EE 241 – Experiment #5: TERMINAL CHARACTERISTICS OF LINEAR & NONLINEAR RESISTORS

PURPOSE:

• To experimentally determine some of the important characteristics of common linear and non-linear resistors.
• To study the dependence of resistance on shape (physical geometry).
• To study the resistance of a human body!

This experiment relates to the following course learning objectives of the course:

1. Ability to interconnect equipment and devices such as multimeter, counters, and oscilloscope to achieve required results.
2. Ability to relate practical laboratory results with lecture theory.
3. Ability to analyze and evaluate data.

LAB EQUIPMENT:

1 Agilent E3640A DC Power Supply
1 Decade Resistance Box
1 100 Ω Potentiometer
1 Agilent 34410A Digital Multimeter/Timer/Counter
1 Mounted Incandescent Lamp (use the small clear lamp, not the large frosted lamp)

STUDENT PROVIDED EQUIPMENT:

2 Alligator clips
5 Banana-to-banana leads
1 Common (carbon) 100 Ω, ¼ Watt Resistor (provided by the instructor)
2 Large metal paper clips
1 Ruler

Note: Be sure to get banana-to-alligator-clip leads that actually terminate with alligator clips. The latter will not be able to withstand the heat generated in the experiment.

Experiment Sections:

1) The Commercial Linear Resistor
2) A Non-linear Resistor
3) Dependence of Resistance on the Physical Shape (Geometry)
4) Measuring the Resistance of Your Body

Section 1) The Commercial Linear Resistor

a) Obtain a resistor from the instructor and verify with the color code that it has a nominal resistance of 100 Ω and 5% tolerance, and that it is ¼ watt.

1 Version 6, last revised 9/8/10 , EE Dept., Cal Poly
b) Measure the resistance of the resistor with the Multimeter and record this value.

c) With the Agilent power supply off, set up the following simple circuit. \( R_x \) is the 100 \( \Omega \) resistor to be tested. Set the power supply to “High voltage” and set the current limit to 0.2A. Note that in this circuit \( V_s = V_x \).

d) In your lab notebook, set up a table with five columns labeled as follows:

| column 1:  | V_x (recorded from power supply display) |
| column 2:  | I_x (recorded from power supply display)  |
| column 3:  | P_x (calculated)                        |
| column 4:  | R_x (calculated)                        |
| column 5:  | % difference between R_x calculated and R_x nominal |

e) Turn on the power supply and adjust its output voltage until V_x is 1.0 V; use a current limit of 0.2 A.

f) Wait about 30 seconds and record V_x and I_x. If you do not wait this period of time, your data will be unreliable.

g) Use V_x, I_x, and your prelab equations to calculate R_x, and P_x. Record these values in your notebook.

h) Repeat steps e) through g) for values of V_x between 2.0 V and 14.0 V in 1.0 V increments or until the resistor obviously fails. The resistor will become quite hot, so be careful not to touch it.

i) Allow the resistor to completely cool then measure its resistance. Record this value and make a visual and olfactory check of the resistor.

Questions: Section 1

1) In step f), why was it necessary to wait 30 seconds after increasing the power supply voltage?

2) If the resistor is not completely destroyed, it should still have some value of resistance. Would you ever want to use this device as a resistor again? Why or why not?

3) Plot R_x as a function of the power dissipated (P_x). Make your graph provide as much information as possible by suppressing zero on the vertical axis and using an expanded scale. Do not expand the scale beyond necessary limits. Indicate the resistor’s tolerance region on the graph and any other points of interest. In other words, fully display all the areas of importance on the graph. Additionally, indicate the resistor’s power rating with a vertical line.

4) Discuss how the resistance varied as the dissipated power increased and the ability of the resistor to operate with a power greater than its rated value.

5) At what value of power (if at all) does the resistor exceed its indicated tolerance? How much greater is the power at this point with respect to the indicated wattage rating?

Section 2) A Non-linear Resistor

a) With the power supply switched off, construct the following circuit:
b) Set the potentiometer resistance to about 50 Ω.

c) In your lab notebook, set up a table with two columns and label them as follows:

    column 1:  \( V_{\text{lamp}} \) (measured from multimeter)
    column 2:  \( I_{\text{lamp}} \) (use power supply current display)

d) Turn on the power supply and adjust its voltage so that \( V_{\text{lamp}} = 1.0 \text{ V} \). Use the pot for fine tuning (very sensitive!). Both the power supply and the pot may require adjustment to obtain the desired voltage.

e) Record \( V_{\text{lamp}} \) and \( I_{\text{lamp}} \).

f) Via adjusting the power supply and the pot, increase \( V_{\text{lamp}} \) in steps of 1.0 V but stop at 12 V or when \( I_{\text{lamp}} \) is 150 mA - WHICHEVER COMES FIRST. At each step, record \( V_{\text{lamp}} \) and \( I_{\text{lamp}} \).

Questions: Section 2)

1) Use your experimental values to plot \( V_{\text{lamp}} \) vs. \( I_{\text{lamp}} \). Does your graph indicate that this was a non-linear resistor?

2) From your table of values, compute the resistances (ratios of voltage to current) at all voltage and current values. These are DC resistances. Display your calculation of the DC resistance in a three-column table:

    column 1:  \( V_{\text{lamp}} \) (measured)
    column 2:  \( I_{\text{lamp}} \) (measured)
    column 3:  \( R_{\text{DC}} \) (calculated from columns 1 and 2)

How is it obvious from your table that this resistor is nonlinear?

3) For a nonlinear resistor, the AC resistance at a given current is defined as the derivative of the voltage versus current (\( V-I \) curve) at that current. AC resistance at a given current \( I_x \) can be approximated via the voltage and current values of a point on the \( V-I \) curve which is above \( I_x \), and a point on the \( V-I \) curve which is below \( I_x \) (the two points are equally-spaced from \( I_x \)). Calculate the approximate AC resistance of the lamp using the following formula

\[
R_{\text{AC}} \approx \frac{V_2 - V_1}{I_2 - I_1} = \frac{\Delta V}{\Delta I} \mid _{I_x}
\]

where \( I_1 \) is the current when \( V_{\text{lamp}} = V_1 \), \( I_2 \) is the current when \( V_{\text{lamp}} = V_2 \), and \( I_x \) is the average of \( I_1 \) and \( I_2 \). To be clear, \( V_{\text{lamp}} \) lies midway between \( V_1 \) and \( V_2 \) and \( I_{\text{lamp}} \) (which is the same as \( I_x \)) lies midway between \( I_1 \) and \( I_2 \). Compute \( R_{\text{AC}} \) for all \( \{V, I\} \) pairs measured in part (e). Display your calculations of the AC resistance in a five-column table:

    column 1:  \( V_{\text{lamp}} \) (measured)
    column 2:  \( I_{\text{lamp}} \) (measured)
    column 3:  \( \Delta V \) (calculated from the before and after entries of column 1)
    column 4:  \( \Delta I \) (calculated from the before and after entries of column 2)
    column 5:  \( R_{\text{AC}} \) (calculated from column 3 and 4)
(Thus the first and last entries of the columns 3, 4, and 5 will be empty.). Compare the AC and DC values of resistance over the entire range (some simple observations will suffice).

4) In the AC approximation formula above, state one advantage and one disadvantage of selecting the two points \((V_1, I_1)\) and \((V_2, I_2)\) very close to each other.

Section 3) Dependence of Resistance on the Physical Shape (Geometry)

For ordinary objects, the dependence of the resistance \(R\) of a material of cross-section \(A\) \((m^2)\) and length \(L\) \((m)\) is calculated as:

\[
R = \frac{\rho L}{A}
\]

where the constant of proportionality \(\rho\) is called the resistivity of the material.

Resistivity has different values for different materials, for example, copper and carbon. Although resistivity is temperature dependent, it can be used at a given temperature to calculate the resistance of an object given its geometry. For example, the electrical resistance of a wire is expected to be greater for a longer wire, less for a wire of larger cross-sectional area, and depends upon the material out of which the wire is composed of.

The diagram below illustrates the dependence of resistance on the length \(L\) based on the particular shape. Assume that the two opposing sides of the resistor to which the leads are connected are coated with the same material as that of the lead itself (ideally a zero-resistance conducting material). From the above equation, it can be seen that if we double the length \(L\) of a one-dimensional resistor (while leaving its cross-section \(A\) constant), then its resistance doubles. Thus for a one-dimensional resistor, \(R\) is proportional to \(L^1\). For a two-dimensional resistor, if we double the length and the width of the sheet (while holding the thickness constant), its resistance remains constant. This is because doubling the length and width, of a sheet resistor results in doubling both \(L\) and \(A\) (i.e., the new length is \(2L\) and the new cross-section is \(t \times 2 \times L = 2 \times t \times L = 2 \times A\)). Since \(R\) is proportional to the ratio of length over cross-section, then the total resistance does not change. Thus for a two-dimensional resistor, \(R\) is proportional to \(L^0\). For a three-dimensional resistor, if we double the length of each side of the cube, its resistance is halved. This is because doubling the three sides of a cube results in doubling its length (i.e., new length is \(2xL\)) and quadrupling its cross-section area (i.e., new cross-section is \(2 \times L \times 2 \times L = 4 \times L \times L = 4 \times A\)). That means the resistance which is proportional to the ratio of length over cross-section is halved. Thus for a three-dimensional resistor, \(R\) is proportional to \(L^{-1}\).

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Experimental Procedure

Note: In the following procedure, since it is not possible to make the distribution and density of the graphite consistent for various shapes of graphite that you construct, your experimental values (measured resistance) may not match the expected or theoretical values. For best results follow the following tips:
- TRY to make pencil shadings with identical darkness for all of the resistors constructed; shade heavily.
- Press hard on the paper clips for good contact with the resistors; but, be sure to avoid any electrical contact with your fingers.
- For each resistor, record the lowest resistance observed over multiple attempts at measuring it.

a) Using a regular pencil, draw a narrow 0.25” by 1.5” rectangle on a piece of paper. Fill-in the entire surface of the rectangle with pencil as uniformly as you can. Using a multimeter, measure and record the graphite resistance across the length of the rectangle. To make measurement of the graphite resistance, place two paper clips along the two narrow opposing sides of the rectangle and press the multimeter probes against them to make contact (do not let your fingers touch the probe ends or paper clips).

b) Draw a second rectangle of length 3 inches and repeat step (a). The measured resistance should be twice as large as the resistance measured in part (a).

c) Repeat step (a) except draw a 1/2” by 1/2” square instead of the rectangle.

d) Repeat step (c) except draw a 1” by 1” square.

e) Color-in the square used in step (d) one more time with pencil and measure the new resistances of the square.

Questions: Section 3

1) Should the resistance measured in part (b) be twice the resistance in part (a)? (Explain). Determine the percent difference between the measured and expected value. Explain the reasons for the difference.

2) Should the resistance measured in part (d) be the same as in part (c)? (Explain). Determine the percent difference between the measured and expected value. Explain the reasons for the difference.

3) Should the resistance measured in part (e) be the less than in part (d)? (Explain).

4) Suppose you measure the resistance across two opposite sides of a hollow $L \times L \times L$ cube made from a sheet of paper that is uniformly shaded with pencil. Assume that the two opposing sides of the cube to which the leads are connected are coated with the same material as that of the lead itself (ideally a zero-resistance conducting material). What do you expect the resistance to be if the cube was enlarged to $2L \times 2L \times 2L$?

Section 4) Measuring Body Resistance

a) Connect a pair of banana-to-banana leads to the multimeter. Tightly hold the bare end of each lead between the thumb and forefinger of each hand. Measure and record your body resistance for each person in your group.

Questions: Section 4)

1) State two reasons why the resistance of your body may be very different from your lab partner.

2) Considering that a current of 100-200 mA through your heart will almost certainly kill you, how much voltage across your hands would be lethal?

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3 Partially adapted from “Resistance Measurement,” by Christopher E. Cramer, Electrical & Computer Engineering, Duke University,
Notes:

1) The actual resistance of the body varies depending upon the points of contact (e.g., between the ears, from hand to foot), body fluids, and the skin condition (moist or dry).

2) The answer to above question may lead you to believe that only very high voltage, e.g., above 10000 volts, would be fatal. However, this may not be true. You may be electrocuted by ordinary household appliances using currents of 110 volts and by electrical apparatus in industry using as little as 42 volts direct current. The real measure of electric shock's intensity lies in the amount of current (amperes) forced though the body, and not the voltage. Any electrical device used on a house wiring circuit can, under certain conditions, transmit a fatal current.