

Mobile Studio Desktop™

Workshop for Teachers of Physics, Engineering, and Technology

Welcome!

It's time to take a one-day look at a new tool for your classroom! Mobile Studio provides a simple way to bring into your classroom some of the standard electrical instruments that would be found in an instrumented teaching laboratory—at a fraction of the cost.

Today you'll have an opportunity to try some experiments with electrical circuits using Mobile Studio Desktop and an interface board. The Red2 IOBoard™ connects your electric circuit to your computer through the USB port and lets you use your laptop as if it were a collection of expensive instruments.

This manual contains over two dozen activities that all include making electrical measurements on real circuits. You build the circuits on a standard breadboard and then use Mobile Studio as your set of instruments to collect data. These activities range from measuring resistance values to varying the power factor of an a-c power system.

Curriculum

It's tempting to say, "Just start with Lab A1 and work your way through all the labs. But hurry! You only have a few hours." Not a good idea. Instead, why not try a few labs in areas that you find interesting? Or do some that you think might be carried back to your students?

Getting started

Start by getting familiar with Mobile Studio Desktop with *Introduction*. You can skip the part about installing the software; that's been done for you. Go on to the section, *Now Let's Play!* to walk through a simple exercise using the software.

At some point you will want to calibrate your Red2 board

to improve the accuracy of the instrument readings. But you can skip *Red2 Board Calibration* today and save that for later if you wish. If you skip this, your results today won't always check out as perfectly as they will with a carefully calibrated board.

OK, now that you have gotten started, what next?

D-c measurements

If you want a dull, low-impact start, do Labs A1, A2, A3, and B2. You will use just your digital multimeter and never do anything with Mobile Studio Desktop. These labs might be good for students who are just getting introduced to resistors, voltage, and current.

- A1 Series and parallel and the resistor color code
- A2 Voltage and current, Ohm's Law, voltage divider
- A3 Kirchhoff's Laws
- B2 Superposition, which is an interesting measurements exercise

Diodes

Diodes are non-linear electrical devices and Labs A4, A5, and K1 go through a series of measurements of the characteristics of a green LED. Why green? Because it isn't red. These labs provide some experience in making voltage and current measurements.

- A4 Diode i-v curve by traditional techniques
- A5 Diode i-v curve using Mobile Studio Desktop top as the measuring instruments
- K1 Diode i-v curve traced directly by Mobile Studio Desktop on the oscilloscope

Time domain

Linear circuits in the time domain respond with exponentials, the outcomes of linear differential equations. Labs E1, E2, and E3 are an opportunity to do some measuring of these exponentials.

- E1 Measuring a time constant using the scope
- E2 Determining the inductance of an inductor from a circuit's exponential response
- E3 Deducing the parameters of a second-order circuit by measuring the characteristics of its second-order damped response (this sounds scary, but it's a good, practical use of the scope!)

Phasors

Phasors are the way electrical engineers represent what is happening in alternating-current circuits, especially in power systems. Phasors are a way of representing sine waves by keeping track of their magnitudes and phase angles. Labs F1, F2, and F3 are about phasors and concentrate especially on using the scope to measure phase difference.

- F1 Voltage and phase-angle measurement
- F2 Inductance of an inductor from magnitude and phase-angle measurements
- F3 Resonant circuit

Op-amps

That's short for *operational amplifier*. Labs G1 and G2 go through measurements of the characteristics of a simple one-stage op-amp circuit. We have the op-amp circuits already made up for you to borrow during the day.

- G1 Op-amp d-c gain and saturation
- G2 Op-amp a-c gain and saturation
- H1 Frequency plot of a low-pass active filter

Spectrum analyzer

Mobile Studio Desktop includes a spectrum analyzer that plots the responses of a circuit as a function of the frequency applied. Two labs, H2 and H3, will walk you through the use of the spectrum analyzer.

- H2 Spectrum analysis of a signal with two distinct frequencies
- H3 Effects of a low-pass active filter on a signal with two frequencies

Try things and have fun!

Can I Get in Trouble?

Yup! You (and your students) can get in trouble with these circuits and instruments, but it's very hard to get hurt. The highest voltage you'll deal with is 6 volts d-c. But there are a couple of ways you can get into trouble nevertheless.

- Be careful of battery power supplies. If you short-circuit their terminals, you can draw currents high enough to burn up leads and components.
- Treat the terminals of the Red2 board with care. It is possible to make connections that might damage your laptop by destroying the USB port.

Now It's Your Turn!

Go do something! Try a lab or two and see how things go. If you need help, ask—there's plenty of help available.

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Mobile Studio Desktop

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Mobile Studio Desktop™

Introduction: What This is All About

Purpose

Mobile Studio Desktop™ (MSD) provides the equivalent of a number of bench-top electrical instruments in the form of software on a personal computer. The purpose of this Introduction is to tell you a little about MSD, what kinds of things you can be doing, and what you'll need for doing them.

A Brief History

Mobile Studio Desktop grew out of an idea of Professor Don Millard, an idea that good electrical laboratory pedagogy could be accomplished by using computer representations of typical laboratory instruments plus computer interface boards to connect to actual electrical devices and circuits.

Professor Millard and his graduate students began to develop this idea at Rensselaer Polytechnic Institute. As the project expanded, he obtained financial support from the National Science Foundation and involved four other schools: Howard, Morgan State, Rose-Hulman, and SUNY Albany.

The concept is simple: Use a computer as the instrument, provide an interface board to connect electrical devices to the computer thru the USB port, and manipulate the virtual instruments just as one would when using real instruments on a lab bench—but at a much lower cost. Figure 1 shows a complete set-up with a small circuit attached to it.

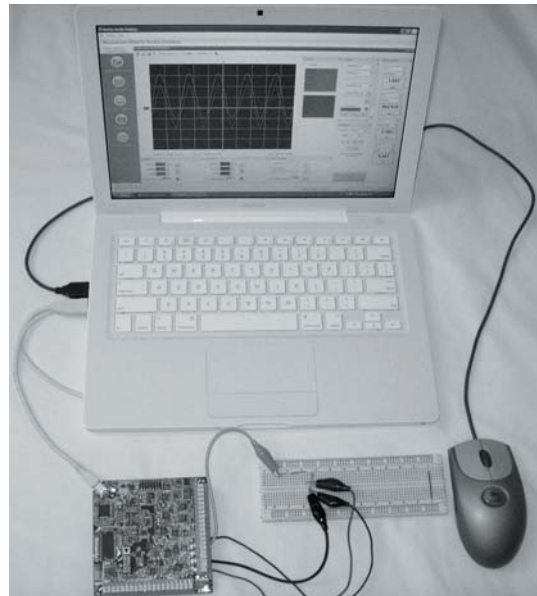


Fig. 1—Complete MSD setup

- C. D-c power
- D. A-c power
- E. Time-domain circuits
- F. Frequency-domain circuits
- G. Op-amps
- H. Filters
 - I. Signals and spectra
 - J. Instrumentation
 - K. Other MSD applications

Laboratory Topics

Available laboratory exercises will be divided into a number of basic categories:

- A. Resistor and resistive circuits
- B. Circuit theorems

Equipment

You'll need a number of items to be able to execute the laboratory exercises in this series:

- An Intel-based computer, either desktop or laptop with a USB 2.0 port, running Windows



Fig. 2—Half clip leads

2000, XP (except x64), or Vista. This includes newer Macs running Windows either under OS X and Parallels or as stand-alone via Boot Camp.¹

- The current version of Mobile Studio Desktop. See the next section for how to get this.
- The current Mobile Studio IOBoard™ and the appropriate USB cable.
- Several “half” clip leads. The non-clip ends should be soldered to make a solid end for inserting in the I/O board terminals (Fig. 2).
- For some exercises, a simple 3-V battery supply (Fig. 3).



Fig. 3—3-V supply

- For op-amp exercises, a dual 6-V battery supply (Fig. 4).



Fig. 4—Dual 6-V supply



Fig. 5—Digital multimeter

- A standard breadboard for building circuits.
- A collection of resistors, capacitors, and inductors.
- A simple digital multimeter (DMM) for many different measurements. An inexpensive three-digit meter with several d-c voltage ranges and several resistance ranges is a minimum. The Tenma model pictured (Fig. 5) is a “3¾ digit” DMM for under \$20.

Each exercise will state at the beginning the parts and equipment needed to carry out the work.

A word of warning! The I/O boards are powered by your computer’s USB port. The circuits you build will be connected to the board and will derive power from it. **DON’T SHORT-CIRCUIT ANY POWER CONNECTIONS FROM THE I/O BOARD!** It is possible to destroy the board and, under the right (wrong?) conditions, your USB port.

Getting Mobile Studio Desktop

Before downloading Mobile Studio Desktop, **YOU MUST DISCONNECT ANY I/O BOARD FROM YOUR USB PORT.** Don’t connect the board until you have MSD running on your computer.

Go to <http://www.mobilestudioproject.com> and click on the “Software Download” button to download and install the software.

¹ I have not been successful on the Mac with Fusion or VirtualBox. Parallels is slow.

After downloading, go through the license and installer screens. If you get a security warning, allow installation to continue. If you are asked to allow installation of .NET or National Instrument software, allow them because they are needed for MSD to run.

Once installation is finished, connect your I/O board. If you get a notice of a need for drivers, follow the Add New Hardware instructions, accepting all defaults. You also may get a request to update the board's firmware before the board will work properly. Go to the Device menu and follow instructions.

Now Let's Play!

You've installed your software and connected your I/O board, so now you probably would like to try it out. Let's play with a couple of instruments without connecting anything to the I/O Board.

I'm going to walk you through some simple exercises to try out the instruments. I'll use a few screen shots, but don't be surprised if your screen differs a bit from mine. The MSD software is continually being updated and screens change from time to time.

I'll assume that you have MSD running, an I/O board connected, and a display of icons for six instruments on the left. We'll start with the Function Generator.

Function Generator

1. Click on the FUNCTION GENERATOR icon.
2. Leave the frequencies unchanged, but change Ch 2 to a TRIANGLE output.
3. Change Ch 1 to a d-c offset of 0.5 volt. Figure 6 shows the result.
4. Locate the small pushpin in the upper right corner and click on it to get the Function Generator window out of the way.
5. Mouse over the Function Generator tab at the bottom of the working area and note that the settings pop up. Moving the mouse out of the Function Generator sinks them from sight.

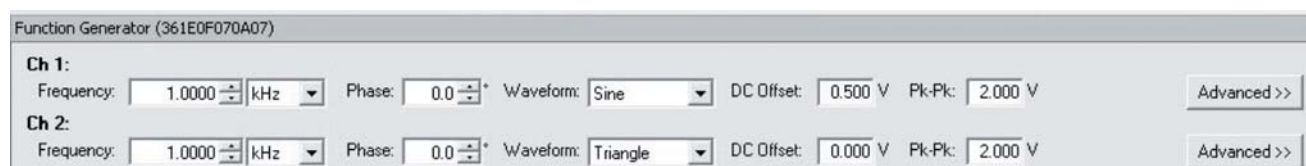


Fig. 6—Function generator screen

Oscilloscope

1. Click on the OSCILLOSCOPE icon.
2. Set up Channel 1 to 500 mV, DC coupling, and AWG1 input. (Input is from the Function Generator or the Arbitrary Waveform Generator if it has been set up instead.) See Fig. 7.
3. Enable the channel by clicking the switch to the left.
4. Set up and enable Channel 2 the same way, except that the input is to be AWG2.
5. Click on the red Start button near the bottom right of the screen

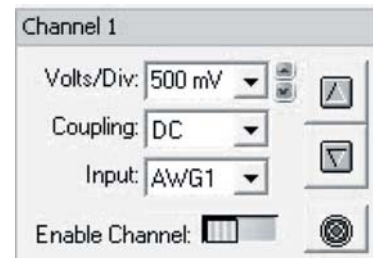


Fig. 7—Scope channel screen

Your MSD screen should look like Fig. 8 on the next page.

Updates

Near the lower right corner of the screen is “No Updates Available.” This isn't quite true—there may be updates available. However, once you start students on one version, you don't want them to change versions unless the whole class changes together. Otherwise, you will be trying to help different students with different versions.

The End

Now you have Mobile Studio Desktop set up to begin the various laboratory exercises.

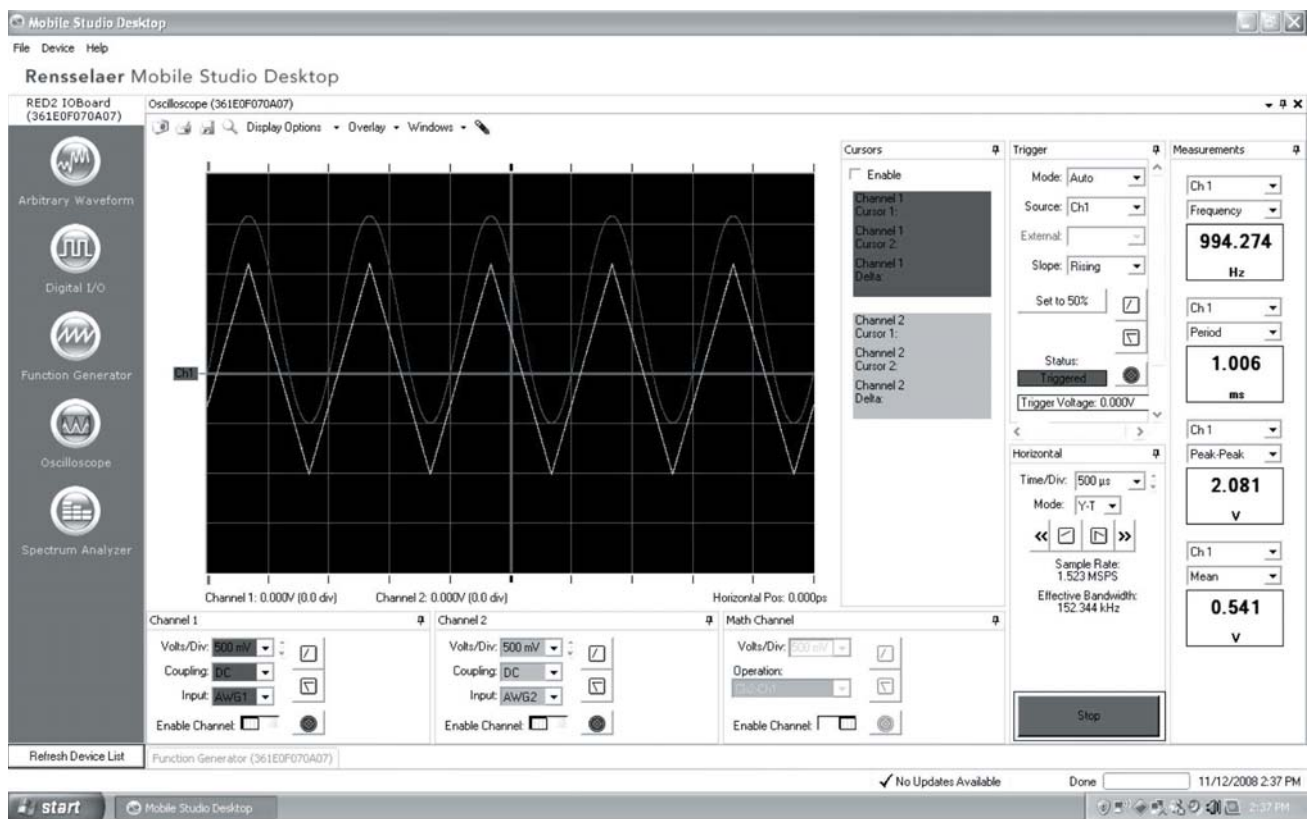


Fig. 8—Overall MSD screen

Mobile Studio Desktop™

Red2 Board Calibration

The Mobile Studio Desktop system consists of a set of electrical instruments for making circuit measurements and a computer interface to manipulate those instruments. All of these instruments and their connections are on the interface board. The computer merely controls the instruments.

These instruments and their interfaces need calibration, all of which can be done through the computer. You will need a digital multimeter that can resolve to ± 1 mV (i.e., can be read to 0.000). You'll also need a number of clipleads to make interconnections.

The IO Board has a semiautomatic calibration procedure built in, but you need to do some manual settings first.

Initial Calibration

This initial calibration sets the Gain and the Offset of AWG Channel 1:

- A. Launch the Function Generator panel.
- B. Set Ch1: Frequency: 1 kHz; Phase: 0°; Waveform: Square; DC Offset: 0.000 V; and Pk-Pk: 3.000 V.
- C. Set Ch2 the same way.
- D. Connect a DMM with at least ± 1 mV resolution to the AWG1 and Ground terminals of the board.
- E. Select DEVICE -> ANALOG CALIBRATION
- F. In "calibration settings," select "channel 1," although it probably already is.
- G. On the "AWG output" line, adjust "Offset (SE)" to get the DMM to read 0.000—if you can. If you can't, get as close as you can.
- H. Change the Function Generator Ch1 settings to Frequency: 1 kHz; Phase: 0°; Waveform: Square; DC Offset: 3.000 V; and Pk-Pk: 0.000 V.

- I. On the "AWG output" line, adjust "Gain" to get the DMM to read 3.000—get as close as you can.
- J. Change the Function Generator Ch1 **offset** setting to -3.000 V.
- K. Note the exact reading of the DMM. Calculate the mean value between this number and -3.000. For example, if the reading is -3.227, the mean value is -3.114 V.
- L. On the "AWG output" line, adjust "Offset (SE)" to get the DMM to read the value just calculated.
- M. On the "AWG output" line, adjust "Gain" to get the DMM to read -3.000 V.
- N. Change the Function Generator Ch1 **offset** setting to +3.000 V.
- O. Check the DMM, which should read 3.000 V. If it doesn't, split the difference and return to Step L above.

Automatic Calibration

When you are done with this manual calibration, let the automatic procedure finish the job. Follow all the steps from 2 through 8.

The End

Your interface board should now be calibrated. One way to check is to reset both channels of the Function Generator to a 3-V (peak-to-peak) square wave. Then display both of these on the Oscilloscope with both channels set for 500-mV per division. The tops of the square waves should be superimposed right on the third grid line from the middle, both up and down.

Your board should retain its calibration from now on.

Mobile Studio Desktop™

Lab A1: At Ω with Resistors

Purpose

This is a good time to learn a little about one very simple electrical device—the resistor. While we don't necessarily need to know the physics of resistors, we can learn what they are and how they combine in circuits.

Objectives

The objectives of this lab are

- Recognize a resistor and read its color code
- Recognize a resistor in a schematic circuit drawing
- Measure a resistor's resistance
- Determine how resistors combine in series
- Determine how resistors combine in parallel

Introduction

A resistor resists electrical current, which is kind of stating the obvious! In doing this “resisting,” the resistor causes the current to lose energy, thereby heating the resistor.

The important characteristic of a resistor is its resistance. This is measured in ohms, a unit named after Georg Simon Ohm, a 17th-century German physicist. Resistance can range from thousandths of ohms to millions of ohms. The symbol for “ohm” is the Greek capital omega: Ω .

We'll see in later labs how current and resistance interact. For this lab we are going to consider just the resistor and its resistance, and how resistors combine.

Equipment

All of your measurements are going to be done using the ohmmeter portion of your digital multimeter (DMM). You'll need three resistors, too. The ones I'll be using are all called “1/4 watt” and have resistances of...but wait! How do we know how to determine their values?

Let's go on to the lab exercises and learn how to recognize resistances by learning to read their color codes. Then we can select the right resistors and carry out our measurements.

Procedure

Resistance measurement

1. Select three resistors with color-codes:
orange-black-brown-gold
brown-black-red-gold
red-black-red-gold
2. Set up your DMM to measure resistance. The DMM should be “auto-ranging,” meaning that it chooses the proper range for the measurement.”
3. Measure the resistance of each of the three resistors using your DMM. Figure 1 shows how to do this. Record in a journal the color codes of the three resistors and their measured resistance values. Figure 2 (next page) is a sample of what your record should look like.

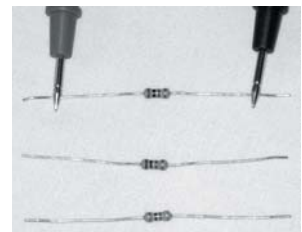


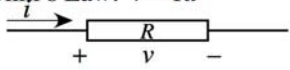
Fig. 1—Ohmmeter probes

4. Now use the table of Figure 3 to determine the nominal value of each of the resistors and record those values in your table as well. I've expanded the table in my journal (Fig. 4) to show the outcome for one of the three.

Color code	Meas. Ω
Or-bk-br-gold	294
Br-bk-red-gold	
Red-bk-red-gold	

Fig. 2-Journal table

Ohm's Law: $v = Ri$



Resistor color code:

Color	1 st , 2 nd . Digit	3 rd . Multiplier
Black	0	$10^0=1$
Brown	1	$10^1=10$
Red	2	$10^2=100$
Orange	3	$10^3=1k$
Yellow	4	$10^4=10k$
Green	5	$10^5=100k$
Blue	6	$10^6=1M$
Violet	7	$10^7=10M$
Grey	8	$10^8=100M$
White	9	$10^9=1G$
Silver	-	$10^{-1}=100m$
Gold	-	$10^{-2}=10m$

4th: Tolerance None = $\pm 20\%$
Silver = $\pm 10\%$
Gold = $\pm 5\%$

Example: a resistor labeled red-violet-orange-gold is "2" "7" " 10^3 " $\pm 5\%$ which is $27\text{ k}\Omega \pm 5\%$

Fig. 3-Resistor color code

5. For each of the three resistors, calculate the percent error by which the measured value differs from the nominal value. Use the error formula

$$\%error = \frac{R_{measured} - R_{nominal}}{R_{nominal}} 100$$

Color code	Meas. Ω	Nom. Ω
Or-bk-br-gold	294	300
Br-bk-red-gold		
Red-bk-red-gold		

Fig. 4-Nominal value added

This formula produces an error with a sign, whereby plus indicates the measured value is larger than the nominal value. Record the results in your journal (Fig. 5).

Color code	Meas. Ω	Nom. Ω	%Error
Or-bk-br-gold	294	300	-2%
Br-bk-red-gold			
Red-bk-red-gold			

Fig. 5-Percent error added

Resistors in series

- Now let's put two resistors in series. The word *series* means that the current flowing through the resistors flows through one and then the next. Put the 300- Ω and 1-k Ω resistors in series in your breadboard:
 - Each vertical group of five holes in the breadboard is one single connection that can receive as many as five wires. This group of five holes is a node.
 - There is no connection between groups of five in either direction except for the board-length rows along the top and bottom edges.
 - Figure 6 shows the 300- Ω resistor straddling two sets of five holes and the 1-k Ω resistor straddling the gutter in the middle of the board.

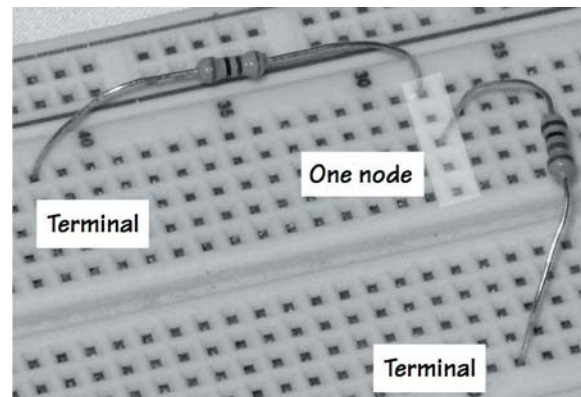


Fig. 6-Two resistors in series

- Note that the top end of the 1-k Ω resistor and the right end of the 300- Ω resistor are in the same node (the group of five holes).

- Figure 7 is the schematic representation of this connection. The



Fig. 7-Series schematic

jagged symbol denotes a resistor with its resistance value along side it. Draw this in your journal.

- Measure the resistance of the two resistors in series by touching one probe of the ohmmeter to the left end of the 300-Ω resistor and the other probe to the bottom of the 1-kΩ resistor. Record this as the measured series value.
- The rule for combining resistors in series is that resistors in series add. The general equation for n resistors is

$$R_{series} = R_1 + R_2 + R_3 + \cdots + R_n$$

- How does the measured value compare with the calculated value. Use the actual measured resistance values in your calculation. I hope the results check out very closely!
- Now connect the 2-kΩ resistor in series with the first two. Figure 8 shows both the physical and the schematic arrangements. Predict what the total resistance of the series string will be. Then measure this. Does the formula check out?

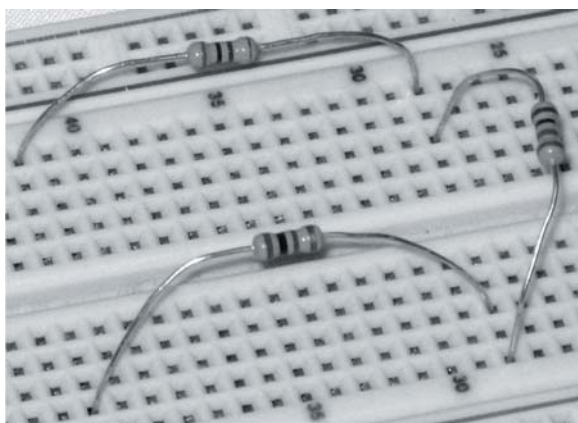


Fig. 8—Three resistors in series with schematic

Resistors in parallel

- Resistors in *parallel* means that they are arranged so the flow of current splits between the resistors and then comes back together at the other end. This requires that the resistors in parallel must have their ends in the same nodes.
- Put the 1-kΩ and 2-kΩ resistors in parallel by pushing one end of each into a common node and then doing the same with the other ends. See Fig. 9.
- Measure the resistance of this combination by

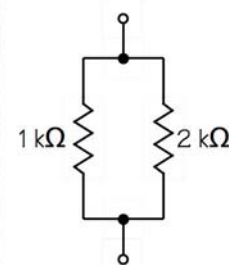
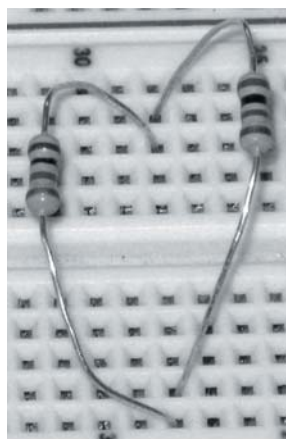


Fig. 9—Two resistors in parallel with schematic

touching your ohmmeter probes to the bare wires in the two nodes. Record this as the measured parallel value.

- The rule for combining resistors in parallel is that resistors in parallel add reciprocally. The general equation for n resistors is

$$R_{parallel} = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}}$$

- How well do the measured and calculated values compare?
- Now add the 300-Ω resistor in parallel with the other two (Fig. 10). Predict what the total parallel resistor of this combination will be. Then measure this. How does the result turn out?

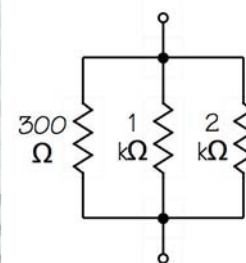
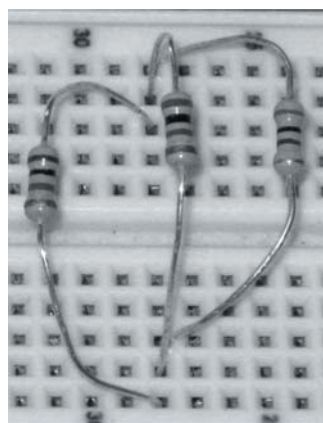


Fig. 10—Three resistors in parallel with schematic

One more arrangement

- Arrange three resistors in a series/parallel configuration as shown in the schematic of Fig. 11.

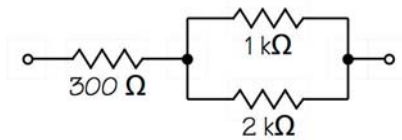


Fig 11–Resistor circuit

No picture this time! It's up to you to arrange the resistors properly on the breadboard.

2. Predict what the total resistance will be. Then measure it and record how close this turns out. [Clue: It's around 1000.]

Results

Look back over your results and notice several things:

- As resistors are added to a series string, the total resistance increases. The same current is passing through each of them and each is resisting that current, making it lose energy.
- As resistors are added in parallel, the total resistance decreases. The incoming current splits among multiple paths and has an “easier time” passing through compared with passing through just one resistor.

- Resistors are pretty well behaved electrical elements. Your measured and calculated results should be very similar if you have been calculating using the measured values of the individual resistors.
- The fourth band of the color code states a percentage guarantee of the actual value. Although your resistors are $\pm 5\%$ (if the fourth band is gold), your actual deviations have probably been at most 2%.
- The schematic drawing shows only the electrical connections, not the physical layout. The numbers on the schematic are the nominal values of the resistances.

The End

Your lab journal should contain a tabulation of the resistors' color-codes, nominal values, measured values, and percent errors. For each circuit constructed and measured, there should be a schematic drawing, the calculated value, and the measured value.

Mobile Studio Desktop™

Lab A2: Current Thinking

Purpose

Two quantities represent “electricity,” current and voltage. In this lab we are going to relate these by measuring them in circuits involving resistors. We’ll also make some measurements on a simple resistor circuit and see how meters can affect measurements.

Objectives

The objectives of this lab are

- Set up circuit with a source
- Measure voltage
- Measure current
- Relate voltage and current through Ohm’s Law
- Construct and measure a voltage divider
- Observe the effects of an ammeter

Introduction

Before we start, let’s take a brief look at what current and voltage are.

“Electricity” is the flow of electrons through a conductor. Electrons are small negative charges, -1.6×10^{-19} coulombs each, that make up a portion of all matter. When they move, we have a flow of charge that we call current. This current is measured in coulombs per second. We call this an *ampere*, abbreviation A, named after André-Marie Ampère, who was a French physicist in the early 1800s.

Charges don’t just “flow” by themselves—they need a source of energy to push them. If we do work on a

charge, we can impart to it potential energy. This potential energy is measured in joules per coulomb. We call this a *volt*, abbreviation V, named after Alessandro Giuseppe Antonio Anastasio Volta, who was an Italian physicist in the early 1800s. (Fortunately, we didn’t use his entire name!)

Mr. Ohm, and probably numerous other experimenters of their day, began to observe that there was a simple relationship among voltage, current, and resistance. They all probably observed that a current passing through a resistance developed a voltage across that resistance. This led to Ohm’s Law, which states the quantities using the units we’ve just described:

$$v = Ri$$

The voltage v in the equation is measured in volts and the current i is measured in amperes. The resistance R , the quantity we examined in the previous lab, is measured in ohms. If we apply a current of 2 milliamperes (mA) to a 1.2-k Ω resistor, the voltage across the resistor will be

$$v = (1.2 \times 10^3)(2 \times 10^{-3}) = 2.4 \text{ V}$$

The directions of these quantities are important. Figure 1 shows that the current of 2 mA is flowing through the resistor from left to right, developing a voltage of 2.4 V that is positive at the left end.

The directions shown in Fig.1 are known as the *passive sign convention*. This convention always shows that positive current, indicated by the arrow’s direction, flows *into* the positive terminal of the voltage. This is called passive because the voltage is decreasing from end to end, indicating a decrease in energy and a dissipation of power. I will consistently use the passive sign convention

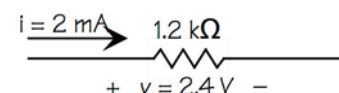


Fig. 1—Passive sign convention

for all electrical elements except those that are sources of energy like batteries and generators.

Equipment

The circuits in this lab are made up of two different resistors: 1.2 k Ω , and 2 k Ω , with the 3-V battery as the power source. You'll need your digital multimeter (DMM) for all the measurements.

Procedure

Begin by selecting the two resistors. You may need the color-code table from Lab A1.

Voltage and current

In this section you'll measure voltage across and current through a resistor.

1. Set up the circuit shown in the schematic of Fig. 2 and the photo of Fig. 3. Note that the plus lead of the 3-V supply is at the top of the 1.2-k Ω resistor.
2. Set your DMM to measure d-c volts (a V with a bar and dots).
3. Touch the red lead of the voltmeter to the top end of the resistor and the black lead to the bottom end.
4. Observe and record in your journal the voltage

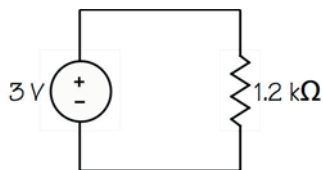


Fig. 2—Battery and resistor

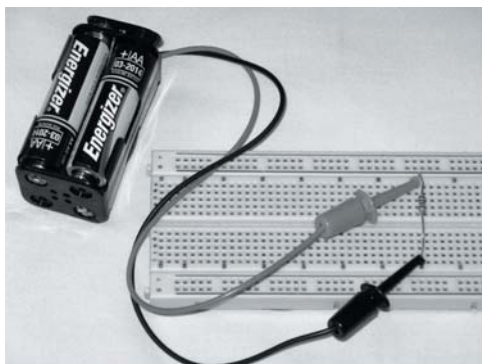


Fig. 3—Battery and resistor

measured. Record all digits displayed.

Current is trickier to measure. You can't just "look" at it in the way you used the DMM to measure the voltage. In order to measure current, you must get in the current's way. To say this another way, you must interrupt the current and put the meter in its path. The next steps will walk you through this.

5. Set your DMM to measure d-c amperes, selecting the microampere (μ A) range.
6. Remove the battery's plus lead from the top of the resistor.
7. Clip together this plus lead and the red lead of the DMM.
8. Touch the DMM's black lead to the top of the resistor. Figures 4 and 5 show these connections.

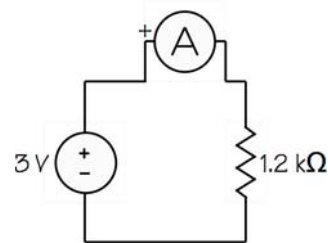


Fig. 4—Ammeter inserted

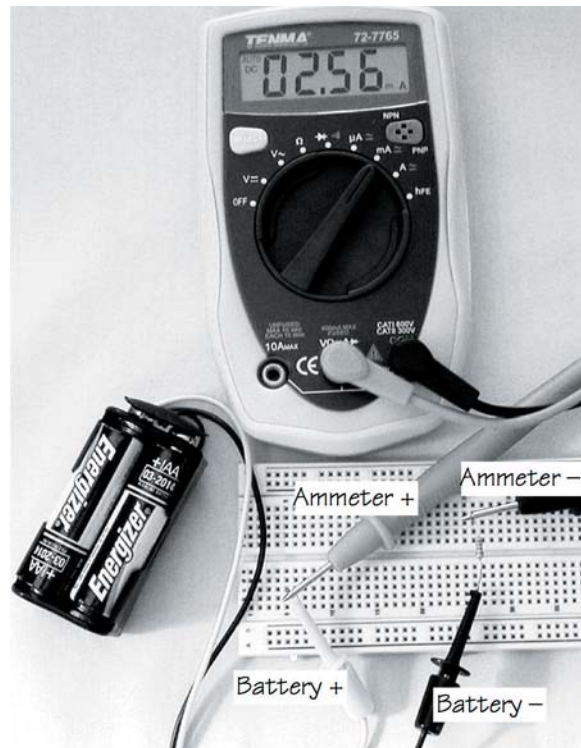


Fig. 5—Ammeter inserted

9. Now you have the current flowing from the battery *through* your DMM to the resistor, through the resistor, and back to the battery.
10. Observe and record this current in your journal. Record all digits displayed.

Ohm's Law

Now let's see what Ohm's Law has to say about the data just collected.

1. Remove the battery connections from your circuit. You are about to use your ohmmeter in the circuit and this must *never* be done with power applied.
2. Use your DMM to measure the actual resistance of the 1.2-k Ω resistor. Record all digits of this value.
3. Using the resistor voltage and the resistor current measured in the previous section, calculate the value of the resistance using Ohm's Law:

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

4. Compare the resistance you just calculated with the resistance you measured in step 2. They probably won't be the same! In fact, the calculated resistance will most likely be higher.

Meter effects

Meters measure quantities by extracting some energy from what is being measured. Really good meters extract very little energy and therefore have very little effect on the quantity itself.

Typical digital multimeters have very good voltage ranges, meaning that they require very little energy to make their measurements. Therefore, the voltage readings will be very close to the actual values.

Current ranges on typical digital multimeters, however, often introduce resistance into the circuit that affects the circuit. When you used your DMM in the previous section, the meter inserted a resistance in series with your circuit. We are going to calculate that resistance and then determine the inserted resistance using another circuit.

Calculate a possible value of the meter resistance by subtracting the resistance you just measured from the resistance calculated in step 4 above.

My data and calculations look like this:

$$R_{\text{measured}} = 1.187 \text{ k}\Omega$$

$$v_{\text{measured}} = 3.111 \text{ V}$$

$$i_{\text{measured}} = 2422 \text{ }\mu\text{A}$$

$$R_{\text{calculated}} = \frac{3.111}{2422 \times 10^{-6}} = 1.285 \text{ k}\Omega$$

$$R_{\text{difference}} = 1.285 - 1.187 = 98 \text{ }\Omega$$

The point to be learned from the measurement is that digital multimeters have an effect on the circuit. These effects are much more pronounced in the current ranges than in the voltage ranges. In future labs, we will often be finding current by measuring the voltage across a known resistor and calculating the current through Ohm's Law.

Voltage divider

A voltage divider is a pair of resistors that provide a voltage that is less than the supply voltage. This circuit is useful both in various measurement situations and in simplifying some circuit calculations.

1. Construct the voltage divider shown in the schematic of Fig. 6 and the photo of Fig. 7 (next page).

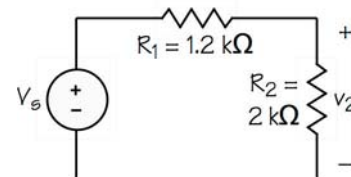


Fig. 6—Voltage divider

2. Measure and record the values of R_1 and R_2 .
3. Measure and record the source voltage V_s .
4. Measure and record v_2 .
5. Use the voltage-divider relationship to calculate the voltage v_2 from V_s and the recorded resistance values. The equation for a voltage divider is

$$v_2 = V_s \frac{R_2}{R_1 + R_2}$$

The voltage divider divides the source voltage by the ratio of the "output" resistor to the sum of the resistors. In this example, the output resistor is the one across which we measured v_2 . How does your measured v_2 compare with the calculated value?

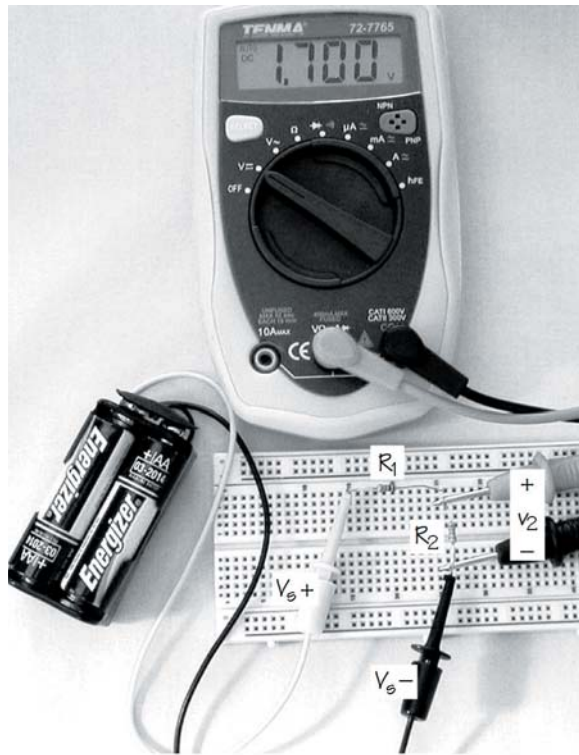


Fig. 7—Voltage divider

Results

The most important lesson in this lab is that current can be measure only by “getting in its way.” The current path must be interrupted and the ammeter inserted into the break. Current cannot be measured by just “looking” at the conductor.

But current measurement is often the one that affects the circuit the most. The ammeter we are using inserts a resistance of $100\ \Omega$ into the path on its μA range. If circuit resistances are *much* larger than $100\ \Omega$, this has little effect. But if the resistances are, say, $100\ \Omega$, then adding $100\ \Omega$ creates a 100% error in the reading.

In our lab work in the future, we will generally use a different technique if we need to know the current somewhere. Either we will measure the voltage across one of the known resistors and calculate the current, or we will choose a resistor to insert that will have little effect and measure the voltage across it.

We also worked with a voltage divider, a simple circuit that divides the source voltage into two values. The output voltage of the divider is a fraction of the input voltage, that fraction determined by the resistors of the divider.

The voltage divider also has a benefit as an aid to circuit analysis. Sometimes, a complicated-looking circuit is nothing more than a voltage divider and we can use the voltage-divider relationship to calculate the output.

The End

You should have a record in your journal of the results of measuring a current, a comparison between the calculated and measured currents, and the data that show how the ammeter affects the circuit. You should also have data on the voltage divider and how the outcome compares with theory.

Mobile Studio Desktop™

Lab A3: Kirchhoff's Student Days

Purpose

Kirchhoff's Laws are very fundamental to circuits. Now that we've experimented with Ohm's Law, it's time to take a look at the application of Kirchhoff's Laws to circuits.

Objectives

Our goal is to collect data to demonstrate Kirchhoff's Laws in a simple circuit, including:

- Measurement of voltages to show the application of Kirchhoff's Voltage Law.
- Measurement of currents to show the application of Kirchhoff's Current Law.
- Calculation of currents using Ohm's Law and again demonstrating Kirchhoff's Current Law.

Introduction

Gustav Robert Kirchhoff was still a physics student in the mid 1800s when he formulated two laws that are fundamental to electric circuits. He later developed his Law of Thermal Emission and his Laws of Spectroscopy.

Kirchhoff's Voltage Law recognizes that voltage implies potential energy and that this potential energy must be conserved:

**The algebraic sum
of the voltages
around any closed loop
is zero
at every instant of time.**

Let's take this law apart by phrases. "Algebraic sum" means that we add and pay attention to signs. "Closed

loop" means any closed path, not necessarily along the paths of circuit elements. "At any instant of time" says there is no way you can find a time when, say, part of the circuit is "ahead of" another part and thus violating the law.

Kirchhoff's Current Law notes that current is movement of charge. Charge can neither be created nor destroyed so charge must be conserved:

**The algebraic sum
of the currents
leaving any node
is zero
at every instant of time.**

The one different phrase is "leaving a node." Since current has direction, we must establish our positive reference. "Leaving" turns out to be generally convenient for many circuits. A "node" is simply the junction of electrical elements. Connecting wires are considered part of the element itself and not considered separately.

In this lab, we'll see how closely what we can measure comes to matching what Kirchhoff's Laws say.

Equipment

For the circuit in this lab you'll need the 3-V battery source and four resistors: 100 and 300 Ω , and 1 and 2 k Ω .

Procedure

Construct the circuit shown in the schematic of Fig. 1 and the photograph of Fig. 2. Notice that I have used one of the two busses on the bottom of the breadboard for the bottom wire of the circuit. All the board holes along each of these busses are connected to one another..

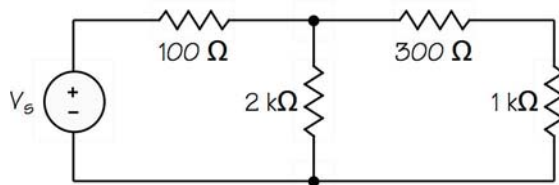


Fig. 1—Circuit for Kirchhoff's Laws

Voltage measurements

1. Use your digital multimeter to measure the voltage across each of the elements of the circuit. Record the results in the boxes of Fig. 3.
2. Pay close attention to sign, remembering that the red lead of the DMM is the lead designated as positive. For example, when we measure the voltage across the 100-Ω resistor, the *red* lead should be placed at the left end. If the voltage reading has a minus sign, you have the leads reversed.
3. Sum the voltages around each of the three loops (left loop, right loop, and outside loop). Follow a simple convention for traversing each loop: Always start at the lower left corner, proceed clockwise, and record the first sign encountered as the sign of the voltage. Your equation for the left loop might look like this:

$$-3.17 + 0.36 + 2.82 = 0.01$$

You should have written three KVL equations. How close to zero are your sums?

Current measurements

1. Measure the three currents that involve the node that is the junction of the three resistors at the top of the circuit. Remember that you must interrupt the path of the current and put the ammeter into that opening to measure current. Notice the arrows that give the reference directions of the three currents. All data collected go in the upper boxes of the pairs of boxes in Fig. 4.

For example, to measure the current flowing to the right through the 100-Ω resistor, first lift the right end of the resistor out of the breadboard. Then connect the *red* ammeter lead to the lifted end of the resistor and the *black* lead to the node you pulled the wire from.

Then put the 100-Ω resistor's wire back into the node and lift the left end of the 300-Ω resistor. Now, because the current reference arrow is from left to right, put the *red* ammeter lead on the node

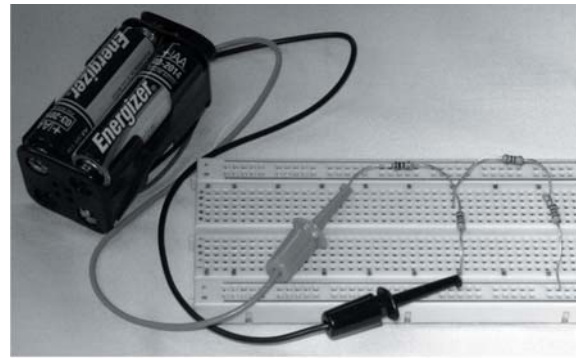


Fig. 2—Circuit layout

and the *black* lead on the lifted end of the resistor.

Do the same for the 2-kΩ resistor.

2. Sum the currents that you have measured by following a simple convention. Currents leaving a node are positive, so currents arriving are negative. In your data set, the current through the 100-Ω resistor is arriving, so it is recorded in the equation with the opposite sign. The current down through the 2-kΩ resistor is leaving, so it is recorded as measured. Your equation for this node might look like this:

$$-3.60 + 1.44 + 2.12 = -0.04$$

You should have written one KCL equation. How close to zero did you get?

Current by calculation

1. Use Ohm's Law to calculate the three currents. You have collected the voltage data for each of the resistors. Apply Ohm's Law and use the Passive Sign Convention to compute the three currents. Then fill in the three lower boxes of the pairs of boxes in Fig. 4.
2. Apply Kirchhoff's Current Law to these measurements.

You should now have a second KCL equation. How closely does this one fit? Why does one data set seem to give "better" results than the other.

Results

There are several things to be learned from the work you have completed:

- Application of Kirchhoff's Laws.

- Signs and the need to pay attention to reference directions. In the circuit drawing you have been using, I chose all the voltage references so the outcomes of your measurements are positive. I also chose the current references so your currents are positive. But there's nothing that says you have to get the chosen signs right. If, for example, I had drawn the arrow for the $300\text{-}\Omega$ resistor facing to the left instead of the right, your measurement would have produced a minus sign.
- When applying Kirchhoff's Laws, follow a strict convention of directions and signs. The goal of doing this is to do the work without having to

think about what you might be choosing. In other words, just do the arithmetic! Don't think! This means always summing voltages clockwise from the lower left, taking the first sign you come to for each element. It means summing currents at a node as positive leaving the node.

The End

Your journal should contain the diagrams of Figs. 3 and 4, your KVL and KCL calculations, and a comment on why the two KCL equations don't come out the same.

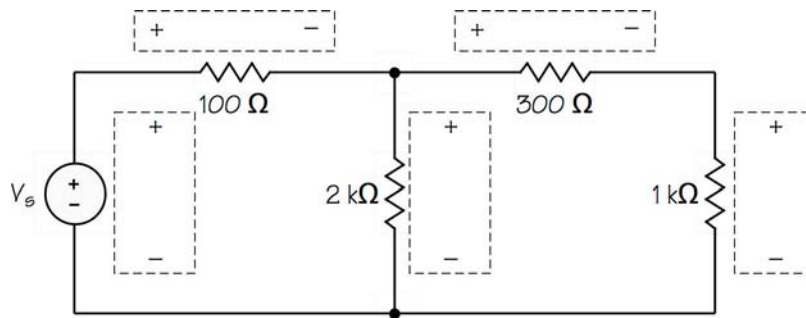


Fig. 3—Circuit for voltage data

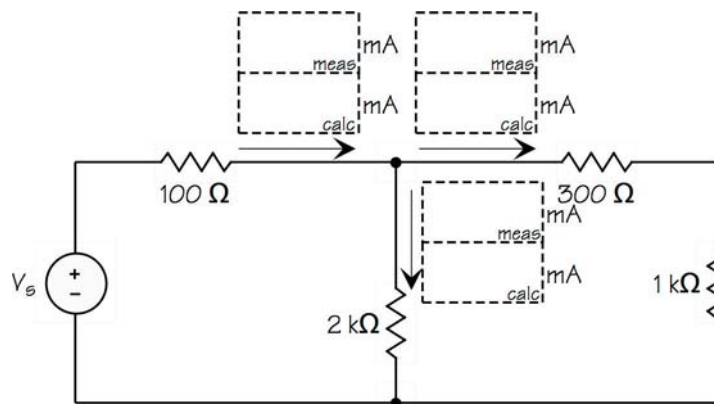


Fig. 4—Circuit for current data

Mobile Studio Desktop™

Lab A4: Linear is Nice, but...

Purpose

But what? Our simple circuit devices such as resistors, capacitors, and inductors are linear, or at least appear to be linear. This means that the graph of current versus voltage is a straight line. Linear is nice because it simplifies our mathematical analysis and makes these devices easy to deal with. For example, double the current through a resistor and the voltage across it doubles.

But what? Well, the world isn't linear, and even our "linear" devices aren't really. Double the current through a resistor too many times and you get smoke and, eventually, destruction.

In this lab we are going to draw a current-vs.-voltage graph for an LED, a light-emitting diode, which is a distinctly non-linear device. It is so non-linear that current will pass through the diode in one direction only.

Objectives

We are going to make measurements of current and voltage for a non-linear device:

- Determine current by measuring voltage across a known resistance
- Learn to manipulate a "pot" in a circuit
- Collect current and voltage data for an LED
- Graph the LED's i - v curve for use in a later lab

Equipment

This lab is going to be done using one of the 6-volt battery packs and the digital multimeter. You'll need a 100- Ω resistor and an 10-k Ω "pot," which is short for potentiometer.

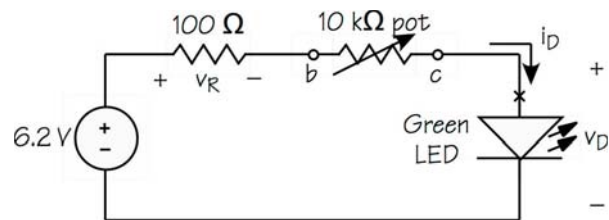


Fig. 1-LED test circuit

Procedure

1. We'll be determining current by measuring the voltage across the 100- Ω resistor, measure its actual resistance and record it for later calculations.
2. Build the circuit of Fig. 1, paying special attention to a number of new things:
 - The direction of the current is important, so the 6.2-V battery source must be positive at the top.
 - The LED is directional, so the longer of the two leads of the LED must be at the point x in the circuit.
 - The pot, shown in Fig. 2, is a variable resistance that will let us control the current during our measurements. Note in Fig. 2 that the b lead of the pot is connected to the moving contact so that it moves around the resistance as the screw is turned. If the screw is fully counter-clockwise, the resistance between a and b is 0 and the resistance between b and c is 10 k Ω .
- Insert the pot into the board in the orientation shown in Fig. 2. (The leads form a triangle as shown.) The three leads

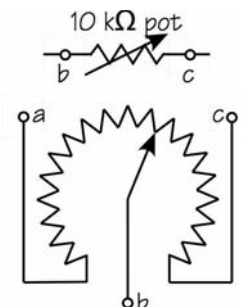


Fig. 2-What's a pot?

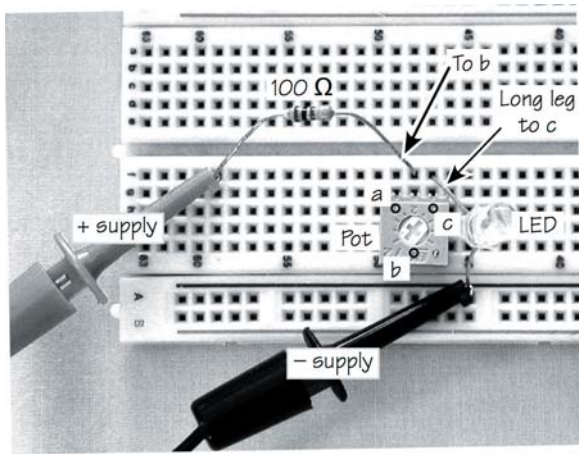


Fig. 3–Board layout

should be in three adjacent nodes on the board.

- Look at Fig. 3 for a photo of how the circuit is laid out on the board.
 - If you have the circuit built correctly, the LED should light brightly when you turn the screw of the pot fully clockwise. If it doesn't, recheck your work and match up what you have with Fig. 3.
3. Turn the pot's screw fully counterclockwise, which should leave a tiny green glow in the LED. This should put the slot pointing at about the 7:30 o'clock position.
 4. Make a three-column table to record the voltage v_D across the LED, the voltage v_R across the 100- Ω resistor, and the calculated current i_D through the LED (to be calculated later).
 5. Measure and record v_D using the DMM, red lead at the top of the LED, black lead at the bottom. (This should be around 1.7 or 1.8 V.)
 6. Measure and record v_R using the DMM, red lead to the left. (This should be 10-15 mV.)
 7. Turn the screw on the pot so it is at about the 1:00 o'clock position and measure v_D and v_R again.
 8. Repeat these measurements at about 2:00, 3:00, 3:30, and 3:45 o'clock, and finally with the pot turned fully clockwise. (The final measurements should yield v_D around 2.0 V and v_R around 1.0 V.)

Calculation and Graphing

Fill in the values of i_D in the third column of your data table by using the resistor voltage v_R and the known value of the 100- Ω resistance. (Your currents should range from about 0.1 mA to about 10 mA.)

Plot the data (i_D vs. v_D) on the graph on the next page. Before plotting, label the axes to make a proper graph:

- A proper graph has readable steps such as by 1's, 2's, 4's, or 5's. Anything else (like 3's) is hard to read. For our LED, making each current square 1 mA and each voltage square 0.1 V will provide a "good" graph.
- A proper graph always has the plot variables and the units labeled, so add the axis units (mA and V) near the axis labels.
- A proper graph always has a title as shown.
- Your data will plot in a narrow range in the middle of the graph. The apparently excess space to the left and right is to make the graph useful in a later lab.
- After carefully marking all the data points (about seven in all), draw a smooth curve through all the points.

Results

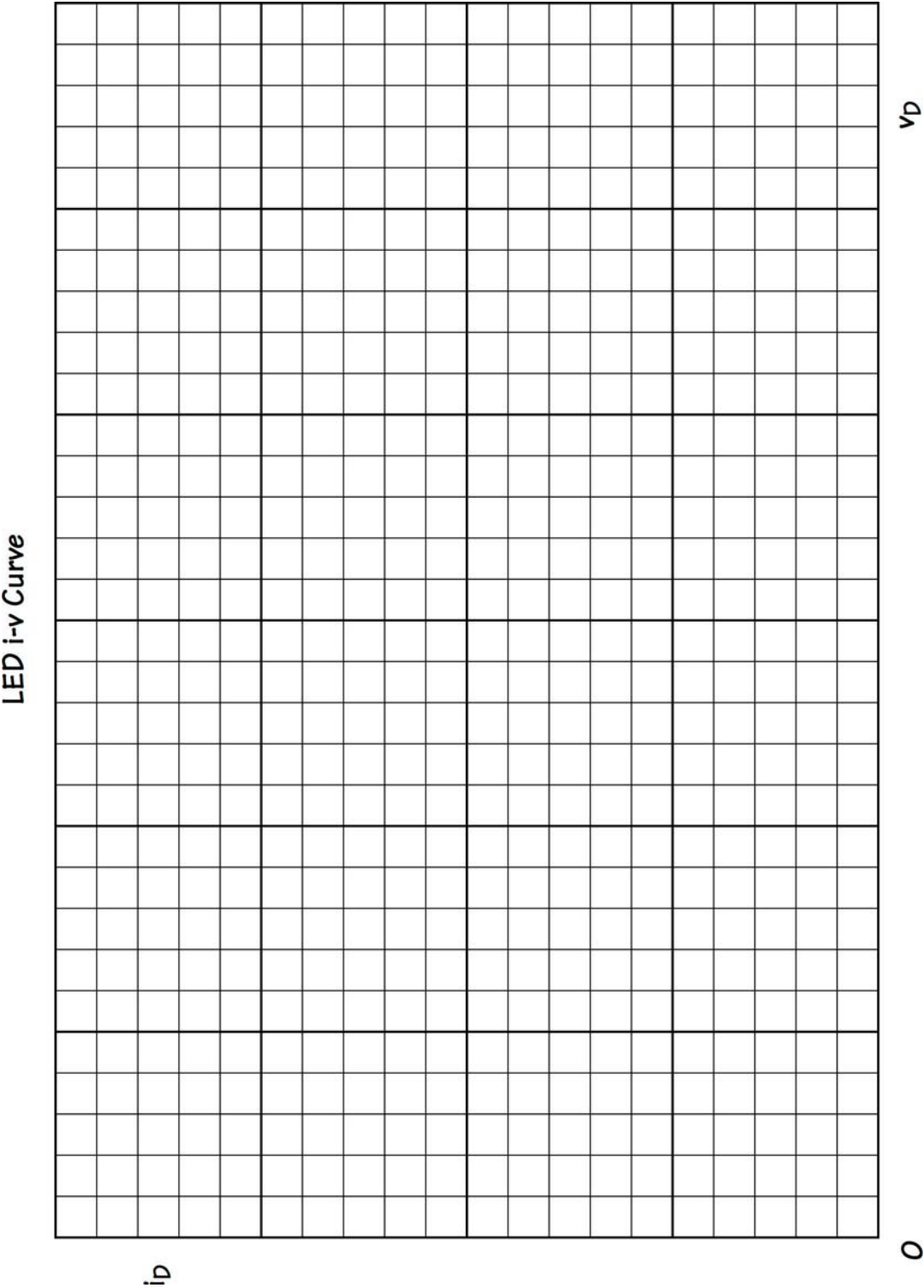
Your graph should show that the LED is a distinctly non-linear device. But note that a portion of the curve looks "pretty linear" if you ignore the bend at the bottom. The upper region is pretty close to a straight line, so the LED could be treated as a linear device over a restricted range.

If you had taken more data for lower voltages, you would have found that the curve to the left of your data hugs the v_D axis all the way to 0 V and beyond into negative voltages.

The End

Well, non-linear devices really don't change things very much in our measurement of current and voltage. We measured the LED voltage and we determined the LED current from a voltage measurement.

Be sure your graph is complete with properly labeled and calibrated axes, then save the graph for later use in a Thévenin lab.



Mobile Studio Desktop™

Lab A5: Linear is Nice, but...Again

Purpose

This lab is a repeat of Lab A4, which you need to do before you do this one, please. This lab introduces a different way to collect the i-v data for the LED by using one of the features of Mobile Studio Desktop.

Objectives

You've already met the objectives of Lab A4 (you have, haven't you?) so our goals here relate to methods for making measurements rather than the LED itself:

- Set up a measurement circuit using both an ammeter and Mobile Studio Desktop
- Handle an ammeter in a situation where it is possible to burn out the meter

Equipment

You need the Mobile Studio IO Board with clip leads attached to AWG1+ and its Ground, and A1+ and A1-. You'll also need the green LED you used in Lab A4, plus a lead with clips on each end.

Procedure

1. Build the circuit shown in Fig. 1. The photo of Fig. 2 will perhaps be of help. Notice the following:

The LED is staked into the breadboard with its longer lead (the + lead) at the top, which is the X in Fig. 1.

A1+ and A1- are clipped directly to opposite leads of the LED.

AWG1 Ground is clipped to the same leg of the LED as A1-

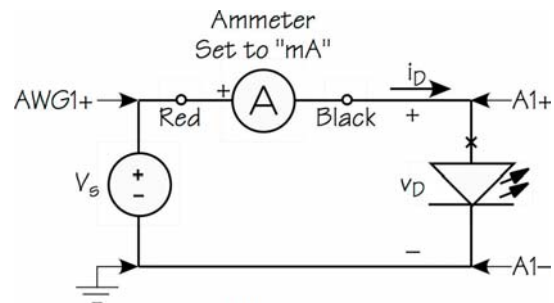


Fig. 1-LED test circuit

A clip lead is used to join the + leg of the LED to the black lead of the ammeter.

The ammeter is set to the "mA" scale.

To protect the DMM ammeter, **do not connect the AWG1+ clip** to the red ammeter lead until you have set up the power source from Mobile Studio Desktop.

2. Launch Mobile Studio Desktop and plug the IO Board into the USB port.

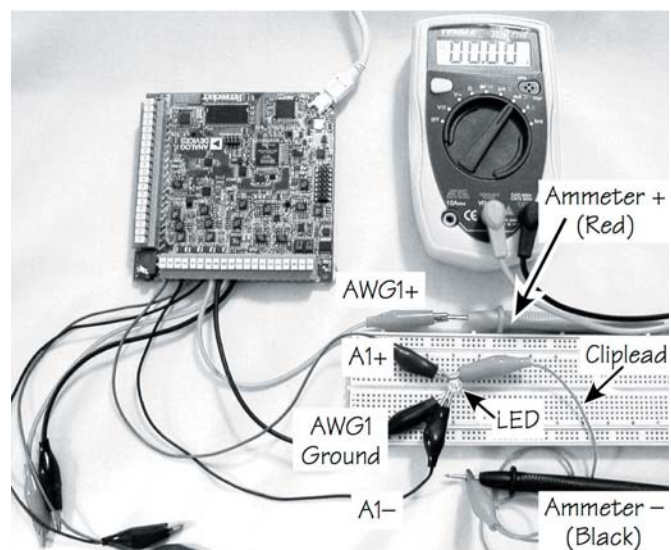


Fig. 2-LED test circuit layout

3. On the left edge of the screen, click on Analog I/O. This will bring up a source of two d-c voltages, labeled “Analog Out,” and an “Analog In” voltmeter.

4. Analog Out Ch 1 supplies a d-c voltage to the IO Board’s AWG1 port, which will drive the LED through the ammeter.

Set Ch 1 to 0. This can be done by moving the slider with the mouse, or double-clicking in the box and typing “0,” or clicking near the slider and using the mouse wheel to change the voltage.

5. In the Analog In Channel, choose A1DIF so the voltmeter will read the voltage across the LED. (Averaging should be set to 1; Range has no effect except on the strange display below it.)
6. **Now** connect the AWG1+ clip to the red lead of the ammeter. Why not till now? To protect the meter from possible excessive current, we waited until the source voltage was set to 0.
7. It’s time to collect data. You can read the LED current i_D and the LED voltage v_D directly without any calculation. Hence you can, if you wish, plot the graph as you go along. There’s graph paper on the next page, but you could add your new data to the graph you already made in Lab A4 if you wish.

8. To save time, adjust the voltage Ch 1 upward until the ammeter reads about 1 mA. Then record i_D from the ammeter and v_D from the Analog In voltmeter.

9. Continue to take i_D - v_D data in steps of about 1 mA until you reach 20 mA.

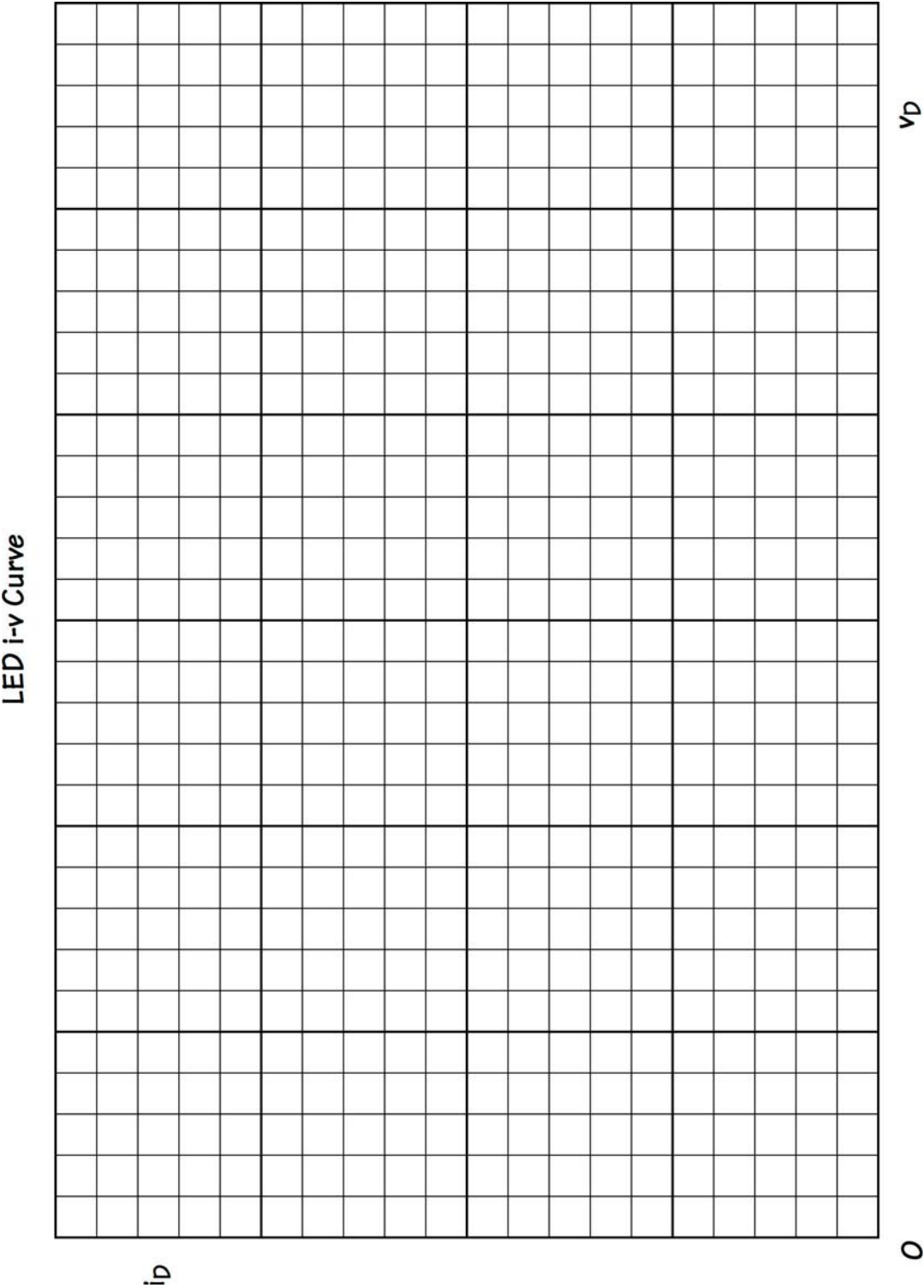
10. Plot the i_D - v_D graph if you haven’t been plotting as you go along. The curve ought to match closely the curve you got in Lab A4.

Results

The primary results are seeing how to use one of the instruments in Mobile Studio Desktop and using the DMM ammeter. The secondary result is another LED curve.

The End

Analog I/O in Mobile Studio Desktop is a simple source of two d-c voltages, completely adjustable over a range of ± 3.500 V. The Analog In voltmeter can be linked to any of the analog ports on the IO Board. Note, though, that the meter isn’t perfect; it probably reads a small but non-zero voltage even with the two A1 leads clipped directly together.



Mobile Studio Desktop™

Lab B1: Flat Earth?

Purpose

Linearity is a great concept! If you carry it to the extreme, you can even have a flat earth. Nah...let's not go there. We'll stick with circuits. Our circuits are linear, which helps keep things simple. Let's look at the elements that make up our circuits.

We build with resistors, which are linear devices. That means that the relationship between the voltage across a resistor and the current through it is a linear one. No squares, no functions of any kind, just a simple $v = Ri$. The other two passive elements, the inductor and the capacitor, are also linear. So are our ideal sources.

What does *linear* mean? Consider $v = Ri$. Double i and v doubles. Divide v by 2.65×10^4 and i will be divided by the same amount. And so on.

Our goal in this lab is to make some measurements of voltage and current for a linear circuit and observe that linearity does what it says it will do. We'll also look at power dissipated in a resistor to see that power is not a linear function.

Objectives

We will take data for the voltage and current shown in Fig. 1. We want to demonstrate two things:

- changing the source voltage by a known ratio changes the voltage and the current by that same ratio
- the change in the source voltage does not affect the power dissipated in a resistor in a linear way

Equipment

All of the data will be taken on a d-c circuit; all of the measurements will be done with your digital multimeter. For sources you'll need the two-cell battery pack for a nominal 3 volts and one of the four-cell packs for a nominal 6 volts. The circuit requires a breadboard plus 100- Ω , 200- Ω , 1-k Ω , and 2-k Ω resistors.

Procedure

Before building the circuit, measure and record the resistance of the 2-k Ω resistor. Then build the circuit of Fig. 1 on your breadboard. Then we'll make voltage and current measurements for both v and i with two different sources for V_S . Create a table for two sets of values of V_S , v , and i . Then take data as follows:

1. Connect the two-cell battery pack to the circuit to supply V_S .
2. Measure V_S and v .
3. Measure, using the "mA" current range on your DMM, the current i through the 200- Ω resistor. Remember that you must "get in the way of the current" by pulling loose one end of the 200- Ω resistor and putting the ammeter in that opening.
4. Replace the two-cell pack with one four-cell pack from the double pack to supply a new V_S .

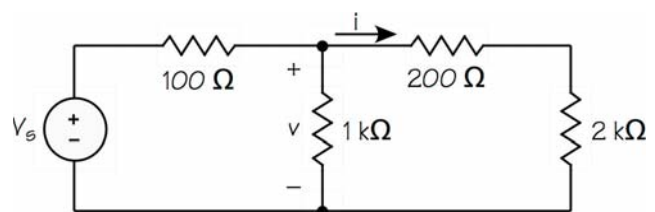


Fig. 1-Linear circuit

5. Again measure V_S , v , and i .

Results

From the data you have, calculate the ratio of the second voltage source V_2 to the first one. Then multiply by this ratio both v and i from the first measurement. By what percentage do these numbers differ from the v and i data from the second measurement? These should agree within experimental error.

For each of the two data sets, calculate the power absorbed by the $1\text{-k}\Omega$ and $200\text{-}\Omega$ resistors. Does multiplying the first power value by the ratio of voltage sources yield the second power value? Why?

The End

Your data should show that the voltage and the current in the circuit are linearly related to the supply voltage but the power is not. Your journal should show how well these data match—or don't match.

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Lab B2: Up on Top?

Purpose

Superposition is a strange word, because it literally means “on top.” *Super* means *above*, so the word appears to mean a position on top of something. That’s what we are going to study in this lab. We are going to place something on top of something else, namely, sources.

Introduction

Consider the circuit of Fig. 1. It has two sources. A certain voltage v is being observed. This observed voltage v is going to be the result of some combination of the effects of the two sources. If the circuit being observed is linear, as this one is, then the value of v is a linear combination of the effects of each of the sources acting alone. In other words, the effect on v of the source V_s and the effect on v of the source I_s can be *superimposed*.

Figure 2 shows the circuit with just the voltage source

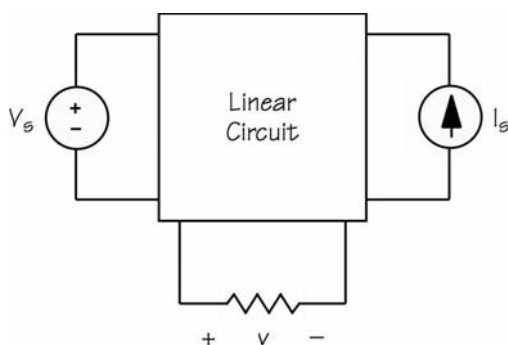


Fig. 1—Linear circuit

V_s operating. The current source is set to zero. Notice that, to have a current source of 0, we must have an *open* circuit so that there is no path for current through the source branch. With this arrangement, the value of the observed voltage v_1 is dependent solely on the voltage source.

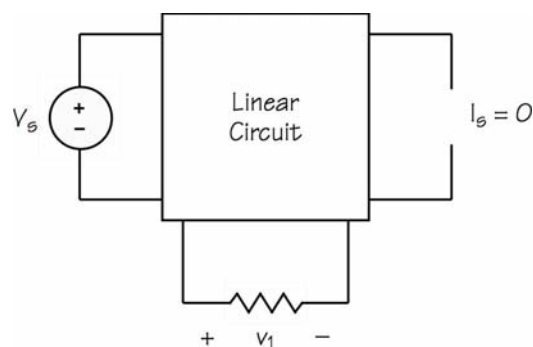


Fig. 2—Dead current source ($=0$)

Figure 3 shows the circuit with just the current source I_s operating. The voltage source is set to zero. To have a voltage source of 0 requires that we have a *short* circuit so no voltage exists where the source was. With this arrangement, the observed voltage v_2 is dependent solely on the current source.

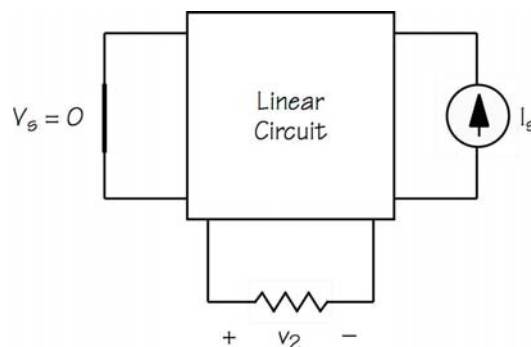


Fig. 3—Dead voltage source ($=0$)

Superposition says that, in a linear system, the observed voltage is the sum of the voltages observed when each of the sources is operating individually. As an equation, $v = v_1 + v_2$. That’s superposition and that’s what we are going to observe in this lab.

Objectives

Our primary objective is to observe the effects of superposition, although we will limit our lab circuit to two voltage sources. Current sources are a little too messy to make here.

We'll do this by observing a voltage in a circuit under three conditions: both sources active, one source active and the other dead, and the other source active with the first one dead.

Equipment

You'll need your digital multimeter, two voltage sources (the two-cell and four-cell battery packs), and five resistors: $300\ \Omega$, $560\ \Omega$, $1\ \text{k}\Omega$, $1.2\ \text{k}\Omega$, and $2\ \text{k}\Omega$.

Procedure

Build the circuit of Fig. 4. Use one of the four-cell battery packs for V_1 (nominal voltage 6 V) and the two-cell pack for V_2 (nominal voltage 3 V). Pay attention to polarity so the + end of each pack is in the right direction.

1. Both sources active: Measure and record V_1 , V_2 , and v , the voltage across the $2\text{-k}\Omega$ resistor.

2. Remove the source V_2 and replace it with a short circuit. In other words, remove the wires from the source V_2 and put a wire in the gap you left. Don't short out the source itself!
3. Only V_1 active: Measure and record v .
4. Remove the shorting wire and replace the source V_2 where it belongs.
5. Remove the source V_1 and replace it with a short circuit just as you did for V_2 .
6. Only V_2 active: Measure v .

Results

Verify that the voltages measured for v with V_1 alone and with V_2 alone add to the voltage v measured with both sources active. How close (percentage) do you come to the theoretical value?

The End

This is a simple demonstration of superposition in a d-c circuit. If all has gone well, your journal should show that the results of the two tests with just one source add to the result with both sources to within a small percentage error. Remember that superposition requires that the circuit be linear, which this one is.

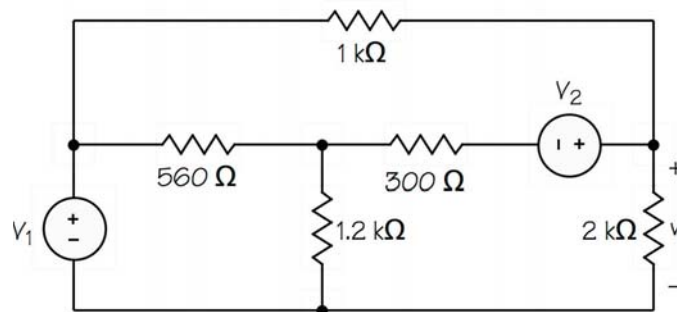


Fig. 4-D-c superposition

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Lab B3: More on the Top

Purpose

Superposition says that in a linear system, if you have more than one source, you can determine the effects of each of them individually and then sum (superimpose) those results to get the total effect.

Suppose I have a circuit (linear) with two voltage sources. I “kill” one of them, which means replacing it with a short circuit. Then I observe a certain current. Then I restart the first and kill the second in the same way. Again I observe that current. With both sources running, that current in question will be the sum of the two observations.

This works with a-c circuits and phasors just as well as it works with d-c circuits. The only complication is that we now have phase angles to deal, not just magnitudes.

Objectives

The primary effort in this lab will be to show that superposition works for a-c circuits using phasors. We are going to do this by building a circuit with two sources and measuring the phasor voltage with each source acting alone. Then we’ll show that these phasors add to the phasor measured with both sources functioning.

This lab is perhaps the first time that you will be measuring phase angles, so another purpose is to learn to use the oscilloscope in Mobile Studio Desktop. We will also learn to use the built-in cursors to measure both magnitude and phase of phasors.

Equipment

You will be using Mobile Studio Desktop to connect to the circuit, so you’ll need clip leads on AWG1+ and Ground, AWG2+ and Ground, and A2+ and -. Parts are 560- Ω , 1-k Ω , and 1.2-k Ω resistors and a 0.1- μ F capacitor.

Procedure

The work of the lab is going to go through several major steps. First, you’ll build the circuit and set up Mobile Studio Desktop so it can supply the voltages and make the measurements. Then we’ll walk through the use of the cursors to measure magnitude and phase on the scope. Finally, you’ll collect data on superposition of the effects of the two sources.

Setup

1. Build the circuit of Fig. 1. Connect the clip leads of the Red Board as follows:
 - a) AWG1 + and Ground to provide the voltage source on the left, + at the top
 - b) AWG2 + and Ground to provide the voltage source on the right, + at the top
 - c) A2+ and A2- to measure V_0 across the 1-k Ω resistor
2. Launch Mobile Studio Desktop and connect the IO Board’s USB
3. Launch the Function Generator and set it up as follows:
 - a) Set Channel 1 to 2.0 kHz, 0° phase, sine wave, 0 offset, 2.0 V peak-to-peak
 - b) Set Channel 2 to 2.0 kHz, 40° phase, sine wave,

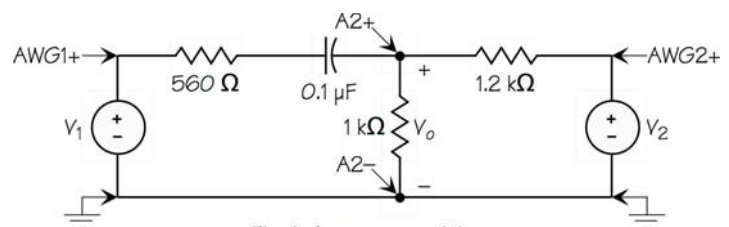


Fig. 1-A-c superposition

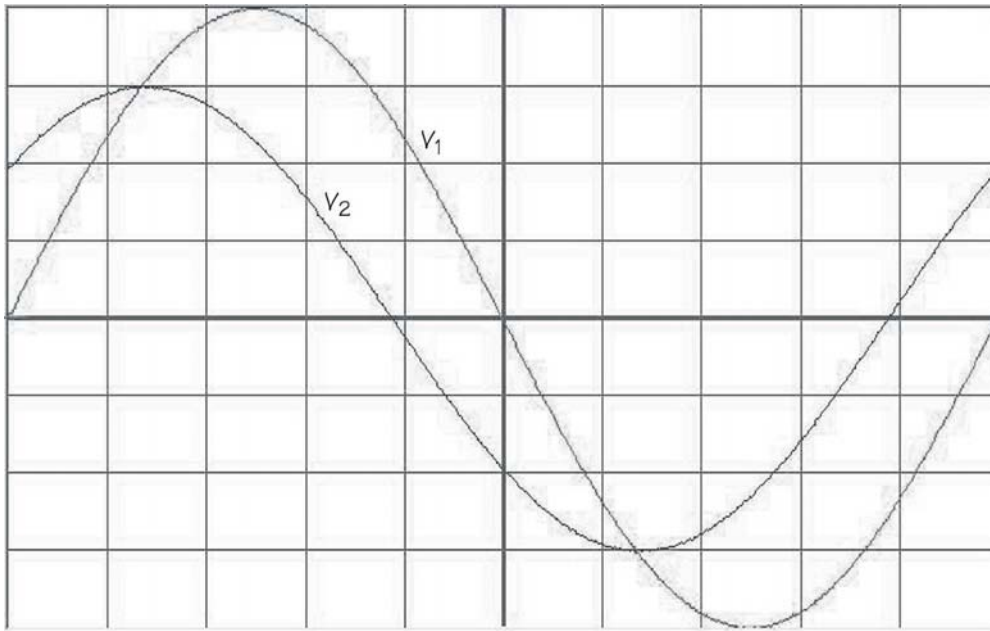


Fig. 2–Initial scope display

- 0 offset, 1.5 V peak-to-peak
- c) AutoHide (pushpin) the Function Generator
4. Launch the Oscilloscope and set it up:
 - a) Set Channel 1 to 250 mV, DC, AWG1, and enable it
 - b) Set Channel 2 to 250 mV, DC, AWG2, and enable it
 - c) Be sure Trigger is set to Auto, Ch1, Rising
 - d) Set Horizontal to 50.0 μ s
 - e) Be sure the Measurements block is showing on the right. Set the top section for Ch1 and RMS and the next section for Ch2 and RMS
5. Start the scope and you should see two sine-wave traces (see Fig. 2)

Trial measurements

Let's use the scope display of the two voltage waveforms to practice measuring magnitudes and phases.

1. Enable the cursors (there are eight of them!) by checking the block near the upper right corner of the screen
2. Locate the vertical green long-dash cursor. This sounds funny, but where it is depends on where it was left last and what channel settings have been changed. It may be on one edge or the other of the scope or hidden right on a grid line
3. Use this vertical green long-dash cursor to collect time information. You'll read the time data in the green cursor block as "Cursor 1."
 - a) Position this cursor exactly on the first downward zero-crossing of the V_1 sine wave. Read the time for Cursor 1 and call this t_{half} because it is half the period of these sine waves
 - b) Position this cursor exactly on the first downward zero-crossing of the V_2 sine wave. Read the time for Cursor 1 and call this t_2 . The phase angle by which V_2 leads V_1 is

$$angle = 180 \frac{t_{half} - t_2}{t_{half}}$$

4. Now we can do the calculations needed to get the actual values of the phasors V_1 and V_2 :

Phasor V_1 will have a magnitude read from the RMS value of Ch 1 in the Measurements section and a phase angle of 0° . (We have to establish a reference phase angle somewhere and I have chosen V_1 .)

Phasor V_2 will have a magnitude read from the RMS value of Ch 2 in the Measurements section and a leading (positive) phase angle as calculated above.

5. Suppose the data are as follows (the data here are my example but yours should be similar):

- a) $t_{\text{half}} = 250.35 \mu\text{s}$
- b) $t_2 = 193.55 \mu\text{s}$
- c) The RMS value of V_1 is 0.751 V
- d) The RMS value of V_2 is 0.506 V

Therefore the angle of V_2 is

$$\angle V_2 = 180^\circ \frac{250.35 - 193.55}{250.35}$$

and the two phasors are

$$V_1 = 0.751 \angle 0^\circ \text{ V}_{\text{RMS}}$$

$$V_2 = 0.506 \angle 40.8^\circ \text{ V}_{\text{RMS}}$$

6. Now record your own display's data and determine the values of the two phasors.

Superposition measurements

Now that we can measure amplitudes and phases and determine the values of phasors, we can go ahead with data collection for demonstrating superposition in a-c circuits.

1. Change Channel 2 of the scope to observe the voltage V_0 by changing the Input to A2DIF
2. Collect data and calculate the phasor value of the voltage V_0 with both sources operating (see the example above)
3. Replace the voltage source V_2 with a short circuit. This means disconnecting the clip leads and replacing the connection with a wire. The wire will go from the right end of the $1.2\text{-k}\Omega$ resistor to the ground at the bottom of the board. Do not short out the voltage source and do not simply turn it off. Neither of these makes $V_2 = 0$ and one may make smoke!

4. Collect data and calculate the phasor value of the voltage V_0 with V_1 as the only source
5. Remove the short circuit and reinstall the clip leads for the source V_2
6. Remove the clip leads for the source V_1 and replace the source with a short circuit. The wire will go from the left end of the $560\text{-}\Omega$ resistor to the ground at the bottom. Again, do not short the source itself or simply turn it off
7. Notice that the smaller wave (V_0) has gotten quite a bit smaller. Make it larger by changing Channel 2's setting to 100 mV/division .
8. Collect data and calculate its phasor value of V_0 with V_2 as the only source

Results

Now you have data to show whether superposition works. You have the phasor value of V_0 with both sources operating and with each source operating alone. Perform a phasor addition of the two "alone" values see if the result is the same as the "both" value. (You are adding complex numbers, which requires complex arithmetic.)

Compare the results by calculating the percent difference in magnitudes. Percent error doesn't make much sense for angles, so simply state the angular difference.

We have kept Channel 1 of the scope connected to the V_1 source through this whole lab. Why? Because we need a constant phase reference. We are saying that the phase angle of V_1 is 0° no matter how things are connected.

The End

Whew! A bit complicated at the beginning, but once you have done it, this isn't too bad. If you have measured carefully and precisely, you should have gotten very close agreement between the value of V_0 and the value found by superposition.

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Lab B4: Going Back and Forth

Purpose

To *reciprocate* means to go back and forth, and that's where the Reciprocity Theorem in circuits gets its name. We're going to investigate a strange theorem that doesn't sound right when you first encounter it. The Reciprocity Theorem says you can swap a voltage source and an ammeter and the meter will read the same value. (Really!) Let's make some measurements to show how this works.

Introduction

Suppose we have a circuit with several branches. In these branches are the usual circuit elements such as resistors, inductors, and capacitors, along with sources. But most important, all these elements, and hence our circuit, are linear.

Figure 1 shows such a circuit, except that I've suppressed most of the details. Only two branches show, one with a voltage source in it and another with an ammeter in it. Now we observe the reading on the ammeter; suppose it indicates X amperes.

Once we have the reading, we switch the positions of the voltage source and the ammeter. Figure 2 shows this new arrangement. The circuit in the box is unchanged. Again we observe the ammeter reading. Lo and behold! It's X! And that's what the Reciprocity Theorem says is supposed to happen.

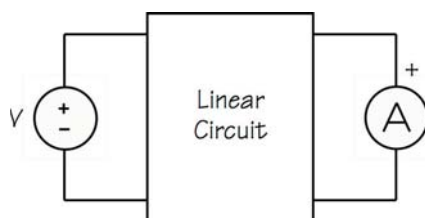


Fig. 1—Reciprocity

Notice the polarities in the two figures. In each, the positive terminal of the source is at the top, and the positive terminal of the ammeter is likewise at the top. The Theorem doesn't say which way these should be; all it asks is that we be consistent. For example, we could invert the source in both drawings and the ammeter readings will still be equal.

What good is all this? In the study of circuits, this Theorem isn't of major importance. But when it comes to electromagnetics, it is very useful. For example, the Theorem says that you can't tell the difference between a transmitting antenna and a receiving antenna. An antenna's transmitting and receiving characteristics are the same.

Objectives

We are going to do just one thing in this lab, namely, show that, for a simple d-c circuit the Reciprocity Theorem really does work.

We will also measure current by measuring the voltage across a known resistance because our ammeter does affect the circuit a little.

Equipment

We are not going to use Mobile Studio Desktop in this lab because our circuit is a simple d-c circuit that requires d-c measurements. Measurements will be made using

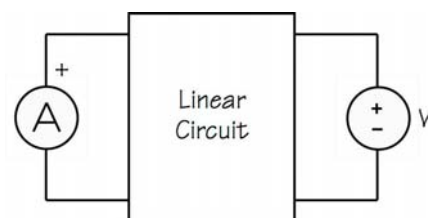


Fig. 2—Reciprocity again

your digital multimeter and the circuit will be built with one of the four-cell battery packs and four resistors: 100 Ω , 300 Ω , 1.2 k Ω , and 2 k Ω .

Procedure

Measure and record the resistance of each of the resistors shown in Fig. 3 so that you can use their actual values to calculate current. Then build on your breadboard the circuit of Fig. 3. Use one of the four-cell battery packs to supply approximately 6 volts to the circuit. Then proceed as follows:

1. Measure the voltage V_S and record it so that we can check later to make sure it hasn't changed.
2. Determine the current i_1 by measuring the voltage across the 2-k Ω resistor and calculating the current. Be sure to use the measured value of the resistor.
3. Likewise, determine the current i_2 by measuring the voltage across the 1.2-k Ω resistor and calculating the current.
4. Remove the voltage source and replace it with a short circuit. This means that the 100- Ω resistor will be connected between the top and bottom nodes of the circuit.
5. Place the voltage source in the right-hand branch in series with the 2-k Ω resistor as shown in Fig. 4. Note that you'll have to separate the ends of the 300- Ω and 2-k Ω resistors to insert the voltage source into the path.
6. Measure the voltage V_S to show that it wasn't changed when the source is moved.
7. Again determine the current i_1 by measuring the voltage across the 100- Ω resistor.
8. Determine the current i_2 by measuring the voltage across the 1.2-k Ω resistor

Results

Tabulate the outcomes of this experiment for these tests to show the source voltage V_S , the measured voltages across the resistors, the measured values of the resistors and the calculated values of the currents.

Compare the currents for the two circuit arrangements. Does i_1 for Fig. 3 equal i_1 for Fig. 4, at least within experimental error? They should, which demonstrates reciprocity.

Now, how about i_2 for both circuits? Are they equal? Why not? Are we attempting to misapply reciprocity here? V_S and i_2 were never exchanged because i_2 wasn't moved. So i_2 is different for different placements of the voltage source.

The End

That's reciprocity. You've shown that it works with d-c circuits provided we properly exchange the voltage source and the ammeter. We could do the same thing with a-c circuits as long as they are linear.

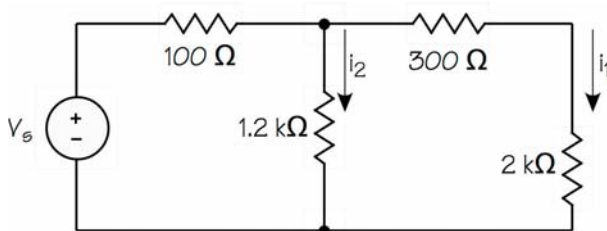


Fig. 3—First circuit

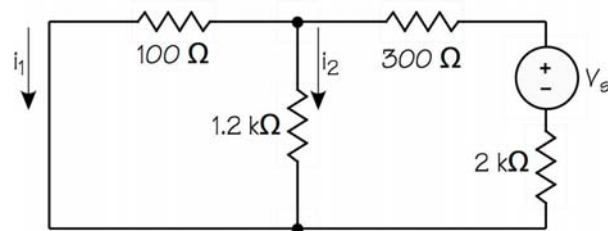


Fig. 4—Second circuit

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Lab B5: Thévenin can be Useful

Purpose

A French telegraph engineer, Léon Charles Thévenin, gets credit for stating that any linear source can be replaced by a simple equivalent consisting of a voltage source and a resistor. When you do this, he said, there is no test you can make at the terminals to determine whether you have the original circuit or the equivalent.

(Thévenin somehow gets credit for saying this in 1883, even though Hermann von Helmholtz made the same statement thirty years previously.)

But why might we want to do this? One answer is that this allows us to find out how such a source and a nonlinear device will interact. To say this another way, it allows us to find the *operating point* of the non-linear device under certain conditions.

What's the operating point? It's just the values of the device's current and voltage. In this lab we are going to determine the operating point for the LED from Lab A4 when it is connected to a particular source. You'll need the graph from Lab A4 or A5 to be able to do this lab.

Goals

Our goals are to determine the Thévenin characteristics of a particular source and then use that information to find the operating point of the LED from Lab A4. The circuit of Fig. 1 is the Thévenin equivalent source, which we will end up connecting to the LED.

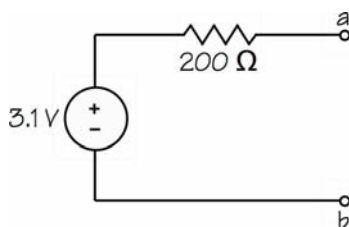


Fig. 1—Thévenin equivalent

Equipment

You'll need the 3-V battery pack, a 200-Ω resistor, a 1-kΩ pot (note: 1-kΩ, not 10 kΩ), and the digital multimeter.

Procedure

1. Record the actual resistance of the 200-Ω resistor, which you'll need for current calculations.
2. Build the circuit of Fig. 1, which is just the battery pack and one resistor. Don't put the 1-kΩ pot into the circuit yet.
3. Use the DMM to measure the open-circuit voltage v_{ab} of the circuit. Mark this point on the graph from Lab A4. Note that the current is 0, so the point will be on the v_D axis.
4. Set the DMM to measure milliamperes. Then use the DMM as an ammeter to short out the terminals $a-b$ and determine the short-circuit current i_{sc} . Mark this point on the graph from A4. Since the voltage is 0 because the ammeter has shorted the terminals, this will be a point on the i_D axis.
5. Now put the 1-kΩ pot into the circuit. Refer to the text and drawings of Lab A4 if you need help. The a and b terminals of the pot should be as shown in Fig. 2.
6. Make a three-column table to record v_{ab} and v_{200} .

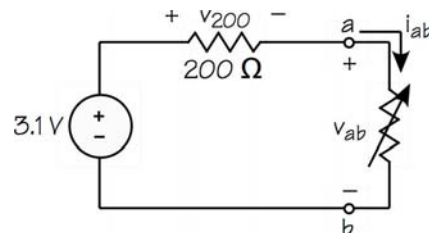


Fig. 2—Test Method

the voltage across the 200- Ω resistor, along with the calculated current i_{ab} .

7. Start with the slot of the pot all the way counter-clockwise and measure v_{200} and v_{ab} .
8. Repeat these measurements at about 9:00, 10:30, noon, and 2:00 o'clock, and fully clockwise.
9. Using the known value of the 200- Ω resistor, calculate the currents i_{ab} and record those in the table.

Operating Point

Plot the data points on the graph from Lab A4, then draw the line for the Thévenin equivalent. All of the points should lie in a straight line.

The operating point of the LED, when connected to this circuit, should be where the straight line of the source and the curve of the LED cross. Why? Because the straight line represents the i - v terminal characteristic of the source and the curve represents the i - v terminal characteristic of the LED. When the LED is in the circuit, it and the source will have the same terminals a - b .

Remove the pot and put the diode into the circuit, connecting the longer of its two leads to the a terminal. If you have the polarities correct, the diode should light up.

Now measure the LED voltage v_{ab} and v_{200} , the voltage across the 200- Ω resistor. Calculate the LED current. This operating current and operating voltage, are the operating point of the LED in this circuit.

Results

Check two things:

- Is the i - v curve for the source itself a straight line? It should be, because the source is a linear source until we draw so much current from it that the battery or the 200- Ω resistor starts to become non-linear.
- Does the measured operating point of the LED match the operating point determined graphically? It should!

What we have just seen is how the Thévenin equivalent can be used with a non-linear device to find the operating point, especially where the i - v characteristic of the non-linear device is hard to represent mathematically. (The Shockley ideal-diode equation for the LED is approximately $i_D = I_D(e^{kv_D}-1)$ where I_D and k have to be determined for the particular diode structure. Note that v_D is in the exponent of the exponential, a very non-linear relationship.)

The End

So it is possible to deal with non-linear devices, and the graphical approach is a simple one! And Thévenin does have an application!

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Lab D1: A-C Power

Purpose

How does energy get from one place to another? Alternating-current systems do this, so it's appropriate to experiment with some aspects of what is called "a-c power." Our purpose in this lab is to collect some data on such a system.

But how? Our small Mobile Studio Desktop and the little IO Board aren't going to let us deal with "power" currents and voltages. We can't try 50 amperes or 13,200 volts. We can't have a load of 30 kilowatts. So it's not hard to conclude that we can't perform any reasonable experiments.

We can, though, if we are clever. We can use much smaller voltages and currents as scaled-down versions of the real values. We can work with small numbers and get results that are, except for size, entirely comparable to what we'd get with real-world values.

Objectives

We will begin by learning how to scale voltages and currents so that we can make power measurements using Mobile Studio Desktop. Then we will study a circuit that, except for the numbers, is typical of a load fed by a non-ideal conductor.

The goals of this lab are

- scale voltages and currents to "small" values
- set up a circuit with a load that is supplied by lossy conductors
- obtain data to be able to calculate load power and reactive power, line losses, and generator voltage

- find the overall efficiency and voltage regulation of our system

Introduction

If we are going to be able to bring the "numbers" for our power circuit into ranges that the IO Board can handle, we have to *scale* them. Here's what I am going to do:

- Scale the frequency by a factor of 100 upward, which changes 60 Hz to 6,000 Hz. Doing this places our usual circuit elements, the inductors and the capacitors, into a range of impedance that allows us to make good measurements.
- Scale the voltages by a factor of 100 downward. This means that a real 120-volt system now becomes a 1.2-volt system.

Is this going to work? Yes, you really will get results that include watts and VARs and volt-amperes. It's just that you have to get used to the idea that, with the scaling, the numbers are much smaller. The first time you get a result of 563 μ VARs...well, it's a bit odd! (Now you know why the word "power" is very small in the title.)

Equipment

Our data collection is via Mobile Studio Desktop and the IO Board. You'll need clip leads on AWG1 and its ground, A1+ and –, and A2+ and –. You'll also need the circuit elements in Fig. 1.

The elements in Fig. 1 model several parts of the power system:

- The resistor and the inductor on the right represent the load, which is where we want to deliver energy. In real life, this might be a motor.

- The two elements at the top represent the power wiring that brings the energy from the generator. In a real circuit, both line wires would have these elements, but to keep things simple, just one will do.
- The source on the left is the generator.

Procedure

1. Measure the resistance of the 200- Ω resistor so it can be used for current calculations.
2. Build the circuit of Fig. 1 and connect the IO Board as shown. You will be using A1 to display the voltage across the load. A2 will be displaying the current as observed via the voltage across the 200- Ω resistor. From these two pieces of data we can find out just about everything about our “power” system.
3. Launch the Function Generator and set it to provide a 6-kHz sine wave at $3.4 V_{\text{peak-to-peak}}$, which is $1.7 V_{\text{peak}}$, which is $1.2 V_{\text{RMS}}$.
4. Hide the Function Generator and launch the Oscilloscope. Adjust the scope to give good displays of the load voltage (via A1DIF) and the line current (via A2DIF).
5. Be sure the Measurement area of the scope is visible on the far right. Then set up the first two blocks there for Ch 1 and Ch 2 in RMS.
6. Now comes a tricky part. This load is designed to operate on $1.2 V_{\text{RMS}}$. The load needs this voltage and it is up to the power system to provide it. Therefore we must adjust the output of the Function Generator so that the load voltage is actually $1.2 V_{\text{RMS}}$. In other words, we need to increase V_{gen} . Watch the RMS voltage displayed for Ch 1 and adjust the output of the Function Generator until the load voltage is $1.2 V_{\text{RMS}}$.

7. Measure the following on the scope:
 - a. Load voltage V_{load} , using 0° as its angle.
 - b. Line current I_{line} , both magnitude and phase, by measuring the voltage across the 200- Ω resistor and calculating the current. (We learned how to do phase-angle measurements in Lab B3.)
7. Move the A2+ and A2– connections to observe the generator voltage V_{gen} and measure this voltage, both magnitude and phase (using the phase of the load voltage as the reference angle of 0°).

Calculations

You now have all the data needed to make a number of power calculations. Knowledge of the load voltage and the line current will lead to everything else. You may wish to make a table of these results, reserving a column for the theoretical values and errors. Use “micro” throughout; i.e., μW , μVAR , and μVA .

1. For the load, calculate P , Q , and the power factor.
2. Calculate the power loss in the line.
3. Determine for the generator P , Q , and the power factor.
4. Calculate the system’s percent efficiency.
5. Calculate the system’s percent voltage regulation.

Impedances

You also have enough data to be able to calculate the impedances in the circuit:

1. Knowing the voltage and the current for the load,

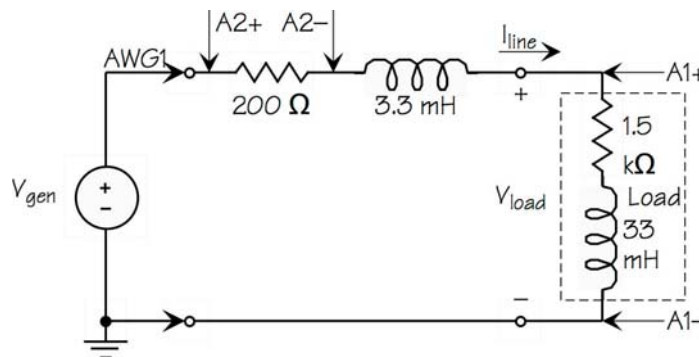


Fig. 1—"Power" measurement

you can calculate Z_{load} .

- From Z_{load} , determine the values of the resistor and the inductor and note how they compare with the nominal values. The frequency is 6 kHz—and don't forget 2π .
- From the generator and load voltages, calculate the phasor voltage drop through the line elements.
- Knowing the voltage and current for the line, you can calculate Z_{line} .
- From Z_{line} , determine the measured values of the resistor and the inductor and note how they compare with the nominal values.
- Recalculate the power loss in the line using this new information about Z_{line} . Where is the additional resistance that has caused a significant error in this loss value?

Results

The values of circuit elements have been determined, so you can calculate the theoretical values of all of the various power parameters. Remember that the frequency is 6 kHz. Add these theoretical values to your data table and then calculate percent errors (except for angles, where error difference is more appropriate).

It isn't hard to scale our results back to the original voltage and current levels. Here are the steps:

- We scale the voltage back up by a factor of 100.
- We scale the frequency and hence the impedances back down by a factor of 100. This means resistors get divided by 100 but inductances stay the same because the frequency in $2\pi fL$ is divided by 100.
- Current is proportional to voltage for a given impedance, but the impedance has been scaled down by 100, so current is scaled up by a factor of 10,000.
- Power to a circuit element is proportional to voltage squared and inversely proportional to impedance. We scale voltage up by a factor of

100, which scales power up by 10,000. We scale impedance down by a factor of 100, which scales power up by 100. The net change is that we scale power up by a factor of 10^6 . In other words, we convert μW and μVAR and μVA by removing the " μ " to get W and VAR and VA.

Let's apply these rescalings to an example set of outcomes of your measurements (not the real data):

$$P_{\text{load}} = 500 \mu\text{W} \Rightarrow 500 \text{ W}$$

$$Q_{\text{load}} = 400 \mu\text{VAR} \Rightarrow 400 \text{ VAR}$$

$$I_{\text{line}} = 0.600/-40^\circ \text{ mA} \Rightarrow 6.0/-40^\circ \text{ A}$$

$$V_{\text{gen}} = 1.30/-2^\circ \text{ V} \Rightarrow 130/-2^\circ \text{ V}$$

$$R_{\text{line}} = 200 \Omega \Rightarrow 2 \Omega$$

$$L_{\text{line}} = 3.3 \text{ mH} \Rightarrow 3.3 \text{ mH} \quad (\text{the scaling is in } f)$$

$$R_{\text{load}} = 1.5 \text{ k}\Omega \Rightarrow 15 \Omega$$

$$L_{\text{load}} = 33 \text{ mH} \Rightarrow 33 \text{ mH}$$

Percent efficiency and percent voltage regulation don't change, but for these data:

$$P_{\text{line}} = (200)(0.600 \times 10^{-3})^2 = 72 \mu\text{W}$$

$$\% \eta = (100)[500/(500+72)] = 87\%$$

$$\% \text{VR} = (100)[(130-120)/120] = 8.3\%$$

The End

How did this scaled system check out? Other than results with strange ranges of values, this system and its measurements are a good analog of a real full-sized system.

This type of scaling is *analog* scaling, where we use analogies to represent a real system. Here we used considerably reduced ranges of voltages and currents to stand in for the real thing. In the days before digital computers, there were analog computers that modeled real systems. Some of these, called network analyzers, were very extensive, capable of modeling very large power systems.

Mobile Studio Desktop™

Lab D2: Power Factor

Purpose

The power factor of a load is of some concern for several reasons, including the cost of electrical energy. Power companies often add charges to power bills that in one way or another are connected with the power factor of the load. Controlling and often improving the power factor of a load has fiscal implications.

Objectives

This lab begins where Lab D1 leaves off—with a circuit that represents a load fed by a lossy feeder. As in Lab D1, we will scale the frequency upward by a factor of 100 from 60 Hz to 6 kHz and scale the voltage down by a factor of 100 from 120 V_{RMS} to 1.2 V_{RMS}.

Our objectives here are to “correct” the power factor of our load from Lab D1 and observe several effects:

- reduction in load current and hence reduction in line losses
- increase in overall efficiency
- increase in load voltage
- improvement in voltage regulation—up to a point
- loss of control of voltage by going “too far”

Equipment

Use the same setup that you used in Lab D1 (repeated here as Fig. 1). You’ll also need a range of capacitors from 0.001 μF up to about 0.047 μF . (Suggested values are 0.001, 0.0022, 0.0047, 0.01, 0.022, and 0.047 μF .)

Procedure

You’ll be using the setup of Fig. 1 to collect four pieces of data for the circuit while changing the capacitor several times.

Measurements

Start by creating a table with ten columns and at least seven rows for recording the data you’ll be collecting. Headings for the first five columns should be C(μF), V_{load}(V), V₂₀₀(mV), I_{line}(mA), and V_{gen}(V).

Measure the actual resistance of the 200- Ω resistor so you can calculate current from the voltage across it.

The first data points are with no added capacitor. Then you’ll put various capacitors in parallel with the entire load (i.e., across the 1.5-k Ω resistor and the 33-mH inductor together). In other words, the capacitor goes between the terminals marked A1+ and A1–.

Collect the following data, all of which are phasors:

- Measure the voltage across the load (scope display for A1), choosing its phase angle as 0°
- Measure the phasor voltage across the 200- Ω resistor

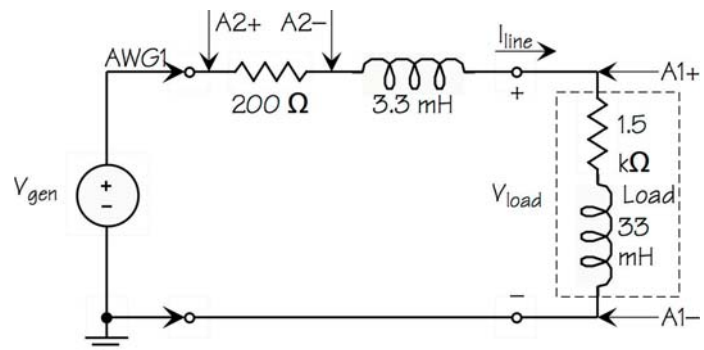


Fig. 1—"Power" measurement

tor (from the scope display for A2)

- Calculate I_{line} (mA)
- Move the A2– clip so A2 observes the generator voltage
- Measure the phasor generator voltage
- Move the A2– clip back to the 200- Ω resistor

Do these steps first without added capacitance and then with six different capacitors, one at a time. If things are going well, you should be noting a slight increase in the load voltage, an increase in the phase angle of the voltage across the 200- Ω resistor from negative to positive, and a steady generator voltage.

Calculations

Complete the remaining columns headed pf_{load} , $P_{\text{load}}(\mu\text{W})$, $Q_{\text{load}}(\mu\text{VAR})$, $P_{\text{loss}}(\mu\text{W})$, and $\%\eta$. Do the calculations needed to fill in these columns:

- pf_{load} calculated from the phase angle of the load current. (Be sure to note lagging or leading)
- P_{load} in μW
- $P_{\text{loss}} = R_{\text{line}}|I_{\text{line}}|^2$ in μW , where R_{line} = measured value of 200- Ω resistor
- Q_{load} in μVAR
- percent efficiency ($\%\eta$)

When you have finished your calculations, draw a line to divide the table at the point where the power factor changes from lagging to leading.

Results

All of the following questions can be answered by looking at the tables you have created:

- What has increasing parallel capacitance done to the power factor?
- Until the power factor “crossed over” from lagging, what is the magnitude of the current doing?
- Until the power factor crossed over, what has happened to the system’s losses?
- Likewise, what has happened to percent efficiency?
- What has the leading power factor done to the load voltage? Remember that the load voltage was supposed to be $1.2 V_{\text{RMSK}}$, but we didn’t readjust the generator voltage to hold the load voltage constant.

The End

Your results should show that improving the power factor makes some important changes in the operation of the electrical system. There are two important lessons to be learned here. First, moving a lagging power upward to closer to unity reduces system losses. Second, crossing over to a leading power factor yields undesirable voltage problems.

How does a customer decide whether to add capacitors to the load to improve the power factor? The decision is a financial one, made by looking at the amortized cost of adding capacitors compared with the savings on the bill from the power company.

Mobile Studio Desktop™

Lab E1: It's Time to be Constant

Purpose

The “E” series of labs is about circuits in the time domain. It's about the response of a circuit to a disturbance such as a step input of voltage. Since our circuit elements are all linear, their responses are all governed by linear n^{th} -order differential equations with constant coefficients. These solutions are always in the form of exponentials and combinations of exponentials.

In this lab we'll observe and collect data from the exponential response of a 1st-order circuit when excited by a step input voltage. Our primary goal is to measure the time constant of the circuit and relate it to the circuit's element values.

Objectives

The objectives of this lab are

- Observe on the oscilloscope the exponential response of a 1st-order circuit
- Measure on the scope the circuit's time constant
- Relate the time constant to the circuit's element values
- Measure the rise time of the exponential response and relate this to the time constant

Equipment

This lab requires a laptop running Mobile Studio Desktop and the IO Board with four clip leads attached. Clip leads should be attached to the output of the Function Generator: AWG1+ and Ground, and A2+ and A2–.

Procedure

1. Measure the 2-k Ω resistor so you know its value.
2. Build the circuit of Fig. 1. AWG1+ is the output of the Function Generator. A2+ and A2– are the A2 differential input that will drive one channel of the scope. (We use differential so that connecting the scope does not introduce a second ground.)

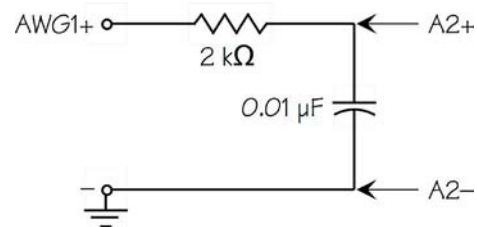


Fig. 1—Circuit setup

3. Set the Function Generator, Channel 1, to 4.00 kHz, 0°, square wave, 0 offset, 2.0V peak to peak. Then click its pushpin in the upper right corner to hide it.
4. Set up the Oscilloscope as follows:
 - a. Channel 1 to 500 mV/div, DC, AWG1
 - b. Channel 2 to 500 mV/div, DC, A2DIF
 - c. Trigger to Auto, Ch1, Rising
 - d. Horizontal to 50 μ s/div
 - e. Click Start
5. You should see the display of Fig. 2 (next page).

Measure time constant

The time constant of the circuit is fairly easy to measure, but doing it with some precision requires attention to the

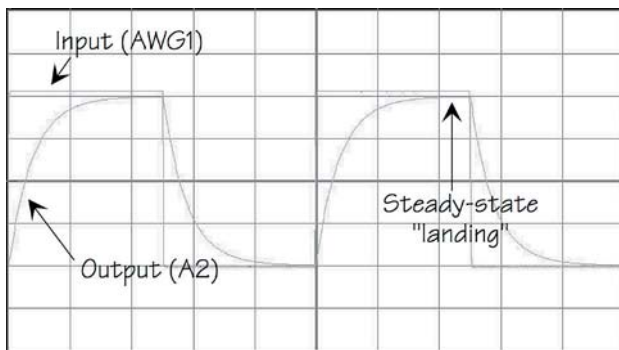


Fig. 2—Exponential response

scope settings. The basic idea is that one single sweep of the exponential waveform should fill the screen, both vertically and horizontally.

1. Change the horizontal setting to 10 $\mu\text{s}/\text{div}$. This should make the exponential fill the screen from left to right. The goal is to fill the screen with the exponential starting on the left and getting close to steady-state by the time it gets to the right end.
2. Change the vertical setting of Channel 2 to 250 mV/div, which should just fill the screen vertically. The start should be in the lower left corner and the steady-state “landing” should be at the top.
3. The scope gives you finer control of both amplitude and position with the two sets of up and down arrows in the controls for the vertical channels. Use these if you need to so the trace looks like Fig. 3.
4. Recall that the time constant τ is the time the exponential takes to go from its start to $1/e$ of its starting value. If the exponential starts at, say, A and heads for 0, the time constant is the time taken to reach A/e .

Your scope should show an exponential that starts in the lower left corner and “falls” to its steady-state value by crossing through eight divisions. Now, $1/e = 0.368$, very close to $0.375 = 3/8$ (1.9% off).

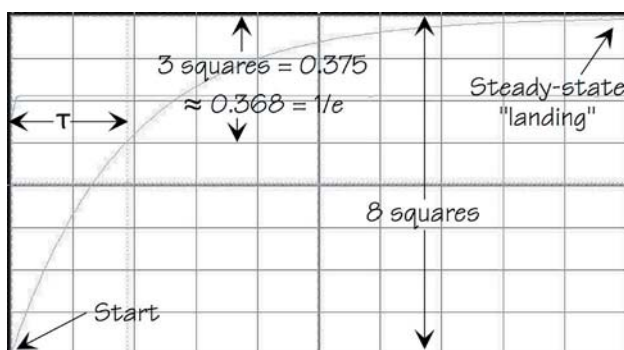


Fig. 3—Measuring time constant τ

So the time constant can be taken from the time the exponential requires to cross through five of the eight divisions.

5. The measurement is made using the cursors. The blue long-dash vertical cursor is set to the start of the exponential; the blue short-dash cursor is set to the point where the exponential crosses the third grid line from the top.
6. The time constant τ is read from the “delta” portion of the data for the blue cursors.
7. Using your knowledge of the time constant τ of an RC circuit and the value of the resistance R , calculate the value of the capacitance C . How does this compare with the capacitor’s marked value? [Clue: The data shown in Fig. 3 yield $C = 0.00955 \mu\text{F}$, a difference of 4.5% from the marked value in Fig. 1.]

Measure rise time

The rise time of a pulse or an exponential is the time it takes to go from 10% of its amplitude to 90% of its amplitude. Once this time is known, it is not hard to show that the time constant is the rise time divided by 2.20 (more exactly, $\ln(9) = 2.1972$). In this part we’ll measure the rise time.

1. Your exponential should be rising from -1 V to $+1 \text{ V}$, a total of 2 V . Hence 10% is at -0.8 V and 90% is at $+0.8 \text{ V}$.
2. Use the cursors to establish these points on the scope (see Fig. 4):
 - a. Blue long-dash cursors intersecting on exponential at -0.8 V
 - b. Blue short-dash cursors intersecting on exponential at $+0.8 \text{ V}$

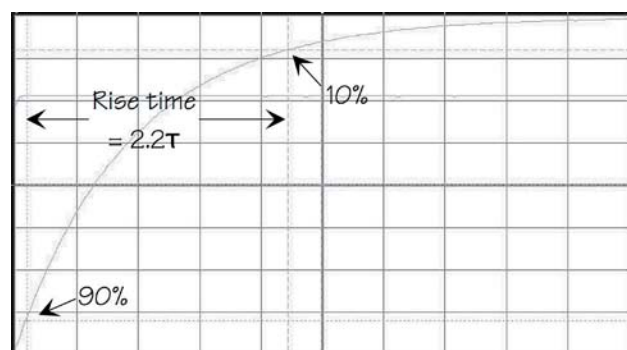


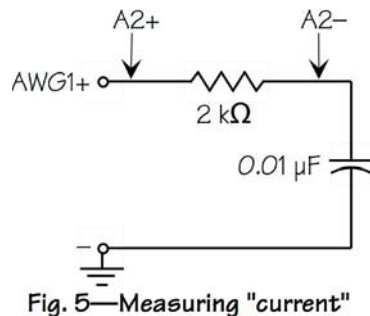
Fig. 4—Measuring rise time

3. Read the rise time t_r from the “delta” portion of the data for the blue cursors.
4. Calculate the time constant τ as $t_r/2.20$.
5. Calculate C again. [Clue: Data in Fig. 4 yield $0.00988 \mu\text{F}$.]
6. Restore the scope to the original display: both channels set to 500 mV/div , horizontal set to $50.0 \mu\text{s/div}$.
4. Set the vertical for Channel 2 to 250 mV/div . Then use the larger down arrow to move the steady-state level to the bottom of the screen.
5. These actions don’t quite fill the screen, so we use the tiny up and down arrows next to the Volts/Div box to expand the waveform. We want the waveform to start exactly at the top of the screen and “land” exactly on the bottom.
6. Now we can use the 3/8 method to read τ again.
7. Calculate C once more. [Clue: Data in Fig. 7 yield a time constant of $18.65 \mu\text{s}$.]

Observe the current

Although the scope responds only to voltage, we can observe current by observing the voltage across a known resistor. In this part we’ll observe the current by looking at the voltage across the $2\text{-k}\Omega$ resistor, whose value you have already measured.

1. Move the A2 inputs to positions shown in Fig. 5.



2. You should see the “wild” exponentials as in Fig. 6. The current is not continuous from one step of the input to the next. Why?
3. Spread the waveform horizontally by setting the horizontal to $10.0 \mu\text{s/div}$.

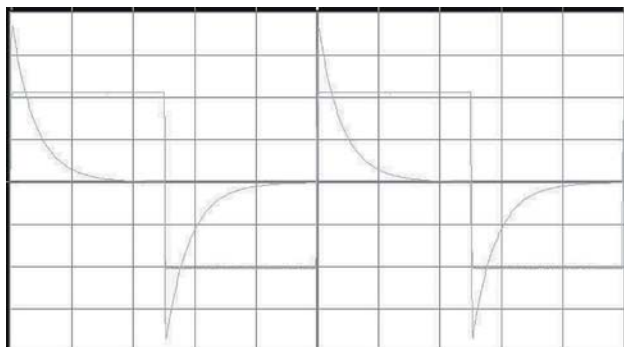


Fig. 6—Current waveform

Results

We’ve had a few new things in this exercise:

- The scope provides an excellent way to measure characteristics of a waveform.
- The scope’s cursors are very useful for getting numerical data from the screen.
- The time constant is related only to the values of the circuit elements, in this case R and C .
- The rise time is a characteristic of waveforms that can yield the time constant for an exponential.

The End

Show in your lab journal the circuit and the connections you have used, data taken from the ohmmeter and the scope, the time constant as measured several times, and the value of the capacitor calculated several times.

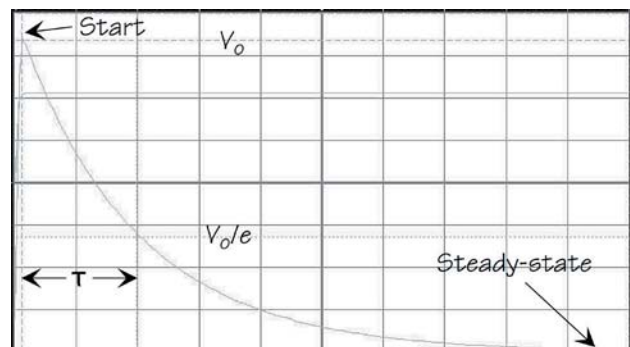


Fig. 7—Current rise time

Mobile Studio Desktop™

Lab E2: Inducing an Inductor's Value

Purpose

Now it's time to test our ability to measure time constants by determining the value of an inductor. In this lab we'll use an RL circuit with a known R, measure the time constant of the circuit's step response, and calculate the value of the inductance.

Objectives

The objectives of this lab are

- Practice making scope adjustments
- Measure the time constant of a first-order circuit
- Determine the value of the inductor in the circuit

Equipment

This lab is based on Mobile Studio Desktop and the IO Board with four clip leads attached. Two leads should be on AWG1+ and Ground and two on A2+ and A2–.

The circuit requires an inductor in the range of 10 to 100 mH and a 100- Ω resistor

Procedure

1. Measure and record the resistance of the 100- Ω resistor for use in calculations later.

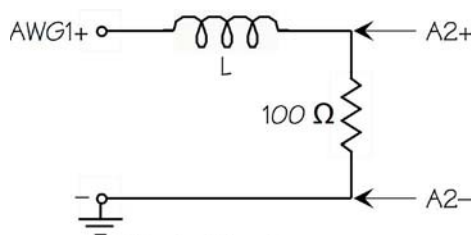


Fig. 1—Circuit setup

2. Build the circuit of Fig. 1 and connect it to the IO Board as shown.
3. Set the Function Generator, Channel 1, to provide a square wave, 2 V peak-to-peak. Try an initial frequency of 1 kHz.
4. Adjust the Oscilloscope to get a good display of the square wave (AWG1 on Channel 1) and the exponential response (A2DIF on Channel 2).
5. The display of the exponential is probably not good enough for measurement of the time constant. You probably have a quick sweep of the exponential and a lot of "tail" before the next repetition. Change the frequency of the Function Generator to shorten the "tail." [Clue: Raising the frequency makes the periods shorter.]
6. Once you have a good exponential, expand it horizontally so one exponential fills the length of the screen.
7. Expand the exponential vertically and move it up or down until you have it starting in the lower left corner and the steady-state "tail" running along the top of the screen. You may need to use the large up and down arrows to move the waveform vertically and the very small up and down arrows

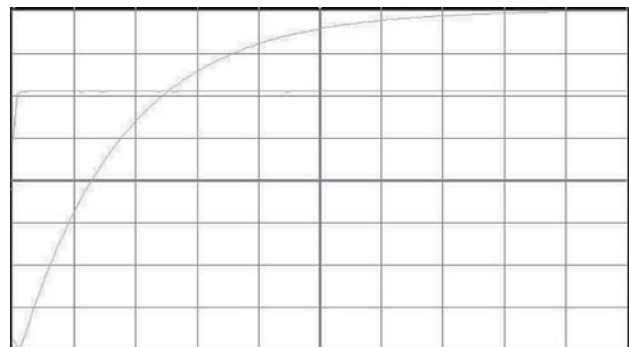


Fig. 2—Exponential expanded to full screen

to adjust the volts/division by a small amount. You can also change the voltage provided by the Function Generator. Figure 2 shows a good exponential display.

8. Recalling that $3/8 \approx 1/e$, determine the time constant.
9. Calculate the value of the inductance from the resistor value and the time constant.
10. Reset the scope so that the original square wave and the exponential appear.
11. Move the A2 clip leads to observe the inductor voltage and note that it is discontinuous whereas the voltage across the resistor was continuous. Why?

Results

The most important result is the practice at adjusting the scope to get the desired display. The second result is finding a technique for measuring inductance.

The End

You have made a lot of different settings of the scope to get “good” displays, and these should be noted in your journal along with the measured resistance, the time constant, and the calculated inductance. Also include a sketch of the inductor voltage waveform (or a printout of the scope screen).

Mobile Studio Desktop™

Lab E3: Phrenology of a Waveform

Purpose

Phrenology is the “science” of determining mental characteristics by reading the bumps on a person’s head. It was popular in the 1800s. In this lab we are going to read the bumps on a waveform produced by a second-order system and deduce the system’s characteristics from them.

Objectives

The objectives of this lab are

- Observe the response of a second-order system on the Oscilloscope
- Use zero crossings to determine the period and frequency of oscillation
- Use heights of adjacent peaks to determine the system’s damping ratio
- Relate these characteristics to the differential equation for the system

Equipment

Lab data will be collected using Mobile Studio Desktop and the IO Board. The IO Board needs clip leads on AWG1 and its Ground and on A2+ and A2–.

The circuit requires a 33-mH inductor, a 1-k Ω resistor, and a 0.01- μ F capacitor.

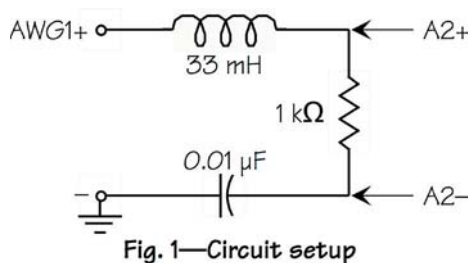


Fig. 1—Circuit setup

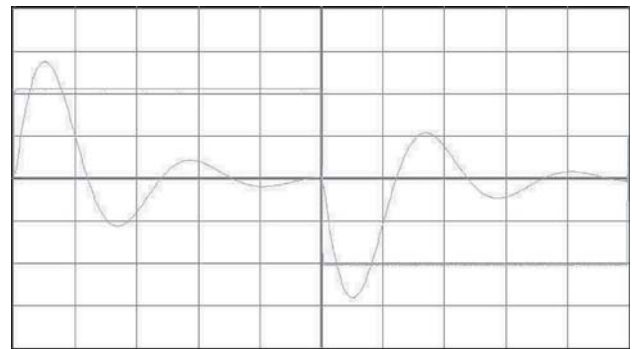


Fig. 2—Oscillatory response

Procedure

1. Measure and record the resistor’s resistance. If you have facilities for doing it, measure and record the inductance and the capacitance. Otherwise, just record their nominal labeled values.
2. Adjust the Function Generator to provide 2-kHz, 0°, square wave, 0 offset, 2.0 V peak-to-peak.
3. Display the waveform on the Oscilloscope.
4. Adjust the scope so that the resultant waveform occupies a large part of the screen. Figure 2 shows how a good picture should look.

Waveform measurements

1. We will use the scope to measure period. This can be done in three ways:
 - a. Measure the time between successive zero crossings that cross in the same direction
 - b. Measure the time between two adjacent zero crossings and double the result

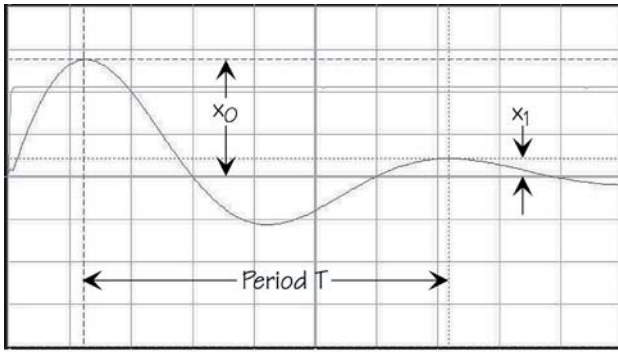


Fig. 3—Parameter measurement

- c. Measure the time between two adjacent peaks
2. We'll do all three. Adjust the scope once more so that just one repetition of the waveform appears. [Clue: Change the horizontal setting.]
3. Use all three methods above to measure the period. Record your results. Figure 3 shows how the third method was carried out. Average the three readings to get the period T .
4. Measure the heights of the first two peaks of the waveform, recording the values of x_0 and x_1 in consistent units (voltages as read from the cursors).

Parameter extraction

We now have enough data to extract the three parameters that define a second-order system: the damped natural frequency, the undamped natural frequency, and the damping ratio.

1. Calculate the frequency of oscillation f :

$$f = \frac{1}{T}$$

2. Calculate the damped natural frequency ω_d :

$$\omega_d = 2\pi f$$

The result is in radians/second.

3. Calculate the logarithmic decrement δ :

$$\delta = \ln \frac{x_0}{x_1}$$

The result is unitless.

4. From the logarithmic decrement δ , calculate the damping ratio ζ :

$$\zeta = \frac{1}{\sqrt{1 + \left(\frac{2\pi}{\delta}\right)^2}}$$

The result is also unitless.

5. Finally, calculate the undamped natural frequency ω_n :

$$\omega_n = \frac{1}{\sqrt{1 - \zeta^2}} \omega_d$$

The result is in radians/second.

Comparison with circuit

The differential equation for the natural response of this circuit is

$$L \frac{d^2 i}{dt^2} + R \frac{di}{dt} + \frac{1}{C} i = 0.$$

If we assume zero initial conditions, the Laplace transform transforms this to

$$Ls^2 + Rs + \frac{1}{C} = 0,$$

$$s^2 + \frac{R}{L}s + \frac{1}{LC} = 0.$$

The standard form of this polynomial, using the parameters we have extracted, is

$$s^2 + 2\zeta\omega_n s + \omega_n^2 = 0.$$

Using the known values of the circuit elements, calculate the undamped natural frequency ω_n and the damping ratio ζ . Then compare these with the results you have extracted from the scope display of the response. If you have worked carefully (and if the circuit elements really have the right values!), you may be surprised at how closely your results and the theoretical values compare.

Results

We have used the scope in a fairly complicated setting to determine the parameters of a second-order system.

- The procedure used in this lab works quite well for circuits whose damping ratio is less than about 0.5.
- For second-order systems with damping ratios between 0.5 and 0.8, a method other than logarithmic decrement is needed, namely, fractional overshoot.
- It is difficult to get precise parameter extraction for damping ratios between 0.8 and 1.0.
- This procedure doesn't apply to second-order systems with damping ratios greater than 1.0 because they are overdamped and do not exhibit oscillatory behavior.

The End

Your lab journal should contain a complete record of what you have done, all of your data and calculations, and the comparisons between your results and what theory says.

Mobile Studio Desktop™

Lab F1: Going through a Phase

Purpose

Phasors are the bread-and-butter of the sinusoidal steady state, so we need to be able to “measure phasors,” whatever that might mean.

Since phasors consist of just two pieces of information, the magnitude of the sinusoid and its phase relative to some other sinusoid, it seems logical that we need to be able to measure magnitude and phase!

Oscilloscopes are good at measuring magnitudes. They are also good at measuring the time difference between two events. So it sounds like our scope can do the whole job.

Objectives

We’ve got three objectives, all of which are related to “measuring phasors” using the scope:

- Measure a phasor’s magnitude, which we will do in RMS, since that is the standard way that “power people” state magnitudes
- Determine the phase relationship between two sine waves using the scope to get the time difference between them, which will be a review of Lab B3
- Make phasor measurements on a simple R-C circuit and compare the outcomes to theory

Prelab

Before beginning this lab exercise, you should do some preliminary calculations for the circuit of Fig. 1:

- Determine the phasor voltage V_o , stating both its magnitude (V_{RMS}) and its phase (in degrees)

- Determine the phasor current I_1 , both magnitude and phase

Equipment

You’ll need Mobile Desktop Studio and the IO Board with four clip leads attached (A2+, A2–, and AWG1 and its ground), plus the parts shown in Fig. 1.

Procedure

Here is a trick that will help your observations if you find the scope traces too jittery to deal with. Go to DISPLAY OPTIONS → AVERAGING and set the number of traces to average to, say, 8. This tends to smooth out noise while enhancing the repetitive signal.

Voltage measurement

1. Measure the actual resistance of the 2-k Ω resistor so we can use it to determine current.
2. Build the circuit of Fig. 1 on your breadboard, including the connections to the IO Board.
3. Launch the Function Generator and set its output to provide a 5-kHz sine wave with zero offset and a magnitude of 6.0 V_{peak-to-peak}.

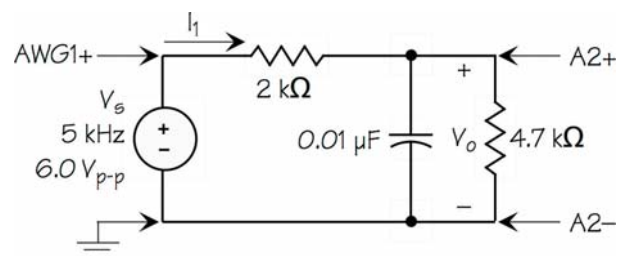


Fig. 1—Circuit setup

4. Set the Oscilloscope as follows:
 - a. Channel 1 to 1 V/div, DC, AWG1
 - b. Channel 2 to 500 mV/div, DC, A2DIF
 - c. Sweep to 20 μ s/div
5. Start the scope and you should have a display of two sine waves.
6. In the Measurements section of the scope (on the far right), set Ch1 and Ch2 for RMS voltages. Then read and record the RMS values of V_s and V_o (Ch1 and Ch2).
7. Enable the Cursors. Then locate the vertical green long-dash cursor, which may be hiding on a grid line or on one edge or the other of the screen.
8. This vertical green cursor is "Cursor 1" in the green box that shows cursor readings. Use it to measure the times of two events on the screen:

Move this cursor to the first downward zero crossing of the green sine wave and record the time shown for Cursor 1. Call this time t_{half} because it's half the period of the green sine wave.

Move this cursor to the first **upward** zero crossing of the blue sine wave and record the time, calling it t_{delay} .

Calculate the phase angle as follows, noting that the result must be marked negative because the output occurs later than the input:

$$angle = -180^\circ \frac{t_{delay}}{t_{half}}$$

9. Write down the output phasor V_o and compare it with the theoretical value you calculated in your prelab calculations. If you have been careful placing the cursors, these should match well.

Current measurement

We are going to find the phasor current I_1 by viewing the voltage across the 2-k Ω resistor.

1. Move the clip leads A2+ and A2– so they measure the voltage across the 2-k Ω resistor, + on the left.
2. In the Measurements section of the scope, read the RMS value of the voltage across the 2-k Ω resistor. Then use this and the measured value of the 2-k Ω resistor to calculate the magnitude of the current I_1 .
3. Notice that this voltage is happening sooner than the input, because it is already started when the input voltage begins. This means it leads the input and hence has a positive phase angle. Measure this phase angle, which is positive because the current here leads the voltage.
4. Record the phasor current I_1 and check to see how well it compares with the theoretical value.

Results

The scope has provided a fairly direct way of measuring the magnitude and the phase of a phasor. The only thing better than the scope would be a meter that measures both of these directly.

We measured phase by measuring the time by which a given waveform was either advanced or delayed relative to another. We then used the half-period of 180° to determine how many degrees were represented by that time measurement.

Did your results come out as expected?

The End

Complete your lab journal to show all of your data and your conclusions. Keep in mind that there is a Print button on the scope that you can use to get a screen shot of what you did.

Mobile Studio Desktop™

Lab F2: Inducing an Inductor

Purpose

How do you measure an impedance? If you have an impedance meter, that's an easy question. For resistors, we have an ohmmeter. An impedance meter, if we had one, would solve the problem.

But we don't have one at the moment! What's next? We certainly know that impedance $Z = V/I$, where both V and I are phasors with magnitude and phase. The oscilloscope can determine magnitude and phase, so it looks like the scope is the way to go.

Objectives

Our primary objective is to measure the impedance of an inductor. We'll use the scope to collect the data and then do some calculations to figure out both the impedance and the inductance of the inductor. This lab has three objectives:

- Determine the inductor's current and voltage when there are grounding restrictions imposed by the scope
- Determine the inductor's current and voltage when there are no grounding restrictions
- Calculate the inductor's inductance and its inherent series resistance

Equipment

You'll be using Mobile Studio Desktop and the IO Board with six clip leads attached. The clip leads should be on AWG1 and its ground, A1+, A1-, A2+, and A2-.

You'll need an inductor, which should be in the 10 to 50 mH range, and a 2-k Ω resistor.

Procedure

Impedance—Method 1

Measure the 2-k Ω resistor with your ohmmeter so you know the exact value.

Build the circuit of Fig. 1 on your breadboard. Connect the IO Board clip leads as shown so that you can observe the signal from the Function Generator (AWG1) on Channel 1 of the scope and the voltage across the 2-k Ω resistor on Channel 2.

Now collect the necessary data to be able to calculate the voltage V across the inductor, the current I through it, and the inductor's impedance Z :

1. Set the Function Generator, Channel 1, to 5.00 kHz, sine wave, 6.0 V peak-to-peak. Then hide its window.
2. Set the Oscilloscope:
 - a. Channel 1 to 1 V/div, DC, AWG1
 - b. Channel 2 to 500 mV/div, DC, A2DIF
 - c. Trigger to Auto, Ch1, Rising
 - d. Horizontal to 20 μ s/div
 - e. Start
3. On the scope, measure
 - a. RMS value of the input voltage V_s
 - b. RMS value of the resistor voltage V_o
 - c. Time by with V_o is delayed from V_s

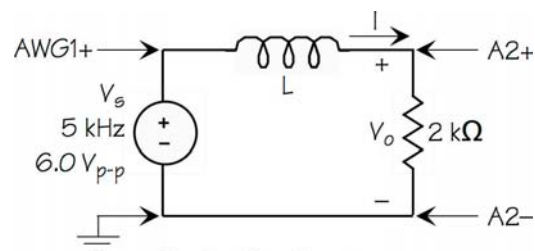


Fig. 1—Circuit setup

- Calculate the phase angle of V_o relative to V_s and record the phasor values of V_s and V_o .
- Now you have enough information to calculate the impedance of the inductor and hence L and R_L :
 - $V_L = V_s - V_o$ (as phasors)
 - $I = V_o / R_{2k}$
 - $Z_L = R_L + jX_L = R_L + j\omega L = V_L / I$ (Clue: Don't miss the need for 2π !)
 - Record R_L and L
- Repeat your measurements and calculations at 10 kHz. Be sure to readjust the scope to give a "good" display, meaning the waveforms fill the screen in both directions. [Note: Phase angles close to 90° can introduce large errors—your data could show, incorrectly, that the resistance is negative.]
- Do this all once more at 1 kHz.
- Set the scope to measure V_L and V_o which means Channel 1 is A1DIF and Channel 2 is A2DIF and get a "good" scope picture again.
- Measure
 - RMS magnitude of V_L
 - RMS magnitude of V_o
 - Time by which V_o is delayed from V_L
- As before, calculate R_L and L . You measured V_L this time, so you don't have to calculate it.

Results

You now have several measures of R_L , the inherent series resistance of the inductor, and L , its inductance. Tabulate these values, showing in your table the values and the frequencies at which they are measured.

Why do they vary? Why especially does the resistance change so much with frequency? A simple explanation is that the inductor model we are using is incomplete. There is also capacitance involved! After all, two conductors side by side exhibit capacitance just by being near one another. As the frequency goes up, this capacitance, which in the model would appear in parallel with both R_L and L , becomes a more prominent factor in the inductor's impedance.

There is also another thing to consider: How did we choose the value of the resistor across which we measured a voltage proportional to the current? If you can, choose a resistance value that is in the same ballpark as the impedance being measured.

For example, the inductor is being tested at 5 kHz = 31.4 krad/s. A 30-mH inductor at this frequency has a reactance of about 950 ohms. Hence the series resistor should have a value somewhere near that. I chose 2-k Ω , but perhaps 1 k Ω would have been a better choice by this rule. Why, considering the accuracy of the desired outcome?

When angles are close to 90° or 0° , large errors can develop in either the real part or the imaginary part of an impedance. In general, best outcomes appear when the phase angle is near 45° .

The End

The primary record of your work in this lab is the tabulation of inductance and resistance values. Also, remember what it means to have common-ground inputs compared with totally ungrounded ("floating") inputs.

Impedance—Method 2

The method for measuring impedances that you just followed will work for any oscilloscope. A problem you will often encounter with scopes is that they have grounded inputs. In other words, each of their inputs is referenced to a common ground. In Fig. 1, this would be as if both AWG1 and A2 had a common ground (i.e., A2— was grounded).

But the scope in Mobile Studio Desktop does not have this common ground. You have been using A2 in *differential* mode, which means the scope is observing the difference between A2+ and A2— without a ground reference.

With no ground restriction, we can measure V_L and I directly. Well, *almost* directly, because we have to calculate I from the voltage across the 2-k Ω resistor.

Add to your circuit the clip leads of the IO Board for A1+ and A1— as shown in Fig. 2. Note that the only ground in the circuit is the ground of AWG1 at the bottom left.

- Set the Function Generator back to 5 kHz.

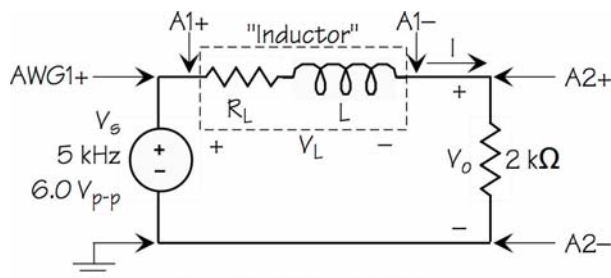


Fig. 2—Second setup

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Lab F3: Resonating with L and C

Purpose

Resonance is a phenomenon that can be observed in second- and higher-order systems. If two energy-storage elements are set up in such a way that they can swap stored energy back and forth, that's resonance. A mass hanging on a spring is an example: the kinetic energy of the bouncing mass is swapped back and forth with the potential energy stored in the spring.

Inductors and capacitors store energy, so placing one of each in a circuit should produce resonance. The circuit we are going to be using here is an RLC series circuit. Magnetic-field energy stored in the inductor and electric-field energy stored in the capacitor swap back and forth as the circuit "resonates."

But something else happens in our RLC circuit: energy is lost during each swap. The swap involves a current that is flowing through the resistance, losing energy during every swap. To keep resonance going, the source makes up the missing energy.

Objectives

Our primary objective is to observe resonance in an RLC circuit, but in getting there, we are going to do several other things:

- Measure the capacitance of a capacitor
- Determine the resonant frequency of the circuit
- Calculate the inductance of the inductor
- Observe the various voltage and current waveforms in the circuit during resonance
- Calculate the total peak stored energy in the inductor and the capacitor and compare the results

Equipment

You'll need Mobile Studio Desktop and the IO Board with six connections: AWG1 and its ground, A1+ and –, and A2+ and –. You'll also need the three circuit elements shown in Fig. 2. The inductor should be in the range of 10 to 50 mH and the capacitor should have a nominal value of 0.1 μF .

Procedure

There are three major parts of this lab, beginning with measuring the value of what should be a 0.1- μF capacitor. Then we'll determine the resonant frequency of the RLC circuit and from that, the value of the inductance.

Measure capacitance

1. Before building the circuit of Fig. 1, measure the actual resistance of the 1-k Ω resistor.
2. Construct the circuit of Fig. 1.
3. Set the Function Generator to 2 kHz, 6 V_{p-p}.
4. Use the scope to display and read the RMS voltages V_C and V_R , and the phase angle by which V_R leads V_C .

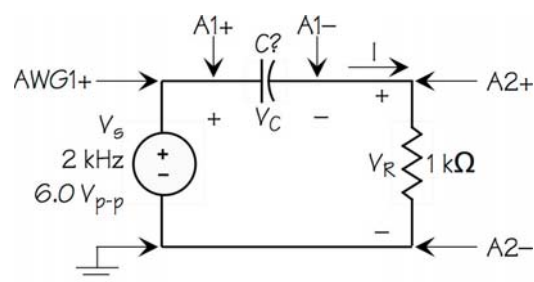


Fig. 1—Capacitor measurement

- Calculate the value (magnitude and phase) of the phasor current I .
- Recalling that $Z_C = V_C / I = R_C + 1/j\omega C$, determine the actual value of capacitance.

Determine f_0

- Build the RLC circuit of Fig. 2. The inductor L should be in the range of 10 to 50 mH.
- Set the Function Generator to provide a 2-kHz sine wave.
- Observe both V_s (AWG2) and the current I (via V_R on A2) on the scope
- Adjust the frequency of V_s until the phase angle difference between V_s and I is zero. This is the resonant frequency f_0 .

Calculate the inductor's value

- The resonant frequency of this circuit is $1/\sqrt{LC}$ where the frequency is in radians/second. Calculate L from f_0 [Clue: Don't forget to bring the pie!]
- Compare the value of inductance with the values measured in Lab F2.

Observe circuit waveforms

For the following observations, the current waveform is provided by A2+ and –. The relevant voltages will be provided by A1+ and A1–. Observations are at the resonant frequency f_0 determined above.

- Connect the A1 inputs to observe the voltage V_L across the inductor. Measure the phase of the current relative to this voltage. I should lag V_L by 90° . Does it?

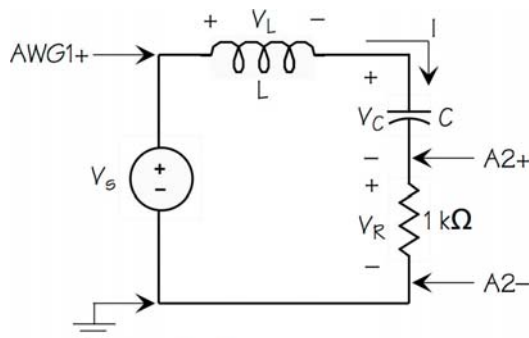


Fig. 2—Resonant circuit

- Likewise, observe the voltage V_C across the capacitor. Measure the phase of the current relative to this voltage. I should lead V_L by 90° . Does it?
- While observing I , slowly reduce the frequency of the input V_s . Note what happens to the magnitude of the current. Increase the frequency above the resonant frequency and note what happens.
- At the resonant frequency f_0 measure the values of V_C and I (via V_R):
 - The energy stored in the inductor is $\frac{1}{2}LI^2$. What is the peak stored energy at the resonant frequency? (Use peak voltage and current.)
 - The energy stored in the capacitor is $\frac{1}{2}Cv^2$. What is the peak stored energy at the resonant frequency? (Use peak voltage.)
 - How do these peak energies compare?

Results

Your data should show the measured value of the capacitor, the resonant frequency, and the calculated value of the inductor.

Be sure to note what happens to the magnitude of the current as the frequency moves in either direction away from f_0 .

Do your data show that the current through an inductor lags the inductor voltage by close to 90° and that the current through a capacitor leads the voltage across it by 90° ?

Finally, resonance is a swapping of energy between the inductor and the capacitor. Hence the peak stored energies in these elements should be equal. How well did these turn out?

The End

Your journal should have collected quite a bit of data on resonance! Be sure you include the circuit and the element values, as well as answers to the questions posed.

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Lab G1: Op-amps Make D-C Bigger

Purpose

The operational amplifier is one of the most useful analog circuit elements. It's a simple device in a way, because all it basically does is amplify. But that ability can be put to use in numerous ways, not only enlarging signals but filtering them in various ways, comparing them, and so on.

In this lab we'll measure some of the d-c characteristics of an op-amp (we get tired of saying operational amplifier pretty quickly!). The circuit we are going to use is an inverter, which means that the op-amp circuit, while amplifying the signal, also turns it upside down. Hence if we put in a positive voltage, we get a negative voltage out.

Objectives

This lab uses a prebuilt op-amp inverter as the basic circuit. Our goals here are

- Learn to power an op-amp properly
- Measure the d-c output-input characteristics of an op-amp inverter
- Graph the output-input characteristic
- Use the oscilloscope to obtain the same graph

Equipment

Along with the standard Mobile Studio Desktop and IO Board, you'll need a prebuilt op-amp board, a dual six-volt power supply (batteries), and two resistors (1 and 3 k Ω) for the prebuilt board.

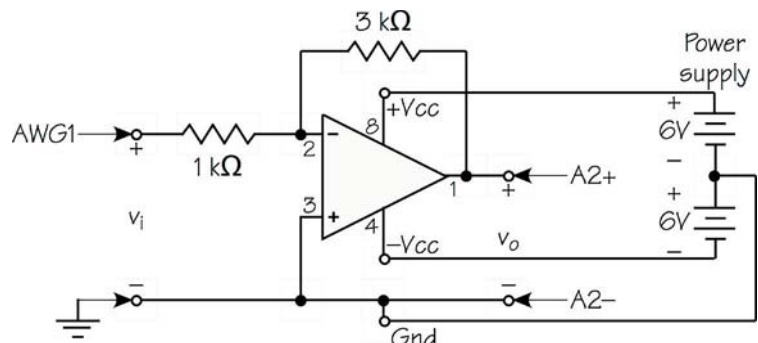


Fig. 1-Op-amp inverter

Procedure

Build the Circuit

Our op-amp inverter needs a couple of things done to it to make it an operating circuit. The circuit you are going to use is shown in Fig. 1:

1. Power the board (see Fig. 2, next page). Be sure to do this right the first time or you'll release the magic smoke and kill the op-amp chip! If you are not certain which leads are which on the battery pack, use your DMM to check them.
2. Populate the bottom eight-pin socket (Fig. 2) as shown in Fig. 3. These two resistors and the jumper will set the op-amp inverter's d-c gain.
3. Connect the leads from the IO Board as shown in the photograph (Fig. 2).

Set up Mobile Studio Desktop

1. Launch Analog I/O
2. Set Analog Out Ch 1: to -3.5 V, which sets the d-c voltage driving the input to the op-amp inverter.

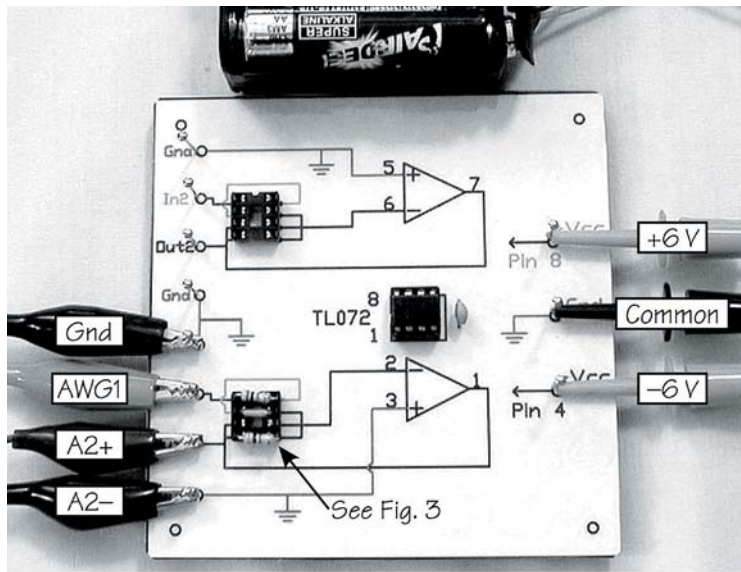


Fig. 2—Op-amp board with connections

- Set up the Analog In meter to Channel: A1DIF to measure the op-amp inverter's output voltage. (Ignore Range and Averaging.)

Measure d-c data

Create a table to record v_i and v_o from -3.5 V to $+3.5\text{ V}$ in steps of 0.5 V . Record voltages to the nearest hundredth of a volt. Then graph this curve on the enclosed graph paper.

[Clue: You can set many of the variables in Mobile Studio by moving the slider with your mouse, rolling the mouse wheel while the slider area is selected, or typing the desired value into the box.]

Same data using the oscilloscope

We can make the scope do the same thing and produce a graph of v_o vs. v_i by setting the scope to plot voltages on both axes rather than time on the x axis. Our input will be a triangular wave that sweeps linearly back and forth between -3.5 V and $+3.5\text{ V}$.

- Launch the Function Generator
- Set Ch 1: 1.000 kHz, 0° , Triangle, 0.0 V offset, 7.000 V Pk-Pk
- Auto Hide the Function Generator (push pin)
- Launch the Oscilloscope
- Set up the scope as follows:

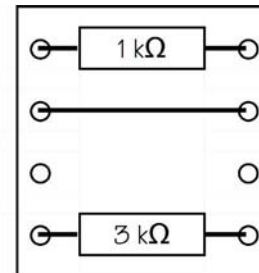


Fig. 3—Input and output resistors

Horizontal: Mode: X-Y

Channel X: 1 V/div, DC, AWG1

Channel Y: 2 V/div, DC, A2DIF

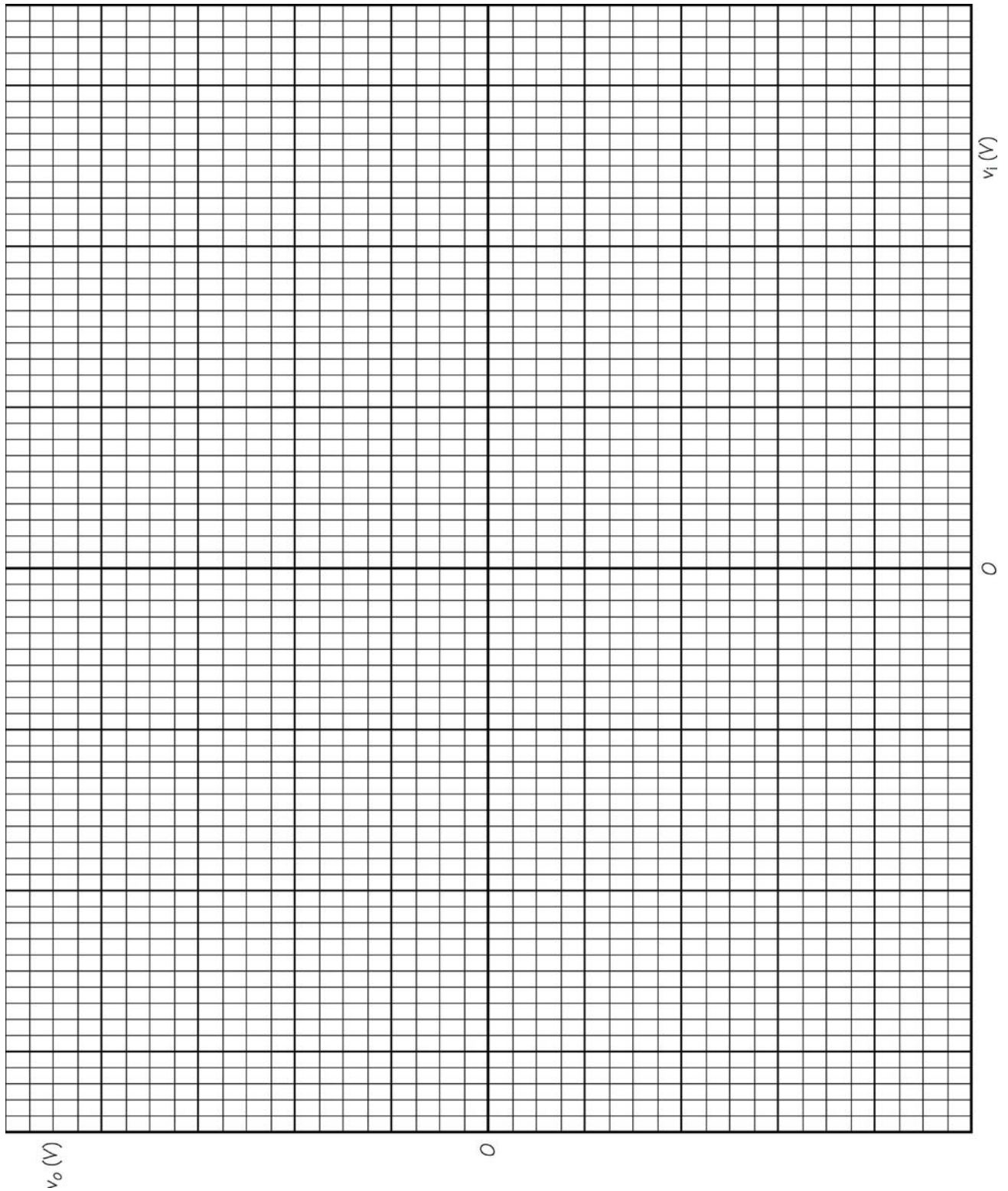
- Start the scope, which should display a trace much like what you have plotted from your d-c measurements
- Take a snapshot of the scope using the camera button on the upper left. Choose an image type (PNG is default) and location (Desktop will work). Name the file and save it. When asked, choose a white background, which prints better than black
- Check the saturation voltages (roughly $\pm 4.5\text{ V}$) against the d-c graph that you drew earlier

Results

You should have a hand-drawn graph of v_o vs. v_i for the circuit of Fig. 1 and a picture of the scope drawing the same graph. How well do they compare? Do they yield the same saturation voltage values? Can you figure out a way to use the scope controls to make that graph occupy the majority of the screen in both directions instead of only about half of it?

The End

Two things should stick with you. First, the op-amp circuit really does both amplify and invert. Second, the scope is a versatile tool that can even plot graphs.



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Lab G2: And A-C, Too

Purpose

The op-amp inverter of Lab G1 (redrawn here as Fig. 1) also does interesting things to sine waves and other signals. We'll take a look at the effect this circuit has on signals to get some idea of what its limits are.

Objectives

We are going to do two things in this lab:

- Observe what happens to a sine wave when that sine wave is larger than the op-amp inverter can handle
- Drive the op-amp inverter with a square wave and see how this affect the "squareness" of the signal

Equipment

You'll need the standard Mobile Studio Desktop and IO Board, the prebuilt op-amp board you used in Lab G1, along with the dual 6-V power supply.

Procedure

Be sure the prebuilt op-amp inverter is set up the same way as it was in Lab G1. Go back to that lab, especially Fig. 2 there, if you aren't sure the board is correct.

Sine waves

Let's see first what happens when we drive the input with a sine wave, and then with a "too big" sine wave:

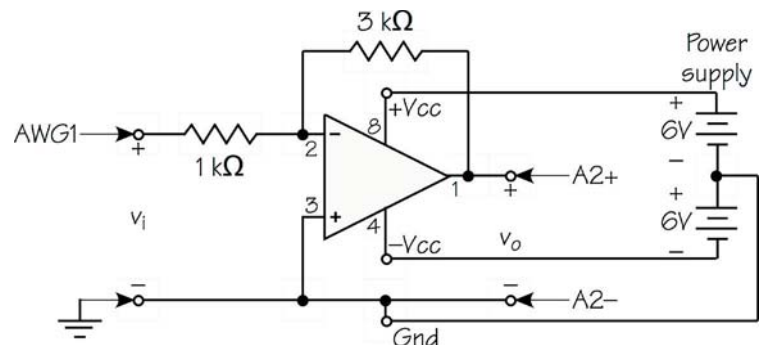


Fig. 1—Op-amp inverter

1. Function Generator: Ch 1: 1.000 kHz, 0°, Sine, 0.0 V offset, 2.000 V Pk-Pk
2. Scope: Trigger: Auto, Ch 1, Rising
Horizontal: Y-T, 100 μs/div
Channel 1: 500 mV, DC, AWG1, Enabled
Channel 2: 2 V, DC, A2DIF, Enabled
3. Observe that the output is shifted 180° from the input because the op-amp inverts
4. Change Channel 1 of the Function Generator to 3.000 V Pk-Pk. Does the output still keep its "sine" shape?
5. Change Channel 1 of the Function Generator to 4.000 V Pk-Pk. What has happened to the sine wave?
6. Use the scope's cursors to measure both the positive and negative values of the output saturation voltage.
7. Compare the clipping voltage results with your results from Lab G1

Square waves

Now let's see what happens when the input is a square wave:

1. Set Channel 1 of the Function Generator to 1.000 kHz, 0°, Square, 0.0 V offset, 2.000 V Pk-Pk
2. On the Scope, disable Channel 1 (just to get it out of the way) and change Channel 2 to 1 V/div
3. How does the square wave look? Look at it carefully to see if you can determine how "square" it looks
4. Change the Function Generator frequency to 10.000 kHz
5. Set the Scope's Horizontal sweep to 10 μ s

Are the vertical lines of the square wave really vertical? Exactly? Determine the slope of one of the vertical transitions in volts per microsecond. You can do this by noting the total voltage swing of one of the lines and how many microseconds that swing takes.

You probably have observed something like 3 or 4 volts/ μ s. This "swing" in amplifier parlance is called the *slew rate* and is generally given in the op-amp's data sheet. For the TL072 that you are using, the slew rate is nominally 16 V/ μ s. Why does this particular chip appear to be performing poorly? Let's do some checking.

On the Scope, enable Channel 1 and disable Channel 2. Look closely at the "slew rate" of the square wave coming from the Function Generator. Is this where the apparently-faulty data about the op-amp really is coming from? How "good" is MSD's square wave?

Results

You should have collected some data on the voltage levels at which this op-amp inverter clips the sine wave by saturating, and these numbers should agree with the results from Lab G1.

You also have data to show that the circuit can handle square waves, but the slope of the vertical transitions is not 100% vertical. Can it ever be perfect? Why or why not?

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Lab H1: Low-Pass Active Filter

Purpose

The circuit of Fig. 1 is almost the same as the op-amp inverter in Labs G1 and G2. It still has the 1-k Ω input resistor and the 3-k Ω feedback resistor; these give the inverter a gain of $-3/1 = -3$. It still has the same power supply.

But the one additional part, a 0.022- μ F capacitor, changes this inverter into a low-pass filter. Now the op-amp has a gain that is dependent upon the frequency of the input signal. For example, a 100-Hz signal will still be amplified with a gain of -3 . But a 3,000-Hz signal will see a gain of only about -2 .

The capacitor looks more and more like a short circuit as the frequency goes up, so the feedback impedance is reduced more and more as the frequency rises. The gain of the circuit diminishes as the frequency goes up.

Objectives

While our primary goal is to see how this low-pass filter responds to a range of frequencies, we are going to deal with several other matters:

- Collection of output-vs.-input data over a large range of frequencies
- Conversion of the observed gain to decibels (dB)
- Presentation of the results graphically on a semilog graph, known as a Bode (bo' duh) plot

Equipment

This lab uses the usual Mobile Studio Desktop and IO Board and the prebuilt op-amp board as in Labs G1 and G2. But the op-amp board has a capacitor added to

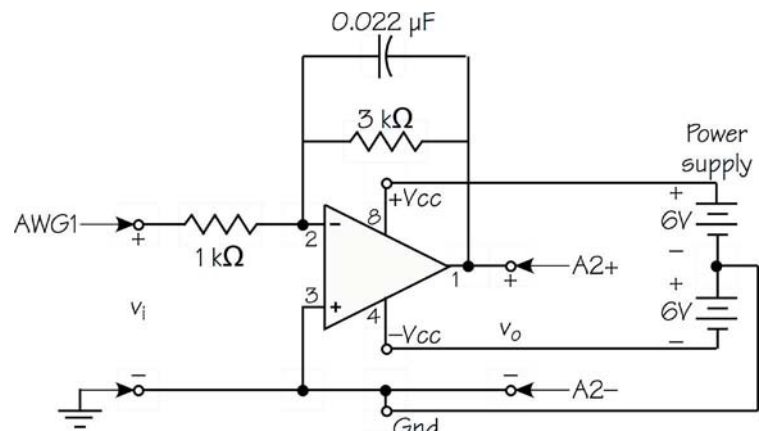


Fig. 1—Op-amp inverter

the square block (Fig. 2) to give the circuit the low-pass characteristic.

Procedure

Build, by adding the 0.022- μ F capacitor, the circuit of Fig. 1 with the dual 6-V (battery) power supply and the connections to the IO Board.

(See Fig. 2 in Lab G1 if you need help.)

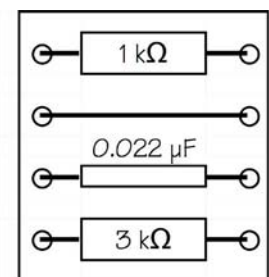


Fig. 2—Input and output impedances

Measurement

The Function Generator is going to provide a sine wave signal for the filter's input at 2 V peak-to-peak. We'll vary the frequency and observe the output voltage. We are interested in the magnitude of the gain of the circuit as a function of frequency. This means we need to be consistent in the input and output voltage units. Here we will use **peak-to-peak** for both input and output.

1. Set the Function Generator to Ch 1: 0.100 kHz, 0°, Sine, 0.0 V offset, 2.000 V Pk-Pk

- Set the Function Generator aside by clicking on the small triangle in the upper right corner and selecting *Floating*, which will shrink the window, leaving the frequency visible
- Set the Oscilloscope as follows:

Channel 1: 500 mV/div, DC, AWG1

Channel 2: 1 V/div, DC, A2DIF

Horizontal: 1 ms/div

Trigger: Auto, Ch1, Rising
- Create a table with five columns and about thirteen lines. Head the columns f (kHz), v_i (V), v_o (V), $|Gain|$, and dB

Data collection

Look at the semilog paper on the next page and note the logarithmic axis. It steps by decades. We'll put 0.1 kHz on the left, 1.0 kHz at the beginning of the next decade (about 1/3 of the way along the axis), 10 kHz on the next decade, and 100 kHz on the far right. There is no sense taking data along a linear scale such as 100, 200, 300, etc., because these are very small steps in decades to the right.

We need to collect data in *logarithmic* steps that are roughly uniform along the logarithmic axis. One set of steps that works pretty well is "1, 2, 4, 7." We use those steps in every decade. In the leftmost decade, they are 0.1, 0.2, 0.4, and 0.7. In the next decade they are 1, 2, 4, and 7. And so on.

Read on the scope the peak-to-peak input (v_i) and output (v_o) voltages and record them at the frequency of 0.100 kHz

Change the Function Generator's frequency to 0.200 kHz and record the next voltages. Continue, using the 1, 2, 4, 7 stepping, until you reach 100 kHz.

Keep the scope picture *large*. This means that, as the displayed output voltage gets smaller, change the V/div to keep it as large as possible.

Calculation and graphing

Calculate the gain of the low-pass filter at each frequency as $|gain| = |v_o| / |v_i|$ and record these in the data table.

Calculate the gain in dB and record these results in the data table:

$$dB = 20 \log_{10} |gain| = 20 \log_{10} \frac{|v_o|}{|v_i|}$$

Plot the data on the semilog Bode plot. There is only one way to hold the graph paper: Turn the paper as you see it on the next page one quarter turn *clockwise*. That maneuver places the small printed numbers at the top of your graph.

Label the horizontal axis in logarithmic units: 0.1, 0.2, 0.4, 0.7, 1.0, 2.0, and so on to 100. Label the vertical axis in dB. -25 dB at the bottom with major steps of 5 dB works well.

Plot the data (dB vs. frequency) on the graph.

Results

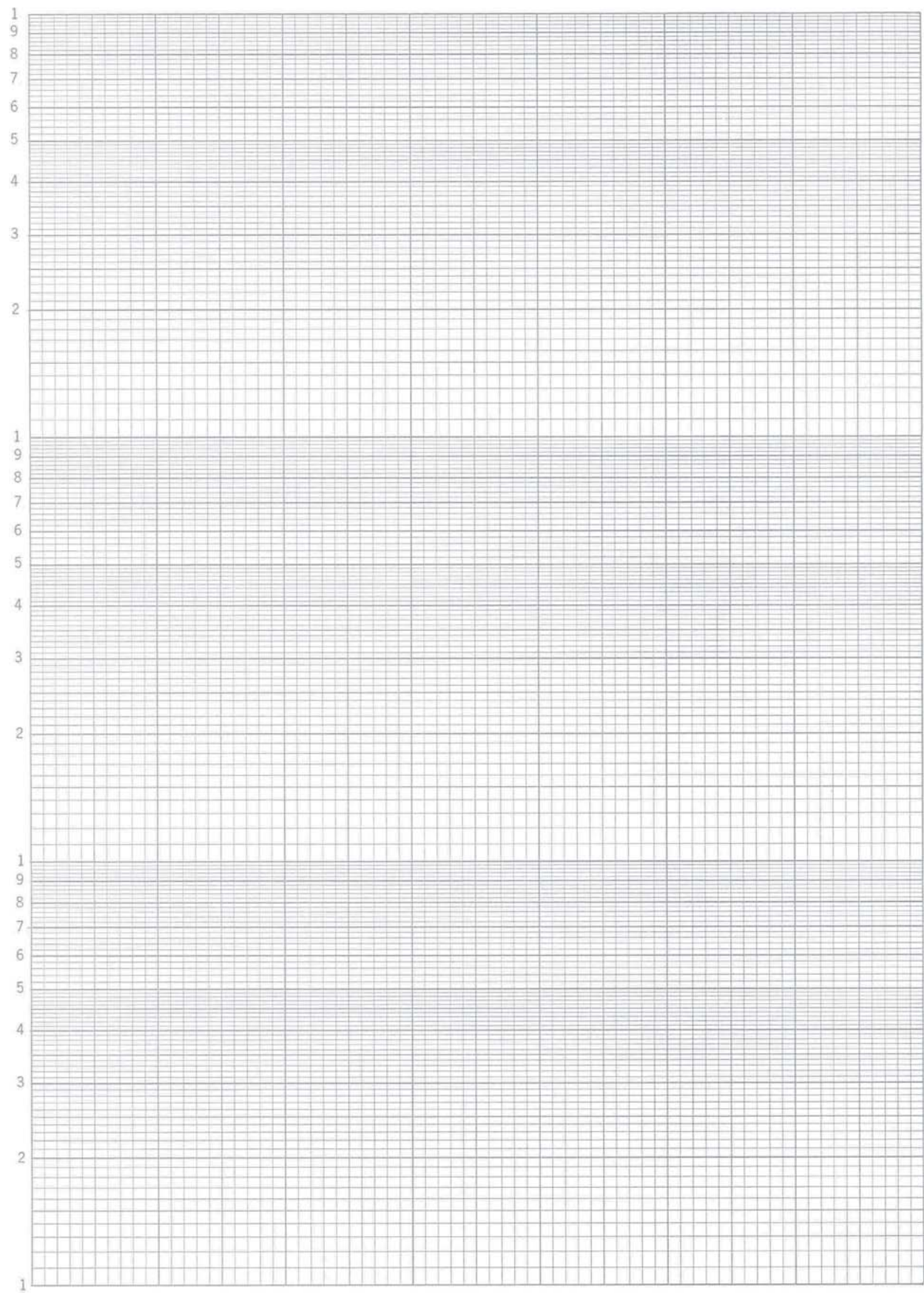
The outcome of this lab is the Bode plot of a simple, single-stage, active, low-pass filter. What does all this mean?

- Simple* means few parts that are inexpensive
- Single-stage* means there is just one op-amp with feedback
- Active* means it has an op-amp in it that receives power from a power source and can amplify the signal. The opposite is *passive*, which cannot have a gain of more than 1.
- Low-pass* says this filter passes low frequencies and attenuates higher ones. The dividing line between "passes" and "attenuates" is called the *cutoff frequency or the half-power point*. It is the point on your graph where the signal is 3 dB below the passband, which is the long flat section on the left.

What is the cutoff frequency of your circuit as shown on your Bode plot? Mark that point and label it.

The End

The Bode plot gives us a picture of the frequency response of a circuit like this low-pass filter. It is almost always a plot of the gain of the system in dB vs. the log of the frequency using a semilog grid.



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Lab H2: Looking at a Spectrum

Purpose

Let's look at a spectrum! No, not Roy G. Biv, the spectrum that we normally see. Instead, the frequency spectrum of electrical signals. Mobile Studio Desktop has a Spectrum Analyzer that displays the energy in a signal as a function of frequency.

The Spectrum Analyzer accepts a signal and separates it into its frequency components. If, for example, a signal is made up of two frequencies, 1 and 3 kHz, the Spectrum Analyzer will tell us the value of the voltage associated with each of those two components, displaying them as two spikes along a frequency axis.

Objectives

This is an introduction to the Spectrum Analyzer, so we won't involve any circuits, just a few connections between terminals on the Mobile Studio Desktop board. We are going to:

- Set up the Spectrum Analyzer to display the spectra of signals
- Try the analyzer with a couple of standard signals

[Note: As this is being written, I am using Mobile Studio Desktop version 2.3.3468.11535, which has a flaw in the implementation of the Spectrum Analyzer. It works fine as long as the signal being studied is not delivered via the A2 board inputs.]

Equipment

In addition to Mobile Studio Desktop and the IO Board you'll need two 300- Ω resistors and a breadboard.

Procedure

Initial set up:

1. Set up the Function Generator:

Ch 1: 5 kHz, 0°, Sine, 0.0 V offset, 2.0 V Pk-Pk

Ch 2: 12 kHz, 0°, Sine, 0.0 V offset, 1.5 V Pk-Pk

2. AutoHide the Function Generator (push pin)

3. Set up the Spectrum Analyzer:

Controls: Mode: Automatic

Ch 1 Input: A1DIF, Enabled

Ch 2: Disabled

Frequency Span: Start 0.0 kHz, Center 10 kHz, Span 20 kHz, Stop 20 kHz. As you set these, you may encounter red blocks; ignore them and go on because they will clear up when you finish.

4. Turn on and locate the cursors, which work just like those on the Oscilloscope
5. On the IO Board, connect the two clips of the AWG1 output to A2+ and A2- (AWG1 to A2+, AWG1 Ground to A2-)

Observe a simple signal

Start the Spectrum Analyzer and observe the spike that represents the 5-kHz signal. Use the cursors to measure the frequency and the peak voltage.

What is the frequency? Why doesn't it come out exactly 5.000 kHz?

How does the voltage peak match up with the input voltage? Why are they different? Or are they?

Combine and observe two signals

Connect the outputs of the Function Generator (AWG1 and AWG2) together through a couple of resistors as shown in Fig. 1. Then connect the middle between the resistors to A1+ and the grounds of AWG1 and AWG2 to A2-.

Now what does the Spectrum Analyzer show? Do the numbers that you measure for the peaks fit what you set up for the inputs from the Function Generator?

Now turn off the Spectrum Analyzer and launch the Oscilloscope. Display the signal on A1DIF. (For settings, try 250 mV, A1DIF, Auto, Ch1, 100 μ s.) Got a mess? That's because the scope won't sync to the combined waveform.

Press the Stop button to see what the waveform looks like. Can you see the two frequencies? The 12-kHz signal is pretty obvious, but the other isn't.

Now change the Function Generator Ch 2 to 10 kHz and display the result. Since these two frequencies are related by an integer multiple, the waveforms combine into a stable trace.

Close the Oscilloscope and launch the Spectrum Analyzer again. You should still have your previous settings and now should see two peaks at 5 and 10 kHz.

Square wave

Disassemble the resistor network and connect the AWG1 output directly to the A1+ input. Start the Spectrum Analyzer and you should have a peak at 5 kHz again.

Change the Function Generator Ch 1 to Square. Note the additional spikes on the Spectrum Analyzer. There's a small one at 10 kHz, which is the second harmonic. (Remember that the first harmonic is the fundamental at 5 kHz.) There is a fairly large spike at 15 kHz, the third harmonic.

Change the Stop frequency on the Spectrum Analyzer to 100 kHz. Now you should see 20 of the square-wave's harmonic. (Well, just 19 show because the 20th is on the edge of the screen.)

If the square wave were perfectly symmetric, it would display only odd harmonics.

Now collect data on these harmonics. Draw a table with three columns and six rows. Head the columns f (kHz), Peak (V), and Ideal. Then measure the frequency and the peak voltage for the first six odd harmonics (5, 15, 25, 35, 45, and 55 kHz).

Fill in the third column with the voltages for the ideal square wave. Ideally, the harmonics for a square wave should fall off as $1/n$ where n is the number of the odd harmonic (1, 3, 5,...). Divide the voltage of the fundamental (at 5 kHz) by n and record these results in the third column.

How does Mobile Studio's square wave compare with the ideal?

Results

Our goal has been to become familiar with the Spectrum Analyzer, which we have done by looking at some standard signals. You should have answers to a number of questions that were posed throughout the lab, plus a table of square-wave harmonics with comparisons to an ideal square wave.

The End

Now that you are familiar with the Spectrum Analyzer, we'll use it to see how our low-pass filter performs.

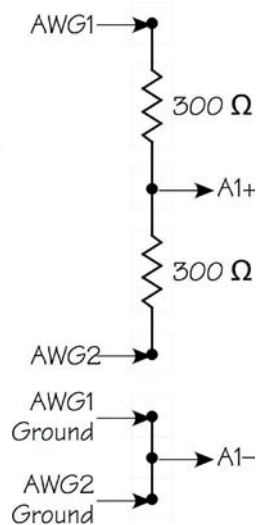


Fig. 1—Combining two signals

Mobile Studio Desktop™

Lab H3: Sorting Signals

Purpose

In Lab H1 we tested an active, low-pass filter. Now it's time to see what that filter does to a couple of different input signals. We are going to test it with the sum of two sine waves of different frequencies and also with a square wave. These will show how the low-pass filter modifies the incoming signal by reducing the higher frequencies.

Objectives

- Observe the effect of the low-pass filter on the sum of two waves by observing the spectrum of the input and output signals
- Observe the effect of the low-pass filter on a square wave via both the Spectrum Analyzer and the Oscilloscope

Equipment

You'll need the low-pass filter from Lab H1 as shown in Fig. 1, the MSD system and the IO Board, and two 300- Ω resistors with a breadboard.

Procedure

Build the op-amp low-pass filter shown in Fig. 1. This is the same filter that was used in Lab H1, but notice that the output terminals are connected to A1+ and A1- instead of the A2 terminals. (If you need help connecting this board, go back to Lab G1.)

[Note: The shift of connections from A2 to A1 is because of a problem with the Spectrum Analyzer in Version 2.3.3468.11535 of Mobile Studio Desktop. The problem may be corrected in later versions.]

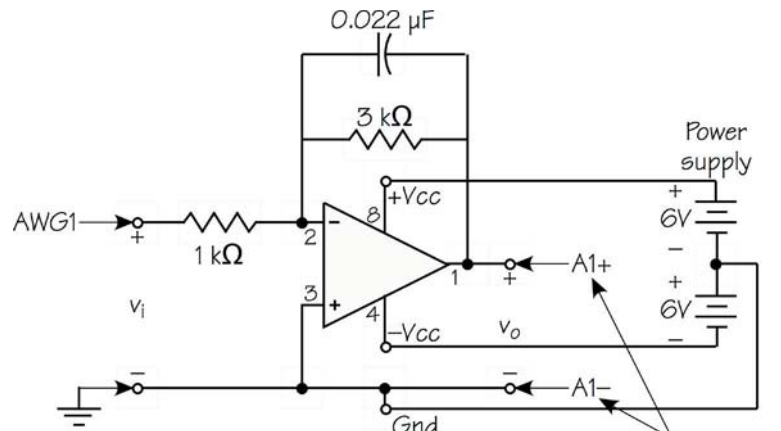


Fig. 1—Op-amp low-pass filter

Note A1, not A2

Two signals summed

For the input to the op-amp circuit, use the resistor summer like the one you built in Lab H2 (see Fig. 2). You'll need a clip lead to connect the junction of the two resistors to the In terminal of the op-amp.

On the op-amp board, move the A1+ connection to the input terminal In.

Set the Function Generator to produce the two signals: For Ch 1, use 1 kHz, 0°, Sine, 0.0 V offset, 2.0 V Pk-Pk; For Ch 2, use 25 kHz with the other four settings the same as Ch 1.

Set the Spectrum Analyzer to Automatic Mode, Ch1 Input from A1DIF, Enabled, Ch2 Input Disabled. Set the frequencies for Start 0.0 kHz, Center 20 kHz, Span 40 kHz, Stop 40 kHz.

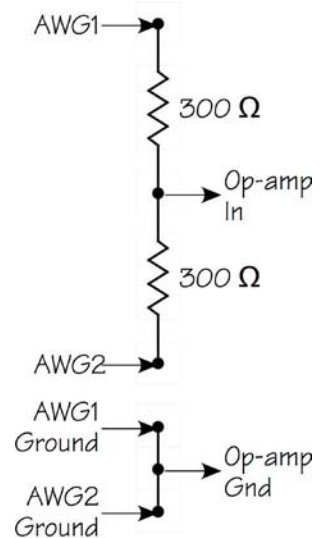


Fig. 2—Combining two signals

Start the Spectrum Analyzer and observe the two peaks. Record their voltages and frequencies.

Then change the A1+ connection on the op-amp board to the Out terminal so you can look at the output of the circuit.

Again observe the two spikes on the Spectrum Analyzer, recording their voltages and frequencies.

Let's compare the output with what the Bode plot of Lab H1 predicts. Divide the voltage of the 25-kHz peak by the voltage of the 1-kHz peak. Convert this ratio to dB using $20 \log_{10}$.

On your Bode plot, mark the 1-kHz and 25-kHz points on the curve. Then determine by how many dB the output is reduced from 1 kHz. How close does this come to the dB value you calculated above? If this were a perfect world, you'd be exactly on!

Filtering a square wave

Disassemble the resistor summing network and connect AWG1 directly to the In1 input of the op-amp circuit. Connect AWG1's ground to one of the ground terminals on the board. Connect A1+ and A1- to the output terminals as shown in Fig. 1.

Set the Function Generator to Ch 1: 1 kHz, 0°, Square, 0.0 V offset, 2.0 V Pk-Pk.

Set the Spectrum Analyzer to Automatic Mode, Ch1 Input: A1DIF, **Disabled**; Ch 2 Input: AWG1, **Enabled**. The frequency settings remain the same.

Observe the spectrum of the input square wave, which should look pretty much like that for the square wave in Lab H2.

Now enable the Ch 1 input so you also see the spectrum of the filter's output waveform. Are the higher harmonics reduced? Take a picture of this screen for your records.

It's useful to look at the two waveforms on the Oscil-

loscope, but we have to kill the Spectrum Analyzer to do this. Close the Spectrum Analyzer and launch the Oscilloscope.

Set up a display of a "nice" square wave from AWG1 on Channel 1 by adjusting the V/div and the time/div to get a display of about two periods of the square wave.

Now switch to observe the filter's output by changing the input of Channel 1 to A1DIF. What has happened to the "squareness" of the waveform? It's been "rounded off" or "smoothed out." This is because the filter has suppressed the higher frequencies, which are the ones that contribute to the sharpness of corners and steepness of the rises.

Take a picture of this screen for your records.

Results

You should have three things in your records:

- Marked Bode plot from Lab H1 with the results from the Spectrum Analyzer two-frequency test marked on it
- "Photo" of the spectra of the square wave with both the input and the filtered output visible
- "Photo" of the scope showing the inverted, filtered square-wave output

The End

We've seen the use of the Spectrum Analyzer and the Oscilloscope for making measurements of the characteristics of a filter to show how it affects incoming signals.

Mobile Studio Desktop™

Lab K1: Tracing the Curve

Purpose

The oscilloscope is a graphing device! OK, you knew that, I'm sure. But we really don't think of it as a way to make graphs, even though we constantly use it to plot voltages versus time. We think of it as an instrument for making electrical measurements, not much different from, say, a voltmeter.

The scope does make graphs, and in this lab we are going to use it to graph the current-versus-voltage curve of a light-emitting diode (LED). In other words, instead of graphing voltage versus time, we are going to plot current versus voltage.

We'll use the same LED you studied in Labs A4 and A5, where you made enough measurements to be able to plot by hand the LED's i-v curve.

Objectives

Our primary goal is to learn to use the oscilloscope as a versatile graphing device:

- Draw the graph of current versus voltage for an LED
- Use a voltage sweep to create a test voltage
- Use the scope in both the usual voltage-versus-time mode and the voltage-versus-voltage mode

Introduction

A typical oscilloscope generally can draw two kinds of graphs. The usual one is a plot of voltage on the vertical axis and time on the horizontal axis. If I want to plot the current through a diode on the vertical axis and the voltage across that diode on the horizontal axis, I'm going to have to transform the diode current into a voltage

and transform the diode voltage into time. The first isn't hard to do; the second is a little messier.

The obvious transformation of the current into a voltage is to place a small resistor in the current path and send to the scope the voltage across the resistor. In this lab, we'll put a $10\text{-}\Omega$ resistor in the current path and display the resistor voltage on Channel 2 of the scope.

Transforming the diode's voltage into time requires a voltage source that "sweeps" with time. Suppose we create a ramp-shaped voltage that starts at 0 volts and ramps up smoothly to, say, 3 volts. Now when we use that voltage to drive the LED, we will get a current reading (via the resistor) that "follows" the i-v curve of the diode.

That's not quite enough, though. We need to synchronize the sweep of the voltage ramp with the sweep of the scope. Suppose we make the ramp voltage repeat itself every millisecond, which means the frequency is 1,000 Hz. Then the ramp sweeps smoothly from 0 volts at $t = 0$ to 3 volts at $t = 1\text{ ms}$ and repeats.

Now we set the horizontal sweep of the scope to 100 microseconds per division, which is 1 millisecond across the whole graph. This makes the horizontal axis of the scope effectively the same as the voltage sweep of the ramp.

The scope has another mode of operation, however, X-Y. It can display a voltage on both the horizontal and the vertical axes. Time is not a factor in this mode. To display the i-v curve of the diode, we display the resistor voltage on the Y axis (Channel 2), thereby displaying the current, and the diode voltage on the X axis (Channel 1). We still need to sweep the voltage to get a continuous curve.

We'll use both methods to get the i-v curve of the LED. But if all those words don't make the process clear, let's set up the measurements and just do it. We will try both scope modes, voltage-versus-time and voltage-versus-voltage, to display the LED's i-v curve.

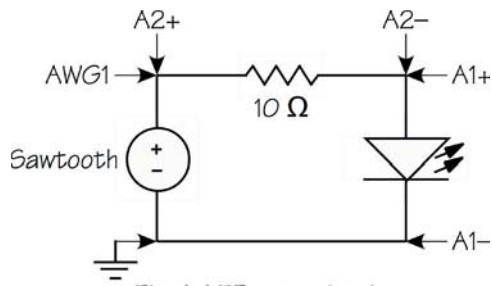


Fig. 1—LED test circuit

Equipment

This lab uses the Oscilloscope and the Arbitrary Waveform Generator (AWG) of Mobile Studio Desktop. We use the AWG because we need a waveform that is more complicated than the Function generator can provide. For the test circuit we need the green LED and a 10- Ω resistor.

Procedure

Build the circuit of Fig. 1 and connect all six leads from the Mobile Studio IO Board.

Creating the ramp voltage

We need a ramp voltage that looks like Fig. 2, so we'll set up the Arbitrary Waveform Generator to do this. This ramp is called a *sawtooth* because it rises (or falls) smoothly from one voltage to another and then sharply returns to the starting voltage. (A waveform that goes smoothly in both directions is called *triangular*.)

Launch the Arbitrary Waveform Generator. Set Channel 1 to provide a sawtooth, 1.0 kHz, 3 V peak-to-peak, 1.5 V offset, 0° phase. That should give you a waveform that looks almost like Fig. 2. The difference is that the AWG display is starting in what we think of as the middle of the ramp, running up to 3 V, dropping sharply to 0 V at the middle of the sweep, and then finishing.

Curve using Y-T mode

The scope requires a number of settings to make the display show a "good" curve of diode current versus voltage. We need to set up the time base (horizontal

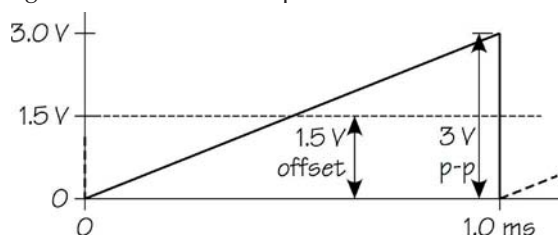


Fig. 2—Sawtooth voltage

sweep) and both channels. Our goal is to get a picture that looks like Fig. 3.

1. Under Trigger, set Auto, Ch1, Falling. The trigger point should be "Set 50%."
2. Under Horizontal, set 100 μ s. The Mode should be Y-T.
3. Set Channel 1 to 250 mV/div, DC, AWG1, and disable the channel (we don't need to see the input signal because we are using it just for timing).
4. Set Channel 2 to 25 mV/div, DC, A2DIF.
5. Start the scope.

You should have a display on the scope that looks somewhat like Fig. 3, but the trace will be in the top half of the screen. Adjust the scope as follows:

6. Remove the A2+ lead from your circuit and clip it to the same point on the 10- Ω resistor that A2- is clipped, thereby shorting the input.
7. Use Channel 2's large down button to move the trace so that the long horizontal trace is resting on the bottom of the scope window.
8. Put A2+ back on the other end of the 10- Ω resistor.

Now the display should look like Fig. 3. The artifact is caused by sweeping the voltage past a limit of about 2.5 V and can be ignored.

What's the scope telling us? The horizontal axis is directly related to the sawtooth's voltage with 0 volts at the left end and 3 volts at the right. The vertical axis is directly related to the current. Since the vertical calibration is 25 mV per division, the bottom is 0 volts and the top is 200 millivolts. Dividing these by 10 ohms means the bottom is 0 milliamperes and the top is 20 milliamperes.

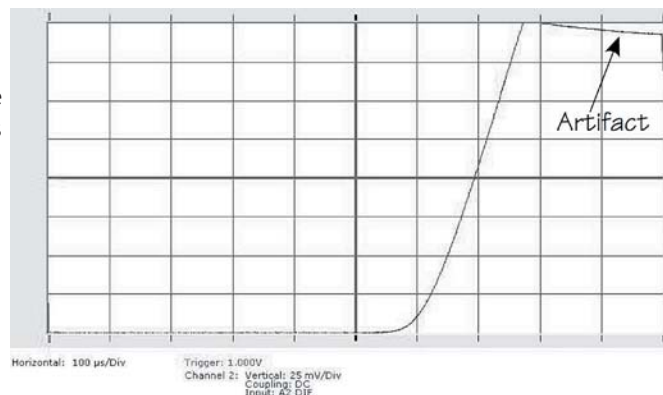


Fig. 3—Scope picture

Ah! Pretty neat, eh? Well, it does sound good and it certainly looks good. In fact, it should look pretty much like the diode curve we obtained by hand in Lab A4. If you look back at that data, the top point on your curve was probably something like a diode voltage of 2 V and a current of 20 mA. This means the diode at that point has a resistance of $100\ \Omega$. Hence the $10\text{-}\Omega$ resistor we are using for determining current represents about 10% of the resistance in the circuit.

Oh, you say, why not use the voltage across the resistance to supply Channel 1 of the scope? That way, the time axis will be proportional to the actual diode voltage.

That's true, but there's a flaw. The voltage across the diode won't be linear with time because the diode is non-linear. Therefore the horizontal axis won't be linearly calibrated in volts and you can't read i-v data accurately from the display.

Is there a way to get the horizontal axis to show the diode voltage linearly? Yes, by using the scope in the X-Y mode.

Curve using X-Y mode

We can make the scope plot one voltage against another by switching to X-Y mode. In this mode we'll plot the diode voltage (from the A1DIF input) on the horizontal axis and the diode current (as a voltage from the A2DIF input) on the vertical axis.

The scope settings are about the same, and we still need a trigger to get a repetitive trace:

1. Trigger: Auto, Ch1, Falling, Set 50%
2. Horizontal: 100 μs , Mode X-Y
3. Channel X: 250 mV/div, DC, A1DIF

4. Channel Y: 25 mV/div, DC, A2DIF
5. Start

When you have a display, adjust it to properly fill the screen:

6. Use the down arrow on Channel X to move the display to the left until the notation under the screen reads "Channel 1: -1.000 V."
7. Short together the clips of input A2 and use the down arrow on Channel Y to move the horizontal portion of the trace to the very bottom of the screen.

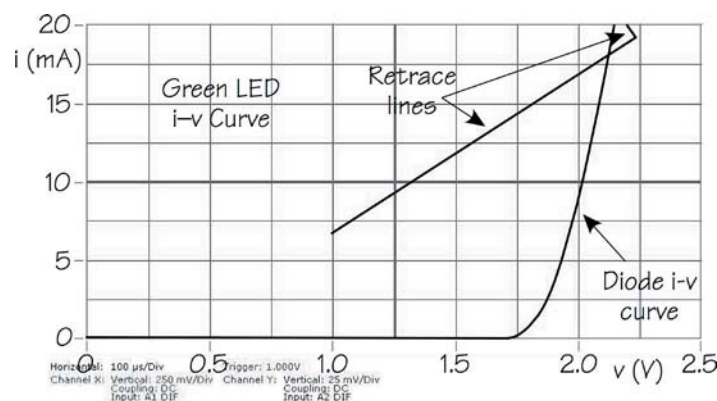
The curve should now look like Fig. 4. (The extraneous lines are caused by the sharp downward return to 0 of the sawtooth.) Each division on the horizontal axis is 250 mV, so the axis displays 0 to 2.5 V. Each division on the vertical axis is 25 mV, which across a $10\text{-}\Omega$ resistor is 2.5 mA, so the axis displays 0 to 20 mA.

Results

Record the display you have just gotten for inclusion in your journal. How well does it compare with the diode curve that you obtained by hand in Lab A4?

The End

How's that for an easier way to get a diode curve? We used a sweep of voltage to drive the circuit and observed the diode current and voltage, arranging the scope to make an X-Y plot of those data. It's often said that if you are allowed just one electrical measuring instrument, the scope is the only choice.





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TENMA® Model 72-7765: OPERATING MANUAL
Unpacking Inspection

Open the package case and take out the Meter. Check the following items carefully for missing or damaged parts:

Item	Description	Qty
1	English Operating Manual	1 piece
2	Test Lead	1 pair
3	Holster	1 piece
4	1.5V Battery (AAA)(installed)	2 piece

In the event you find items missing or damaged, please contact your dealer immediately.

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TENMA® Model 72-7765: OPERATING MANUAL
Safety Information(2)

In this manual, a **Warning** identifies conditions and actions that pose hazards to the user, or may damage the Meter or the equipment under test. A **Note** identifies the information that user should pay attention to.

International electrical symbols used on the Meter and in this Operating Manual are explained on page 10.

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Model 72-7765: OPERATING MANUAL **TENMA®**
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1

Model 72-7765: OPERATING MANUAL **TENMA®**
Overview

This Operating Manual covers information on safety and cautions. Please read the relevant information carefully and observe all the **Warnings** and **Notes** strictly.

Warning
To avoid electric shock or personal injury, read the "Safety Information" and "Rules for Safety Operation" carefully before using the Meter.

The Model 72-7765 Multimeter (hereafter referred as "the Meter") is a 3 3/4 digits with steady operations, fashionable design and highly reliable hand-held measuring instrument. The Meter can measure AC/DC voltage, AC/DC Current, Resistance, Transistor hFE, Diode and Continuity. It is an ideal tool for maintenance.

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Model 72-7765: OPERATING MANUAL **TENMA®**
Safety Information(1)

Safety Information

This Meter complies with the standards IEC61010: in pollution degree 2, overvoltage category (CAT I 600V, CAT II 300V) and double insulation.

CAT. I: Signal level, special equipment or parts of equipment, telecommunication, electronic, etc., with smaller transient overvoltages than overvoltages CAT. II.

CAT. II: Local level, appliance, PORTABLE EQUIPMENT etc., with smaller transient overvoltages than CAT. III

Use the Meter only as specified in this operating manual, otherwise the protection provided by the Meter may be impaired.

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Model 72-7765: OPERATING MANUAL **TENMA®**
Rules For Safe Operation (1)

Warning
To avoid possible electric shock or personal injury, and to avoid possible damage to the Meter or to the equipment under test, adhere to the following rules:

- Before using the Meter inspect the case. Do not use the Meter if it is damaged or the case (or part of the case) is removed. Look for cracks or missing plastic. Pay attention to the insulation around the connectors.
- Inspect the test leads for damaged insulation or exposed metal. Check the test leads for continuity. Replace damaged test leads with identical model number or electrical specifications before using the Meter.
- Do not apply more than the rated voltage, as marked on the Meter, between the terminals or between any terminal and grounding.
- The rotary switch should be placed in the proper position, and no change of range shall be made during measurement to prevent damage of the Meter.

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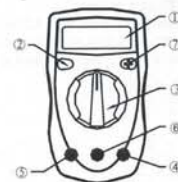
- When the Meter is working at an effective voltage over 60V DC or 42V rms AC, special care should be taken for there is danger of electric shock.
- Use the proper terminals, function, and range for your measurements.
- Do not use or store the Meter in an environment of high temperature, humidity, explosive, flammable and strong magnetic field. The performance of the Meter may deteriorate after dampened.
- When using the test leads, keep your fingers behind the finger guards.
- Disconnect circuit power and discharge all high-voltage capacitors before testing resistance, continuity, diodes and current.
- Before measuring current, check the Meter's fuses and turn off power to the circuit before connecting the Meter to the circuit.
- Replace the battery as soon as the battery indicator "⌵" appears. With a low battery, the Meter might produce false readings that can lead to electric shock and personal injury.

- Remove test leads from the Meter and turn the Meter power off before opening the case.
- When servicing the Meter, use only the same model number or identical electrical specifications replacement parts.
- The internal circuit of the Meter shall not be altered at will to avoid damage of the Meter and any accident.
- Soft cloth and mild detergent should be used to clean the surface of the Meter when servicing. No abrasive and solvent should be used to prevent the surface of the Meter from corrosion, damage and accident.
- The Meter is suitable only for indoor use.
- Turn the Meter off when it is not in use and take out the battery when not using for a long time.
- Periodically check the battery as it may leak after some time. If leakage is apparent, the battery should be immediately replaced to prevent damage.

	AC or DC
	AC Current
	DC Current
	Ground
	Double Insulated
	Low Battery
	Diode
	Fuse
	Continuity Test
	Warning. Refer to the Operating Manual
	Conforms to Standards of European Union.

The Meter Structure (figure 1)

- 1) LCD Display
- 2) SELECT Button
- 3) Rotary Switch
- 4) COM Input Terminal
- 5) 10A Input Terminal
- 6) Other Input Terminal
- 7) Transistor Input Terminal

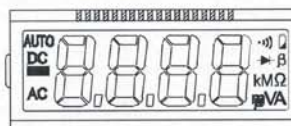


(figure 1)

SELECT button

Selecting for DC and AC current measurement, Continuity Test and Diode Test. The buzzer sounds when switching from one function to the other. Press this button to activate the Meter when it is under Sleep Mode.

LCD Display (see figure 2)



(figure 2)

A. DC Voltage Measurement (see figure 3)

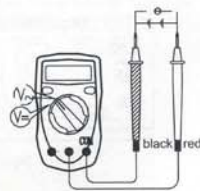
Warning

To avoid harm to you or damage to the Meter from electric shock, please do not attempt to measure voltages higher than 500V although readings may be obtained.

The DC Voltage ranges are : 400.0mV, 4.000V, 40.00V, 400.0V and 500V

1. Insert the red test lead into the VΩmA terminal and the black test lead into the COM terminal.
2. Set the rotary switch to V $\overline{\text{---}}$ range.
3. Connect the test leads across with the object being measured.

The measured value shows on the display.



(figure 3)

Note:

- DCV Measurement is autoranging, the Meter has an input impedance of approx. 10MΩ. This loading effect can cause measurement errors in high impedance circuits. If the circuit impedance is less than or equal to 10kΩ, the error is negligible (0.1% or less).
- When DC voltage measurement has been completed, disconnect the connection between the testing leads and the circuit under test.

B. AC Voltage Measurement (see figure 3)

Warning

To avoid harm to you or damage to the Meter from electric shock, please do not attempt to measure voltages higher than 500V although readings may be obtained.

The AC voltage ranges are : 4.000V, 40.00V, 400.0V and 500V

1. Insert the red test lead into the VΩmA terminal and the black test lead into the COM terminal.

TENMA®Model 72-7765: OPERATING MANUAL
Measurement Operation (3)

- Set the rotary switch to V~ range.
- Connect the test leads across with the object being measured.

The measured value shows on the display.

Note:

- DCV Measurement is autoranging, the Meter has an input impedance of approx. 10M Ω . This loading effect can cause measurement errors in high impedance circuits. If the circuit impedance is less than or equal to 10k Ω , the error is negligible (0.1% or less).
- When DC voltage measurement has been completed, disconnect the connection between the testing leads and the circuit under test.

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TENMA®Model 72-7765: OPERATING MANUAL
Measurement Operation (5)

- Insert the red test lead into the V Ω mA or 10A terminal and the black test lead into the COM terminal.
- Set the rotary switch to an appropriate measurement position in A~ range. DC measurement is default or press SELECT button to select DC measurement mode.
- Break the current path to be tested. Connect the red test lead to the more positive side of the break and the black test lead to the more negative side of the break.
- Turn on power to the circuit. The measured value shows on the display.

Note

- If the value of current to be measured is unknown, use the maximum measurement position (10A) and reduce the range step by step until a satisfactory reading is obtained.
- When current measurement has been completed, disconnect the connection between the testing leads and the circuit under test.

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TENMA®Model 72-7765: OPERATING MANUAL
Measurement Operation (7)

- Break the current path to be tested. Connect the red test lead to the more positive side of the break and the black test lead to the more negative side of the break.
- Turn on power to the circuit.

The measured value shows on the display.

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TENMA®Model 72-7765: OPERATING MANUAL
Measurement Operation (9)**Note**

- The test leads can add 0.1 Ω to 0.3 Ω of error to resistance measurement. To obtain precision readings in low-resistance measurement, that is the range of 200 Ω , short-circuit the input terminals beforehand and record the reading obtained (called this reading as X). (X) is the additional resistance from the test lead. Then use the equation: measured resistance value (Y) - (X) = precision readings of resistance.
- For high-resistance measurement (>1M Ω), it normally requires several seconds to obtain a stable reading.
- When resistance measurement has been completed, disconnect the connection between the testing leads and the circuit under test.

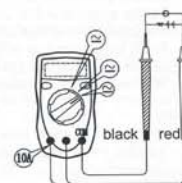
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Model 72-7765: OPERATING MANUAL
Measurement Operation (4)**TENMA®****C. DC Current Measurement (see figure 4)****Warning**

Never attempt an in-circuit current measurement where the voltage between terminals and ground is greater than 60V. If the fuse burns out during measurement, the Meter may be damaged or the operator may be injured. Use proper terminals, function, and range for the measurement. When the test leads are connected to the current terminals, do not parallel them across any circuit.

To measure current, do the following:

- Turn off power to the circuit. Discharge all high-voltage capacitors.



(figure 4)

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Model 72-7765: OPERATING MANUAL
Measurement Operation (6)**TENMA®****D. AC Current Measurement (see figure 4)****Warning**

Never attempt an in-circuit current measurement where the open-circuit voltage between the circuit and ground is greater than 500V. If the fuse burns out during measurement, the Meter may be damaged or the operator may be injured. Use proper terminals function, and range for the measurement. When the test leads are connected to the current terminals, do not parallel them across any circuit.

- Turn off power to the circuit. Discharge all high-voltage capacitors.
- Turn the rotary switch to suitable range, press SELECT to change from DC to AC measurement.
- Insert the red test lead into the V Ω mA or 10A terminal and the black test lead into the COM terminal.
- Set the rotary switch to an appropriate measurement position in A~ range.

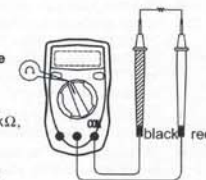
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TENMA®Model 72-7765: OPERATING MANUAL
Measurement Operation (8)**TENMA®****E. Resistance Measurement (see figure 5)****Warning**

To avoid damage to the Meter or to the devices under test, disconnect circuit power and discharge all the high-voltage capacitors before measuring resistance.

The Ω ranges are : 400.0 Ω , 4.000k Ω , 40.00k Ω , 400.0k Ω , 4.000M Ω , and 40.00M Ω .

- Insert the red test lead into the V Ω mA terminal and the black test lead into the COM terminal.
- Set the rotary switch to the Ω range.
- Connect the test leads across with the object being measured. The measured value shows on the display.



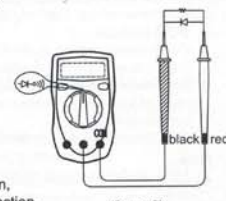
(figure 5)

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TENMA®Model 72-7765: OPERATING MANUAL
Measurement Operation (10)**TENMA®****F. Diode and Continuity Test (see figure 6)****Testing Diodes****Warning**

To avoid damage to the Meter or to the devices under test, disconnect circuit power and discharge all the high-voltage capacitors before diodes.

Use the diode test to check diodes, transistors, and other semiconductor devices. The diode test sends a current through the semiconductor junction, and then measures the voltage drop across the junction. A good silicon junction drops between 0.5V and 0.8V.



(figure 6)

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To test a diode out of a circuit, connect the Meter as follows:

1. Insert the red test lead into the **VΩmA** terminal and the black test lead into the **COM** terminal.
2. Set the rotary switch to **→|←**. Diode measurement is default or press **SELECT** button to select diode measurement mode.
3. For forward voltage drop readings on any semiconductor component, place the red test lead on the component's anode and place the black test lead on the component's cathode.
The measured value shows on the display.

Note

- In a circuit, a good diode should still produce a forward voltage drop reading of 0.5V to 0.8V; however, the reverse voltage drop reading can vary depending on the resistance of other pathways between the probe tips.
- Connect the test leads to the proper terminals as said above to avoid error display. The LCD will display "OL" indicating open-circuit for wrong connection. The unit of diode is Volt (V), displaying the positive-connection voltage-drop value.

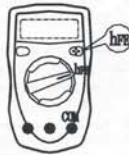
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G. Transistor hFE Measurement (see figure 7)

Warning

To avoid damages to the Meter or to the devices under test, do not input any current over 60V DC or 30V AC.

1. Check that the transistor is PNP or NPN type.
2. Connect the transistor to be measured to the corresponding jacks.
3. LCD display hFE reference value.



(figure 7)

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- Maximum Voltage between any Terminals and Ground: 500V rms.
- Fused Protection for VΩmA Input Terminal: 500mA, 250V fast type, φ5x20 mm
- 10A Terminal: Un-fused.
- Range: Auto ranging
- Maximum Display: Display: 3999.
- Measurement Speed: Updates 3 times / second.
- Temperature:
 - Operating: 0°C~40°C (32°F~104 °F).
 - Storage: -10°C~50°C (14°F~122°F).
- Relative Humidity: 75% @ 0°C - 30°C; 50% @ 31 - 40°C.
- Altitude: Operating: 2000 m.
Storage: 10000 m.

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Accuracy: (a% reading + b digits), guarantee for 1 year.
Operating temperature: 23°C -5°C.
Relative humidity: <75%.

A. DC Voltage

Range	Resolution	Accuracy	Overload Protection
400mV	100μV	±(0.8%+3)	500V DC or AC
4V	1mV	±(0.8%+1)	
40V	10mV		
400V	100mV		
500V	1V	±(1%+3)	

Remark: Input impedance: 10MΩ.

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- When diode testing has been completed, disconnect the connection between the testing leads and the circuit under test.

Testing for Continuity

To test for continuity, connect the Meter as below:

1. Insert the red test lead into the **VΩmA** terminal and the black test lead into the **COM** terminal.
2. Set the rotary switch to **→|←**.
3. Press **SELECT** button to select continuity measurement mode.
4. Connect the test leads across with the object being measured.
The buzzer sounds if the resistance of a circuit under test is less than 100Ω.

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To preserve battery life, the Meter automatically turns off after 30minutes of inactivity. The Meter can be activated by pressing the **SELECT** button or turning the rotary switch.

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- Battery Type: Two piece of 1.5V AAA Battery.
- Low Battery : Display: **⏻**.
- Negative reading: Display: **-**.
- Overloading: Display: **"OL"**.
- Dimensions (HxWxL): 130 x 73.5 x 35mm.
- Weight: Approx. 156g (battery included).
- Safety/Compliance: IEC61010 CAT I 600V, CAT II 300V overvoltage and double insulation standard.
- Certification: **CE**

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B. AC Voltage

Range	Resolution	Accuracy	Overload Protection
4V	1mV	±(1.2%+3)	500V DC or AC
40V	10mV		
400V	100mV		
500V	1V	±(1.5%+5)	

Remarks:

- Input impedance: approx. 10MΩ.
- Displays effective value of sine wave (mean value response).
- Frequency response 40Hz ~ 400Hz.

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TENMA®Model 72-7765: OPERATING MANUAL
Accuracy Specifications(3)**C. DC Current**

Range	Resolution	Accuracy	Overload Protection
400μA	0.1μA	±(1%+2)	500mA/250V fast type fuse φ 5x20mm
4000μA	1μA		
40mA	10μA		
400mA	100μA	±(1.2%+2)	Un-Fused
4A	1mA		
10A	10mA		

Remark:

- **At 10A Range:** For continuous measurement 10 seconds and interval not less than 15 minutes.
- Input impedance: approx. 10MΩ.
- Measurement voltage drop: Full range at 400mV.

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TENMA®Model 72-7765: OPERATING MANUAL
Accuracy Specifications(5)**E. Resistance**

Range	Resolution	Accuracy	Overload Protection
400Ω	0.1Ω	±(1.2%+2)	250V DC or AC
4kΩ	1Ω	±(1%+2)	
40kΩ	10Ω		
400kΩ	100Ω		
4MΩ	1kΩ	±(1.2%+2)	
40MΩ	10kΩ	±(1.5%+2)	

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Model 72-7765: OPERATING MANUAL
Accuracy Specifications(4)**TENMA®****D. AC Current**

Range	Resolution	Accuracy	Overload Protection
400μA	0.1μA	±(1.5%+5)	500mA/250V fast type fuse φ 5x20mm
4000μA	1μA		
40mA	10μA		
400mA	100μA	±(2%+5)	Un-Fused
4A	1mA		
10A	10mA		

Remark:

- **At 10A Range:** For continuous measurement 10 seconds and interval not less than 15 minutes.
- Input impedance: approx. 10MΩ.
- Measurement voltage drop: Full range at 400mV.

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TENMA®Model 72-7765: OPERATING MANUAL
Accuracy Specifications(6)**F. Diodes and Continuity Measurement**

Range	Resolution	Remark	Overload Protection
→←	1mV	Displays approximate forward voltage drop	250V DC or AC
~	0.1Ω	Buzzer beeps at <100Ω	

G. Transistor hFE Test

Range	Remark	Testing Condition
hFE	Test NPN and PNP type transistors. Display range: 0-1000β	I _{BO} ≈ 10μA V _{CE} ≈ 1.5V

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TENMA®Model 72-7765: OPERATING MANUAL
Maintenance(1)

This section provides basic maintenance information including battery and fuse replacement instructions.

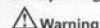
**Warning**

Do not attempt to repair or service your Meter unless you are qualified to do so and have the relevant calibration, performance test, and service information. To avoid electrical shock or damage to the Meter, do not get water inside the case.

A. General Service

- Periodically wipe the case with a damp cloth and mild detergent. Do not use abrasives or solvents.
- To clean the terminals with cotton bar with detergent, as dirt or moisture in the terminals can affect readings.
- Turn the Meter to OFF position when it is not in use and take out the battery when not using for a long time.
- Do not store the Meter in a place of humidity, high temperature, explosive, inflammable and strong magnetic field.

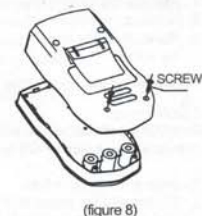
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Model 72-7765: OPERATING MANUAL
Maintenance(3)**TENMA®****B. Replacing the Battery (see figure 8)**

To avoid false readings, which could lead to possible electric shock or personal injury, replace the battery as soon as the battery indicator "⚡" appears.

To replace the battery:

1. Disconnect the connection between the test leads and the circuit under test, and remove the test leads from the input terminals of the Meter.
2. Turn the Meter to OFF position.
3. Remove the screw from case bottom, and separate the case bottom from the case top.



(figure 8)

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TENMA®Model 72-7765: OPERATING MANUAL
Maintenance(4)

4. Remove the battery from the battery compartment.
5. Replace the battery with a new 1.5V AAA battery.
6. Rejoin the case bottom and case top, and reinstall the screw.

C. Replacing the Fuses (see figure 8)**Warning**

To avoid electrical shock, arc blast, personal injury or damage to the Meter, use specified fuses ONLY in accordance with the following procedure.

To replace the Meter's fuse:

1. Disconnect the connection between the test leads and the circuit under test, and remove the test leads from the input terminals of the Meter.
2. Turn the Meter to OFF position.
3. Remove the screws from case bottom, and separate the case bottom from the case top.

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Model 72-7765: OPERATING MANUAL
Maintenance(5)**TENMA®**

4. Remove the fuse by gently prying one end loose, and then take out the fuse from its bracket.
5. Install ONLY replacement fuses with the identical type and specification as follows and make sure the fuse is fixed firmly in the bracket.
Fuse 1: 500mA 250 V, fast type, φ5x20mm.
6. Rejoin the case bottom and case top, and reinstall the screw.

Replacement of the fuses is seldom required. Burning of a fuse always results from improper operation.

** END **

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