Electricity and New Energy

Permanent Magnet DC Machine

Courseware

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Safety and Common Symbols

The following safety and common symbols may be used in this course 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 danger. Consult the relevant user documentation.
	Caution, risk of electric shock
	Caution, lifting hazard
	Caution, hot surface
	Caution, risk of fire
	Caution, risk of explosion
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation

Safety and Common Symbols

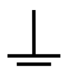
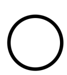
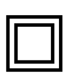
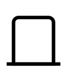
Symbol	Description
	Consult the relevant user documentation.
	Direct current
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

Table of Contents

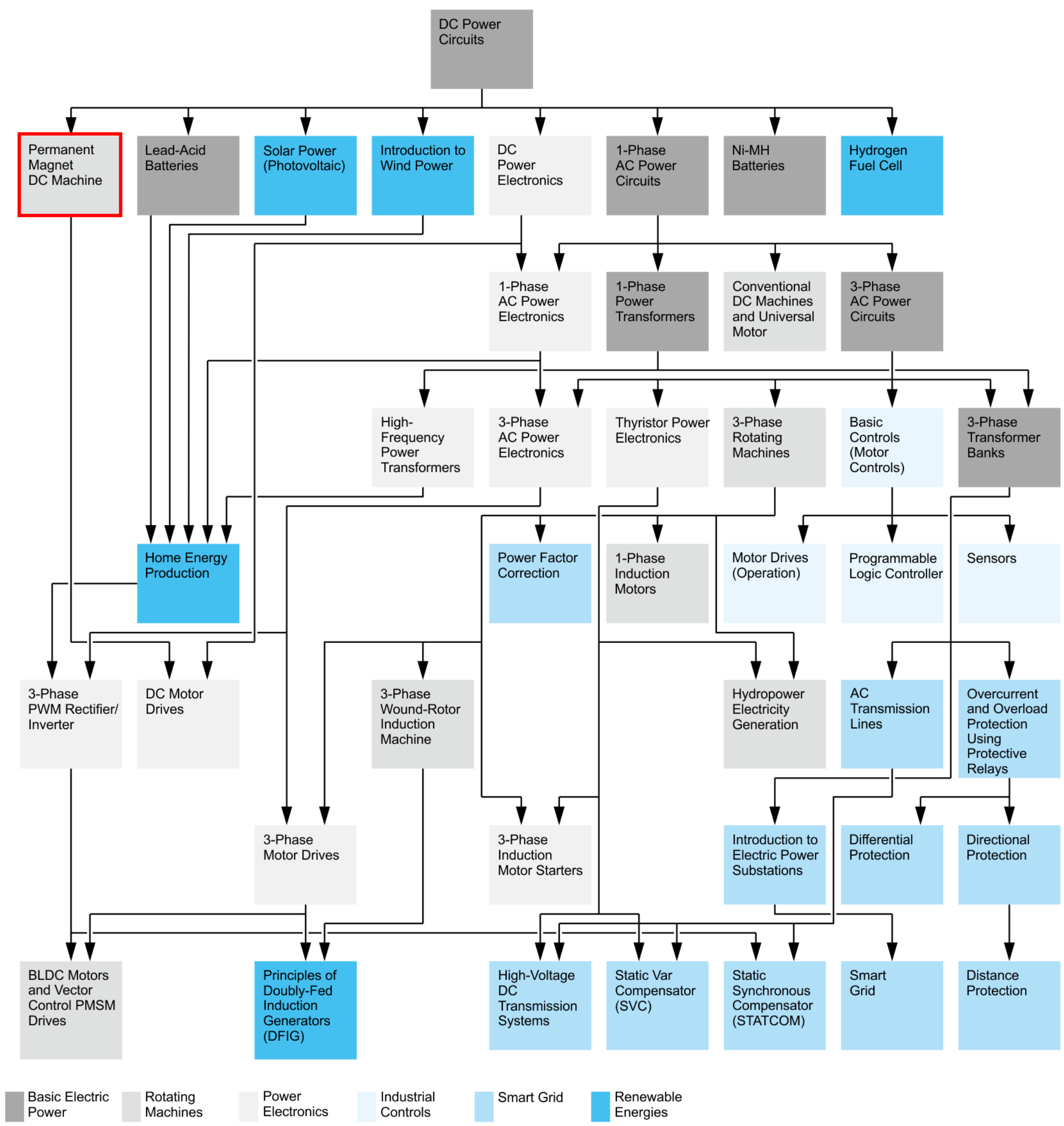
Table of Contents

Table of Contents

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 motor starters and drives, storage of electrical energy in batteries, home energy production from renewable resources (wind and sunlight), large-scale electricity production from hydropower, protective relaying, and smart-grid technologies (SVC, STATCOM, HVDC transmission systems, etc.).

We invite readers to send us their tips, feedback, and suggestions for improving the course.

Please send these to services.didactic@festo.com.

The authors and Festo Didactic look forward to your comments.

About This Course

Rotating machines such as electrical motors and generators (or alternators) are found in almost every sector of the industry. The basic principles of operation of these rotating machines have been known for almost two centuries. Rotating machines operate due to the interaction between magnetic fields and current-carrying conductors, and are split into two basic categories: motors and generators.

Permanent magnet dc machines are rotating machines that operate using direct current (i.e., they are dc powered). They can be used as either generators or motors. Permanent magnet dc machines are rugged components that are easy to connect and require little maintenance. They are found in a variety of applications, such as battery charging, small electric vehicles, windmill technology, mobility scooters, pumps, machine tools, kitchen appliances, optical equipment, etc.

The present course introduces the student to permanent magnet dc machines used as either generators or motors. The course covers the construction, operating principles, and characteristic curves of permanent magnet dc machines related to each of these two operating modes.

The equipment for the course mainly consists of the Permanent Magnet DC Machine and the Four-Quadrant Dynamometer/Power Supply. The operation of the machine is controlled using the LVDAC-EMS software, which also provides the instrumentation required to record the experimental data and plot characteristic curves.

Safety considerations

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

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 completed the course *DC Power Circuits*.

Systems of units

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

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this course should be considered as a guide. Students who correctly perform the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

Equipment installation

In order for students to be able to perform the exercises in the Student Manual, the Electric Power Technology Training Equipment must have been properly installed, according to the instructions given in the user guide Electric Power Technology Training Equipment.

Sample

Extracted from

Instructor Guide

Permanent Magnet DC Machine Operating as a Generator

EXERCISE OBJECTIVE

When you have completed this exercise, you will be familiar with the construction of permanent magnet dc machines, as well as their operation as generators.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Permanent magnets
- Magnetic field around a conductor
- Magnetic field in a loop of wire (electromagnet)
- Electromagnetic induction
- Construction of a permanent magnet dc machine
- Permanent magnet dc machine operating as a generator
- Reducing the fluctuations of the generated dc voltage
- Characteristic of the generated voltage as a function of the rotation speed
- Torque opposing rotation in a permanent magnet dc machine operating as a generator
- Opposition torque-versus-current characteristic

DISCUSSION

Permanent magnets

A permanent magnet is a piece of iron or metal surrounded by a magnetic field, as Figure 13 shows. This magnetic field is constant, i.e., it persists naturally without the need of an electrical current. The magnet has a north (N) pole and a south (S) pole. These poles are situated near the ends of the magnet where the magnetic field strength is the strongest.

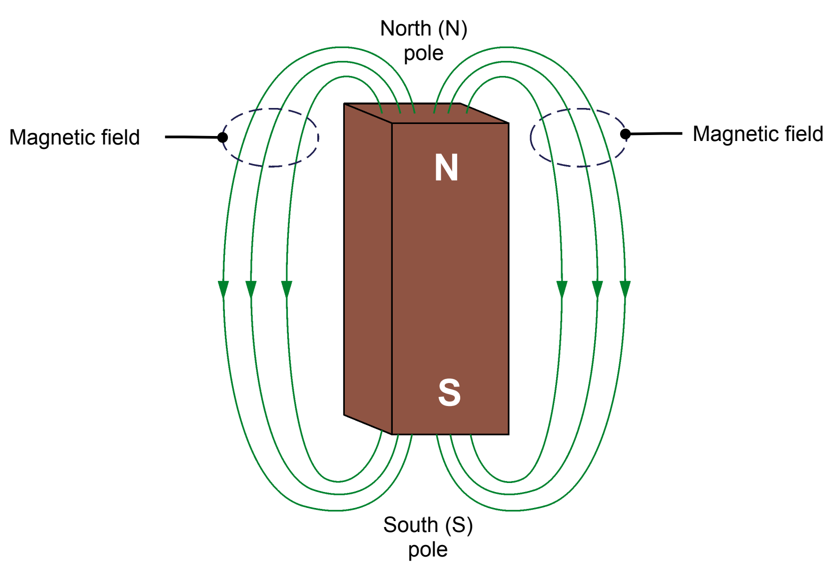


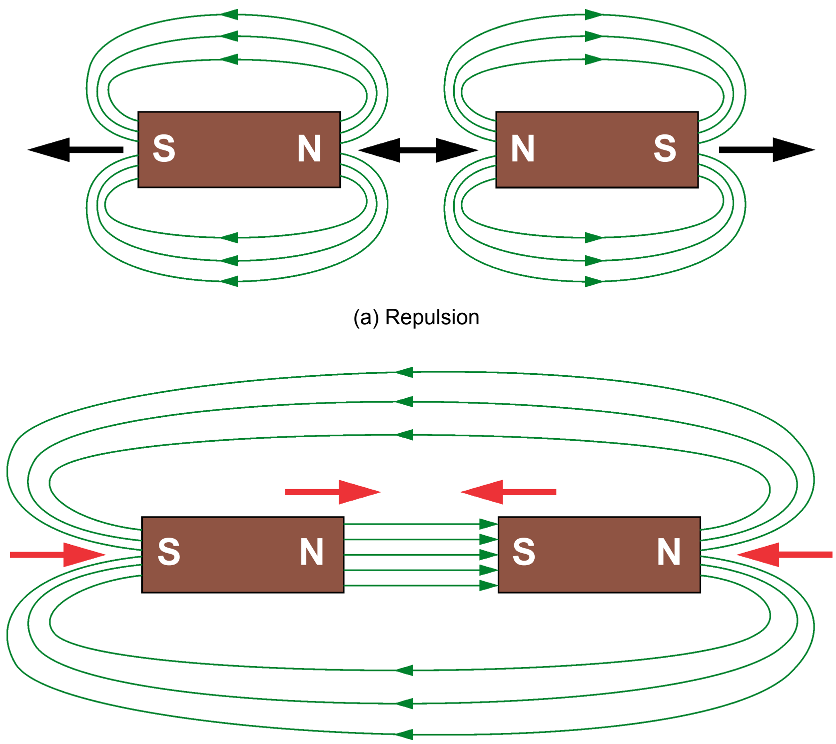
Figure 13. A permanent magnet has two poles called north (N) and south (S).

The direction of the magnetic field is indicated by the line arrows: from north to south outside the magnet, and from south to north within the magnet.

Like poles on magnets repel each other while unlike poles attract each other, as Figure 14 shows.

- **Repulsion**: when a pole on a magnet is moved toward a pole of identical polarity on another magnet, the magnets repel each other, as Figure 14a shows.

- **Attraction**: when a pole on a magnet is moved toward a pole of opposite polarity on another magnet, the magnets attract each other, as Figure 14b shows.



(a) Repulsion

(b) Attraction

Figure 14. Like poles repel each other while opposite poles attract each other.

Magnetic field around a conductor

When electrical current flows through a conductor like an electric wire, a magnetic field is created. The magnetic field is represented by concentric lines centered around the wire axis, as Figure 15 shows. The direction of the magnetic field lines can be determined by using the right-hand rule, as Figure 15 shows.

- The thumb represents the direction of the current in the conductor.

- The other fingers represent the direction of the magnetic field lines.

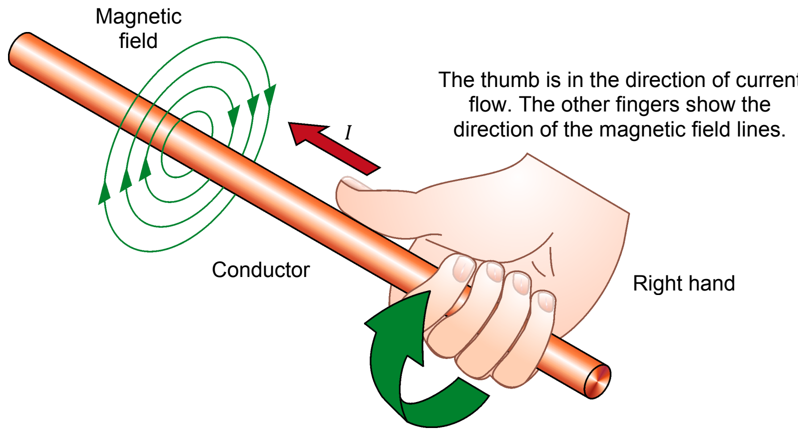


Figure 15. When electrical current flows through a conductor, a magnetic field is created around the conductor.

Magnetic field in a loop of wire (electromagnet)

When current flows through a loop of wire, a magnetic field is created in the loop. As Figure 16 shows, this magnetic field has north and south poles, like a permanent magnet. In this condition, the loop of wire forms an **electromagnet**.

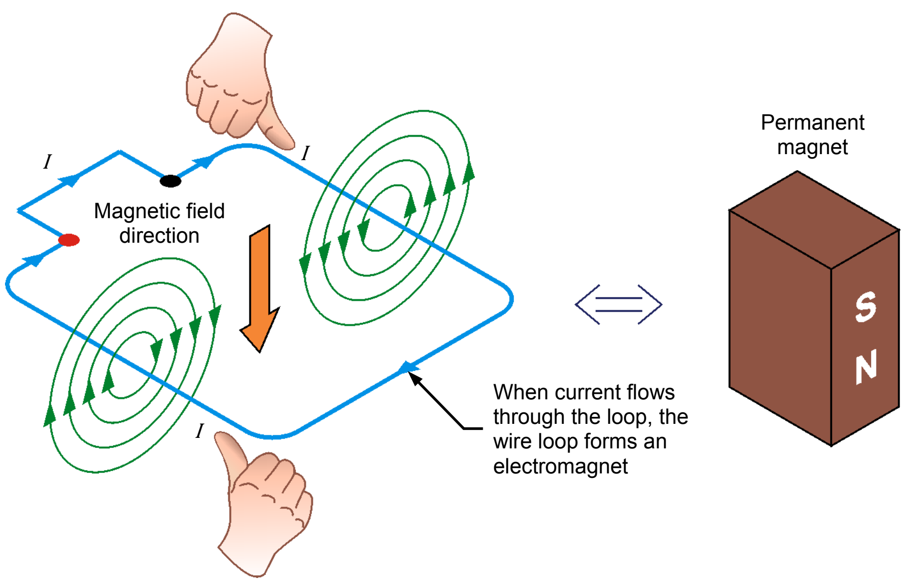


Figure 16. Magnetic field created in a loop of wire.

By using the right-hand rule, the direction of the magnetic field inside the loop of wire and, therefore, the location of the north and south poles can be determined. The higher the current flowing through the loop, the stronger the magnetic field produced in the loop. When the current flow is interrupted, the magnetic field disappears.

Figure 17. Permanent magnet dc generators can be used for battery charging.

Figure 18. Permanent magnet dc generators can be used in small-scale wind turbines.

Electromagnetic induction

The operation of various electric devices (transformers, generators, alternators, motors, etc.) is based on Faraday's law of **electromagnetic induction**, which states the following:

1. A voltage is induced across 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 across the terminals of a wire loop when the magnetic flux passing through the loop varies can be calculated using Equation (7).

$$E = N_{Turns}\,\frac{\Delta\phi}{\Delta t} \qquad (7)$$

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 19 gives an example of the voltage induced across a wire loop that is exposed to a magnetic flux varying in intensity. Between instants t_0 and t_1, the intensity of the magnetic flux ϕ remains constant (3 mWb), and thus, the induced voltage is zero. Between instants t_1 and t_2, the intensity of the magnetic flux ϕ increases at a constant rate, and thus, a constant voltage is induced in the wire loop. Between instants t_2 and t_3, the intensity of the magnetic ϕ flux remains constant (5 mWb), and thus, the induced voltage is zero.

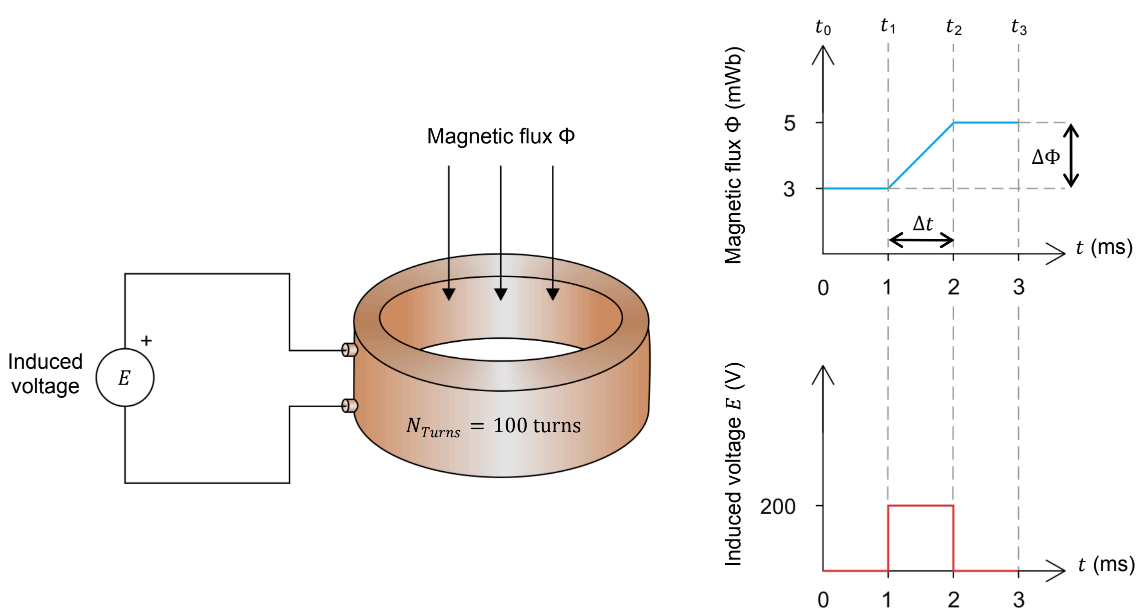


Figure 19. Voltage induced in a loop exposed to a magnetic flux varying in intensity.

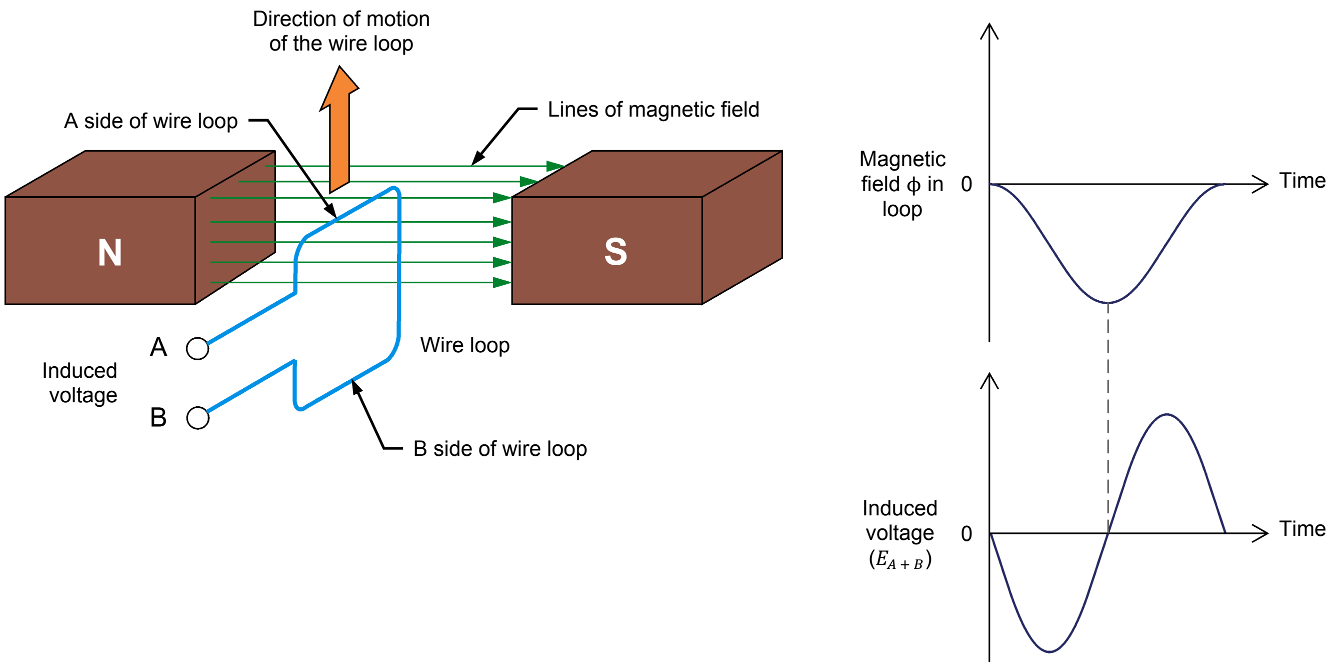
Using the values given in Figure 19, the voltage E induced across the coil between instants t_1 and t_2 can be calculated by using Equation (7), as shown below.

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

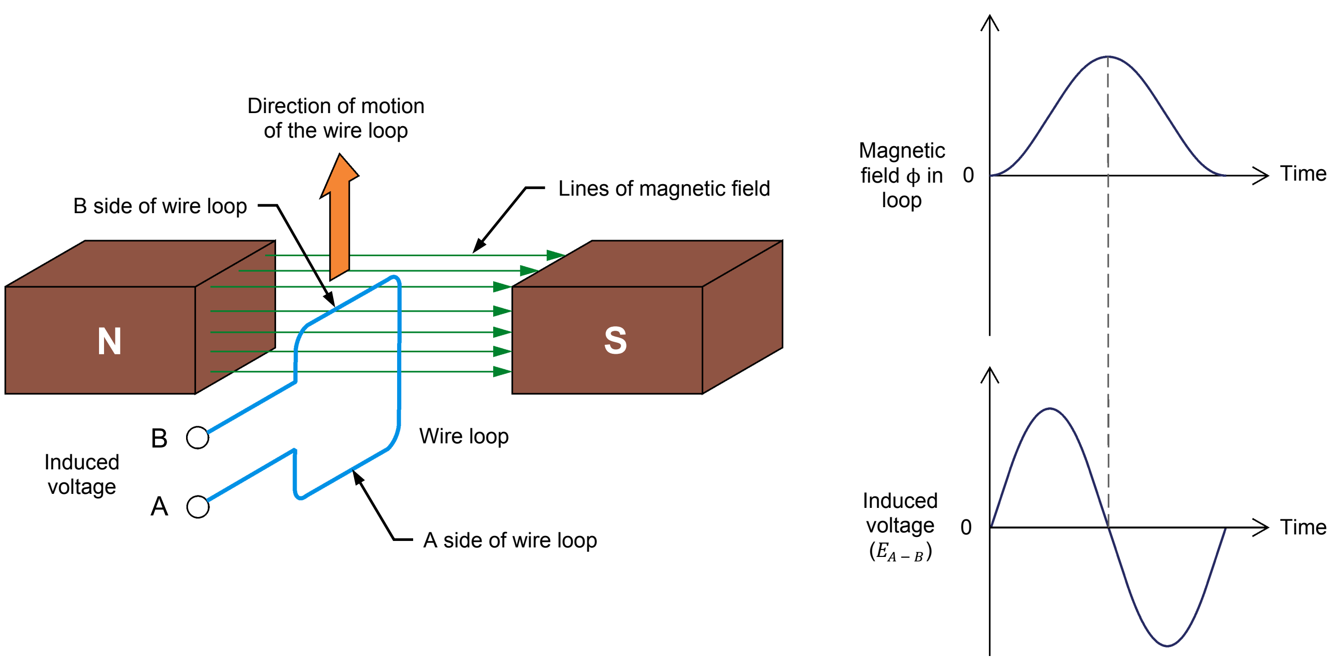
Figure 20 shows another example illustrating electromagnetic induction. Two permanent magnets are aligned so that poles of opposite polarities face each other. This creates a magnetic field going from left to right between the magnets, as indicated by the lines of magnetic field shown in the figure. As the wire loop is moved upward between the two magnets, the magnetic flux ϕ that passes through the loop increases up to a maximum value then returns to zero, and thus, voltage is induced across the loop terminals.

- In Figure 20a, the lines of magnetic field pass from the A side of the wire loop to the B side of the wire loop, resulting in a magnetic flux ϕ of negative polarity through the loop. The voltage E_{AB} induced across the loop terminals has a negative polarity when the magnetic flux passes from zero to the negative maximum, because the rate of change $\frac{\Delta\phi}{\Delta t}$ of the magnetic flux has a negative value. The induced voltage E_{AB} is zero when the magnetic flux ϕ reaches the negative maximum because the magnetic flux momentarily stops varying (i.e., the rate of change $\frac{\Delta\phi}{\Delta t}$ of the magnetic flux is zero). The induced voltage E_{AB} reverses polarity (i.e., it becomes positive) when the magnetic flux passes from the negative maximum to zero because the rate of change $\frac{\Delta\phi}{\Delta t}$ of the magnetic flux has a positive value.

- In Figure 20b, the same wire loop is moved upward between the two magnets. However, the loop has rotated 180° so that the lines of magnetic field pass from the B side of the loop to the A side of the loop, resulting in a magnetic flux ϕ of positive polarity through the loop (i.e., the polarity of the magnetic flux is opposite to that in Figure 20a). Consequently, the magnetic flux ϕ and the voltage E induced across the loop are similar to those in Figure 20a but are of opposite polarity. Thus, the voltage E_{AB} induced across the loop terminals has a positive polarity when the magnetic flux passes from zero to the positive maximum, because the rate of change $\frac{\Delta\phi}{\Delta t}$ of the magnetic flux has a positive value. The induced voltage E_{AB} is zero when the magnetic flux ϕ reaches the positive maximum because the magnetic flux momentarily stops varying. The induced voltage E_{AB} reverses polarity (i.e., it becomes negative) when the magnetic flux passes from the positive maximum to zero because the rate of change $\frac{\Delta\phi}{\Delta t}$ of the magnetic flux has a negative value.



(a) The lines of magnetic field pass from the A side to the B side of the wire loop.



(b) The lines of magnetic field pass from the B side to the A side of the wire loop.

Figure 20. Voltage induced across a wire loop that is moved in the magnetic field created by permanent magnets.

Construction of a permanent magnet dc machine

Figure 21 shows a simplified diagram of a permanent magnet dc machine.

- The **stator** is the fixed part of the machine, in which the **rotor** turns. The stator consists of a pair of permanent magnets aligned so that poles of opposite polarities face each other. Thus, one magnet has its north (N) pole close to the armature, while the other magnet has its south (S) pole close to the armature. Therefore, lines of magnetic field pass from one permanent magnet to the other through the metallic armature.
- The rotor is the rotating part of the machine. It consists of a wire loop mounted on a rotary metallic armature. The ends of the wire loop are connected to terminals located on the stator of the machine, via a **commutator** and a pair of brushes (usually made of carbon). The commutator has two segments isolated from one another. Each segment is connected to one terminal of the wire loop. (The role of the commutator will be explained later.)

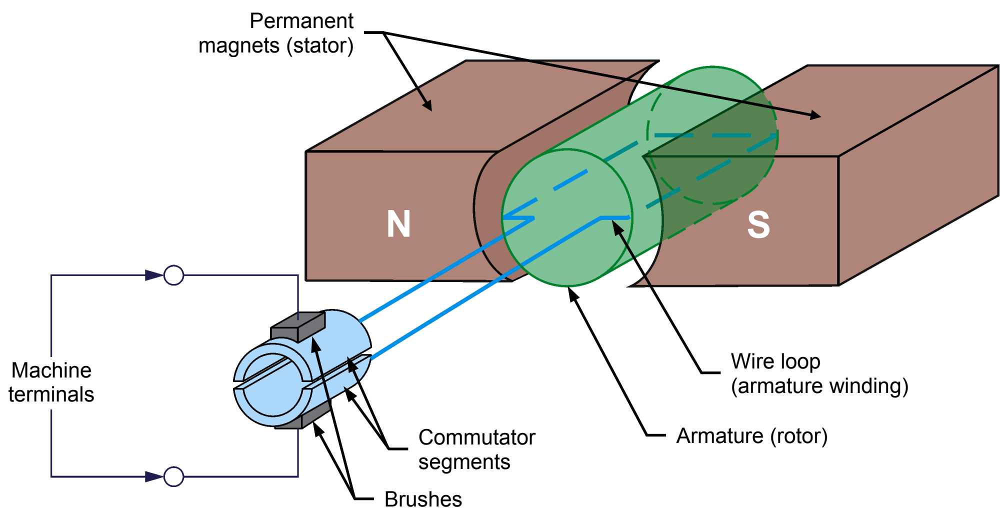


Figure 21. Construction of a simple permanent magnet dc machine.

Such a dc machine is referred to as a permanent magnet dc machine because permanent magnets are used to produce the magnetic field necessary for operation.

The diagram in Figure 21 shows the simplest way of constructing a permanent magnet dc machine. In real dc machines, the armature is made up of several wire loops instead of a single loop and the commutator has several segments instead of a single pair of segments. Also, each wire loop consists of several turns of wire instead of a single turn.

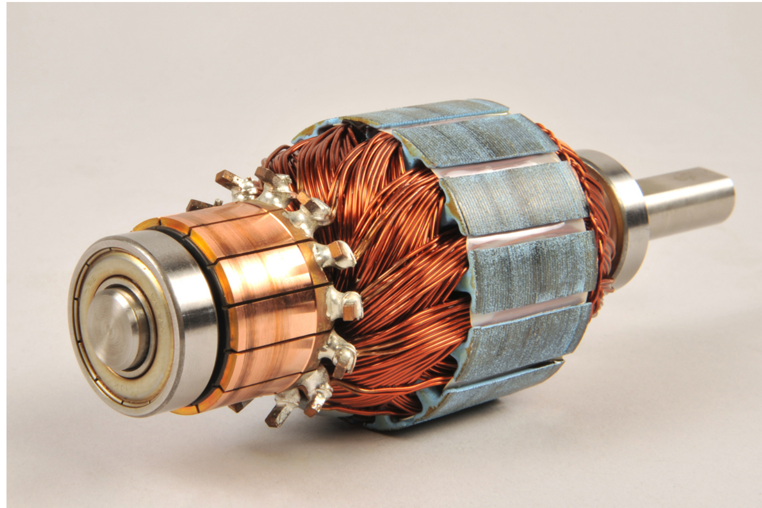


Figure 22. In real dc machines, the armature (rotor) is made up of several wire loops and the commutator has several segments.

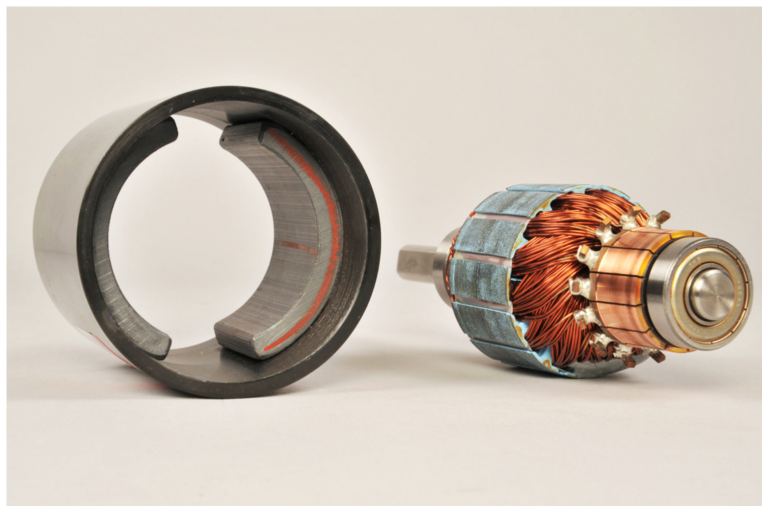


Figure 23. Machine stator and rotor. The stator is the fixed part of the machine, in which the rotor turns. The stator consists of a pair of permanent magnets aligned so that poles of opposite polarities face each other.

Permanent magnet dc machine operating as a generator

Figure 24 shows a permanent magnet dc machine operating as a generator. When the rotor wire loop rotates within the magnetic field produced by the stator permanent magnets, 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 machine 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 machine 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 machine terminals.

This cycles 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 machine terminals at wire loop positions 0 and 4, the voltage E_2 at the machine terminals always has the same polarity (positive), as shown in Figure 24. The voltage E_2 at the machine terminals is thus a pulsating positive **direct-current (dc)** voltage (two pulses per rotation).

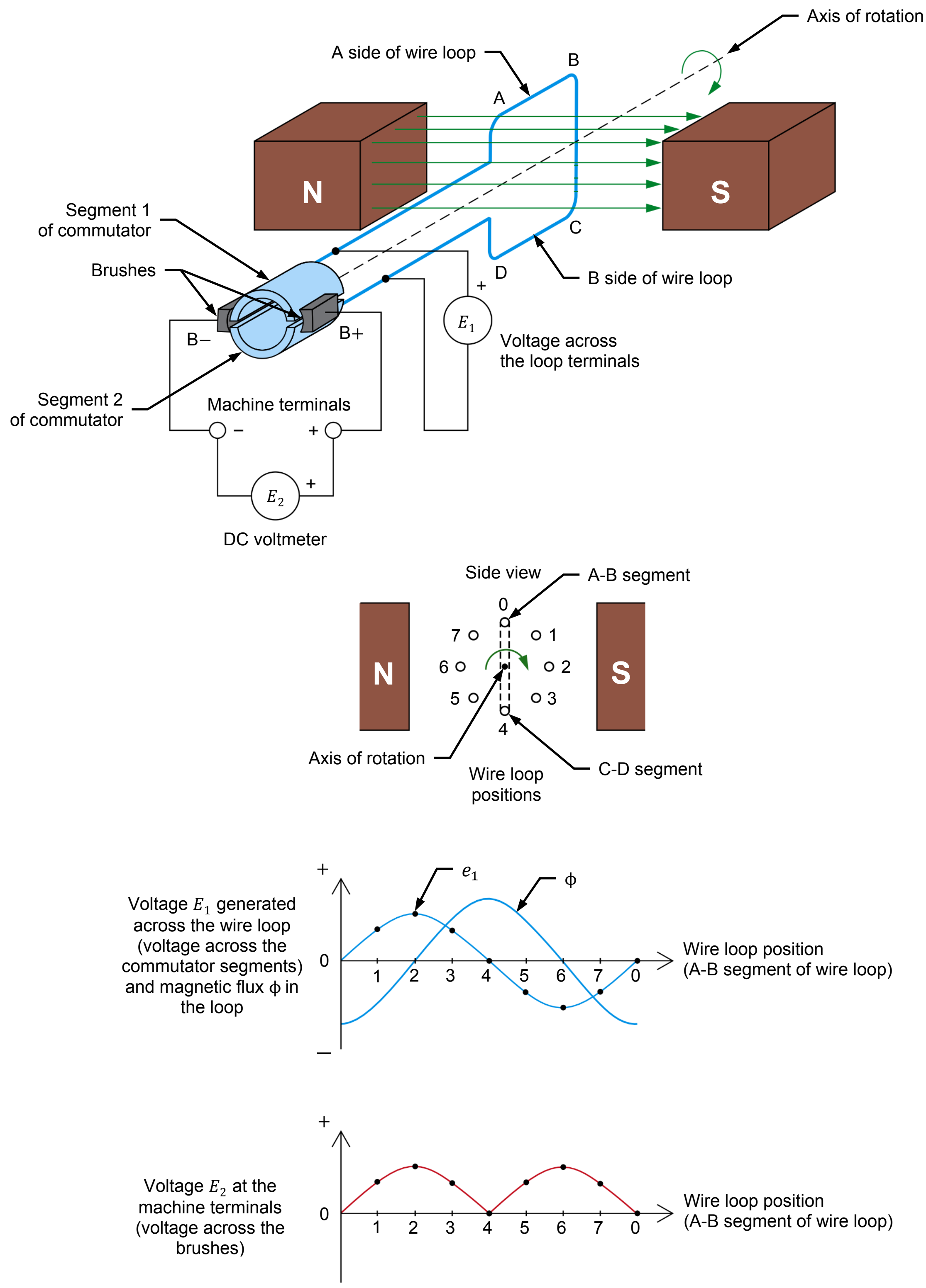


Figure 24. Permanent magnet dc machine operating as a generator (clockwise rotation).

When the direction of rotation of the wire loop is reversed, the polarity of the dc voltage E_2 at the machine terminals also reverses, as Figure 25 shows. The voltage E_2 at the machine terminals is thus a pulsating negative dc voltage (two pulses per rotation).

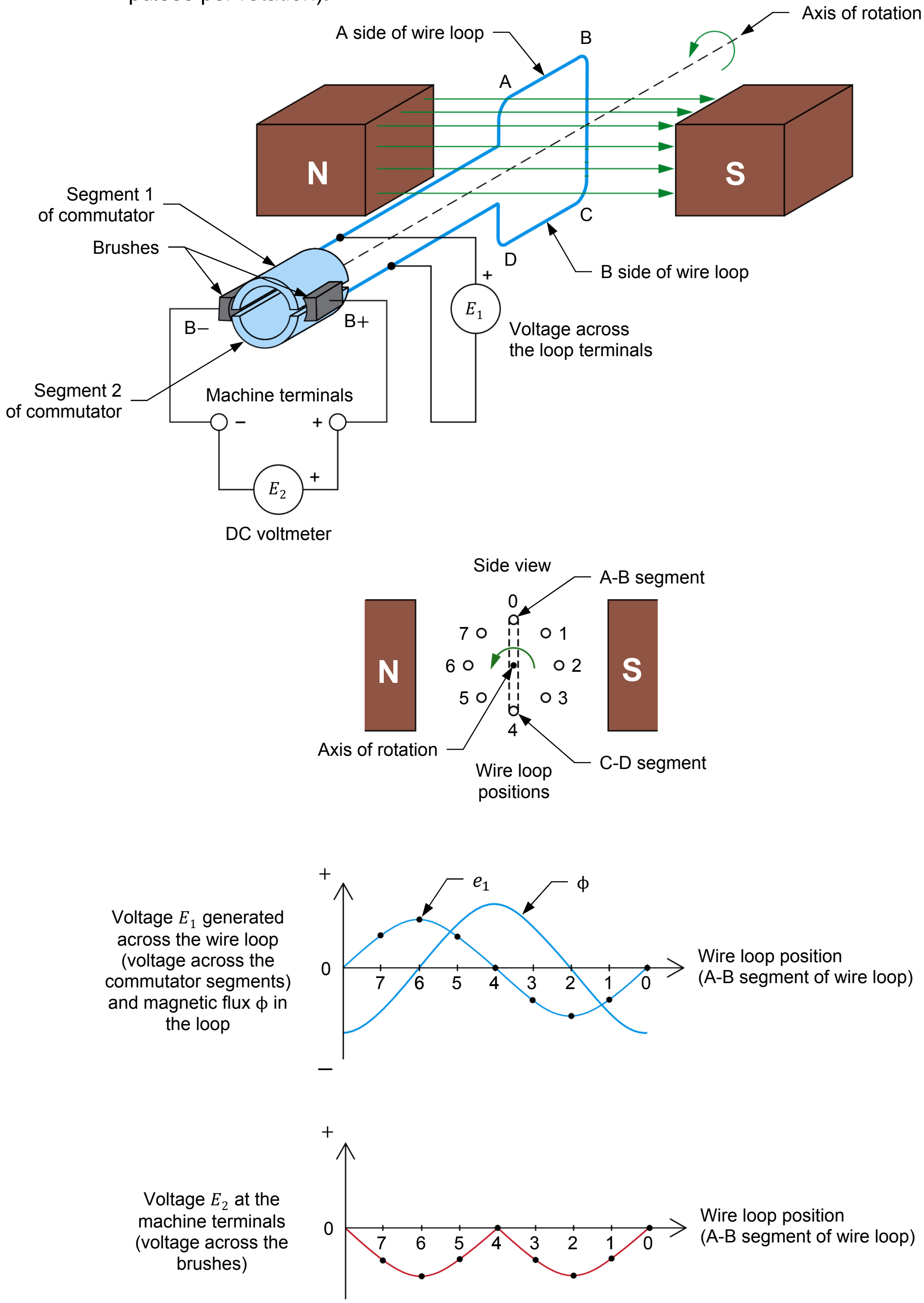


Figure 25. Permanent magnet dc machine operating as a generator (counterclockwise rotation).

Reducing the fluctuations of the generated dc voltage

All permanent magnet dc machines have an armature made of several wire loops and commutator segments. Increasing the number of wire loops and commutator segments reduces the fluctuation of the voltage at the dc machine terminals that is due to the pulsating effect (i.e., the generated voltage is a nearly pure dc voltage). Figure 26 shows an example of the voltage generated at the terminals of a dc machine when a second loop of wire is added to the armature. Two extra segments are also added to the commutator to connect the additional wire loop of the armature to the machine terminals via the brushes.

As Figure 26 shows:

- Two alternating-current (ac) voltages E_1 and E_2 are generated, one across each wire loop.
- However, the voltage E_3 at the machine terminals always has the same polarity. This voltage consists of four pulses per rotation of the armature instead of only two pulses per rotation. Consequently, the fluctuation of the generated dc voltage caused by the pulsating effect is reduced.

The higher the number of wire loops at the armature, the higher the number of segments on the commutator and thus, the higher the number of pulses per rotation and the lower the voltage fluctuation at the dc machine terminals.

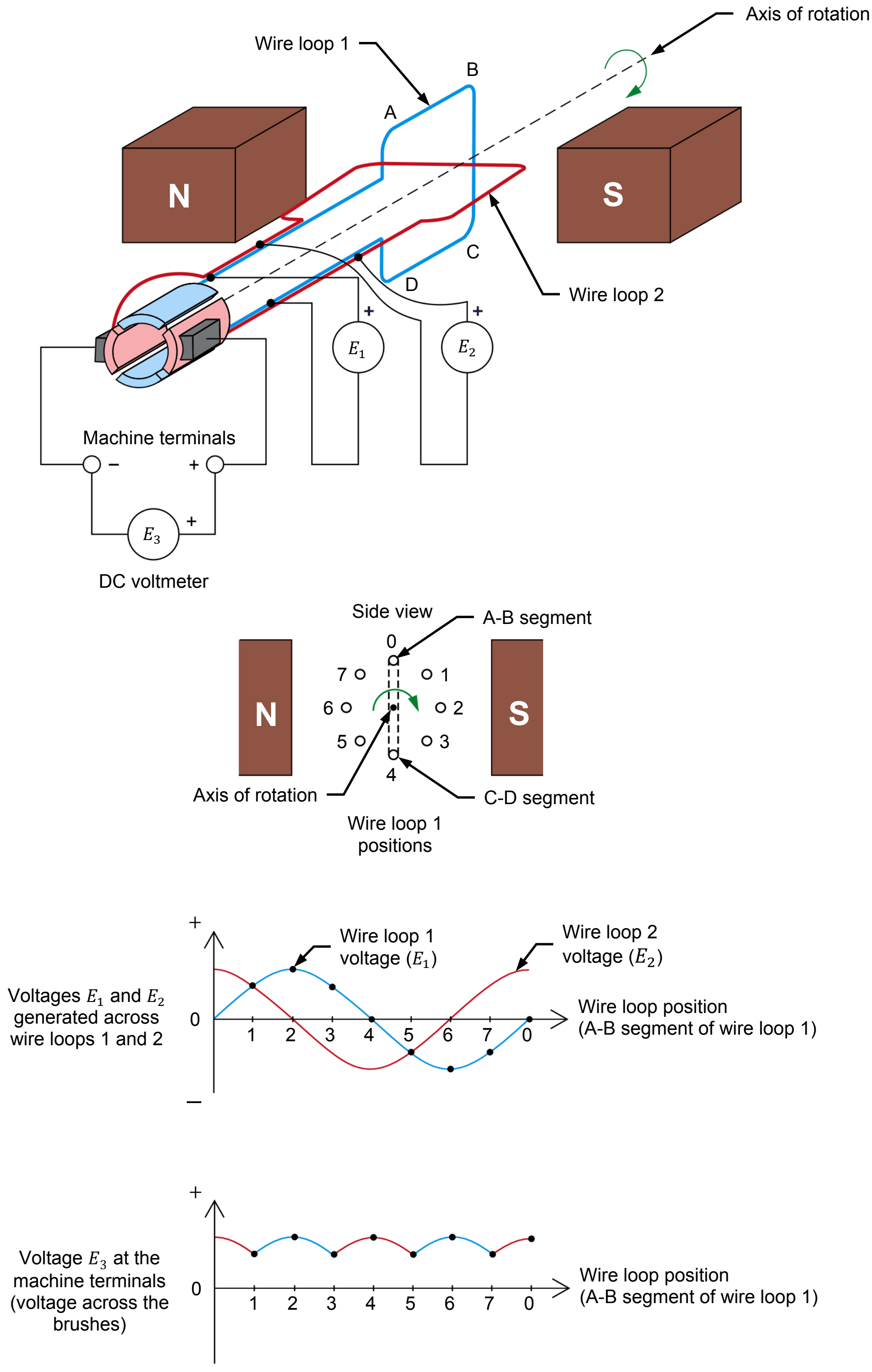


Figure 26. Adding loops of wire to the dc machine armature increases the value of the generated dc voltage and reduces the voltage fluctuation due to the pulsating effect.

Characteristic of the generated voltage as a function of the rotation speed

Figure 27 shows the generated voltage-versus-speed characteristic of a permanent magnet dc machine operating as a generator. The generated voltage is proportional to the rotation speed of the armature. This is because the higher the rotation speed of the armature, the higher the rate of change of the magnetic flux ($\frac{\Delta\phi}{\Delta t}$) in the rotor wire loops, and thus, the higher the generated voltage. The polarity of the generated voltage depends on the direction of rotation of the armature. When the armature rotates in clockwise (CW) direction, the generated voltage is positive. Conversely, when the armature rotates in counterclockwise (CCW) direction, the generated voltage is negative.

The relationship between the polarity of the generated dc voltage and rotor direction of rotation is arbitrarily selected. Thus, the polarity of the generated dc voltage could be considered positive when the rotor rotates clockwise and negative when the rotor rotates counterclockwise.

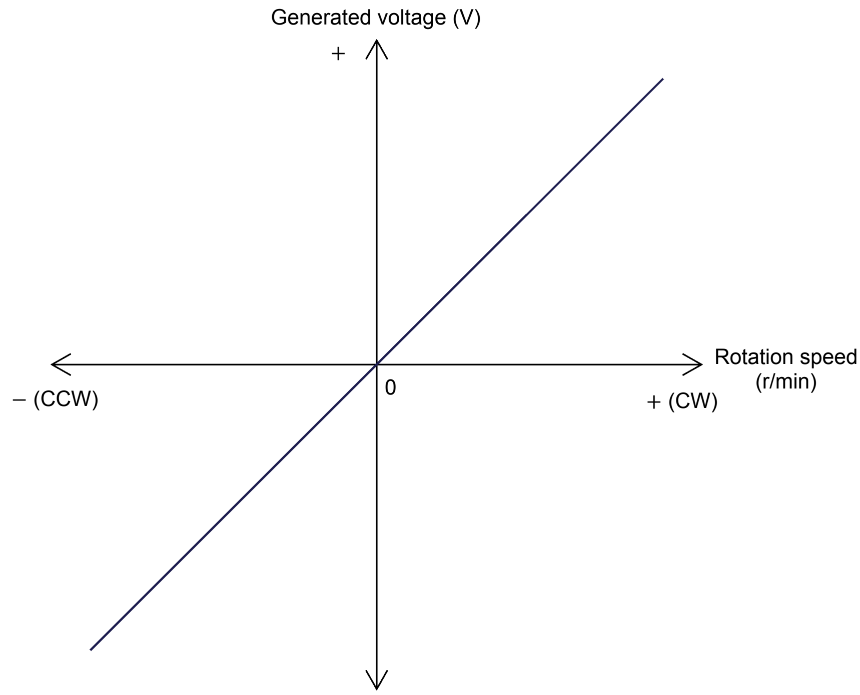


Figure 27. Generated voltage versus speed characteristic of a permanent magnet dc machine operating as a generator.

Torque opposing rotation in a permanent magnet dc machine operating as a generator

Torque is a force used to make an object rotate or, conversely, a force opposing the rotation of an object. This object may be, for example, the rotor of a generator. In that case, torque is applied to the rotor of the generator to make it turn, and, in reaction, the generator produces torque that opposes rotation. Conversely, a torque opposes the rotation of the rotor when a load is applied to the generator.

Figure 28 illustrates the above example using a permanent magnet dc machine operating as a generator. When a load like a resistor is connected to the terminals of a dc machine operating as a generator, current starts to flow in the armature wire loop through the load. This current produces a magnetic field inside the wire loop with a north pole and a south pole, as shown by the red lines of force around the loop in Figure 28. The green lines in this figure show the magnetic field produced by the permanent magnets.

The location of the poles of the magnetic field produced in the wire loop with respect to the poles of the permanent magnets on the machine stator creates forces of **attraction and repulsion** that oppose armature rotation, as Figure 28 shows. The combined effect of these forces is to apply torque to the machine shaft that opposes rotation. The higher the current flowing in the loop, the stronger the magnetic field produced in the loop and the stronger the torque that opposes rotation.

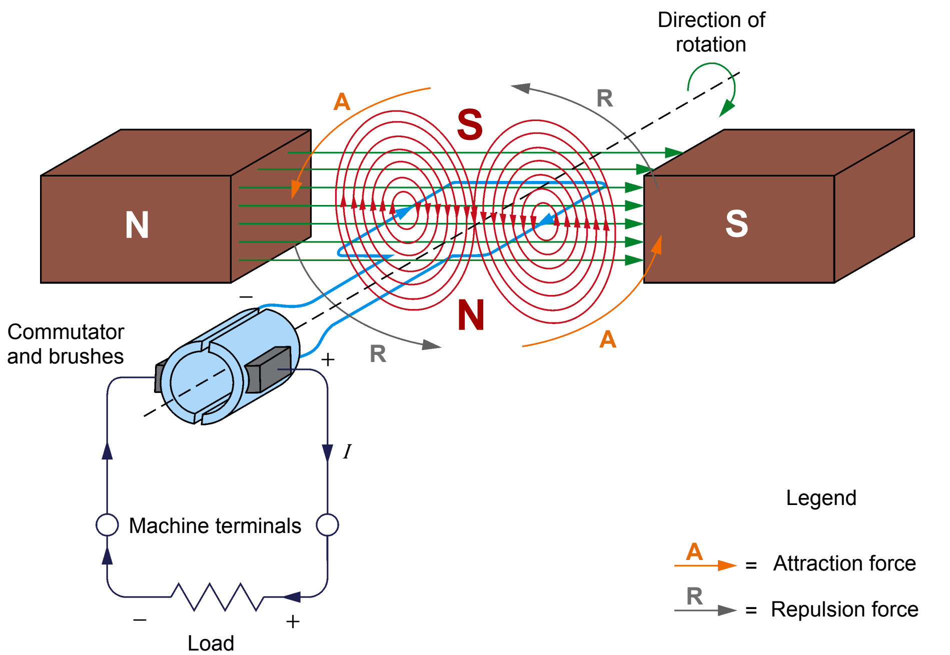


Figure 28. The interaction between the magnetic field produced by the permanent magnets in a dc machine and the magnetic field produced in the armature wire loop when an electric load is connected to the dc machine creates attraction and repulsion forces in the machine that result in torque opposing the armature rotation.

In Figure 28, the magnetic fields produced by the wire loop and the permanent magnets are shown as two separate fields to make the explanation clearer. However, since magnetic lines of force cannot intersect each other, the resulting magnetic field in an actual dc machine operating as a generator resembles that shown in the cross-sectional view of the machine in Figure 29. However, this does not change the end result, i.e., the combined effect of the forces of attraction and repulsion result in a torque that opposes rotation (opposition torque).

Since the opposition torque produced by a permanent magnet dc machine operating as a generator acts in the direction opposite to the direction of rotation of the armature, its polarity is opposite to the polarity of the rotation speed. Thus, when the armature rotates clockwise (i.e., when the polarity of the rotation speed is positive), the polarity of the opposition torque is negative. Conversely, when the armature rotates counterclockwise (i.e., when the polarity of the rotation speed is negative), the polarity of the generator torque is positive.

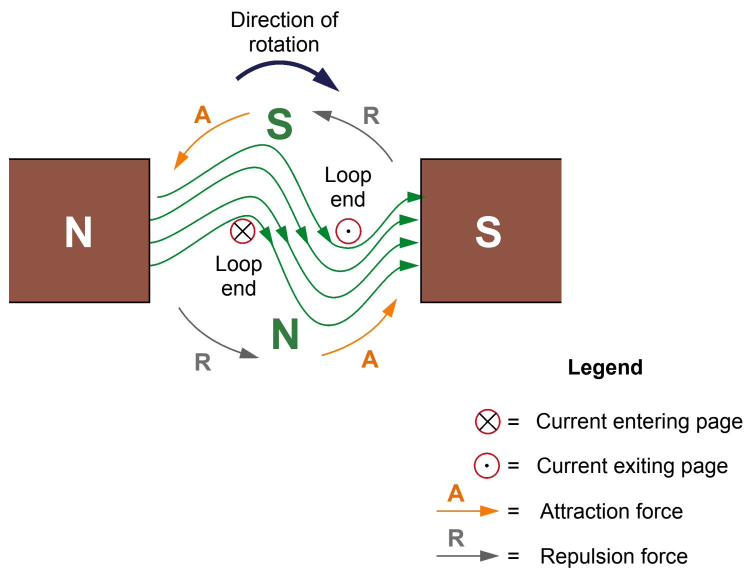


Figure 29. Magnetic field in an actual dc machine operating as a generator.

Opposition torque-versus-current characteristic

Figure 30 shows the opposition torque-versus-load current characteristic of a permanent magnet dc machine operating as a generator. The opposition torque is proportional to the current supplied to the load. Notice that the opposition torque is expressed with a negative polarity to indicate that it opposes armature rotation (the rotation speed is generally considered to be positive).

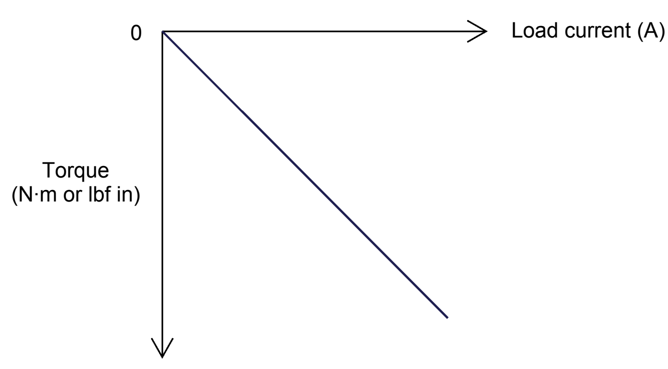


Figure 30. Opposition torque-versus-current characteristic of a permanent magnet dc machine operating as a generator.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Electromagnetic induction phenomenon
- Opposition to rotation
- Voltage-versus-speed characteristic of a permanent magnet dc machine operating as a generator
  Clockwise rotation. Counterclockwise rotation.
- Torque-versus-current characteristic of a permanent magnet dc machine operating as a 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.

Electromagnetic induction phenomenon

In this section of the exercise, you will connect a dc voltmeter across the machine terminals and observe the voltage developed across these terminals when the machine shaft is rotated manually.

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

2. Place the Permanent Magnet DC Machine on your work surface. Connect a dc voltmeter to the terminals of the Permanent Magnet DC Machine. The red machine terminal is the positive terminal.

3. Make the shaft of the Permanent Magnet DC Machine rotate clockwise with your hands. Notice that a dc voltage of positive polarity appears across the machine terminals. Explain why a dc voltage is developed at the machine terminals when its shaft is rotated.

   When the machine shaft is rotated, the armature wire loops cut the magnetic field produced by the stator permanent magnets, causing a voltage to be induced across the wire loop terminals. This voltage is collected by the commutator segments and delivered to stationary brushes connected to the machine terminals.

4. Make the shaft of the Permanent Magnet DC Machine rotate counterclockwise with your hands. Does a dc voltage of negative polarity appear across the machine terminals? Why?

   Yes. When the direction of rotation of the machine shaft is reversed, the polarity of the dc voltage at the machine terminals also reverses.

5. Disconnect the dc voltmeter from the Permanent Magnet DC Machine.

Opposition to rotation

In this section, you will observe the opposition to rotation of the Permanent Magnet DC Machine when the terminals of the machine are not short-circuited and when they are.

6. Make the shaft of the Permanent Magnet DC Machine rotate with your hands. Notice that it is easy to make the machine shaft rotate. Explain why.

   When no load is connected to the terminals of the Permanent Magnet DC Machine, no current flows in the armature wire loops, and thus, no magnetic field is produced in the wire loops. Therefore, no force (torque) opposes the rotation of the machine shaft.

7. Short-circuit the two terminals of the Permanent Magnet DC Machine with a lead.

   Make the machine shaft rotate clockwise with your hands, then make it rotate counterclockwise. Notice that it is less easy to make the machine shaft rotate when the machine terminals are short-circuited. Explain why.

   When a load (in the present case, a short circuit) is connected to the terminals of the Permanent Magnet DC Machine, current starts to flow in the armature wire loops through the load. This current produces a magnetic field inside each of the wire loops. The location of the poles of the magnetic field produced by the wire loops with respect to the poles of the permanent magnets on the machine stator creates forces of attraction and repulsion. The combined effect of these forces is to apply torque to the machine shaft that opposes rotation.

8. Remove the lead short-circuiting the machine terminals.

Voltage-versus-speed characteristic of a permanent magnet dc machine operating as a generator

In this section, you will use a prime mover to drive the Permanent Magnet DC Machine and make it operate as a generator. You will vary the rotation speed of the prime mover by steps and measure the dc voltage generated across the machine terminals.

9. Install the equipment in the Workstation.

Mechanically couple the Four-Quadrant Dynamometer/Power Supply to the Permanent Magnet DC Machine using a timing belt.

⚠ WARNING

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

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

Connect the *Power Input* of the Data Acquisition and Control Interface (DACI) to a 24 V ac power supply. Turn the 24 V ac power supply on.

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

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

12. 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).

13. 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 for the Data Acquisition and Control Interface is available. Select the network voltage and frequency that correspond to the voltage and frequency of your local ac power network, then click the *OK* button to close the LVDAC-EMS Start-Up window.

14. Connect the equipment as shown in Figure 31. In this circuit, the Permanent Magnet DC Machine is driven, via a belt, by the machine in the Four-Quadrant Dynamometer/Power Supply. *E1* is a voltage input of the Data Acquisition and Control Interface.

Appendix C shows in more detail the equipment and the connections required for the circuit diagram below.

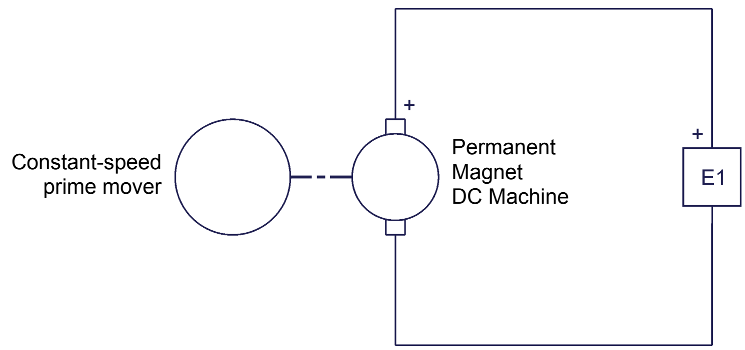


Figure 31. Setup used to plot the voltage-versus-speed characteristic of the Permanent Magnet DC Machine operating as a generator.

Clockwise rotation

15. 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 24:12. 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 Permanent Magnet DC Machine), respectively.

– Make sure that the *Speed Control* parameter is set to *LVDAC-EMS Command 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 by entering 1000 in the field next to this parameter. 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 Permanent Magnet DC Machine 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.*

16. In LVDAC-EMS, start the Metering application. Set meter *E1* as a dc voltmeter.

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

17. 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 Permanent Magnet DC Machine.

The *Speed* meter in the Four-Quadrant Dynamometer/Power Supply window indicates the rotation speed of the Permanent Magnet DC Machine. Is this speed approximately equal to the value of the *Speed* parameter (1000 r/min)?

❑ Yes ❑ No

Yes.

Meter *E1* in the Metering window indicates the dc voltage generated across the Permanent Magnet DC Machine terminals. Record this voltage below.

DC voltage generated = _______ V

The dc voltage generated is about 11 V.

18. In LVDAC-EMS, open the Data Table window. Set the Data Table to record the rotation speed of the Permanent Magnet DC Machine (indicated by the *Speed* meter in the Four-Quadrant Dynamometer/Power Supply window) and the dc voltage generated across the machine terminals (indicated by meter *E1* in the Metering window).

To select the parameters to be recorded in the Data Table, click the Options menu of the Data Table and then click Record Settings. In the Settings list, select Four-Quadrant Dynamometer/Power Supply, then check the Speed box. In the Settings list, select Metering, then check the box of meter E1. Click OK to close the Record Settings box.

19. Make the rotation speed of the Permanent Magnet DC Machine vary from 0 to 4000 r/min in steps of 500 r/min by adjusting the *Speed* parameter. For each speed setting, record the machine rotation speed (indicated by the *Speed* meter) and the dc voltage (meter *E1*) generated across the machine terminals in the Data Table by clicking the *Record Data* button in this table.

Voltage generated across the terminals of the Permanent Magnet DC Machine as a function of the rotation speed.

Clockwise rotation		Counterclockwise rotation	
Machine rotation speed (r/min)	**Generated dc voltage (V)**	**Machine rotation speed (r/min)**	**Generated dc voltage (V)**
0	0.0	0.0	0.0
500	5.7	-500	-6.2
1000	11.5	-1000	-12.1
1500	17.3	-1500	-18.1
2000	23.0	-2000	-24.1
2500	28.7	-2500	-30.1
3000	34.5	-3000	-36.1
3500	40.2	-3500	-42.1
4000	46.0	-4000	-48.1

Counterclockwise rotation

20. 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.

– Set the *Pulley Ratio* parameter to 24:12.

– Make sure that the *Speed Control* parameter is set to *LVDAC-EMS Command Knob*.

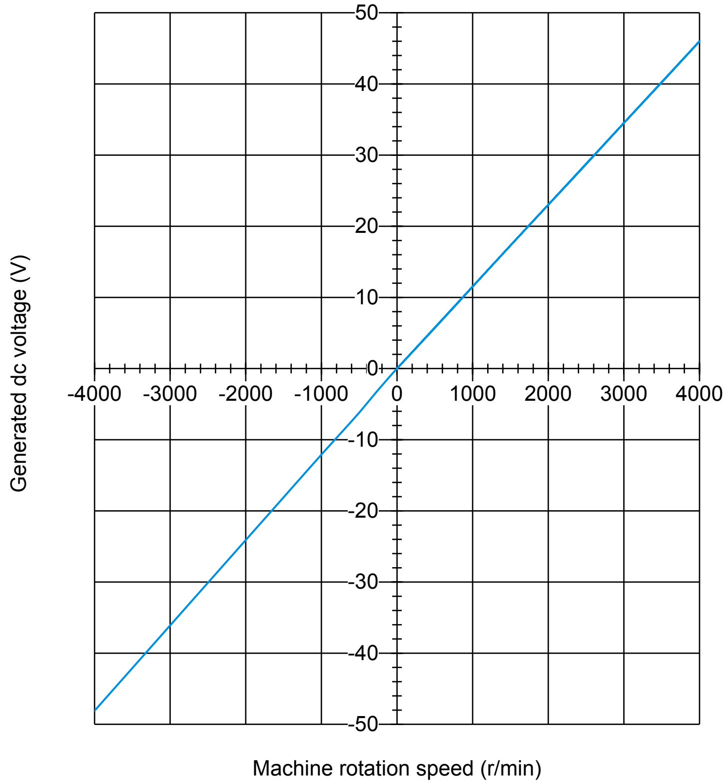
– Set the *Speed* parameter to 0 r/min.

– Start the *CCW Constant-Speed Prime Mover/Brake* by clicking the *Start/Stop* button or by setting the *Status* parameter to *Started*.

21. Make the rotation speed of the Permanent Magnet DC Machine vary from 0 to -4000 r/min in steps of about -500 r/min by adjusting the *Speed* parameter in the Four-Quadrant Dynamometer/Power Supply window. For each speed setting, record the machine rotation speed and the dc voltage (meter *E1*) generated across the machine terminals in the Data Table.

22. 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*.

23. From the results recorded in the Data Table, plot the curve of the dc voltage generated across the machine terminals versus the machine rotation speed.



Voltage generated across the terminals of the Permanent Magnet DC Machine as a function of the rotation speed.

According to the obtained curve, is the voltage generated across a permanent magnet dc machine operating as a generator proportional to the rotation speed?

❑ Yes ❑ No

Yes

Does the polarity of the generated dc voltage depend on the direction of rotation, thereby confirming what has been observed at the beginning of this exercise when you turned the machine shaft manually and measured the generated voltage with a dc voltmeter? Explain.

Yes. When the machine rotates in the clockwise direction, the dc voltage generated across the machine terminals is of positive polarity. Conversely, when the machine rotates in the counterclockwise direction, the dc voltage generated across the machine terminals is of negative polarity.

Save the data recorded in the Data Table, then close this table.

Torque-versus-current characteristic of a permanent magnet dc machine operating as a generator

In this section, you will use a prime mover to drive the Permanent Magnet DC Machine and make it operate as a generator. You will vary the opposition torque developed at the machine shaft and measure the current flowing through the machine armature.

24. Connect the equipment as shown in Figure 32. Use the high-current (40 A) terminal of current input *I1* on the Data Acquisition and Control Interface.

In the Data Acquisition and Control Settings window of LVDAC-EMS, set the *Range* of current input *I1* to *High*.

Appendix C shows in more detail the equipment and the connections required for the circuit diagram.

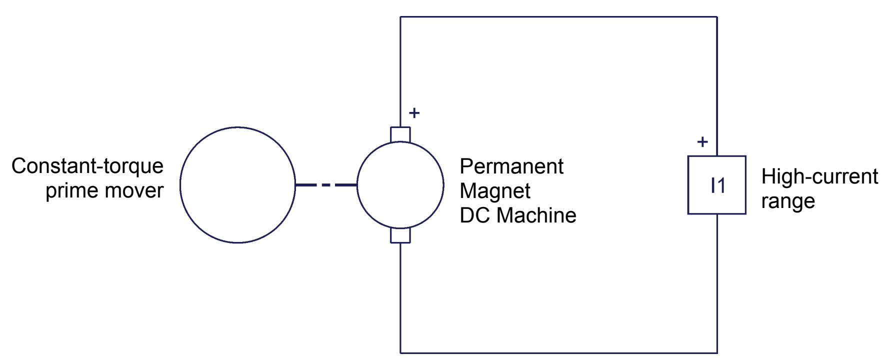


Figure 32. Setup used to plot the torque-versus-current characteristic of the Permanent Magnet DC Machine operating as a generator.

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

– Set the *Function* parameter to *Positive Constant-Torque Prime Mover/Brake*. This setting makes the Four-Quadrant Dynamometer/Power Supply operate as a constant-torque prime mover/brake with a torque setting corresponding to the *Torque* parameter.

– Set the *Pulley Ratio* parameter to 24:12.

– Set the *Torque* parameter to 0.3 N·m (2.7 lbf in) by entering 0.3 (2.7) in the field next to this parameter.

26. In the Metering window of LVDAC-EMS, set meter *I1* to display dc values. Ensure the continuous refresh mode of the meters is enabled.

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

Observe that the prime mover starts to rotate clockwise, thereby driving the shaft of the Permanent Magnet DC Machine.

The *Speed* and *Torque* meters in the Four-Quadrant Dynamometer/Power Supply indicate the rotation speed and torque at the shaft of the Permanent Magnet DC Machine. Notice that the torque is of negative polarity, i.e., opposite to the polarity (positive) of the rotation speed. This is because the Permanent Magnet DC Machine is operating as a generator. Is the torque (absolute value) indicated by the *Torque* meter approximately equal to the value of the *Torque* parameter?

❑ Yes ❑ No

Yes

Meter *I1* in the Metering window indicates the dc current flowing in the armature of the Permanent Magnet DC Machine. Record this current below.

DC current flowing in the armature (load current) = _______ A

DC current flowing in the armature (load current) ≅ 2.6 A

28. In LVDAC-EMS, open the Data Table and make the settings required to record the torque developed at the shaft of the Permanent Magnet DC Machine (indicated by the *Torque* meter in the Four-Quadrant Dynamometer/Power Supply window) and the dc current flowing in the armature of this machine (indicated by meter *I1* in the Metering window).

To select the parameters to be recorded in the Data Table, click the Options menu of the Data Table and then click Record Settings. In the Settings list, select Four-Quadrant Dynamometer/Power Supply, then check the Torque box. In the Settings list, select Metering, then check the box of meter I1. Click OK to close the Record Settings box.

CAUTION

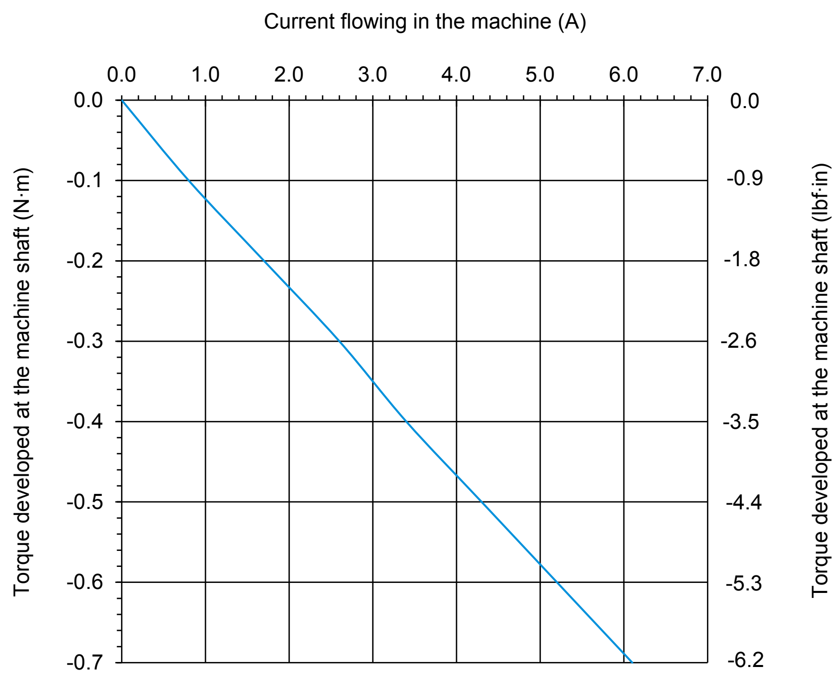
Since the output of the Permanent Magnet DC Machine is short circuited by current input *I1*, high currents can flow in the machine at low torques and rotation speeds. Make sure not to exceed the current rating of the Permanent Magnet DC Machine. Perform the next manipulation in less than 5 minutes, then immediately stop the *Positive Constant-Torque Prime Mover/Brake* in LVDAC-EMS.

29. Make the torque developed at the shaft of the Permanent Magnet DC Machine vary from 0 to -0.7 N·m (or from 0 to -6.0 lbf·in) in steps of -0.1 N·m (or -1 lbf·in) by adjusting the *Torque* parameter. For each torque setting, record the current flowing in the armature of the dc machine (meter *I1*) and the torque developed at the machine shaft (indicated by the *Torque* meter) in the Data Table. Then immediately stop the *Positive Constant-Torque Prime Mover/Brake* in LVDAC-EMS.

Torque developed at the dc machine shaft as a function of the current flowing in the armature of the machine.

Current flowing in the armature of the dc machine (A)	Torque developed at the machine shaft	
0.0	0.0 N·m	0.0 lbf·in
0.8	-0.1 N·m	-0.9 lbf·in
1.7	-0.2 N·m	-1.8 lbf·in
2.6	-0.3 N·m	-2.6 lbf·in
3.4	-0.4 N·m	-3.5 lbf·in
4.3	-0.5 N·m	-4.4 lbf·in
5.2	-0.6 N·m	-5.3 lbf·in
6.1	-0.7 N·m	-6.2 lbf·in

30. From the results recorded in the Data Table, plot a curve of the torque developed at the dc machine shaft as a function of the current flowing in the armature of the dc machine.



Torque developed at the shaft of the Permanent Magnet DC Machine (clockwise direction of rotation) as a function of the armature current flowing in the machine.

According to the obtained curve, is the torque developed at the shaft of a permanent magnet dc machine operating as a generator proportional to the current flowing in the machine armature?

❑ Yes ❑ No

Yes

31. Save the data recorded in the Data Table, then close this table. Turn the Four-Quadrant Dynamometer/Power Supply off by setting the main power switch to *O* (off). Close the LVDAC-EMS software. Disconnect all leads and return them to their storage location.

CONCLUSION

In this exercise, you familiarized yourself with a permanent magnet dc machine operating as a generator. You learned that this machine consists of a rotor (armature) made of several loops of wire, and a stator made of permanent magnets that produce a fixed magnetic field. When the rotor is driven by a prime mover, it cuts the lines of force of the stator magnetic field. This produces a dc voltage across the armature terminals of the machine, which thus, operates as a dc generator. The magnitude of the generated voltage is proportional to the rotation speed, while the polarity of this voltage depends on the direction of rotation. For instance, when the rotor rotates clockwise, the dc voltage is positive, and vice-versa. You learned that when a load is connected across the armature terminals of the machine, a force (torque) opposing rotor rotation is produced. This torque is in the direction opposite to the direction of rotation. The higher the armature current (load current), the stronger the torque opposing rotation.

Review Questions

1. By referring to Figure 21, describe the construction of a simple permanent magnet dc machine.

   The stator is the fixed part of the machine in which the rotor turns. The stator consists of permanent magnets aligned so that poles of opposite polarities face each other. Therefore, lines of magnetic field pass from one permanent magnet to the other through the metallic armature. The rotor is the rotating part of the machine. It consists of a wire loop mounted on a rotary metallic armature. The ends of the wire loop are connected to terminals on the dc machine, via a commutator and a pair of brushes (usually made of carbon). The commutator has two segments isolated from one another. Each segment is connected to one terminal of the wire loop.

2. By referring to Figure 24, describe the operation of a simple permanent magnet dc machine used as a generator. Explain how an alternating-current (ac) voltage is induced across the armature wire loop, and why this voltage is unipolar (i.e., why it always has the same polarity) at the machine terminals.

   When the armature wire loop rotates within the magnetic field of the magnets, it cuts the lines of magnetic field and a voltage is induced across the loop terminals. This voltage is collected by the two commutator segments and delivered to stationary brushes connected to the machine terminals. The polarity of the voltage across the wire loop (voltage across the commutator segments) continually alternates: it is positive for half a turn, then negative for the next half turn, and so on. Because of this, the voltage across the wire loop is an alternating-current (ac) voltage. However, the voltage at the machine terminals (voltage across the brushes) is unipolar (i.e., it always has the same polarity) because the commutator reverses the connections between the loop terminals and machine terminals each time the two slots of the commutator pass by the stationary brushes (i.e., twice per rotation at the exact instant when the polarity of the voltage across the wire loop reverses).

3. What effect does increasing the number of wire loops and commutator segments have on the voltage generated by a permanent magnet dc machine operating as a generator? Explain.

   Increasing the number of wire loops and commutator segments reduces the fluctuation of the voltage generated at the dc machine terminals. This is because a higher number of wire loops and commutator segments provides a higher number of pulses per rotation in the voltage at the dc machine terminals.

4. Describe the relationship between the voltage generated by a dc machine operating as a generator as a function of the rotation speed of the machine. When is the generated voltage of positive polarity? When is this voltage of negative polarity?

The voltage generated by a dc machine operating as a generator is proportional to the armature rotation speed. Thus, the higher the armature rotation speed, the higher the generated voltage.

The polarity of the generated voltage depends on the direction of rotation of the armature. In general, when the machine rotates in clockwise (CW) direction, the generated voltage is considered to be positive. Conversely, when the armature rotates in counterclockwise (CCW) direction, the generated voltage is considered to be negative.

5. Explain why a force (torque) opposes the rotation of a dc machine operating as a generator when an electrical load like a resistor is connected to the dc machine terminals. When is this force of positive polarity? When is this force of negative polarity?

When an electrical load like a resistor is connected to a dc machine operating as a generator, currents flow in the armature wire loops and magnetic field is produced in each of these loops. The location of the poles of the magnetic field produced in the loops with respect to the poles of the stator permanent magnets creates forces of attraction and repulsion. The combined effect of these forces is a torque that opposes rotation of the machine shaft.

Since the opposition torque is in the direction opposite to the direction of rotation of the armature, its polarity is opposite to the polarity of the rotation speed. Thus, when the armature rotates clockwise (i.e., when the polarity of the rotation speed is positive), the polarity of the opposition torque is negative. Conversely, when the armature rotates counterclockwise (i.e., when the polarity of the rotation speed is negative), the polarity of the generator torque is positive.

Bibliography

Wildi, Theodore, *Electrical Machines, Drives, and Power Systems*, 2nd edition, New Jersey, Prentice Hall, 1991. ISBN 0-13-251547-4.