

# DC Power Circuits

FESTO

**FESTO**

Electricity and New Energy

LabVolt Series

Student Manual



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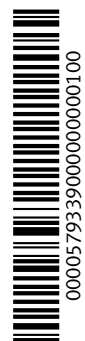
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Student Manual

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**Electricity and New Energy**

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**Student Manual**

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By the staff of Festo Didactic

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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
	<b>DANGER</b> indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
	<b>WARNING</b> indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
	<b>CAUTION</b> indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
	<b>CAUTION</b> used without the <i>Caution, risk of danger</i> 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. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
	Direct current

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# Safety and Common Symbols

Symbol	Description
	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

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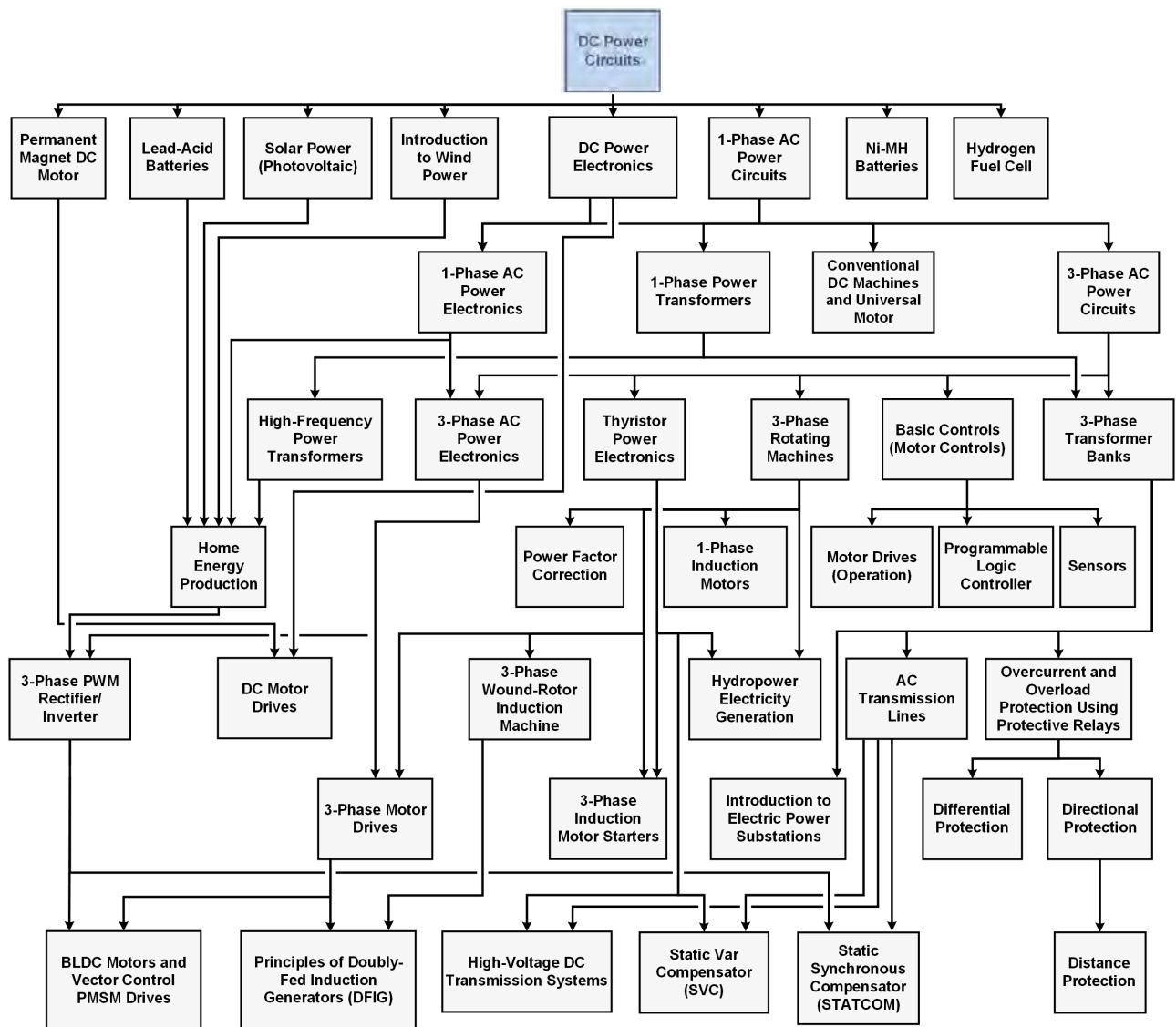


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# Preface

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.

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# 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 [did@de.festo.com](mailto:did@de.festo.com).

The authors and Festo Didactic look forward to your comments.

# About This Course

## **About the course DC Power Circuits**

The *DC Power Circuits* course teaches the basic concepts of electricity. Students are introduced to the fundamental laws of electricity. They learn how to calculate voltage, current, resistance, and power in direct-current (dc) circuits. Students analyze simple dc circuits, and learn how to determine their equivalent resistance for various combinations of series and parallel resistors. Finally, students use the acquired knowledge to simplify complex circuits. They verify their calculations by performing circuit measurements.

## **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.

## **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).

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## DC Power Circuits

### DISCUSSION OUTLINE

The Discussion of Fundamentals covers the following points:

- Introduction
- Energy
- Electricity
- Positive and negative charges
- Electric field
- Voltage (potential difference)
- Resistance
- Current
- Ohm's law, Kirchhoff's voltage and current laws

### DISCUSSION OF FUNDAMENTALS

#### Introduction

Electricity is used universally. The word electricity derives from the Greek word "elektron", which means amber. Amber is fossil tree resin which the Greeks connected to the Sun God. As early as 600 BC, the Greek philosopher and scientist Thales observed that, when rubbing a piece of amber on a cloth, it becomes charged with static electricity.

In the early 17th century, the English physician William Gilbert did a lot of research on electricity and magnetism. He developed an electrical measuring instrument, called the electroscope, to detect the presence and magnitude of the electric charge of a body.

Then, in the 18th and the early 19th centuries, experiments of electricity and magnetism led to important inventions and discoveries:

- The discovery of the electrical nature of lightning and the principle of electric charge conservation by Benjamin Franklin.
- The discovery of the electromagnetic phenomenon of self-inductance and mutual inductance by Joseph Henry.
- The definition of the electrostatic force of attraction and repulsion by Charles-Augustin de Coulomb.
- The discovery of the production of electricity by cells and nerves by Luigi Galvani.
- The development of the first electrochemical cell by Alessandro Volta. This cell, also called the voltaic cell, was made from alternating layers of zinc and copper.
- The discovery of electromagnetism by Hans Christian Ørsted and André-Marie Ampère.

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- The invention of an instrument for detecting and measuring electric current by Johann Schweigger and André-Marie Ampère.
- The establishment of the basis for the electromagnetic field concept, the statement of the law of induction, and the invention of electromagnetic rotary devices like the electric dynamo by Michael Faraday.
- The establishment of the relationship between voltage, current, and resistance, and the analysis of electrical circuits by Georg Simon Ohm and Gustav Kirchhoff.
- The demonstration of the existence of electromagnetic waves with an apparatus able to produce and detect radio waves by Heinrich Hertz.
- The invention of the phonograph, the motion picture camera, and the incandescent electric light bulb by Thomas Edison.
- The development of mathematical analysis of electricity, the invention of an electric telegraph, and the development of signaling on long submarine communications cables by William Thomson (Lord Kelvin).
- The development of modern alternating current (ac) electric power systems, including the polyphase system of electrical distribution and the ac motor, by Nikola Tesla.

In the late 19th century, electricity became part of the everyday life through the invention of electric devices used in transport, heating, lighting, communications, and computation, by such inventors as Thomas Edison, Nikola Tesla, Charles Steinmetz, William Thomson Kelvin, Alexander Graham Bell, George Westinghouse, Guglielmo Marconi, and Ernst Werner von Siemens.

### **Energy**

Energy is the ability to do a work. Energy can be transferred from a body to another, and converted from one form to another. Energy is measured in joules (J). Energy exists in two forms, potential and kinetic:

- **Potential energy** is energy a body possesses due to its position or its particular physical or chemical state.
- **Kinetic energy** is energy a body possesses due to its motion.

Depending on the context in which it is used, produced, or analyzed, energy can be described as electrical, chemical, mechanical, thermal, gravitational, nuclear, etc. In any case, energy is made up of either potential or kinetic energy, or of both potential and kinetic energy.

### **Electricity**

Electricity is a fundamental property of matter, associated with atomic particles whose movement develops fields of force and generates kinetic or potential energy.

The **law of conservation of energy** states that energy cannot be created or destroyed, it can only change form. Therefore, to obtain electricity, a source of energy is required. This source can be

- chemical energy from batteries;
- electrical energy from wind power turbines;
- hydraulic energy from the moving water of a river or fall;
- thermal energy from burning coal or gas;
- nuclear energy from a controlled nuclear reaction;
- solar energy from the Sun.

For example, the chemical energy in a dry-cell battery can be used to produce electricity.

Electricity is used to power everyday electric devices in heating, lighting, communications, computation, and transport.

### **Positive and negative charges**

Electricity is intimately linked to the atomic structure of matter.

Atoms are made up of three types of particles called protons, neutrons, and electrons.

- **Protons** and **neutrons** together make up the center or core of the atom, called the **nucleus**. Protons have a positive (+) electric charge, while neutrons have no electric charge.
- **Electrons** circle around, or orbit the nucleus. They have a negative (–) electric charge.

The negatively-charged electrons and positively-charged protons attract each other. A balanced atom has one negatively-charged electron for each positively-charged proton. The positive electric charge of the nucleus attracts the negatively-charged electrons and holds them in place.

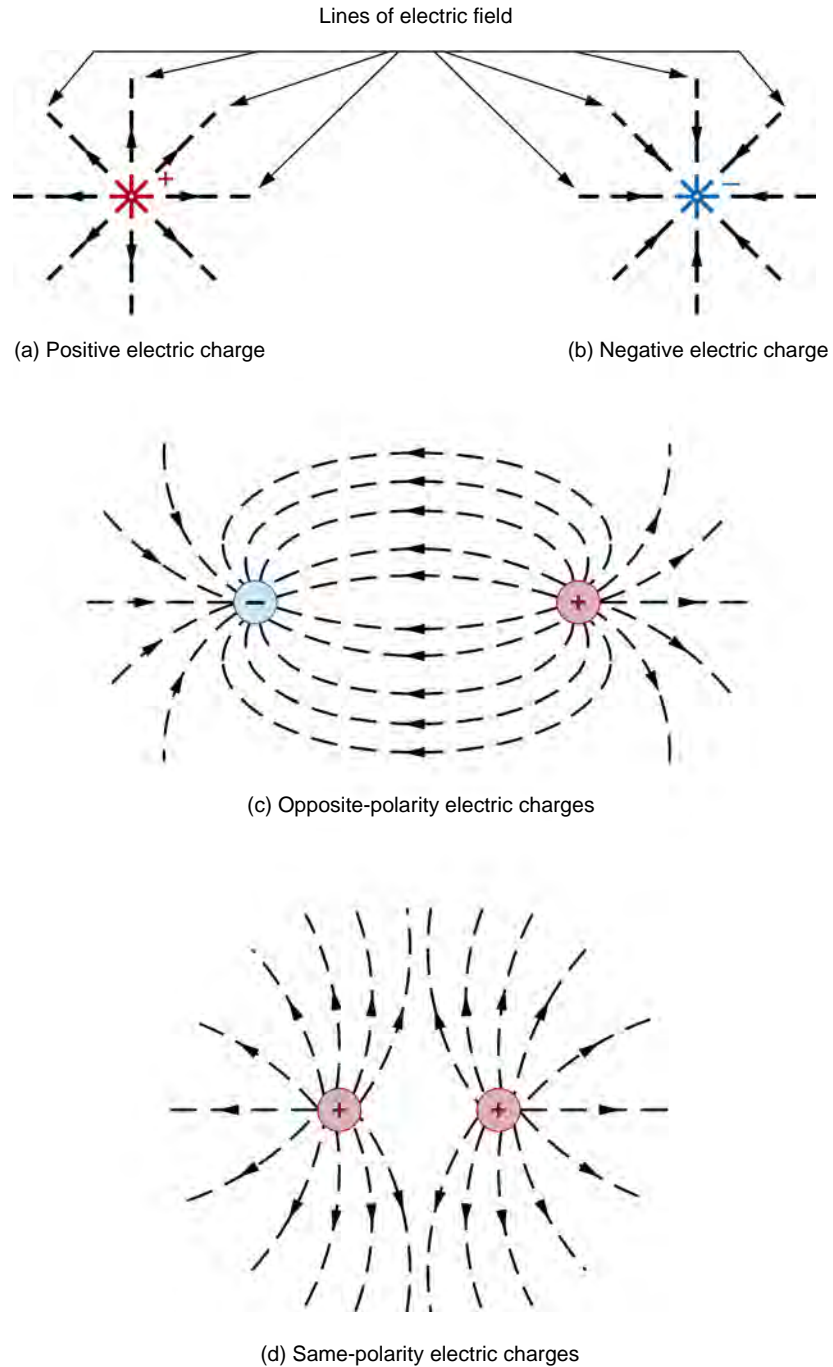
### **Electric field**

The further an electron is from the nucleus, the lower the atomic force attracting it. Certain materials, called **conductors**, have electrons in their outer orbit that can be easily dislodged by using external means like heating, or the application of an **electric field**.

The electrons thus removed from their orbits become free electrons and move between atoms. The movement of many electrons at the same time creates a flow of electric current.



Figure 1 shows simplified representations of the electric field around a single positive electric charge Figure 1a, around a single negative electric charge Figure 1b, between electric charges of opposite polarities Figure 1c, and between electric charges of the same polarity Figure 1d.



**Figure 1. Simplified representations of electric fields.**

## Voltage (potential difference)

The greater the electric field applied to dislodge electrons is, the greater the number of electrons moving at the same time is and, therefore, the greater the electric current will be.

The magnitude of the electric field, expressed in V/m, is measured between two points of the field. The **voltage**, or **potential difference** is the electromotive force between two points.

The concept of potential difference is similar to that of hydraulic pressure. Thus, a water dam having a height of 300 meters produces a higher pressure on water confined in a pipe than a dam which is only 30 meters high. This occurs because potential energy increases when height increases.

Similarly, a voltage of 100 V creates a greater electric pressure on electrons in a conductor wire (to make them move) than a voltage of 10 V.

Some of the various sources used to produce voltage are: mechanical generators and alternators, lead-acid and dry-cell batteries, and photoelectric cells.

## Resistance

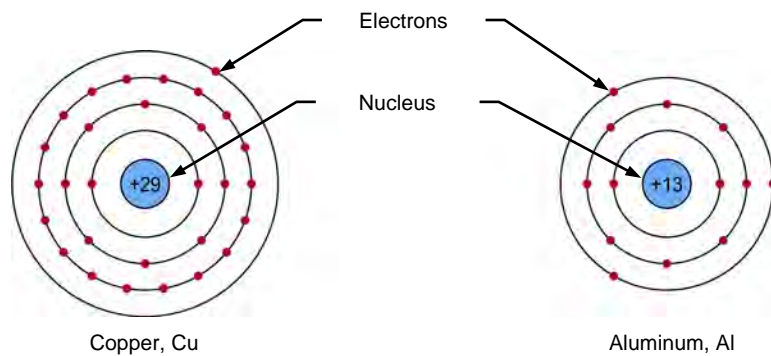
As mentioned previously, it is relatively easy to dislodge electrons in materials whose electrons are in the outer orbit of their atoms and, therefore, create an electric current.

Conversely, it is difficult to dislodge electrons in materials whose electrons are all located in the inner orbits of their atoms and, therefore, create an electric current.

Therefore, the opposition to the electric current flow varies from one material to another. This opposition is referred to as **resistance**.

Copper, aluminum, and gold, although considered good electrical conductors, offer a certain resistance to current flow, whereas ceramic, plastic, and rubber, which are considered good insulators, offer a high resistance to current flow.

Figure 2 shows the simplified atomic structure of two conductors: copper and aluminum.



**Figure 2. Conducting materials have electrons in the outer orbits of their atoms.**

A German scientist, Georg Simon Ohm (1787-1854), discovered that the ratio of voltage to current is constant for a given metal conductor of specified length and cross-sectional area. This ratio is the resistance, and is expressed in units of ohms ( $\Omega$ ) in his honor.

### **Current**

Early experimenters in electricity found that electric **current** was the flow of free electrons passing through a conductor per unit of time. Current is measured in amperes (A). Since the direction of current flow was unknown, it was arbitrarily stated to be from a positively charged body to a negatively charged body.

This convention was so vastly accepted that it is now almost universal. Thus, the conventional direction of current flow is from positive to negative, even though the actual direction of electron flow is from negative to positive.

In this manual, the **conventional direction of current flow** will be used: that is, from a positive terminal to a negative terminal.

### **Ohm's law, Kirchhoff's voltage and current laws**

The basic principles used in the study of electricity are **Ohm's law** and **Kirchhoff's voltage and current laws**.

These laws are dealt with in this manual. You will use these laws to calculate voltage, current, resistance, and power in **series circuits** and **parallel circuits**.

## Voltage, Current, and Ohm's Law

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to measure voltages and currents in electrical circuits. You will be able to demonstrate Ohm's law, through the measurement of current and voltage.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Electromotive force and voltage
- Batteries
- A simple dc circuit
- Ohm's law
- Types of electrical current
- Measuring resistance, voltage, and current
- The Resistive Load module
- Safety rules

### DISCUSSION

#### Electromotive force and voltage

Electric components such as wires and lamps are made of conducting material, and so allow electrons to pass through them.

To produce a flow of electrons, the electric components must be connected to a source of electromotive force that pushes the electrons through the components.

- In electrical dc circuits, the source of electromotive force is a dc power source or a battery. The source produces a **voltage**, or potential difference, i.e. an electromotive force between two points called. The magnitude of the voltage is measured in **volts (V)**.
- There is always an opposition to the flow of electrons through an electric component. This opposition to electron flow is called **resistance**. Resistance is measured in **ohms**. Ohms are symbolized by the Greek letter **omega ( $\Omega$ )**.
- The result of electrons flowing through electric components is called **current**. The magnitude of the current is measured in **amperes (A)**. One ampere is equal to the motion of  $6.24 \times 10^{18}$  electrons past a given cross section in 1 second.

## Batteries

Around 1745, Ewald Georg von Kleist and Pieter van Musschenbroek invented a device used to store electric charges, called the **Leyden jar**. They combined several Leyden jars in parallel to increase the maximum stored charge.

In 1749, Benjamin Franklin introduced the term **battery** for an arrangement of multiple Leyden jars. A battery is a device with two or more electrochemical cells that converts chemical energy into electrical energy. It has a positive terminal (cathode) and a negative terminal (anode).

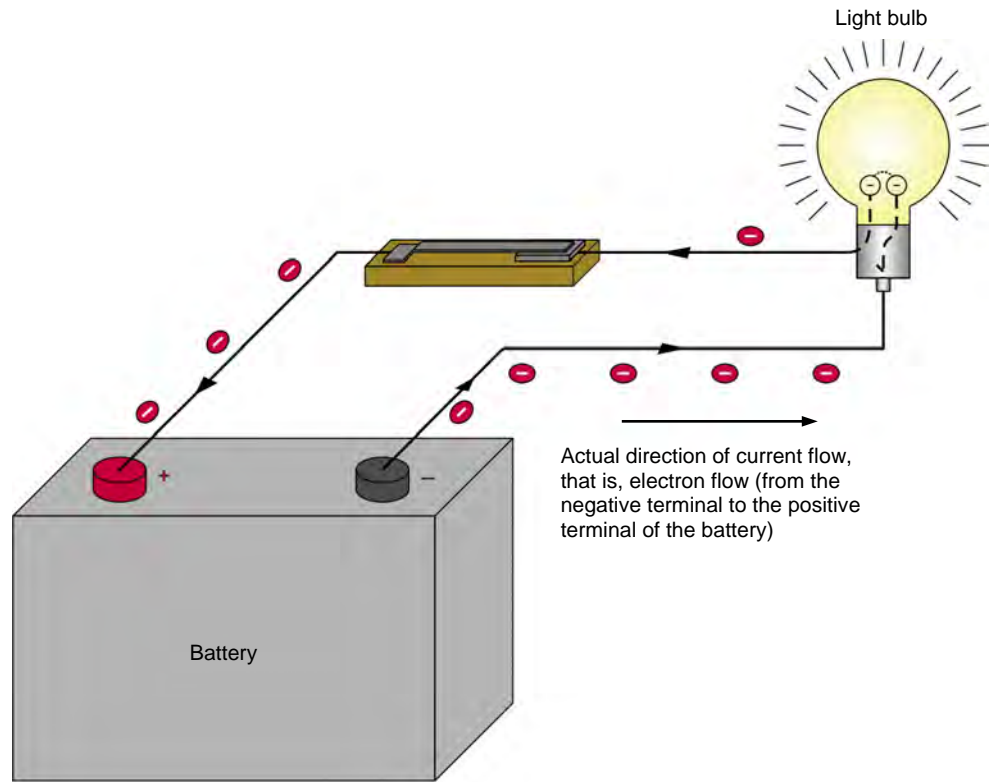
Then, in 1799, Alessandro Volta invented the first **voltaic cell**, which led to the development of modern batteries. Nowadays, batteries are made of several electrochemical galvanic cells. During the charging of a battery, the battery cells store chemical energy, which creates a **voltage (potential difference)** between the positive (+) and negative (–) terminals of the battery.

## A simple dc circuit

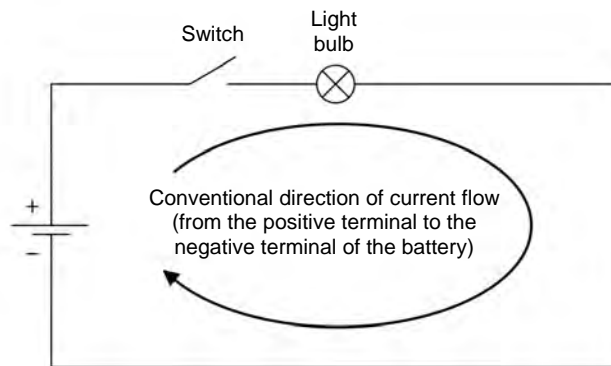
Figure 3 shows a simple dc circuit consisting of a battery, a switch used to start and stop the flow of current in the circuit, conductor wires, and a load (a light bulb). The battery could also be a dc voltage source.

When the switch is closed, the voltage difference between the positive (+) and negative (-) terminals of the battery exerts an electrical pressure that pushes the electrons through the wires, causing the bulb to turn on.

Technically, the direction of current flow, that is, the direction of electron flow, is from the negative terminal to the positive terminal of the battery, as the upper section of Figure 3 shows. When analyzing circuits with schematic diagrams, however, the convention is that the direction of current is from the positive terminal to the negative terminal, as the lower section of Figure 3 shows.



(a) Pictorial diagram



(b) Schematic diagram

Figure 3. Simple electrical dc circuit.

### Ohm’s law

The relationship between voltage, current, and resistance is called **Ohm’s law**. This law is expressed in Equation (1).

$$I = \frac{E}{R} \tag{1}$$

where  $I$  is the current flowing through the device, expressed in amperes (A).  
 $E$  is the voltage, or potential difference across an electric device, in volts (V).  
 $R$  is the resistance of the electric device, in ohms ( $\Omega$ ).

Ohm’s law can be reformulated to permit calculation of the current, voltage, or resistance when the values of the other two variables are known. This is illustrated in Figure 4.

Parameter	Common symbol	Unit of measurement
Current	$I$	Ampere (A)
Voltage	$E$	Volt (V)
Resistance	$R$	Ohm ( $\Omega$ )

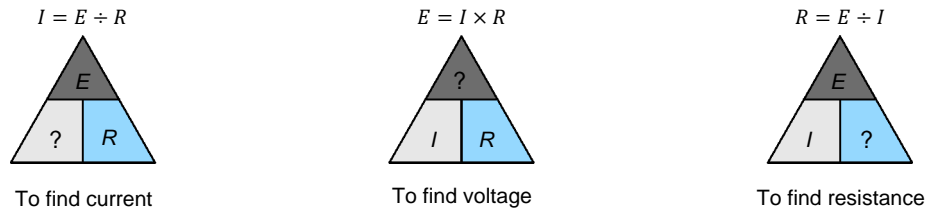


Figure 4. Ohm’s law.



The letter “V” can also be used to represent voltage. We can therefore write  $I = V/R$ ,  $V = I \times R$ , etc.

For example, Ohm’s law can be reformulated to find voltage:

$$E = I \times R \tag{2}$$

Equation (2) indicates that the voltage,  $E$ , present across an electrical device is equal to the current,  $I$ , flowing through the device multiplied by the resistance,  $R$ , of the device.

Ohm’s law can also be reformulated to find resistance:

$$R = \frac{E}{I} \tag{3}$$

### Types of electrical current

The current flow through an electrical circuit may be one of two types: direct current or alternating current.

- **Direct current (dc)** is the type of current produced by batteries and dc sources. This type of current flows in only one direction: from the positive (+) terminal of the battery or power source to the negative (–) terminal (conventional direction).
- **Alternating current (ac)** is the type of current supplied to most houses and factories. This type of current changes direction (polarity) many times each second. Examples of devices that produce ac current are rotating machines such as alternators and ac generators.

Figure 5 shows symbols used to represent dc and ac voltage sources in electrical diagrams. The arrow on a symbol indicates that the source voltage can be varied.

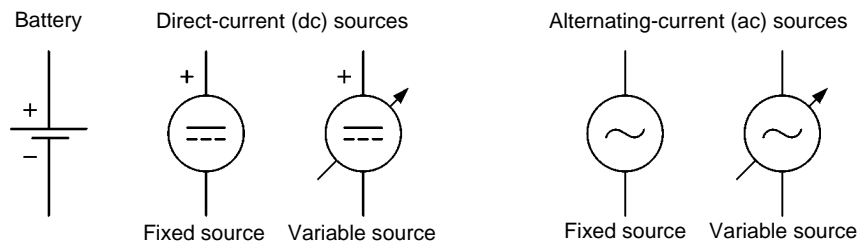


Figure 5. Symbols used to represent dc and ac voltage sources in electrical diagrams.



### Measuring resistance, voltage, and current

Resistance is measured with an **ohmmeter**, voltage is measured with a **voltmeter**, and current is measured with an **ammeter**.

#### The ohmmeter

The ohmmeter is used to measure resistance. The ohmmeter normally contains a voltage source (usually a battery) used to produce a current flow through the component under test. The ohmmeter determines the resistance of the component under test from the magnitude of the current flowing through it.

The ohmmeter is connected across the component of unknown resistance value, as Figure 6 shows. If the component is part of an electrical circuit, **the voltage source must be turned off and the component must be disconnected from the circuit**. This is illustrated in Figure 6.

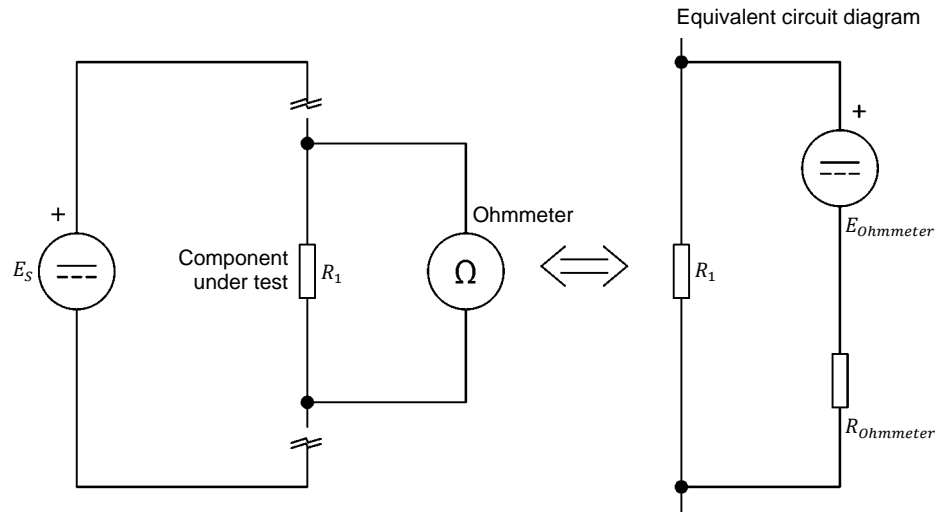


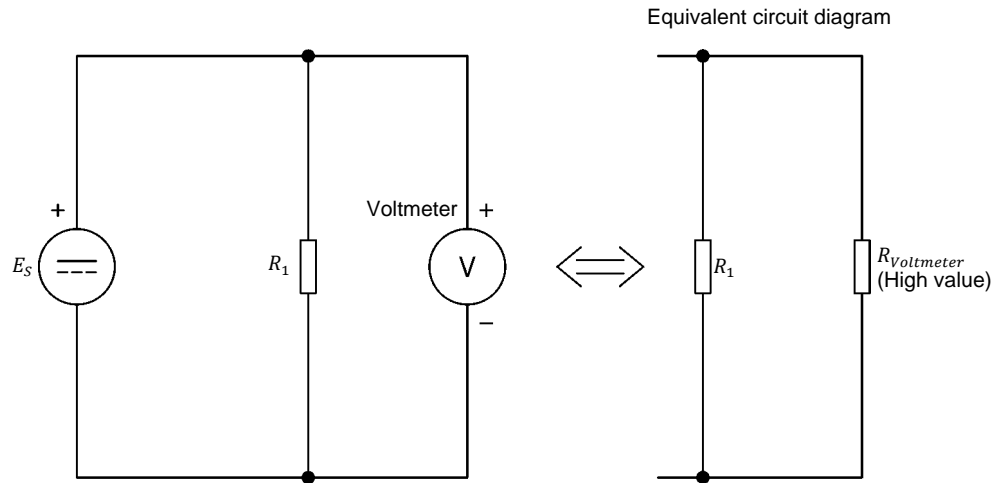
Figure 6. Measuring resistance with an ohmmeter.

Note that a resistor ( $R_{Ohmmeter}$ ) is connected in series with the dc voltage source in the ohmmeter. This resistor prevents too high a current from flowing through the dc voltage source in case the ohmmeter terminals are involuntarily connected together (short-circuited).

**The voltmeter**

The voltmeter is used to measure voltage. The voltmeter must be connected in parallel with (across) the circuit or component, and the power source must be turned on. As an example, Figure 7 shows a voltmeter connected in parallel with a resistor; the power source is a battery.

Voltmeters have a high internal resistance to minimize the current flow via their terminals. This minimizes their effect on circuit operation.



**Figure 7. Measuring voltage with a voltmeter.**

When used in dc circuits, the voltmeter must be connected according to the conventional direction of current flow for its reading to have the proper polarity. This means that the positive terminal (red probe) of the voltmeter must be connected to the positive side of the component under test, and the negative terminal (black probe) of the voltmeter to the negative side of this component.

The positive side of a component is the side that is nearest to the positive terminal of the power source. The voltage on the positive side of a component is always higher than the voltage on its negative side.

**The ammeter**

The ammeter is used to measure current. As Figure 8 shows, the ammeter must be connected in series with the components in the circuit. Ammeters have a low internal resistance to minimize the addition of extra resistance to the circuit. As for the voltmeter, polarities must be observed when connecting an ammeter in a dc circuit.



*Series means that all the source current will flow through the ammeter and the rest of the circuit when the power source is turned on.*

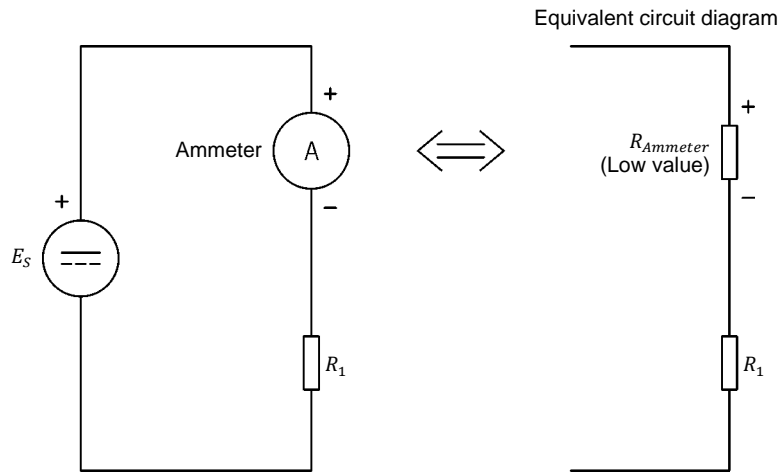


Figure 8. Measuring current with an ammeter.

**Multimeters**

Multimeters combine an ohmmeter, a voltmeter, and an ammeter in a single enclosure. They allow the measurement of several parameters including dc and ac voltages, dc and ac currents, and resistance.

Figure 9 shows a multimeter set to measure resistance (ohmmeter). The probes of the multimeter are connected to the V/ $\Omega$  (volt/ohm) terminal and the COMMON (COM) terminal of the multimeter. The selector switch on the multimeter is set to resistance ( $\Omega$ ).

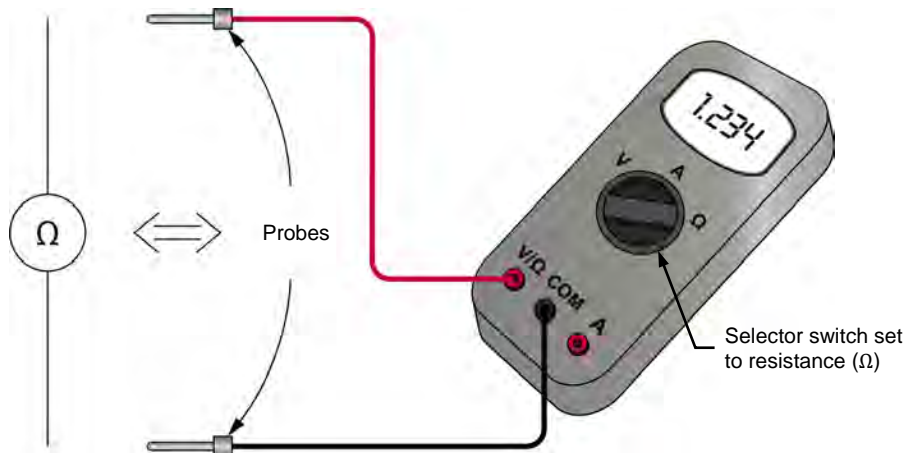


Figure 9. The multimeter is used as an ohmmeter.

Figure 10 shows a multimeter set to measure voltage (voltmeter). The probe (usually red) connected to the V/Ω (volt/ohm) terminal of the multimeter is the positive (+) terminal of the voltmeter. The probe (usually black) connected to the COMMON (COM) terminal of the multimeter is the negative (–) terminal of the voltmeter. The selector switch on the multimeter is set to voltage (E or V).

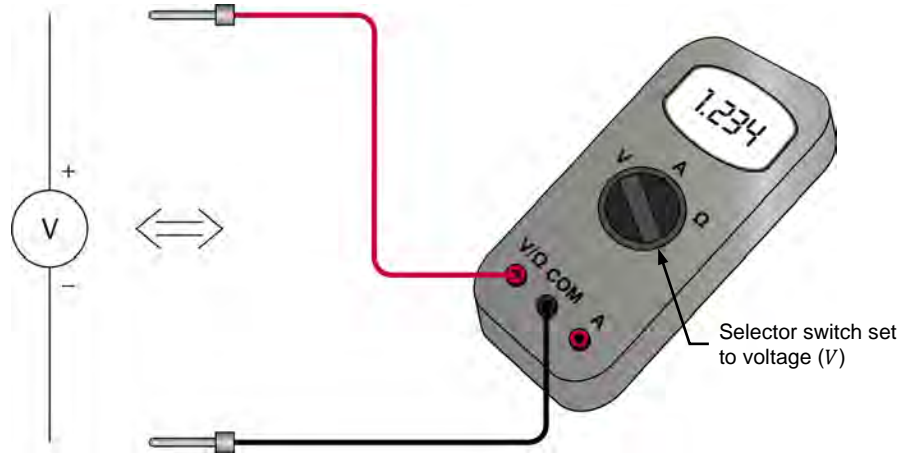


Figure 10. The multimeter is used as a dc voltmeter.

Figure 11 shows a multimeter set to measure current (ammeter). The probe (usually red) connected to the I (current) terminal of the multimeter is the positive (+) terminal of the ammeter. The probe (usually black) connected to the COMMON (COM) terminal of the multimeter is the negative (–) terminal of the ammeter. The selector switch on the multimeter is set to current (I).

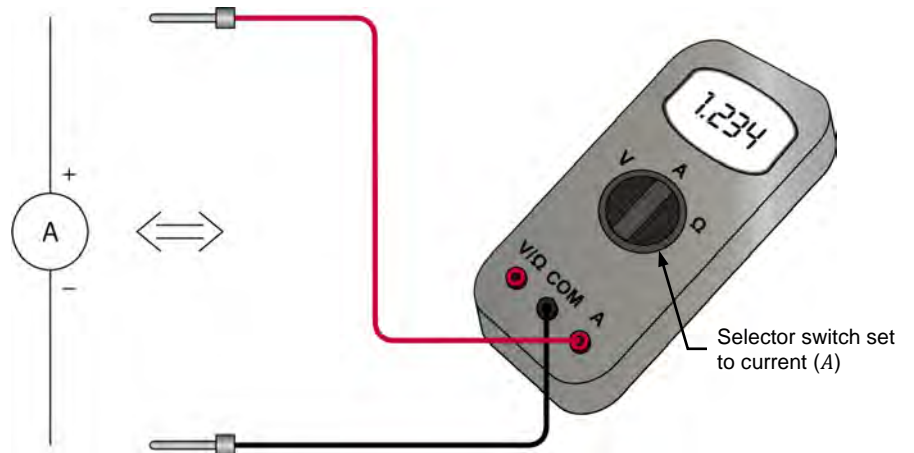


Figure 11. The multimeter is used as a dc ammeter.

### The Resistive Load module

Figure 12 shows the **Resistive Load** module. This module consists of three identical sections. Each section has three resistors of different values which can be connected to electrical circuits through a pair of terminals.

To insert a particular resistor in an electrical circuit, the terminals of the section in which this resistor is located are connected to the circuit, and the toggle switch associated with this resistor is set to the I (on) position.

In Figure 12, for example, the toggle switch associated with the resistor at the extreme left of the module front panel is set to the I (on) position, while the toggle switches associated with all other resistors are set to the O (off) position. This allows this particular resistor to be inserted in a circuit, using the corresponding section terminals (red terminals).

Several combinations of switch positions are possible, allowing you to place different resistance values in a circuit, as you will see in the next exercise. Appendix C of this manual lists combinations of switch positions required to obtain various resistance values.

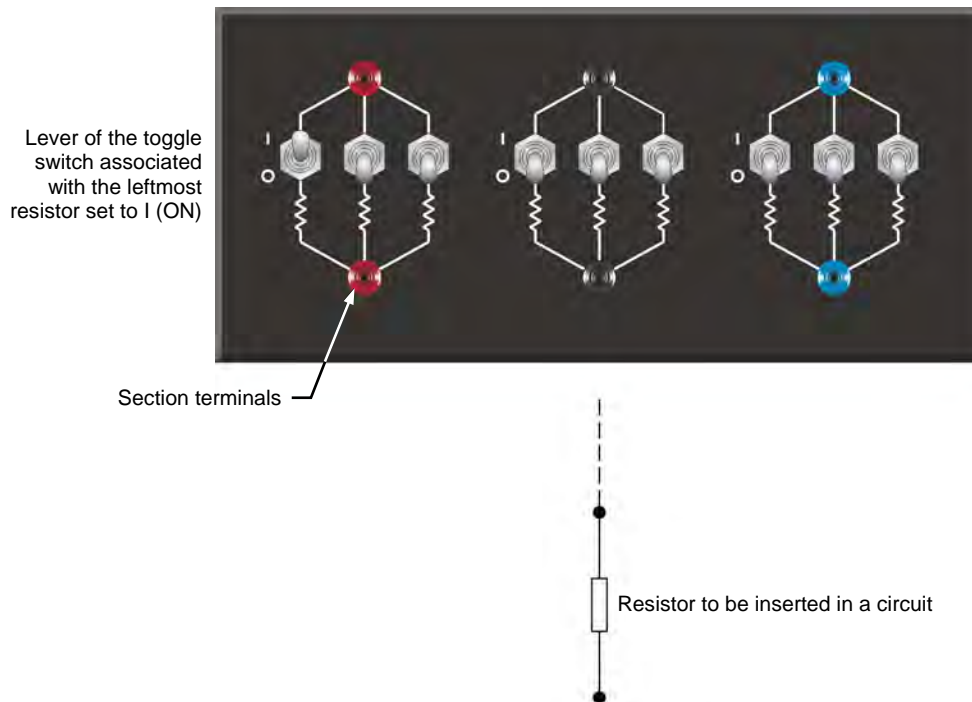


Figure 12. The Resistive Load module.

### Safety rules

Observe the following safety rules when using electrical equipment:

1. Always make sure that the electrical power supply is disabled when connecting or disconnecting leads or components.
2. Never leave any electrical lead unconnected. Touching the unconnected end of a lead while the electrical power supply is enabled could give you an electric shock. A short circuit could also occur if the unconnected end of a lead touches a conducting surface.
3. Make sure that the power switch on the electrical power supply is set to the off position before connecting the power supply line cord.
4. When connecting an electrical circuit, make sure that the contact terminals are free of dirt, oil, and water. Dirt and oil are insulators and impair the connection between two components. Water is a conductor and might make a connection where it is not wanted.

### PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Plotting the source current as a function of the source voltage on a graph
- Demonstrating Ohm’s law by performing voltage, current, and resistance measurements



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

### PROCEDURE

#### Setup and connections

*In this section, you will connect a simple electrical circuit. You will set the multimeters to measure dc current (ammeter mode) and dc voltage (voltmeter mode). You will set the switches of the resistive load module to insert a specific resistance value into the circuit.*

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

Install the equipment required in the [Workstation](#).

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

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3. Set up the circuit shown in Figure 13. The upper part of the figure shows the electrical diagram of the circuit to connect. The bottom part of the figure shows the detailed circuit connections.

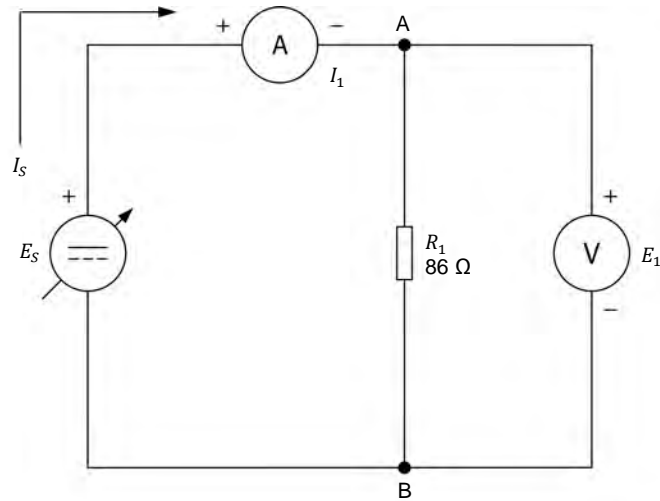
The **Resistive Load** module is used to insert a resistor ( $R_1$ ) in the circuit. To obtain the resistance value indicated next to  $R_1$  in the electrical diagram, make the necessary connections and switch settings on the **Resistive Load** module. Terminals A and B in Figure 13 correspond to the terminals of the resistor sections of the module that are used to implement  $R_1$ .

- Set multimeter 1 to measure dc current and connect it in series with resistor  $R_1$ . Be careful to observe the terminal polarity.
- Set multimeter 2 to measure dc voltage and connect it across (in parallel with) the resistor. Be careful to observe the terminal polarity.

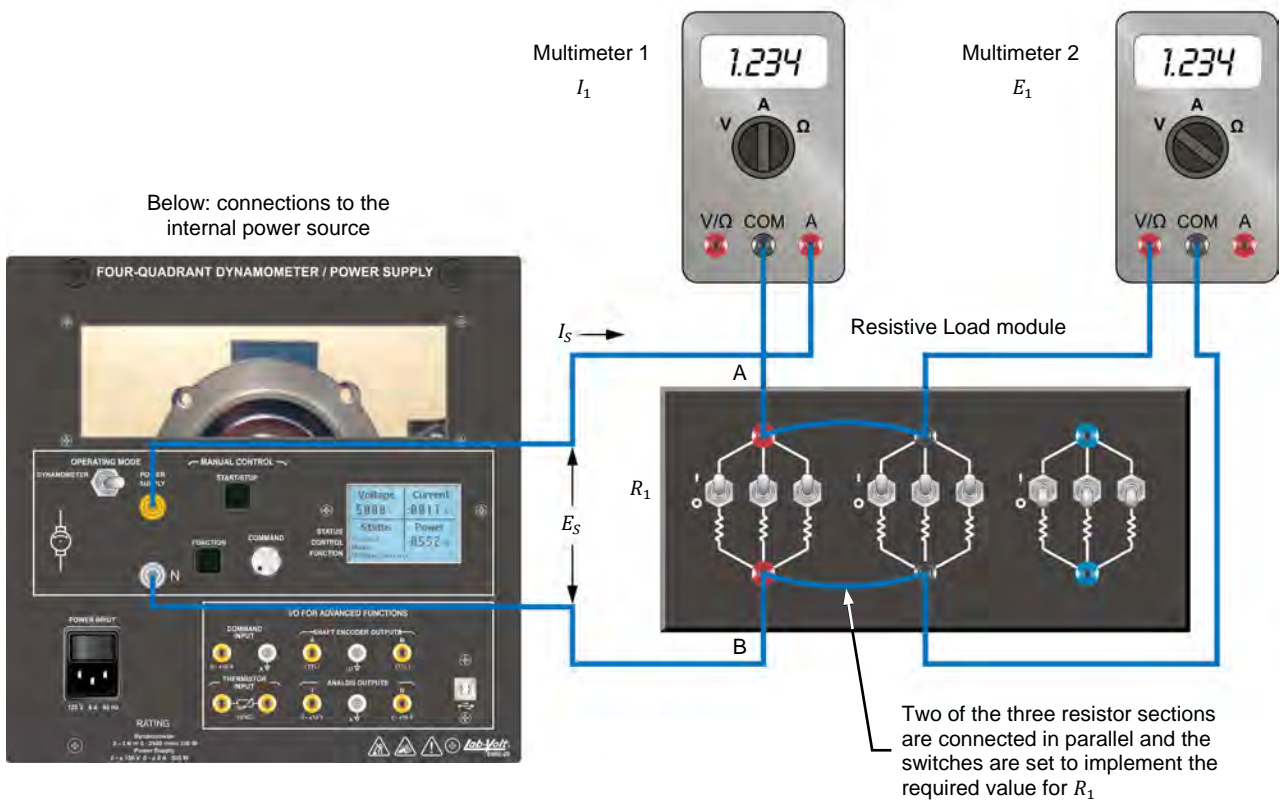


*Appendix C of this manual lists the switch settings to perform on the **Resistive Load** module in order to insert various resistance values into the circuit. For example, to insert a resistance value equivalent to  $86\ \Omega$  into the circuit, two resistor sections of the **Resistive Load** module must be connected in parallel, and the levers of the toggle switches associated with resistors  $R_1$ ,  $R_2$ ,  $R_3$ ,  $R_4$ ,  $R_5$ , and  $R_6$  in these sections must be set to the | (on) position. The concept of equivalent resistance will be studied in detail in the next exercise.*

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



(a) Electrical diagram



(b) Connection diagram

Figure 13. Setup for voltage and current measurement.



5. Make the following settings on the **Four-Quadrant Dynamometer/Power Supply**:
  - Set the **Operating Mode** switch to **Power Supply**. This connects the internal power source of the module to the **Power Supply** terminals on the front panel.
  - Select the **Voltage Source (+)** mode of operation of the power source using the **Function** push button. The mode of operation selected is indicated on the module display. Selecting this mode makes the internal power source operate as a positive voltage source. When the **Four-Quadrant Dynamometer/Power Supply** operates as a positive voltage source, the voltage at the yellow terminal is positive with respect to the voltage at the white terminal (neutral terminal N).
  - Set the voltage of the positive voltage source to 50.0 V by using the **Command** knob. This voltage is indicated on the module display. Notice that the displayed voltage is blinking. This occurs because the output of the internal power source is disabled. The output of the internal power source can be enabled by depressing the **Start/Stop** push button. This will be done in the next section of the Procedure.

### Plotting the source current as a function of the source voltage on a graph

*In this section, you will increase the voltage of the positive voltage source by steps. For each new setting, you will record the voltage indicated by the voltmeter and the current indicated by the ammeter. This will allow you to plot the source current as a function of the source voltage on a graph.*

6. On the **Four-Quadrant Dynamometer/Power Supply**, enable the output of the internal power source by depressing the **Start/Stop** push button. The display indicates **Started**, thereby confirming that the internal power source is on.
7. Observe that the voltage indicated by the voltmeter ( $E_1$ ) is virtually the same as the source voltage indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**.

Also, observe that the current indicated by the ammeter ( $I_1$ ) is virtually the same as the source current ( $I_s$ ) indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**. Is this your observation?

Yes     No

8. Set the source voltage to 0 V by setting the **Command** knob of the source to the fully counterclockwise position.

9. Fill in Table 1. To do this, increase the voltage of the positive voltage source by steps from 0 to 50 V. Seven or eight steps will be enough. For each setting, record the source voltage and the source current in the table.

Table 1. Measured voltages and currents.

Voltage $E_S$ (V)	Current $I_S$ (A)
0	0
50	

10. From the results recorded in Table 1, plot in Figure 14 the source current,  $I_S$ , as a function of the source voltage,  $E_S$ .

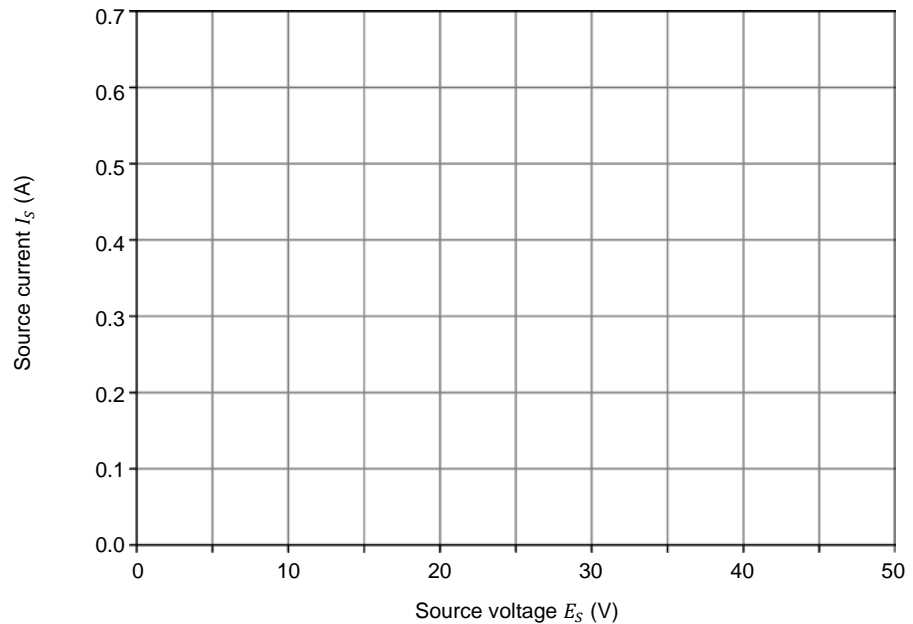


Figure 14. Source current  $I_S$  as a function of the source voltage  $E_S$ .

According to the obtained curve, does the source current vary linearly in direct proportion to the source voltage (the current doubles, triples, etc. when the voltage doubles, triples)?

- Yes     No

11. Calculate the ratio  $E_S / I_S$  for several voltage/current values. Is the ratio approximately equal to the resistance  $R_1$  of the resistor used in the circuit?

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12. Calculate the ratio  $E_S / R_1$  for a source voltage  $E_S$  of 50 V. Is this ratio equal to the current  $I_S$  recorded in Table 1 for this voltage?

$$\frac{E_S}{R_1} = I_S = \text{_____ A}$$

Yes       No

**Demonstrating Ohm’s law by performing voltage, current, and resistance measurements**

*In this section, you will demonstrate Ohm’s law, through the measurement of the circuit voltage, current, and resistance.*

13. On the [Resistive Load](#) module, modify the position of the switches for the value of  $R_1$  to be 100  $\Omega$ . (Refer to Appendix C to find the switch setting to perform on the [Resistive Load](#) module).

Then, readjust the voltage of the positive voltage source until the source current  $I_S$  is equal to 0.4 A. Record the source voltage  $E_S$  below.

$$E_S = \text{_____ V}$$

Is the source voltage  $E_S$  equal to the product  $I_S \cdot R_1$ ?

Yes       No

14. Adjust the source voltage  $E_S$  to 30 V.

15. Calculate the equivalent resistance  $R_{Eq.}$  required to allow a current  $I_S$  of 0.25 A to flow in the circuit, with a source voltage  $E_S$  of 30 V.

$$R_{Eq.} = \frac{E_S}{I_S} = \text{_____ } \Omega$$

16. On the [Resistive Load](#) module, modify the position of the switches for the value of the circuit resistance to allow a current  $I_S$  equal to 0.25 A approximately.

17. Turn off the **Four-Quadrant Dynamometer/Power Supply** by setting the **Power Input** switch to the **O** (off) position.

Measure the equivalent resistance used to allow a current  $I_S$  of 0.25 A in the previous step, using the steps below.

**CAUTION**

When measuring the resistance of a component, make sure that the voltage source is turned off and that the component is disconnected from the circuit to prevent damage to the ohmmeter.

- Disconnect the circuit except the leads interconnecting the resistor sections that you used on the resistive load module. Take care not to change the position of the toggle switch levers on this module. Return the other leads to their storage location.
- Set a multimeter to measure resistance (ohmmeter mode).
- Connect the ohmmeter to the terminals of one of the resistor sections that you used on the resistive load module in order to measure its equivalent resistance. Record the ohmmeter reading below.

$R_{Eq.} = \underline{\hspace{2cm}} \Omega$

Is the measured resistance approximately equal to the equivalent resistance you calculated in step 15?

- Yes     No

18. Remove all circuit connections, then return all equipment to its storage location.

**CONCLUSION**

In this exercise, you performed voltage, current, and resistance measurements to demonstrate Ohm’s law. You verified that Ohm’s law permits calculation of the circuit current, voltage, or resistance when the values of any two of these three variables are known.

**REVIEW QUESTIONS**

1. Will a voltmeter having an internal resistance of 100 000  $\Omega$  have less effect on circuit operation than a voltmeter having an internal resistance of 1 000 000  $\Omega$ ? Why?

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2. An ammeter has an internal resistance equal to the equivalent resistance of the circuit in which the current must be measured. What will happen to the circuit current when the ammeter is inserted into the circuit? Explain.

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3. What does “potential difference” (voltage) mean when speaking of a battery or dc power source? How is this potential difference (voltage) used in electrical circuits?

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4. What is the resistance of a circuit in which a dc current of 0.25 A flows when a dc voltage of 50 V is applied to the circuit?

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5. What is the dc voltage required across a resistor of 15  $\Omega$  to make a dc current of 3 A flow through it?

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## Equivalent Resistance

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to determine the equivalent resistance of a combination of resistors connected in series, in parallel or in series-parallel. You will also be able to explain the concept of equivalent resistance.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Introduction
- Resistors in series
- Resistors in parallel
- The Resistive Load module

### DISCUSSION

#### Introduction

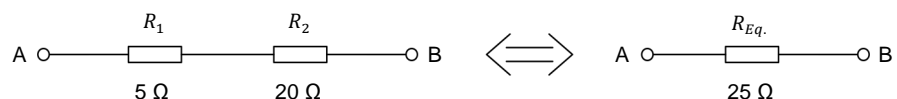
Most electrical circuits contain different combinations of resistors connected in series, in parallel or in series-parallel. A combination of resistors can be represented by a single **equivalent resistance**.

The value of the equivalent resistance depends on the resistance of each individual resistor, and on the way the resistors are connected together.

#### Resistors in series

When two or more resistors are connected in series, the total resistance is equal to the sum of the values of the resistors.

Figure 15 shows an example in which a resistor of 5 ohms ( $5 \Omega$ ) is connected in series with a resistor of  $20 \Omega$ .



**Figure 15. Resistors connected in series.**

The equivalent resistance between terminals A and B is equal to  $5 \Omega + 20 \Omega = 25 \Omega$ .

This implies that the two resistors between terminals A and B could be replaced by a single resistor of  $25 \Omega$ . This single resistor is the equivalent resistance,  $R_{Eq}$ .

**Calculating the equivalent resistance**

Use Equation (4) to calculate the equivalent resistance of a number of resistors connected in series.

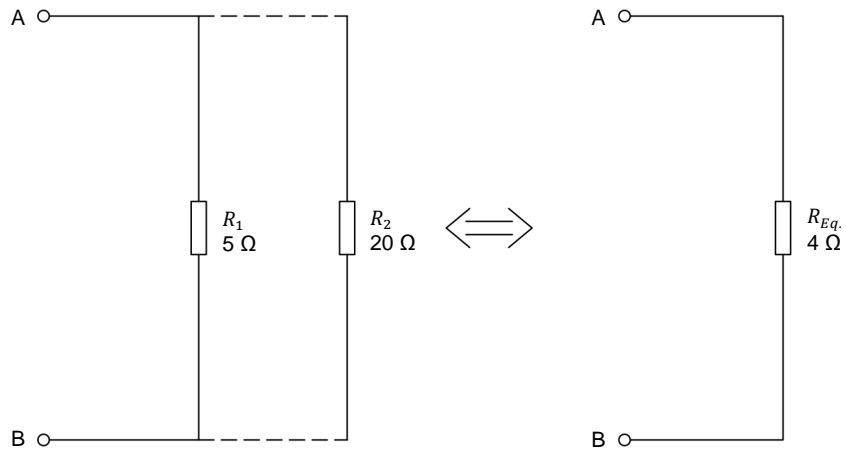
$$R_{Eq.} = R_1 + R_2 + R_3 + R_4 + \dots + R_n \tag{4}$$

**Resistors in parallel**

When two or more resistors are connected in parallel between two terminals, the equivalent resistance is always lower than the value of the resistor having the lowest resistance.

Figure 16 shows an example. Before resistor  $R_2$  is added to the circuit, the resistance between terminals A and B is equal to  $5\ \Omega$  ( $R_1$ ).

When the resistor of  $20\ \Omega$  ( $R_2$ ) is connected in parallel with  $R_1$ , the resistance between terminals A and B decreases below that of  $R_1$ . This occurs because the addition of  $R_2$  creates a second path for the current to flow through.



**Figure 16. Resistors connected in parallel.**

Electrical current, like water, flows through any path available. When a single resistor is connected across a voltage source, the current can flow through this resistor only. If a second resistor is added in parallel with the first, more current can flow through the circuit, meaning that the effective resistance of the circuit has decreased.

For instance, when two resistors of equal values are connected in parallel, the same amount of current flows through each of them. Therefore, if a resistor is added in parallel with another resistor of the same value, the current through the circuit will double, and the equivalent circuit resistance will decrease by half.

Similarly, when a third resistance of the same value is added in parallel, the circuit current will triple (with respect to the initial value), while the equivalent circuit resistance will decrease to one-third of the initial resistance. This relationship is valid for any number of equal resistors.

**Calculating the equivalent resistance**

Use Equation (5) to calculate the equivalent resistance of a number of resistors connected in parallel.

$$\frac{1}{R_{Eq.}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \frac{1}{R_4} \dots + \frac{1}{R_n} \quad (5)$$

When only two resistors are in parallel, Equation (5) becomes:

$$R_{Eq.} = \frac{R_1 \times R_2}{R_1 + R_2} \quad (6)$$

For example, the equivalent resistance of 20 Ω in parallel with 5 Ω is

$$R_{Eq.} = \frac{20 \Omega \times 5 \Omega}{20 \Omega + 5 \Omega} = \frac{100 \Omega}{25 \Omega} = 4 \Omega$$

The above calculation implies that resistors  $R_1$  and  $R_2$  in Figure 16 can be replaced by a single equivalent resistor  $R_{Eq.}$  of 4 Ω.



### The Resistive Load module

As mentioned in the previous exercise, the Resistive Load module consists of three identical sections. Figure 17 shows this module.

Each section consists of three resistors of different values.

Any two, or all three resistors of a section can be placed in parallel to obtain various resistance values. Moreover, the resistor sections can be connected in series, in parallel or in series-parallel to obtain various resistor arrangements. Figure 17 shows the various resistor arrangements possible.

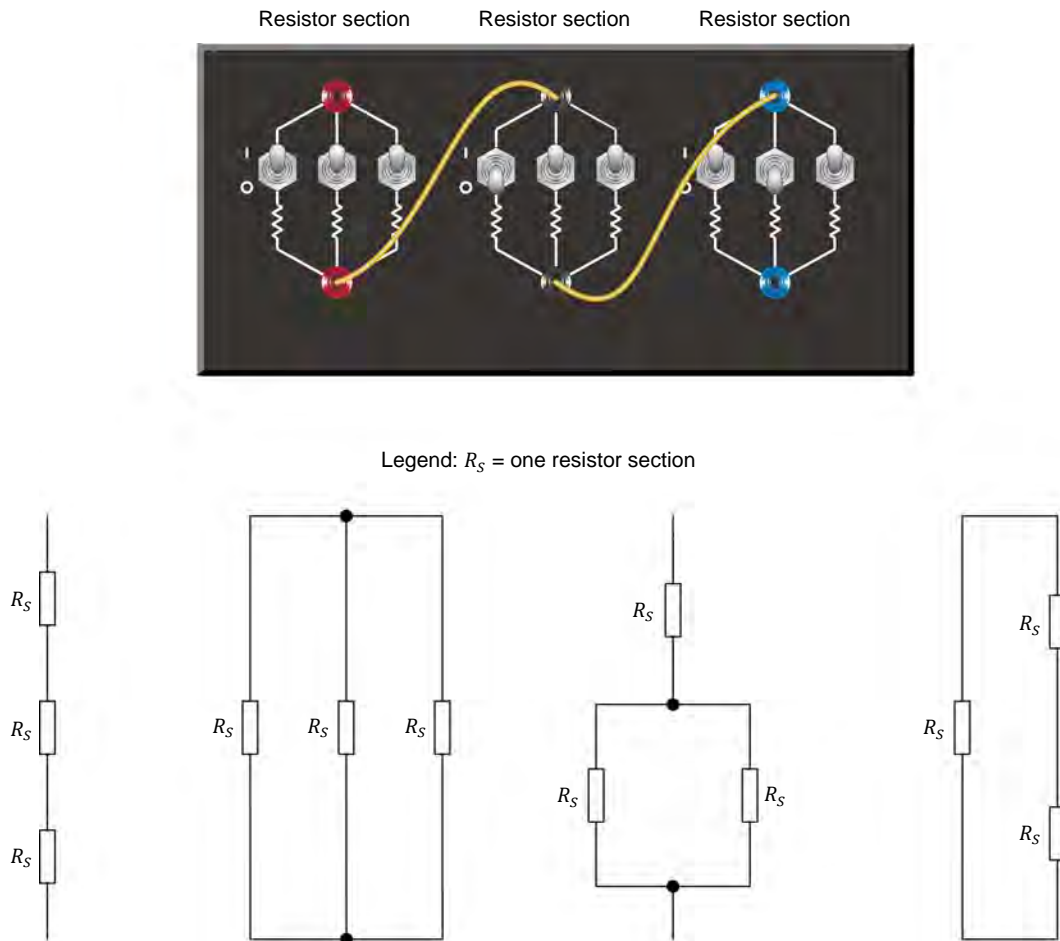


Figure 17. Any two or all three resistors of a section can be placed in parallel. Moreover, the resistor sections can be connected in series, in parallel or in series-parallel to obtain various resistor arrangements.

## PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Resistors in series
- Resistors in parallel
- Resistors in series-parallel (case 1)
- Resistors in series-parallel (case 2)



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

## PROCEDURE

### Setup and connections

*In this section, you will set up a circuit containing two series resistors. You will connect and set a multimeter to measure the dc voltage across the resistors.*

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

Install the equipment required in the [Workstation](#).

2. Make sure that the main power switch on the [Four-Quadrant Dynamometer/Power Supply](#) is set to the O (off) position then connect the [Power Input](#) to an ac power wall outlet.

3. Set up the series circuit shown in Figure 18. To obtain the resistor arrangement of Figure 18, make the necessary connections and switch settings on the **Resistive Load** module.

Set a multimeter to measure dc voltage and connect it in parallel with the two resistors. Be careful to observe the instrument polarities.



Throughout this exercise, keep in mind that the resistance values shown in the figures are equivalent resistances. To obtain a given resistance value with the **Resistive Load** module, you may need to connect two or three resistors in parallel in a resistor section. Appendix C of this manual lists the switch settings required to obtain the various resistance values used in the exercise.

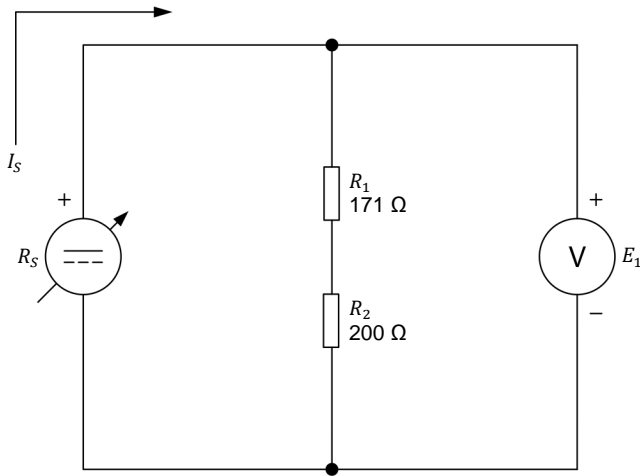


Figure 18. Determining the equivalent resistance of resistors connected in series.

4. Turn on the **Four-Quadrant Dynamometer/Power Supply** by setting the **Power Input** switch to the I (on) position.
5. Make the following settings on the **Four-Quadrant Dynamometer/Power Supply**:
  - Set the **Operating Mode** switch to **Power Supply**. This connects the internal power source of the module to the **Power Supply** terminals on the front panel.
  - Select the **Voltage Source (+)** mode of operation of the power source using the **Function** push button. The mode of operation selected is indicated on the module display. Selecting this mode makes the internal power source operate as a positive voltage source. When the **Four-Quadrant Dynamometer/Power Supply** operates as a positive voltage source, the voltage at the yellow terminal is positive with respect to the voltage at the white terminal (neutral terminal N).
  - Set the voltage of the positive voltage source to 50 V by using the **Command** knob. This voltage is indicated on the module display. Notice that the displayed voltage is blinking. This occurs because the output of the internal power source is disabled.

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### Resistors in series

In this section, you will calculate the equivalent resistance of the series-connected resistors. You will then measure the voltage across these resistors and the current flowing through them to determine their equivalent resistance with Ohm's law. You will compare your result with the calculated equivalent resistance. Finally, you will measure the equivalent resistance with an ohmmeter.

6. Calculate the equivalent resistance ( $R_{Eq.}$ ) of series resistors  $R_1$  and  $R_2$  in Figure 18.

$$R_{Eq.} = R_1 + R_2 = \underline{\hspace{2cm}} \Omega$$

7. Enable the output of the internal power source by depressing the *Start/Stop* push button. The display indicates *Started*, thereby confirming that the output of the internal power source is enabled.

Record below the voltage  $E_1$  indicated by the voltmeter and the source current  $I_S$  indicated on the display of the *Four-Quadrant Dynamometer/Power Supply*. Then, calculate the equivalent resistance  $R_{Eq.}$ .

$$E_1 = \underline{\hspace{2cm}} \text{ V}$$

$$I_S = \underline{\hspace{2cm}} \text{ A}$$

$$R_{Eq.} = \frac{E_1}{I_S} = \underline{\hspace{2cm}} \Omega$$

8. Measure the equivalent resistance ( $R_{Eq.}$ ) of series resistors  $R_1$  and  $R_2$ , using the procedure below.

### CAUTION

When measuring the resistance of a component, make sure the voltage source is turned off and that the component is disconnected from the circuit to prevent damage to the ohmmeter.

On the *Four-Quadrant Dynamometer/Power Supply*, disable the output of the internal power source by depressing the *Start/Stop* push button once. Make sure that the display indicates *Stopped*, thereby confirming that the source output is disabled and that power is removed.

Disconnect the multimeter used as a voltmeter from the circuit and set it to measure resistance.

As Figure 19 shows, disconnect the resistors from the positive voltage source and connect the ohmmeter across the resistors.

Record the ohmmeter reading below.

$R_{Eq.} = \underline{\hspace{2cm}} \Omega$

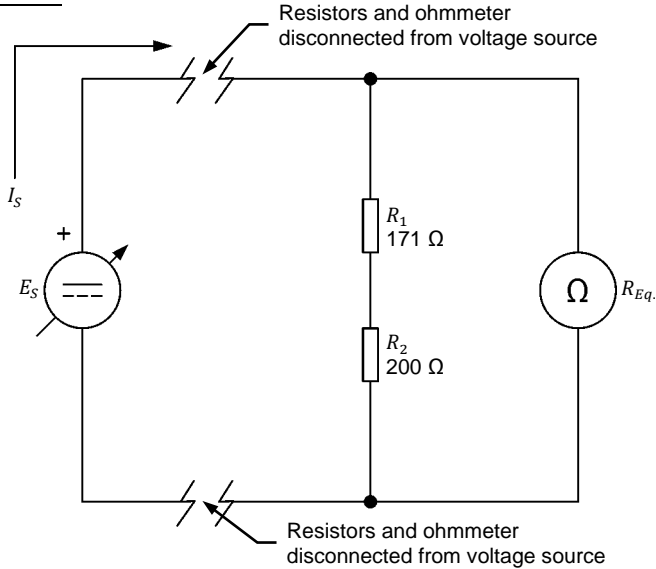


Figure 19. Measuring the equivalent resistance of resistors connected in series.

9. Are the calculated and measured equivalent resistances obtained in steps 6, 7, and 8 approximately the same?

Yes     No

### Resistors in parallel

*In this section, you will set up a circuit containing three resistors connected in parallel. You will first calculate the equivalent resistance of these resistors. You will then measure the voltage across the resistors and the source current to determine the equivalent resistance with Ohm's law. You will compare your result with the calculated equivalent resistance. Finally, you will measure the equivalent resistance with an ohmmeter.*

10. Set up the parallel circuit shown in Figure 20. To obtain the resistor arrangement of Figure 20, make the necessary connection(s) and switch settings on the [Resistive Load](#) module.

Set a multimeter to measure dc voltage and connect it in parallel with the resistors. Be careful to observe the instrument polarities.

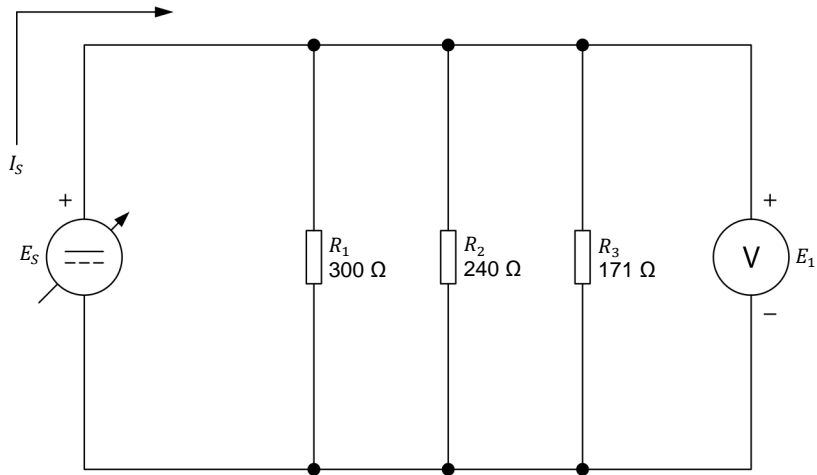


Figure 20. Determining the equivalent resistance of resistors connected in parallel.

11. Calculate the equivalent resistance ( $R_{Eq.}$ ) of the parallel resistors  $R_1$ ,  $R_2$ , and  $R_3$  in Figure 20.

$$\frac{1}{R_{Eq.}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

$$R_{Eq.} = \underline{\hspace{2cm}} \Omega$$

12. On the [Four-Quadrant Dynamometer/Power Supply](#), turn the internal power source on by depressing the [Start/Stop](#) push button. Make sure that the source voltage  $E_S$  indicated on the display of the [4 Quadrant Power Supply and Dynamometer Controller](#) is 50.0 V.

Record below the voltage  $E_1$  indicated by the voltmeter and the source current  $I_S$  indicated on the display of the [Four-Quadrant Dynamometer/Power Supply](#). Then, calculate the equivalent resistance  $R_{Eq.}$ .

$$E_1 = \underline{\hspace{2cm}} \text{ V}$$

$$I_S = \underline{\hspace{2cm}} \text{ A}$$

$$R_{Eq.} = \frac{E_1}{I_S} = \underline{\hspace{2cm}} \Omega$$

- 13.** Measure the equivalent resistance  $R_{Eq.}$  of the parallel resistors  $R_1$ ,  $R_2$ , and  $R_3$  by using the procedure below.

On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off by depressing the **Start/Stop** push button once. Make sure that the display indicates **Stopped**, thereby confirming that power is removed.

**CAUTION**

When measuring the resistance of a component, make sure that the voltage source is turned off and that the component is disconnected from the circuit to prevent damage to the ohmmeter.

Disconnect the multimeter used as a voltmeter from the circuit and set it to measure resistance.

Disconnect the parallel resistors from the positive voltage source and connect the ohmmeter across them to measure the equivalent resistance  $R_{Eq.}$

Record the ohmmeter reading below.

$$R_{Eq.} = \text{_____ } \Omega$$

- 14.** Are the calculated and measured equivalent resistances obtained in steps 11, 12, and 13 approximately the same?

Yes     No

**Resistors in series-parallel (case 1)**

*In this section, you will calculate the equivalent resistance of resistors connected in series-parallel. You will then measure the voltage across these resistors and the current flowing through them to determine their equivalent resistance, using Ohm's law. You will compare your result with the calculated equivalent resistance. Finally, you will measure the equivalent resistance with an ohmmeter.*

15. Set up the series-parallel circuit shown in Figure 21. To obtain the resistor arrangement of Figure 21, make the necessary connection(s) and switch settings on the [Resistive Load](#) module.

Set a multimeter to measure dc voltage and connect it across the resistors. Be careful to observe the instrument polarities.

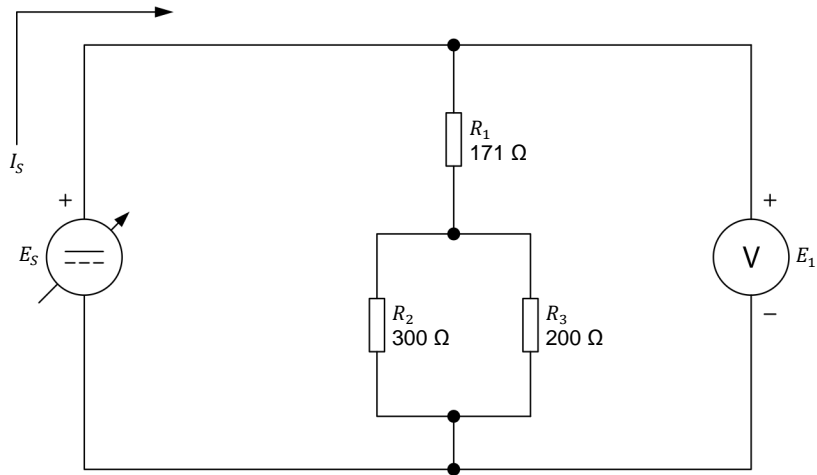


Figure 21. Determining the equivalent resistance of resistors connected in series-parallel (case 1).

16. Calculate the equivalent resistance  $R_{Eq.}$  of series-parallel resistors  $R_1$ ,  $R_2$ , and  $R_3$  in Figure 21.

$$R_{Eq.} = R_1 + \left( \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}} \right) = \text{_____ } \Omega$$

17. On the [Four-Quadrant Dynamometer/Power Supply](#), turn the internal power source on by depressing the [Start/Stop](#) push button. Make sure that the source voltage  $E_S$  indicated on the display is 50 V.

Record below the voltage  $E_1$  indicated by the voltmeter and the source current  $I_S$  indicated on the display of the [Four-Quadrant Dynamometer/Power Supply](#). Then, calculate the equivalent resistance  $R_{Eq.}$ .

$$E_1 = \text{_____ } \text{V}$$

$$I_S = \text{_____ } \text{A}$$

$$R_{Eq.} = \frac{E_1}{I_S} = \text{_____ } \Omega$$



18. Measure the equivalent resistance  $R_{Eq.}$  of the series-parallel resistors by using the procedure below.

**CAUTION**

When measuring the resistance of a component, make sure that the voltage source is turned off and that the component is disconnected from the circuit to prevent damage to the ohmmeter.

On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off by depressing the **Start/Stop** push button once. Make sure that the display indicates **Stopped**, thereby confirming that power is removed.

Disconnect the multimeter used as a voltmeter from the circuit and set it to measure resistance.

Disconnect the series-parallel resistors from the positive voltage source and connect the ohmmeter across them to measure the equivalent resistance  $R_{Eq.}$

Record the ohmmeter reading below.

$$R_{Eq.} = \text{_____ } \Omega$$

19. Are the calculated and measured equivalent resistances obtained in steps 16, 17, and 18 approximately the same?

Yes     No

**Resistors in series-parallel (case 2)**

*In this section, you will calculate the equivalent resistance of resistors connected in series-parallel. You will then measure the voltage across these resistors and the current flowing through them to determine their equivalent resistance, using Ohm's law. You will compare your result with the calculated equivalent resistance. Finally, you will measure the equivalent resistance with an ohmmeter.*

20. Set up the series-parallel circuit shown in Figure 22. To obtain the resistor arrangement of Figure 22, make the necessary connections and switch settings on the [Resistive Load](#) module.

Set a multimeter to measure dc voltage and connect it across the resistors. Be careful to observe the instrument polarities.

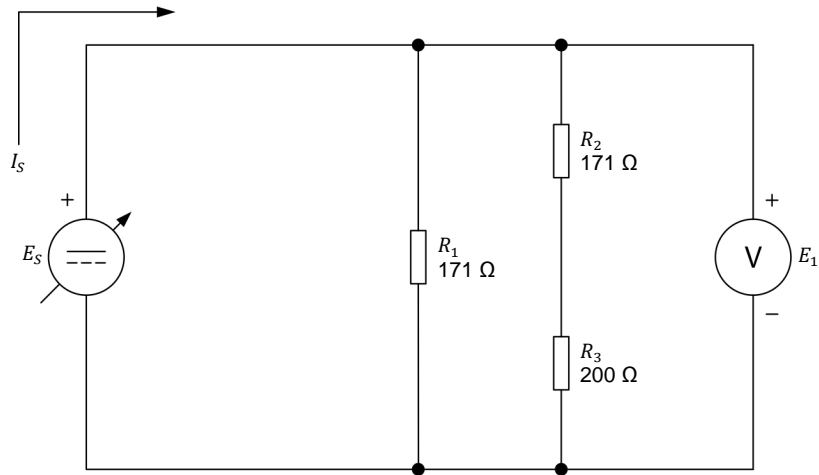


Figure 22. Determining the equivalent resistance of resistors connected in series-parallel (case 2).

21. Calculate the equivalent resistance  $R_{Eq.}$  of series-parallel resistors  $R_1$ ,  $R_2$ , and  $R_3$  in Figure 22.

$$R_{Eq.} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2 + R_3}} = \text{_____ } \Omega$$

22. On the [Four-Quadrant Dynamometer/Power Supply](#), turn the internal power source on by depressing the [Start/Stop](#) push button. Make sure that the source voltage  $E_s$  indicated on the display is 50 V.

Record below the voltage  $E_1$  indicated by the voltmeter and the source current  $I_s$  indicated on the display of the [Four-Quadrant Dynamometer/Power Supply](#). Then, calculate the equivalent resistance  $R_{Eq.}$ .

$$E_1 = \text{_____ } \text{V}$$

$$I_s = \text{_____ } \text{A}$$

$$R_{Eq.} = \frac{E_1}{I_s} = \text{_____ } \Omega$$

23. Measure the equivalent resistance  $R_{Eq.}$  of the series-parallel resistors by using the procedure below.

**CAUTION**

When measuring the resistance of a component, make sure that the voltage source is turned off and that the component is disconnected from the circuit to prevent damage to the ohmmeter.

On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off by depressing the **Start/Stop** push button once. Make sure that the display indicates **Stopped**, thereby confirming that power is removed.

Disconnect the multimeter used as a voltmeter from the circuit and set it to measure resistance.

Disconnect the series-parallel resistors from the dc source and connect the ohmmeter across them.

Record the ohmmeter reading below.

$$R_{Eq.} = \text{_____} \Omega$$

24. Are the calculated and measured equivalent resistances obtained in steps 21, 22, and 23 approximately the same?
- Yes     No
25. Remove all circuit connections, then return all equipment to its storage location.

**CONCLUSION**

In this exercise, you learned how to calculate and measure the equivalent resistance of a combination of resistors connected in series, in parallel, or in series-parallel.

**REVIEW QUESTIONS**

1. What is the general formula for calculating the equivalent resistance of several resistors connected in series?
- \_\_\_\_\_
2. What is the general formula for calculating the equivalent resistance of several resistors connected in parallel?
- \_\_\_\_\_

3. Refer to Figure 20. If resistors  $R_1$ ,  $R_2$ , and  $R_3$  each have a value of  $100\ \Omega$ , what is the equivalent resistance  $R_{Eq}$ ?

---

---

4. Refer to Figure 21. Assume that resistors  $R_1$ ,  $R_2$ , and  $R_3$  have a value of  $300\ \Omega$ ,  $171\ \Omega$ , and  $200\ \Omega$ , respectively. If an additional  $100\ \Omega$  resistor is connected across these resistors, will the equivalent resistance increase, decrease, or remain the same as before? Why?

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5. What is the equivalent resistance of a circuit composed of a resistor of  $1\ \Omega$  connected in series with 100 resistors of  $100\ \Omega$  connected in parallel?

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## Power in DC Circuits

**EXERCISE OBJECTIVE** When you have completed this exercise, you will be able to calculate the power dissipated in a dc circuit. You will verify your power calculations by performing voltage and current measurements.

**DISCUSSION OUTLINE** The Discussion of this exercise covers the following points:

- Energy and power
- Electrical power
- DC power source
- Power conversion in a dc circuit
- Calculating power

### DISCUSSION

#### Energy and power

**Energy** is the ability to do work. Energy can be transferred from a body to another, or converted from one form to another. In the international system (SI) of units, energy is measured in joules (J). One joule (1 J) is equal to one watt-second (1 W·s).

**Power** is the rate at which energy is supplied by a source or consumed by a load to do a work.

Depending on the context in which it is used, power can be described as electrical, hydraulic, mechanical, nuclear, etc.

#### Electrical power

One of the most common available forms of power is electrical power.

Many everyday household devices use electrical power: televisions, computers, electric stoves, refrigerators, water heaters, clothes dryers, air conditioning systems, etc.

In factories, machines consume electrical power to perform useful functions such as powering motors, circulating air and liquids, actuating cylinders, etc.

In the SI system of units, electrical power is measured in watts (W).

One watt (1 W) is the power required to produce energy at the rate of 1 joule per second. Therefore,  $1\text{ W} = 1\text{ joule per second (1 J/s)}$ .

### DC power source

In dc circuits, electrical power is supplied by a dc **power source**. The electrical power of the source is its capability to push electrons through a circuit and make the current flow. The higher the source power, the higher its capability to push electrons through the circuit to make current flow.

The electrical power provided by a source is equal to the voltage supplied by the source multiplied by the current delivered to the circuit by the source, as Equation (7) shows.

$$P = E \times I \quad (7)$$

where  $P$  is the electrical power provided by the source, in watts (W).  
 $E$  is the voltage supplied by the source, in volts (V).  
 $I$  is the current delivered to the circuit by the source, in amperes (A).

### Power conversion in a dc circuit

According to the law of conservation of energy, energy cannot be created or destroyed; it can only change form. Therefore, the power supplied to an electrical circuit by a dc source is equal to the power consumed or dissipated by all the resistive components in this circuit:

- Normally, most of the power is consumed by a device called a **load** to perform a useful function, such as producing light (lamp) or rotary motion (dc motor).
- The rest of the power is dissipated as heat by each circuit component, due to the resistance of these components.

Figure 23 shows a simple dc circuit, in which the load consists of two resistors.

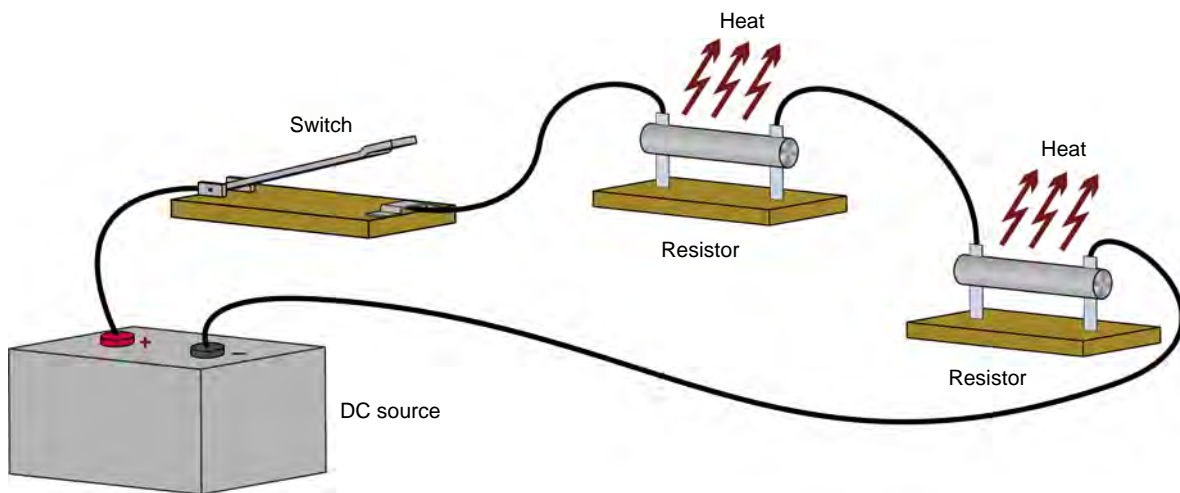


Figure 23. Power conversion in a simple dc electrical circuit.

When the switch is closed, a complete conducting path exists between the positive (+) terminal and the negative (-) terminal of the battery, which permits the flow of current through the resistors.

The resistors strongly oppose the flow of current, so that most of the electrical power they consume is dissipated as heat into the surrounding air.

The higher the power supplied to the resistors is, the hotter the resistors will become. Beyond a certain power level, the resistors or even nearby component(s) will burn out.

For this reason, resistors are physically sized by the power they must dissipate, rather than the resistance they offer. Thus, resistors dissipating high amounts of power are larger than resistors dissipating lower amounts of power.

For the same reason, **incandescent** light bulbs of 150 watts are bigger than incandescent light bulbs of 25 watts: a bigger light bulb provides better cooling by **convection** and **radiation**.

### Calculating power

The power consumed by an electrical component can be calculated by using Equation (8).

$$P = E \times I \quad (8)$$

where  $P$  is the consumed power, in watts (W).

$E$  is the voltage drop across the component, in volts (V).

$I$  is the current flowing through the component, in amperes (A).

Equation (8) can be reformulated as:

$$E = \frac{P}{I} \quad (9)$$

or

$$I = \frac{P}{E} \quad (10)$$

Besides, replacing  $E$  in Equation (8) by the product  $IR$  gives Equation (11):

$$P = IR \times I = I^2 \times R \quad (11)$$

Or, replacing  $I$  in Equation (8) by the ratio  $E/R$  gives Equation (12):

$$P = E \times E/R = \frac{E^2}{R} \quad (12)$$



Figure 24 summarizes how to calculate either power, current, resistance, or voltage when the values of two other variables are known.

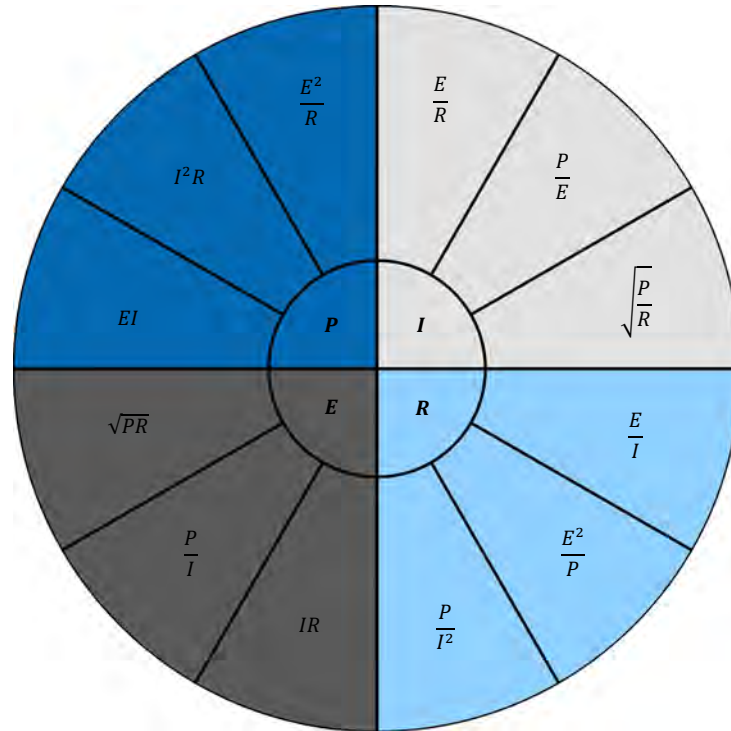


Figure 24. Calculating power, current, resistance, or voltage when the values of two other variables are known.

### PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Setup and connections
- Measuring the power consumed by a resistor
- Measuring power in a circuit with resistors in series
- Measuring power in a circuit with resistors in parallel



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

### PROCEDURE

#### Setup and connections

*In this section, you will set up a circuit used to measure the power consumed by a resistor.*

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

Install the equipment required in the [Workstation](#).

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2. Make sure that the main power switch on the **Four-Quadrant Dynamometer/Power Supply** is set to the **O** (off) position then connect the **Power Input** to an ac power wall outlet.
3. Set up the circuit shown in Figure 25. To obtain the resistance value ( $R_1$ ) of Figure 25, make the necessary connections and switch settings on the **Resistive Load** module.

Set a multimeter to measure dc voltage and connect it across the resistor. Be careful to observe the instrument polarities.

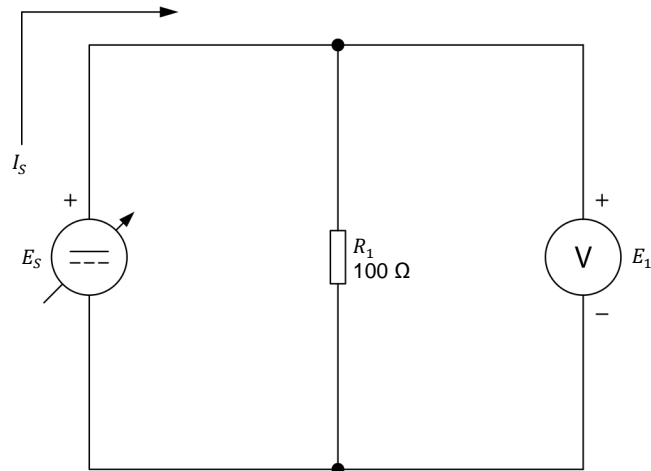


Figure 25. Measuring the power consumed by a resistor.

4. Turn the **Four-Quadrant Dynamometer/Power Supply** on by setting the **Power Input** switch to the **I** (on) position.
5. Make the following settings on the **Four-Quadrant Dynamometer/Power Supply**:
  - Set the **Operating Mode** switch to **Power Supply**. This connects the internal power source of the module to the **Power Supply** terminals on the front panel.
  - Select the **Voltage Source (+)** mode of operation of the power source using the **Function** push button. The mode of operation selected is indicated on the module display. Selecting this mode makes the internal power source operate as a positive voltage source. When the **Four-Quadrant Dynamometer/Power Supply** operates as a positive voltage source, the voltage at the yellow terminal is positive with respect to the voltage at the white terminal (neutral terminal N).
  - Set the voltage of the positive voltage source to 50 V by using the **Command** knob. This voltage is indicated on the module display. Notice that the displayed voltage is blinking. This occurs because the output of the internal power source is disabled.

### Measuring the power consumed by a resistor

*In this section, you will verify that most of the power consumed by a resistor is dissipated as heat. You will find the power consumed by the resistor by measuring the voltage drop across it and the current flowing through it. You will double the resistance value and see the effect that this has on the amount of power consumed.*

6. Enable the output of the internal power source by depressing the **Start/Stop** push button. The display indicates **Started**, thereby confirming that the output of the internal power source is enabled.
7. Record below the voltage  $E_1$  indicated by the voltmeter and the source current  $I_S$  indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**. Then, calculate the power  $P_{R1}$  consumed by the resistor.

$$E_1 = \text{_____ V}$$

$$I_S = \text{_____ A}$$

$$P_{R1} = E_1 \times I_S = \text{_____ W}$$

8. Double the resistance of  $R_1$  by modifying the connection(s) and the switch settings as necessary on the **Resistive Load** module. Leave the voltmeter connected across  $R_1$ .
9. Record the voltage  $E_1$  indicated by the voltmeter and the source current  $I_S$  indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**.

$$E_1 = \text{_____ V}$$

$$I_S = \text{_____ A}$$

Compare the measured values with those previously recorded in step 7.

Does voltage  $E_1$  stay the same when the resistance is doubled?

Yes     No

Does the source current  $I_S$  decrease by half when the resistance is doubled?

Yes     No

10. Based on the voltage and current measured in step 9, calculate the power  $P_{R1}$  consumed by the resistor using each of the formulas below.

$$P_{R1} = E_1 \times I_S = \text{_____ W}$$

$$P_{R1} = I_S^2 \times R = \text{_____ W}$$

$$P_{R1} = \frac{E_1^2}{R} = \text{_____ W}$$

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Do the three formulas give approximately the same results?

- Yes     No

Compare the power obtained in this step with that previously recorded in step 7. Does the power consumed by resistor  $R_1$  decrease by half when the resistance value is doubled?

- Yes     No

### Measuring power in a circuit with resistors in series

*In this section, you will perform power measurements in a circuit containing two resistors connected in series.*

11. On the [Four-Quadrant Dynamometer/Power Supply](#), turn the internal power source off by depressing the *Start/Stop* push button once. Make sure that the display indicates *Stopped*, thereby confirming that power is removed.
12. Set up the circuit shown in Figure 26. To obtain the resistor arrangement of Figure 26, make the necessary connection(s) and switch settings on the [Resistive Load](#) module.

Set a multimeter to measure dc voltage and connect it across resistor  $R_1$ .



*The voltage across resistor  $R_2$  will be measured separately in another step. For this reason, the voltmeter symbol is dashed for  $E_{R2}$  in Figure 26.*

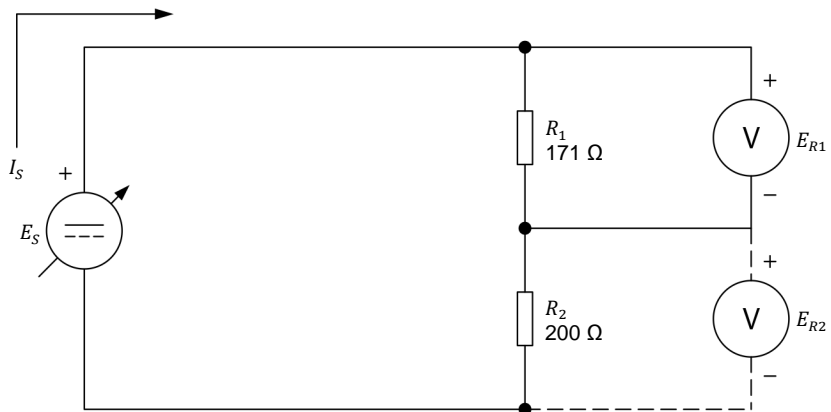


Figure 26. Measuring power in a circuit with resistors in series.

13. On the [Four-Quadrant Dynamometer/Power Supply](#), turn the internal power source on by depressing the *Start/Stop* push button. Make sure that the source voltage  $E_s$ , indicated on the display is still set to 50 V.

14. In Table 2, record the source current  $I_S$ , indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**. Then, record the voltage  $E_{R1}$  indicated by the voltmeter.

**Table 2. Measuring the circuit current and the voltage across each resistor to determine the total power consumed by the circuit.**

$I_S$ (A)	$E_{R1}$ (V)	$E_{R2}$ (V)

15. Disconnect the voltmeter from resistor  $R_1$  and connect it across resistor  $R_2$ , as shown in Figure 26.
16. In Table 2, record the voltage  $E_{R2}$  indicated by the voltmeter.
17. Based on the source current  $I_S$ , and on the two voltages recorded in Table 2, calculate the total power  $P_T$  consumed by the circuit.

$$P_T = (E_{R1} + E_{R2}) \cdot I_S = \text{_____ W}$$

18. Based on the source current  $I_S$ , recorded in Table 2 and on the source voltage  $E_S$  of 50 V, calculate the power  $P_S$  supplied by the dc source.

$$P_S = E_S \cdot I_S = \text{_____ W}$$

19. Is the total power consumed by the circuit approximately equal to the power supplied by the dc source? Explain.

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20. Increase the source voltage  $E_S$  using the **Command** knob of the **Four-Quadrant Dynamometer/Power Supply** until the voltage indicated on the display is equal to 62.5 V (this corresponds to an increase of 25%).

Record the source current  $I_S$  indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**.

$$I_S = \text{_____ A}$$

21. Using the current recorded in step 20, calculate the power consumed by each of resistors  $R_1$  and  $R_2$ .

$$P_1 = I_S^2 \cdot R_1 = \text{_____ W}$$

$$P_2 = I_S^2 \cdot R_2 = \text{_____ W}$$

22. Based on the results recorded in the previous steps, calculate the total power  $P_T$  consumed by the circuit and the power  $P_S$  supplied by the dc source.

$$P_T = P_1 + P_2 = \underline{\hspace{2cm}} \text{ W}$$

$$P_S = E_S \cdot I_S = \underline{\hspace{2cm}} \text{ W}$$

Are these answers approximately the same?

Yes     No

### Measuring power in a circuit with resistors in parallel

*In this section, you will perform power measurements in a circuit containing two resistors connected in parallel.*

23. On the [Four-Quadrant Dynamometer/Power Supply](#), turn the internal power source off by depressing the *Start/Stop* push button once. Make sure that the display indicates *Stopped*, thereby confirming that power is removed.

24. Set up the circuit shown in Figure 27. To obtain the resistor arrangement of Figure 27, make the necessary connection(s) and switch settings on the [Resistive Load](#) module.

Set a multimeter to measure dc voltage and connect it across resistors  $R_1$  and  $R_2$ , as Figure 27 shows.

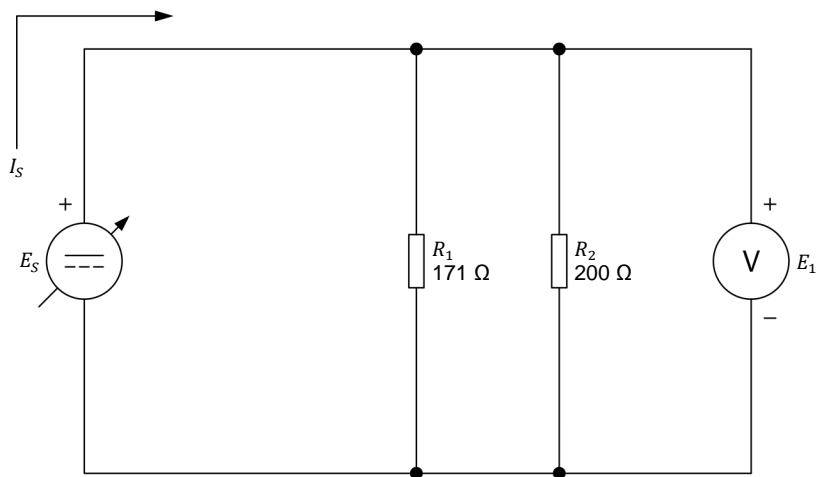


Figure 27. Measuring power in a circuit with resistors in parallel.

25. Given a source voltage  $E_S$  of 50 V, calculate the power  $P_{R1}$  and  $P_{R2}$  consumed by each resistor. Then, calculate the total power  $P_T$  consumed by the circuit.

$$P_{R1} = \frac{E_S^2}{R_1} = \text{_____ W}$$

$$P_{R2} = \frac{E_S^2}{R_2} = \text{_____ W}$$

$$P_T = P_{R1} + P_{R2} = \text{_____ W}$$

26. Knowing that the dc source supplies the total power consumed by the circuit, calculate the source current  $I_S$ , based on the value obtained for  $P_T$  in step 25 and on a source voltage  $E_S$  of 50 V.

$$I_S = \frac{P_T}{E_S} = \text{_____ A}$$

27. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source on by depressing the **Start/Stop** push button. Using the **Command** knob, set the source voltage  $E_S$  to 50 V.

28. Record below the source current  $I_S$  indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**. Is this current approximately equal to the current calculated in step 26?

$$I_S = \text{_____ A}$$

29. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off by depressing the **Start/Stop** push button.

Remove all circuit connections, then return all equipment to its storage location.

### CONCLUSION

In this exercise, you learned how to calculate the power dissipated by resistors connected in series, or parallel in dc circuits. You verified your power calculations by performing voltage and current measurements. You learned that the power supplied by a dc source is equal to the power consumed or dissipated by all the resistive elements in the electrical circuit.

### REVIEW QUESTIONS

1. What is power? How is electrical power measured in the international (SI) system of units?

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2. State three formulas used to calculate power in a dc circuit, when two of the following parameters are known: voltage, current, and resistance.

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3. A light bulb has a filament whose resistance is  $28.8 \Omega$ . Calculate the power consumed by the light bulb when the dc voltage across it is 12 V.

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4. The earth ground resistance at the base of a transmission tower is  $2 \Omega$ . If the tower is struck by a lightning bolt of 20 000 A (= 20 kA), how much power will be dissipated in the ground?

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5. A dc motor draws a current of 50 A at 230 V. The motor dissipates 1200 W as heat. How much power is left for the motor to do mechanical work?

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## Series and Parallel Circuits

### EXERCISE OBJECTIVE

When you have completed this exercise, you will be able to solve complex series and parallel circuits, using a few fundamental rules. These rules are directly related to Ohm's law, Kirchhoff's voltage and current laws, and the formulas used to calculate the equivalent resistance.

### DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Kirchhoff's voltage and current laws
- Simplification of series circuits
- Simplification of parallel circuits
- The voltage divider principle
- The current divider principle

### DISCUSSION

#### Kirchhoff's voltage and current laws

**Kirchhoff's voltage law** states that "the algebraic sum of all voltages in a closed-circuit loop is equal to zero".

**Kirchhoff's current law** states that "the sum of the currents entering any junction equals the sum of the currents leaving that junction".

#### Simplification of series circuits

Series circuits can be simplified by using the following rules:

1. Since a single path is available for the current flow, the same current flows through each resistor in the circuit.
2. The voltage supplied by the source is equal to the algebraic sum of the voltage drops across each resistor in the circuit.
3. The equivalent resistance of the circuit is equal to the sum of the resistance values of each resistor in the circuit.



*The term "resistor" is used in the general sense to designate any circuit component opposing to the current flow and causing a voltage drop.*

Figure 28 shows how to use the above rules to simplify a circuit made of three resistors connected in series.

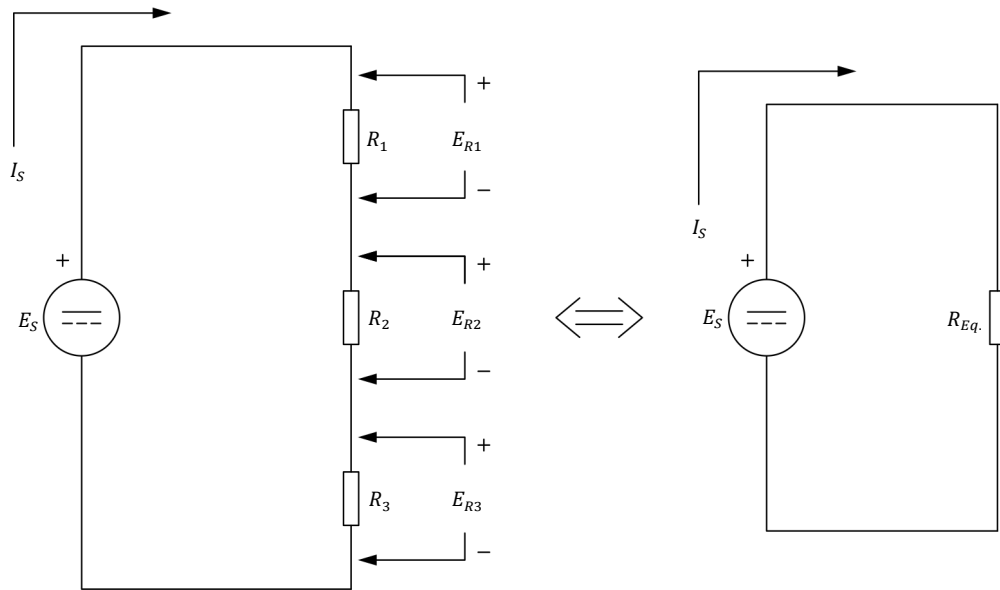


Figure 28. Simplification of a series circuit.

According to Rule 1, a source current  $I_S$  of equal amplitude flows through resistors  $R_1$ ,  $R_2$ , and  $R_3$ . From Ohm's law, the voltage drop  $E_R$  across each resistor is

$$E_{R1} = I_S R_1$$

$$E_{R2} = I_S R_2$$

$$E_{R3} = I_S R_3$$

According to Rule 2, the source voltage  $E_S$  is equal to the sum of the voltage drops across each resistor. Therefore,

$$E_S = E_{R1} + E_{R2} + E_{R3}$$

or

$$E_S = I_S R_1 + I_S R_2 + I_S R_3$$

In the equation above, the source current  $I_S$  is common to all terms. Therefore, this equation can be rewritten as

$$E_S = I_S (R_1 + R_2 + R_3)$$

According to Rule 3, the equivalent resistance  $R_{Eq.}$  of the circuit is equal to the sum of the resistance of each resistor:

$$R_{Eq.} = R_1 + R_2 + R_3$$

This leads to

$$E_S = I_S \cdot R_{Eq.}$$

Therefore, the circuit can be simplified to a source with a voltage  $E_S$ , connected to a single resistor having a resistance  $R_{Eq.}$  through which a current  $I_S$  flows, as Figure 28 shows.

### Simplification of parallel circuits

Parallel circuits can be simplified by using the following rules:

1. The total current supplied by the source is equal to the sum of the currents flowing through all the parallel branches of the circuit.
2. A same voltage is present across each parallel branch of the circuit.
3. The reciprocal of the equivalent resistance of the circuit is equal to the sum of the reciprocals of the individual resistor values.

Figure 29 shows how to use the above rules to simplify a circuit made of three resistors connected in parallel.

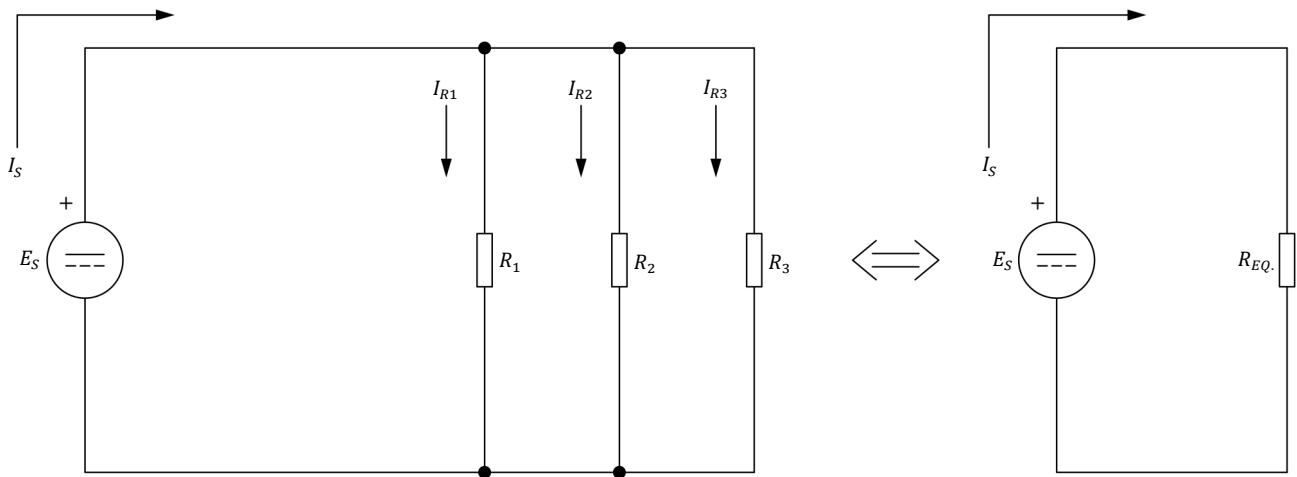


Figure 29. Simplification of a parallel circuit.

According to Rule 1, the total current  $I_S$  supplied by the source is equal to the sum of the currents flowing through all the parallel branches (in this case, through resistors  $R_1$ ,  $R_2$ , and  $R_3$ ). Therefore,

$$I_S = I_{R1} + I_{R2} + I_{R3}$$

According to Rule 2, a source voltage  $E_S$  of equal amplitude is present across each parallel resistor. Based on this rule and on Ohm's law, the above equation can be rewritten as

$$I_S = \frac{E_S}{R_1} + \frac{E_S}{R_2} + \frac{E_S}{R_3}$$

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In the equation above, the source voltage  $E_S$  is common to all terms. Therefore, this equation can be rewritten as

$$I_S = E_S \left( \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)$$

According to Rule 3, the reciprocal of the equivalent resistance of the circuit,  $1/R_{Eq.}$ , is equal to the sum of the reciprocals of the individual resistor values:

$$\frac{1}{R_{Eq.}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

This equation leads to

$$I_S = E_S \cdot \frac{1}{R_{Eq.}}$$

and

$$I_S = \frac{E_S}{R_{Eq.}}$$

Therefore, the circuit can be simplified to a source with a voltage  $E_S$  connected to a single resistor having a resistance  $R_{Eq.}$  through which a current  $I_S$  flows, as Figure 29 shows.

### The voltage divider principle

Another fundamental rule used to simplify a circuit is the **voltage divider principle**. This principle states that when a voltage  $E_S$ , is applied across two **series** resistors  $R_1$  and  $R_2$ , the voltage will divide so that the ratio of the voltage drops across these resistors is equal to the ratio of the resistor values. In equation form:

$$\frac{E_{R1}}{E_{R2}} = \frac{R_1}{R_2}$$

The voltage drop  $E_R$  across each resistor is, therefore,

$$E_{R1} = \frac{E_S \cdot R_1}{R_1 + R_2}$$

and

$$E_{R2} = \frac{E_S \cdot R_2}{R_1 + R_2}$$

### The current divider principle

The **current divider principle** states that when a voltage  $E_S$  is applied across two **parallel** resistors,  $R_1$  and  $R_2$ , the current  $I_S$  entering the resistors will split so that the ratio of the currents in the resistors ( $I_{R1}$  and  $I_{R2}$ ) is equal to the inverse ratio of the resistor values. In equation form:

$$\frac{I_{R1}}{I_{R2}} = \frac{R_2}{R_1}$$

The current flowing through each resistor is, therefore,

$$I_{R1} = \frac{I_S \cdot R_2}{R_1 + R_2}$$

and

$$I_{R2} = \frac{I_S \cdot R_1}{R_1 + R_2}$$

### PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Series circuit
- Parallel circuit
- Series-parallel circuit (case 1)
- Series-parallel circuit (case 2)



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

### PROCEDURE

#### Series circuit

*In this section, you will set up a circuit containing two resistors connected in series. You will calculate the equivalent resistance and the circuit current to determine the theoretical voltage drop across each resistor. You will then measure these voltage drops with a voltmeter.*

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

Install the equipment required in the [Workstation](#).

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

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3. Set up the circuit shown in Figure 30. To obtain the resistor arrangement of Figure 30, make the necessary connections and switch settings on the **Resistive Load** module.

Set a multimeter to measure dc voltage and connect it in parallel with resistor  $R_1$ . (The voltage across resistor  $R_2$  will be measured separately in another step).

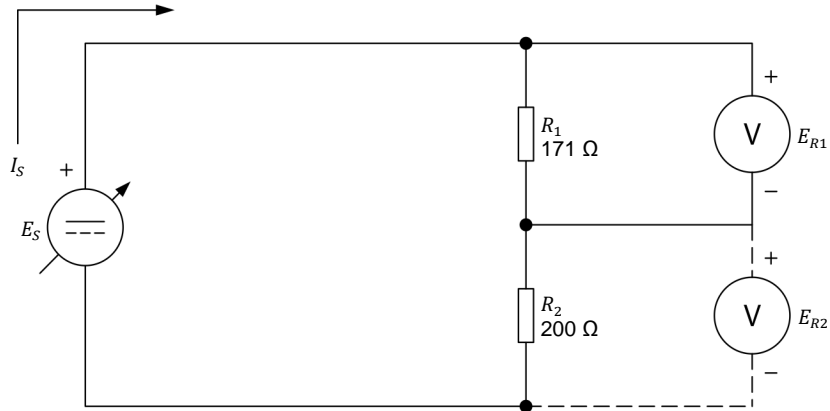


Figure 30. Circuit made of resistors connected in series.

4. Turn the **Four-Quadrant Dynamometer/Power Supply** on by setting the **Power Input** switch to the I (on) position.
5. Make the following settings on the **Four-Quadrant Dynamometer/Power Supply**:
  - Set the **Operating Mode** switch to **Power Supply**. This connects the internal power source of the module to the **Power Supply** terminals on the front panel.
  - Select the **Voltage Source (+)** mode of operation of the power source using the **Function** push button. The mode of operation selected is indicated on the module display. Selecting this mode makes the internal power source operate as a positive voltage source. When the **Four-Quadrant Dynamometer/Power Supply** operates as a positive voltage source, the voltage at the yellow terminal is positive with respect to the voltage at the white terminal (neutral terminal N).
  - Set the voltage of the positive voltage source to 50 V by using the **Command** knob. This voltage is indicated on the module display. Notice that the displayed voltage is blinking. This occurs because the output of the internal power source is disabled.

6. Calculate the equivalent resistance  $R_{Eq.}$  of the series resistors in Figure 30. Then, calculate the source current  $I_S$  based on the equivalent resistance  $R_{Eq.}$  and the source voltage  $E_S$  of 50 V.

$$R_{Eq.} = R_1 + R_2 = \underline{\hspace{2cm}} \Omega$$

$$I_S = \frac{E_S}{R_{Eq.}} = \underline{\hspace{2cm}} \text{ A}$$

7. Calculate the theoretical voltage drop across each resistor, based on the source current  $I_S$  obtained in step 6 and on the resistor values.

$$E_{R1} = I_S R_1 = \underline{\hspace{2cm}} \text{ V}$$

$$E_{R2} = I_S R_2 = \underline{\hspace{2cm}} \text{ V}$$

8. On the **Four-Quadrant Dynamometer/Power Supply**, enable the output of the internal power source by depressing the **Start/Stop** push button. The display indicates **Started**, thereby confirming that the internal power source is enabled.

9. Note the voltage indicated by the voltmeter  $E_{R1}$  and compare it with the theoretical value of  $E_{R1}$  recorded in step 7. Are these voltages approximately the same?

Yes       No

10. Disconnect the voltmeter from resistor  $R_1$  and connect it across resistor  $R_2$ , as Figure 30 shows.

11. Compare the voltage indicated by the voltmeter,  $E_{R2}$ , with the theoretical value of  $E_{R2}$  recorded in step 7. Are these voltages approximately the same?

Yes       No

### Parallel circuit

*In this section, you will set up a circuit containing resistors connected in parallel. You will calculate the equivalent resistance, the source current, and the current flowing through each resistor. You will then measure these currents and compare them with the calculated values. You will verify that the sum of the currents flowing through the circuit branches is equal to the source current.*

12. On the **Four-Quadrant Dynamometer/Power Supply**, disable the internal power source by depressing the **Start/Stop** push button. Make sure that the display indicates **Stopped**, thereby confirming that the internal power source is disabled and that power is removed.



*For the rest of the exercise, always use the **Start/Stop** push button to enable or disable (turn on or off) the internal power source.*

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13. Set up the circuit shown in Figure 31. To obtain the resistor arrangement of Figure 31, make the necessary connections and switch settings on the **Resistive Load** module.

Set a multimeter to measure dc current and connect it in series with resistor  $R_1$ , as Figure 31 shows.

Set a multimeter to measure dc voltage and connect it across the three resistors, as Figure 31 shows.



The ammeter symbol is dashed for  $I_{R2}$  and  $I_{R3}$  in Figure 31. This occurs because the ammeter (A) will be moved in the other circuit branches to measure currents  $I_{R2}$  and  $I_{R3}$ . Close the branches of resistors  $R_2$  and  $R_3$  for now, using a connection lead, in order to have the three resistors connected in parallel.

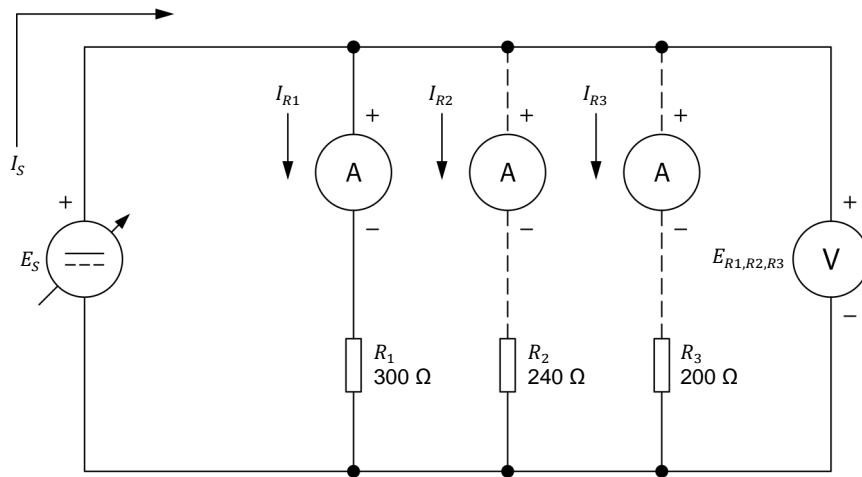


Figure 31. Circuit made of resistors connected in parallel.

14. Calculate the equivalent resistance  $R_{Eq.}$  of the parallel resistors in Figure 31. Then, calculate the source current  $I_S$  based on the equivalent resistance  $R_{Eq.}$  and the source voltage  $E_S$  of 50 V.

$$R_{Eq.} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}} = \text{_____} \Omega$$

$$I_S = \frac{E_S}{R_{Eq.}} = \text{_____} \text{ A}$$

15. Calculate the current flowing through each resistor, based on the fact that the source voltage  $E_S = E_{R1,R2,R3} = 50 \text{ V}$ :

$$I_{R1} = \frac{E_{R1,R2,R3}}{R_1} = \text{_____} \text{ A}$$

$$I_{R2} = \frac{E_{R1,R2,R3}}{R_2} = \text{_____} \text{ A}$$

$$I_{R3} = \frac{E_{R1,R2,R3}}{R_3} = \text{_____} \text{ A}$$

16. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source on. The display indicates *Started*, thereby confirming that the internal power source is on.
17. In Table 3, record the source current  $I_S$  indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**.

Record the voltage  $E_{R1,R2,R3}$  indicated by the voltmeter.

Record the current  $I_{R1}$  indicated by the ammeter.

**Table 3. Measuring the circuit currents and voltage.**

$I_S$ (A)	$E_{R1,R2,R3}$ (V)	$I_{R1}$ (A)	$I_{R2}$ (A)	$I_{R3}$ (A)

18. Turn the internal power source off. Disconnect the ammeter from resistor  $R_1$  and connect it in series with resistor  $R_2$ , as Figure 31 shows. Make sure to keep the three resistors connected in parallel.

Turn the internal power source on and record the current  $I_{R2}$  indicated by the ammeter in Table 3.

19. Turn the internal power source off. Disconnect the ammeter from resistor  $R_2$  and connect it in series with resistor  $R_3$ , as Figure 31 shows. Make sure to keep the three resistors connected in parallel.

Turn the internal power source on and record the current  $I_{R3}$  indicated by the ammeter in Table 3.

20. Calculate the equivalent resistance  $R_{Eq.}$  based on the source current and the voltage across the resistors recorded in Table 3.

$$R_{Eq.} = \frac{E_{R1,R2,R3}}{I_S} = \text{_____ } \Omega$$

Compare the equivalent resistance with the theoretical value recorded in step 14. Are these resistances approximately the same?

Yes       No

21. Compare the currents  $I_{R1}$ ,  $I_{R2}$ , and  $I_{R3}$  recorded in Table 3 with the theoretical values recorded in step 15.

Are these currents approximately the same?

Yes       No

22. Is the sum of the currents entering each circuit branch ( $I_{R1} + I_{R2} + I_{R3}$ ) equal to the source current  $I_S$ ?

---



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**Series-parallel circuit (case 1)**

In this section, you will set up a circuit containing resistors connected in a series-parallel arrangement. You will calculate the equivalent resistance of the circuit and the circuit current to determine the voltage drops across the resistors. You will then measure these voltage drops with the voltmeter.

23. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off.
24. Set up the circuit shown in Figure 32. To obtain the resistor arrangement of Figure 32, make the necessary connections and switch settings on the **Resistive Load** module.

Set a multimeter to measure dc voltage and connect it across resistor  $R_1$ .

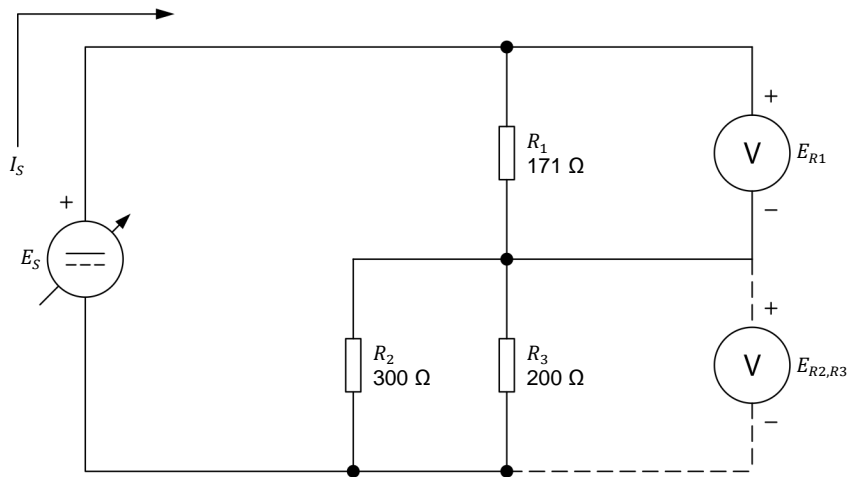


Figure 32. Circuit made of resistors connected in series-parallel.

25. Calculate the equivalent resistance  $R_{Eq.}$  of the resistors in Figure 32. Then, calculate the source current  $I_S$  based on the equivalent resistance  $R_{Eq.}$  and the source voltage  $E_S$  of 50 V.

$$R_{Eq.} = R_1 + \left( \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}} \right) = \text{_____ } \Omega$$

$$I_S = \frac{E_S}{R_{Eq.}} = \text{_____ } A$$

26. Calculate the voltage drops across  $R_1$  and across parallel resistors  $R_2$  and  $R_3$ , using the source current  $I_S$  calculated in step 25.

$$E_{R1} = I_S R_1 = \text{_____ V}$$

$$E_{R2,R3} = I_S \left( \frac{1}{\frac{1}{R_2} + \frac{1}{R_3}} \right) = \text{_____ V}$$

27. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source on.
28. In Table 4, record the source current  $I_S$  as indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**.

Record the voltage  $E_{R1}$  indicated by the voltmeter in Table 4.

Disconnect the voltmeter from resistor  $R_1$  and connect it across parallel resistors  $R_2$  and  $R_3$ , as Figure 32 shows. Record the voltage  $E_{R2,R3}$  indicated by the voltmeter in Table 4.

**Table 4. Measuring the circuit current and voltages.**

$I_S$ (A)	$E_{R1}$ (V)	$E_{R2,R3}$ (V)

29. Compare the source current  $I_S$  recorded in Table 4 with the theoretical value recorded in step 25. Are these currents approximately the same?

Yes     No

30. Compare the voltage drops  $E_{R1}$  and  $E_{R2,R3}$  recorded in Table 4 with the theoretical values recorded in step 26. Are they approximately the same?

Yes     No

### Series-parallel circuit (case 2)

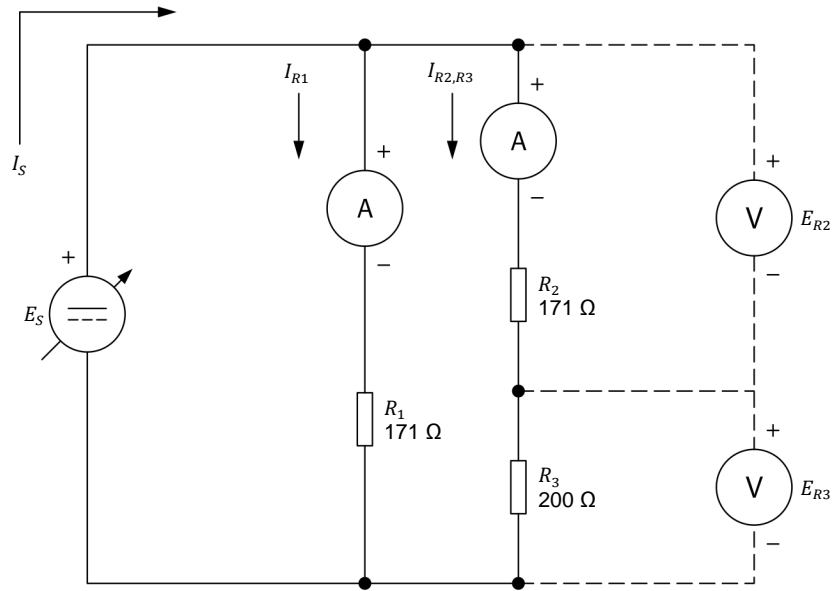
*In this section, you will set up another circuit containing resistors connected in a series-parallel arrangement. You will calculate the equivalent resistance and the circuit current to determine the currents flowing through each resistor and the voltage drops across them. You will then measure these currents and voltage drops with the ammeter and the voltmeter.*

31. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off.

- 32.** Set up the circuit shown in Figure 33. To obtain the resistor arrangement of Figure 33, make the necessary connections and switch settings on the **Resistive Load** module.

Set a multimeter to measure dc current and connect it in series with resistor  $R_1$ , as Figure 33 shows.

Set another multimeter to measure dc current and connect it in series with resistor  $R_2$ , as Figure 33 shows.



**Figure 33.** Circuit made of resistors connected in series-parallel.

- 33.** Calculate the equivalent resistance  $R_{Eq.}$  of the resistors in Figure 33. Then, calculate the source current  $I_S$  based on the equivalent resistance  $R_{Eq.}$  and the source voltage  $E_S$  of 50 V.

$$R_{Eq.} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2 + R_3}} = \text{_____} \Omega$$

$$I_S = \frac{E_S}{R_{Eq.}} = \text{_____} \text{ A}$$

- 34.** Calculate the currents flowing through resistor  $R_1$  and through series resistors  $R_2$  and  $R_3$ , based on the resistor values and on the source voltage  $E_S$  of 50 V.

$$I_{R1} = \frac{E_S}{R_1} = \text{_____} \text{ A}$$

$$I_{R2,R3} = \frac{E_S}{R_2 + R_3} = \text{_____} \text{ A}$$

35. Calculate the voltage drops across resistors  $R_2$  and  $R_3$ , using the current  $I_{R2,R3}$  calculated in step 34.

$$E_{R2} = I_{R2,R3} \cdot R_2 = \underline{\hspace{2cm}} \text{ V}$$

$$E_{R3} = I_{R2,R3} \cdot R_3 = \underline{\hspace{2cm}} \text{ V}$$

36. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source on.

37. In Table 5, record the circuit current  $I_S$  as indicated on the display of the **Four-Quadrant Dynamometer/Power Supply**.

Record the current  $I_{R1}$  indicated by the first ammeter.

Record the current  $I_{R2,R3}$  indicated by the other ammeter.

**Table 5. Measuring the circuit currents and voltages.**

$I_S$ (A)	$I_{R1}$ (A)	$I_{R2,R3}$ (A)	$E_{R2}$ (V)	$E_{R3}$ (V)

38. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off. Remove both multimeters from the circuit and close the two circuit branches by using connection leads.

Set the multimeters to measure dc voltage. As Figure 33 shows, connect a voltmeter across resistor  $R_2$ . Connect the other voltmeter across resistor  $R_3$ .

39. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source on.

In Table 5, record the voltages  $E_{R2}$  and  $E_{R3}$  indicated by the voltmeters.

40. Compare the source current  $I_S$  recorded in Table 5 with the theoretical value recorded in step 33. Are these currents approximately the same?

Yes     No

41. Compare the currents  $I_{R1}$  and  $I_{R2,R3}$  recorded in Table 5 with the theoretical values recorded in step 34. Are these currents approximately the same?

Yes     No

42. Is the sum of the branch currents recorded in Table 5 ( $I_{R1} + I_{R2,R3}$ ) equal to the source current  $I_S$ ? Explain.

Yes     No

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43. Compare the voltage drops  $E_{R2}$  and  $E_{R3}$  recorded in Table 5 with the theoretical values recorded in step 35. Are they approximately the same?

- Yes     No

44. On the **Four-Quadrant Dynamometer/Power Supply**, turn the internal power source off.

Remove all circuit connections, then return all equipment to its storage location.

**CONCLUSION**

In this exercise, you learned that different combinations of series and parallel circuits can be solved by using rules related to Ohm's law and Kirchhoff's laws. You used these rules to calculate the circuit currents and voltages, and verified your results by comparing them with the measured values.

**REVIEW QUESTIONS**

1. Briefly define Kirchhoff's voltage and current laws.

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2. Consider the circuit of Figure 32. If the voltage of the source  $E_S$  doubles, what happens to the current flowing through each resistor and to voltages  $E_{R1}$  and  $E_{R2,R3}$ ?

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3. If the value of resistor  $R_3$  in the circuit of Figure 32 is reduced by half, does the current through resistor  $R_2$  increase or decrease?

---

4. Refer to Figure 31. If one of the resistors is removed from the circuit, what happens to the source current  $I_S$  and the source voltage  $E_S$ ?

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5. Refer to Figure 33. How can the source current  $I_S$  be reduced by half?

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## Equipment Utilization Chart

The following equipment is required to perform the exercises in this course.

Equipment		Exercise			
Model	Description	1	2	3	4
8131 <sup>(1)</sup>	Workstation	1	1	1	1
8311 <sup>(2)</sup>	Resistive Load	1	1	1	1
8946-2	Multimeter	2	2	2	2
8951-L	Connection Leads and Accessories	1	1	1	1
8960-B <sup>(3)</sup>	Four-Quadrant Dynamometer/Power Supply	1	1	1	1
<p>(1) The Mobile Workstation, Model 8110, or the Workstation, Model 8134, can also be used.            (2) Resistive Load unit with low (120 V) voltage rating. Use model variant -00, -01, -02, or -A0.            (3) Model 8960-B consists of the Four-Quadrant Dynamometer/Power Supply, Model 8960-2, with the Standard Functions (manual control) set, Model 8968-1.</p>					



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## Glossary of New Terms

<b>alternating current (ac)</b>	Alternating current is the type of current supplied to most houses and places of business. This type of current changes direction (polarity) many times each second. Examples of devices that produce ac current are alternators and ac generators.
<b>ammeter</b>	An instrument used for measuring the intensity of electrical current. It is provided with a scale, usually graduated in either milliamperes (mA) or amperes (A).
<b>battery</b>	Term introduced in 1749 by Benjamin Franklin for an arrangement of multiple Leyden jars. A battery is a device with two or more electrochemical cells that converts chemical energy into electrical energy. It has a positive terminal (cathode) and a negative terminal (anode).
<b>conductors</b>	Materials that allow electrical current to flow. Conductors have electrons in their outer orbit that can be easily dislodged by external means like heating, or applying an electric field. The farther an electron is from the nucleus, the lower the atomic force attracting it.
<b>convection</b>	The transfer of thermal energy that occurs between a surface and a moving fluid (such as air or water) when they are not at the same temperature.
<b>conventional direction of current flow</b>	The conventional direction of current flow is from a positively charged body to a negatively charged body.
<b>current</b>	Flow of free electrons passing through a conductor per unit of time. Current is measured in amperes (A). The current flow through an electrical circuit may be one of two types: direct current (dc) or alternating current (ac).
<b>current divider principle</b>	This principle states that when a voltage is applied across two parallel resistors, the current entering the resistors will split so that the ratio of the currents in the resistors is equal to the inverse ratio of the resistor values.
<b>direct current (dc)</b>	Direct current is the type of current produced by batteries and dc sources. This type of current flows in one direction (conventional direction) only: from the positive (+) terminal of the battery or power source towards the negative (-) terminal.
<b>electric field</b>	A region of space where an electric state exists capable of exerting forces.
<b>electrons</b>	Electrons are very light particles that rotate around the nucleus of an atom and carry a negative (-) electric charge.
<b>energy</b>	Energy is the ability to do work. Energy can be transferred from a body to another, or converted from one form to another. In the international system (S I) of units, energy is measured in joules (J). One joule (1 J) is equal to one watt-second (1 W·s).
<b>equivalent resistance</b>	Single equivalent resistance representing a combination of resistors connected in series, parallel or series-parallel.
<b>incandescent</b>	Term generally applied to a light source in which the light is emitted by a glowing metal filament heated to incandescence by an electric current.
<b>kinetic energy</b>	The energy a body possesses due to its motion.
<b>Kirchhoff's voltage and current laws</b>	Kirchhoff's voltage law states that "the algebraic sum of all voltages in a closed-circuit loop is equal to zero". Kirchhoff's current law states that "the sum of the currents entering any junction equals the sum of the currents leaving that junction".
<b>law of conservation of energy</b>	The law of conservation of energy states that energy cannot be created or destroyed, it can only change form.

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<b>Leyden jar</b>	A device used to store electric charges, invented around 1744. Combining several Leyden jars in parallel increases the maximum stored charge.
<b>load</b>	A device which consumes power supplied by the source to perform a useful function, such as producing light, heat, or rotary motion.
<b>neutrons</b>	Neutrons are uncharged subatomic particles. Neutrons, together with protons, make up the center or core of the atom, called the nucleus.
<b>nucleus</b>	The nucleus is the center or core of the atom. It consists of protons and neutrons.
<b>ohmmeter</b>	An instrument used for measuring electrical resistance. It is provided with a scale, usually graduated in either ohms ( $\Omega$ ), kilohms ( $k\Omega$ ), and megohms ( $M\Omega$ ).
<b>Ohm's law</b>	The relationship between voltage, current, and resistance. The Ohm's law states that the current flowing through an electric device is equal to the voltage, or potential difference, across this device, divided by the resistance of this device. In equation form: $I = E/R$ . The Ohm's law can be reformulated as $E = RI$ or $R = E/I$ .
<b>parallel circuits</b>	Circuits in which the components are connected so that the current divides and travels through two or more paths and then returns through a common path.
<b>potential difference</b>	A synonym for voltage.
<b>potential energy</b>	The energy a body possesses due to its position or its particular physical or chemical state.
<b>power</b>	Power is the rate at which energy is supplied by a source or consumed by a load to do work.
<b>power source</b>	Source of electrical power that pushes electrons through a circuit and makes current flow.
<b>protons</b>	Protons are positively charged subatomic particles. Protons, together with neutrons, make up the center or core of the atom, called the nucleus.
<b>radiation</b>	The transfer of thermal energy via electromagnetic waves or particles.
<b>resistance</b>	The opposition to the flow of electric current. The value of resistance is expressed in ohms ( $\Omega$ ).
<b>series circuits</b>	Circuits in which the components are connected so that the current travels through a single path.
<b>voltage</b>	The electromotive force exerted by a power source or a battery to make free electrons flow from one point to another. The magnitude of a voltage is expressed in volts (V). In electro-kinetics, voltage is the magnitude of the electric field measured between two points of the field.
<b>voltage divider principle</b>	This principle states that when a voltage is applied across two series resistors, the voltage will divide so that the ratio of the voltage drops across these resistors is equal to the ratio of the resistor values.
<b>voltaic cell</b>	An electric cell invented in 1799 by Alessandro Volta, consisting of two electrodes of dissimilar metals immersed in a solution which acts chemically upon one or both of them, thus producing an electromotive force. This device led to the development of modern batteries.
<b>voltmeter</b>	An instrument used for measuring the magnitude of voltage. It is provided with a scale, usually graduated in either millivolts (mV), volts (V), or kilovolts (kV).

## 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 34 shows the load elements and connections. Other parallel combinations can be used to obtain the same impedance values listed.

Table 6. Impedance table for the load modules.

Impedance ( $\Omega$ )			Position of the switches								
120 V 60 Hz	220/230 V 50 Hz/60 Hz	240 V 50 Hz	1	2	3	4	5	6	7	8	9
1200	4400	4800									
600	2200	2400									
300	1100	1200									
400	1467	1600									
240	880	960									
200	733	800									
171	629	686									
150	550	600									
133	489	533									
120	440	480									
109	400	436									
100	367	400									
92	338	369									
86	314	343									
80	293	320									
75	275	300									
71	259	282									
67	244	267									
63	232	253									
60	220	240									
57	210	229									

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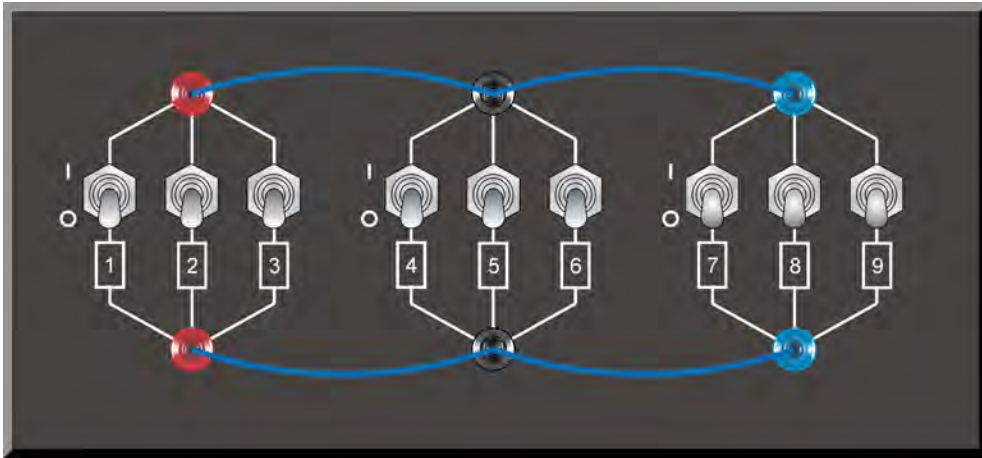


Figure 34. Location of the load elements on the Resistive Load, Inductive Load, and Capacitive Load, Models 8311, 8321, and 8331, respectively.

# Index of New Terms



The bold page number indicates the main entry. Refer to the Glossary of New Terms on page 71 for definitions of new terms.

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# Bibliography

Jackson, Herbert W., *Introduction to Electric Circuits*, 5<sup>th</sup> edition, New Jersey: Prentice Hall, 1981, ISBN 0-13-481432-0.

Wildi, Theodore, *Electrical Machines, Drives, and Power Systems*, 6<sup>th</sup> ed., Upper Saddle River: Prentice Hall, 2005, ISBN 978-0131776913.