Lab 3: Simple DC Circuits

1 Introduction

This lab will allow you to acquire hands-on experience with the basic principles of simple electric circuits. These circuits consist of discrete resistors and light bulbs that are connected to a DC power supply using conducting wires. Discrete resistors are usually made from poor electrical conductors such as carbon. Conducting wires have negligible resistance because they are usually made from copper, which is an excellent electric conductor.

In the first part of this lab, you will test Ohm's law, which describes the properties of resistors. In the next part, you will verify Kirchhoff's rules that apply to all circuits that are in steady state, i.e. circuits with a constant current flow. You will discover that it is possible to derive rules for how resistors combine in series and parallel circuits using Kirchhoff's rules. The experiments will allow you to test your derivations. You will also learn how the resistance of a wire is related to its length and area of cross section. In, the last part of the lab, you will perform some simple experiments with circuits consisting of light bulbs. These experiments will test your understanding, and allow you to figure out how these circuits are wired.

EXERCISES 1 AND 2 PERTAIN TO THE BACKGROUND CONCEPTS AND EXER-CISES 3-10 PERTAIN TO THE EXPERI-MENTAL SECTIONS.

2 Background

When a (typical) resistor is connected to a power supply, the current I flowing through the resistor is proportional to the electric potential difference V across the terminals of the resistor. This relationship is called Ohm's law, and is expressed by the following equation,

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

Here, R is the resistance. The SI unit of resistance is the ohm, Ω . Consider a closed circuit loop consisting



Figure 1: A circuit containing three resistors

of a network of resistors connected to a DC power supply or battery as shown in figure 1. When any closed loop in this circuit (such as ABCDA or BEFCB) is traversed, the algebraic sum of the changes in electric potential is equal to zero. This is a statement of **Kirchhoff's voltage rule**, and it follows from the law of conservation of energy.

At any junction in the circuit (such as B), the current flowing into the junction is the same as the sum of currents flowing out of the junction. This is known as **Kirchhoff's current rule**, and it is a consequence of the fact that charge is conserved.

Using Kirchhoff's rules and Ohm's law it is possible to derive rules for how resistors can be combined in circuits. When a circuit is made up of resistors (R_1 , R_2 , R_3 , etc.) connected in series, it can be shown that the total or effective resistance R_T is just the sum of the individual resistances,

$$R_T = R_1 + R_2 + R_3 \tag{2}$$

When these resistors are connected in parallel, the effective resistance is given by,

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \tag{3}$$

The resistance R of a cylindrical conductor, such as a segment of the wire shown in figure 1, is proportional to its length L and inversely proportional to its area of cross section A. This relationship is expressed as,

$$R = \frac{L\rho}{A} \tag{4}$$

Here, ρ is the resistivity (or specific resistance) of the material. The resistivity is a characteristic of the material of the conductor (for example, copper) and is independent of its geometry. The resistivity is defined by,

$$\rho = \frac{E}{J} \tag{5}$$



Figure 2: A condcutor carrying a current



Figure 3: A vernier caliper with a 0.1mm sliding scale magnitude

Here, \vec{E} and \vec{J} are the magnitudes of the electric field and current density inside the conductor respectively, as represented in figure 2. These are vector quantities that, in general, can have different values at every point within the conductor. For this reason ρ , \vec{E} , and \vec{J} are referred to as microscopic quantities. On the other hand, R, V, and I are macroscopic quantities used to describe electrical properties over an extended conductor.

The equations,

$$E = \frac{V}{L} \tag{6}$$

and

$$J = \frac{I}{A} \tag{7}$$

can be used to relate the microscopic version of Ohm's law given by equation 5 to the macroscopic (and more familiar) version given by equation 1.

Exercise 1: Derive equations 2 and 3 using Ohm's law and Kirchhoff's rules.

Exercise 2: Use equations 6 and 7 in equation 5, and obtain the relationship given by equation 4.

In one of the experiments you will use a vernier caliper, shown in figure 3. The vernier caliper is an extremely precise measuring instrument. Notice the fixed scale and the smaller sliding scale below it. To measure an object, place it between the caliper's jaws and tighten firmly, avoiding excessive tightening. First read the value on the fixed scale. In the example above, the 0 on the sliding scale lies just past 7mm. To read the sliding scale you have to find the tick mark that aligns best with a tick mark on the fixed scale. In other words, the value for the fixed scale is determined by where the 0 on the sliding scale lines up with the fixed scale. On the other hand, the number on the sliding scale is determined by finding which tick mark on it best lines up with any mark on the fixed scale. Therefore the reading in the figure above is 7.5mm because the tick mark labeled 5 lines up perfectly.

To obtain a measurement from a caliper add the main scale reading to the sliding scale reading. The sliding scale reading is obtained by multiplying its value by the caliper's sliding scale magnitude. Its magnitude is 0.1 mm in this case. Therefore, in general,

3 Suggested Reading

Refer to the chapters on Current and Resistance and DC Circuits,

R. Wolfson and J. Pasachoff, **Physics with Modern Physics** (3rd Edition, Addison-Wesley Longman, Don Mills ON, 1999)

D. Halliday, R. Resnick and K. S. Krane, **Physics** (Volume 2, 5th Edition, John Wiley, 2002)

4 Apparatus

Refer to Appendix E for photos of the apparatus

- Plexiglas circuit board with binding posts
- DC power supply with digital display of voltage and current
- Two Digital multi-meters



Figure 4: A circuit with an ammeter and a voltmeter

- An analogue multi-meter
- Banana wires
- 3 known resistors (approximate values)
 - 1. 15 k Ω
 - 2. 32.5 k Ω
 - 3. 200 k Ω
- Six circuit boxes with light bulbs
- Six nichrome wires of the same length
- Vernier caliper
- Ruler

5 Experiment I: Verifying Ohm's Law

Setup the circuit shown in figure 4. Setup digital multimeters to record the voltage between the terminals of the resistor and the current through the resistor as shown in the figure. Before you turn on the power supply, make sure that the current limit is set to its maximum and that the voltage control knob is set to zero.

Vary the voltage control knob in small increments (of about 1 volt up to a maximum of 10 volts) and record the voltage and current shown by the multimeters. Make sure that the data is recorded in the form of a table.

Exercise 3: Plot a graph of voltage vs. current and find the value of the resistance used in the circuit. Turn off the power supply and use one of the multimeters to measure the resistance directly. How well does the value of R_1 measured by the multimeter compare with the value of R_1 calculated from the graph?



Figure 5: A series resistor circuit



Figure 6: A parallel resistor circuit

6 Experiment II: Resistors in series

Setup three resistors in series, as shown in figure 5. Turn on the power source and adjust the power supply voltage to approximately 15 volts. Use the multimeter to measure the potential difference (voltage drop) across each resistor as well as the potential difference between the terminals of the power supply. Record your observations in the form of a table.

Turn off the power supply and disconnect it from the resistor network. Measure the resistance of each resistor as well as the total resistance using a multimeter. Record your measurements.

Exercise 4a: Show that your data verifies Kirchhoff's voltage rule. Comment on any discrepancy.

Exercise 4b: Show that the predictions of equation 2 are valid.

7 Experiment III: Resistors in Parallel

Connect three different resistors in a parallel circuit as shown in figure 6. For a fixed value of the power supply voltage, use the multimeter to measure the current through each resistor, as well as the current entering and leaving the power supply. Measure the voltage drop across each resistor. Record your results in a table. Disconnect the resistor network from the power supply and measure the values of the individual resistors. Then measure the effective resistance of the network.

Exercise 5a: Show that your data verifies Kirchhoff's current rule.

Exercise 5b: Why does a different current flow through each resistor? Is the measured current in agreement with the prediction of Ohm's law?

Exercise 5c: Show that the predictions of equation 3 are valid.

8 Experiment IV: Electrical resistivity

In this experiment you will be measuring the resistivity of nichrome (a common alloy used to make heater wires such as those found in toasters) by measuring the resistances and geometrical properties of several segments of wire. For convenience, the wires provided will have the same length.

Measure the diameters of the six wires using the vernier caliper. Measure the length of the wires using a ruler or tape measure. Finally, measure the resistance of each wire with the multimeter. Record your data in the form of a table.

Exercise 6: Figure out how your results can be plotted so that it is possible to obtain the resistivity of nichrome from the graph. Compare the measured value of the resistivity to the accepted value $\sim 1 \times 10^{-6}$ Ω m. Estimate the percentage difference between these results.

Exercise 7: List the magnitudes of the uncertainties associated with your measurements. Are they sufficient to account for the discrepancy reported in exercise 6?

9 Experiment V: Do you really understand Ohm's law?

Boxes numbered 1-5 use identical light bulbs. These light bulbs are resistors that obey Ohm's law. Each

of the boxes is a circuit consisting of three light bulbs. Your goal is to perform simple tests to determine how these circuits are wired (you are not supposed to open the boxes).

You can perform two different tests on these boxes,

Test 1: All the light bulbs on boxes 1-5 have two binding posts on each side. These posts are connected to the terminals of the resistive filament inside the light bulb. If you connect a particular set of binding posts with a conducting wire (that has a negligible resistance), a **short circuit** is created around that particular bulb.

Test 2: It is also possible to unscrew each light bulb from its socket during the experiments. Since the light bulbs may be hot to touch, use a piece of paper or cloth to unscrew the bulbs.

Begin your investigation by measuring the resistance of a single light bulb with a multimeter. Use the bulb on box 6. Compare the resistance of the bulb to the resistance of the conducting wire that will be used to form a short circuit around a given light bulb.

Next, connect box 6 to the power supply. Turn on the power supply and set the voltage to approximately 15 volts. The brightness of the bulb on box 6 will serve as a **reference** for your experiments. Now use the same power supply voltage to diagnose boxes 1-5.

Connect the power supply to box 1. Perform tests 1 and 2 described above on each light bulb in the circuit. Record your observations. Compare the brightness of each of the light bulbs to that of the reference bulb on box 6.

Repeat this procedure on boxes 2-5.

NOTE: For box 5, you can lower the voltage on the power supply and observe the relative brightness of the light bulbs.

Exercise 8: Deduce and draw the circuits corresponding to boxes 1-5. Your circuit diagram must be consistent with your table of observations.

Exercise 9: Explain whether the following circuits are wired in series or parallel,

- 1. The light bulbs and other electrical devices in your residence
- 2. Lights on a Christmas tree
- 3. Headlights on a car

Exercise 10: What is the purpose of a fuse or a circuit breaker?

Your lab report should include:

Answers to exercises 1-10 with relevant data tables, graphs, figures and qualitative comments.

Refer to Appendix D for Maple worksheets.