losses. Mechanical losses are due to bearing friction, brushes friction, as well as windage friction or cooling-fan friction. Mechanical losses increase significantly as the motor speed increases from zero to its nominal value, but remain fairly constant over the normal operating range between the no-load and full-load conditions.

Electrical losses are classed as copper losses, brushes losses, and iron losses. Copper losses (RI^2 losses) result from the resistance of the conductors used in the machine. They increase with the square of current and result in heat dissipation. Brushes losses are usually very small, and are due to the resistance of the brushes contact, which causes a voltage drop typically between 0.8 V and 1.3 V. Finally, iron losses are due to hysteresis and eddy currents in the machine, and depend on the magnetic flux density, the speed of rotation or frequency, the type of steel, and the size of the motor.

For example, Figure 1-12 shows an example of typical losses-versus-mechanical output power curve (in red) for a 10-kW dc motor.

Prime Mover and Brake Operation

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the basic functions of the Four-Quadrant Dynamometer/Power Supply used in this manual. You will also be familiar with the polarity of the speed, torque, and mechanical power for a rotating machine operating as either an electric motor or a generator.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to the Four-Quadrant Dynamometer/Power Supply
  Two-quadrant constant-torque brake. Clockwise constant-speed prime mover/brake. Counterclockwise constant-speed prime mover/brake.
- Speed, torque, and mechanical power measurements using the Four-Quadrant Dynamometer/Power Supply
  Motor operation. Generator operation.

DISCUSSION

Introduction to the Four-Quadrant Dynamometer/Power Supply

The Four-Quadrant Dynamometer/Power Supply module used in this manual consists of complex power electronics circuits, a microcontroller, and a dc motor. The module can be used to implement a multitude of functions. All mechanical functions (i.e., all functions using the dc motor) enable the Four-Quadrant Dynamometer/Power Supply module to act as a **dynamometer**, i.e., to measure the torque created by the machine connected to it. The following three basic functions are described in this exercise:

1. Two-quadrant constant-torque brake

2. Clockwise constant-speed prime mover/brake

3. Counterclockwise constant-speed prime mover/brake

These three functions are explained in more details below.

Two-quadrant constant-torque brake

This function is used to study rotating machines operating as motors (i.e., converting electrical energy into mechanical energy). The two-quadrant constant-torque brake can be used to mechanically load a motor (i.e., to create an opposition torque acting against the torque produced by the motor to rotate), as Figure 1-13 shows. It is thus possible to study the speed, torque, and mechanical power of the motor under test as load torque is applied to it.

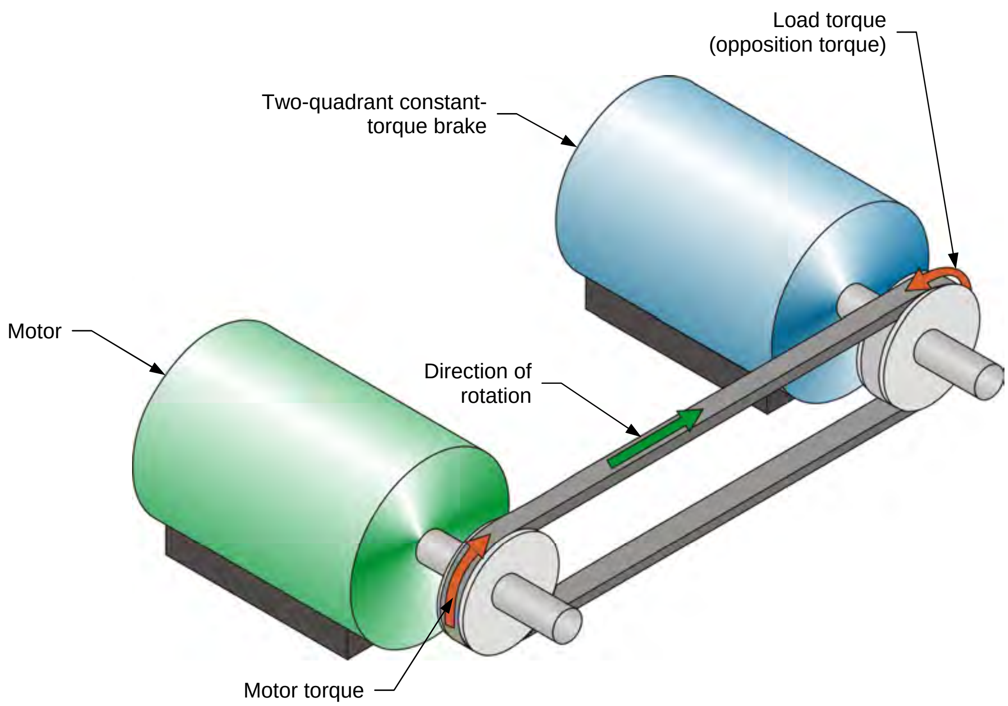


Figure 1-13. Motor coupled to a two-quadrant constant-torque brake.

When the Four-Quadrant Dynamometer/Power Supply is operating as a two-quadrant, constant-torque brake, it is possible to set the magnitude of the load torque produced by the brake. The Four-Quadrant Dynamometer/Power Supply window in the LVDAC-EMS software has speed, torque, power, and energy meters that indicate the different parameters measured for the machine under test. For example, the torque indicated by the torque meter corresponds to the torque produced by the motor under test, not the load torque produced by the two-quadrant, constant-torque brake.

When determining the torque produced by the motor to which it is coupled, the Four-Quadrant Dynamometer/Power Supply automatically compensates for its own friction torque and for the belt friction torque. Thus, the torque indicated by the torque meter in the Four-Quadrant Dynamometer/Power Supply window of the LVDAC-EMS software represents the **actual** torque produced at the shaft of the motor under test. Similarly, the mechanical power indicated by the power meter in the Four-Quadrant Dynamometer/Power Supply window represents the **corrected** mechanical power at the shaft of the motor under test.

Clockwise constant-speed prime mover/brake

This control function is used mainly to study rotating machines operating as generators (i.e., converting mechanical energy into electrical energy). The clockwise constant-speed prime mover/brake can be used to drive a rotating machine (i.e., to make the machine rotate with the prime mover/brake), as Figure 1-14 shows. In this case, the Four-Quadrant Dynamometer/Power Supply operates as a **prime mover**. Since the clockwise constant-speed prime mover/brake can operate in two quadrants, it can also be used to reduce the speed of a machine operating as a motor (i.e., to create an opposition torque acting against the torque produced by the motor to rotate). In this case, the Four-Quadrant Dynamometer/Power Supply operates as a brake.

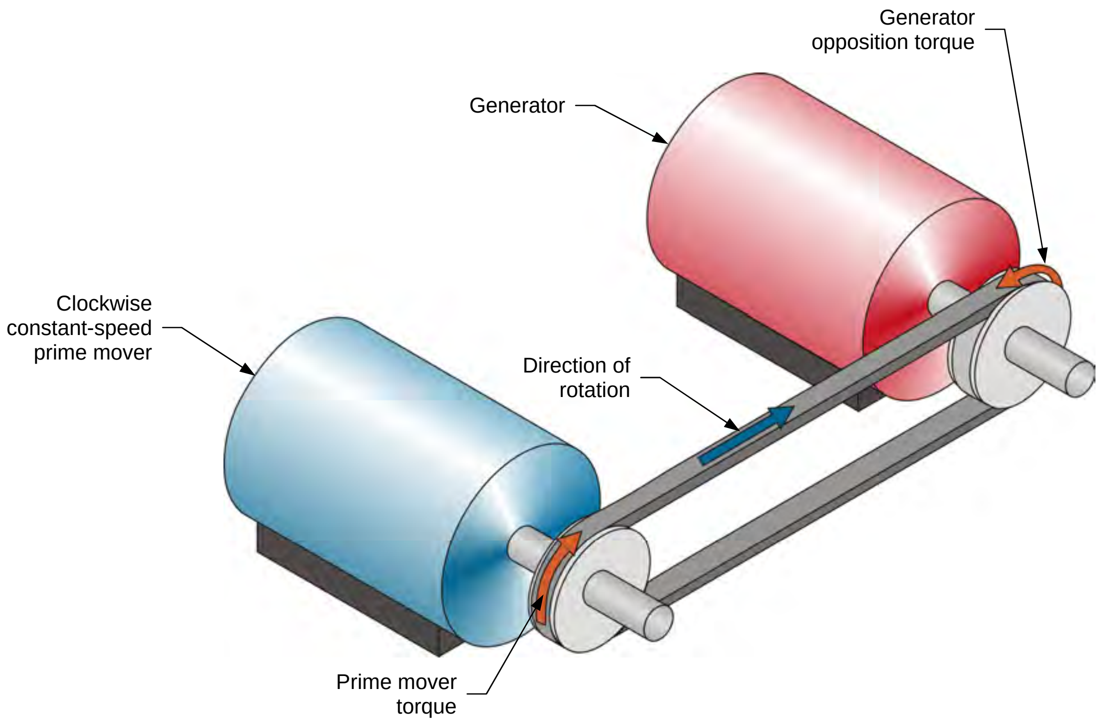


Figure 1-14. Clockwise constant-speed prime mover coupled to a generator.

When the Four-Quadrant Dynamometer/Power Supply is operating as a clockwise constant-speed prime mover/brake, it is possible to set the rotation speed. In the Four-Quadrant Dynamometer/Power Supply window, speed, torque, power, and energy meters indicate the different parameters measured for the machine under test.

The Four-Quadrant Dynamometer/Power Supply operating as a clockwise constant-speed prime mover maintains constant the speed of the machine to which it is connected. When the machine speed differs from the specified value, the Four-Quadrant Dynamometer/Power Supply automatically adjusts the torque it produces in order to maintain the machine speed to the specified value.

Counterclockwise constant-speed prime mover/brake

This function is identical to the clockwise constant-speed prime mover/brake, except that it makes the Four-Quadrant Dynamometer/Power Supply rotate in the counterclockwise direction. The polarity of the parameters measured for the machine under test is modified accordingly.

Speed, torque, and mechanical power measurements using the Four-Quadrant Dynamometer/Power Supply

By convention, the speed of a machine rotating in the clockwise direction is of positive polarity while the speed of a machine rotating in the counterclockwise direction is of negative polarity.

The polarity of the torque and mechanical power measured for the machine connected to the Four-Quadrant Dynamometer/Power Supply depends on the machine's mode of operation. There are two modes of operation: motor and generator.

Motor operation

As Figure 1-13 shows, when a machine operates as a motor, the motor torque is in the same direction as the motor's direction of rotation, i.e., the speed at which the motor rotates is of the same polarity as the torque produced by the motor. Consequently, the mechanical power produced by the motor, which is proportional to the product of the motor speed and torque, is always positive, regardless of the motor's direction of rotation (i.e., regardless of whether the motor speed and torque are positive or negative). This is consistent with the definition of a motor, which states that a motor uses electrical energy to produce mechanical energy, thus resulting in a positive mechanical power value.

Any load torque applied to the motor (such as the load torque created by the brake in Figure 1-13) acts against the torque produced by the motor, and thus has a polarity that is opposite to the polarity of the motor torque and speed.

Generator operation

As Figure 1-14 shows, when a machine operates as a generator, the generator torque is in the direction opposite to the direction of rotation, i.e., the speed at which the generator rotates has a polarity opposite to the polarity of the torque produced by the generator. Consequently, the mechanical power at the shaft of the generator, which is proportional to the product of the motor speed and torque, is always negative, regardless of the generator's direction of rotation (i.e., regardless of whether the generator speed is positive or negative). This is consistent with the definition of a generator, which states that a generator uses mechanical energy to produce electrical energy, thus resulting in a negative mechanical power value.

The torque produced by the machine driving the generator (such as the prime mover torque in Figure 1-14) acts against the generator torque and thus has the same polarity as the generator speed.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Two-quadrant, constant-torque brake operation
- Constant-speed prime mover operation
- Constant-speed prime mover driving a loaded generator

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.

Set up and connections

In this section, you will mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply. You will then set the equipment to study the two-quadrant, constant-torque brake operation.

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

   Install the equipment in the Workstation.

   Mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

   WARNING

   Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

2. Make sure that the main power switch of the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power wall outlet.

3. On the Power Supply, make sure that the main power switch and the 24 V ac power switch are set to the O (off) position, and that the voltage control knob is set to 0% (turned fully counterclockwise). Connect the Power Supply to a three-phase ac power outlet.

4. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24 V ac power source of the Power Supply.

   Turn the 24 V ac power source of the Power Supply on.

5. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

6. Connect the equipment as shown in Figure 1-15. Use the variable dc voltage output (terminals *7* and *N*) of the Power Supply to implement the variable-voltage dc power source E_S. Use the fixed dc voltage output (terminals *8* and *N*) of the Power Supply to implement the fixed-voltage dc power source. *I1* is a current input of the Data Acquisition and Control Interface (DACI).

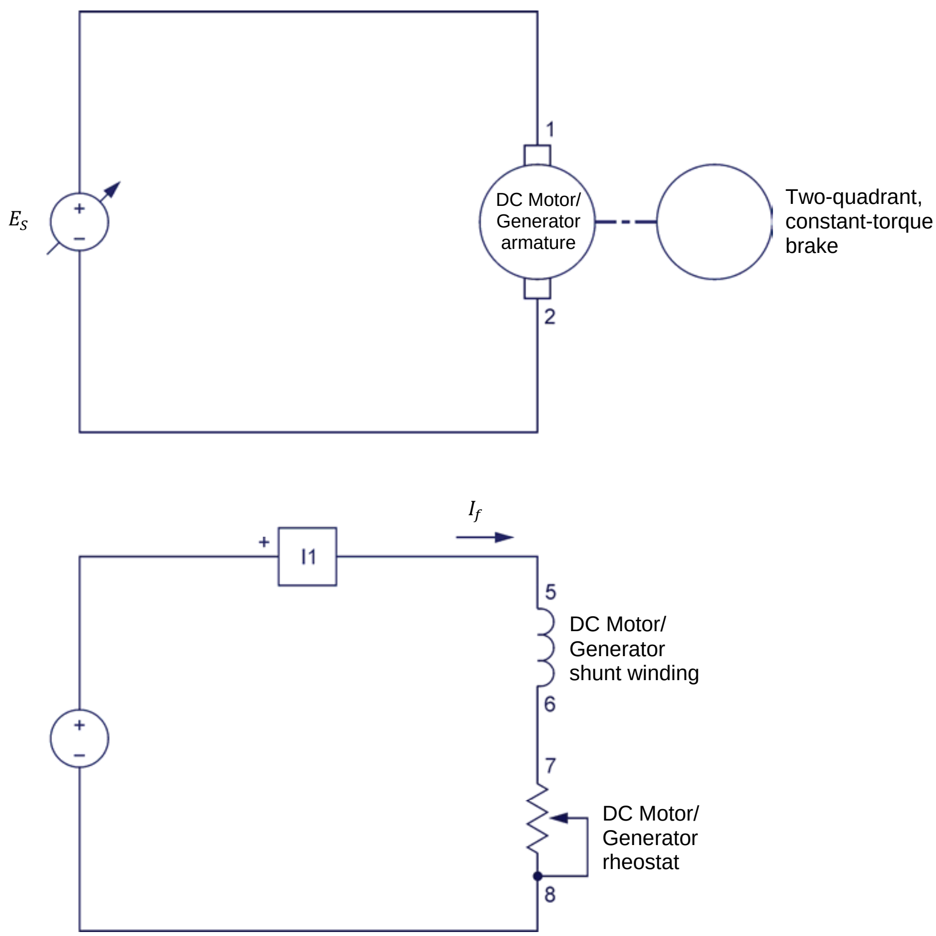


Figure 1-15. DC Motor/Generator coupled to a brake.

7. On the Four-Quadrant Dynamometer/Power Supply, set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

   Turn the Four-Quadrant Dynamometer/Power Supply on by setting the main power switch to I (on).

8. Turn the host computer on then start the LVDAC-EMS software.

   In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure that the *Computer-Based Instrumentation* function is available for the Data Acquisition and Control Interface module. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

9. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

   – Set the *Function* parameter to *Two-Quadrant, Constant-Torque Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a two-quadrant brake with a torque setting corresponding to the *Torque* parameter.

   – Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test (i.e., the DC Motor/Generator), respectively. It is important to ensure that the *Pulley Ratio* parameter corresponds to the actual pulley ratio between the Four-Quadrant Dynamometer/Power Supply and the machine under test.

   The pulley ratio between the Four-Quadrant Dynamometer/Power Supply and all machines under test in this manual is 24:24.

   – Make sure that the *Torque Control* parameter is set to *Knob*. This allows the torque of the two-quadrant brake to be controlled manually.

   – Set the *Torque* parameter to 0.0 N·m (or 0.0 lbf·in). This sets the torque command of the *Two-Quadrant, Constant-Torque Brake* to 0.0 N·m (0.0 lbf·in).

   The torque command can also be set by using the Torque control knob in the Four-Quadrant Dynamometer/Power Supply window.

10. In LVDAC-EMS, open the Metering window. Set meter *I1* as a dc ammeter.

    Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the Metering application.

Two-quadrant, constant-torque brake operation

In this section, you will make the DC Motor/Generator rotate in the clockwise direction and observe what happens to the torque produced by the motor when you increase the load torque applied to it. You will observe the polarity of the torque and the mechanical power produced by the DC Motor/Generator, and confirm that this machine is operating as a motor. You will then make the DC Motor/Generator rotate in the counterclockwise direction and observe what happens to the torque produced by the motor, the polarity of the torque, and the mechanical power produced by the motor.

11. Turn the Power Supply on by setting the main power switch to the I (on) position, then set the voltage control knob to 100%.

On the DC Motor/Generator, set the *Field Rheostat* knob so that the field current I_f (indicated by meter *I1* in the Metering window) is equal to the value indicated in Table 1-1 for your local ac power network.

Table 1-1. Field current I_f.

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

12. In the Four-Quadrant Dynamometer/Power Supply window, start the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

The *Speed* meter in the Four-Quadrant Dynamometer/Power Supply window indicates the rotation speed n of the DC Motor/Generator. Is this speed positive, indicating that the motor is rotating in the clockwise direction?

❑ Yes ❑ No

13. In the Four-Quadrant Dynamometer/Power Supply window, slowly increase the value of the *Torque* parameter to 1.0 N·m (8.8 lbf·in). While you do so, observe the torque T produced by the DC Motor/Generator (indicated by the *Torque* meter in the Four-Quadrant Dynamometer/Power Supply window.

What happens to the torque T produced by the DC Motor/Generator as the load torque applied to the motor by the *Two-Quadrant, Constant-Torque Brake* increases?

14. What is the polarity of the torque T produced by the DC Motor/Generator?

____

What is the polarity of the DC Motor/Generator speed n?

____

Is the torque T of the same polarity as the DC Motor/Generator speed n?

❑ Yes ❑ No

15. Is the DC Motor/Generator mechanical power P_m (indicated by the *Power* meter in the Four-Quadrant Dynamometer/Power Supply window) of positive polarity?

❑ Yes ❑ No

Does this confirm that the DC Motor/Generator currently operates as a motor? Explain.

____

____

16. Stop the DC Motor/Generator by setting the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.0 N·m (0.0 lbf·in).

17. On the Power Supply, reverse the connections at the variable dc voltage output (voltage source E_S in Figure 1-15) to reverse the polarity of the voltage applied to the armature of the DC Motor/Generator.

Reversing the polarity of the voltage applied to the armature of the DC Motor/Generator reverses the direction of rotation of the machine.

18. Start the DC Motor/Generator by setting the main power switch of the Power Supply to the I (on) position. Is the DC Motor/Generator speed n negative, indicating that the direction of rotation of the motor has been reversed and that the motor is rotating in the counterclockwise direction?

❑ Yes ❑ No

19. In the Four-Quadrant Dynamometer/Power Supply window, slowly increase the value of the *Torque* parameter to 1.0 N·m (8.8 lbf·in). While you do so, observe the torque T produced by the DC Motor/Generator.

What happens to the torque T produced by the DC Motor/Generator as the braking torque applied to the motor by the *Two-Quadrant, Constant-Torque Brake* increases?

____

____

____

20. Is the torque T produced by the DC Motor/Generator of the same polarity as the motor speed n?

❑ Yes ❑ No

21. Is the polarity of the DC Motor/Generator mechanical power P_m positive?

❑ Yes ❑ No

Does this confirm that the DC Motor/Generator currently operates as a motor?

❑ Yes ❑ No

22. Stop the DC Motor/Generator by setting the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on.)

In the Four-Quadrant Dynamometer/Power Supply window, stop the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Stopped* or by clicking the *Start/Stop* button.

23. From your observations, does the direction of rotation of the DC Motor/Generator determine the polarity (positive or negative) of the motor speed n and torque T? Explain.

____

____

____

Can the DC Motor/Generator operate as a motor in either direction of rotation (clockwise or counterclockwise)? Explain.

____

____

____

Constant-speed prime mover operation

In this section, you will set up a circuit containing a prime mover (implemented using the Four-Quadrant Dynamometer/Power Supply) mechanically coupled to the DC Motor/Generator. You will make the prime mover rotate in the clockwise direction and confirm that the DC Motor/Generator rotates at the specified speed determined by the prime mover speed. You will also confirm that the torque produced by the machine is virtually zero. You will make the prime mover rotate in the counterclockwise direction and confirm that the speed of the DC Motor/Generator is negative when it rotates in the counterclockwise direction. You will also confirm that the torque produced by the machine is virtually zero.

24. Set up the equipment as shown in Figure 1-16. In this circuit, no electrical load is connected to the DC Motor/Generator. Use the fixed dc voltage output (terminals *8* and *N*) of the Power Supply to implement the fixed-voltage dc power source. Set the *Field Rheostat* knob of the DC Motor/Generator to the mid position.

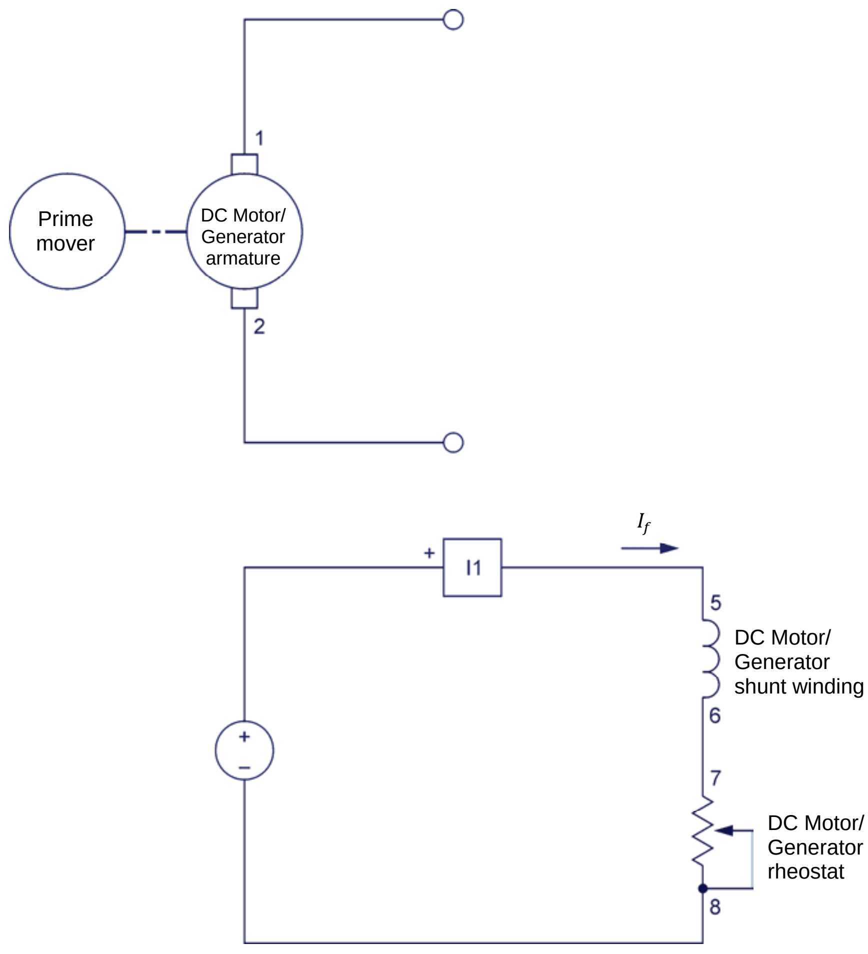


Figure 1-16. Prime mover coupled to the DC Motor/Generator (no electrical load).

25. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

– Set the *Function* parameter to *CW Constant-Speed Prime Mover/Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a clockwise prime mover/brake with a speed setting corresponding to the *Speed* parameter.

– Make sure that the *Pulley Ratio* parameter is set to 24:24.

– Make sure that the *Speed Control* parameter is set to *Knob*. This allows the speed of the clockwise prime mover/brake to be controlled manually.

– Set the *Speed* parameter (i.e., the speed command) to 1000 r/min. Notice that the speed command is the targeted speed at the shaft of the machine coupled to the prime mover, i.e., the speed of the DC Motor/Generator in the present case.

The speed command can also be set by using the Speed *control knob in the* Four-Quadrant Dynamometer/Power Supply *window.*

26. In the Four-Quadrant Dynamometer/Power Supply window, start the *CW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

Observe that the prime mover starts to rotate, thereby driving the shaft of the DC Motor/Generator.

Turn the Power Supply on by setting the main power switch to the I (on) position.

27. On the DC Motor/Generator, slightly readjust the *Field Rheostat* knob so that the field current I_f (indicated by meter *I1* in the Metering window) is equal to the value indicated in Table 1-1 for your local ac power network.

28. In the Four-Quadrant Dynamometer/Power Supply window, observe that the *Pulley Ratio* parameter is now grayed out as it cannot be changed while the prime mover is rotating. The *Speed* meter indicates the rotation speed n of the DC Motor/Generator. Record this speed below.

Rotation speed of the DC Motor/Generator = _______ r/min

Is the rotation speed of the DC Motor/Generator approximately equal to the value of the *Speed* parameter?

❑ Yes ❑ No

Is the rotation speed positive, indicating that the DC Motor/Generator is rotating in the clockwise direction?

❑ Yes ❑ No

29. Observe the rotation speed indicated on the front panel display of the Four-Quadrant Dynamometer/Power Supply module. It corresponds to the rotation speed of the prime mover. Notice that this speed is the same as the speed of the DC Motor/Generator. This is because the pulley ratio is 24:24.

30. In the Four-Quadrant Dynamometer/Power Supply window, observe the torque T of the DC Motor/Generator.

Is the torque virtually zero, indicating that no torque is produced by the DC Motor/Generator?

❑ Yes ❑ No

31. In the Four-Quadrant Dynamometer/Power Supply window, increase the *Speed* parameter to 1500 r/min.

Does the speed n of the DC Motor/Generator increase with the value of the *Speed* parameter of the *CW Constant-Speed Prime Mover/Brake*?

❑ Yes ❑ No

Does the motor torque T remain virtually zero as the speed increases?

❑ Yes ❑ No

32. On the Power Supply, set the main power switch to O (off).

In the Four-Quadrant Dynamometer/Power Supply window, stop the *CW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*, then make the following settings:

– Set the *Function* parameter to *CCW Constant-Speed Prime Mover/Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a counterclockwise prime mover/brake with a speed setting corresponding to the *Speed* parameter.

– Make sure that the *Speed Control* parameter is set to *Knob*. This allows the speed of the counterclockwise prime/mover brake to be controlled manually.

– Set the *Speed* parameter to −1000 r/min.

33. In the Four-Quadrant Dynamometer/Power Supply window, start the *CCW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

On the Power Supply, set the main power switch to the I (on) position.

34. Wait a few seconds, then observe the DC Motor/Generator speed and torque.

Is the rotation speed of the DC Motor/Generator approximately equal to the value of the *Speed* parameter?

❑ Yes ❑ No

Is the motor speed n negative, indicating that the DC Motor/Generator is rotating in the counterclockwise direction?

❑ Yes ❑ No

Is the motor torque T virtually zero, indicating that no torque is produced by the DC Motor/Generator?

❑ Yes ❑ No

35. In the Four-Quadrant Dynamometer/Power Supply window, increase the *Speed* parameter to −1500 r/min.

Does the speed n of the DC Motor/Generator increase (with a negative polarity) as the value of the *Speed* parameter of the *CCW Constant-Speed Prime Mover/Brake* increases?

❑ Yes ❑ No

Does the motor torque T remain virtually zero as the speed increases?

❑ Yes ❑ No

36. On the Power Supply, set the main power switch to the O (off) position.

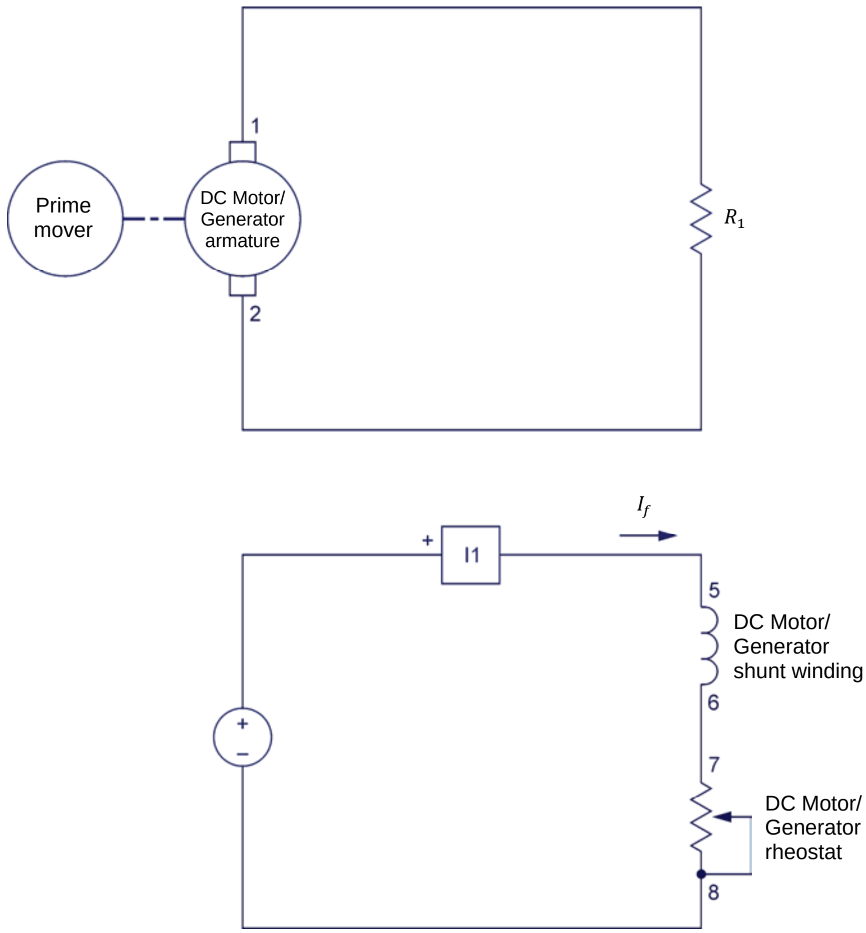
In the Four-Quadrant Dynamometer/Power Supply window, stop the *CCW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

Constant-speed prime mover driving a loaded generator

In this section, you will set up a circuit containing a prime mover (implemented using the Four-Quadrant Dynamometer/Power Supply) mechanically coupled to the DC Motor/Generator operating as a generator. The output of the generator will be connected to a resistive load. You will make the generator rotate in the clockwise direction and confirm that the generator speed and torque are of opposite polarity, and that the generator mechanical power is negative, thus indicating that the machine is operating as a generator. You will then make the generator rotate in the counterclockwise direction and verify that the generator speed and torque are of opposite polarity, and that the generator mechanical power is negative. Finally, you will confirm that the machine can operate as a generator, regardless of the direction of rotation.

37. Connect a load resistor (R_1) to the DC Motor/Generator as shown in Figure 1-17. Use the Resistive Load module to implement resistor R_1. The resistance value to be used for this resistor depends on your local ac power network voltage and frequency (see table in the diagram). Leave all other connections unchanged.

Appendix C of this manual lists the switch settings and connections to be performed on the Resistive Load module in order to obtain various resistance values.



Local ac power network		R_1 (Ω)
Voltage (V)	**Frequency (Hz)**	
120	60	150
220	50	550
240	50	600
220	60	550

Figure 1-17. Prime mover coupled to the DC Motor/Generator (with an electrical load).

38. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

– Set the *Function* parameter to *CW Constant-Speed Prime Mover/Brake*.

– Make sure that the *Speed Control* parameter is set to *Knob*.

– Set the *Speed* parameter to 1500 r/min.

39. In the Four-Quadrant Dynamometer/Power Supply window, start the *CW Constant-Speed Prime Mover/Brake* to make the DC Motor/Generator rotate.

Turn the Power Supply on by setting the main power switch to the I (on) position.

40. On the DC Motor/Generator, slightly readjust the *Field Rheostat* knob, if necessary, so that the field current I_f (indicated by meter *I1* in the Metering window) is equal to the value indicated in Table 1-1 for your local ac power network.

41. What is the polarity of the torque T produced by the DC Motor/Generator?

___

What is the polarity of the DC Motor/Generator speed n?

___

Are the speed and torque of opposite polarity?

❑ Yes ❑ No

42. Is the polarity of the motor mechanical power negative?

❑ Yes ❑ No

Does this confirm that the DC Motor/Generator currently operates as a generator? Explain.

___

43. On the Power Supply, set the main power switch to the O (off) position. In the Four-Quadrant Dynamometer/Power Supply window, stop the *CW Constant-Speed Prime Mover/Brake*, then make the following setting:

– Set the *Function* parameter to *CCW Constant-Speed Prime Mover/Brake*.

– Make sure that the *Speed Control* parameter is set to *Knob*.

– Set the *Speed* parameter to −1500 r/min.

– Start the *CCW Constant-Speed Prime Mover/Brake* to make the DC Motor/Generator rotate.

44. On the Power Supply, set the main power switch to the I (on) position. What is the polarity of the torque T produced by the DC Motor/Generator?

____

What is the polarity of the DC Motor/Generator speed n?

____

Are the speed and torque of opposite polarity?

❑ Yes ❑ No

45. Is the polarity of the motor mechanical power P_m negative?

❑ Yes ❑ No

Does this confirm that the DC Motor/Generator currently operates as a generator?

❑ Yes ❑ No

46. On the Power Supply, set the main power switch to the O (off) position. In the Four-Quadrant Dynamometer/Power Supply window, stop the *CCW Constant-Speed Prime Mover/Brake* by setting the *Status* parameter to *Stopped* or by clicking the *Start/Stop* button.

47. From your observations, does the direction of rotation determine the polarity of the generator speed n and torque T? Explain.

____

____

____

Can the DC Motor/Generator operate as a generator in either direction of rotation (clockwise or counterclockwise)?

❑ Yes ❑ No

48. On the Power Supply, set the voltage control knob to 0%. Turn the 24 V ac power source of the Power Supply off. Close the LVDAC-EMS software. Disconnect all leads and return them to their storage location.

Conclusion

In this exercise, you familiarized yourself with the basic functions of the Four-Quadrant Dynamometer/Power Supply used in this manual. You observed the polarity of the speed, torque, and mechanical power for a rotating machine operating either as a motor or a generator.

Review Questions

1. What is the power P of a motor rotating at a speed n of 2000 r/min and producing a torque T of 1.2 N·m (10.6 lbf·in)?

2. Briefly describe a brake and a prime mover.

3. Briefly describe the energy conversion occurring in a motor, as well as the energy conversion occurring in a generator.

4. Consider a motor rotating in the clockwise direction that is coupled to a brake applying a load torque to the motor. Determine the polarity of the motor speed and torque, as well as the polarity of the braking torque. Also, determine the polarity of the motor mechanical power.

5. Consider a prime mover making a generator rotate in the clockwise direction. Determine the polarity of the prime mover torque, as well as the polarity of the generator speed and torque. Also, determine the polarity of the generator mechanical power.

Unit Test

1. A force F of 12.0 N (2.70 lbf·in) is applied on a pulley having a diameter of 5 cm (1.97 in). Determine the work W that is done when the pulley rotates ten complete turns.

   a. 1.88 J (16.6 lbf·in)
   b. 3.77 J (33.4 lbf·in)
   c. 18.8 J (167 lbf·in)
   d. 37.7 J (334 lbf·in)

2. A moving loop of wire passes through a magnetic field. Given that the magnetic flux Φ linking the loop rises from 0 mWb to 280 mWb in 0.05 s as the loop passes through the magnetic field, determine the voltage E induced across the loop of wire.

   a. $E = 14.0$ V
   b. $E = 5.60$ V
   c. $E = 28.0$ V
   d. $E = 11.2$ V

3. The motor of a water pump produces a torque T of 10 N·m (88.5 lbf·in). How much work is done by the pump motor if it rotates at a speed of 3000 r/min during 10 minutes?

   a. 188 kJ ($1.67 \cdot 10^6$ lbf·in)
   b. 1.88 MJ ($16.7 \cdot 10^6$ lbf·in)
   c. 314 kJ ($3.34 \cdot 10^6$ lbf·in)
   d. 3.14 kJ ($33.4 \cdot 10^6$ lbf·in)

4. Knowing that a motor has a power P of 300 W, calculate the torque T that the motor must produce in order to rotate at a speed n of 1600 r/min?

   a. $T = 1.79$ N·m (15.8 lbf·in)
   b. $T = 2.50$ N·m (22.1 lbf·in)
   c. $T = 5.33$ N·m (47.2 lbf·in)
   d. $T = 4.14$ N·m (36.6 lbf·in)

5. A two-quadrant, constant-torque brake is mainly used to

   a. study the operation of a generator.
   b. supply electrical power to a rotating machine.
   c. drive a rotating machine at a specified speed.
   d. apply load torque to a rotating machine.

6. A constant-speed prime mover is mainly used to

   a. study the operation of a motor.
   b. supply electrical power to a rotating machine.
   c. drive a rotating machine at a specified speed.
   d. apply load torque to a rotating machine.

7. The mechanical power produced by a motor is

   a. always positive.
   b. positive only when the motor rotates in the clockwise direction.
   c. always negative.
   d. positive only when the motor rotates in the counterclockwise direction.

8. The mechanical power produced by a generator is

   a. always positive.
   b. positive only when the generator rotates in the clockwise direction.
   c. always negative.
   d. positive only when the generator rotates in the counterclockwise direction.

9. When a motor rotates in the counterclockwise direction?

   a. the motor speed is of negative polarity, while the motor torque is of positive polarity.
   b. the motor speed and torque are of negative polarity.
   c. the motor speed is of positive polarity, while the motor torque is of negative polarity.
   d. the motor speed and torque are of positive polarity.

10. When a generator rotates in the clockwise direction?

   a. the generator speed is of negative polarity, while the generator torque is of positive polarity.
   b. the generator speed and torque are of negative polarity.
   c. the generator speed is of positive polarity, while the generator torque is of negative polarity.
   d. the generator speed and torque are of positive polarity.

DC Motors and Generators

UNIT OBJECTIVE

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

DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Operating principle of dc motors
- Operating principle of dc generators

DISCUSSION OF FUNDAMENTALS

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 shows 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 power source E_S is made through **brushes**. Note that the rotor of a dc motor is also referred to as the **armature**.

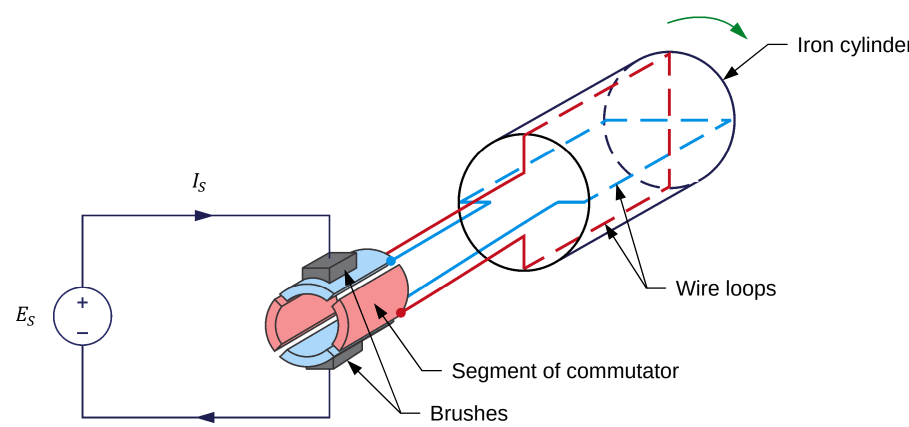


Figure 2-1. The main parts of a dc motor rotor (armature).

Figure 2-2 and Figure 2-3 show what happens to the magnetic field in the armature wire loops when the rotor of the dc motor in Figure 2-1 rotates. In Figure 2-2a, the brushes make contact with commutator segments A and B. Therefore, current flows from the dc power source to wire loop A-B via the brushes. No current flows in wire loop C-D. This creates an electromagnet A-B with north and south poles, as shown in Figure 2-2a. When the rotor is rotated clockwise a little as in Figure 2-2b, current still flows in wire loop A-B, and the north and south poles of the electromagnet are rotated clockwise.

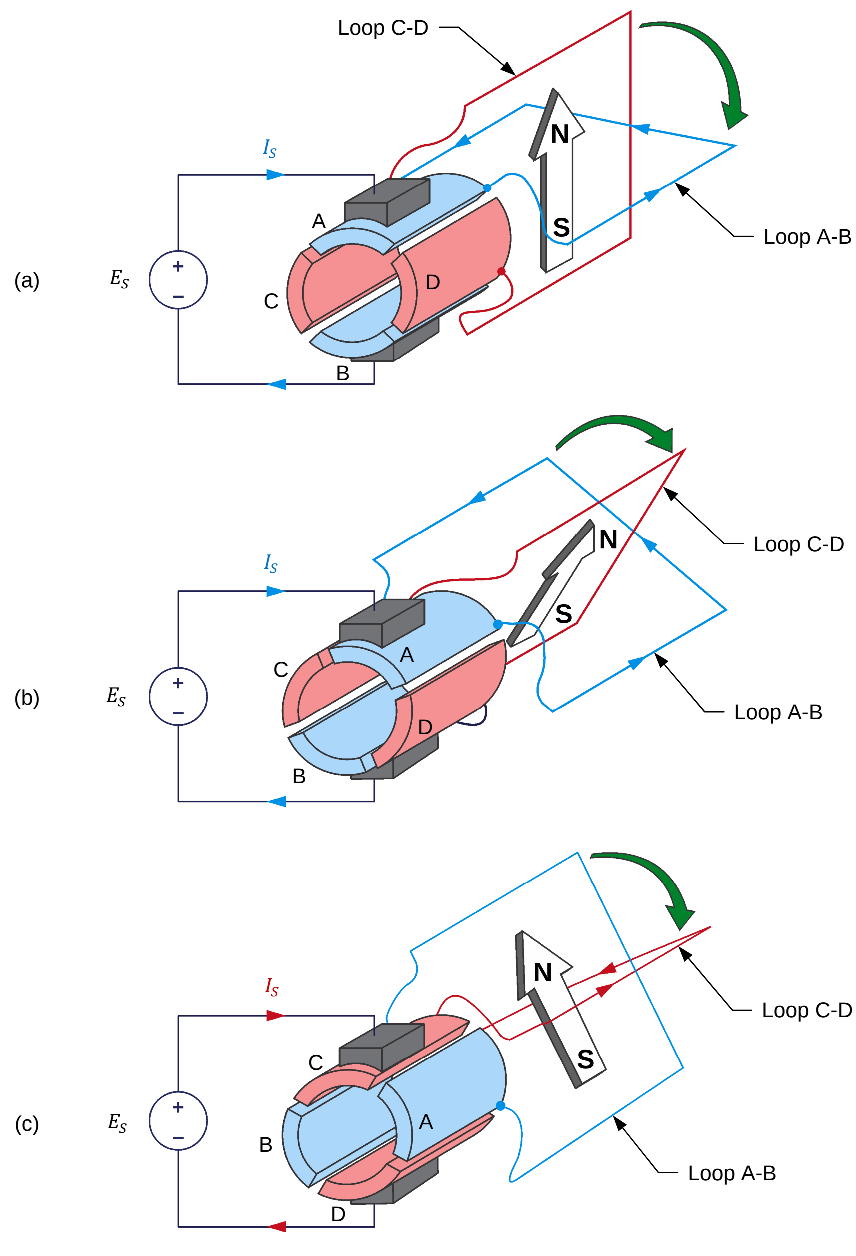


Figure 2-2. Magnetic field produced at the armature when the rotor rotates clockwise (part I).

As the rotor continues to rotate clockwise, the commutator slots pass by the brushes and a commutation occurs, i.e., the brushes stop making contact with commutator segments A and B and make contact with commutator segments C and D instead, as shown in Figure 2-2c. Consequently, current stops flowing in wire loop A-B and starts to flow in wire loop C-D. This creates an electromagnet C-D with north and south poles, as shown in Figure 2-2c.

A comparison of Figure 2-2b and Figure 2-2c shows that, at commutation, the north and south poles of the electromagnet are rotated 90° counterclockwise. As the rotor continues to rotate clockwise, the same phenomenon repeats every 90° rotation (i.e., at every commutation), as shown in Figure 2-3.

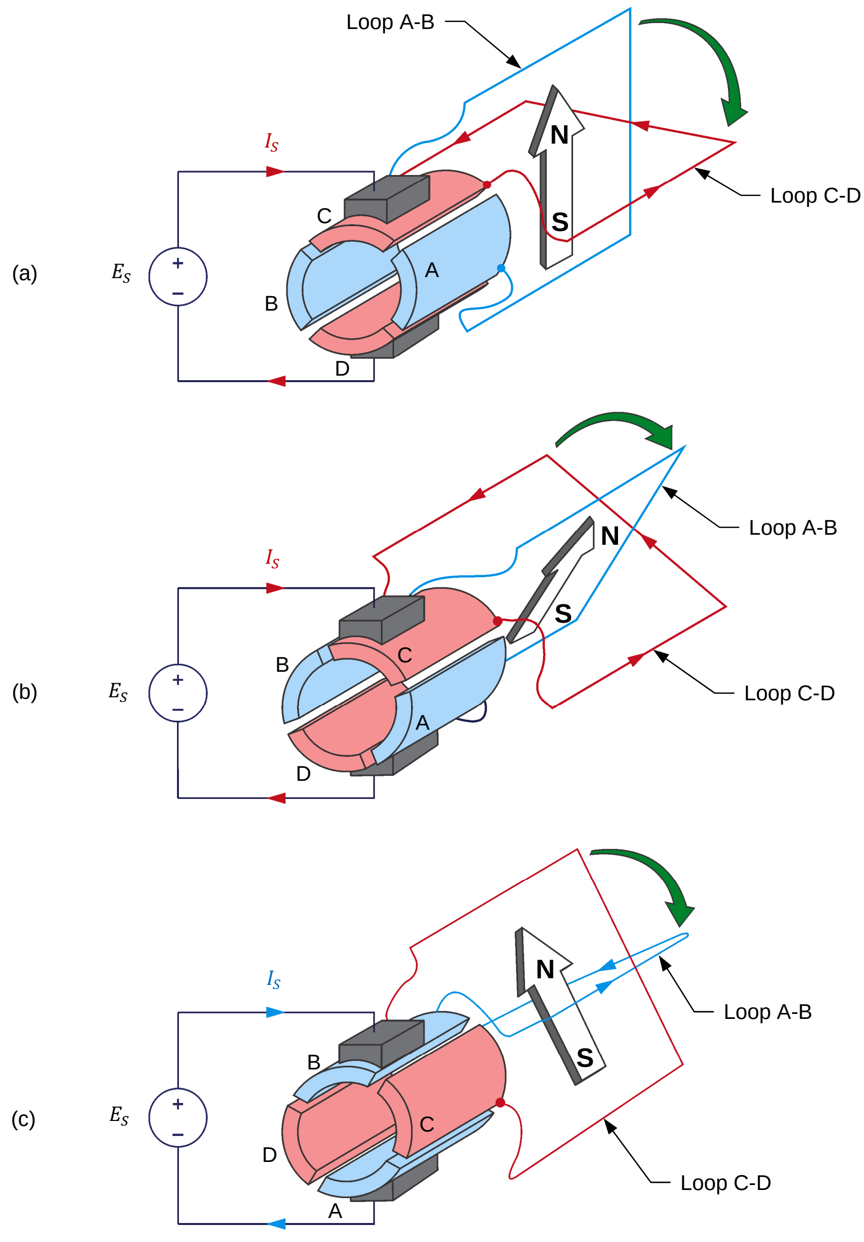


Figure 2-3. Magnetic field produced at the armature when the rotor rotates clockwise (part II).

In summary, as the rotor rotates, the north and south poles of the electromagnet go back and forth (oscillate) over a 90° angle, as Figure 2-4 shows. In other words, the north and south poles can be considered as stationary, i.e., they do not rotate as the rotor rotates. 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 thus, the lower the angle over which the north and south poles of the electromagnet oscillate. For example, if the commutator shown in Figure 2-1, Figure 2-2, and Figure 2-3 were having 32 segments instead of 4, the north and south poles would oscillate over an angle of only 11.25° instead of 90°.

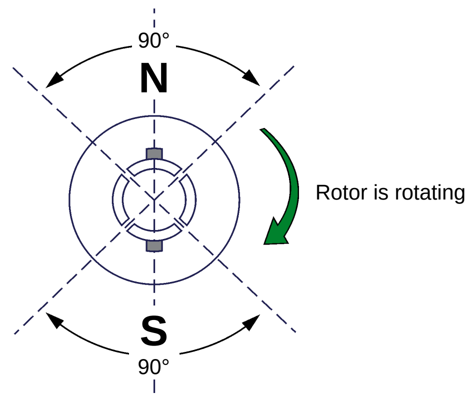


Figure 2-4. The north and south poles of the electromagnet at the armature oscillate around a fixed position.

When this rotor is placed next to a fixed permanent magnet **stator** as shown in Figure 2-5, the magnetic poles of opposite polarities attract each other (in order to align), while the magnetic poles of the same polarity repel each other, 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 to their initial location. Once again, the magnetic poles of opposite polarity attract each other (in order to align), while the magnetic poles of the same polarity repel each other, and the rotor starts to turn, and the rotor continues to rotate in the same direction. However, another commutation occurs a little after and the north and south poles of the electromagnet go back to their initial location 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 rotating machine converting electrical energy into mechanical energy, i.e. an electric motor, is achieved. The direction of rotation depends on the polarity of the voltage applied to the brushes of the rotor.

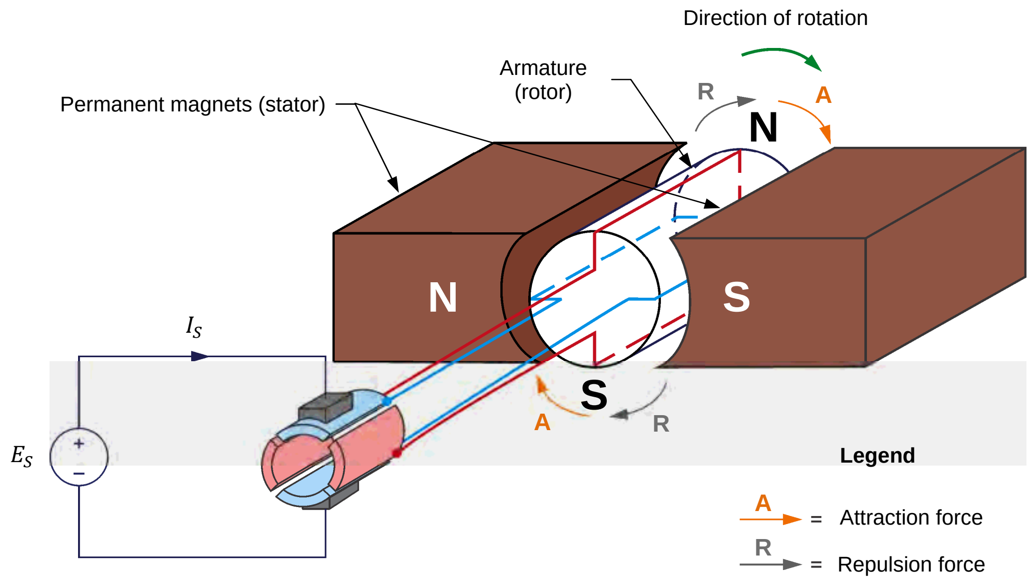


Figure 2-5. Rotation resulting from interaction of magnetic fields in the stator and the rotor.

Operating principle of dc generators

Previously, you saw that the variation of magnetic flux in a loop of wire causes a voltage to be induced across the ends of the loop. When a wire loop is placed between two magnets and rotated as shown in Figure 2-6, the magnetic flux ϕ that passes through the loop varies and a voltage, E_1, is induced across the loop terminals. Voltage E_1 is collected by the two commutator segments and delivered to stationary brushes (B+ and B-) connected to the generator terminals.

- As the loop passes from position 0 to position 4, the magnetic flux ϕ in the loop passes from a negative maximum (maximum flux passing from the A side to the B side of the loop) to a positive maximum (maximum flux passing from the B side to the A side of the loop). During this 180° interval of rotation, the voltage E_1 induced across the loop has a positive polarity because the rate of change $\frac{\Delta\phi}{\Delta t}$ of the magnetic flux has a positive value.

- When the loop reaches position 4, the connections of the two commutator segments to brushes B- and B+ are reversed. Consequently, this reverses the connections between the wire loop terminals and the generator terminals.

- As the loop passes from position 4 to position 0, the magnetic flux ϕ in the loop passes from a positive maximum (maximum flux passing from the B side to the A side of the loop) to a negative maximum (maximum flux passing from the A side to the B side of the loop). During this 180° interval of rotation, the voltage E_1 induced across the loop has a negative polarity because the rate of change $\frac{\Delta\phi}{\Delta t}$ of the magnetic flux has a negative value.

- When the loop reaches position 0, the connections of the two commutator segments to brushes B- and B+ are reversed again, thereby reversing the connections between the wire loop terminals and the generator terminals.

This cycle repeats as long as the rotor continues to rotate, so that the polarity of the voltage E_1 generated across the rotor wire loop continually alternates: it is positive for half a turn, then negative for the next half turn, then positive for the next half turn, and so on. Because of this, the voltage E_1 generated across the rotor wire loop is referred to as an alternating-current (ac) voltage. Because the commutator reverses the connections between the wire loop terminals and the generator terminals at wire loop positions 0 and 4, the voltage E_2 at the generator terminals always has the same polarity (positive), as is shown in Figure 2-6. The voltage E_2 at the generator terminals is thus a pulsating positive direct current (dc) voltage (two pulses per rotation).

The faster the speed of rotation of the rotor, the higher the rate of change of the magnetic flux ϕ passing through the wire loop, and therefore, the higher the voltage E_2 at the generator terminals. Also, the stronger the magnetic field of the permanent magnet, the higher the intensity of the magnetic flux, and therefore, the higher the voltage E_2 at the generator terminals.

In Figure 2-6, the A side of the wire loop designates the plane of the loop viewed from the north (N) pole, while the B side of the wire loop designates the plane of the loop viewed from the south (S) pole.

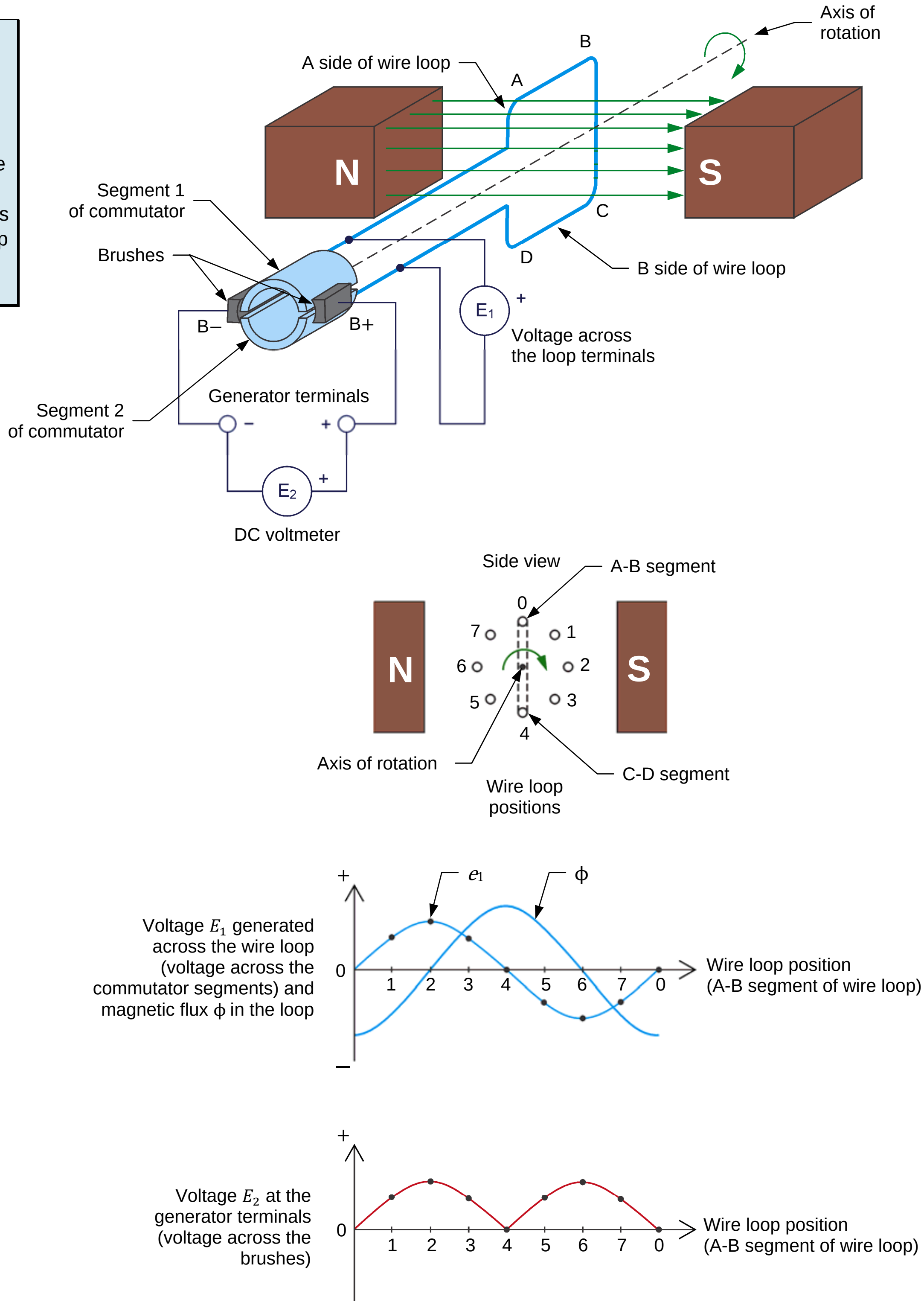


Figure 2-6. A wire loop rotating in a magnetic field results in an induced voltage (clockwise rotation).

When the direction of rotation of the wire loop is reversed, the polarity of the dc voltage E_2 at the generator terminals also reverses, as Figure 2-7 shows. The voltage E_2 at the generator terminals is thus a pulsating negative dc voltage (two pulses per rotation).

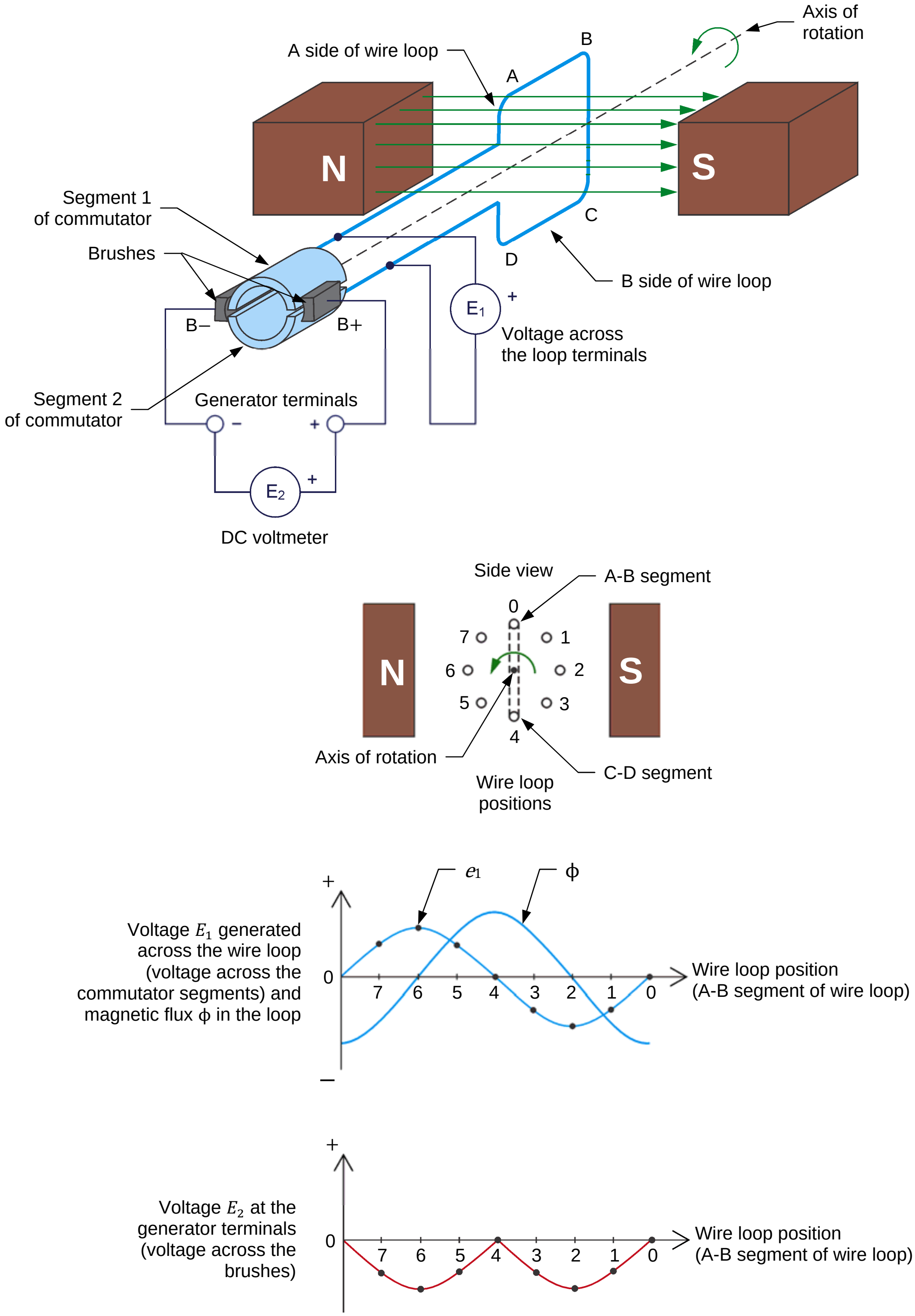


Figure 2-7. When the direction of rotation of the wire loop is reversed, the polarity of the dc voltage at the generator terminals also reverses.

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.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Simplified equivalent circuit of a dc motor
- Relationship between the motor rotation speed and the armature voltage when the armature current is constant
- Relationship between the motor torque and the armature current
- Relationship between the motor rotation speed and the armature voltage when the armature current varies

DISCUSSION

Simplified equivalent circuit of a dc motor

Previously, you saw that a dc motor is made up of a fixed magnet (stator) and a rotating magnet (rotor). Many dc motors use an electromagnet at the stator, as Figure 2-8 shows.

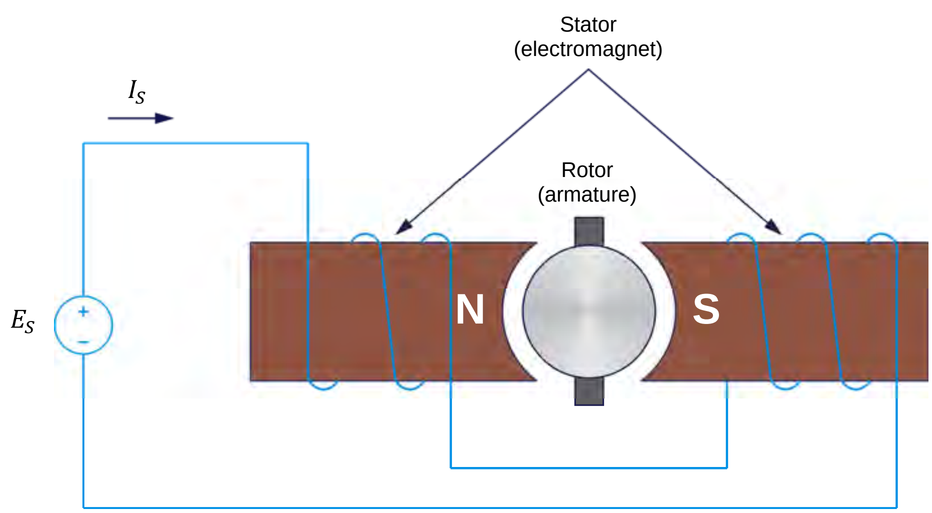


Figure 2-8. Simplified dc motor using an electromagnet as stator.

When power for the stator electromagnet is supplied by a separate dc source, of either fixed or variable voltage, 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 behavior of the dc motor can be understood by examining its simplified equivalent electric circuit shown in Figure 2-9.

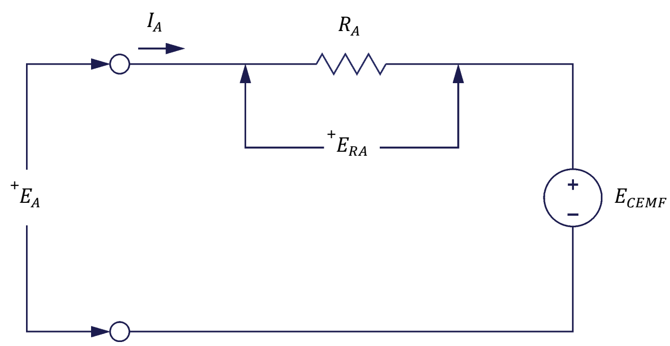


Figure 2-9. Simplified equivalent circuit of a dc motor.

In the circuit, E_A is the voltage applied to the motor brushes, I_A is the current flowing in the armature 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 2-9. The motor also develops a torque T proportional to the armature current I_A flowing in the motor. The motor behavior is based on the two equations given below. Equation (2-1) relates motor speed n and the induced voltage E_{CEMF}. Equation (2-2) relates the motor torque T and the armature current I_A.

$$n = \mathrm{K}_1 \cdot E_{CEMF} \tag{2-1}$$

where n is the motor rotation speed, expressed in revolutions per minute (r/min).

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

E_{CEMF} is the voltage induced across the armature, expressed in volts (V).

$$T = \mathrm{K}_2 \cdot I_A \tag{2-2}$$

where T is the motor torque, expressed in newton-meters (N·m) or in pound-force inches (lbf·in).

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

I_A is the armature current, expressed in amperes (A).

Relationship between the motor rotation speed and the armature voltage when the armature current is constant

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 2-9 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 rotation speed n and the armature voltage E_A is a straight line because E_{CEMF} is proportional to the motor rotation speed n. This linear relationship is shown in Figure 2-10. The slope of the straight line equals constant K_1.

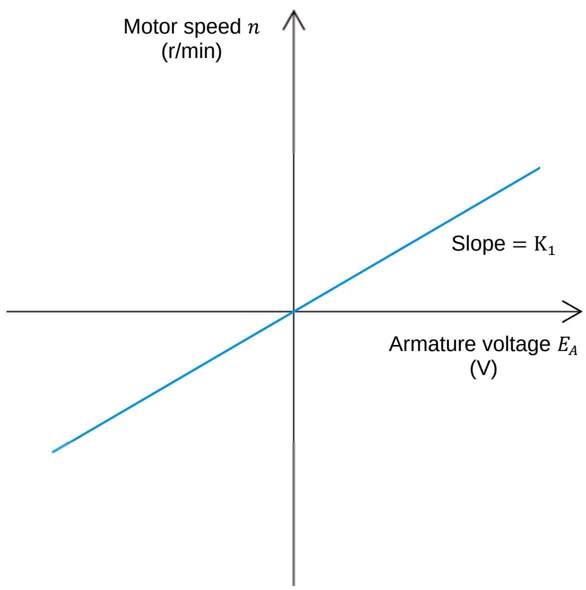


Figure 2-10. Linear relationship between the motor rotation speed and the armature voltage.

Since the relationship between voltage E_A and the rotation speed n is linear, a dc motor can be considered to be a linear voltage-to-speed converter, as shown in Figure 2-11.

Figure 2-11. DC motor as a voltage-to-speed converter.

Relationship between the motor torque and the armature current

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 2-12 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. The linear current-to-torque converter is shown in Figure 2-13.

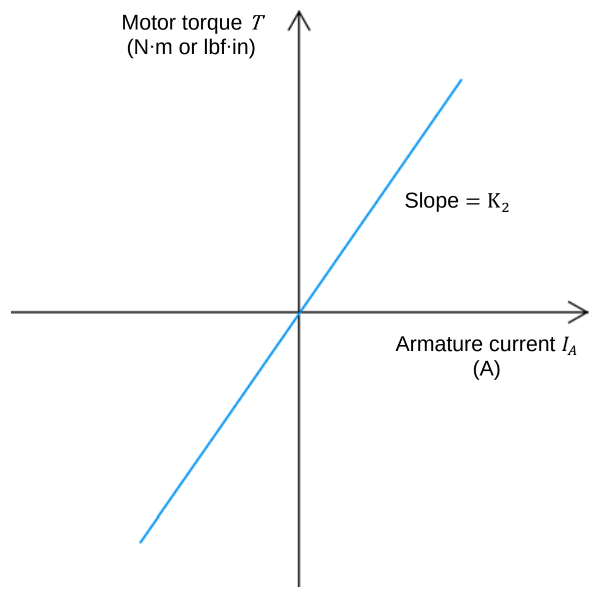


Figure 2-12. Linear relationship between the motor torque and the armature current.

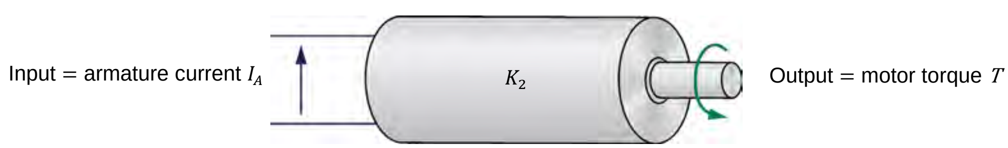


Figure 2-13. DC motor as a current-to-torque converter.

Relationship between the motor rotation speed and the armature voltage when the armature current varies

When the armature current I_A increases, the voltage drop E_{RA} $(R_A \cdot I_A)$ 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 equal to E_{CEMF}, but rather the sum of E_{CEMF} and E_{RA}, as Equation (2-3) shows:

$$E_A = E_{CEMF} + E_{RA} \qquad (2\text{-}3)$$

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 rotation speed n to decrease because it is proportional to E_{CEMF}. This is shown in Figure 2-14, which is a graph of the motor rotation speed n versus the armature current I_A for a fixed armature voltage E_A.

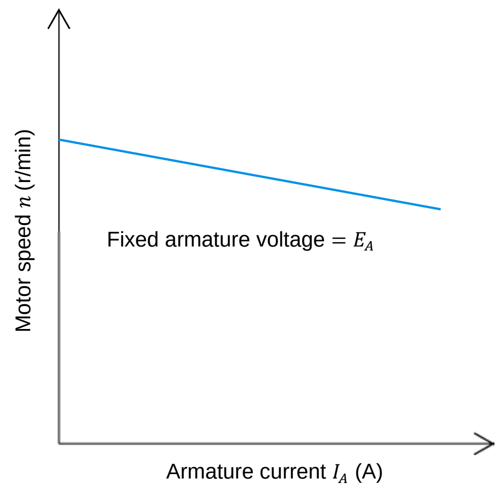


Figure 2-14. The motor rotation speed drops as the armature current increases (fixed armature voltage E_A).

Figure 2-15. Example of a separately-excited dc motor used in a racing kart.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Determining the armature resistance
- Motor speed versus armature voltage
- Motor torque versus armature current
- Speed decrease versus armature current
- Additional experiments (optional)
  Motor speed-versus-armature voltage and motor torque-versus-armature current characteristics for reversed armature connections.

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.

Set up and connections

In this section, you will mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply and set up the equipment.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the exercise. Install the equipment in the Workstation.

   Before performing the exercise, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect a variable-voltage 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 and Control Interface (DACI). Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to voltage input E1 of the DACI. In LVDAC-EMS, open the Metering window. Set two meters to measure the rms values (ac) of the armature voltage E_A and armature current I_A at inputs E1 and I1 of the DACI, respectively. Turn the Power Supply on and adjust its voltage control knob so that an ac current (indicated by meter I1 in the Metering window) equal to half the nominal 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 E1 in the Metering window) is minimal. Turn the Power Supply off, close LVDAC-EMS, and disconnect all leads and cable.

   Mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

WARNING

Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

2. Make sure that the main power switch of the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power wall outlet.

3. On the Power Supply, make sure that the main power switch and the 24 V ac power switch are set to the O (off) position, and that the voltage control knob is set to 0% (turned fully counterclockwise). Connect the Power Supply to a three-phase ac power outlet.

4. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24 V ac power source of the Power Supply.

   Turn the 24 V ac power source of the Power Supply on.

5. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

   Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

6. Connect the equipment as shown in Figure 2-16. Use the variable dc voltage output of the Power Supply to implement the variable-voltage dc power source E_S. Use the fixed dc voltage output of the Power Supply to implement the fixed-voltage dc power source. *E1*, *I1* and *I2* are voltage and current inputs of the Data Acquisition and Control Interface (DACI). Leave the circuit open at points A and B shown in the figure.

7. On the Four-Quadrant Dynamometer/Power Supply, set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

   Turn the Four-Quadrant Dynamometer/Power Supply on by setting the main power switch to the I (on) position.

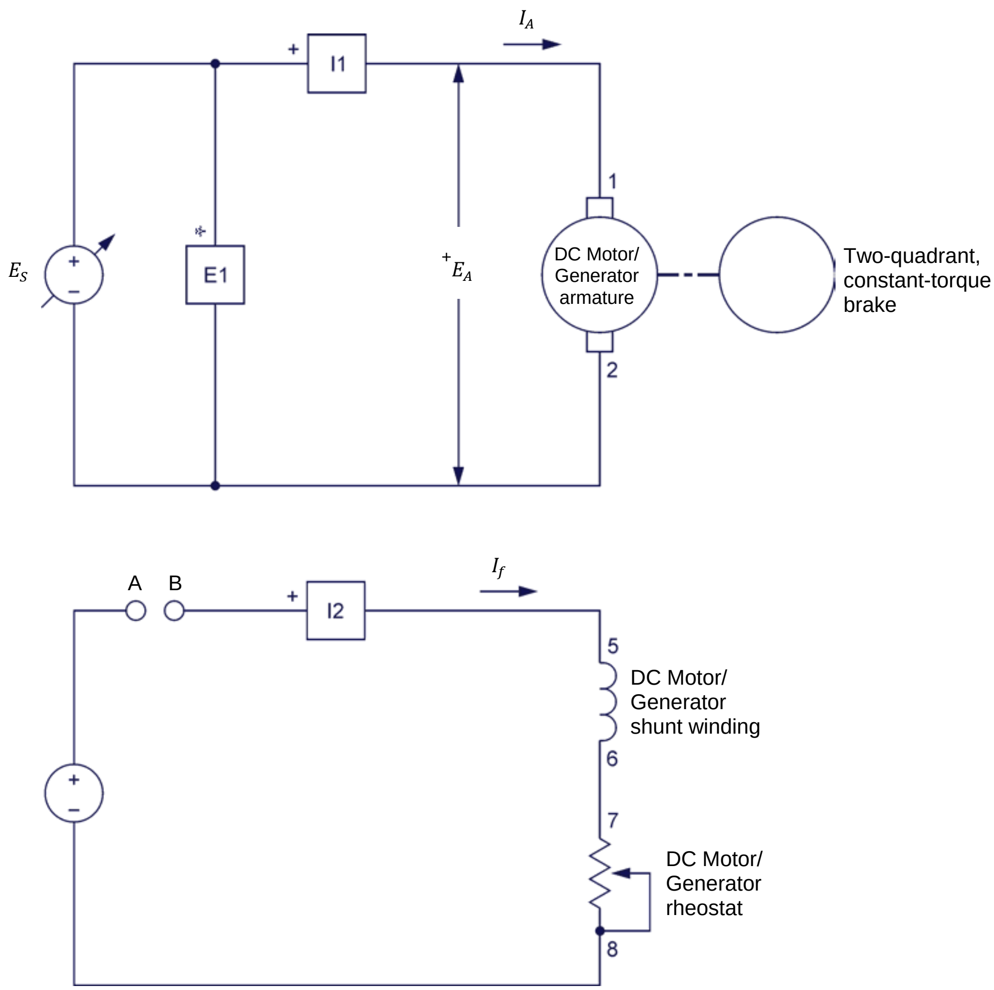


Figure 2-16. Separately-excited dc motor coupled to a brake.

8. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure that the *Computer-Based Instrumentation* function is available for the Data Acquisition and Control Interface module. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

9. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

– Set the *Function* parameter to *Two-Quadrant, Constant-Torque Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a two-quadrant brake with a torque setting corresponding to the *Torque* parameter.

– Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test (i.e., the DC Motor/Generator), respectively.

– Make sure that the *Torque Control* parameter is set to *Knob*. This allows the torque of the two-quadrant brake to be controlled manually.

– Set the *Torque* parameter to the maximum value (3.0 N·m or 26.5 lbf·in). This sets the torque command of the *Two-Quadrant, Constant-Torque Brake* to 3.0 N·m (26.5 lbf·in).

The torque command can also be set by using the Torque control knob in the Four-Quadrant Dynamometer/Power Supply window.

– Start the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

10. In LVDAC-EMS, open the Metering window. Set two meters to measure the dc motor armature voltage E_A (*E1*) and armature current I_A (*I1*). Set a meter to measure the dc motor armature resistance R_A [*RDC (E1, I1)*]. Finally, set a meter to measure the dc motor field current I_f (*I2*).

Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the Metering application.

Determining the armature resistance

In this section, you will measure the armature resistance R_A of the DC Motor/Generator. It is not possible to measure the armature resistance R_A of the DC Motor/Generator with a conventional ohmmeter because the non-linear characteristic of the motor brushes causes incorrect results when the armature current I_A is too low. The general method used to measure R_A consists in connecting a dc power source to the motor armature and measuring the voltage required to make nominal current flow in the armature windings. No power source is connected to the motor stator to ensure that the motor does not rotate, and that 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 rotating because it is mechanically loaded.

11. Turn the Power Supply on by setting the main power switch to the I (on) position. Set the voltage control knob of the Power Supply so that the armature current I_A (indicated by meter *I1* in the Metering window) flowing in the DC Motor/Generator is equal to the rated armature current.

The rating of any of the supplied machines is indicated in the lower section of the module front panel.

Record the value of the armature resistance R_A [indicated by meter *RDC (E1, I1)* in the Metering window].

Armature resistance R_A = _______ Ω

12. On the Power Supply, set the voltage control knob to 0%, then set the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on.)

Interconnect points A and B in the circuit of Figure 2-16.

Motor speed versus armature voltage

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

13. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the dc motor rotation speed n and torque T (indicated by the *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply window), as well as the dc motor armature voltage E_A, armature current I_A, and field current I_f (indicated by meters *E1*, *I1*, and *I2* in the Metering window).

14. In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.0 N·m (or 0.0 lbf·in).

15. Turn the Power Supply on by setting the main power switch to the I (on) position.

On the DC Motor/Generator, set the *Field Rheostat* knob so that the field current I_f (indicated by meter *I2* in the Metering window) is equal to the value indicated in Table 2-1 for your local ac power network.

Table 2-1. Field current I_f.

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

16. On the Power Supply, vary the voltage control knob setting from 0% to 100% in 10% steps in order to increase the armature voltage E_A by steps. For each setting, wait until the motor speed stabilizes, then record the motor armature voltage E_A, armature current I_A, and field current I_f, as well as the motor rotation speed n and torque T in the Data Table.

17. When all data has been recorded, stop the DC Motor/Generator by setting the voltage control knob to 0% and the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on.)

In the Data Table window, confirm that the data has been stored, save the data table under filename DT211, and print the data table if desired.

18. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed n as a function of the armature voltage E_A. Name the graph “G211”, name the x-axis “Armature voltage”, name the y-axis “Motor speed”, and print the graph if desired.

What kind of relationship exists between the armature voltage E_A and 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

19. 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.

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

20. In the Data Table window, clear the recorded data.

Motor torque versus armature current

In this section, you will measure data and plot a graph of the separately-excited dc motor torque T as a function of the armature current I_A to demonstrate that the motor torque is proportional to the armature current.

21. In the Four-Quadrant Dynamometer/Power Supply window, make sure that the *Torque* parameter is set to 0.0 N·m (0.0 lbf·in).

22. Turn the Power Supply on by setting the main power switch to the I (on) position.

    On the DC Motor/Generator, slightly readjust the *Field Rheostat* knob, if necessary, so that the field current I_f (indicated by meter *I2* in the Metering window) is equal to the value indicated in Table 2-1 for your local ac power network.

    On the Power Supply, set the voltage control knob so that the motor rotation speed n is 1500 r/min. Note and record the value of the motor armature voltage E_A (*E1*).

    Armature voltage E_A $(n = 1500\ \text{r/min}) =$ _______ V

    Note and record the value of the motor torque T indicated by the *Torque* meter in the Four-Quadrant Dynamometer/Power Supply.

    Motor torque T (minimum) = _______ N·m (lbf·in)

23. In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to the minimum value measured in step 22. Record the motor rotation speed n and torque T, as well as the motor armature voltage E_A, armature current I_A, and field current I_f in the Data Table.

    Increase the *Torque* parameter from the minimum value to about 1.9 N·m (about 16.8 lbf·in) if your local ac power network voltage is 120 V, or from the minimum value to about 2.3 N·m (about 20.4 lbf·in) if your local ac power network voltage is 220 V or 240 V, in steps of 0.2 N·m (or 2.0 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 step 22, readjust the field current I_f to the value given in Table 2-1, then record the motor rotation speed n and torque T, as well as the motor armature voltage E_A, armature current I_A, and field current I_f in the Data Table.

CAUTION

The armature current I_A will exceed the rated value while performing this manipulation. Therefore, perform this manipulation in less than 5 minutes.

24. When all data has been recorded, stop the DC Motor/Generator by setting the voltage control knob to 0% and the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.0 N·m (0.0 lbf·in).

In the Data Table window, confirm that the data has been stored, save the data table under filename DT212, and print the data table if desired.

25. In the Graph window, make the appropriate settings to obtain a graph of the dc motor torque T as a function of the armature current I_A. Name the graph "G212", name the x-axis "Armature current", name the y-axis "Motor torque", and print the graph if desired.

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 I_A exceeds the nominal value because of a phenomenon called armature reaction. This phenomenon is described in the next unit of this manual.

26. 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.

$$\mathrm{K}_2 = \frac{T_2 - T_1}{I_2 - I_1} = \frac{\_\_\_\_ - \_\_\_\_}{\_\_\_\_ - \_\_\_\_} = \_\_\_\_ \ \frac{\mathrm{N \cdot m\ (lbf \cdot in)}}{\mathrm{A}}$$

Speed decrease versus armature current

In this section, 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.

27. Using the values determined previously for the armature resistance R_A (step 11), constant K_1 (step 19), and armature voltage E_A (step 22), calculate the motor rotation speed n for each of the three armature currents I_A given in Table 2-2 for your local ac power network.

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

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

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

Table 2-2. DC motor armature currents I_A.

Local ac power network		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
240	50	0.5	1.0	1.5
220	60	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 voltage E_{CEMF} and the dc motor speed n vary as the armature current I_A is increased?

28. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed n as a function of the armature current I_A, using the data recorded previously in data table DT212. Name the graph “G212-1”, name the x-axis “Armature current”, name the y-axis “Motor speed”, and print the graph if desired.

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

❑ Yes ❑ No

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

29. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed n as a function of the dc motor torque T using the data recorded previously in data table DT212. Name the graph “G212-2”, name the x-axis “Motor torque”, name the y-axis “Motor speed”, and print the graph. This graph will be used in the next exercise of this unit.

If you want to perform the additional experiments, skip the next step, then return to it when all additional manipulations are finished.

30. On the Power Supply, make sure that the main power switch is set to the O (off) position, then turn the 24 V ac power source off. Close the LVDAC-EMS software. Turn the Four-Quadrant Dynamometer/Power Supply off. Disconnect all leads and return them to their storage location.

Additional experiments (optional)

Motor speed-versus-armature voltage and motor torque-versus-armature current characteristics for reversed armature connections

You can obtain graphs of the dc motor speed n as a function of the armature voltage E_A, and dc motor torque T as a function of the armature current I_A, with reversed armature connections. To do so, make sure that the Power Supply is turned off [main power switch set to the O (off) position] and reverse the connections at the variable dc voltage output (voltage source E_S) in Figure 2-16. Make sure that the voltage control knob of the Power Supply is set to *0%*. Refer to steps 13 to 25 of this exercise to record the necessary data and obtain the graphs. This will allow you to verify that the linear relationships between the motor speed n and armature voltage E_A, and between the motor torque T and armature current I_A, are valid regardless of the polarity of the armature voltage E_A. 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 learned how to measure the armature resistance of a dc motor. You saw that the rotation 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 performed the additional experiments, you observed that the speed-versus-armature voltage and torque-versus-armature 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 rotation speed and armature voltage of a separately-excited dc motor?

   ____

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?

   ____

3. Connecting a dc power 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?

   ____

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

____

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?

____

____

Exercise 2-2

Separately-Excited, Series, Shunt, and Compound 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. You will also be able to demonstrate the main operating characteristics of series, shunt, and compound motors.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Separately-excited dc motor
- Series motor
- Shunt motor
- Compound motor

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 2-17 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 increases, while constant K_2 decreases. 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.

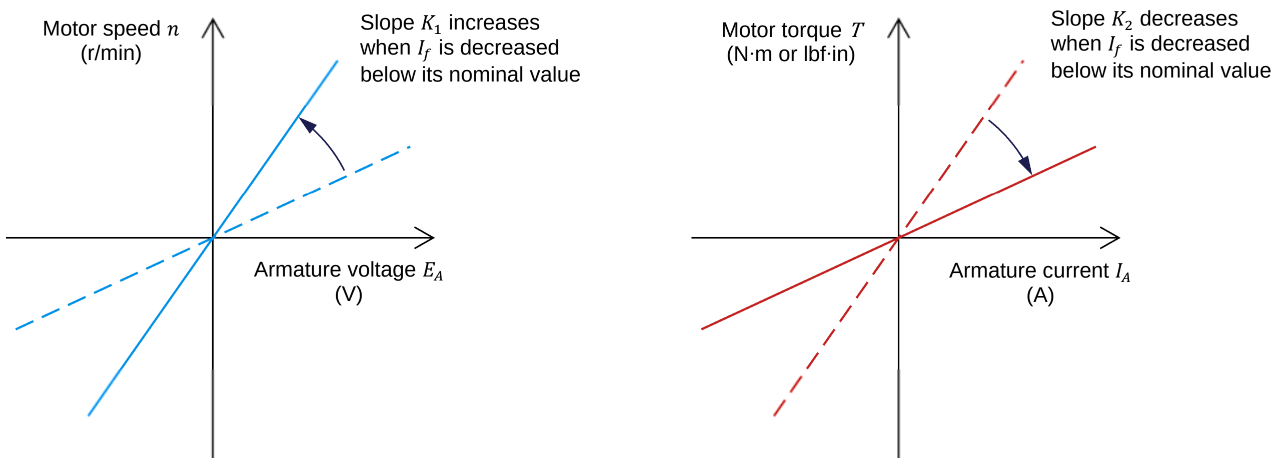


Figure 2-17. Decreasing current I_f below its nominal value affects constants K_1 and K_2.

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 decreases, while constant K_2 increases. 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 a 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, i.e., 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 power source. This was necessary when the first dc motors were in use, because variable-voltage dc power sources were not available at that time. 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 2-18. The strength of the field electromagnet, therefore, varies as the armature current varies. As a result, constants K_1 and K_2 vary when the armature current varies. Figure 2-18 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.

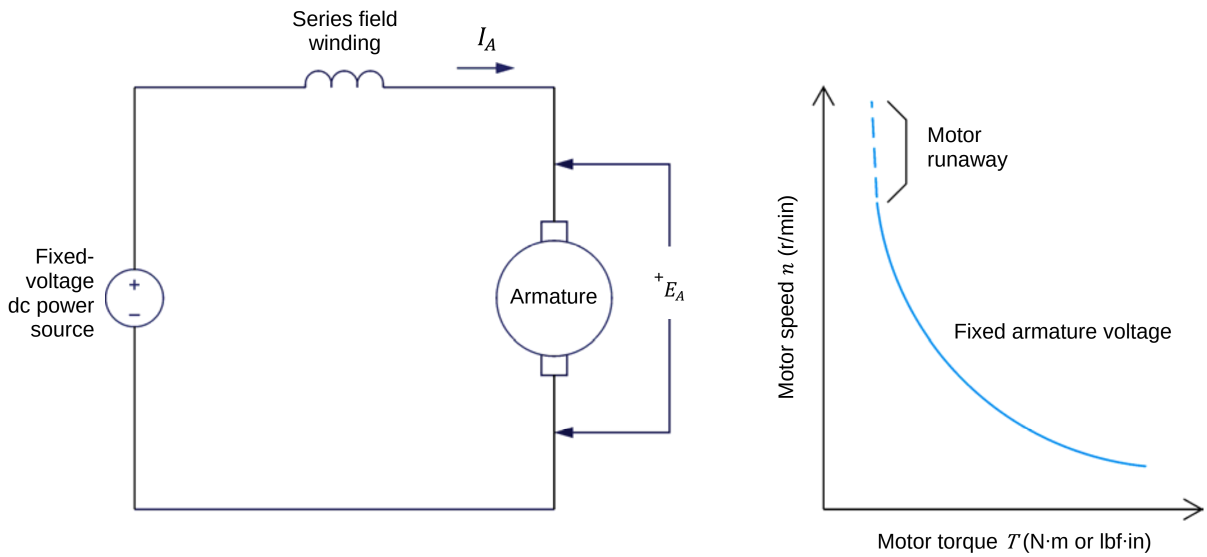


Figure 2-18. Series motor and its speed-versus-torque characteristic.

The series motor provides a strong starting torque and a wide range of operating speeds when it is powered by a fixed-voltage dc power 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 2-18. 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 with no 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 2-19. 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 power source, as shown in Figure 2-19. 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.

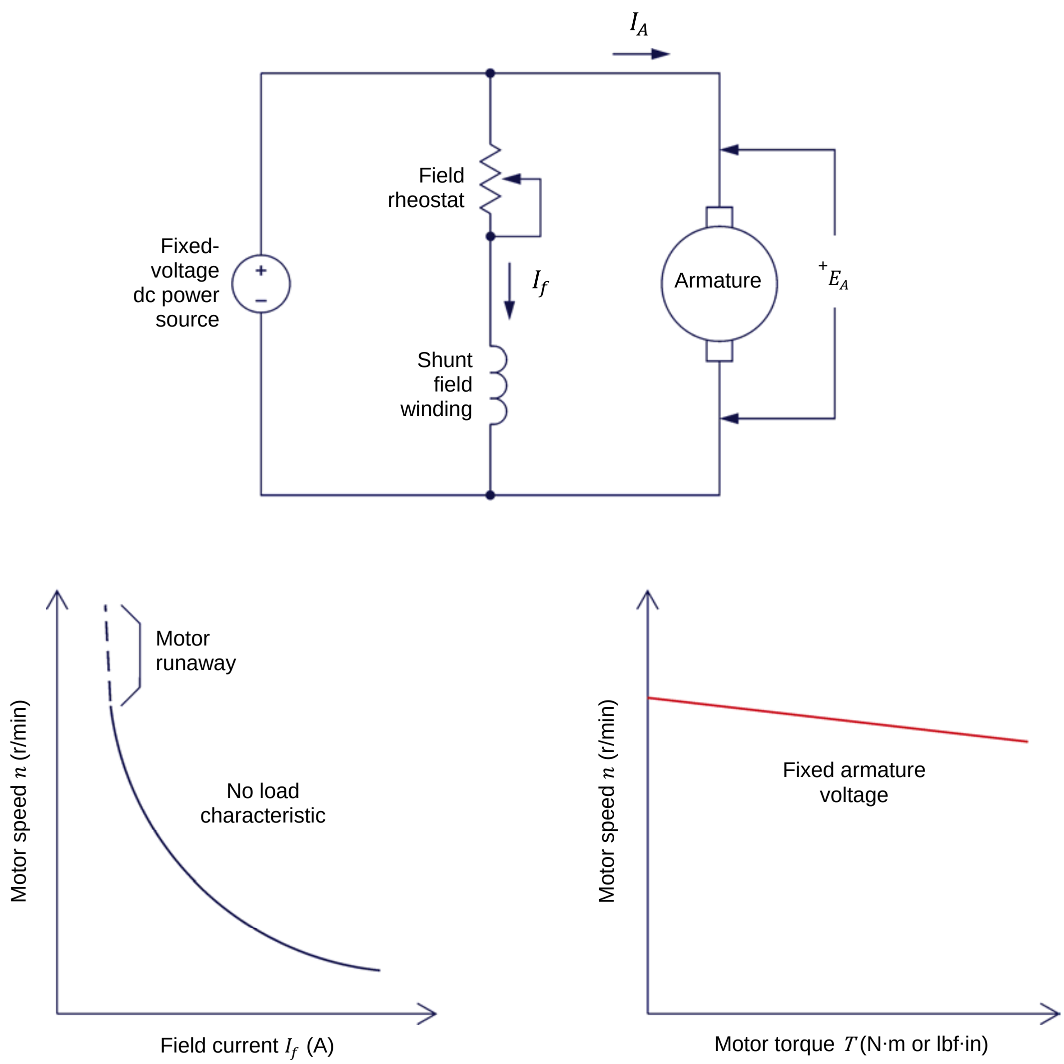


Figure 2-19. Shunt motor and its characteristics.

The main advantage of a shunt motor is the fact that only one fixed-voltage dc power source is required to supply power to both the armature and the shunt winding. Also, the motor 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 2-19.

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 2-20 shows a compound motor and its speed-versus-torque characteristic (cumulative compound).

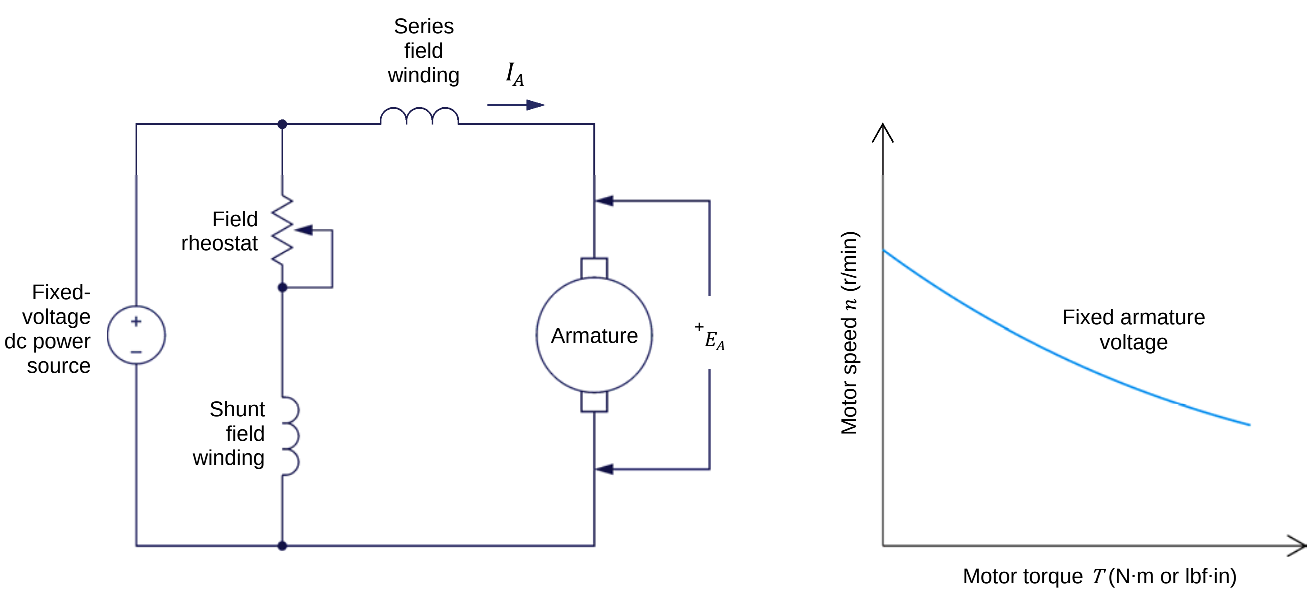


Figure 2-20. Compound motor and its speed-versus-torque characteristic.

Figure 2-21 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 non linear 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.

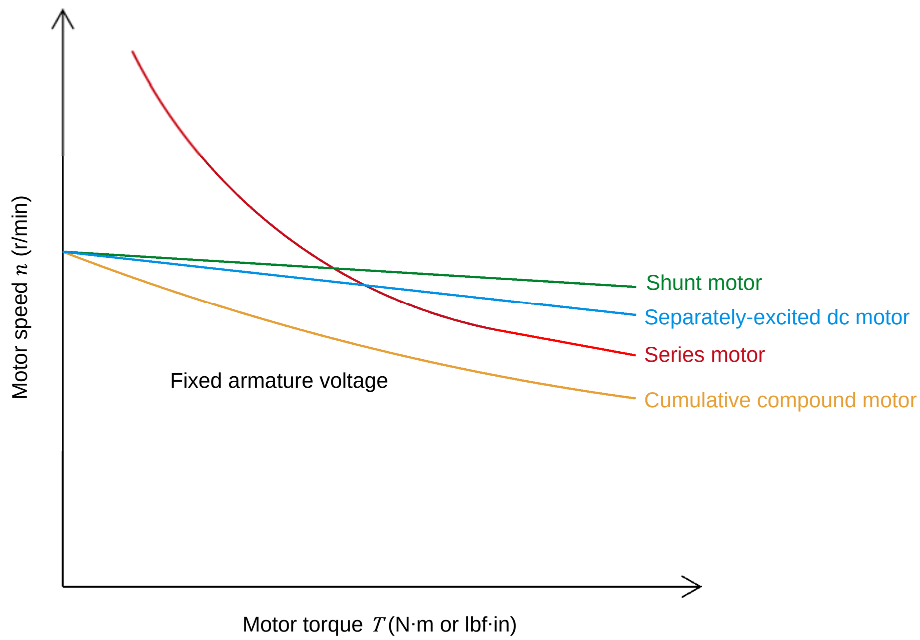


Figure 2-21. Speed-versus-torque characteristics of various dc motors.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Speed-versus-armature voltage characteristic of a separately-excited dc motor
- Torque-versus-armature current characteristic of a separately-excited dc motor
- Speed-versus-torque characteristic of a series motor
- Additional experiments (optional)
  Motor speed-versus-torque characteristic of a shunt motor. Motor speed-versus-torque characteristic of a cumulative compound motor.

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**.**

Set up and connections

In this section, you will mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply. You will then set up a separately-excited dc motor and the equipment required to measure the motor parameters.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the exercise. Install the equipment in the Workstation.

   Before performing the exercise, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect a variable-voltage 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 and Control Interface (DACI). Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to voltage input E1 of the DACI. In LVDAC-EMS, open the Metering window. Set two meters to measure the rms values (ac) of the armature voltage E_A and armature current I_A at inputs E1 and I1 of the DACI, respectively. Turn the Power Supply on and adjust its voltage control knob so that an ac current (indicated by meter I1 in the Metering window) equal to half the nominal 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 E1 in the Metering window) is minimal. Turn the Power Supply off, close LVDAC-EMS, and disconnect all leads and cable.

   Mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

   WARNING

   Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

2. Make sure that the main power switch of the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power wall outlet.

3. On the Power Supply, make sure that the main power switch and the 24 V ac power switch are set to the O (off) position, and that the voltage control knob is set to 0% (turned fully counterclockwise). Connect the Power Supply to a three-phase ac power outlet.

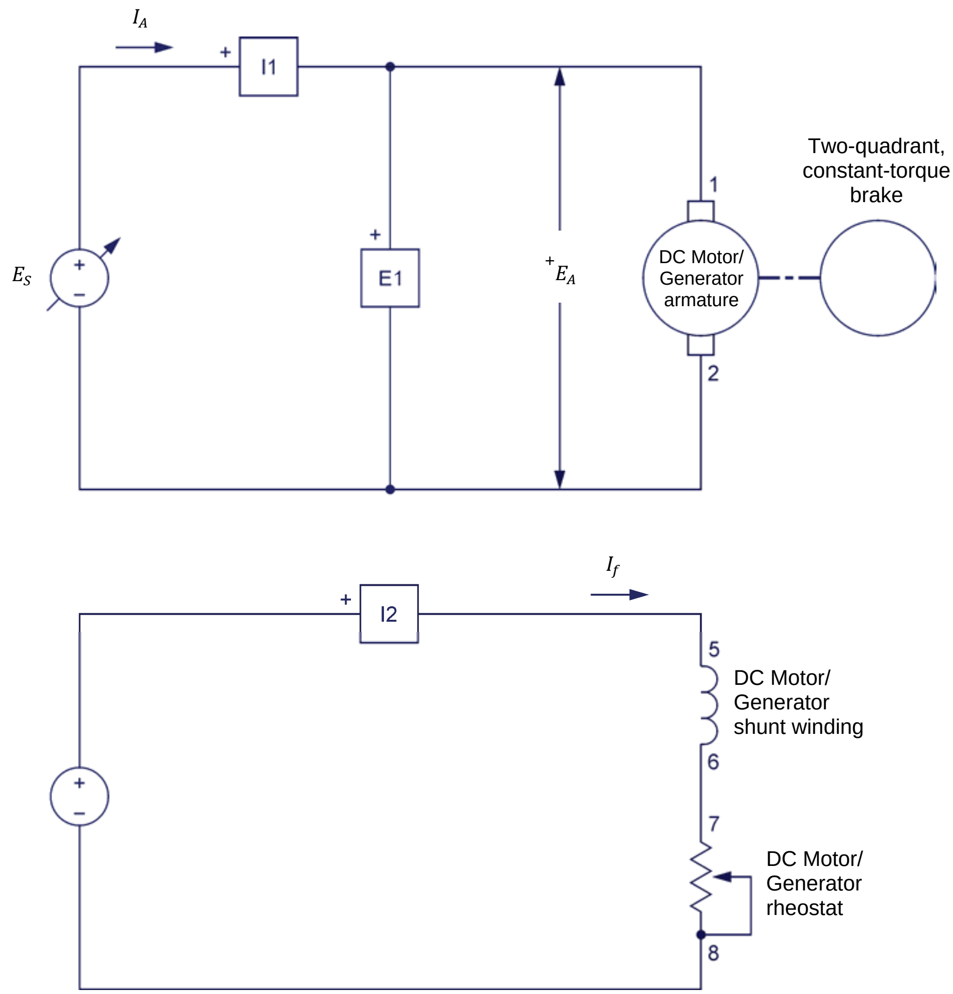
4. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24 V ac power source of the Power Supply.

   Turn the 24 V ac power source of the Power Supply on.

5. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

   Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

6. Connect the equipment as shown in Figure 2-22. (Note that this set up is the same as that used in the previous exercise). Use the variable dc voltage output of the Power Supply to implement the variable-voltage dc power source E_S. Use the fixed dc voltage output of the Power Supply to implement the fixed-voltage dc power source. *E1*, *I1* and *I2* are voltage and current inputs of the Data Acquisition and Control Interface (DACI).



* If your local ac power network voltage is 220 V, use the Resistive Load module to connect an 880-Ω resistor in series with the rheostat. If your local ac power network voltage is 240 V, connect a 960-Ω resistor in series with the rheostat. If your local ac power network voltage is 120 V, do not connect any resistor.

Figure 2-22. Separately-excited dc motor coupled to a brake.

7. On the Four-Quadrant Dynamometer/Power Supply, set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

   Turn the Four-Quadrant Dynamometer/Power Supply on by setting the main power switch to the I (on) position.

8. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure that the *Computer-Based Instrumentation* function is available for the Data Acquisition and Control Interface module. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

9. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

– Set the *Function* parameter to *Two-Quadrant, Constant-Torque Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a two-quadrant brake with a torque setting corresponding to the *Torque* parameter.

– Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test (i.e., the DC Motor/Generator), respectively.

– Make sure that the *Torque Control* parameter is set to *Knob*. This allows the torque of the two-quadrant brake to be controlled manually.

– Set the *Torque* parameter to 0.0 N·m (or 0.0 lbf·in).

The torque command can also be set by using the Torque control knob in the Four-Quadrant Dynamometer/Power Supply window.

– Start the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

10. In LVDAC-EMS, open the Metering window. Set two meters to measure the dc motor armature voltage E_A (*E1*) and armature current I_A (*I1*). Set a meter to meter to measure the dc motor field current I_f (*I2*).

Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the Metering application.

11. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the dc motor rotation speed n and torque T (indicated by the *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply window), as well as the dc motor armature voltage E_A, armature current I_A, and field current I_f (indicated by meters *E1*, *I1*, and *I2*, respectively, in the Metering window).

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

In this section, 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 also calculate the value of constant K_1. You will compare the value of constant K_1 and the graph with those obtained in the previous exercise to determine how decreasing the field current affects these characteristics.

12. Turn the Power Supply on by setting the main power switch to the I (on) position.

On the DC Motor/Generator, set the *Field Rheostat* knob so that the field current I_f (indicated by meter *I2* in the Metering window) is equal to the value indicated in Table 2-3 for your local ac power network.

Table 2-3. Field current I_f.

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

13. On the Power Supply, vary the voltage control knob setting from 0% to 100% in 10% steps in order to increase the armature voltage E_A by steps. For each setting, wait until the motor speed stabilizes, then record the motor armature voltage E_A, armature current I_A, and field current I_f, as well as the motor rotation speed n and torque T in the Data Table.

14. When all data has been recorded, stop the DC Motor/Generator by setting the voltage control knob to 0% and the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Data Table window, confirm that the data has been stored, save the data table under filename DT221, and print the data table if desired.

15. In the Graph window, make the appropriate settings to obtain a graph of the dc motor speed n as a function of the armature voltage E_A. Name the graph "G221", name the x-axis "Armature voltage", name the y-axis "Motor speed", and print the graph if desired.

16. 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.

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

Compare graph G221 and constant K_1 obtained in this exercise to graph G211 and constant K_1 obtained in the previous exercise. Describe the effect that decreasing the field current I_f has on the speed-versus-voltage characteristic and constant K_1 of a separately-excited dc motor.

____

____

17. In the Data Table window, clear the recorded data.

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

In this section, you will measure data and plot a graph of the separately-excited dc motor torque T as a function of the armature current I_A. You will calculate the value of constant K_2. You will compare the value of constant K_2 and the graph with those obtained in the previous exercise to determine how decreasing the field current affects these characteristics.

18. In the Four-Quadrant Dynamometer/Power Supply window, make sure that the *Torque* parameter is set to 0.0 N·m (0.0 lbf·in).

Turn the Power Supply on by setting the main power switch to the I (on) position.

On the DC Motor/Generator, slightly readjust the *Field Rheostat* knob, if necessary, so that the field current I_f (meter *I2*) still equals the value given in Table 2-3 for your local ac power network.

On the Power Supply, set the voltage control knob so that the motor rotation speed n is 1500 r/min. Note and record the value of the motor armature voltage E_A (meter *E1*).

Armature voltage E_A $(n = 1500 \text{ r/min}) =$ _______ V

Note and record the value of the motor torque T (indicated by the *Torque* meter in the Four-Quadrant Dynamometer/Power Supply).

Motor torque T (minimum) = _______ N·m (lbf·in)

19. In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to the minimum value measured in step 18. Record the motor rotation speed n and torque T, as well as the motor armature voltage E_A, armature current I_A, and field current I_f in the Data Table.

Increase the *Torque* parameter from the minimum value to about 1.5 N·m (about 14.0 lbf·in) in steps of 0.2 N·m (or 2.0 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 step 18, readjust the field current I_f to the value given in Table 2-3, then record the motor rotation speed n and torque T, as well as the motor armature voltage E_A, armature current I_A, and field current I_f in the Data Table.

CAUTION

The armature current I_A may exceed the rated value while performing this manipulation. Therefore, perform this manipulation in less than 5 minutes.

20. When all data has been recorded, stop the DC Motor/Generator by setting the voltage control knob to 0% and the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.0 N·m (0.0 lbf·in).

In the Data Table window, confirm that the data has been stored, save the data table under filename DT222, and print the data table if desired.

21. In the Graph window, make the appropriate settings to obtain a graph of the dc motor torque T as a function of the armature current I_A. Name the graph "G222", name the x-axis "Armature current", name the y-axis "Motor torque", and print the graph if desired.

The torque-versus-current characteristic 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.

22. 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.

$$\mathrm{K}_2 = \frac{T_2 - T_1}{I_2 - I_1} = \frac{\_\_\_\_ - \_\_\_\_}{\_\_\_\_ - \_\_\_\_} = \_\_\_\_ \ \frac{\mathrm{N \cdot m\ (lbf \cdot in)}}{\mathrm{A}}$$

Compare graph G222 and constant K_2 obtained in this exercise with graph 212 and constant K_2 obtained in the previous exercise. Describe the effect that decreasing the field current I_f has on the torque-versus-current characteristic and constant K_2 of a separately-excited dc motor.

---

23. In the Data Table window, clear the recorded data.

Speed-versus-torque characteristic of a series motor

In this section, you will connect the DC Motor/Generator as a series motor. You will measure data and plot a graph of the motor speed n as a function of 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.

24. Modify the connections in order to obtain the series motor circuit shown in Figure 2-23. Use the variable dc voltage output of the Power Supply to implement the variable-voltage dc power source E_S. *E1* and *I1* are voltage and current inputs of the Data Acquisition and Control Interface (DACI).

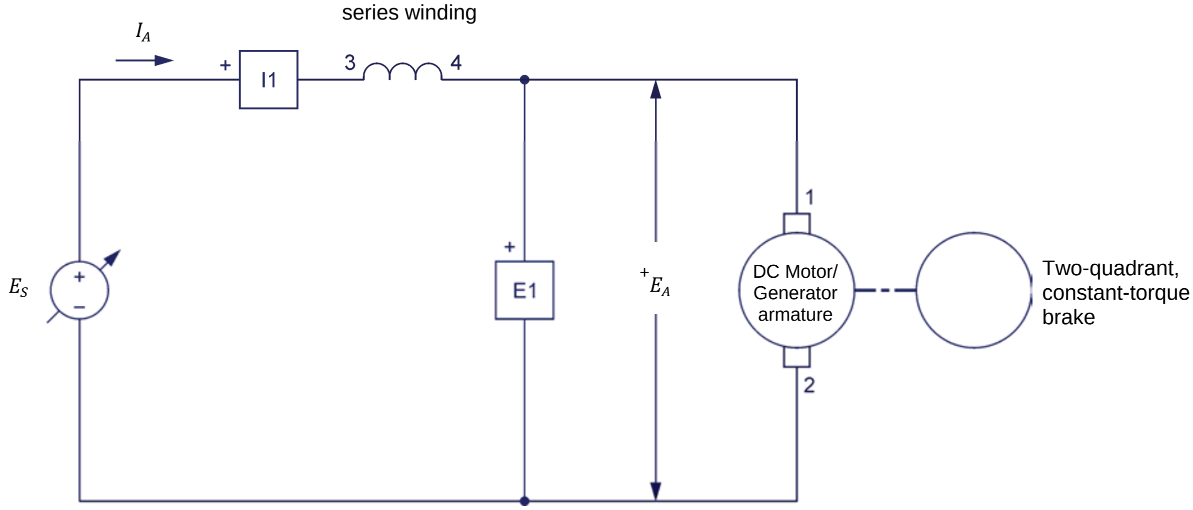


Figure 2-23. Series motor coupled to a brake.

25. In the Metering window, make sure that the meters are set to measure the dc motor armature voltage E_A (*E1*) and armature current I_A (*I1*).

Make sure that the Data Table is set to record the dc motor rotation speed n and torque T (indicated by the *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply window), as well as the dc motor armature voltage E_A and armature current I_A (indicated by meters *E1* and *I1* in the Metering window).

26. In the Four-Quadrant Dynamometer/Power Supply window, make sure that the *Torque* parameter is set to 0.0 N·m (0.0 lbf·in).

Turn the Power Supply on by setting the main power switch to the I (on) position, then set the voltage control knob so that the armature voltage E_A (indicated by meter *E1* in the Metering window) is equal to the value recorded in step 22 of the previous exercise. The motor should start to rotate.

27. Note and record the value of the motor torque T indicated by the *Torque* meter in the Four-Quadrant Dynamometer/Power Supply.

Motor torque T (minimum) = _______ N·m (lbf·in)

28. In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to the minimum value measured in step 27. Record the motor rotation speed n and torque T, as well as the motor armature voltage E_A, and armature current I_A in the Data Table.

Increase the *Torque* parameter from the minimum value to about 2.3 N·m (about 20.3 lbf·in) in steps of 0.2 N·m (or 2.0 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 set in the previous step, wait until the motor speed stabilizes, and then record the motor rotation speed n and torque T, as well as the motor armature voltage E_A and armature current I_A in the Data Table.

It may not be possible to maintain the armature voltage E_A to its original value as the torque T is increased.

CAUTION

The armature current I_A may exceed the rated value while performing this manipulation. Therefore, perform this manipulation in less than 5 minutes.

29. When all data has been recorded, stop the DC Motor/Generator by setting the voltage control knob to 0% and the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.0 N·m (0.0 lbf·in).

In the Data Table window, confirm that the data has been stored, save the data table under filename DT223, and print the data table if desired.

30. In the Graph window, make the appropriate settings to obtain a graph of the series motor speed n as a function of the series motor torque T. Name the graph "G223", name the x-axis "Motor torque", name the y-axis "Motor speed", and print the graph if desired.

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 (G212-2 obtained in the previous exercise).

If you want to perform the additional experiments, skip the next step, then return to it when all additional manipulations are finished.

31. On the Power Supply, make sure that the main power switch is set to the O (off) position, then turn the 24 V ac power source off. Close the LVDAC-EMS software. Turn the Four-Quadrant Dynamometer/Power Supply off. Disconnect all leads and return them to their storage location.

Additional experiments (optional)

Motor speed-versus-torque characteristic of a shunt motor

You can obtain the speed-versus-torque characteristic of a shunt motor and compare it to the characteristics obtained for the separately-excited dc motor and series motor. To do so, make sure that the Power Supply is turned off [voltage control knob set to 0% and main power switch set to the O (off) position] and set up the shunt motor circuit shown in Figure 2-24. In the Four-Quadrant Dynamometer/Power Supply window, make sure that the *Torque* parameter is set to 0.0 N·m (0.0 lbf·in). Turn the Power Supply on [set the main power switch to the I (on) position], then set its voltage control knob so that the armature voltage E_A is equal to the value recorded in step 22 of the previous exercise. On the DC Motor/Generator, set the *Field Rheostat* knob so that the field current I_f is equal to the value indicated in Table 2-1 of the previous exercise for your local ac power network. Clear the data recorded in the data table. Refer to steps 27 to 30 of this exercise to record the necessary data and obtain the graph. (For each torque setting in step 27, readjust the field current I_f to keep it to the value indicated in Table 2-1.) Save the data table under filename DT224, and name the graph “G224”. 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).

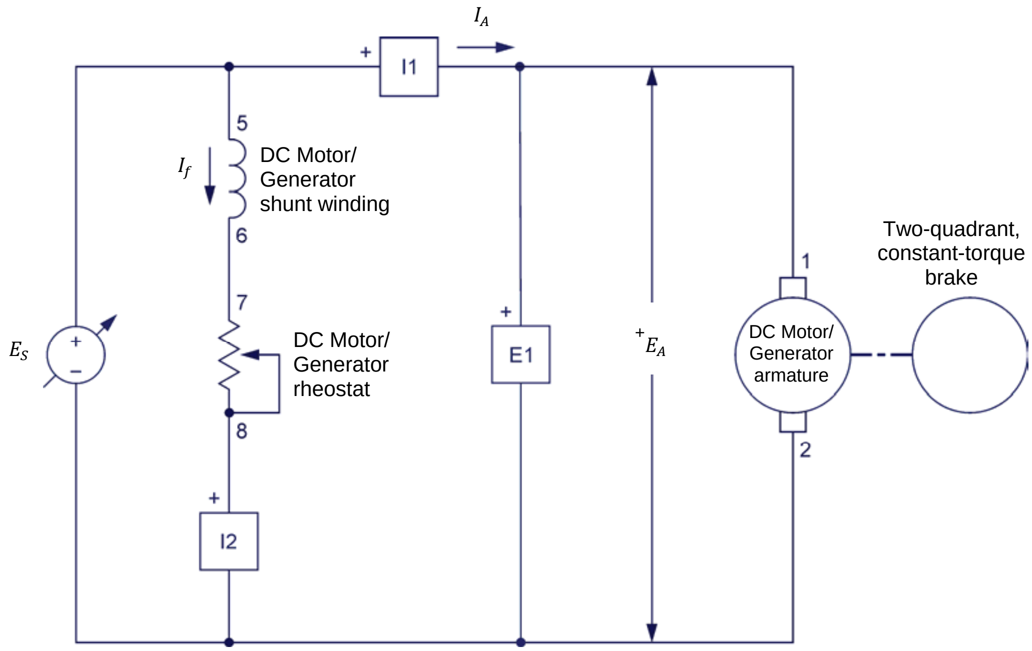


Figure 2-24. Shunt motor circuit.

Motor 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 that the Power Supply is turned off [voltage control knob set to 0% and main power switch set to the O (off) position] and set up the cumulative compound motor circuit shown in Figure 2-25. In the Four-Quadrant Dynamometer/Power Supply window, make sure that the *Torque* parameter is set to 0.0 N·m (0.0 lbf·in). Turn the Power Supply on [set the main power switch to the I (on) position], then set its voltage control knob so that the armature voltage E_A is equal to the value recorded in step 22 of the previous exercise. On the DC Motor/Generator, set the *Field Rheostat* knob so that the field current I_f is equal to the value indicated in Table 2-1 of the previous exercise for your local ac power network. Clear the data recorded in the Data Table. Refer to steps 27 to 30 of this exercise to record the necessary data and obtain the graph. (For each torque setting in step 27, readjust the field current I_f to keep it to the value indicated in Table 2-1.) Save the data table under filename DT225, and name the obtained graph G225. 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).

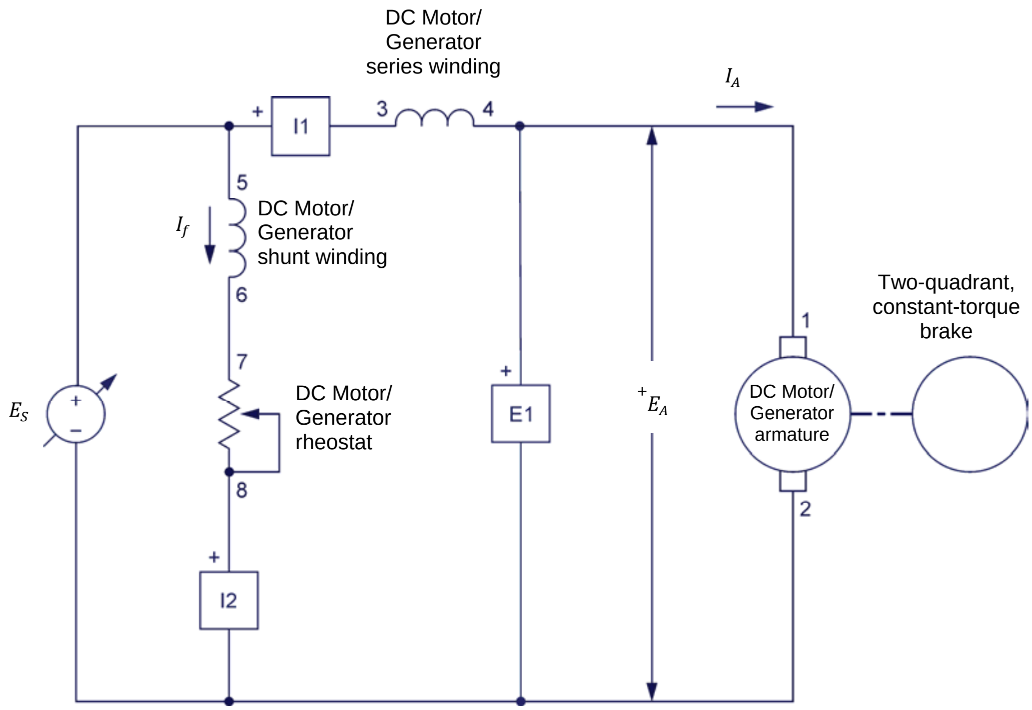


Figure 2-25. Cumulative-compound motor circuit.

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 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?

___

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

___

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?

___

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

___

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

___

Separately-Excited, Shunt, and Compound DC Generators

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate the main operating characteristics of separately-excited, shunt, and compound generators using the DC Motor/Generator.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction to dc generators
- Separately-excited dc generator
- Self-excited dc generator
- Voltage-versus-current characteristics of various dc generators

DISCUSSION

Introduction to dc generators

Although dc generators are rarely used today, it is important to know their operation because this helps understanding how a separately-excited dc motor can be used as an electric brake in modern dc motor drives.

You saw earlier in this unit that a dc motor can be considered as a linear voltage-to-speed converter. This linear conversion process is reversible, meaning that when a fixed speed is imposed on the motor by an external driving force, the motor produces an output voltage E_O, and thus, operates as a linear speed-to-voltage converter, i.e., a dc generator. Figure 2-26 illustrates a dc motor operating as a dc generator.

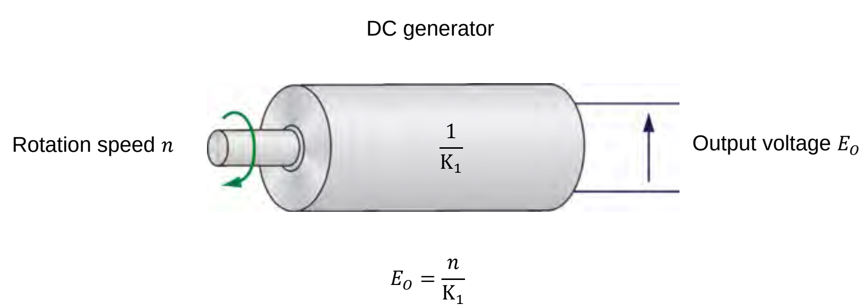


Figure 2-26. DC motor as a speed-to-voltage converter (dc generator).

The linear relationship that exists between torque and current for the dc motor is also reversible and applies to the dc generator, i.e., a torque must be applied to the generator's shaft to obtain a certain output current. Figure 2-27 illustrates a dc motor operating as a linear torque-to-current converter, i.e., a dc generator.

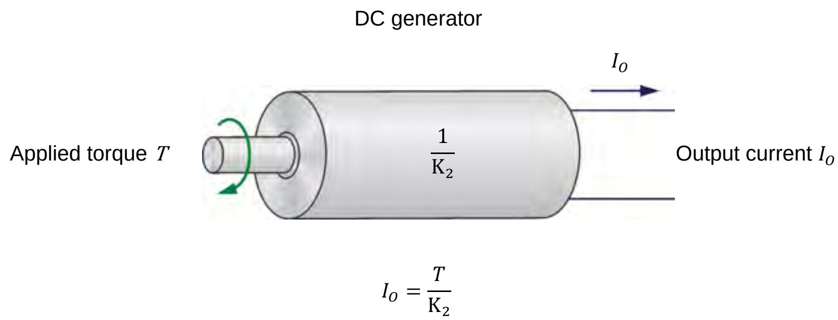
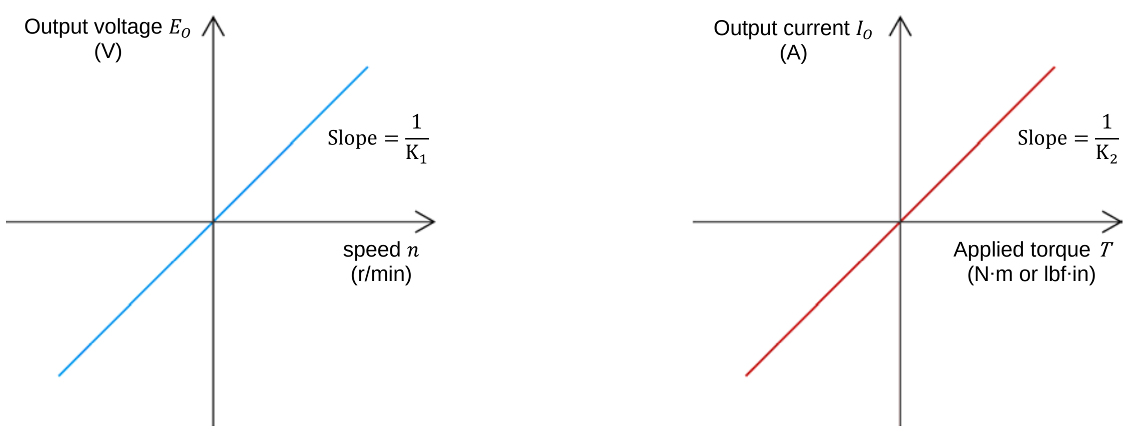


Figure 2-27. DC motor as a torque-to-current converter (dc generator).

Separately-excited dc generator

Figure 2-28a shows the output voltage-versus-speed relationship of a **separately-excited dc generator**. Figure 2-28b shows the output current-versus-applied torque relationship of a separately-excited dc generator. Notice that the slopes of these linear relationships are equal to the reciprocal of constants K_1 and K_2.



(a) Output voltage versus speed

(b) Output current versus applied torque

Figure 2-28. Input-output relationships of a separately-excited dc generator.

In a manner similar to that for a separately-excited dc motor, the field current I_f of a separately-excited dc generator can be varied to change the strength of the field electromagnet, and thereby, the relative values of constant K_1 and K_2. When the field current is decreased, constant K_1 increases and constant K_2 decreases, as for a separately-excited dc motor. As a result, the slope of the output voltage-versus-speed relationship decreases, whereas the slope of the output current-versus-torque relationship increases. Conversely, when the field current is increased, constant K_1 decreases and constant K_2 increases, and thereby, the slope of the output voltage-versus-speed relationship increases, whereas the slope of the output current-versus-torque relationship decreases. Therefore, the output voltage E_O of a generator operating at a fixed speed can be varied by varying the field current I_f. This produces the equivalent of a dc power source whose output voltage can be controlled by varying the field current I_f. Figure 2-29 shows the variation of output voltage E_O for a separately-excited dc generator operating at a fixed speed, when the field current I_f is varied from zero to its nominal value.

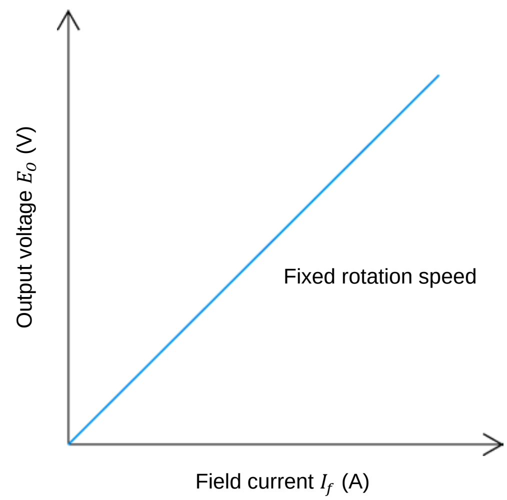


Figure 2-29. Output voltage E_O versus field current I_f for a separately-excited dc generator operating at a fixed speed.

The simplified equivalent electric circuit of a separately-excited dc generator is shown in Figure 2-30. It is the same as that for the dc motor, except that the direction of current flow is reversed and voltage E_{CEMF} becomes E_{EMF}, which is the voltage induced across the armature winding as it rotates in the magnetic flux produced by the stator electromagnet. When no load is connected to the dc generator output, the output current I_O is zero and the output voltage E_O equals E_{EMF}.

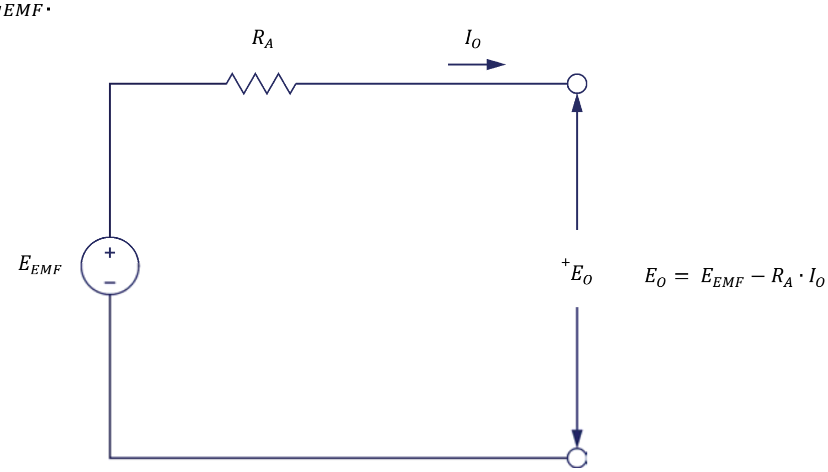


Figure 2-30. Simplified equivalent circuit of a dc generator.

In the first exercise of this unit, you observed that when a fixed armature voltage E_A is applied to a separately-excited dc motor, its speed decreases as the armature current I_A increases. You found that this decrease in speed is due to the armature resistance R_A. Similarly, when the same motor operates as a generator and at a fixed speed, the armature resistance causes the output voltage E_O to decrease with increasing output current, as shown in Figure 2-31.

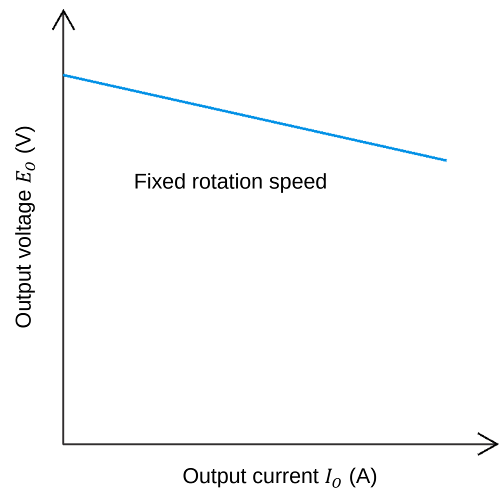


Figure 2-31. Voltage-versus-current characteristic of a separately-excited dc generator (fixed speed).

The output voltage E_O can be calculated by using the following equation:

$$E_O = E_{EMF} - R_A \cdot I_O \quad (2\text{-}4)$$

where E_O is the dc generator output voltage, expressed in volts (V).
E_{EMF} is the voltage induced across the armature winding, expressed in volts (V).
R_A is the armature resistance, expressed in ohms (Ω).
I_O is the dc generator output current, expressed in amperes (A).

Self-excited dc generator

The separately-excited dc generator provides flexible use because its characteristics can be changed by changing the field current. However, a separate dc power source is needed to excite the field electromagnet. This was a disadvantage when the first dc generators were used because dc sources were not commonly available at the time. Therefore, dc generators that operate without a dc power source were designed. This type of generator is referred to as **self-excited dc generator**.

In a self-excited dc generator, the field electromagnet is a shunt winding connected across the generator output (shunt generator) or a combination of a shunt winding connected across the generator output and a series winding connected in series with the generator output (compound generator). The generator output voltage and/or current excite(s) the field electromagnet. The way the field electromagnet is implemented (shunt or compound) determines many of the generator's characteristics.

Self-excitation is possible because of the residual magnetism in the stator pole pieces. As the armature rotates, a low voltage is induced across its winding and a low current flows in the shunt field winding. If this small field current is flowing in the proper direction, the residual magnetism is reinforced, which further increases the armature voltage. Thus, a rapid voltage build-up occurs. If the field current flows in the wrong direction, the residual magnetism is reduced and voltage build-up cannot occur. In this case, reversing the connections of the shunt field winding corrects the situation.

In a self-excited dc generator, the output voltage after build-up can have a polarity opposite to that required. This can be corrected by stopping the generator and setting the polarity of the residual magnetism. To set the residual magnetism, a dc power source is connected to the shunt field winding to force nominal current flow in the proper direction. Interrupting the current suddenly sets the polarity of the magnetic poles in the shunt field winding. When the generator is started once again, voltage build-up at the proper polarity occurs.

Voltage-versus-current characteristics of various dc generators

Figure 2-32 is a graph that shows the voltage-versus-current characteristics of various types of dc generators. As can be seen, the separately-excited dc generator and the shunt generator have very similar characteristics. The difference is that the output voltage of the shunt generator decreases a little more than that of the separately-excited dc generator as the output current increases. In both cases, the output voltage decreases because the voltage drop across the armature resistor increases as the output current increases. In the shunt generator, the voltage across the shunt field winding, and thereby, the field current, decreases as the output voltage decreases. This causes the output voltage to decrease a little more.

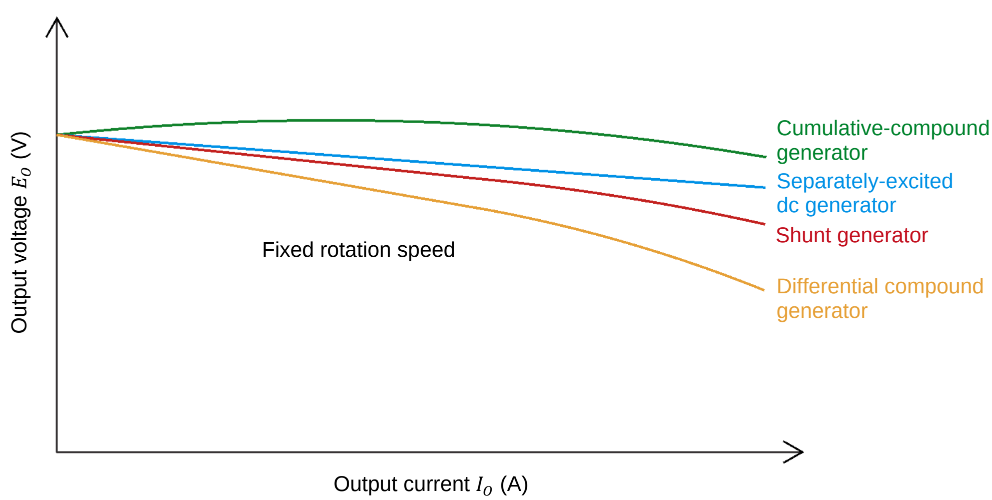


Figure 2-32. Voltage-versus-current characteristics of various dc generators.

It is possible to compensate the variation in output voltage by automatically changing the magnetic flux produced by the field electromagnet as the output current varies. The shunt and series field windings of a compound generator can be connected so that the magnetic flux increases when the output current increases. Thus, the output voltage remains fairly constant and changes very little as the output current increases as shown in Figure 2-32. This type of connection results in a cumulative compound generator because the magnetic fluxes created by the two field windings add together in a cumulative manner. For other applications where the output voltage must decrease rapidly when the output current increases, the shunt and series windings can be connected so that the magnetic fluxes subtract from each other, resulting in a differential compound generator.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Output voltage-versus-speed characteristic of a separately-excited dc generator
- Output current-versus-torque characteristic of a separately-excited dc motor
- Output voltage versus field current characteristic of a separately-excited dc generator
- Output voltage-versus-output current characteristic of a separately-excited dc generator operating at a fixed speed
- Additional experiments (optional)
  Output voltage-versus-output current characteristic of a shunt generator operating at a fixed speed. Voltage-versus-current characteristic of a cumulative-compound generator operating at a fixed speed. Output voltage-versus-output current characteristic of a differential compound generator operating at a fixed speed.

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.

Set up and connections

In this section, you will mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply and set up the equipment.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the exercise. Install the equipment in the Workstation.

   Before performing the exercise, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect a variable-voltage 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 and Control Interface (DACI). Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to voltage input E1 of the DACI. In LVDAC-EMS, open the Metering window. Set two meters to measure the rms values (ac) of the armature voltage E_A and armature current I_A at inputs E1 and I1 of the DACI, respectively. Turn the Power Supply on and adjust its voltage control knob so that an ac current *(indicated by meter I1 in the Metering window) equal to half the nominal 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 E1 in the Metering window) is minimal. Turn the Power Supply off, close LVDAC-EMS, and disconnect all leads and cable.*

Mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

⚠ WARNING

Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

2. Make sure that the main power switch of the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power wall outlet.

3. On the Power Supply, make sure that the main power switch and the 24 V ac power switch are set to the O (off) position, and that the voltage control knob is set to 0% (turned fully counterclockwise). Connect the Power Supply to a three-phase ac power outlet.

4. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24 V ac power source of the Power Supply.

Turn the 24 V ac power source of the Power Supply on.

5. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

6. Connect the equipment as shown in Figure 2-33. Use the fixed dc voltage output of the Power Supply to implement the fixed-voltage dc power source. *E1* and *I2* are voltage and current inputs of the Data Acquisition and Control Interface (DACI). Notice that no electrical load is connected to the generator output.

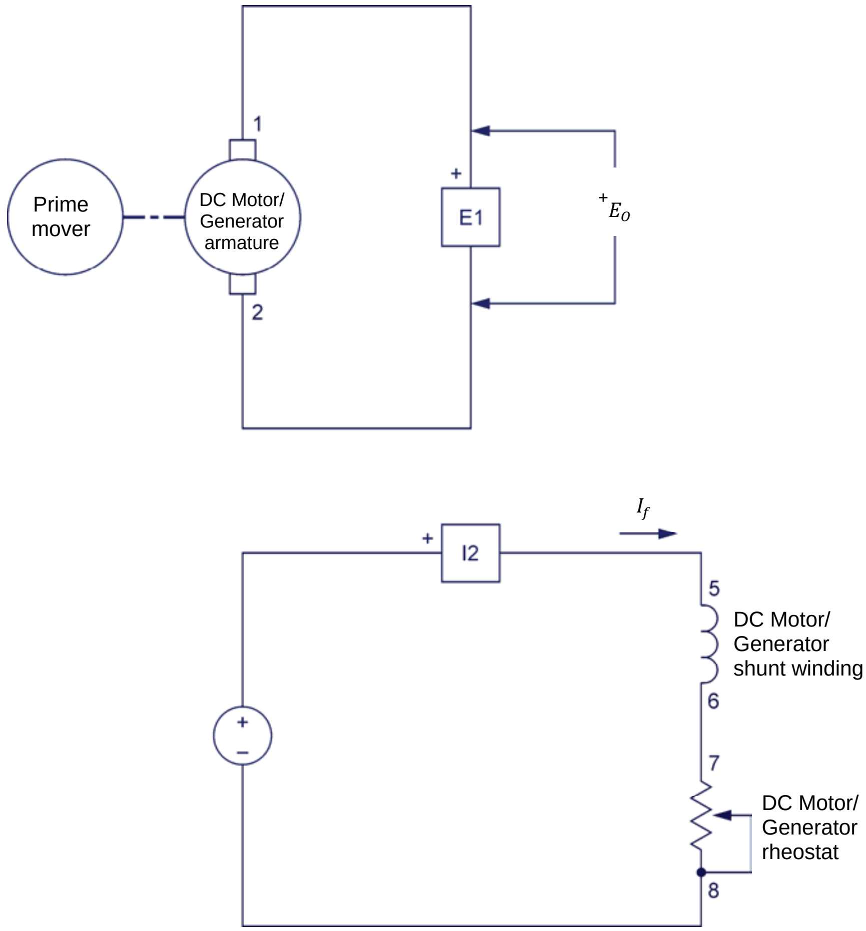


Figure 2-33. Separately-excited dc generator coupled to a prime mover (no electrical load).

7. On the Four-Quadrant Dynamometer/Power Supply, set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

Turn the Four-Quadrant Dynamometer/Power Supply on by setting the main power switch to the I (on) position.

8. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure that the *Computer-Based Instrumentation* function is available for the Data Acquisition and Control Interface module. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

9. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

– Set the *Function* parameter to *CW Constant-Speed Prime Mover/Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a clockwise prime mover/brake with a speed setting corresponding to the *Speed* parameter.

– Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test (i.e., the DC Motor/Generator), respectively.

– Make sure that the *Speed Control* parameter is set to *Knob*. This allows the speed of the clockwise prime mover/brake to be controlled manually.

– Set the *Speed* parameter (i.e., the speed command) to 0 r/min. Notice that the speed command is the targeted speed at the shaft of the machine coupled to the prime mover, i.e., the speed of the DC Motor/Generator in the present case.

The speed command can also be set by using the Speed control knob in the Four-Quadrant Dynamometer/Power Supply window.

10. In LVDAC-EMS, open the Metering window. Set two meters to measure the dc generator output voltage E_O (*E1*) and field current I_f (*I2*).

Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the Metering application.

Output voltage-versus-speed characteristic of a separately-excited dc generator

In this section, you will set the field current of the separately-excited dc generator to the same value as that used in Exercise 2-1. You will measure data and plot a graph of the generator output voltage E_O as a function of speed n when no electrical load is connected to the generator output. You will calculate the slope of the voltage-versus-speed relationship and compare it to constant K_1 determined in Exercise 2-1 when the DC Motor/Generator was operating as a separately-excited dc motor.

11. In the Four-Quadrant Dynamometer/Power Supply window, start the *CW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

Turn the Power Supply on by setting the main power switch to I (on).

12. On the DC Motor/Generator, set the *Field Rheostat* knob so that the dc generator field current I_f (meter *I2*) is equal to the value given in Table 2-4 for your local ac power network.

Table 2-4. Field current I_f.

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

13. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the dc generator output voltage E_o and field current I_f (indicated by meters *E1* and *I2* in the Metering window), as well as the dc generator rotation speed n and torque T (indicated by the *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply window).

14. Increase the prime mover speed from 0 to 1500 r/min by 150 r/min increments, using the *Speed* parameter in the Four-Quadrant Dynamometer/Power Supply window. For each speed setting, record the dc generator output voltage E_o and field current I_f, as well as the dc generator speed n and torque T in the Data Table.

15. When all data has been recorded, set the *Speed* parameter in the Four-Quadrant Dynamometer/Power Supply window to 0 r/min, then click the *Start/Stop* button in this window to stop the *CW Constant-Speed Prime Mover/Brake*.

Turn the Power Supply off by setting its main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Data Table window, confirm that the data has been stored, save the data file under filename DT231, and print the data table if desired.

16. In the Graph window, make the appropriate settings to obtain a graph of the dc generator output voltage E_O as a function of the dc generator speed n. Name the graph "G231", name the x-axis "DC generator speed", name the y-axis "DC generator output voltage", and print the graph if desired.

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

❑ Yes ❑ No

17. Use the two end points to calculate the slope of the relationship obtained in graph G231. The values of these points are indicated in data table DT231.

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

Compare the slope of the output voltage-versus-speed relationship to constant K_1 obtained in Exercise 2-1.

____

____

18. In the Data Table window, clear the recorded data.

Output current-versus-torque characteristic of a separately-excited dc motor

In this section, you will connect an electrical load to the generator output. You will measure data and plot a graph of the separately-excited dc generator output current I_O as a function of the torque T applied to the generator shaft, when the generator rotates at a fixed speed You will calculate the slope of the current-versus-torque relationship and compare it to constant K_2 determined in Exercise 2-1 when the DC Motor/Generator was operating as a separately-excited dc motor.

19. Connect a load resistor (R_1) in series with a dc ammeter (*I1*) across the separately-excited dc generator output, as shown in Figure 2-34. *I1* is a current input of the Data Acquisition and Control Interface (DACI). Use the Resistive Load module to implement resistor R_1. Set the resistance value of R_1 to infinite (∞) by connecting the three resistor sections of the Resistive Load module in parallel and setting the levers of all toggle switches to the O (off) position. Leave all other connections unchanged.

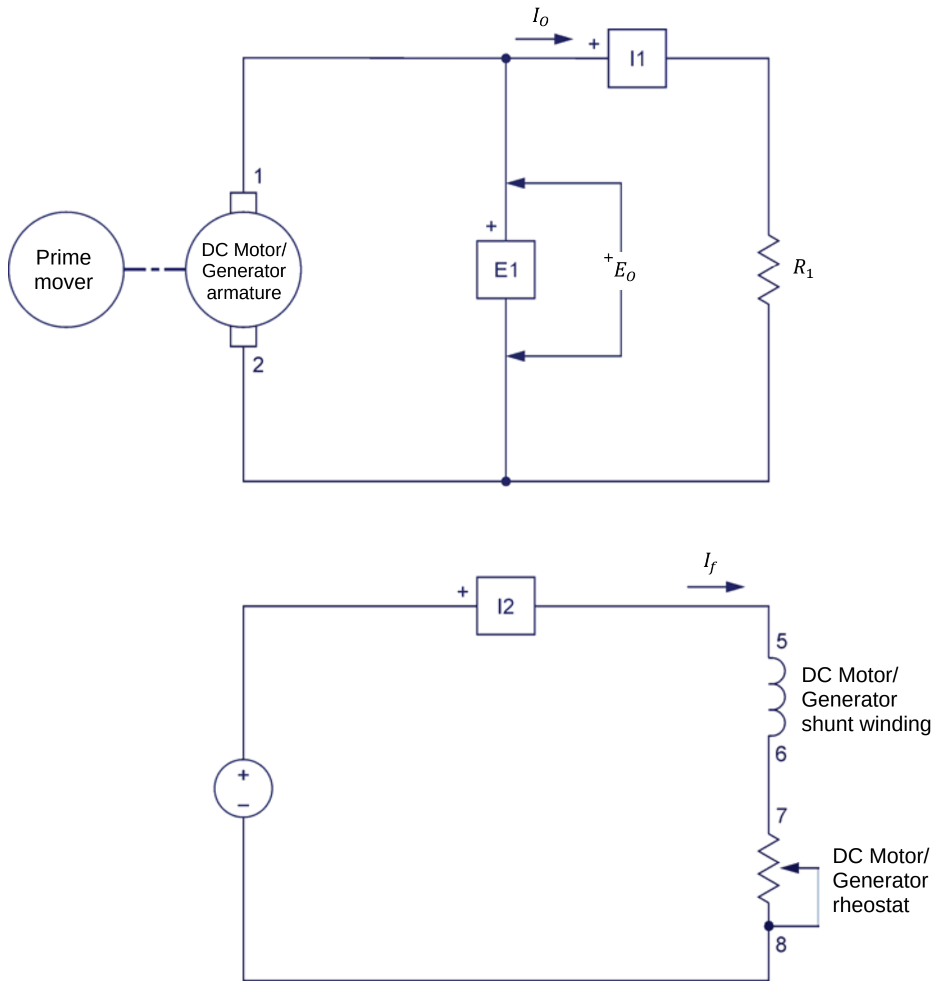


Figure 2-34. Separately-excited dc generator coupled to a prime mover (with an electrical load).

20. In the Metering window, make sure that the meters are set to measure the dc generator output voltage E_O (*E1*), output current I_O (*I1*), and field current I_f (*I2*). Make sure that the Data Table is set to record the dc generator output voltage E_O, output current I_O, and field current I_f as well as the dc generator rotation speed n and torque T.

21. In the Four-Quadrant Dynamometer/Power Supply window, set the *Speed* parameter so that the prime mover speed is equal to the nominal speed of the DC Motor/Generator. Start the *CW Constant-Speed Prime Mover/Brake* to make the prime mover rotate.

The nominal speed value of the DC Motor/Generator is indicated in the lower section of its front panel.

Turn the Power Supply on by setting the main power switch to I (on).

On the DC Motor/Generator, slightly readjust the *Field Rheostat* knob, if necessary, so that the field current I_f indicated by meter *I2* still equals the value given in Table 2-4 for your local ac power network.

22. Record the dc generator output voltage E_O, output current I_O, and field current I_f, as well as the rotation speed n and torque T in the Data Table.

Then, modify the settings on the Resistive Load module to decrease the resistance of resistor R_1 by steps as indicated in Table 2-5 for your local ac power network. (You can refer to Appendix C of this manual to know how to obtain the various resistance values given in Table 2-5). For each resistance setting, readjust (if necessary) the *Speed* parameter value in the Four-Quadrant Dynamometer/Power Supply window so that the prime mover speed remains equal to the nominal speed of the DC Motor Generator, and then record the dc generator output voltage E_O, output current I_O, and field current I_f, as well as the rotation speed n and torque T in the Data Table.

CAUTION

The dc generator output voltage will exceed the rated voltage of the Resistive Load module. Therefore, perform this manipulation in less than 5 minutes.

Table 2-5. Decreasing the resistance value of R_1 to load the dc generator.

Local ac power network		Resistance value of resistor R_1 (Ω)							
Voltage (V)	Frequency (Hz)								
120	60	1200	600	300	171	120	86	71	57
220	50	4400	2200	1100	629	440	314	259	210
240	50	4800	2400	1200	686	480	343	282	229
220	60	4400	2200	1100	629	440	314	259	210

23. When all data has been recorded, set the *Speed* parameter in the Four-Quadrant Dynamometer/Power Supply window to 0 r/min, then click the *Start/Stop* button in this window to stop the CW Constant-Speed Prime Mover/Brake.

Turn the Power Supply off by setting its main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Data Table window, confirm that the data has been stored. Reverse the polarity of the torque values recorded in the data table to obtain the torque applied to the dc generator's shaft. Save the data table under filename DT232, and print the data table if desired.

24. In the Graph window, make the appropriate settings to obtain a graph of the dc generator output current I_O as a function of the torque T applied to the generator's shaft. Name the graph "G232", name the x-axis "Torque applied to the dc generator's shaft", name the y-axis "DC generator output current", and print the graph if desired.

The torque is not zero when the generator output current is zero because some torque is required to overcome opposition to rotation due to friction in the dc generator.

Does this graph confirm that the separately-excited dc generator is equivalent to a torque-to-current converter, with higher torque producing greater output current?

❑ Yes ❑ No

25. Use the two end points to calculate the slope of the relationship obtained in graph G232. The values of these points are indicated in data table DT232.

$$\text{Slope} = \frac{I_2 - I_1}{T_2 - T_1} = \frac{\_\_\_\_\_\_ - \_\_\_\_\_\_}{\_\_\_\_\_\_ - \_\_\_\_\_\_} = \_\_\_\_\_\_ \frac{\text{A}}{\text{N} \cdot \text{m (lbf} \cdot \text{in)}}$$

Compare the slope of the output current-versus-torque relationship to constant K_2 obtained in Exercise 2-1.

____

____

26. In the Data Table window, clear the recorded data.

Output voltage versus field current characteristic of a separately-excited dc generator

In this section, you will vary the field current I_f of the separately-excited dc generator and observe how the output voltage is affected.

27. On the Resistive Load module, set the resistance of resistor R_1 to the value given in Table 2-6.

Table 2-6. Resistance value to be set for R_1.

Local ac power network		Resistance value of resistor R_1 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	171
220	50	629
240	50	686
220	60	629

28. In the Four-Quadrant Dynamometer/Power Supply window, set the *Speed* parameter to the nominal speed value of the DC Motor/Generator. Start the *CW Constant-Speed Prime Mover/Brake* to make the prime mover rotate.

Turn the Power Supply on by setting the main power switch to I (on).

On the DC Motor/Generator, readjust the *Field Rheostat* knob, if necessary, so that field current I_f (meter *I2*) still equals the value indicated in Table 2-4 for your local ac power network. Note and record the dc generator output voltage E_O (meter *E1*) and field current I_f (meter *I2*).

E_O = _______ V

I_f = _______ A

29. On the DC Motor/Generator, slowly turn the *Field Rheostat* knob fully clockwise so that the field current I_f (meter *I2*) increases. While doing this, observe the dc generator output voltage E_O (meter *E1*).

CAUTION

The dc generator output voltage will exceed the rated voltage of the Resistive Load module while performing this manipulation. Therefore, perform this manipulation within 1 minute.

Note and record the dc generator output voltage E_O (meter *E1*) and field current I_f (meter *I2*).

E_O = _______ V

I_f = _______ A

On the DC Motor/Generator, set the *Field Rheostat* knob to the mid position.

Describe what happens to the dc generator output voltage E_O when the field current I_f is increased.

____

____

30. On the DC Motor/Generator, slowly turn the *Field Rheostat* knob fully counterclockwise so that the field current I_f (meter *I2*) decreases. While doing this, observe the dc generator output voltage E_O (meter *E1*).

Note and record the dc generator output voltage E_O (meter *E1*) and field current I_f (meter *I2*).

E_O = _______ V

I_f = _______ A

Describe what happens to the dc generator output voltage E_O when the field current I_f is decreased.

____

____

Is a separately-excited dc generator equivalent to a dc power source with variable output voltage?

❑ Yes ❑ No

31. In the Four-Quadrant Dynamometer/Power Supply window, set the *Speed* parameter to 0 r/min, then click the *Start/Stop* button in this window to stop the CW Constant-Speed Prime Mover/Brake.

Turn the Power Supply off by setting its main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

Output voltage-versus-output current characteristic of a separately-excited dc generator operating at a fixed speed

In this section, you will use the data obtained previously to plot a graph of the dc generator output voltage as a function of the dc generator output current, for a fixed speed.

32. In the Graph window, make the appropriate settings to obtain a graph of the separately-excited dc generator output voltage E_O as a function of the dc generator output current I_O output using the data recorded previously in the data table (DT232). Name the graph "G232-1", name the x-axis "DC generator output current", name the y-axis "DC generator output voltage", and print the graph if desired.

Describe how the dc generator output voltage E_O varies as the output current I_O increases.

____

____

If you want to perform the additional experiments, skip the next step, then return to it when all additional manipulations are finished.

33. On the Power Supply, make sure that the main power switch is set to the O (off) position, then turn the 24 V ac power source off. Close the LVDAC-EMS software. Turn the Four-Quadrant Dynamometer/Power Supply off. Disconnect all leads and return them to their storage location.

Additional experiments (optional)

Output voltage-versus-output current characteristic of a shunt generator operating at a fixed speed

You can obtain the output voltage-versus-output current characteristic of a shunt generator and compare it to that obtained for the separately-excited dc generator. To do so, make sure the Power Supply is turned off [voltage control knob set to 0% and main power switch set to the O (off) position] and connect the fixed dc voltage output (terminals *8* and *N*) of the Power Supply across the shunt winding (terminals *5* and *6*) of the DC Motor/Generator. On the Power Supply, set the main power switch to the I (on) position, then set it to the O (off) position. This sets the polarity of the residual magnetism. Set up the shunt generator circuit shown in Figure 2-35. Set the *Field Rheostat* knob to the *0-Ω* position (turned fully clockwise). Set the resistance value of R_1 to infinite (∞) for now.

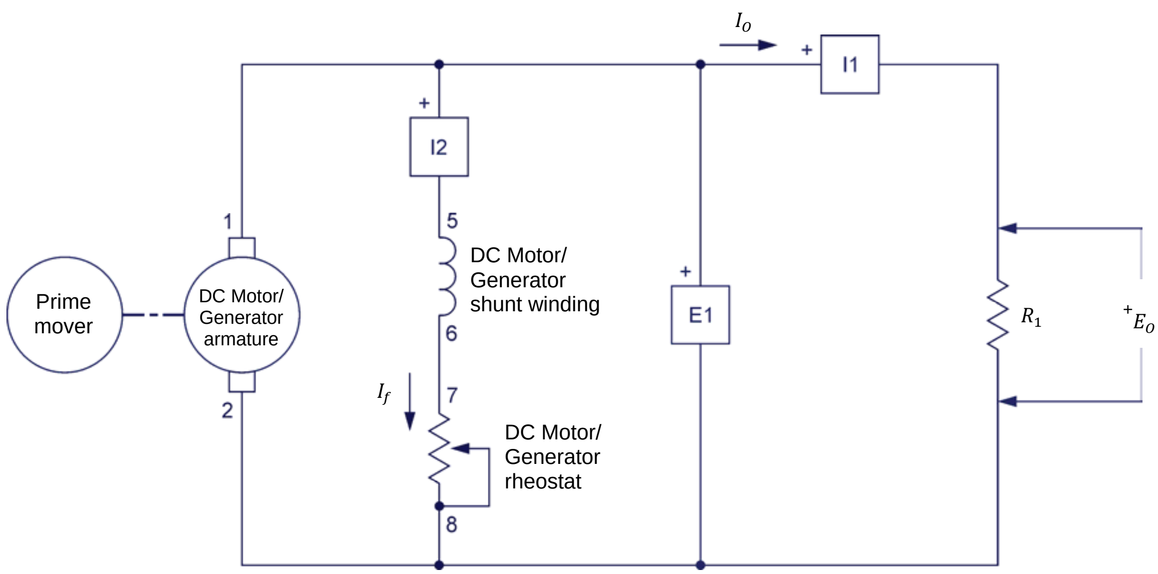


Figure 2-35. Shunt generator coupled to a prime mover (with an electrical load).

In the Four-Quadrant Dynamometer/Power Supply window, set the *Speed* parameter so that the prime mover speed is equal to the nominal speed of the DC Motor/Generator. Start the *CW Constant-Speed Prime Mover/Brake* to make the prime mover rotate. On the DC Motor/Generator, adjust the *Field Rheostat* knob so that the field current I_f is equal to the value indicated in Table 2-4 for your local ac power network. Clear the data recorded in the Data Table. Refer to steps 22 and 23 of this exercise to record the necessary data and save the data table under filename DT233. Refer to step 32 to obtain the graph and name this graph G233. Compare the output voltage-versus-output current characteristic of the shunt generator (graph G233) to that of the separately-excited dc generator (graph G232-1).

The output voltage of the shunt generator decreases rapidly as the output current I_O increases because the armature resistance of the DC Motor/Generator is quite large. This is also due to another phenomenon which is called armature reaction. This phenomenon will be studied in the next unit of this manual.

Voltage-versus-current characteristic of a cumulative-compound generator operating at a fixed speed

You can obtain the output voltage-versus-output current characteristic of a cumulative compound generator and compare it to that obtained for the separately-excited dc generator. To do so, carry out the same manipulations as those used to obtain the output voltage-versus-output current characteristic of the shunt generator using the circuit of a cumulative compound generator shown in Figure 2-36. Save the data table under filename DT234 and name the graph "G234". Compare the output voltage-versus-output current characteristic of the cumulative compound generator (graph G234) to those of the separately-excited dc generator (graph G232-1) and shunt generator (graph G233) obtained previously.

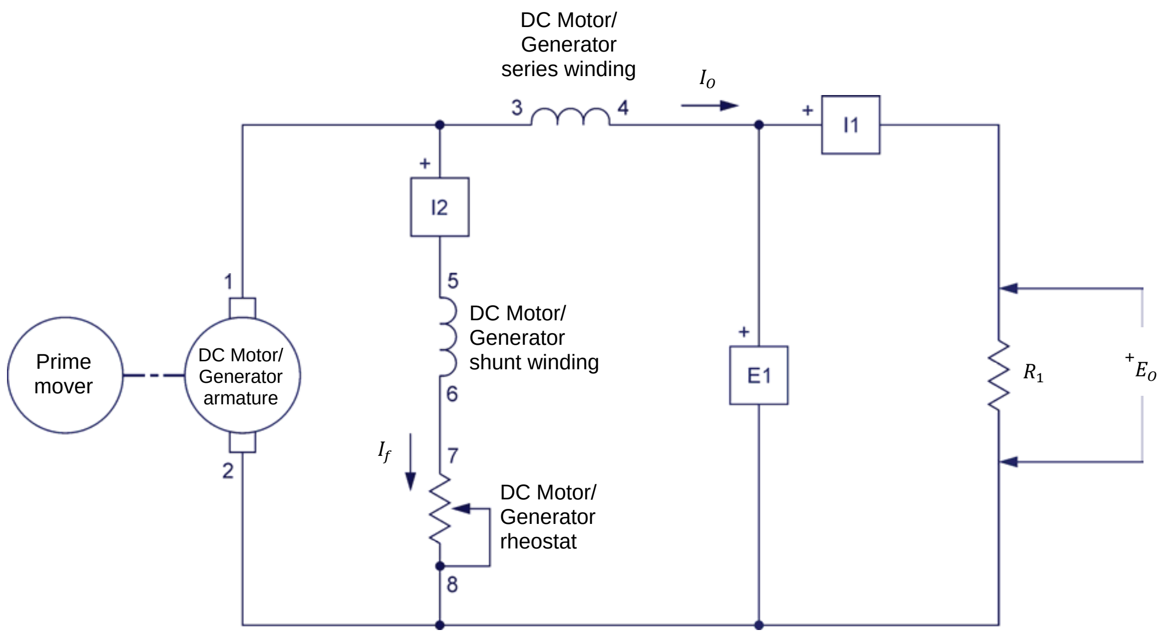


Figure 2-36. Cumulative-compound generator coupled to a prime mover (with an electrical load).

Output voltage-versus-output current characteristic of a differential compound generator operating at a fixed speed

You can obtain the output voltage-versus-output current characteristic of a differential compound generator and compare it to that obtained for the separately-excited dc generator. To do so, carry out the same manipulations as those used to obtain the output voltage-versus-output current characteristic of the shunt generator using the circuit of a differential compound generator shown in Figure 2-37. Save the data table under filename DT235 and name the graph "G235". Compare the output voltage-versus-output current characteristic of the differential compound generator (graph G235) to those obtained with the other types of dc generators (graphs G232-1, G233, and G234).

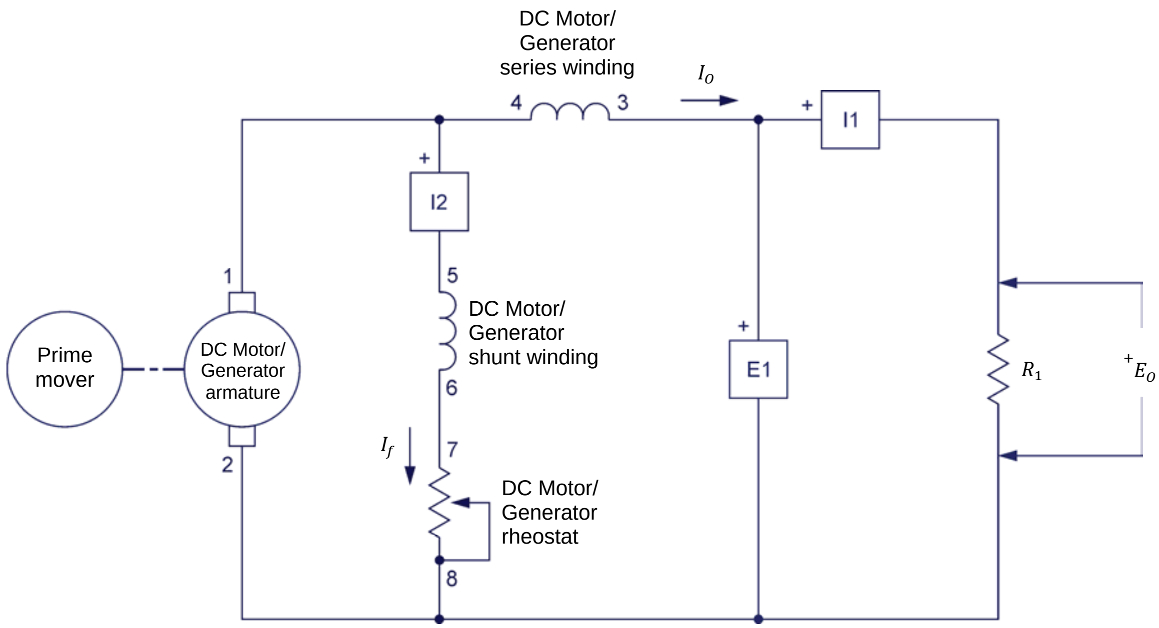


Figure 2-37. Differential-compound generator coupled to a prime mover (with an electrical load).

CONCLUSION

In this exercise, you plotted graphs of the main operating characteristics of a separately-excited dc generator. You observed that the output voltage increases linearly with speed. You also observed that the output current increases linearly with the input torque. You found that the slope of the output voltage-versus-speed characteristic is equal to the reciprocal of constant K_1, and that the slope of the output current-versus-torque characteristic is equal to the reciprocal of constant K_2. You saw that constant K_1 and K_2 can be changed by changing the field current, and that this allows the output voltage to be changed. You observed that the output voltage decreases as the output current increases.

If you performed the additional experiments, you plotted graphs of the voltage-versus-current characteristics for shunt, cumulative compound, and differential compound generators. You compared the various voltage-versus-current characteristics obtained in the exercise. You observed that the output voltage of the shunt generator decreases more rapidly than that of the separately-excited dc generator when the output current increases. You found that the output voltage of a cumulative compound generator varies little as the output current varies. Finally, you saw that the output voltage of a differential compound generator decreases more rapidly than that of the separately-excited and shunt generators when the output current increases.

REVIEW QUESTIONS

1. What effect does decreasing the field current have on the output voltage of a separately-excited dc generator operating at fixed speed?

   ____

2. What effect does increasing the output current have on the input torque of a separately-excited dc generator?

   ____

3. What is the main characteristic of a cumulative compound generator?

   ____

4. What is the main characteristic of a differential compound generator?

   ____

5. What happens when the field current of a separately-excited dc generator is increased and the speed is maintained constant?

   ____

Unit Test

1. The rotor, or armature, of a dc motor consists of

   a. an iron cylinder and windings.
   b. an iron cylinder, windings, and brushes.
   c. an iron cylinder, windings, and a commutator.
   d. an iron cylinder, windings, a commutator, and a dc source.

2. The basic principle of operation of a dc motor is the creation of

   a. an electromagnet.
   b. a rotating electromagnet inside the armature.
   c. a fixed electromagnet inside the armature.
   d. a rotating electromagnet at the stator.

3. The speed n of a separately-excited dc motor is equal to

   a. $\mathrm{K}_2 \cdot E_{CEMF}$
   b. $\mathrm{K}_1 \cdot I_A$
   c. $\mathrm{K}_1 \cdot E_{CEMF} \times I_A$
   d. $\mathrm{K}_1 \cdot E_{CEMF}$

4. The armature resistance R_A and constants K_1 and K_2 of a separately-excited dc motor are 0.2 Ω, 8 r/min/V, and 0.8 N·m/A (7.08 lbf·in/A), respectively. What are the speed n and torque T of this motor, knowing that the armature voltage E_A and current I_A are 300 V and 100 A, respectively?

   a. n = 2400 r/min, T = 80 N·m (708 lbf·in)
   b. n = 2240 r/min, T = 800 N·m (7080 lbf·in)
   c. n = 2240 r/min, T = 80 N·m (708 lbf·in)
   d. n = 2400 r/min, T = 240 N·m (2124 lbf·in)

5. The field current of a separately-excited dc motor operating with a fixed armature voltage and a fixed mechanical load is changed. This causes the speed to increase. The field current has been

   a. decreased.
   b. increased.
   c. This is not possible because the speed is independent of the field current.
   d. None of the above.

6. When the field current of a separately-excited dc motor is increased,

   a. constants K_1 and K_2 decrease.
   b. constant K_1 decreases and constant K_2 increases.
   c. constant K_1 increases and constant K_2 decreases.
   d. constants K_1 and K_2 increase.

7. The speed of a separately-excited dc motor

   a. increases linearly as the motor torque increases.
   b. decreases linearly as the motor torque increases.
   c. is constant as the motor torque increases.
   d. decreases rapidly and non linearly as the motor torque increases.

8. In a series motor, the field electromagnet consists of

   a. a winding connected in parallel with the armature.
   b. a winding connected in parallel with the armature and a second winding connected in series with the armature.
   c. a winding connected in series with the armature.
   d. a winding connected in series with a separate dc power source.

9. The voltage induced in a separately-excited dc generator (E_{EMF}) that rotates at a fixed speed of 1600 r/min is 600 V. This causes a current of 400 A to flow in the electrical load connected across the dc generator. What is the output voltage E_O of the generator knowing that its armature resistance is 0.15 Ω?

   a. $E_O = 360 \text{ V}$
   b. $E_O = 540 \text{ V}$
   c. $E_O = 600 \text{ V}$
   d. $E_O = 200 \text{ V}$

10. The output voltage E_O of a cumulative compound generator

    a. increases linearly as the output current I_O increases.
    b. decreases linearly as the output current I_O increases.
    c. varies little as the output current I_O increases.
    d. decreases rapidly and non linearly as the output current I_O increases.

Unit 3

Special Characteristics of DC Motors

UNIT OBJECTIVE

After completing this unit, you will be able to demonstrate and explain some of the special operating characteristics of dc motors.

DISCUSSION OF FUNDAMENTALS

In Unit 2 of this manual, you observed the main operating characteristics of a separately-excited dc motor, which can be considered as a linear voltage-to-speed converter and a linear current-to-torque converter. You also observed that the dc motor is a reversible converter able to convert electrical power to mechanical power, and vice-versa.

However, the operation of a dc motor is no longer linear when either the field or armature current exceeds its nominal value. When the field current is too high, the phenomenon of saturation in the iron of the dc machine occurs. Consequently, the flux of the fixed magnetic field in the dc machine no longer increases proportionally to the field current. When the armature current is too high, a phenomenon called armature reaction occurs. Armature reaction causes the flux of the fixed magnetic field in the dc machine to be modified, and thereby, changes the characteristic of torque versus armature current. It also causes a reduction in the induced voltage (E_{CEMF} or E_{EMF}, depending on whether the dc machine operates as a motor or a generator).

In Unit 2 of this manual, the operation of shunt and series dc motors connected to a dc power source has been observed. These two motors can also operate from ac power but their performance is poor. In this unit, you will observe that the addition of a special compensating winding allows acceptable performance to be obtained from a series motor operating from an ac power source. This type of series motor is called a universal motor.

Armature Reaction and Saturation Effect

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate some of the effects of armature reaction and saturation in dc machines using the DC Motor/Generator.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Armature reaction
- Saturation effect

DISCUSSION

Armature reaction

Previously, you saw that the rotation speed of a dc motor or generator is proportional to the armature voltage E_A, and that the torque is proportional to the armature current I_A. However, these two relationships no longer apply when the armature current I_A considerably increases and exceeds its nominal value. This is because the magnetic field produced by the armature starts to negatively affect the magnetic field produced by the field electromagnet. The effect of armature reaction on the output voltage of a dc generator is illustrated in Figure 3-1.

When the armature current I_A equals zero, the flux ϕ in the dc generator is horizontal, the commutator perfectly rectifies the voltage induced in the armature winding, and the dc generator output voltage is maximum, as shown in Figure 3-1a. However, when the armature current I_A does not equal zero, the magnetic fields produced by the armature and the field electromagnet add vectorially. The magnetic flux resulting from the interaction of both magnetic fields is no longer horizontal, as shown in Figure 3-1b, and the induced voltage is delayed. Since the instants of commutation have not changed, the average value of the rectified voltage (output voltage) is reduced. Along with producing a lower output voltage, commutation occurs at instants when the induced voltage is not zero, and thus, causes sparking at the brushes and commutator. This increases wear on the brushes and commutator. Another problem created by armature reaction is a decrease in the magnetic torque when the armature current I_A increases.

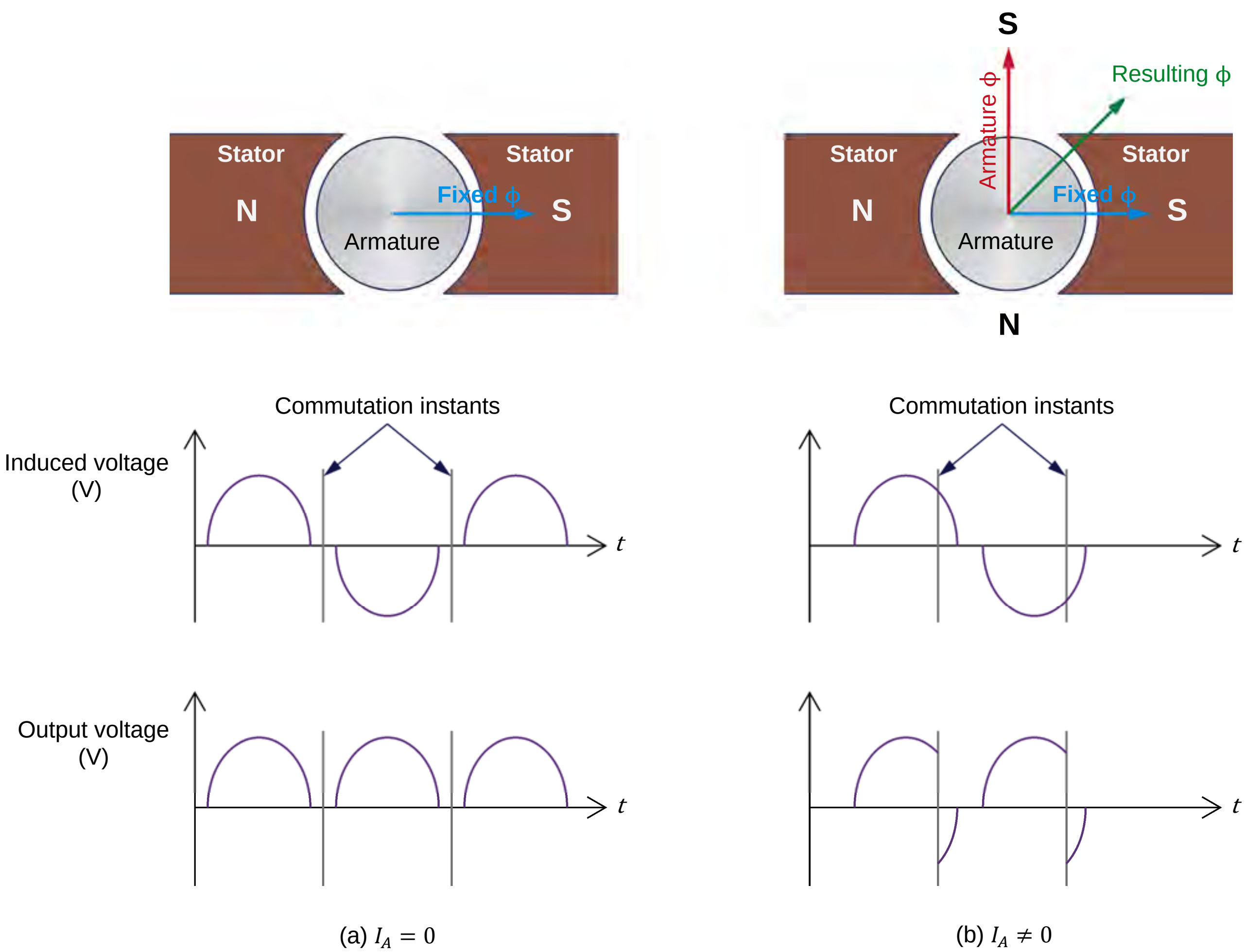


Figure 3-1. Effect of the armature reaction on the generator output voltage.

Figure 3-2a shows the effect of armature reaction on the output voltage-versus-output current relationship of a separately-excited dc generator. The dotted line is the voltage-versus-current relationship for a theoretical dc generator (without armature reaction, i.e., $E_O = E_{EMF} - R_A \cdot I_O$). The other curve is the actual voltage-versus-current relationship of the same generator, including armature reaction. As can be seen, armature reaction causes an additional decrease in the output voltage. This additional decrease becomes higher and higher as the output current increases.

Figure 3-2b shows the effect of armature reaction on the torque-versus-current relationship of a separately-excited dc machine. The dotted line is the theoretical (linear) torque-versus-current relationship, i.e., without armature reaction. The other curve is the actual relationship including armature reaction. As can be seen, armature reaction causes the torque to cease increasing linearly with current (I_A or I_O, depending on whether the dc machine operates as a motor or generator).

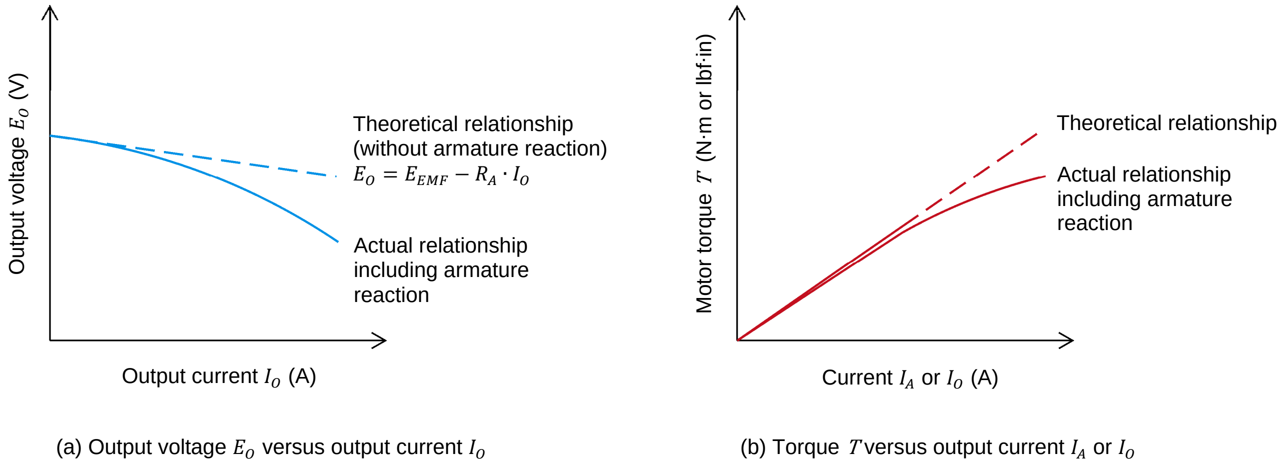


Figure 3-2. Effects of the armature reaction.

The most serious consequence of armature reaction is the increased wear on the brushes and the commutator caused by sparking. For small dc machines, commutation can be improved by shifting the position of the brushes, but this solution only applies to the exact operating point at which they are adjusted. If one wishes to change the direction of rotation or operate the dc machine as a generator, the brush position must be readjusted. To improve commutation, large motors include extra windings, called commutating windings, through which armature current flows. They are physically located so as to produce a magnetic field that causes a weak voltage to be induced in the armature coils being commutated. In this way, proper commutation is ensured independently of the value of the armature current, the direction of rotation, and the machine operation (motor or generator).

Commutation can also be improved by using a permanent-magnet dc motor because it exhibits almost no armature reaction for values of current up to five times greater than the nominal armature current. This is due to the fact that a permanent magnet can create a very powerful magnetic field that is almost completely immune to being affected by another magnetic source. The magnetic field produced by the armature, therefore, has very little effect on the overall magnetic field in the machine.

Another criteria which influences commutation is the inductance L_A of the armature winding. When the armature inductance is too large, commutation is difficult because current flow cannot stop and reverse instantly in inductors having a large inductance. The permanent-magnet dc motor has the particularity of having a small armature inductance which ensures better commutation. For these reasons, the characteristics of permanent-magnet dc motors exceed those of separately-excited, series, and shunt motors. However, it is not possible to build large-size permanent-magnet dc motors.

Saturation effect

As you saw previously, the field current I_f of a dc motor can be varied to modify the operating characteristics. For example, when I_f is decreased, the speed increases even though the armature voltage remains fixed. However, the motor torque developed for a given armature current decreases. As a result, the motor output power remains the same because it is proportional to the product of speed and torque.

Many times, it is desirable to have a motor that produces a maximum value of torque at low speed. To obtain such a motor, the strength of the field electromagnet must be increased (higher field current I_f), as well as the strength of the rotating electromagnet in the armature (higher armature current I_A). However, the armature current must be limited to prevent overheating. Furthermore, the field current must also be limited to prevent saturation. When one starts to increase the field current, constant K_2 increases proportionally. However, once the field current exceeds a certain value, saturation in the iron of the machine starts to occur. As a result, the strength of the field electromagnet no longer increases proportionally to the field current. Figure 3-3 illustrates how the torque produced by a dc motor increases when the field current I_f increases and the armature current I_A remains at a fixed value.

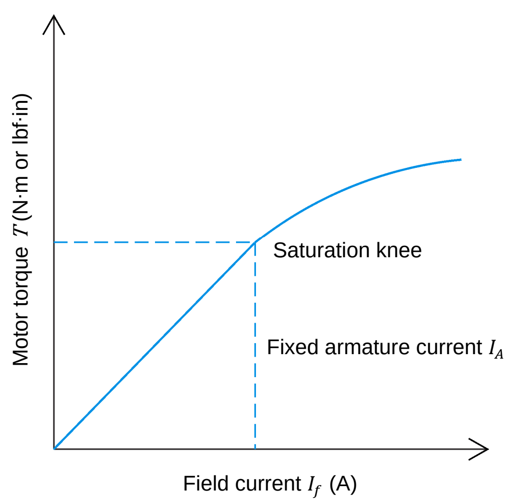


Figure 3-3. Effect of saturation on the torque of a dc motor.

As can be seen, the curve of the torque T versus the field current I_f flattens out for higher values of I_f. The extra increase in torque for additional increases in field current becomes smaller once the saturation knee is exceeded. Higher values of field current also produce more heating in the motor. Usually, the nominal value of the field current is chosen to be just at the beginning of the saturation knee to obtain as much torque as possible with a field current that is as low as possible.

This same characteristic can be visualized using a dc motor as a generator because the stronger the field electromagnet, the higher the induced voltage E_{EMF} at a given speed, and the higher the output voltage E_O. Figure 3-4 shows the relationship between the output voltage E_O and field current I_f for a fixed speed.

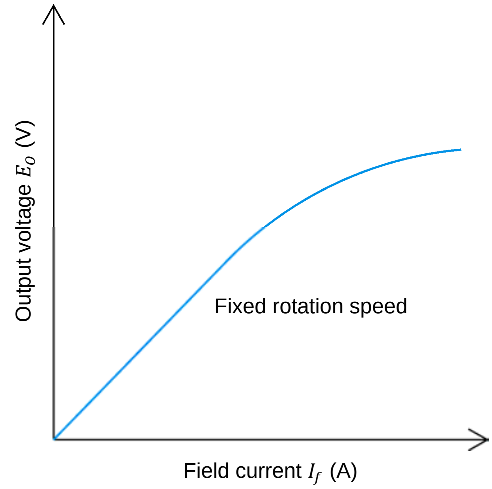


Figure 3-4. Effect of saturation on the output voltage of a dc generator.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Effect of the armature reaction on the output voltage of a dc generator
- Set up and connections
- Effect of the armature reaction on torque
- Effect of the saturation on torque
- Additional experiment (optional)
  Effect of the armature reaction on the torque developed by a dc motor.

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.

Effect of the armature reaction on the output voltage of a dc generator

In this section, you will perform calculations with data obtained in Exercises 2-1 and 2-3. You will use the results of these calculations to draw on Graph G232-1 the theoretical output voltage-versus-output current relationship of the separately-excited dc generator used in Exercise 2-3. This will allow you to illustrate the effect of armature reaction on the output voltage of a dc generator.

1. Record in the following blank the armature resistance R_A of the DC Motor/Generator measured in Exercise 2-1.

   Armature resistance R_A = _______ Ω

2. Refer to graph G232-1 obtained in Exercise 2-3. This graph shows the output voltage-versus-output current relationship of a separately-excited

dc generator operating at a fixed speed. Record the no-load generator output voltage (voltage obtained when the dc generator output current $I_O = 0\ \mathrm{A}$) in the following blank (this voltage is recorded in data table DT232). This voltage is equal to the voltage induced across the armature winding of the dc generator (E_{EMF}).

E_{EMF} = _______ V

3. Calculate the dc generator output voltage E_O for each of the output currents I_O indicated in Table 3-1 for your local ac power network, using the following equation:

$$E_O = E_{EMF} - R_A \cdot I_O$$

Table 3-1. DC generator output currents.

Local ac power network		DC generator output current I_O (A)			
Voltage (V)	Frequency (Hz)				
120	60	0.5	1.0	1.5	2.0
220	50	0.25	0.5	0.75	1.0
240	50	0.25	0.5	0.75	1.0
220	60	0.25	0.5	0.75	1.0

When I_O = _______ A, E_O = _______ V

When I_O = _______ A, E_O = _______ V

When I_O = _______ A, E_O = _______ V

When I_O = _______ A, E_O = _______ V

4. Use the dc generator output voltages and currents obtained in the previous step to plot on graph G232-1 the theoretical output voltage-versus-output current relationship of the separately-excited dc generator.

Compare the theoretical and actual voltage-versus-current relationships plotted on graph G232-1. Does this demonstrate that the armature reaction causes an additional decrease in the output voltage as the output current increases?

❑ Yes ❑ No

Set up and connections

In this section, you will mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply and set up the equipment.

5. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the exercise. Install the equipment in the Workstation.

Before performing the exercise, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect a variable-voltage 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 and Control Interface (DACI). Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to voltage input E1 of the DACI. In LVDAC-EMS, open the Metering window. Set two meters to measure the rms values (ac) of the armature voltage E_A and armature current I_A at inputs E1 and I1 of the DACI, respectively. Turn the Power Supply on and adjust its voltage control knob so that an ac current (indicated by meter I1 in the Metering window) equal to half the nominal 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 E1 in the Metering window) is minimal. Turn the Power Supply off, close LVDAC-EMS, and disconnect all leads and cable.

Mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

WARNING

Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

6. Make sure that the main power switch of the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power wall outlet.

7. On the Power Supply, make sure that the main power switch and the 24 V ac power switch are set to the O (off) position, and that the voltage control knob is set to 0% (turned fully counterclockwise). Connect the Power Supply to a three-phase ac power outlet.

8. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24 V ac power source of the Power Supply.

Turn the 24 V ac power source of the Power Supply on.

9. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

10. Connect the equipment as shown in Figure 3-5. Use the fixed dc voltage output of the Power Supply to implement the fixed-voltage dc power source. *I1* and *I2* are current inputs of the Data Acquisition and Control Interface (DACI). Notice that no electrical load is connected to the generator output.

If your local ac power network voltage is 120 V, use the 40-A current range on the Data Acquisition and Control Interface for current input I1.

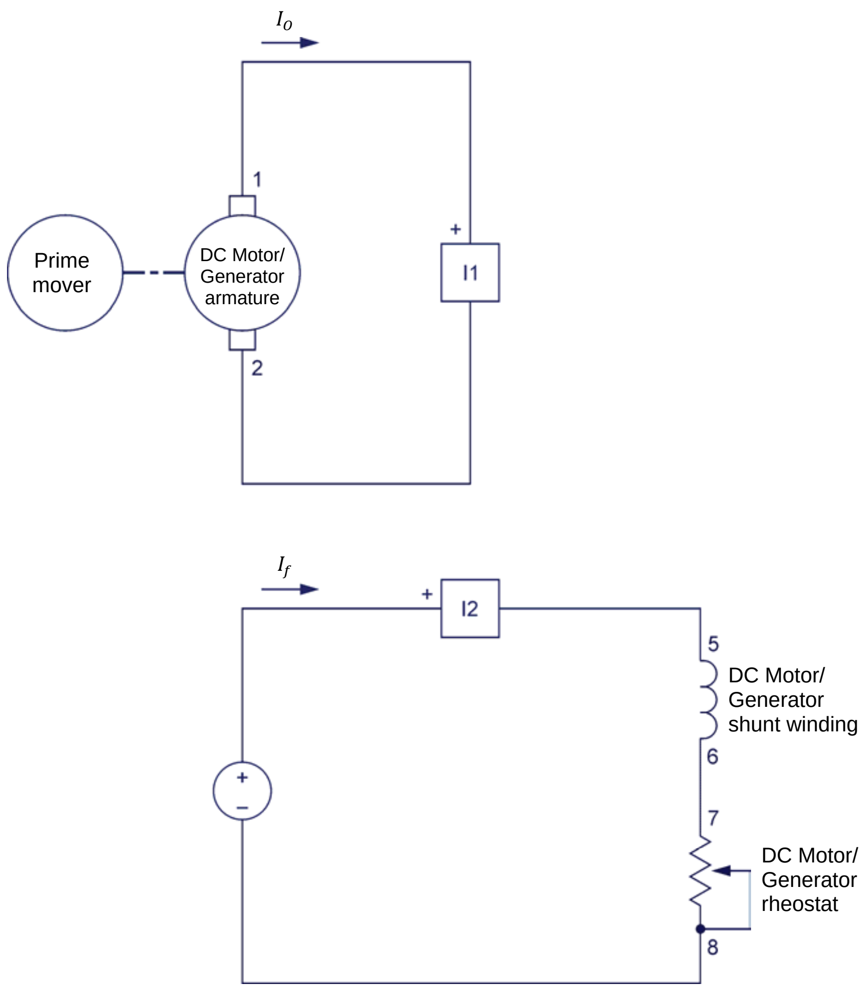


Figure 3-5. Separately-excited dc generator coupled to a prime mover.

11. On the Four-Quadrant Dynamometer/Power Supply, set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

Turn the Four-Quadrant Dynamometer/Power Supply on by setting the main power switch to the I (on) position.

12. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure that the *Computer-Based Instrumentation* function is available for the Data Acquisition and Control Interface module. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

If your local ac power network voltage is 120 V, set the Range of current input I1 to 40 A in the Data Acquisition and Control Settings window of LVDAC-EMS.

13. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

– Set the *Function* parameter to *CW Constant-Speed Prime Mover/Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a clockwise prime mover/brake with a speed setting corresponding to the *Speed* parameter.

– Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test (i.e., the DC Motor/Generator), respectively.

– Make sure that the *Speed Control* parameter is set to *Knob*. This allows the speed of the clockwise prime mover/brake to be controlled manually.

– Set the *Speed* parameter (i.e., the speed command) to 0 r/min. Notice that the speed command is the targeted speed at the shaft of the machine coupled to the prime mover, i.e., the speed of the DC Motor/Generator in the present case.

The speed command can also be set by using the Speed control knob in the Four-Quadrant Dynamometer/Power Supply window.

14. In LVDAC-EMS, open the Metering window. Set two meters to measure the dc generator output current I_O (*I1*) and field current I_f (*I2*).

Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the Metering application.

Effect of the armature reaction on torque

In this section, you will set the field current of the separately-excited dc generator. You will vary the output current of the dc generator from zero to twice its nominal value to obtain the necessary data to plot a graph of the torque applied to the dc generator's shaft versus the dc generator output current I_O. This will allow you to demonstrate the effect of armature reaction on the torque-versus-current relationship of a dc machine.

15. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the dc generator output current I_o and field current I_f (indicated by meters *I1* and *I2* in the Metering window), as well as the dc generator rotation speed n and torque T (indicated by the *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply window).

16. In the Four-Quadrant Dynamometer/Power Supply window, start the *CW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

Turn the Power Supply on by setting the main power switch to I (on).

17. On the DC Motor/Generator, set the *Field Rheostat* knob so that the dc generator field current I_f (meter *I2*) is equal to the value given in Table 3-2 for your local ac power network.

Table 3-2. Field current I_f and maximum dc generator output current I_O.

Local ac power network		Field current I_f (mA)	Maximum dc generator output current I_O (A)
Voltage (V)	Frequency (Hz)		
120	60	250	5.0
220	50	160	2.2
240	50	175	2.0
220	60	160	2.2

18. By using the *Speed* parameter in the Four-Quadrant Dynamometer/Power Supply window, gradually increase the prime mover speed to increase the dc generator output current I_o (meter *I1*) from 0 A to the maximum value indicated in Table 3-2 for your local ac power network, in about 10 steps. For each current setting, record the dc generator output current I_o and field current I_f, as well as the dc generator speed n and torque T in the Data Table.

CAUTION

The output current exceeds the rated armature current of the DC Motor/Generator while performing this manipulation. It is, therefore, suggested to complete the manipulation within a time interval of 5 minutes or less.

19. When all data has been recorded, stop the prime mover by setting the *Speed* parameter in the Four-Quadrant Dynamometer/Power Supply window to 0 r/min. Stop the *CW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Stopped*.

Turn the Power Supply off by setting its main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Data Table window, confirm that the data has been stored. Reverse the polarity of the torque values recorded in the data table to obtain the torque applied to the dc generator's shaft. Save the data file under filename DT311, and print the data table if desired.

20. In the Graph window, make the appropriate settings to obtain a graph of the torque applied to the dc generator's shaft as a function of the dc generator output current I_O. Name the graph "G311", name the x-axis "DC generator output current", name the y-axis "Torque applied to the dc generator's shaft", and print the graph if desired.

Can we say that the variation in torque is linear when the dc generator output current I_O exceeds the nominal armature current of the DC Motor/Generator?

❑ Yes ❑ No

In the Data Table, clear the recorded data.

Effect of the saturation on torque

In this section, you will vary the field current of a separately-excited dc motor from zero to approximately 175% of its nominal value, while maintaining a fixed armature current, to obtain the necessary data to plot a graph of the motor torque T versus the field current I_f. This will allow you to demonstrate the effect of saturation in dc machines.

21. Modify the connections to obtain the separately-excited dc motor circuit shown in Figure 3-6. Use the variable dc voltage output of the Power Supply to implement the variable-voltage dc power source E_S. *E1*, *I1*, and *I2* are voltage and current inputs of the Data Acquisition and Control Interface (DACI). Use the Resistive Load module to implement resistor R_1. Connect the three resistor sections of the Resistive Load module in parallel, and set the levers of all toggle switches to the *I* (on) position. Using a connection lead, short circuit resistor R_1 for now, as indicated by the dashed line in Figure 3-6.

Use the 4-A current range on the Data Acquisition and Control Interface for both current inputs I1 and I2. In the Data Acquisition and Control Settings window of LVDAC-EMS, make sure that the Range of current inputs I1 and I2 are set to 4 A.

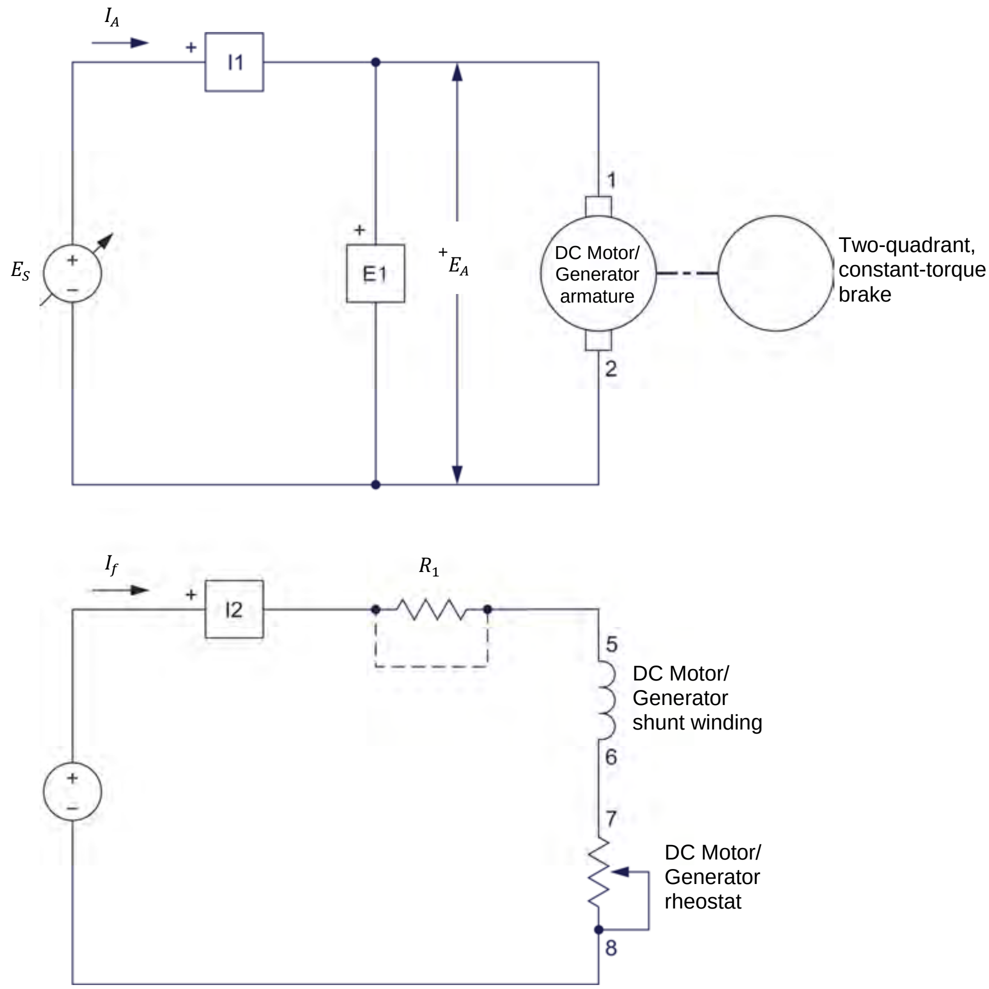


Figure 3-6. Separately-excited dc motor coupled to a brake.

22. On the DC Motor/Generator, turn the *Field Rheostat* knob fully clockwise.

23. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

– Set the *Function* parameter to *Two-Quadrant, Constant-Torque Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a two-quadrant brake with a torque setting corresponding to the *Torque* parameter.

– Make sure that the *Pulley Ratio* parameter is set to 24:24.

– Make sure that the *Torque Control* parameter is set to *Knob*.

– Set the *Torque* parameter to the maximum value (3.0 N·m or 26.5 lbf·in). This sets the torque command of the *Two-Quadrant, Constant-Torque Brake* to 3.0 N·m (26.5 lbf·in).

The torque command can also be set by using the Torque control knob in the Four-Quadrant Dynamometer/Power Supply window.

– In the Four-Quadrant Dynamometer/Power Supply window, start the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

24. In the Metering window, make sure that the meters are set to measure the dc motor armature voltage E_A (*E1*), armature current I_A (*I1*), and field current I_f (*I2*).

Make sure that the Data Table is set to record the dc motor armature voltage E_A (*E1*), armature current I_A (*I1*), and field current I_f (*I2*), as well as the dc motor speed n and torque T (indicated by the *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply window).

On the Power Supply, make sure that the voltage control knob is set to 0%. Turn the Power Supply on by setting the main power switch to I (on), then adjust its voltage control knob so that the dc motor armature current I_A (indicated by meter *I1*) is equal to 50% of the nominal value. Record the dc motor armature voltage E_A, armature current I_A, and field current I_f, as well as the dc motor speed n and torque T in the Data Table.

25. Decrease the field current I_f by steps, as indicated in Table 3-3 for your local ac power network. For each current setting, readjust the voltage control knob of the Power Supply so that the armature current I_A remains equal to 50% of the nominal value, then record the dc motor armature voltage E_A, armature current I_A, and field current I_f, as well as the dc motor speed n and torque T in the Data Table.

To decrease the field current I_f first use the Field Rheostat knob on the DC Motor/Generator only. Once this button has reached the fully counterclockwise position, insert resistor R_1 into the circuit to be able to further decrease field current I_f to the lowest values in Table 3-3, using the following steps:

- *On the Power Supply, set the main power to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).*
- *Insert resistor R_1 into the circuit by removing the lead short-circuiting this resistor.*
- *On the Power Supply, set the main power to the I (on) position.*
- *Set the resistance of resistor R_1 (by changing the settings of the toggle switches on the Resistive Load module) and the field rheostat knob on the DC Motor/Generator to decrease field current I_f to the lowest values indicated in Table 3-3.*

CAUTION

The field current I_f exceeds the nominal value of the DC Motor/Generator in this manipulation. It is therefore suggested to perform this manipulation within 10 minutes.

Table 3-3. Field currents of the separately-excited dc motor.

Local ac power network		Field current I_f (mA)							
Voltage (V)	Frequency (Hz)								
120	60	450	400	350	300	250	200	150	100
220	50	285	255	220	190	160	130	95	65
240	50	315	280	245	210	175	140	105	70
220	60	285	255	220	190	160	130	95	65

26. On the Resistive Load module, set the resistor value to the maximum value indicated in Table 3-4 for your local ac power network. On the DC Motor/Generator, turn the *Field Rheostat* knob fully counterclockwise, readjust the voltage control knob of the Power Supply so that the armature current I_A remains equal to 50% of the nominal value, then record the dc motor armature voltage E_A, armature current I_A, and field current I_f, as well as the dc motor speed n and torque T in the Data Table.

Appendix C of this manual lists the switch settings and connections to be performed on the Resistive Load module in order to obtain the various resistance values.

Table 3-4. Maximum resistance value for R_1.

Local ac power network		R_1 (Ω)
Voltage (V)	Frequency (Hz)	
120	60	1200
220	50	4400
240	50	4800
220	60	4400

27. Stop the DC Motor/Generator by setting the voltage control knob of the Power Supply to 0% and the main power switch of the Power Supply to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

In the Four-Quadrant Dynamometer/Power Supply window, set the *Torque* parameter to 0.0 N·m (0.0 lbf·in), then click the *Start/Stop* button in this window to stop the *Two-Quadrant, Constant-Torque/Brake*.

In the Data Table window, confirm that the data has been stored. Save the data table under filename DT312, and print the data table if desired.

28. In the Graph window, make the appropriate settings to obtain a graph of the dc motor torque as a function of the field current I_f. Name the graph "G312", name the x-axis "Field current", name the y-axis "Motor torque", and print the graph if desired.

Observe graph G312. How does the dc motor torque vary as the field current increases?

____

____

Briefly explain what happens when the field current I_f exceeds the nominal value.

The nominal value of the field current I_f for your local ac power network is indicated in Table 2-1 of Exercise 2-1.

____

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If you want to perform the additional experiments, skip the next step, then return to it when all additional manipulations are finished.

29. On the Power Supply, make sure that the main power switch is set to the O (off) position, then turn the 24 V ac power source off. Close the LVDAC-EMS software. Turn the Four-Quadrant Dynamometer/Power Supply off. Disconnect all leads and return them to their storage location.

Additional experiment (optional)

Effect of the armature reaction on the torque developed by a dc motor

You can observe the effect which armature reaction has on the torque-versus-current characteristic of a separately-excited dc motor. To do so, refer to graph G212. This graph shows the torque-versus-current characteristic of the separately-excited dc motor used in Exercise 2-1. Observe that the torque-versus-current characteristic is no longer linear for high armature currents.

Conclusion

In this exercise, you saw that armature reaction in dc machines causes the output voltage of a generator to decrease rapidly as the armature current increases. You observed that motor torque is also affected in the same manner. You saw that the torque ceases to increase linearly with the field current when the iron in the dc machine begins to saturate.

If you performed the additional experiment, you observed that armature reaction affects the torque-versus-current characteristic of a separately-excited dc motor.

Review Questions

1. What is the most serious consequence of armature reaction in dc machines?

____

____

2. How does armature reaction affect the output voltage of a dc generator?

____

3. How does armature reaction affect the torque of a dc motor?

____

4. Why does a permanent-magnet dc motor have better commutation than a conventional dc motor?

____

5. Do the brushes on a dc machine having commutating windings have to be readjusted for different operating points?

____

The Universal Motor

EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to demonstrate both ac and dc operation of universal motors.

DISCUSSION

You saw in Unit 2 that the armature winding creates a rotating magnetic field in the rotor of a dc motor. This magnetic field rotates at the same speed as the motor but in the opposite direction. As a result, the poles of the rotor electromagnet remain at a fixed location. Furthermore, the poles of the rotor electromagnet are always at 90° to the poles of the stator magnet or electromagnet (field electromagnet), as was illustrated in Figure 2-4.

However, if either the polarity of the stator electromagnet or that of the rotor electromagnet is reversed, the motor direction of rotation is reversed because the forces of attraction and repulsion between the two magnets are reversed. Figure 3-7 illustrates the different possibilities when the polarities of the armature current I_A and field current I_f are changed. When currents I_A and I_f are of the same polarity, the motor rotates clockwise. Conversely, when currents I_A and I_f are of opposite polarity, it rotates counterclockwise.

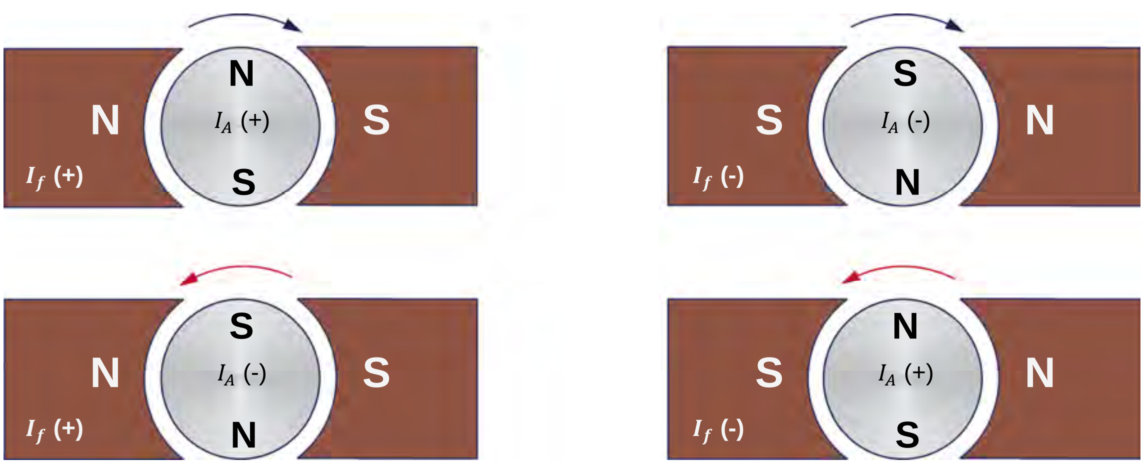


Figure 3-7. The direction of rotation depends on the polarities of the armature and field currents.

When both the armature and the field electromagnet of a dc motor are powered from the same source, which is the case for shunt and series motors, reversing the polarity of the voltage source reverses the polarity of both the armature and field currents. Consequently, the torque does not change direction when the polarity of the voltage applied to the motor changes. Therefore, shunt and series dc motors rotate when connected to an ac power source despite the fact that the source voltage polarity is constantly changing.

However, since motors are made of windings and iron, they always have inductance associated with their windings. For example, the field winding of a shunt motor usually has a large inductance value because it consists of many turns of wire. This makes it difficult for alternating current to flow in the winding because a large inductance means a high impedance. For this reason, it is almost impossible to obtain satisfactory performance from a shunt motor connected to an ac power source.

A series motor has a field winding that consists of only a few turns of wire. Consequently, the field winding of the series motor has a low inductance. Its impedance is therefore much lower than that of the shunt winding, and the series motor operates on ac power with better results than a shunt motor. However, the performance obtained with ac power is naturally much poorer than that obtained when the series motor is connected to a dc power source.

The performance of a series motor operating with ac power can be greatly improved by decreasing the inductance of the armature winding. This can be done by adding a new winding, called compensating winding, to the series motor. This winding is installed in the stator slots and the armature current flows through the winding. The wire loops of the compensating winding are connected so that the direction of current flow in each loop is opposite to the direction of current flow in the corresponding armature loop lying next to it, as illustrated in Figure 3-8.

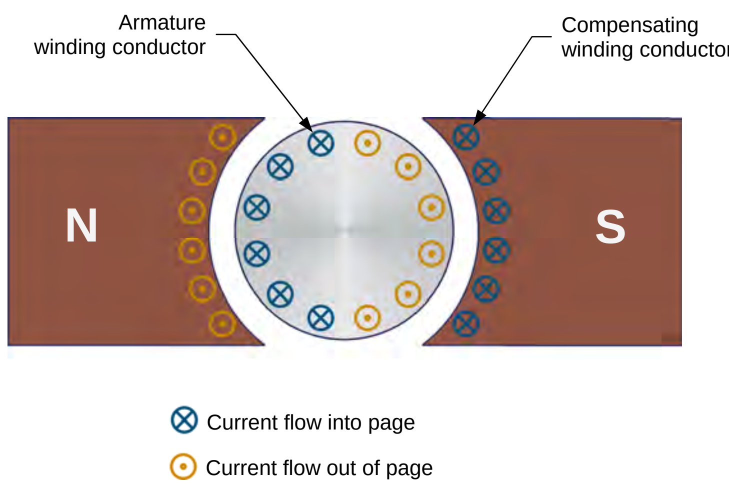


Figure 3-8. Current flow in the compensating winding.

This is equivalent to winding the coil of an inductor with ten turns of wire in one direction, and then ten turns of wire in the opposite direction. The resulting inductor has a very small inductance because of the cancelling effect caused by equal number of coils being wound in opposite directions. This new type of series motor is known as a universal motor because it can operate indifferently on ac power, as well as dc power.

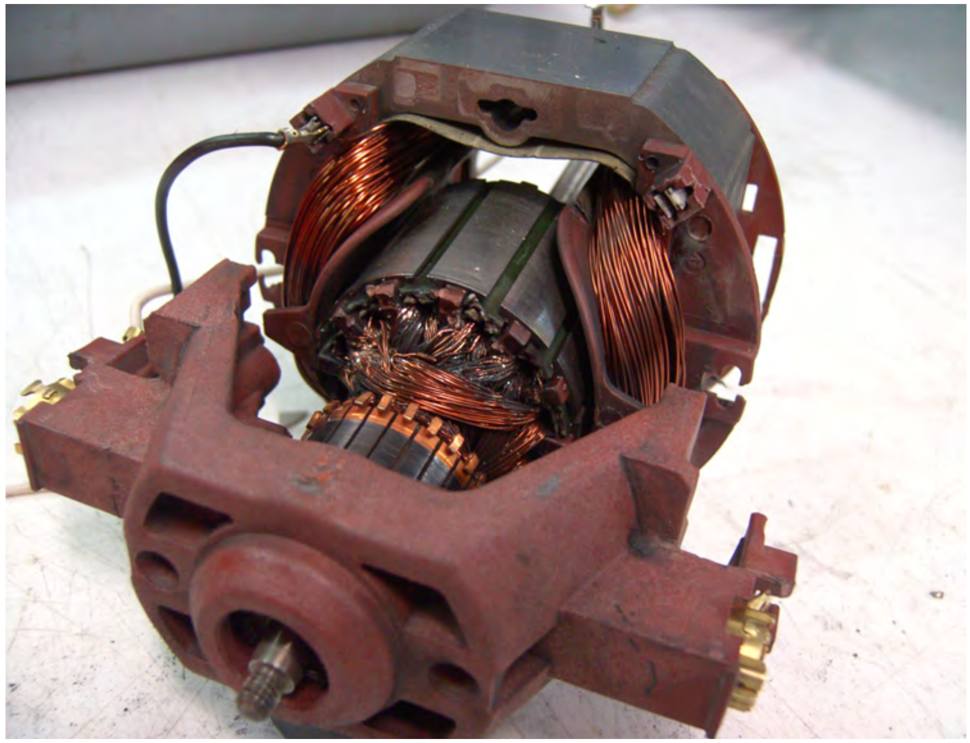


Figure 3-9. Example of a universal motor used in a vacuum cleaner (photo courtesy of Marrrci).

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
- Direction of rotation of a dc series motor
- DC series motor operating on ac power
- Direction of rotation of a universal motor operating on dc power
- Universal motor operating on ac power
- Effect of the compensating winding
- Additional experiments (optional)
  Speed-versus-torque characteristic of an ac-powered universal motor.
  DC shunt motor operating on ac power.

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.

Set up and connections

In this section, you will mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply and set up the equipment.

1. Refer to the Equipment Utilization Chart in Appendix A to obtain the list of equipment required to perform the exercise. Install the equipment in the Workstation.

   Before performing the exercise, ensure that the brushes of the DC Motor/Generator are adjusted to the neutral point. To do so, connect a variable-voltage 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 and Control Interface (DACI). Connect the shunt winding of the DC Motor/Generator (terminals 5 and 6) to voltage input E1 of the DACI. In LVDAC-EMS, open the Metering window. Set two meters to measure the rms values (ac) of the armature voltage E_A and armature current I_A at inputs E1 and I1 of the DACI, respectively. Turn the Power Supply on and adjust its voltage control knob so that an ac current (indicated by meter I1 in the Metering window) equal to half the nominal 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 E1 in the Metering window) is minimal. Turn the Power Supply off, close LVDAC-EMS, and disconnect all leads and cable.

   Also, ensure that the brushes of the Universal Motor are adjusted to the neutral point. To do so, repeat the above procedure, connecting the series winding of the Universal Motor to voltage input E1 of the DACI.

   Mechanically couple the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply using a timing belt.

   ⚠ WARNING

   Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

2. Make sure that the main power switch of the Four-Quadrant Dynamometer/Power Supply is set to the O (off) position, then connect its *Power Input* to an ac power wall outlet.

3. On the Power Supply, make sure that the main power switch and the 24 V ac power switch are set to the O (off) position, and that the voltage control knob is set to 0% (turned fully counterclockwise). Connect the Power Supply to a three-phase ac power outlet.

4. Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to the 24 V ac power source of the Power Supply.

   Turn the 24 V ac power source of the Power Supply on.

5. Connect the USB port of the Data Acquisition and Control Interface to a USB port of the host computer.

Connect the USB port of the Four-Quadrant Dynamometer/Power Supply to a USB port of the host computer.

6. Connect the equipment as shown in Figure 3-10. Use the variable dc voltage output of the Power Supply to implement the variable-voltage dc power source E_S. *E1*, *I1* and *I2* are voltage and current inputs of the Data Acquisition and Control Interface (DACI).

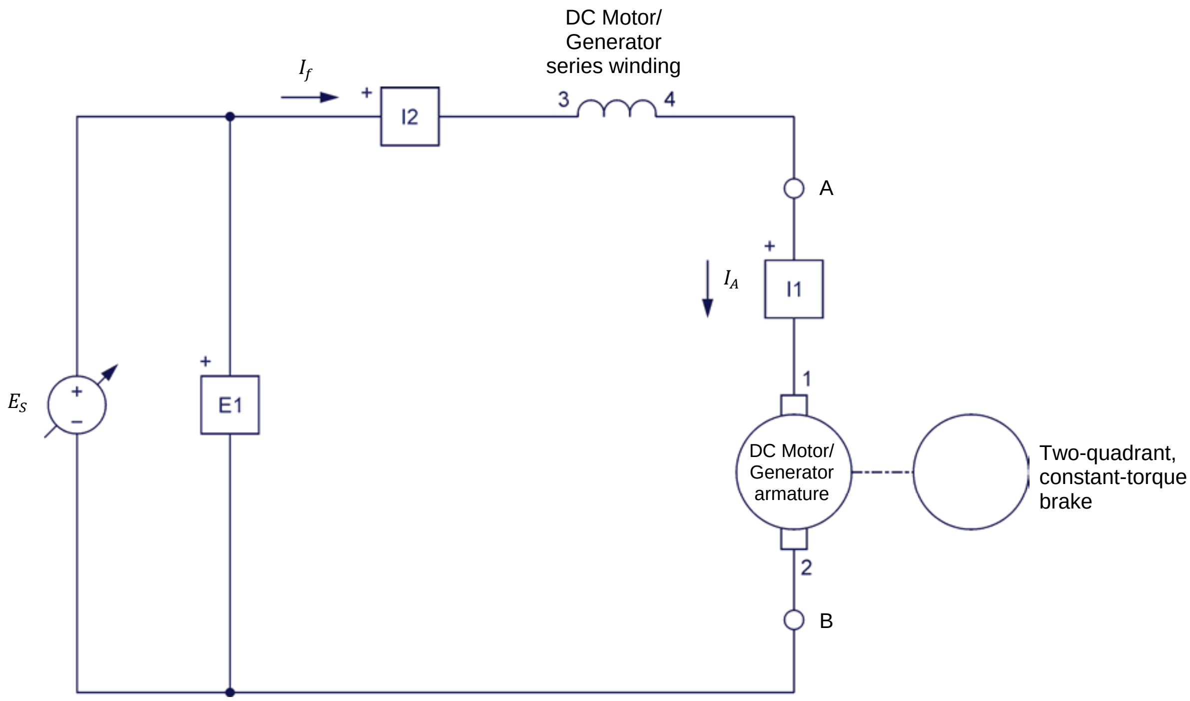


Figure 3-10. Series motor coupled to a brake.

7. On the Four-Quadrant Dynamometer/Power Supply, set the *Operating Mode* switch to *Dynamometer*. This setting allows the Four-Quadrant Dynamometer/Power Supply to operate as a prime mover, a brake, or both, depending on the selected function.

Turn the Four-Quadrant Dynamometer/Power Supply on by setting the main power switch to the I (on) position.

8. Turn the host computer on, then start the LVDAC-EMS software.

In the LVDAC-EMS Start-Up window, make sure that the Data Acquisition and Control Interface and the Four-Quadrant Dynamometer/Power Supply are detected. Make sure that the *Computer-Based Instrumentation* function is available for the Data Acquisition and Control Interface module. Select the network voltage and frequency that correspond to the voltage and frequency of the local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

9. In LVDAC-EMS, open the Four-Quadrant Dynamometer/Power Supply window, then make the following settings:

– Set the *Function* parameter to *Two-Quadrant, Constant-Torque Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a two-quadrant brake with a torque setting corresponding to the *Torque* parameter.

– Set the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test (i.e., the DC Motor/Generator), respectively.

– Make sure that the *Torque Control* parameter is set to *Knob*. This allows the torque of the two-quadrant brake to be controlled manually.

– Set the *Torque* parameter to 0.0 N·m (0.0 lbf·in).

The torque command can also be set by using the Torque control knob in the Four-Quadrant Dynamometer/Power Supply window.

– Start the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

10. In LVDAC-EMS, open the Metering window. Set a meter to record the dc source voltage E_S (*E1*). Set two meters to measure the dc motor armature current I_A (*I1*) and field current I_f (*I2*).

Click the *Continuous Refresh* button to enable continuous refresh of the values indicated by the various meters in the Metering application.

Direction of rotation of a dc series motor

In this section, you will change the polarities of the armature and field currents of a series motor operating on dc power and observe the effect on the direction of rotation. You will also measure the dc voltage required to make the series motor rotate at a speed of approximately 1000 r/min.

11. Turn the Power Supply on by setting the main power switch to the I (on) position. Slowly turn the voltage control knob of the Power Supply until the series motor rotates at a speed of 1000 r/min $\pm$ 25 r/min. Check that both the armature current I_A and field current I_f (indicated by meters *I1* and *I2*, respectively) are of positive polarity. Record the source voltage E_S (indicated by meter *E1*) and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A and I_f of positive polarity)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

12. On the Power Supply, reverse the connection of the leads at terminals *7* and *N* to reverse the polarity of the voltage applied to the series motor.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob until the series motor rotates at a speed of 1000 r/min $\pm$ 25 r/min. Check that the armature current I_A and the field current I_f are of negative polarity. Record the source voltage E_S (indicated by meter *E1*) and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A and I_f of negative polarity)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

What is the direction of rotation when the armature current I_A and the field current I_f are of the same polarity?

____

13. Reverse the connections of the leads at points A and B shown in Figure 3-10.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob so that the series motor rotates at a speed of 1000 r/min $\pm$ 25 r/min.

Neglect the sign of the speed indicated by the Speed meter in the Four-Quadrant Dynamometer/Power Supply window.

Check that the armature current I_A is positive and the field current I_f is negative. Record the source voltage E_S and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A is positive, I_f is negative)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

14. On the Power Supply, reverse the connection of the leads at terminals *7* and *N* to reverse the polarity of the voltage applied to the series motor.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob so that the series motor rotates at a speed of 1000 r/min $\pm$ 25 r/min.

Neglect the sign of the speed indicated by the Speed meter in the Four-Quadrant Dynamometer/Power Supply window.

Check that the armature current I_A is negative and the field current I_f is positive. Record the source voltage E_S and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A is negative, I_f is positive)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

What is the direction of rotation when the armature current I_A and the field current I_f are of opposite polarity?

____

15. Reverse the connection of the leads at points A and B shown in Figure 3-10. The modules should be connected as shown in Figure 3-10.

DC series motor operating on ac power

In this section, you will replace the dc power source with an ac power source. You will observe that the direction of rotation of the series motor can be changed by reversing the armature connections. You will measure the ac source voltage required to make the series motor rotate at a speed of approximately 1000 r/min. You will measure the armature impedance Z_A. You will compare the series motor performance obtained with dc power and ac power

16. Replace the variable-voltage dc power source in the circuit with a variable-voltage ac power source (terminals *4* and *N* of the Power Supply).

In the Metering window, set the meters used to measure the source voltage E_S (*E1*), armature current I_A (*I1*), and field current I_f (*I2*) to display rms values (ac).

17. Turn the Power Supply on by setting the main power switch to the I (on) position. Slowly turn the voltage control knob until the series motor rotates at a speed of 1000 r/min $\pm$ 25 r/min. Record the source voltage E_S (indicated by meter *E1*) and the direction of rotation.

Source voltage $E_S, rms =$ _______ V

Direction of rotation = _____________ (I_A and I_f of the same polarity)

Does the series motor rotate in the same direction as when it was operating on dc power with currents I_A and I_f of the same polarity (steps 11 and 12)?

❑ Yes ❑ No

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

18. Reverse the connections of the leads at points A and B shown in Figure 3-10.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob so that the series motor rotates at a speed of 1000 r/min $\pm$ 25 r/min.

Neglect the sign of the speed indicated by the Speed meter in the Four-Quadrant Dynamometer/Power Supply window.

Record the source voltage E_S and the direction of rotation.

Source voltage $E_S, rms =$ _______ V

Direction of rotation = ______________ (I_A and I_f of opposite polarity)

Does the series motor rotate in the same direction as when it was operating on dc power with I_A and I_f of opposite polarity (steps 13 and 14)?

❑ Yes ❑ No

19. On the Power Supply, slowly turn the voltage control knob counterclockwise until the series motor stops rotating.

In the Metering window, set a meter to measure impedance from inputs *E1* and *I1* [meter *RXZ (E1,I1)*]. On this meter, select the *Z* mode to measure impedance by clicking on the meter *Mode* button.

Record in the following blank the armature impedance Z_A of the series motor indicated by meter *RXZ (E1,I1)*.

Armature impedance $Z_A =$ _______ Ω

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

Compare the dc and ac source voltages E_S required to make the series motor rotate at a speed of approximately 1000 r/min. Briefly explain why they have different values.

____

____

____

20. In the Four-Quadrant Dynamometer/Power Supply window, stop the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Stopped* or by clicking the *Start/Stop* button.

Direction of rotation of a universal motor operating on dc power

In this section, you will modify the connections to obtain the Universal Motor circuit shown in Figure 3-11. You will change the polarities of the armature and field currents of the Universal Motor operating on dc power and observe the effect on the direction of rotation. You will also measure the dc voltage required to make the Universal Motor rotate at a speed of approximately 1000 r/min.

21. Remove the timing belt which couples the DC Motor/Generator to the Four-Quadrant Dynamometer/Power Supply.

⚠ WARNING

Before coupling rotating machines, make absolutely sure that power is turned off to prevent any machine from starting inadvertently.

Mechanically couple the Universal Motor to the Four-Quadrant Dynamometer/Power Supply.

22. Modify the connection to obtain the universal-motor circuit shown in Figure 3-11. Use the variable dc voltage output of the Power Supply to implement the variable-voltage dc power source E_S. *E1*, *I1* and *I2* are voltage and current inputs of the Data Acquisition and Control Interface (DACI).

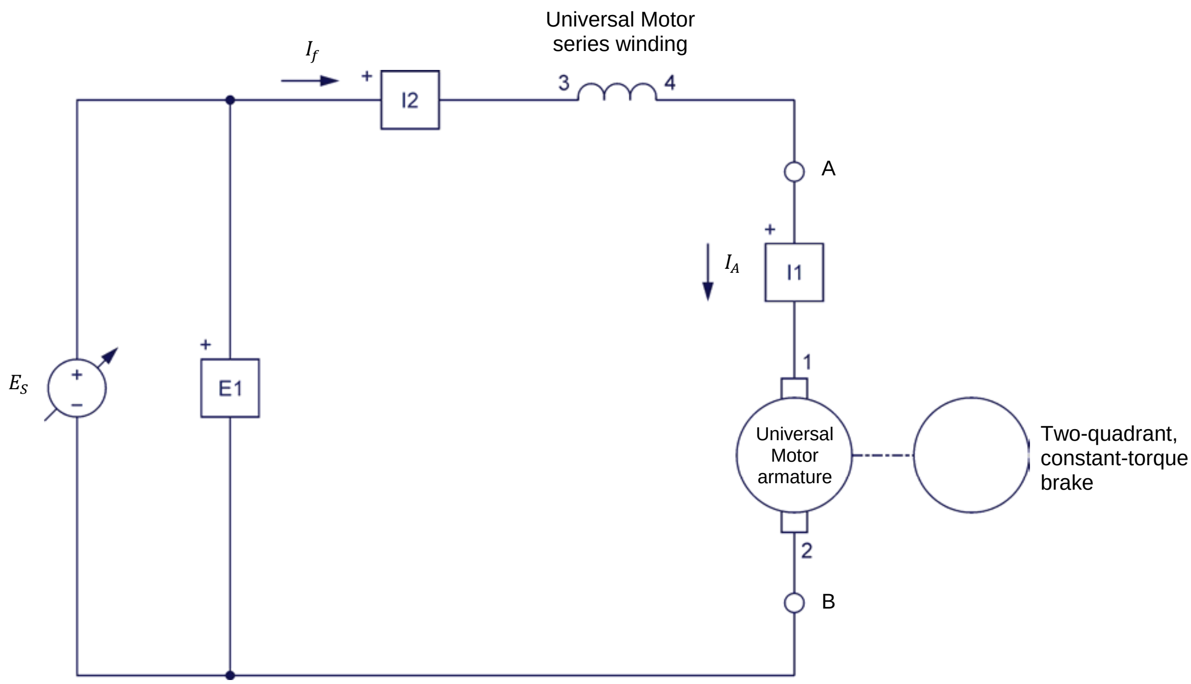


Figure 3-11. DC-powered universal motor coupled to a brake.

23. In the Four-Quadrant Dynamometer/Power Supply window, make the following settings:

– Make sure that the *Function* parameter is set to *Two-Quadrant, Constant-Torque Brake*.

– Make sure that the *Pulley Ratio* parameter to 24:24. The first and second numbers in this parameter specify the number of teeth on the pulley of the Four-Quadrant Dynamometer/Power Supply and the number of teeth on the pulley of the machine under test (i.e., the Universal Motor), respectively.

– Set the *Torque* parameter to 0.0 N·m (0.0 lbf·in). This sets the torque command of the *Two-Quadrant, Constant-Torque Brake* to 0.0 N·m (0.0 lbf·in).

The torque command can also be set by using the Torque control knob in the Four-Quadrant Dynamometer/Power Supply window.

– Start the *Two-Quadrant, Constant-Torque Brake* by setting the *Status* parameter to *Started* or by clicking the *Start/Stop* button.

24. In the Metering window, make sure that meters are set to measure the dc source voltage E_S (*E1*), as well as the dc motor armature current I_A (*I1*) and field current I_f (*I2*).

25. Turn the Power Supply on by setting the main power switch to the I (on) position. Slowly turn the voltage control knob of the Power Supply until the Universal Motor rotates at a speed of 1000 r/min $\pm$ 25 r/min. Check that both the armature current I_A and field current I_f are of positive polarity. Record the source voltage E_S and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A and I_f of positive polarity)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

26. On the Power Supply, reverse the connection of the leads at terminals *7* and *N* to reverse the polarity of the voltage applied to the Universal Motor.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob so that the Universal Motor rotates at a speed of 1000 r/min ± 25 r/min.

Check that the armature current I_A and the field current I_f are both of negative polarity. Record the source voltage E_S (indicated by meter *E1*) and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A and I_f of negative polarity)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

What is the direction of rotation when the armature current I_A and the field current I_f are of the same polarity?

____

27. Reverse the connections of the leads at points A and B shown in Figure 3-11.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob so that the Universal Motor rotates at a speed of 1000 r/min ± 25 r/min.

Neglect the sign of the speed indicated by the Speed meter in the Four-Quadrant Dynamometer/Power Supply window.

Check that the armature current I_A is positive and the field current I_f is negative. Record the source voltage E_S and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A is positive, I_f is negative)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

28. On the Power Supply, reverse the connection of the leads at terminals *7* and *N* to reverse the polarity of the voltage applied to the Universal Motor.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob so that the Universal Motor rotates at a speed of 1000 r/min $\pm$ 25 r/min.

Neglect the sign of the speed indicated by the Speed meter in the Four-Quadrant Dynamometer/Power Supply window.

Check that the armature current I_A is negative and the field current I_f is positive. Record the source voltage E_S and the direction of rotation.

Source voltage E_S = _______ V

Direction of rotation = ______________ (I_A is negative, I_f is positive)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

What is the direction of rotation when the armature current I_A and the field current I_f are of opposite polarity?

____

Does a universal motor act like a series motor when it is powered by a dc power source?

❑ Yes ❑ No

29. Reverse the connections of the leads at points A and B shown in Figure 3-11. The modules should be connected as shown in Figure 3-11.

Universal motor operating on ac power

In this section, you will replace the dc power source with an ac power source. You will observe that the direction of rotation of the Universal Motor can be changed by reversing the armature connections. You will measure the ac source voltage required to make the Universal Motor rotate at a speed of approximately 1000 r/min. You will measure the armature impedance Z_A. You will compare the Universal Motor performance obtained with dc power and ac power.

30. Replace the variable-voltage dc power source in the circuit with a variable-voltage ac power source (terminals *4* and *N* of the Power Supply).

In the Metering window, set the meters used to measure the source voltage E_S (*E1*), armature current I_A (*I1*), and field current I_f (*I2*) to display rms values (ac).

31. Turn the Power Supply on by setting the main power switch to the I (on) position. Slowly turn the voltage control knob until the Universal Motor rotates at a speed of 1000 r/min ± 25 r/min. Record the source voltage E_S and the direction of rotation.

Source voltage $E_S, rms =$ _______ V (without compensating winding)

Direction of rotation = ______________ (I_A and I_f of the same polarity)

Does the Universal Motor rotate in the same direction as when it was operating on dc power with currents I_A and I_f of the same polarity (steps 25 and 26)?

❑ Yes ❑ No

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

32. Reverse the connections of the leads at points A and B shown in Figure 3-11.

Turn the Power Supply on by setting the main power switch to the I (on) position. Adjust the voltage control knob so that the Universal Motor rotates at a speed of 1000 r/min ± 25 r/min.

Neglect the sign of the speed indicated by the Speed meter in the Four-Quadrant Dynamometer/Power Supply window.

Record the source voltage E_S and the direction of rotation.

Source voltage $E_S, rms =$ _______ V (without compensating winding)

Direction of rotation = ______________ (I_A and I_f of opposite polarity)

Does the Universal Motor rotate in the same direction as when it was operating on dc power with currents I_A and I_f of opposite polarity (steps 27 and 28)?

❑ Yes ❑ No

33. On the Power Supply, slowly turn the voltage control knob counterclockwise until the Universal Motor stops rotating.

In the Metering window, set a meter to measure impedance from inputs *E1* and *I1* [meter *RXZ (E1,I1)*]. On this meter, select the *Z* mode to measure impedance by clicking on the meter *Mode* button. Record below the armature impedance Z_A of the Universal Motor indicated by meter *RXZ (E1,I1)*.

Armature impedance $Z_A =$ _______ Ω (without compensating winding)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position. (Leave the 24 V ac power source of the Power Supply turned on).

Compare the dc and ac source voltages E_S required to make the Universal Motor rotate at a speed of approximately 1000 r/min. Briefly explain why they have different values.

____

____

____

Compare the dc voltages required to make the Universal Motor and the series motor rotate at a speed of approximately 1000 r/min.

____

____

Compare the ac voltages required to make the Universal Motor and the series motor rotate at a speed of approximately 1000 r/min.

____

____

34. Reverse the connections of the leads at points A and B shown in Figure 3-11.

Effect of the compensating winding

In this section, you will add a compensating winding to the Universal Motor. You will observe the effect on the performance of the Universal Motor operating on ac power.

35. Modify the connections to connect the compensating winding of the Universal Motor as shown in Figure 3-12.

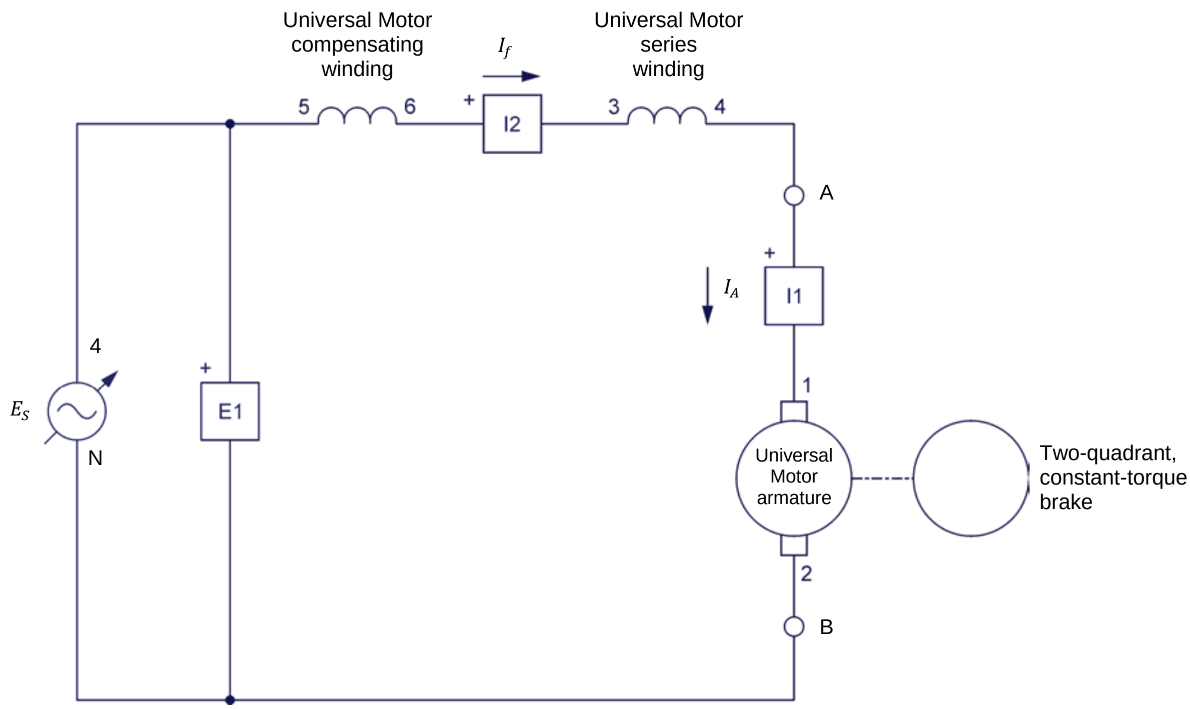


Figure 3-12. AC-powered universal motor (with compensating winding) coupled to a brake.

36. Turn the Power Supply on by setting the main power switch to the I (on) position. Slowly turn the voltage control knob until the Universal Motor rotates at a speed of 1000 r/min $\pm$ 25 r/min. Record the source voltage E_S.

Source voltage $E_S, rms =$ _______ V (with compensating winding)

On the Power Supply, slowly turn the voltage control knob counterclockwise until the Universal Motor stops rotating.

Record in the following blank the armature impedance Z_A of the Universal Motor indicated by meter *RXZ (E1,I1)* in the Metering window.

Armature impedance $Z_A =$ _______ Ω (with compensating winding)

Turn the Power Supply off by setting the voltage control knob to 0% and the main power switch to the O (off) position.

Compare the ac source voltages E_S required to make the Universal Motor with and without compensating winding rotate at a speed of approximately 1000 r/min. Briefly explain why they have different values.

____

____

____

If you want to perform the additional experiments, skip the next step, then return to it when all additional manipulations are finished.

37. On the Power Supply, make sure that the main power switch is set to the O (off) position, then turn the 24 V ac power source off. Close the LVDAC-EMS software. Turn the Four-Quadrant Dynamometer/Power Supply off. Disconnect all leads and return them to their storage location.

Additional experiments (optional)

Speed-versus-torque characteristic of an ac-powered universal motor

You can obtain the speed-versus-torque characteristic of a universal motor (with a compensating winding) powered by an ac power source. To do so, make sure that the Power Supply is turned off [main power switch set to the O (off) position and voltage control knob set to 0%], then make sure that the equipment is connected as shown in Figure 3-12. In the Metering window, make sure that the meters are set to display the rms values (ac) of the source voltage E_S (*E1*), and armature current I_A (*I1*), and field current I_f (*I2*). Open the Data Table and set it to record the following data: the source voltage (*E1*), the armature current I_A (*I1*), as well as the motor speed n and the motor torque T (indicated by the *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply window). In the Four-Quadrant Dynamometer/Power Supply window, make sure that the *Torque* parameter of the *Two-Quadrant, Constant-Torque Brake* is set to 0.0 N·m (0.0 lbf·in). Start the *Two-Quadrant, Constant-Torque Brake*. Turn the Power Supply on by setting the main power switch to the I (on) position and adjust the voltage control knob so that the source voltage E_S is as close as possible to the nominal voltage of the Universal Motor. Note the value of the minimum motor torque T (indicated by the *Torque* meter in the Four-Quadrant Dynamometer/Power Supply) and set the *Torque* parameter to this value. Increase the *Torque* parameter from the minimum value to about 2.3 N·m (about 20.3 lbf·in) in steps of 0.2 N·m (or 2.0 lbf·in). For each torque setting, wait until the motor speed stabilizes, and then record the data in the Data Table. When all data has been recorded, turn the Power Supply off by setting the main power switch to the O (off) position. Save the data table under filename DT321. In the Graph window, make the appropriate settings to obtain a graph of the universal motor speed n as a function of the universal motor torque T. Name the graph “G321”. Compare the speed-versus-torque characteristic of the universal motor (graph G321) to that of the dc series motor (graph G223 obtained in Exercise 2-2).

If your local ac power network voltage is 120 V, use the 40-A current range on the Data Acquisition and Control Interface for current inputs I1 and I2. Set the Range of current inputs I1 and I2 to 40 A in the Data Acquisition and Control Settings window of LVDAC-EMS.

CAUTION

The armature current may exceed the rated value while performing this manipulation. Therefore, perform this manipulation in less than 5 minutes.

DC shunt motor operating on ac power

You can observe the operation of a shunt motor connected to an ac power source. To do so, make sure the Power Supply is turned off [main power switch set to the O (off) position] and that the voltage control knob is set to 0%, then set up the shunt motor circuit shown in Figure 3-13. Use a variable-voltage ac power source (terminals *4* and neutral *N* of the Power Supply) for source E_S. In the Metering window, make sure that the meters are set to display the rms values (ac) of the source voltage E_S (*E1*), armature current I_A (*I1*), and field current I_f (*I2*). Turn the Power Supply on by setting the main power switch to the I (on) position and turn the voltage control knob clockwise until the shunt motor starts to rotate. Note the direction of rotation. Turn the Power Supply off by setting the main power switch to the O (off) position and set the voltage control knob to 0%. Reverse the lead connection at points A and B shown in Figure 3-13. Turn the Power Supply on by setting the main power switch to the I (on) position and turn the voltage control knob clockwise until the shunt motor starts to rotate. Note the direction of rotation. Turn the Power Supply off by setting the main power switch to the O (off) position and set the voltage control knob to 0%.

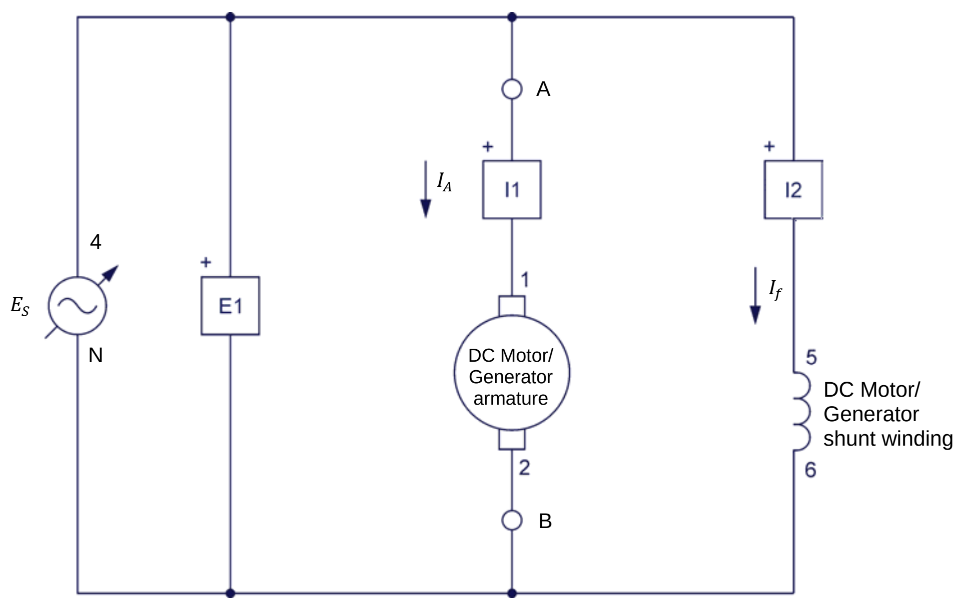


Figure 3-13. AC-powered shunt motor.

Conclusion

In this exercise, you demonstrated that the dc series motor and the universal motor without compensating winding have similar operation, whether they are powered by dc or ac power. You observed that the direction of rotation of these motors depends on the polarities of the armature current and field current. You learned that the performance of these motors is rather poor when they operate on ac power because their armature impedance Z_A is fairly high. You observed that the performance of a universal motor operating on ac power can be greatly improved by adding a compensating winding that reduces the armature impedance Z_A.

If you performed the additional experiments, you plotted a graph of speed versus torque for an ac-powered universal motor with a compensating winding. You learned that the speed-versus-torque characteristic of this motor is similar to that of the dc series motor, i.e., the speed decreases rapidly and non linearly as the torque increases. You verified that a dc shunt motor can operate on ac power.

Review Questions

1. What effect does reversing the dc power connections to a series motor have on its direction of rotation?

2. What effect does reversing the armature winding connections to a series motor have on its direction of rotation

3. A universal motor is a dc series motor with a compensating winding that operates on which type of power (ac or dc)?

4. What does the compensating winding in a universal motor help reducing?

5. When the armature connections to a universal motor are reversed, what happens to the direction of rotation of the motor?

Unit Test

1. Armature reaction in a dc machine

   a. is due to an increase of the armature voltage.
   b. occurs when the motor is connected to an ac power source.
   c. occurs when the motor is connected to a dc power source.
   d. is due to an increase of the armature current.

2. Armature reaction modifies the characteristics of a dc machine because

   a. it increases wear on the brushes and the commutator.
   b. it affects the magnetic field produced by the field electromagnet.
   c. it causes saturation.
   d. Both a and b.

3. Armature reaction causes the output voltage of a dc generator to decrease because

   a. it increases wear on the brushes and the commutator.
   b. it causes saturation.
   c. it delays the voltage induced across the armature winding.
   d. All of the above.

4. A permanent-magnet dc motor has better characteristics than the separately-excited, shunt, and series motors because

   a. the magnetic field produced by the permanent magnet is so strong that it cannot be affected significantly by another magnetic source.
   b. it has a low armature inductance.
   c. it has a compensating winding.
   d. Both a and b.

5. Saturation occurs in a dc machine when

   a. the armature voltage increases and exceeds the nominal value.
   b. the motor is connected to an ac power source.
   c. the field current exceeds the nominal value.
   d. the armature current exceeds the nominal value.

6. The nominal value of the field current of a dc machine is chosen to be at the beginning of the saturation knee

   a. to ensure that the speed versus voltage characteristic is linear.
   b. to ensure that the torque versus current characteristic is linear.
   c. to obtain as much torque as possible with a field current that is as low as possible.
   d. Both a and b.

7. Why is it nearly impossible to obtain satisfactory performance from a shunt motor connected to an ac power source?

   a. Because the shunt winding consist of a large number of turns.
   b. Because the shunt winding has a large inductance.
   c. Because it is difficult for an alternating current to flow in the shunt winding.
   d. All of the above.

8. The direction of rotation of a dc series motor or a universal motor connected to a dc power source depends on

   a. the polarities of the armature and field currents.
   b. exclusively on the polarity of the armature current.
   c. exclusively on the polarity of the field current.
   d. the connection of the compensating winding.

9. The ac voltage required to make a series motor rotate at a given speed is higher than the dc voltage required to make the same motor rotate at the same speed. This is because

   a. armature reaction occurs when the motor operate on ac power.
   b. the armature impedance of the motor is fairly high.
   c. saturation occurs when the motor operate on ac power.
   d. Both a and b.

10. The performance of a series motor operating on ac power can be improved by

    a. adding a compensating winding that increases the armature reactance.
    b. adding permanent magnets.
    c. adding a compensating winding that decreases the armature reactance
    d. None of the above.

Equipment Utilization Chart

The following equipment is required to perform the exercises in this manual.

Equipment		Exercise					
Model	**Description**	**1-1**	**2-1**	**2-2**	**2-3**	**3-1**	**3-2**
8134(1)	Workstation	1	1	1	1	1	1
8211	DC Motor/Generator	1	1	1	1	1	1
8254	Universal Motor						1
8311(2)	Resistive Load	1		1	1	1	
8821	Power Supply	1	1	1	1	1	1
8942	Timing Belt	1	1	1	1	1	1
8951-L	Connection Leads	1	1	1	1	1	1
8960-C(3)	Four-Quadrant Dynamometer/Power Supply	1	1	1	1	1	1
8990	Host Computer	1	1	1	1	1	1
9063-B(4)	Data Acquisition and Control Interface	1	1	1	1	1	1

(1) The Mobile Workstation, Model 8110-2, can also be used.

(2) Resistive Load unit with voltage rating corresponding to your local ac power network voltage. Use model variant -00, -01, -02, -05, -06, -07, or -0A.

(3) Model 8960-C consists of the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, with the Standard Functions (manual control) set, Model 8968-1, and the Standard Functions (computer-based control) set, Model 8968-2.

(4) Model 9063-B consists of the Data Acquisition and Control Interface, model 9063, with the Computer-Based Instrumentation function set, Model 9069-1.

Glossary of New Terms

ac motor An ac motor is an electric motor whose power is supplied by an alternating-current (ac) power source.

armature An armature is the rotating part of an electric motor or generator.

brushes Brushes are strips, blades, or blocks, usually made of metal or carbon, which are mounted on the stator of a rotating machine and provide sliding contact with the commutator or the slip rings of the rotor. Brushes allow current flow between the stator and rotor of a rotating machine.

commutator Part of a rotating machine that is made of many segments (parallel copper bars or strips insulated from each other) that are connected to the rotor windings. As the rotor turns, the segments successively make contact with brushes to distribute current to the rotor windings. The commutator converts dc current into ac current, or ac current into dc current, depending on whether the machine operates as a motor or generator.

cumulative compound motor DC motor having a series winding connected in series with the armature so that the magnetic flux of the series winding adds with the magnetic flux of a shunt winding. As a result, the magnetic flux increases automatically with increasing armature current.

dc motor A dc motor is an electric motor whose power is supplied by a direct-current (dc) power source.

differential compound motor A dc motor having shunt and series windings connected so that the magnetic fluxes subtract from each other. This type of compound motor is rarely used because the motor becomes unstable when the armature current increases.

dynamometer A dynamometer is a device used to measure the torque produced by a rotating machine.

electric generator An electric generator is a rotating machine that converts mechanical energy into electrical energy through the process of electromagnetic induction.

electric motor An electric motor is a rotating machine that converts electrical energy into mechanical energy through the process of electromagnetic induction and interacting magnetic fields.

electromagnet An electromagnet is a device that produces a magnetic field when an electric current flows through it. A coil of wire wound around an iron core is a common example of an electromagnet.

electromagnetic induction Electromagnetic induction consists in the production of an electromotive force (i.e., an induced voltage E_{EMF}) in a circuit resulting from a change in the magnetic flux passing through that circuit.

field current The field current is the dc current which produces the fixed magnetic field in a rotating machine.

magnetic force The force of attraction or repulsion between magnetic poles. Like magnetic poles repel each other. Unlike magnetic poles attract each other.

magnetic poles Magnetic poles are the part of a magnet where the magnetic lines of force exit or enter, and where the lines of force are the most concentrated. By convention, magnetic lines of force exit from the north magnetic pole and enter at the south magnetic pole.

mechanical power The mechanical power P_m produced by a motor, is expressed in watts (W). Mechanical power is calculated by dividing the product of the motor speed n and torque T by 9.55 when the speed and torque are expressed in r/min and N·m, respectively. Mechanical power is calculated by dividing the product of the motor speed and torque by 84.51 when the speed and torque are expressed in r/min and lbf·in, respectively.

motor efficiency The efficiency η of a motor is the ratio of the mechanical power P_m produced by the motor to the electrical power P_{in} supplied to the motor, $\eta = P_m/P_{in}$.

prime mover A prime mover is the primary source of mechanical power for any mechanical system that requires force to drive gears, belts, flywheels, etc.

rotation speed The speed n of a rotating machine is the number of turns per unit of time at which the machine rotates. Speed is usually expressed in revolutions per minute (r/min).

rotor A rotor corresponds to the rotating part of a rotating machine. The rotor is the motor component that produces the mechanical work.

self-excited dc generator DC generator that operates without a dc power source. The field electromagnet is a shunt winding connected across the generator output (shunt generator) or a combination of a shunt winding connected across the generator output and a series winding connected in series with the generator output (compound generator). The generator output voltage and/or current excite(s) the field electromagnet.

separately-excited dc generator DC generator whose stator electromagnet is powered by a separate dc source.

separately-excited dc motor DC motor whose stator electromagnet is powered by a separate dc source, of either fixed or variable voltage.

series motor The series motor is a motor in which the field electromagnet is a series winding connected in series with the armature.

shunt motor DC 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.

stator A stator is the non-rotating part of an electric motor or generator.

torque The torque T is the twisting force applied to an object. Torque can be expressed in newton·meters (N·m) or in pound force·inches (lbf·in). Electric power applied to a motor produces torque that makes the motor turn, and a generator turns because of the torque applied to its shaft by a drive motor, belt, or gear.

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 C-1 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

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

Impedance (Ω)			Position of the switches								
120 V 60 Hz	220 V 50 Hz/60 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

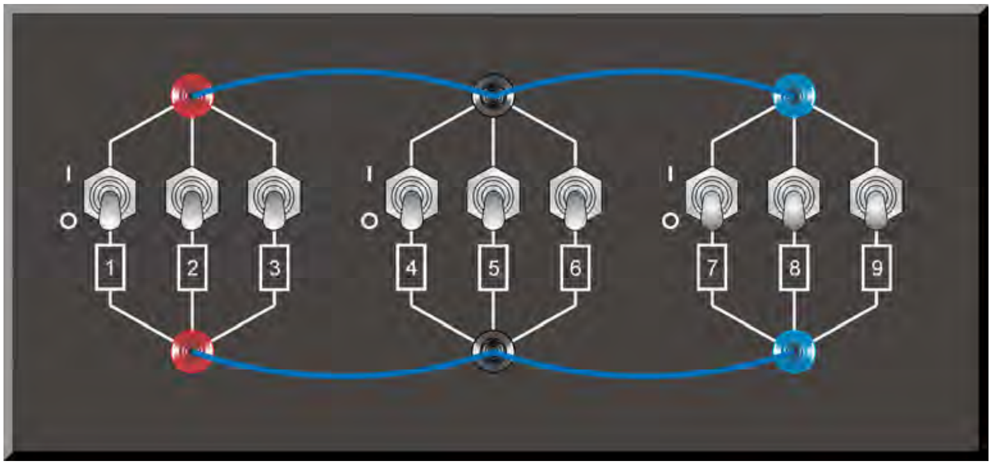


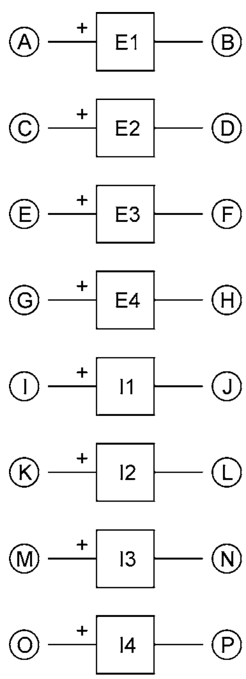
Figure C-1. Location of the load elements on the Resistive Load, Inductive Load, and Capacitive Load, Models 8311, 8321, and 8331, respectively.

Circuit Diagram Symbols

Various symbols are used in the circuit diagrams of this manual. Each symbol is a functional representation of a particular electrical device that can be implemented using the equipment. The use of these symbols greatly simplifies the number of interconnections that need to be shown on the circuit diagram, and thus, makes it easier to understand the circuit operation.

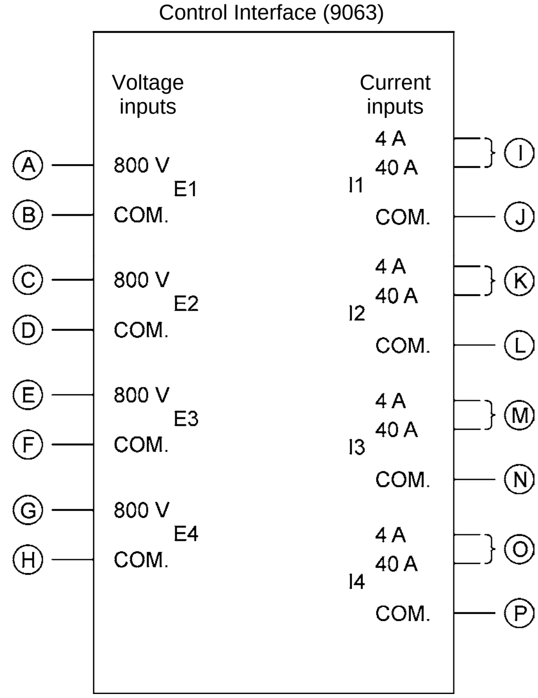
For each symbol other than those of power sources, resistors, inductors, and capacitors, this appendix gives the name of the device which the symbol represents, as well as the equipment and the connections required to properly connect the device to a circuit. Notice that the terminals of each symbol are identified using circled letters. The same circled letters identify the corresponding terminals in the Equipment and Connections diagram. Also notice that the numbers (when present) in the Equipment and Connections diagrams correspond to terminal numbering used on the actual equipment.

Symbol



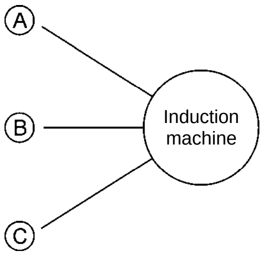
Isolated voltage and current measurement inputs

Equipment and Connections



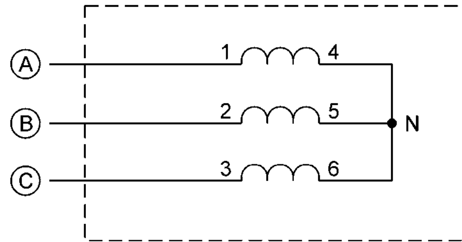
When a current at inputs I1, I2, I3, or I4 exceeds 4 A (either permanently or momentarily), use the corresponding 40 A input terminal and set the Range parameter of the corresponding input to High in the Data Acquisition and Control Settings window of LVDAC-EMS.

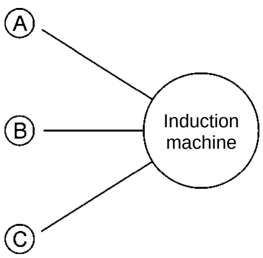
Symbol	**Equipment and Connections**



Three-phase induction machine

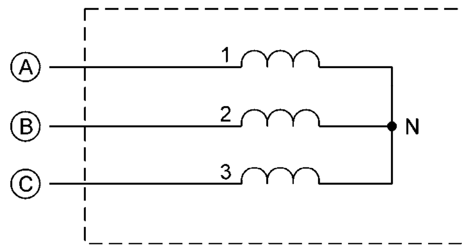
Four-Pole Squirrel Cage Induction Motor (8221-0)

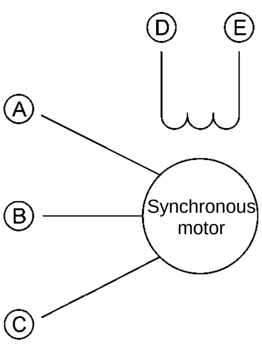




Three-phase induction machine

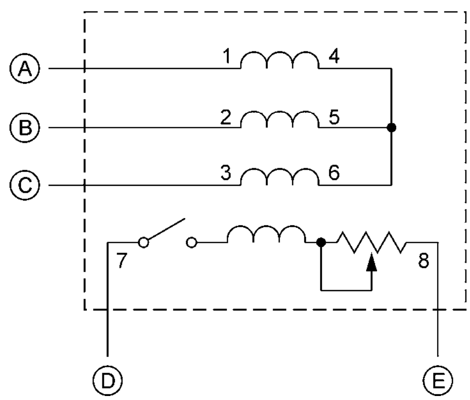
Three-Phase Induction Machine (8221-2)



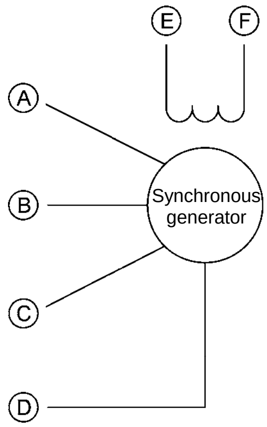


Three-phase synchronous motor

Synchronous Motor / Generator (8241-2)

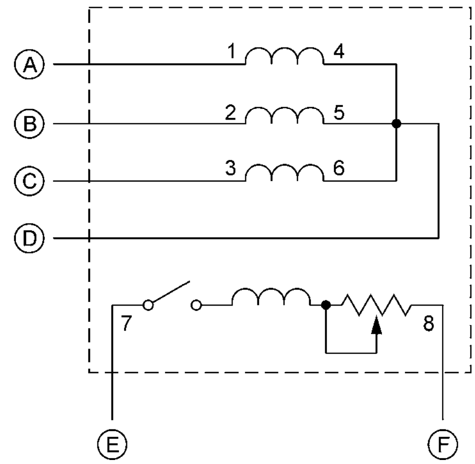


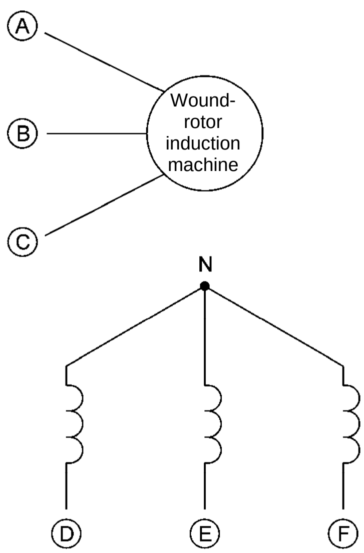
Symbol	**Equipment and Connections**



Three-phase synchronous generator

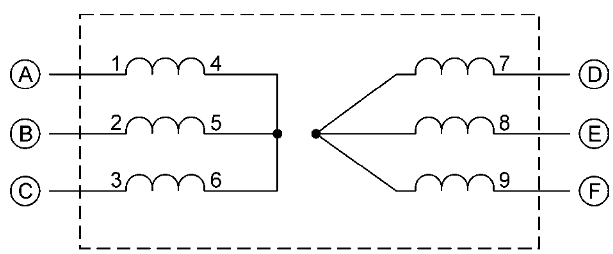
Synchronous Motor / Generator (8241-2)



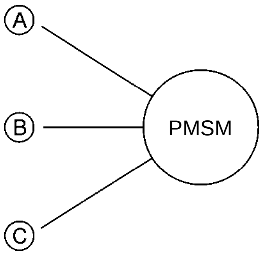


Three-phase wound-rotor induction machine

Three-Phase Wound-Rotor Induction Machine (8231-B)

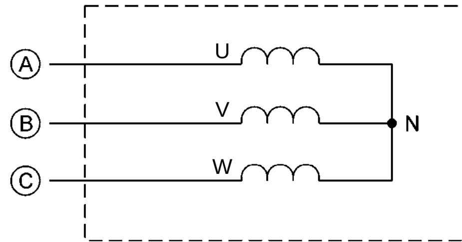


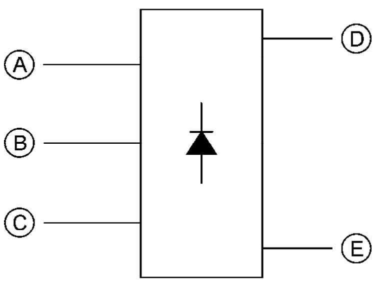
Symbol | **Equipment and Connections**



Permanent Magnet
Synchronous Machine

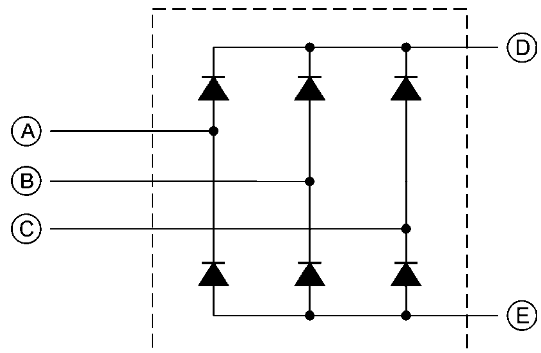
Permanent Magnet
Synchronous Machine (8245)

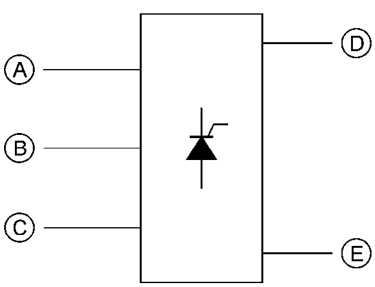




Power diode three-phase
full-wave rectifier

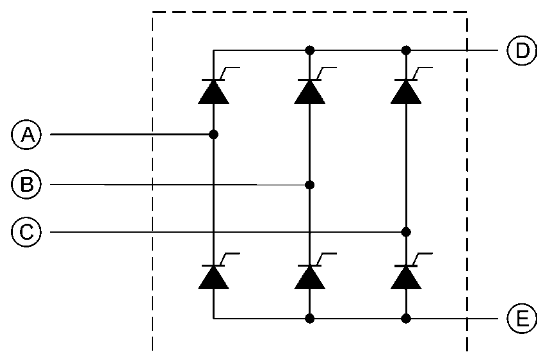
Rectifier and Filtering
Capacitors (8842-A)

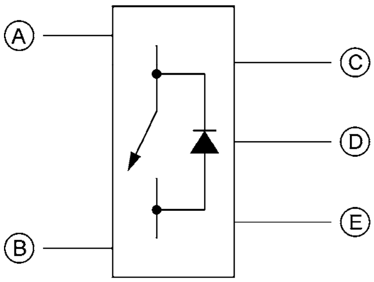
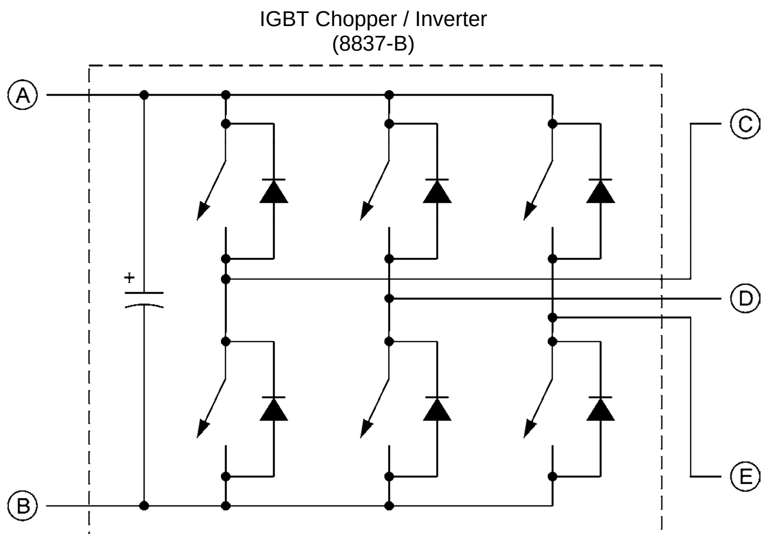




Power thyristor
three-phase bridge

Power Thyristors
(8841)



Symbol	**Equipment and Connections**
 Three-phase inverter	

Index of New Terms

The bold page number indicates the main entry. Refer to Appendix B for definitions of new terms.

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