

California State University, Fresno
Department of Electrical and Computer Engineering

ECE 90L Principles of Electrical Circuits Laboratory
Experiment No. 2: Ohm's Law and Power Measurements

Objective

The objective of this experiment is to become familiar with the solderless breadboard and color-coded resistors and to demonstrate Ohm's Law when a DC or an AC voltage is applied across a resistor.

Prelab

Ohm's Law

Ohm's Law is a characterization of the electrical properties of a resistor. This law relates three quantities:

- v voltage (having units V) across a resistor
- i current (having units A) through a resistor
- R resistance (having units Ω)

Figure 1 illustrates the definitions of v and i . When discussing the voltage across a resistor, we attach a + sign to one terminal (end) of the resistor and a - sign to the other. (A resistor has no intrinsic signs attached to it. We are free to arbitrarily assign the + sign to either terminal of the resistor.) Once we have attached signs to the two terminals of a resistor, we always define i in the direction from the + terminal of the resistor, through the body of the resistor, to the - terminal of the resistor. If v is positive (that is, if the + terminal really does have a higher potential than the - terminal), then the current flows through the resistor from the + terminal to the - terminal and we say that the current is positive. On the other hand, if v is negative, then i will flow in the *opposite* direction to that shown in Figure 1 and we then say that i is negative.

Ohm's Law says:

$$i = \frac{v}{R}$$

In words, the current through a resistor is proportional to the voltage across it, where the constant of proportionality is $1/R$. Sometimes it is more convenient to write this equation as $v = iR$. Since R is always positive in an elementary circuits laboratory, then i will have the same sign as

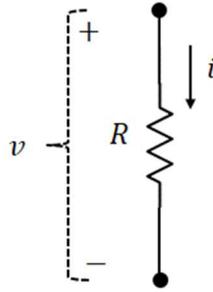


Figure 1: Voltage across and current through a resistor. An electrical current only flows in a complete circuit. The entire circuit is not shown in this figure, but the fact that we define a current here implies that there is a complete circuit.

v . For example, if $v < 0$, then $i < 0$. (In advanced studies of electrical phenomena, a “negative resistance” is sometimes defined, but we won’t see that this in course.)

The electrical power p dissipated in a resistor is

$$p = i \cdot v$$

In this equation, p will be in units of watts (W) when i has units of amperes (A) and v has units of volts (V). Since i and v always have the same sign for a resistor, the power is always positive. (In other words, electrical power is dissipated but never created in a resistor.) Taking advantage of Ohm’s Law, the power equation can also be written as

$$p = \frac{v^2}{R}$$

or as

$$p = i^2 R$$

Figure 2 shows a simple circuit with two different definitions of the voltage across the resistor. Regardless of which definition we use, we arrive at the following conclusions. The current flows out of the + terminal of the DC voltage source, passes through the resistor, and then returns to the voltage source through its – terminal. Also, the power dissipated in the resistor is positive. This illustrates that it really doesn’t matter which of the two definitions we use for voltage across the resistor. We always get the right answer for the power and the right answer for the direction of current flow (assuming we do the math correctly).

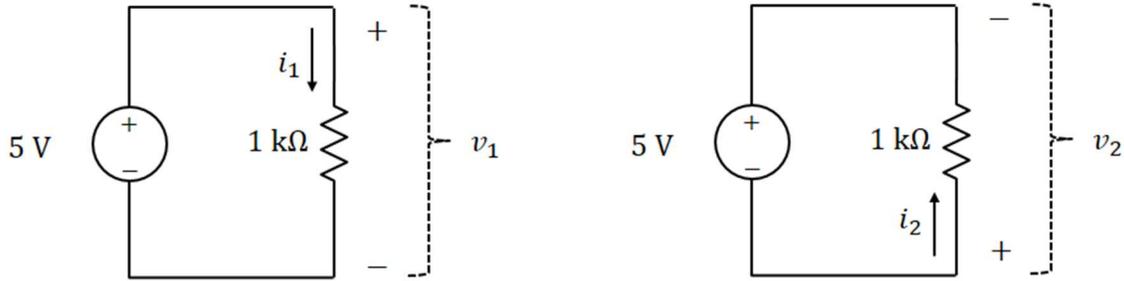


Figure 2: Two different definitions for v for the same resistor

Exercise: Find v_1 , i_1 , and p (the power dissipated in the resistor) for the circuit on the left-hand side of Figure 2. Make sure to identify the sign of each variable.

Find v_2 , i_2 , and p (the power dissipated in the resistor) for the circuit on the right-hand side of Figure 2. Make sure to identify the sign of each variable.

Hopefully, you will find that the current flows *down* through the resistor in both cases and that the power is positive in both cases.

In direct-current (DC) circuits, for which voltages and currents are constant, the meaning of Ohm's Law and the equation for power is clear. In alternating-current (AC) circuits, on the other hand, the interpretation of the above equations is more subtle. We will use the mathematical concept of a root-mean-square (rms) to help with the interpretation of Ohm's Law and power dissipation for AC circuits.

Root-Mean-Square

Here is a simple example of an AC signal, the sinewave:

$$x(t) = A \sin(2\pi ft)$$

This signal could be a voltage or a current. This sinewave is plotted on the left-hand side of Figure 3. The amplitude of this sinewave is A . The period, having units of seconds, is $T = 1/f$, where f is the frequency in hertz. Also plotted in Figure 3 are a square-wave and a triangle-wave. Each of these signals is periodic with period T . For all of these signals, frequency and period are related by $f = 1/T$.

A periodic signal has a zero mean (that is, no DC component) when

$$\frac{1}{T} \int_0^T x(t) dt = 0$$

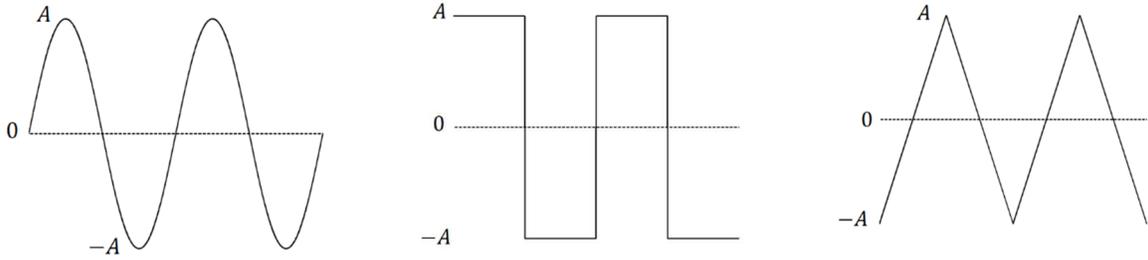


Figure 3: Sinewave, square-wave, triangle-wave (left to right)

The three signals illustrated in Figure 3 all have zero mean. The amplitude for a zero-mean signal is

$$A = \text{peak} = \max(x)$$

If the signal $x(t)$ is a voltage, we define the peak-to-peak voltage as $\max(x) - \min(x)$; but for the waveforms of interest to us here, $\min(x) = -\max(x) = -A$, so

$$\text{peak to peak voltage} = 2A$$

The root-mean-square (rms) of a periodic signal $x(t)$ is defined as

$$X_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T x^2(t) dt}$$

Notice that this is the square-root of the *mean* of the *square* of the signal, as shown in Figure 4.

| | | |
|-------------------------------|-----------------------------------|---------------------------------|
| square-root of | the <i>mean</i> of | the <i>square</i> of the signal |
| $\sqrt{\left(\cdot \right)}$ | $\frac{1}{T} \int_0^T (\cdot) dt$ | $x^2(t)$ |

Figure 4: Meaning of root-mean-square (rms)

The rms X_{rms} of a periodic signal is a measure of the *level* of the signal. The relationship between X_{rms} and the amplitude A depends on the shape of the signal. Table 1 provides several examples of this relationship.

Table 1: Relationship between X_{rms} and A

| Waveform | X_{rms} (Exact) | X_{rms} (Approximate) |
|-----------------|--|--|
| Sinewave | $A/\sqrt{2}$ | $0.707A$ |
| Square-wave | A | A |
| Triangle-wave | $A/\sqrt{3}$ | $0.577A$ |

In the laboratory we can measure both the rms voltage V_{rms} across a resistor and the rms current I_{rms} through a resistor. We say that V_{rms} has the units volts rms and that I_{rms} has the units amps rms.

Ohm's Law can be rewritten as:

$$I_{\text{rms}} = \frac{V_{\text{rms}}}{R}$$

This form of Ohm's Law is quite general. It holds no matter the waveform. For example, this form of Ohm's Law holds if the voltage is a constant (DC), a sinewave, a square-wave, or a triangle-wave. The current through a resistor always has the same type of waveform as the voltage across it.

In the case of DC, $V_{\text{rms}} = v$ (a positive constant), $I_{\text{rms}} = i$ (a positive constant), and $i = v/R$.

If the voltage is a sinewave, then the current is also a sinewave. The rms current is related to the rms voltage by $I_{\text{rms}} = V_{\text{rms}}/R$. The amplitude of the sinusoidal voltage is $\sqrt{2} V_{\text{rms}}$, and the amplitude of the sinusoidal current is $\sqrt{2} I_{\text{rms}}$.

The average power P (watts) delivered to a resistor is

$$P = \frac{V_{\text{rms}}^2}{R}$$

This equation is true for all waveforms.

Exercise: For each of the following voltage waveforms, calculate V_{rms} :

| <u>Waveform</u> | <u>Amplitude</u> |
|-----------------|------------------|
| Sinewave | 5.0 V |
| Square-wave | 5.0 V |
| Triangle-wave | 5.0 V |

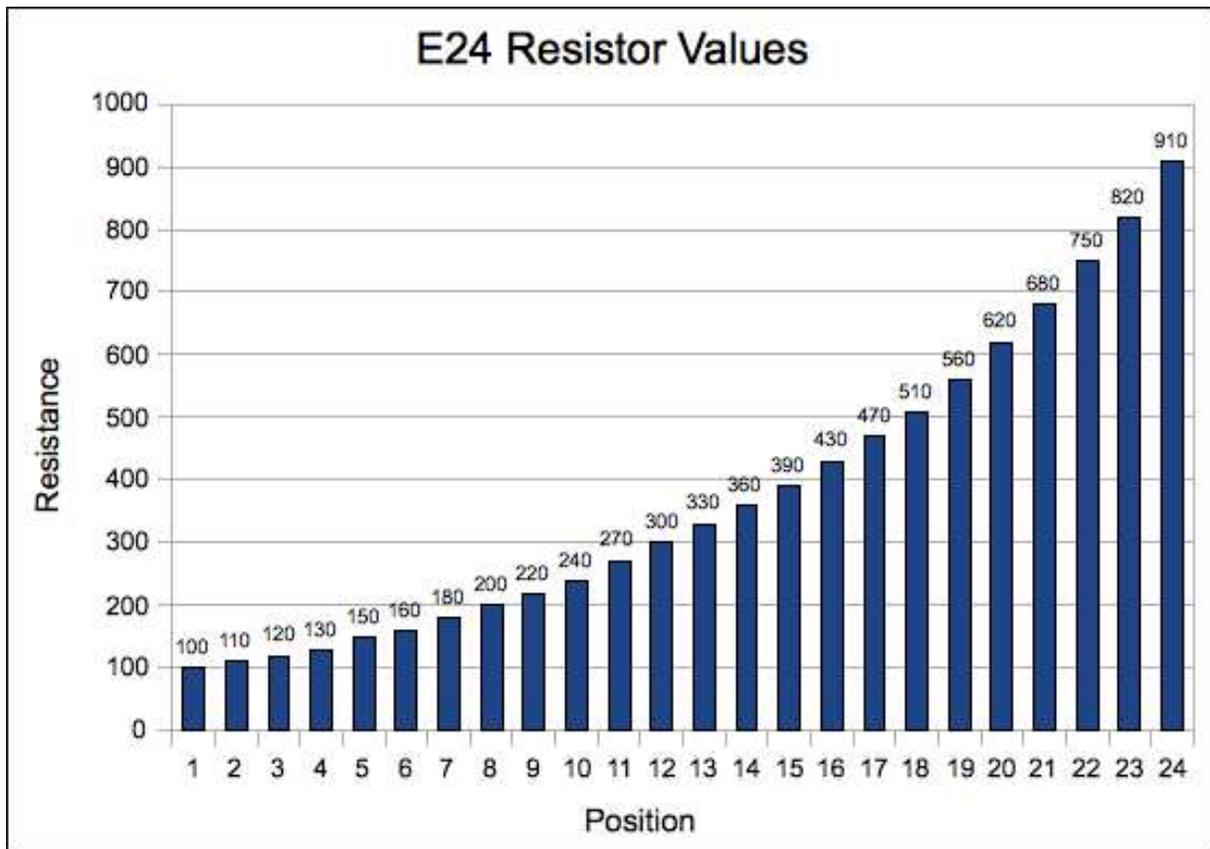


Figure 5: Standard E24 resistor values. In every decade, there are 24 resistance values, spaced (approximately) logarithmically. For example, for the decade 100 Ω to 1000 Ω, the resistor values are as shown in the above chart. As a second example, for the decade 1 k Ω to 10 k Ω, the resistor values are 10 times those shown above.

Fixed, Color-Coded Resistors

The fixed, color-coded resistors that are available to us in this laboratory have the standard E24 design values. With this standard, there are 24 design values in every decade. Figure 5 shows the design values for the decade 100 Ω to 1000 Ω. These resistors have tolerances of $\pm 5\%$. For example, when the design value is 100 Ω, the actual value should lie somewhere between 95 Ω and 105 Ω. All of our fixed resistors are able to dissipate up to $\frac{1}{4}$ watt of electrical power. (Beyond $\frac{1}{4}$ watt, damage may occur to the resistor.)

Every fixed resistor is painted with a color code to indicate its design value. Figure 6 illustrates the color code. This is the 4-band color code used for the E24 design values. The first three color bands indicate the design value. The fourth band for E24 resistors is gold, and this indicates that the tolerance is $\pm 5\%$. It is an important skill for those who work in an electronics

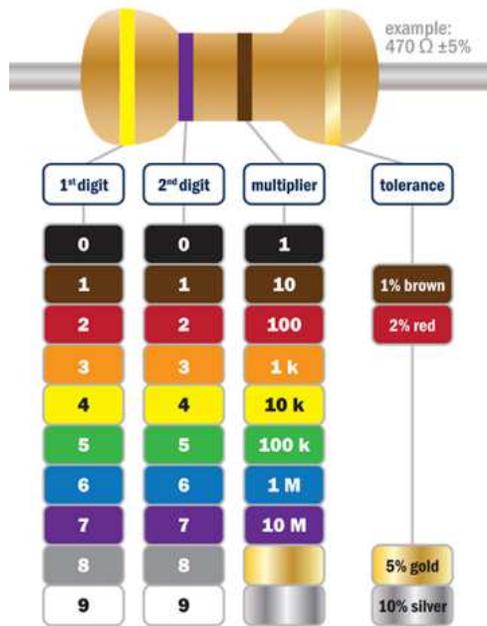


Figure 6: Resistor (4-band) color code

laboratory to be able to read resistor color codes. You should practice this skill. (There are smart-phone apps that do resistor color codes, but you should be able to read the value of an E24 resistor without the aid of a smart-phone app.) Figure 7 shows how we can remember the order of the colors with the help of the rainbow.

Exercise: Consider the following resistor values: 2.4 kΩ, 6.8 kΩ, 24 kΩ, and 68 kΩ. In every case, the tolerance is ±5%. For each of these resistors, identify the 4 color bands and calculate the maximum and minimum values (based on the tolerance).



Figure 7: The rainbow helps us remember the color code.

Procedure

In this experiment you will use a solderless breadboard. See Figure 8. You will also use fixed, color-coded resistors.

You will be making measurements with the multimeter. Recall that two actions are required to configure the multimeter as a voltmeter, or as an ohmmeter, or as an ammeter. Both of these actions should be taken *before* you connect the multimeter to the circuit.

1. The correct red terminal must be used. For voltmeter and ohmmeter, use the top red terminal. For ammeter, use the left red terminal.
2. The correct button must be pressed.

Caution. If you configure the multimeter as an ammeter and then connect it in parallel with a voltage source, you may blow the multimeter's fuse. An ammeter offers little resistance to current flow, so any significant voltage applied between the red and COM terminals of an ammeter will cause a large current to flow through the meter.

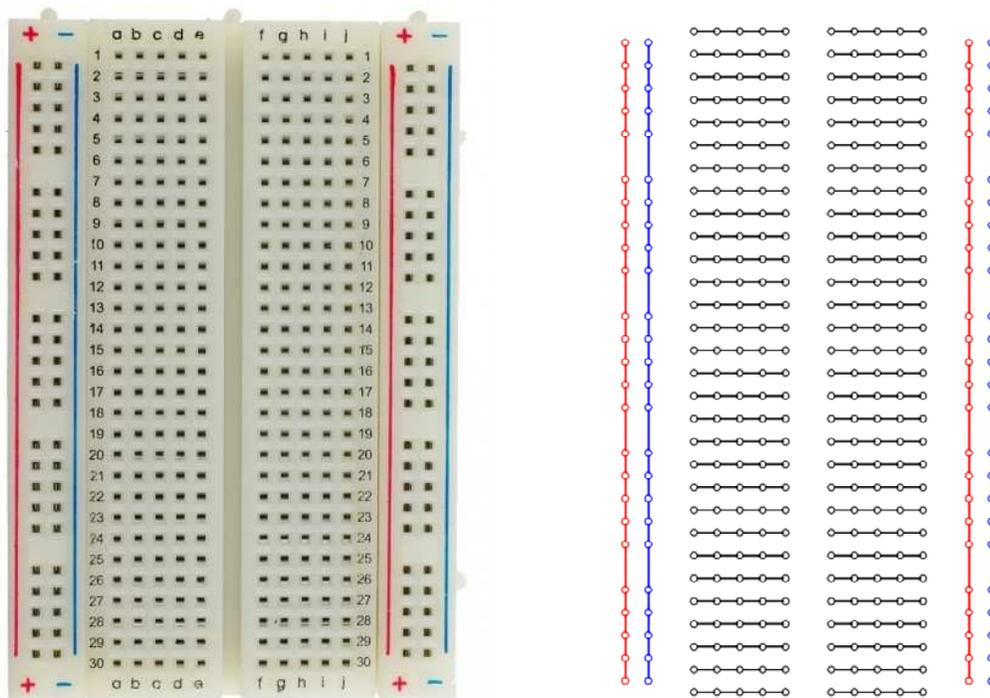


Figure 8: Solderless breadboard. The diagram on the right illustrates how holes in the solderless breadboard are connected internally (underneath the plastic surface). For example, the left-most column of holes are connected; this is called a *bus*. The vertical red line on the left side of the solderless breadboard marks this bus. There are four vertical buses on the solderless breadboard shown here, two marked with red lines and two marked with blue lines. Between the vertical buses, holes are connected horizontally in groups of five.

DC Circuit

You will measure some resistors using an ohmmeter, and you will make a set of measurements using a voltmeter and an ammeter. Construct the DC circuit of Figure 2, using CH1 of the Siglent power supply. Set the current limit to 0.2 A. You will use 4 different values for R .

In your lab notebook, you will complete a table that looks like this:

| R Design | R Measured | v_1 (V) | i_1 (A) | p (W) | v_1/i_1 (Ω) |
|----------------|-----------------|-----------|-----------|---------|------------------------|
| 2.4 k Ω | | | | | |
| 6.8 k Ω | | | | | |
| 24 k Ω | | | | | |
| 68 k Ω | | | | | |

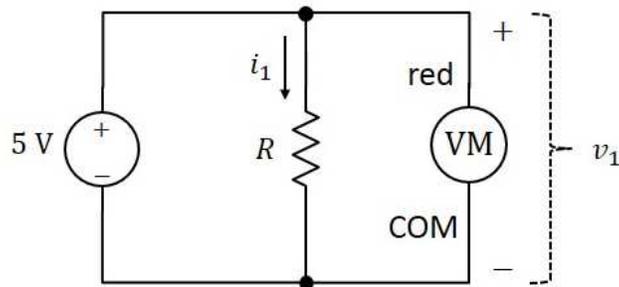


Figure 9: Measure v_1 with a voltmeter (VM). The voltmeter red terminal should be at the same circuit node as the CH1 + terminal.

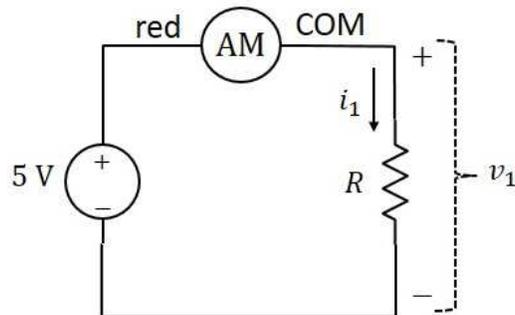


Figure 10: Measure i_1 with an ammeter (AM). The ammeter red terminal should be at the same circuit node as the CH1 + terminal. With this connection, a positive ammeter reading means that the current flows from the CH1 + terminal, through the ammeter and resistor, and then to the CH1 – terminal.

The first column contains the design value of each resistor. (The design value is the value indicated by the color code.) The second column will contain the resistance as measured with an ohmmeter. The third and fourth columns will contain measurements of v_1 and i_1 . Figures 9 and 10 show how to connect the multimeter to the circuit for these measurements. Each number in the fifth column will be the power dissipated in the resistor, as calculated from v_1 and i_1 . Each number in the final column will be calculated from measurements.

Be sure to show the units for each measured value and calculated value in this table. Be sure to include the correct sign (+ or –) with each measured voltage and current. This table has the data needed for a test of Ohm’s Law. The number in the final column should be close to R .

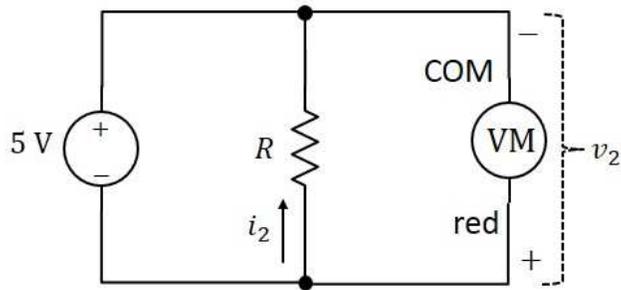


Figure 11: Measure v_2 with a voltmeter. The voltmeter COM terminal should be at the same circuit node as the CH1 + terminal.

In your lab notebook, you will complete a table that looks like this:

| R Design | R Measured | v_2 (V) | i_2 (A) | p (W) | v_2/i_2 (Ω) |
|----------------------------------|------------------------------------|-----------------------------|-----------------------------|---------------------------|---|
| 2.4 k Ω | | | | | |
| 6.8 k Ω | | | | | |
| 24 k Ω | | | | | |
| 68 k Ω | | | | | |

The first column contains the design value of each resistor. The second column will contain the resistance as measured with an ohmmeter. The third and fourth columns will contain measurements of v_2 and i_2 . Figures 11 and 12 show how to connect the multimeter to the circuit for these measurements. Each number in the fifth column will be the power dissipated in the resistor, as calculated from v_2 and i_2 . Each number in the final column will be calculated from measurements.

Be sure to show the units for each measured value and calculated value in this table. Be sure to include the correct sign (+ or -) with each measured voltage and current. The number in the final column should be close to R . If p and the ratio v_2/i_2 are not positive, then you have made a mistake.

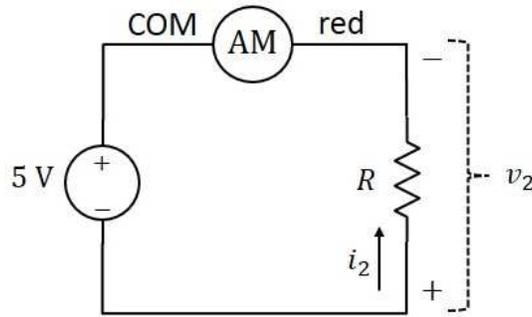


Figure 12: Measure i_2 with an ammeter. The ammeter COM terminal should be at the same circuit node as the CH1 + terminal. With this connection, a positive ammeter reading means that the current flows from the CH1 – terminal, through the resistor and ammeter, and into the CH1 + terminal.

AC Circuit

You will measure rms voltage and rms current in an AC circuit. The AC measurement modes of the multimeter are summarized in Table 2.

Table 2: AC measurement modes for the multimeter

| Mode | Measurement | Red Terminal | Button |
|--------------|-------------|--------------|-------------------|
| AC voltmeter | V rms | top | AC V |
| AC ammeter | A rms | left | AC I (shift AC V) |

An rms voltage is always positive because the definition of the root-mean-square involves a squaring of the voltage. Similarly, an rms current is always positive.

You will now make measurements of voltage and current with an AC circuit. Build the circuit of Figure 13. Initially, the resistor will be 2.4 k Ω . The voltmeter should be connected in parallel with the resistor and with the voltmeter's COM terminal connected to the circuit's ground.

It might seem that the polarity of the AC voltmeter doesn't matter, since rms voltage is always positive. And, in principle, this is true. But there is a practical fact that must be taken into account here. This multimeter, when used for AC measurements, offers the best accuracy when its COM terminal is connected to ground. One terminal of the synthesized frequency generator is internally connected to ground; this is the terminal associated with the outer conductor of the coaxial cable. So the COM terminal of the multimeter, when used for AC measurements, should be connected to the same node as the outer-conductor terminal of the synthesized frequency

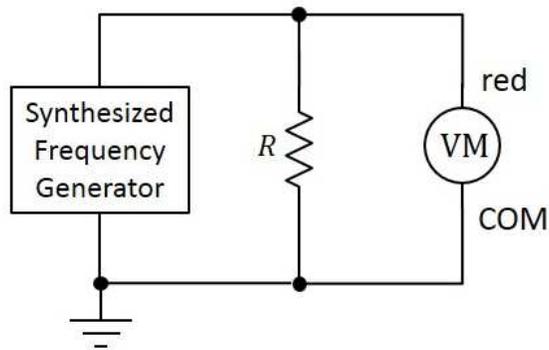


Figure 13: Measure rms voltage across R .

generator. (When making DC measurements, the COM terminal of the multimeter need *not* be connected to ground.)

Set the synthesized frequency generator for a 1.0-kHz sinewave with an amplitude of 5 V. On the oscilloscope, view the voltage across the resistor. The oscilloscope's center-conductor terminal should be placed on the same node as the synthesized frequency generator's center-conductor terminal. (The oscilloscope's outer-conductor terminal is internally connected to ground.)

Each of the oscilloscopes in our laboratory remembers the oscilloscope settings that were in force when that oscilloscope was last turned off. This last turn off was probably done by someone other than you. This means that when you turn on the oscilloscope, there might be some measurements in force that you did not request. For example, the frequency of the channel-1 signal might be displayed. It is recommended that you get in the habit of using the following procedure immediately after turning on the oscilloscope.

1. Push Default Settings button.
2. On Ch-1 menu, select 1X for probe.
3. On Ch-2 menu, select 1X for probe.

In selecting Default Settings, you will get rid of measurements that you inherited from the previous user. Unfortunately for us, the default settings include a probe setting of 10X for each of channels 1 and 2. Since we will always want to use 1X for the probe settings, steps 2 and 3 above are needed after selecting Default Settings.

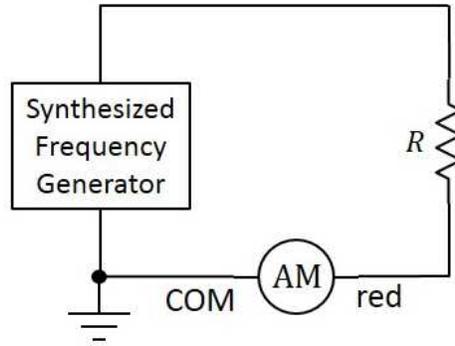


Figure 14: Measure rms current through R .

Measure the peak-to-peak voltage with the oscilloscope. You should also save the oscilloscope signal display to a file, which can later be incorporated into your lab report. Appendix A explains how to do this.

After you have measured the rms voltage across the resistor, place the ammeter in series with R , as shown in Figure 14. The ammeter should be connected with the ammeter's COM terminal connected to the circuit's ground. (Otherwise, measurement accuracy will suffer.)

In your lab notebook, you will complete a table that looks like this:

| R Design | R Measured | V_{rms} | Peak-to-Peak Voltage | I_{rms} | P | $V_{\text{rms}}/I_{\text{rms}}$ |
|----------------|-----------------|------------------|-------------------------|------------------|-----|---------------------------------|
| 2.4 k Ω | | | | | | |
| 6.8 k Ω | | | | | | |
| 24 k Ω | | | | | | |
| 68 k Ω | | | | | | |

Each number in the last two columns will be calculated from the measurements V_{rms} and I_{rms} . This table has the data needed for a test of the rms form of Ohm's Law. The number in the final column should be close to R .

Set the synthesized frequency generator for a 1.0-kHz *square-wave* with an amplitude of 5 V. On the oscilloscope, view the voltage across the resistor and have the oscilloscope measure the peak-to-peak voltage. Using the multimeter, repeat the measurements of V_{rms} and I_{rms} . Make a table, as you did in the case of the sine wave, including calculations of P and $V_{\text{rms}}/I_{\text{rms}}$ for the 4 different resistances.

Set the synthesized frequency generator for a 1.0-kHz *triangle-wave* with an amplitude of 5 V. On the oscilloscope, view the voltage across the resistor and have the oscilloscope measure the peak-to-peak voltage. Using the multimeter, repeat the measurements of V_{rms} and I_{rms} . Make a

table, as you did in the case of the sinewave, including calculations of P and $V_{\text{rms}}/I_{\text{rms}}$ for the 4 different resistances.

Lab Report

For the DC circuit, did you find that the current always flows from the + terminal of the DC source, through the resistor, and back into the – terminal of the DC source, regardless of how you connected the ammeter?

For the DC circuit, do the ratios v_1/i_1 and v_2/i_2 equal, at least approximately, R for the 4 resistors that you measured?

For the AC circuit, does $V_{\text{rms}}/I_{\text{rms}}$ equal, at least approximately, R for the 4 resistors that you measured?

You measured V_{rms} on the voltmeter and the peak-to-peak voltage on the oscilloscope. Do they have the correct relationship? (Recall that this relationship is different for different wave shapes.)

Appendix A: Saving Oscilloscope Signal Display to File on Flash Drive

You can save the current oscilloscope signal display as a graphics file on a flash drive that has been plugged into the oscilloscope. First, you must configure the oscilloscope for saving graphics files to a flash drive. You do that with the following procedure.

1. Plug flash drive into oscilloscope.
2. Wait for oscilloscope to read the formatting of the flash drive.
3. If you want the graphics files to be saved in the root folder of the flash drive, you can skip this step. If you want to select a destination folder within the flash drive, do this:
 - a. Press Save/Recall button.
 - b. Press soft button for Select Folder.
 - c. Wait for the oscilloscope to read the file structure of the flash drive.
 - d. Rotate the Multipurpose knob clockwise until the desired folder is underlined.
 - e. Press Multipurpose button, causing the contents of the selected folder to appear.
 - f. Press the soft button for Back.
4. Press Utility button.
5. Go to page 2 of Utility menu by pressing soft button for “more” once.
6. Press soft button for Options.
7. Press soft button for Print Setup.
8. Select the following options from the Print Setup menu:
 - a. Print Button *Save Image as File*
 - b. Ink Saver *On*
 - c. Layout *Portrait*
 - d. File Format *jpg*

Once you have configured the oscilloscope using the above procedure, you can save the current signal display as a graphics file by simply pressing the Print button (a round button above the column of soft buttons). You can save as many “screen shots” as you like (constrained, of course, by the amount of available memory on your flash drive), just by pressing the Print button each time.

It is recommended that you dismiss all submenus and menus before you save the signal display, so that the signal display is not partially obscured by menus. The graphics files that you save from the oscilloscope will have automatically generated filenames. The first filename will be:

TEK0000 . jpg

The number field of the filename increments by **1** for each new file.