ES 203

ELECTRICAL SYSTEMS

Laboratory Manual

Fall 2011

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Electrical Systems

Lab 0 – General Information

What's the purpose of a laboratory? Or at least a laboratory for students? Some might say that it's to get students as frustrated as possible and convince them that they'd rather be engineers than technicians! There's some truth in that, but the job of an engineer often involves making measurements or guiding those who do.

So the purpose of this part of the course is to introduce you to the basics of working in an electrical laboratory. These will include the use of the most common instruments: oscilloscopes, meters, signal generators, and power supplies. You should complete this course with some knowledge of these instruments.

Another purpose is to let you see that some of the things you learn in the classroom really do work in the physical world. You'll find that much of what you've studied on paper really does work. But you'll also discover that this isn't exactly true, that things are imperfect. So this hands-on experience is important because it helps you develop a better understanding of how the theoretical and the practical fit (or don't fit) together.

There's a third purpose to the lab that we sometimes don't like to admit. A lot of the learning in the lab takes place by encountering problems with equipment and devices. Yes, the op-amp is a very nice device for many things, but it sometimes takes a long time to discover that you've powered it wrong and burned it out. Call it perversity of inanimate objects or whatever you want, you'll have plenty of opportunity to encounter this principle! But don't be put off by your discovery—debugging is merely another form of logical problem-solving.

Relationship to Class Work

These laboratory exercises are a portion of ES 203, Electrical Systems. As such, they will conform fairly closely to the topics taken up in the classroom. For example, you won't be doing lab work on Thévenin's Theorem until you have encountered M. Thévenin in class.

But electrical engineering is more than circuits, and part of that "more" is measurement. It is appropriate for an educated engineer to know about and have a little experience in making electrical measurements. To provide that experience, some of these labs deal with circuits and elements from topics outside of ES203.

An example of an "outside" topic is measurement of the characteristics of a semiconductor light-emitting diode (LED) in Lab 1. The exercise does not require you to know anything about an LED, only to make voltage and current measurements in a circuit with an embedded LED, then plot a graph of the LED's characteristic. The goal with these "outsiders" is to learn to make measurements even if you don't know very much about the devices you are working with.

Course Materials

You'll need three things for this course, this pile of paper that includes the exercises, the expendable parts that you'll use in those exercises, and a lab log book in which you'll keep all your records as a journal.

Each of the exercises in this collection is designed for one lab session. The description of each exercise includes the goals of that lab, some prelab work, what you are to do in the lab, and what you are to hand in at the end. The early labs describe your activities in some detail; the later ones are more sketchy. Note that the lab book is *usually* due at the end of the session.

At the beginning of the course, purchase from the Instrument Room a parts kit for this course (under $10).

You need to get a lab journal in which you'll take data in the lab. The Bookstore has the required book: Lab Book, 10x7 7/8, 80 sheets, 5x5 quadruled, #26-251. In this book you'll complete all prelab requirements, collect all lab data, analyze what you get, sketch results, and answer questions.

Equipment

Each bench in the lab has several pieces of measuring equipment on it. These will provide you with most of the apparatus you'll need. All of it is Agilent industrial-grade equipment:

- 54624A Oscilloscope: 4 channels, 100 MHz
- E3631A Programmable D-C Power Supply: 0 - +6V @ 5A, 0 - –25V @ 1A, 0 - +25V @ 1A, all floating ground
- 34401A Multimeter : $6^1/_2$ digits. d-c voltage (100mV-1000V), a-c true-rms voltage (100mV-750V), resistance (100Ω-100MΩ), d-c current (10mA-3A), a-c true-rms current (3A), frequency or period, continuity, diode test
- 33120A Function/Arbitrary Waveform Generator : sine and square (100μHz-15MHz), triangle and ramp (100μHz-100kHz), approximately 10-V peak-to-peak maximum output, d-c offset 5-V maximum

What is Expected of You

First and foremost, professional work is the norm in the lab just as it is in the other parts of the course.

The exercises themselves contain three different tasks that you will be expected to perform:

- Prelab work is assigned for many of the experiments. This is to help you prepare for the actual measurements in the lab so that you can use your time more efficiently Do all prelab work in your lab log. A *photocopy* of your work is due at the beginning of the class preceding the lab.
- Actual laboratory work involves connecting circuits and equipment, observing results, recording data, and so on. The earlier labs specify this in some detail, while the later ones say much less. You should be thinking about what you are investigating and what kind of observations are appropriate. For example, if you are making measurements of resistance, you should record a description of the resistor (coded nominal value, wattage, condition, etc.) even if these aren't asked for.
- Postlab work involves some consideration of the results. Be sure to check the lab sheets to see what is required and leave enough time at the end of the lab session to do it.

Additional reporting is due for some of the labs. Your reports will be like you might present to an employer.

One word of caution: You are expected to read and understand the procedures and requirements. "I didn't know we were supposed to do that" won't work.

Grading Policy

Your final grade will reflect all the written work that the labs require. Late work is not acceptable unless you have a very substantial reason for the lateness.

Lab Journal

Your lab book is similar to the record kept by an engineer developing some new circuit. It provides not only the record of what was done and how, but also serves as a legal document in such matters as obtaining patents. The lab book you are using meets all but one of the common requirements for such a record: it lacks printed page numbers (adding these really raises the price!).

Since the lab journal will be turned in at the end of each session, each partner will probably need a book. Otherwise, a book may not be available for the prelab or lab work for the next session.

One partner in the lab group should do all the work in the lab journal for one exercise while the other builds the circuit, sets up equipment, and reads instruments. These duties should rotate from one session to the next. Your grade on the lab is a joint grade, no matter who does what.

You are asked to do two seemingly contradictory things when you carry out and record your work. The first is to follow directions to the letter, both the directions listed here and those that go with each exercise. Following these directions makes your work easier to grade and will also get you into some good habits.

The second thing you must do is think for yourself. The lab instructions are usually not a cookbook. At times you will be expected to do something, yet not be told to do it. For example, if the lab says, "Compare your experimental and theoretical results," you are expected to calculate an experimental error; you could lose points if you don't.

Section 5.1 of the ECE Department's *Guidelines and Standards for Writing Assignments* contains some general instructions that you are expected to follow:

`http://ece-1.rose-hulman.edu/ecemm/index.php?option=com_rokdownloads&view=folder&Itemid=36`

Here are some additional instructions for recording your experiment in your lab log:

1. The lab journal is a log, a diary. Record all observations and results in the book **as you are doing** the exercise. Keep accurate records that would enable someone else to repeat the work. Show all of your calculations. If in doubt, write it down in the journal.

2. Make all entries in your journal in ink. If you make a mistake, cross it out with a single line and write the correction beside it. Don't erase because it may turn out that what you wrote the first time was important. The one exception to this rule is that you may, if you wish, draw graphs in pencil.

3. Never tear out any pages. In general, use only the fronts of pages; use the backs for attachments.

4. The first page of each exercise is the title page. Put the title of the project in big, easy-to-spot letters. Next, list the team members. Finally, record instrument and equipment identification for each piece of equipment used. (For this course, do this by recording just the bench number.) This will make it possible for someone to repeat your experiment. It also helps us identify faulty equipment.

5. Do prelab work in your journal. This comes after the title page and before the lab work. A *xerographic copy* of this is due at the beginning of the last class before lab.

6. Complete, labeled circuit diagrams are required for **all** circuits used.

7. All tables should have column headings and appropriate units. A column labeled *Comments* or *Notes* is useful to record extra information, such as a change of scale on an instrument.

8. Many of your graphs can be drawn in the journal. Each graph should have a title, labeled axes, and appropriate units. If a different grid is needed (semi-log, for example) or a graph has to be saved for another experiment, use good-quality graph paper. Permanently attach this graph to the notebook as shown in Fig. 1. Do not leave loose pages in your journal.

9. When you start a new section of the exercise, label this new part in your book. Number your results to match the numbering of the lab parts.

10. Sign the journal on the last page of the record. Include the date. Secure the already-graded pages with a rubber band to make easy for the grader to find the most recent work.

11. Finally, neatness counts. Your lab work must be organized, easy to read, and easy to follow. This is not to say you will be penalized for crossed-out words, spelling errors, or hurried lettering, nor does it say you'll gain extra credit for work that looks like it was done on a word processor. However, despite the fact that this is *your* journal, it is being written for someone else to read, whether it be the grader, the court deciding your patent dispute, or you five years from now. If your journal is difficult to read or follow, your work could be wasted.

Some Ways to Look Good

Since this journal is a "stream" of what is happening, neatness, grammar, and spelling are only minimal factors. It's "nice" if you are neat, spell well, and write perfect sentences, but it is much more important that you record what is happening.

If you really want to look good, pay attention to the following points:

- Use tables to present data, not sentences. Make sure the tables have clear column headings.
- Put units at the top of the column in a table to save writing them on every line.
- Make tables large. There should be enough space in the table to line out one entry and put in a correction without crowding.
- Cross out a mistake with a line. Don't obliterate it.
- All work should read from the bottom of the notebook if possible. If you need to turn something sideways, *always* read from the *right* side of the book. (See Fig. 1.)

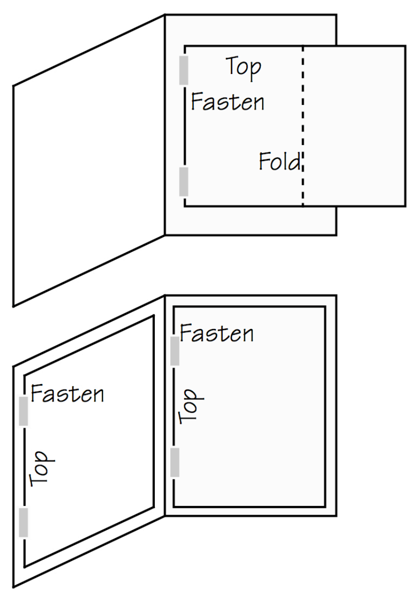


Fig. 1—Fastening papers in lab log

Schematic Diagrams

A drawing of a circuit is very important to have when you are wiring that circuit. Without the drawing, you don't know where you are supposed to be, and you can't see on paper what the circuit is supposed to look like.

The general rule in this course is, "Draw before you wire!" This means a completely labeled schematic that includes all element values, all sources, and all pins of integrated circuits labeled.

A proper schematic diagram is *not* a depiction of the physical layout of a circuit. It is what its name says, a *scheme* that shows the electrical, not the physical form of the circuit. The drawing in Fig. 2 is a properly laid-out schematic diagram of an op-amp inverter. Notice a number of things about it:

- The schematic is laid out from left to right in the direction the signal is flowing.
- Standard symbols for devices are used, not outlines of their physical shapes.
- All parts are labeled with enough information to permit building the circuit from the drawing.
- Semiconductor pin numbers are included.
- Power supply voltages are labeled, although the power wires themselves are usually omitted.
- Input and output terminals are clear, with input on the left and output on the right.
- Integrated circuits are labeled with their standard numbers (TL072) or "U" numbers to reference a listing elsewhere.
- The "A" on "U1A" means that this is one of the op-amps in the integrated circuit U1; the other op-amp would be labeled "U1B."

If you modify the circuit during your testing in the lab, be sure to modify the schematic. For simple changes, such as a change in a resistor's value, mark the change on the original drawing. For large changes, make a new drawing.

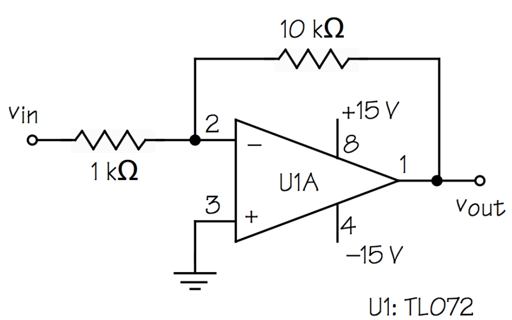


Fig. 2—Proper schematic diagram

Your instructor will not help you with a circuit unless you have a schematic drawing of it that is up to date.

Wiring a Breadboard

There are as many ways to construct a circuit on a breadboard as there are students doing it. But a few simple standards will help by keeping the circuit orderly, reducing wiring errors, preventing the circuit from falling apart, and generally making life simpler.

Here are some simple things you can do in planning your board layout that will help reduce the "spaghetti" and make your board easier to work with:

- Built circuits in advance, then use tape for flags to label power, inputs, and outputs.
- Power goes at the top, ground at the bottom.
- Build your circuit from left to right in the same direction as the "flow" of the signal through the circuit.
- Don't crowd. You need space to work.
- Flatten humps of wire so that they don't get caught and pulled out as you make measurements.

If you wire a board using a spaghetti layout, ignoring basic principles of orderliness, your instructor will probably not have time to help you debug a circuit.

Good Scoping

The oscilloscope is the most valuable instrument in the laboratory. If you were allowed just one instrument for all your work, the scope would have to be your choice. But the scope is a complicated piece of equipment. Paying attention to a few conventions will help you get good results:

- Channel 1 must display the input signal. This signal should generally be the one to which the scope sweep is synchronized. (The scope will do this automatically.) The trace should be toward the upper half of the screen.
- Channel 2 should display the output signal. The trace should be toward the lower half of the screen.
- Use the whole screen to display as large a waveform as possible. For example, don't display six periods of a pulse when you can see just one in more detail.

Capturing the Scope

If you need to capture the display on the scope, get a floppy and insert it into the scope. Press SAVE/RECALL, then FORMATS, then TIF, and then the QUICK PRINT button. This will write a file PRINT_*NN* on the floppy. Take the floppy to the computer/printer, open a blank Word page, drag PRINT_*NN* to it, and print.

Making Graphs

A graph is to convey numerical information in a way that shows a relationship or a trend. See the samples below in Figs. 3 and 4. Here are some standards for making graphs:

- A graph must be a clear picture of the data.
- A title must appear on the graph.
- Axes require labels and units. "Per division" labels are hard to read and understand.
- Axis divisions must be "reasonable" steps such as 1, 2, or 5. Steps like 3 and 7 are unacceptable and hard to read.
- The 0 point on each axis must be present except for a log scale.
- Grid lines are required with spacing close enough to allow the reader to read a value from the curve.
- Logarithmic axes require logarithmic scales and grid lines as in Fig. 4 below.
- A smooth curve is required through the points.
- "Bad" points should be excluded from the curve.
- The reader should be able to determine a value of the data from your graph. For example, in Fig. 3 below, the current at a voltage of 1.5 V appears to be about 10.8 mA.
- If you use Excel, you must force it to do your bidding and conform to the standards just stated. Excel was written for accounting types. "By hand" will usually take a lot less time than "by Excel."

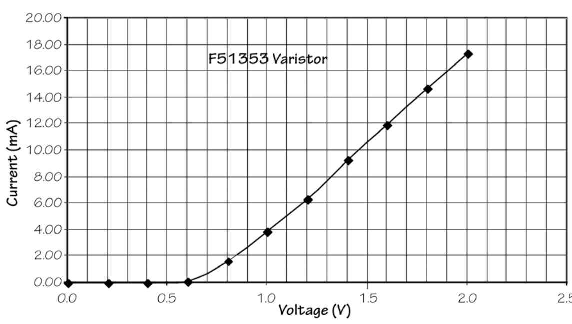


Fig. 3—Sample linear graph

Electrical Safety

Electricity has the ability to kill or injure you. You will be working with "electricity" in the lab this quarter. So you must pay attention to where it and you are at all times.

Electricity is nothing to be feared, no more than an automobile. The automobile can kill or injure, but you try to drive in such a way that you minimize the chances of having something go wrong. The same is true when working with electricity: act in ways that minimize the chances of getting hurt.

What's the problem with electricity? Some people say, "It's the current that kills." Others say, "The voltage is the problem." But since you can't separate these two effects (i.e., the voltage pushes the current through your body), it makes little difference how you think about the effects of electricity on the body.

We can classify the effects of electric shock by noting what the shock does. Damage to the body may be caused by current that disturbs the rhythm of the heart or interferes with the nervous system. Damage may be caused by heat due to current flow through the resistance of the body, especially the skin. Damage may also be caused by current that causes involuntary muscle contractions that make your body do something like falling.

But all these results come about only when your body becomes part of an electrical circuit, allowing current to flow through it in some way. The conclusion? To remain safe, **you must not become part of the circuit.**

How do you avoid becoming part of a circuit? The obvious way is not to have "electricity" in the first place! To say that another way, **turn off the circuit before working on it**. This isn't quite enough, though, because the circuit might get turned on and put you in a dangerous position. So, while you should not work on energized circuits, you need to go further.

Treat the circuit as if it were energized, even if you "know" the circuit is off. This way, you won't be hurt if

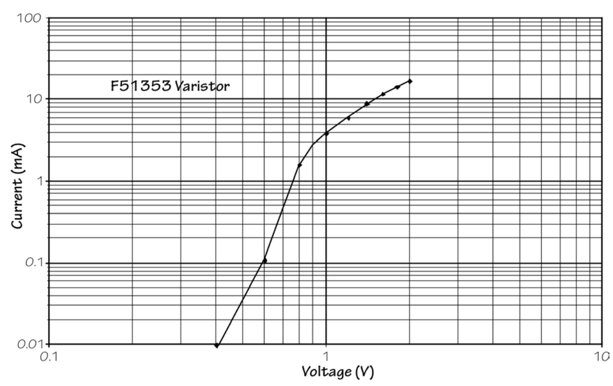


Fig. 4—Sample log-log graph from Excel

the circuit happens to be on. Remember that a circuit is a closed path, so for you to become part of the circuit, you must be part of a closed path. **Never put more than one hand into the circuit;** make sure that the rest of your body (don't forget your feet!) is not touching the circuit or ground. Then you'll be less likely to have a current path through you.

But something still could happen. That's when you want help around. So another safety rule is that you should **never work on a circuit alone**. This way, if something unexpected happens, somebody can get help.

So the three rules for electrical safety are pretty simple:

- **Don't work on live circuits.**
- **Don't assume the circuit is dead, ever.**
- **Don't work alone.**

Ah, you say, we couldn't be working with voltages in this lab that could hurt us. Wrong! Under the right conditions, only a few volts can push enough current through your body to cause muscle contractions or, if in the right path, tangle up the heart's rhythm. So these safety rules apply no matter what the voltage. Besides, how can you be sure that the power supply that is providing this "little voltage" won't malfunction and issue a blast of energy?

Treat electricity the way you treat an automobile: if you don't pay attention to what you are doing, you can get hurt. Or worse.

Writing Assignments

The course includes writing assignments and you'll be graded on the quality of your writing. This means that you may wish to get help from the Learning Center or from other students.

All of your written work must conform to the Department's *Guidelines and Standards for Writing Assignments* `http://ece-1.rose-hulman.edu/ecemm/index.php?option=com_rokdownloads&view=folder&Itemid=36`

Your work must be produced using a word processor. Be aware that the computer can lead you to doing things that aren't proper. For example, a computer-drawn graph is an easy way to present data, but the computer often chooses peculiar or unacceptable axes.

Correct usage of the English language is essential. This means that spelling, punctuation, grammatical structure, and word usage must be correct. Nothing marks you more quickly as inept than misuse of the language. Thee word-processor can help your considerably hear. [That sentence spell-checks!]

Sometimes you hear that you must avoid personal pronouns. Use them! Do <u>not</u> try to write in a formal style, which is becoming less common except in scholarly journals. But don't slip too far into a "familiar" way of writing. Note that "I" means you, while "we" means a group of people.

Compare "Current was applied to the resistor in the manner specified in the laboratory instructions and it was observed to undergo rapid and complete self-destruction, accompanied by a loud and disturbing report, followed by a random scattering of segments of the device over the upper portion of the work surface," and "I applied current to the resistor and it immediately exploded."

Acknowledgment

Lab manuals and the like involve lots of past history in the form of previous labs. What you have here is therefore a melding of the work of many people, but the historical thread is hard to unravel.

Wm. J. Eccles

Electrical Systems

Lab 0.5 – Reading Resistors and Capacitors

Small electronic parts don't have much room for printing, so labeling them with values is often done in code. Resistors and capacitors can be particularly difficult to read if you haven't been initiated into this secret society.

Resistors

A simple code using colored bands gives the resistance of small resistors. There are twelve colors in common use, ten for decimal digits and two primarily for percentage tolerances. The colors have the following meanings:

Black 0	Blue 6
Brown 1	Violet 7
Red 2	Grey 8
Orange 3	White 9
Yellow 4	Silver .... 10^{-1},10%
Green 5	Gold .... 10^{-2},5%

Resistors generally have four bands. Start reading from the band nearest the end of the resistor.

1st band – The tens digit of an integer.

2nd band – The units digit of an integer.

3rd band – The multiplier as a power of 10.

4th band – Percent tolerance (20% if no band).

For example, suppose the bands are red-violet-orange-gold. The resistor's value is found via red = 2, violet = 7, orange = 3, and gold = 5%. So the nominal resistance is 27 x 10^3 = 27 kilo ohms = 27 kΩ. The tolerance of 5% means the actual value is 27 kΩ ± 5%, or somewhere between 25.65 and 28.35 kΩ.

Here are some other examples:

brown-black-brown	= 10x10^1	= 100 Ω
green-blue-brown	= 56x10^1	= 560 Ω
orange-orange-red	= 33x10^2	= 3.3 kΩ
brown-green-orange	= 15x10^3	= 15 kΩ
brown-black-green	= 10x10^5	= 1 MΩ
grey-red-silver	= 82x10^{-1}	= 8.2 Ω

Capacitors

Capacitors have strange markings that are by no means as simple to decode as those on resistors. It's easy to think you have a 20-pF when you actually have a 0.2-μF capacitor. Reading capacitors is an ancient and mystic art! These are general rules that work 98.39% of the time:

Rule 1 – If the value printed on the capacitor has a decimal point in it, you can be reasonably assured that the value is in microfarads (μF, which is 10^{-6} farad). There may be exceptions to this rule for small-valued capacitors. For example, you may encounter a capacitor marked 4.7, but you can usually tell by its physical size whether its value is given in microfarads or picofarads.

Rule 2 – If the value printed on the capacitor has no decimal point and either has fewer than three digits or has a zero as its last digit, the number is the capacitance in picofarads (pF = 10^{-12} farad).

Rule 3 – If the value printed on the capacitor has no decimal point, has more than two digits, and has as its last digit a number other than zero, the value is in picofarads, like this:

- The first two digits are the first two digits of the capacitance.
- The last digit is the multiplier as a power of 10.
- It's like the color code for resistors, but with numbers instead of colors.

Rule 4 – If the value printed has two digits with a letter between them, the letter is the decimal point and the value is in picofarads.

Examples

2.2	2.2 μF	Rule 1
150	150 pF	Rule 2
472K	4700 pF	Rule 3
10	10 pF	Rule 2
104M	0.1 μF	Rule 3
4R7D	4.7 pF	Rule 4

(This set of rules is based on the works of Prof. Derry.)

RETMA Standard Resistors

Standard	**20%**	**10%**	**5%**
Percent step	~ 40%	~ 20%	~10%
Multiplier	$10^{1/6} = 1.46$	$10^{1/12} = 1.21$	$10^{1/24} = 1.10$
	10	10	10
	–	–	11
	–	12	12
	–	–	13
	15	15	15
	–	–	16
	–	18	18
	–	–	20
	22	22	22
	–	–	24
	–	27	27
	–	–	30
	33	33	33
	–	–	36
	–	39	39
	–	–	43
	47	47	47
	–	–	51
	–	56	56
	–	–	62
	68	68	68
	–	–	75
	–	82	82
	–	–	91
	100	100	100

Resistors are generally available for multipliers that give values from 1.0 Ω to 10 MΩ.

How to use the table above:

Suppose your design calls for a 3796-Ω 5% resistor. In the 5% column find "36" and "39," so 3.6 kΩ and 3.9 kΩ are available. 3.9 kΩ is closer to your requirement.

Available Parts

The Instrument Room has most 5% values of resistors available, especialy in the decades from 100Ω to 100 kΩ. Resistors cost 5¢ each.

Capacitors (non-polarized) are available in many standard values as follows:

1.8 pF	27 pF	0.001 μF	0.1 μF
2.2	33	0.0015	0.22
5.0	47	0.0022	0.33
7.5	68	0.0047	0.47
10	100	0.01	
12	220	0.022	
18	330	0.033	
22	470	0.047	

Available capacitors with values of 1.0 μF and above are polarized and are unsuitable for use in signal circuits. (They are common in power supplies and similar applications.)

Capacitors cost from 10 to 40¢ each.

Very few values of inductors are available for checkout: 33 mH, 3.3 mH, and 330 μH.

Table of ratios of 5% resistors

Top/ Side	10	11	12	13	15	16	18	20	22	24	27	30	33	36	39	43	47	51	56	62	68	75	82	91	100
10	1	1.10	1.20	1.30	1.50	1.60	1.80	2.00	2.20	2.40	2.70	3.00	3.30	3.60	3.90	4.30	4.70	5.10	5.60	6.20	6.80	7.50	8.20	9.10	10.00
11	0.91	1	1.09	1.18	1.36	1.45	1.64	1.82	2.00	2.18	2.45	2.73	3.00	3.27	3.55	3.91	4.27	4.64	5.09	5.64	6.18	6.82	7.45	8.27	9.09
12	0.83	0.92	1	1.08	1.25	1.33	1.50	1.67	1.83	2.00	2.25	2.50	2.75	3.00	3.25	3.58	3.92	4.25	4.67	5.17	5.67	6.25	6.83	7.58	8.33
13	0.77	0.85	0.92	1	1.15	1.23	1.38	1.54	1.69	1.85	2.08	2.31	2.54	2.77	3.00	3.31	3.62	3.92	4.31	4.77	5.23	5.77	6.31	7.00	7.69
15	0.67	0.73	0.80	0.87	1	1.07	1.20	1.33	1.47	1.60	1.80	2.00	2.20	2.40	2.60	2.87	3.13	3.40	3.73	4.13	4.53	5.00	5.47	6.07	6.67
16	0.63	0.69	0.75	0.81	0.94	1	1.13	1.25	1.38	1.50	1.69	1.88	2.06	2.25	2.44	2.69	2.94	3.19	3.50	3.88	4.25	4.69	5.13	5.69	6.25
18	0.56	0.61	0.67	0.72	0.83	0.89	1	1.11	1.22	1.33	1.50	1.67	1.83	2.00	2.17	2.39	2.61	2.83	3.11	3.44	3.78	4.17	4.56	5.06	5.56
20	0.50	0.55	0.60	0.65	0.75	0.80	0.90	1	1.10	1.20	1.35	1.50	1.65	1.80	1.95	2.15	2.35	2.55	2.80	3.10	3.40	3.75	4.10	4.55	5.00
22	0.45	0.50	0.55	0.59	0.68	0.73	0.82	0.91	1	1.09	1.23	1.36	1.50	1.64	1.77	1.95	2.14	2.32	2.55	2.82	3.09	3.41	3.73	4.14	4.55
24	0.42	0.46	0.50	0.54	0.63	0.67	0.75	0.83	0.92	1	1.13	1.25	1.38	1.50	1.63	1.79	1.96	2.13	2.33	2.58	2.83	3.13	3.42	3.79	4.17
27	0.37	0.41	0.44	0.48	0.56	0.59	0.67	0.74	0.81	0.89	1	1.11	1.22	1.33	1.44	1.59	1.74	1.89	2.07	2.30	2.52	2.78	3.04	3.37	3.70
30	0.33	0.37	0.40	0.43	0.50	0.53	0.60	0.67	0.73	0.80	0.90	1	1.10	1.20	1.30	1.43	1.57	1.70	1.87	2.07	2.27	2.50	2.73	3.03	3.33
33	0.30	0.33	0.36	0.39	0.45	0.48	0.55	0.61	0.67	0.73	0.82	0.91	1	1.09	1.18	1.30	1.42	1.55	1.70	1.88	2.06	2.27	2.48	2.76	3.03
36	0.28	0.31	0.33	0.36	0.42	0.44	0.50	0.56	0.61	0.67	0.75	0.83	0.92	1	1.08	1.19	1.31	1.42	1.56	1.72	1.89	2.08	2.28	2.53	2.78
39	0.26	0.28	0.31	0.33	0.38	0.41	0.46	0.51	0.56	0.62	0.69	0.77	0.85	0.92	1	1.10	1.21	1.31	1.44	1.59	1.74	1.92	2.10	2.33	2.56
43	0.23	0.26	0.28	0.30	0.35	0.37	0.42	0.47	0.51	0.56	0.63	0.70	0.77	0.84	0.91	1	1.09	1.19	1.30	1.44	1.58	1.74	1.91	2.12	2.33
47	0.21	0.23	0.26	0.28	0.32	0.34	0.38	0.43	0.47	0.51	0.57	0.64	0.70	0.77	0.83	0.91	1	1.09	1.19	1.32	1.45	1.60	1.74	1.94	2.13
51	0.20	0.22	0.24	0.25	0.29	0.31	0.35	0.39	0.43	0.47	0.53	0.59	0.65	0.71	0.76	0.84	0.92	1	1.10	1.22	1.33	1.47	1.61	1.78	1.96
56	0.18	0.20	0.21	0.23	0.27	0.29	0.32	0.36	0.39	0.43	0.48	0.54	0.59	0.64	0.70	0.77	0.84	0.91	1	1.11	1.21	1.34	1.46	1.63	1.79
62	0.16	0.18	0.19	0.21	0.24	0.26	0.29	0.32	0.35	0.39	0.44	0.48	0.53	0.58	0.63	0.69	0.76	0.82	0.90	1	1.10	1.21	1.32	1.47	1.61
68	0.15	0.16	0.18	0.19	0.22	0.24	0.26	0.29	0.32	0.35	0.40	0.44	0.49	0.53	0.57	0.63	0.69	0.75	0.82	0.91	1	1.10	1.21	1.34	1.47
75	0.13	0.15	0.16	0.17	0.20	0.21	0.24	0.27	0.29	0.32	0.36	0.40	0.44	0.48	0.52	0.57	0.63	0.68	0.75	0.83	0.91	1	1.09	1.21	1.33
82	0.12	0.13	0.15	0.16	0.18	0.20	0.22	0.24	0.27	0.29	0.33	0.37	0.40	0.44	0.48	0.52	0.57	0.62	0.68	0.76	0.83	0.91	1	1.11	1.22
91	0.11	0.12	0.13	0.14	0.16	0.18	0.20	0.22	0.24	0.26	0.30	0.33	0.36	0.40	0.43	0.47	0.52	0.56	0.62	0.68	0.75	0.82	0.90	1	1.10
100	0.10	0.11	0.12	0.13	0.15	0.16	0.18	0.20	0.22	0.24	0.27	0.30	0.33	0.36	0.39	0.43	0.47	0.51	0.56	0.62	0.68	0.75	0.82	0.91	1

Laboratory 1

Ohm's Law

Unlike mechanical and biomedical engineers, electrical engineers deal with a "substance" that isn't readily visible like a motor, shaft, piston, bacterium or heart signal. While we cannot see this "substance" turn on a light or power a pump, it can definitely be felt. It can also be measured in the form of voltage, current and power.

Electrical Systems deal with the laws that govern electrical circuits. Although you may not be an electrical or computer engineer, all fields of engineering will use electricity. This may be in the form of delivering energy to your pumping station or powering the instrumentation that measures blood flow.

This laboratory will study the measurement of electrical quantities including voltage, current, resistance and power. However, this lab will not only focus on making measurements but also on how to properly collect, analyze and present technical data. This presentation will be in the form of text, circuit diagrams, graphs and tables.

Purpose

This lab will introduce basic techniques in measurement and presentation of electrical data:

- Resistor color code
- Presentation of data in tabular and graphic forms
- Measurement of resistance, voltage, current and power
- Measurement of the characteristics of a non-linear device, an LED
- Error calculations

Pre-Lab

Each week you will be required to complete a pre-lab to prepare for the laboratory work. The pre-lab should be completed on engineering paper and submitted in class ***the day before*** lab. For this lab, you should read and become familiar with Lab 0, Lab 0.5 and the procedure for lab 1. You also should read the Nilsson and Riedel textbook, Section 2.2. After you complete the required reading, answer the following questions:

1. What is the color code for a 10-Ω resistor?
2. What is the color code for a 100 - resistor?
3. What is the color code for a 1-kΩ resistor?
4. What is the value of a resistor with color code, red-yellow-red?
5. What is the value of a resistor with color code, brown-red-red?
6. What is the value of a resistor with color code, orange- black-red?
7. What is the voltage across the resistor in Figure 1?
8. What is the power delivered to the resistor in Figure 1?
9. What is the current through the resistor in Figure 2?
10. What is the power delivered to the resistor in Figure 2?

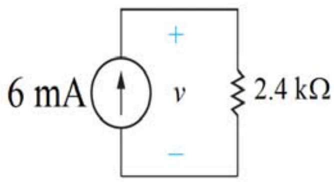


Figure 1: 2.4 kΩ resistor circuit

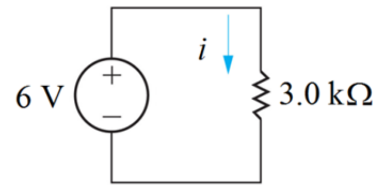


Figure 2: 3.0 kΩ resistor circuit

Each week you also will be required to watch videos on the laboratory equipment and experimental methods to assist you in completing the lab. In order to do this, you must go to the BEEM website (http://ece-2.rose-hulman.edu/beem/) and create an account so that you can view all of the videos. To create an account, click on "create an account" at the bottom of the page and use your Kerberos username. You can activate the account by following the instructions in the message sent to your email address. Finally, log into your BEEM account and view the following videos under the *How_To_Videos* link:

- *How_to_read_resistor_code*
- *How_to_Breadboard*
- *How_to_setup_DMM*
- *How_to_Ohm_Ammeter*
- *How_to_use_DCPowerSupply*
- *How_to_measure_I_with_DMM*
- *How_to_measure_V_with_DMM*
- *How_to_measure_R_with_DMM*

Finally, view the following video under the ES203 Lab Tutorials link:

- *Power Supply Simple Circuit*

If you have any questions, please ask your instructor.

Equipment

2 – 2.4-kΩ resistors
2 – 3.0-kΩ resistors

1 – 100-Ω resistor

1 – LED

2 pair – red and black meter leads for the DMM (located on wall rack)

1 pair – BNC-to-alligator leads for the power supply (located on wall rack)

1 BNC-to-banana adapter (located in bench drawer)

Procedure

The lab is divided into five parts and each part includes writing a procedure sentence, drawing circuit diagrams, recording data, and including your results and analysis. All of your work should be completed in the lab journal (composition book). The lab journal must include a table of contents, proper headings, page numbers, and schematics. Circuit diagrams must be clearly labeled with all component values. The data tables must include measured and nominal values with error analysis. Any graphs created should have a descriptive title, axes labels (with units and sensible intervals). Lastly, answers to questions posed in the lab journal must be included in your notebook.

Part I – Ohmmeter Measurements

You will use three methods to determine the actual value of the two 2.4-kΩ and two 3.0-kΩ resistors, including interpreting their color code, direct metering and calculating resistance based on voltage and current measurements.

- Record the color code and the nominal value of the 2.4 -Ω and 3.0-kΩ resistors
- Measure and record the resistance of each of the 4 resistors by using the digital multimeter (DMM) as an ohmmeter. Figure 3 is a picture of the setup for this measurement.

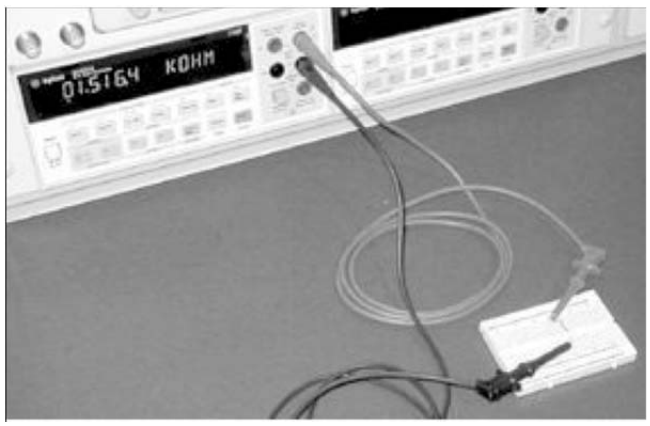


Figure 3: Ohmmeter Setup

- Create the following data table in your lab notebook for recording the data for parts I and II of the lab procedure. Calculate R using Ohm's law with measured voltage and current.

Table 1: Resistance Measurement Data Table

Resistor	R, kΩ measured	R, kΩ nominal	% error	V, V	I, mA	R, kΩ calc.	% error
1		2.4					
2		2.4					
3		3.0					
4		3.0					

- Note that the percent error formula is $\% \, error = \frac{measured - nominal}{nominal} \, x \, 100$

Part II – Ohm's Law Measurements

In this part you will calculate the resistance of each of the four resistors by applying a voltage and measuring the current.

Ohmmeter the Ammeter

Each week that you use the ammeter to measure current, you should **ohmmeter the ammeter** in order to make sure your ammeter does not have a blown fuse. If you do not do this and your ammeter has a blow fuse, all of your current readings will be incorrect! You will use one DMM to test the other one and then swap the connections.

- Place one set of meter leads in the left DMM in the top (red) and middle (black) jacks on the right side of the DMM.
- Set the left DMM to measure resistance by pressing (Ω 2W).
- Place the second set of meter leads in the right DMM in the middle (black) and bottom (red) jacks on the right side of the DMM.
- Set the right meter to measure current by pressing (shift, DC I).
- Next, connect the two red leads together and the two black leads together.
- The left DMM measures the resistance of the ammeter and should show a low resistance between 5 and 10 ohms. If the left DMM shows resistance larger than a few ohms then contact your instructor to have the fuse replaced on the right DMM.
- Repeat this test by setting the left DMM to measure current and setting the right DMM to measure resistance. (Don't forget to move the meter leads into the appropriate jacks for an ammeter and ohmmeter!)
- Record the left and right ammeter resistance in your lab journal.

Voltage-Current Measurements

Build the circuit in Figure 4 using your first 2.4-kΩ resistor. By applying a voltage across the resistor and measuring the current in it, you can calculate the resistor's resistance. (A good habit is to always lay out the circuit on the breadboard exactly like it looks in the diagram in order to aid you in quickly debugging your circuits.)

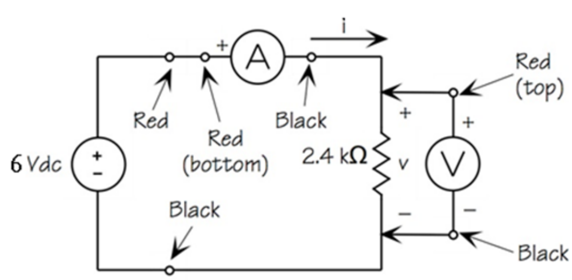


Figure 4: Resistor V-I measurement

- Put the resistor in your breadboard similar to the orientation shown in Figure 5.

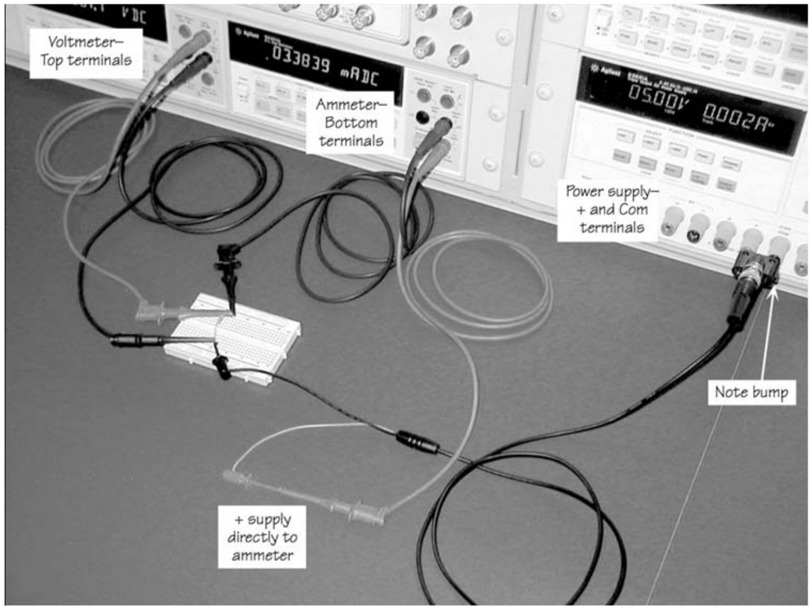


Figure 5: Resistor V-I measurement equipment setup

- Put the meter leads in the left DMM in the top (red) and middle (black) jacks in the right column of the DMM. Set the DMM to measure voltage by pressing (DC V).
- Connect the red lead to the top of the resistor and the black lead to the bottom of the resistor which represents ground.
- Put the second set of meter leads in the right DMM in the bottom (red) and middle (black) jacks in the right column of the DMM. Set the DMM to measure current by pressing (shift, DC I). Connect the black lead from the ammeter to the top of the resistor at the same point as the red lead from the voltmeter and leave the red lead unattached.
- Get a two-wire lead with red and black alligator clips on one end and a BNC connector (shiny round connector) on the other end. Attach this end to the BNC to banana adapter located in your bench drawer. Note that the adapter has a bump on one edge which represents the COM (ground) and this is shown in Figure 6.

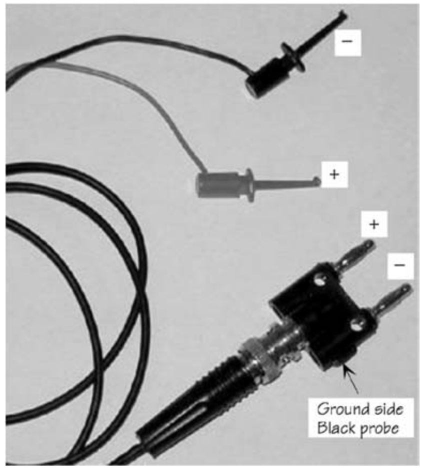


Figure 6: Banana to BNC probe

- Turn on the power supply, press **display limit**, press **+25** so that you can adjust the voltage. Use the knob and the < and the > button so that you can set the voltage to **6 V**
- Next press **Voltage/Current** to set the current limit to **0.1 A** by using the knob and the < and the > buttons
- Insert the adapter into the +25 and COM terminals on the power supply. MAKE SURE THAT THE BUMP OF THE ADAPTER IS AT THE COM TERMINAL ON THE POWER SUPPLY!
- Connect the black probe from the power supply to the bottom of the resistor (which is ground) and connect the red probe from the power supply to the red ammeter lead that was left unconnected earlier. You have now set up the ammeter to read the current from the power supply through the resistor.
- Press **output** on the power supply to energize the circuit. Record the voltage and current from the DMM in Table 1 in your journal and use Ohm's Law to calculate resistance. Also calculate the % error. (Use the resistance measured by the ohmmeter in part I as the nominal value for your error calculation.)
- Repeat the voltage-current measurements for the other 3 resistors and record these data in Table 1 of your lab journal.
- Next, use the measured values of the voltage and current for the four resistors to calculate the ***measured power*** delivered to each (i.e. P = VI). The ***nominal power*** value is calculated as $P = V^2/R$ where V = 6 volts and R is the resistance measured by the ohmmeter. Record these values and the calculated percent error in Table 2.
- When you are finished, press **output** on the power supply to de-energize the circuit.

Table 2: Power Measurement Data Table

Resistor	R, kΩ nominal	P, mW measured	P, mW nominal	% error
1	2.4			
2	2.4			
3	3.0			
4	3.0			

Part III – Three resistor circuit

In this part you will build the circuit in Figure 7 and measure voltages and currents in order to calculate the apparent resistance of each resistor.

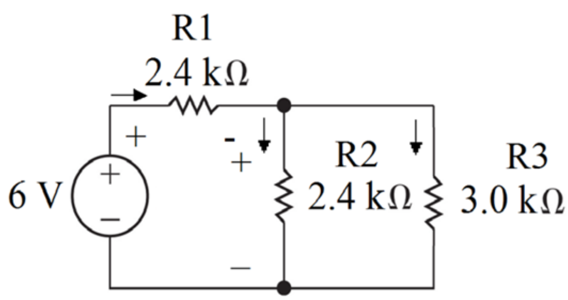


Figure 7: Three resistor circuit

As a reminder, each circuit on the breadboard should be laid out exactly the way that it looks in the drawing in order to make it easier to construct and de-bug (see Figure 8). Briefly, each vertical column of five holes on the breadboard is one node, and all elements placed in a single column are "connected" to each other. Additionally, the red and blue lines (row of holes) down each side of the bread board also are nodes and can be used for ground and power busses. Use these rows when you have multiple elements to connect together.

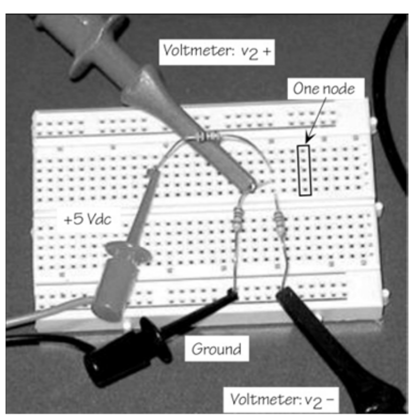


Figure 8: Three Resistor Circuit Set Up

Once you have the circuit set up correctly, you should use the two DMMs to measure the voltage across and current through each of the resistors. These data should be recorded in a data table similar to Table 3.

Table 3: Power Measurement Data Table

Resistor	V, V	I, mA	R, kΩ measured	R, kΩ nominal	% error	P, mW
R1						
R2						
R3						

The ***measured value*** of the resistance is found by using Ohm's law using the measured voltage and current. The ***nominal value*** of the resistance is the ohmmeter measurement found in part I. Students typically don't have problems measuring voltage because it involves placing the voltmeter across the desired element. However, current measurement is a bit more challenging because the circuit must be "broken" so the ammeter can measure current flow. This is what you did to measure the current through the resistor in part II. Figure 9 provides an example of how to "break" the circuit to measure the current through the middle resistor. **Note that it is pulled out of the breadboard** and the black lead of the meter is connected to the lifted end, and the red lead of the ammeter is connected to the node where the resistor was connected.

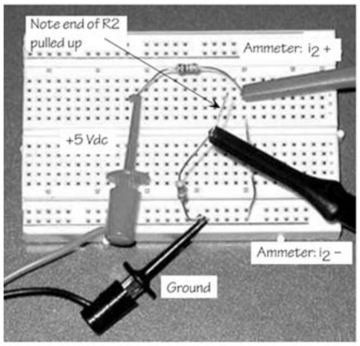


Figure 9: Current Measurement on the three resistor circuit

From the measured voltage and current data, compute the power delivered to each of the resistors and record the value in Table 3 in your lab journal. Finally, use the measured current through the voltage source to find the power delivered by the source. Does the power delivered by the voltage source equal the sum of the power absorbed by the 3 resistors? Confirming that the power delivered is equal to the sum of the power absorbed is an application of what law?

Part IV – Resistor V-I Characteristics

In this part of the lab you will measure and graph the voltage and current characteristics of a resistor. Select one of the 3.0-kΩ resistors, place it in the breadboard and connect it to the **+25 V** power supply. In order to measure the voltage and current, set up the voltmeter and ammeter similar to what you did in part II of the lab procedure. Vary the power supply voltage between 0 and 5 V and record the measured current in Table 4 in your lab journal.

Table 4: 3.0 kΩ resistor V-I characteristics

Power supply voltage, V	V, V measured	I, mA measured
1		
2		
3		
4		
5		

Use the grid in your lab journal to create a graph of the voltage versus the current for the 3.0-kΩ resistor. An acceptable graph should cover at least half of the page, have a descriptive title and axes labeled with units. Use the graph to compute the equation of the line and explain what the slope of the line represents.

Part V – LED I-V Characteristics

You will finish this lab by measuring and graphing the I-V characteristics of a non-linear device, a light-emitting diode (LED).

- Set up the circuit in Figure 10. Make sure that you include the 100-Ω resistor in order to limit the current through the LED (and thus to prevent damaging it).
- Set up the **+25 V** power supply similar to what you did in part II and connect the red lead to the left side of the resistor and the black lead to the bottom of the LED. Next, connect the ammeter and voltmeter as shown in Figure 10. The 'circled A' in the diagram represents the ammeter with the red lead connected to the right side of the 100-Ω resistor and the black lead connected to the top of the LED. The 'circled V' in the diagram represents the voltmeter with the red lead connected to the top of the LED and the ammeter black lead. The black lead of the voltmeter connects to the bottom of the LED, the ground or bottom of the circuit and the power supply.

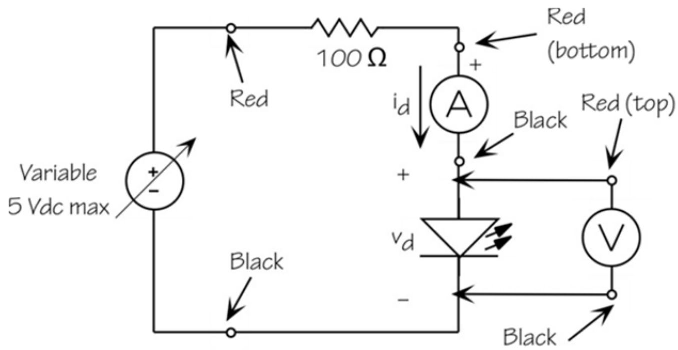


Figure 10: LED measurement circuit

- The LED has a direction! The flat rim on the edge of the cap of the LED should be connected to ground or it will not light up. To test if the LED is in the circuit correctly, turn the power supply up to 3 V and if the LED does not light up then it is backwards and needs to be reversed.
- Collect the I-V data by starting at 0 V across the LED and increasing the voltage in reasonable steps. You should continue to record the LED voltage and current until the current reaches 20 mA. NOTE THAT YOU ARE RECORDING THE VOLTAGE ACROSS THE LED AS READ ON THE VOLTMETER **NOT** THE POWER SUPPLY VOLTAGE. See Table 5 for a sample of a reasonable data table (measured from a different LED). This table may not reflect the exact values for your LED. Note that to save time you should only move in discrete steps when you are close to the 'knee' of the curve and the data are changing quickly. There is no sense in taking points close together during straight sections in the curve.

Table 5: Sample LED Data

V_d, V	I_d, mA
0.020	0.002
0.113	0.005
0.210	0.011
0.465	0.025
0.503	0.24

- Use the grid in your lab journal to draw an acceptable graph of the current, i_d versus the voltage, V_d. Figure 11 provides an example of an acceptable graph (with appropriate axes intervals). This graph should take up at least half of the page of the lab journal, have a descriptive title, labeled axes (with units), and be drawn smoothly with the data points connected.

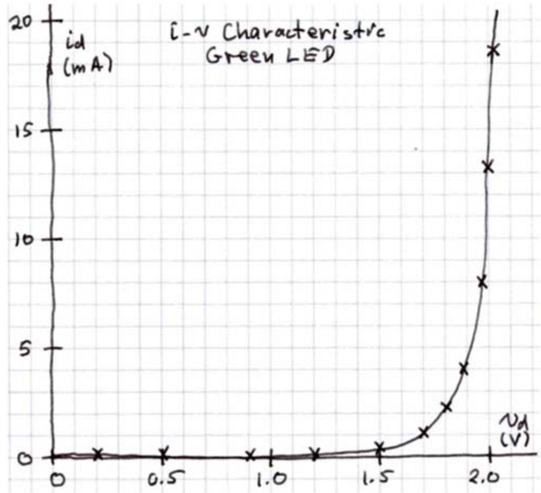


Figure 11: LED I-V characteristics graph

- Does the LED exhibit a linear relationship between voltage and current? Why or why not? What is the power delivered to the LED between 0 and 1 V? What is the ***apparent resistance*** of the LED at i_d = 15 mA? What is the power delivered to the LED at i_d = 15 mA?

Submission Checklist

- Review Lab 0 for journal specifications
- Complete the Table of Contents including lab number, lab title and page number
- Number all of the pages used in your journal for this write up
- Include a title page at the beginning of the lab write up with the lab number, title, date, partner names, and bench number
- Label the heading for each part of the lab procedure
- Write a procedure sentence for each part of the lab procedure. This sentence should include what you built, what quantities were measured and what you used to measure them.
- Draw a circuit diagram for each circuit you built and label all component values
- Tabulate all measured data and include appropriate error analysis
- State all formulas used, including percent error and Ohm's Law
- Graph V-I characteristics for resistor and LED
- Answer all questions posed
- Sign and date the last page of the lab write up (both partners)

This checklist provides the minimum guidelines required in order to receive a passing grade on your lab journal submission. You will not always be provided with a detailed check list for the lab write up because you are required to learn what constitutes an acceptable record of your laboratory work. However, for the first two weeks, if you finish the lab procedure early, your instructor will review your lab journal and provide feedback on how to improve it.

Laboratory 2

Series and Parallel Resistance

Modern instrumentation uses digital multimeters to measure three basic quantities: voltage, current and resistance. In this lab, we will explore series and parallel resistance using both the ohmmeter and voltage-current method (i.e., Ohm's Law). However, measurements are often affected by the measurement instruments. For example, when you measure voltage with a meter, a small amount of energy is extracted from the circuit to power the meter. The result is that a very small current flows in the leads. Thus, some resistance measurements, especially those of very low resistances, are affected by the resistance of the meter leads.

Purpose

This lab will introduce the basic techniques in measurement and presentation of electrical data:

- Series and parallel combinations of resistors
- Two-wire and four-wire ohmmeter connections to measure a very small resistance
- Cross-sectional area and the diameter of the wire, along with the gauge of the wire.

Prelab

For this lab, review Lab 0, Lab 0.5 and the entire lab procedure. You also should read Section 3.1 – 3.2 from the Nilsson and Riedel textbook. Lastly, complete the following problems on engineering paper and submit it in class the day before lab.

1. What is the equivalent resistance across terminals a and b for the circuits in Figures 1, 2 and 3?

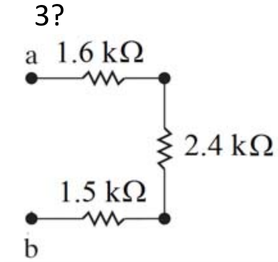


Figure 1: Series Circuit

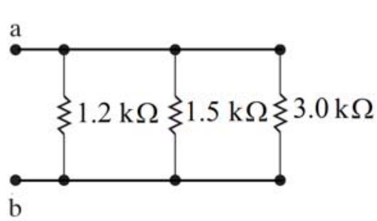


Figure 2: Parallel Circuit

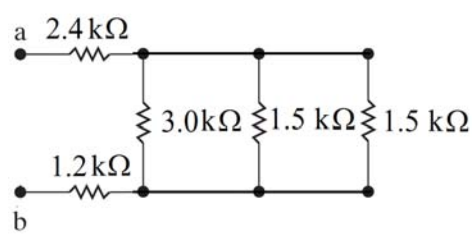


Figure 3: Series-Parallel Circuit

2. For the circuit in Figure 4, if I = 450 μA, what is the value of R_x?
3. For the circuit in Figure 5, if I = 10 mA, what is the value of R_x?

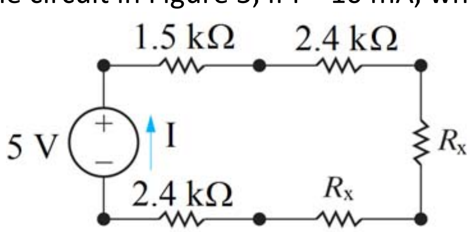


Figure 4: Series Circuit

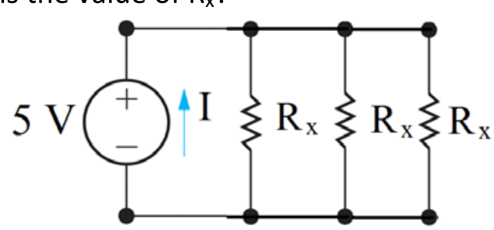


Figure 5: Parallel Circuit

4. For the circuit in Figure 6, if I = 1.25 mA, what is the value of R_x?

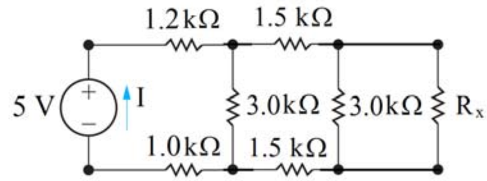


Figure 6: Series-Parallel Circuit

If necessary, you should also review the videos on breadboards, resistors, electrical circuits, power supplies and digital multimeters at the BEEM website. If you have any questions, please ask your instructor.

Equipment

4 – 2.4 kΩ resistors
4 – 3.0 kΩ resistors
2 – 1.2 kΩ resistors
2 pair – red and black meter leads for the DMM (located on wall rack)
1 pair – BNC-to-alligator leads for the power supply (located on wall rack)
1 BNC-to-banana adapter (located in bench drawer)
One meter of bare copper wire

Procedure

In this lab, you will use the ohmmeter, voltmeter and ammeter to measure series and parallel resistance combinations. Therefore, you need to use the ohmmeter to measure the resistance of the ammeter on both DMMs and record the resistance values in your lab notebook. Remember to notify your instructor if the resistance is more than a few ohms. Refer to Lab 1 if you don't remember how to **'ohmmeter the ammeter'**. Also, remember to limit the current from the power supply to 100 mA to keep from accidentally blowing the DMM fuse.

Part I – Series Resistance

In this part, you will test the theory that series resistance sums. Place four 2.4-kΩ resistors in series on your breadboard. Recall that series means 'end-to-end' so resistors that touch must be in the same row or node on the breadboard. Use the ohmmeter to measure the equivalent resistance across the four. Repeat the measurement for four 3.0-kΩ resistors in series. Record the measured data in Table 1 in your lab journal with error analysis and make sure to record your formula for calculating the equivalent resistance. What do you think will happen to the equivalent resistance as you continue to add more resistances of the same value in series?

Table 1: Series Resistance Data

Resistors	R, kΩ meas	R, kΩ nom	% error	V, V	I, mA	R, kΩ meas	R, kΩ nom	% error
4-2.4 kΩ								
4-3.0 kΩ								

Part II – Series Resistance V-I method

In this part, you will measure the series resistance again using the voltage-current method from Lab 1. Apply a 5 V source to the four resistors using the **+25V** power supply and measure the current through the circuit using the ammeter. Refer to Lab 1 if you don't remember how to set up the circuit to read voltage and current on the two DMMs. Use Ohm's law to calculate the resistance seen by the source and record the result on Table 1 in your lab journal. Remember that the nominal value is the ohmmeter resistance from part I. Repeat the V-I method to find the equivalent resistance of the four series 3.0-kΩ resistors.

Part III – Parallel Resistance

In this part, you will test the theory that parallel resistors add reciprocally. Begin by placing two 2.4-kΩ resistors in parallel on the breadboard. Recall that, parallel means that the resistors are connected on 'both sides' so each set of legs should be in the same row or node on the breadboard. Use the ohmmeter to measure the equivalent resistance for 2, 3 and 4 parallel resistors and record your data in Table 2 (in your lab journal). Make sure that you record the formula for calculating the nominal value of parallel resistors.

Table 2: Parallel Resistance Data

Resistors	R, kΩ meas	R, kΩ nom	% error	V,V	I, mA	R, Ω meas	R, Ω nom	% error
2-2.4 kΩ								
3-2.4 kΩ								
4-2.4 kΩ								

You should repeat this procedure for 2, 3 and 4 parallel 3.0-kΩ resistors. Create another table with measured, nominal and error analysis to compare these values. In the future, you will not be explicitly told to make a data table, but be aware that you should do so **and** perform an error analysis when you compare measured data to theoretical or nominal.

Part IV – Parallel Resistance

In this part, you will use the V-I method to measure the resistance of two, three and four parallel resistors (first using 2.4-kΩ resistors, then with 3.0-kΩ resistors). Record your data (and error calculations) in appropriate data tables. What happens as you add more and more identical resistors in parallel? Can you write an expression to describe this relationship?

Part V – Series-Parallel Resistance

In this part you will build the circuit in Figure 7 and use the ohmmeter and V-I method to measure the equivalent resistance across terminals a and b. Make sure that you show how you calculated the nominal value of the resistance and perform an appropriate error analysis.

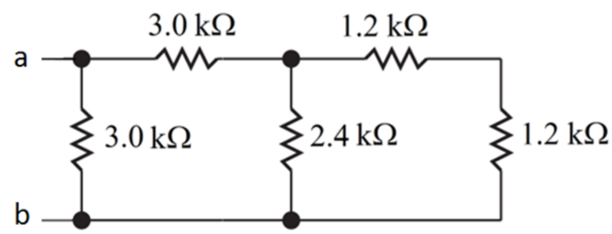


Figure 7: Series-Parallel Circuit

Part VI – Measuring apparent resistance

In this part you will calculate the apparent resistance of an LED when it is lit. Refer to lab 1 for how to build the circuit and to verify that you have placed the LED in the circuit correctly. You should increase the voltage across the LED until right after it turns on. Record the current, i_d and voltage, v_d and use these values to calculate the apparent resistance of the LED.

Part VII – Measuring low resistance

Suppose you need to measure a low resistance such as 0.1 Ω. Could the leads of the ohmmeter be a factor in this measurement? Since they are wires and have a connection, they could also have a small resistance. In this part, you will demonstrate that using a 4-wire resistance measurement is more accurate than the typical 2-wire measurement for small resistances.

- Select one of the longest wires from your parts kit
- Use the ohmmeter to measure the wires resistance by pressing (Ω 2W). Record this value (which likely will be unstable).
- Move the probes you just used to the left hand pair of red and black jacks on the ohmmeter, they are marked "Ω 4W Sense".
- Connect a second set of probes to the right-hand pair of red and black jacks
- Connect the second set of probes to your wire **outside** of the first set, red beyond red and black beyond black.
- On the DMM, press **shift** - **Ω 2W** which yields a 4-wire resistance measurement. This reading is the most precise you can get because the outside set of leads provides a current through the wire and the inside set of leads measures the voltage across the wire. This measurement draws well under a microampere of current through the leads and connectors. By providing the inside leads, this set up minimizes the effects of lead and connector resistance. Record this value and compare it to the 2-wire resistance measurement.

Part VIII – Wire size and gauge

In this part you will use the 4-wire resistance measurement technique to determine the gauge of a meter of copper wire.

- Obtain one meter of bare copper wire from your instructor
- Use the ohmmeter 4-wire technique to measure the resistance of the wire

- From the resistance data, calculate the cross-sectional area of the wire in square millimeters and the diameter in millimeters
- The resistivity of copper is $\rho = 1.673 \times 10^{-8}$ Ω-m at 20°C.
- Resistance is length in meters times resistivity divided by area in square meters
- Find the diameter on the American Wire Gauge (AWG) table to find the gauge of your piece of wire

Submission Checklist

- Review Lab 0 for journal specifications
- Complete the Table of Contents including lab number, lab title and page number
- Number all of the pages of this lab write up
- Include a title page at the beginning of the lab write up with lab number, title, date, partner names, and bench number
- Label the heading for each part of the lab procedure
- Write a procedure sentence for each part of the lab procedure. This sentence should include what you built, what quantities were measured and what you used to measure them.
- Draw a circuit diagram for each circuit you built and label all component values
- Tabulate all measured data and include appropriate error analysis
- State all formulas used, including percent error and Ohm's Law
- Answer all questions posed
- Sign and date the last page of the lab write up (both partners)

This checklist provides the minimum guidelines required in order to receive a passing grade on your lab journal submission. You will not always be provided with a detailed check list for the lab write up because you are required to learn what constitutes an acceptable record of your laboratory work. However, for the first two weeks, if you finish the lab procedure early, your instructor will review your lab journal and provide feedback on how to improve it.

Laboratory 3

Expert Witness

You have been hired to appear as an expert witness in a case involving a dispute over the contents of a particular circuit. Your job is to analyze the circuit completely so that you can testify with certainty how the circuit is constructed. In this lab you will prepare your testimony. The credentials of an expert witness are impeccable which is why they are hired to testify on technical matters. The expert witness is the only person in the court room, other than the judge, who can state an opinion. The expert witness is hired by either the plaintiff or the defendant and is generally well compensated. The case you will prepare is between a customer, the plaintiff, who insists that the box contains the wrong circuit, and the manufacturer, the defendant, who insists that the circuit is correct. The plaintiff feels that, with expert testimony as to what circuit is in the box, the case will be decided in the plaintiff's favor. Your only duty is to testify completely and truthfully as to what circuit the box contains. Whether this favors the plaintiff or the defendant is not for you to determine

Purpose

This lab is to gain experience using the tools you already have learned to evaluate the mystery box and identify shorts, series and parallel resistors in order to completely identify the circuit in the box. This presentation will involve the collection and analysis of lots of data and the preparation of a memo to the lawyer.

Prelab

You should read the entire lab procedure and review the concepts of series and parallel resistances. Complete the following prelab on engineering paper and submit it in class the day before lab. You must show work to receive full credit for this submission.

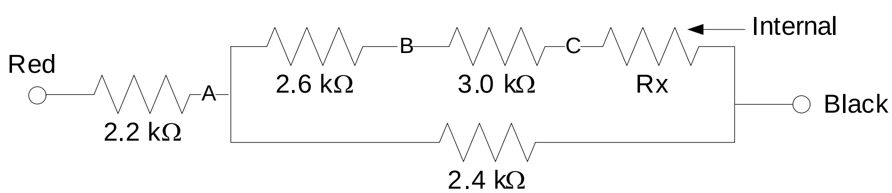


Figure 1: Box 00: Schematic Circuit

1. If an ohmmeter is connected between the *Red* node and *A* node of Figure 1, what does the ohmmeter read?
2. If an ohmmeter is connected between the *Red* node and *Black* node of Figure 1 and reads "4.0 kΩ", what is the value of Rx? What is the closest 5% standard resistor to this value? (*Check Lab 0.5, page 8 of your lab manual for a list of standard resistors.*)
3. Assume Rx = 2.7 kΩ, if an ohmmeter is connected between the *C* node and the *Black* node of Figure 1, what does the ohmmeter read? (It is NOT 2.7 kΩ. Why?)
4. Assume Rx = 17 kΩ. If an ohmmeter is connected between the *B* node and *Black* node, what does the ohmmeter read?

5. Use the diagram in Figure 2 to create a ***physical layout*** of Box 00. Also, make sure to show the location of the internal resistor.

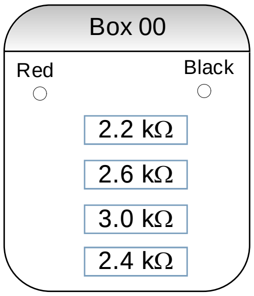


Figure 2: Box 00: Physical Layout

If necessary, review the videos on measuring resistance on the BEEM website. If you have any questions, please ask your instructor.

Equipment

Mystery Box with disputed circuit

1 pair – red and black meter leads for the DMM (located on wall rack)

Procedure

You will obtain the mystery box with the disputed circuit from your instructor. The box should look similar to the one in Figure 3. Your lab journal should include **ALL** of your measurements and calculations, a schematic diagram of the circuit and a diagram of its physical layout. You also should perform error analysis for two different measurement points in the circuit (to confirm your circuit is correct). End the lab by having one of your classmates verify the accuracy of your circuit. This student should write a sentence indicating the validity of your circuit and sign and date your journal. (You and your lab partner also should sign and date your journal.) Both you and your lab partner will submit a technical memorandum of your findings.

Figure 3: Sample Mystery Box

The following rules apply in the analysis of the mystery box:

1. The box may not be opened.
2. The box may not be altered in any way.
3. The two binding posts are terminals of the circuit and these must be referenced in the final diagrams.
4. The four visible resistors are arranged so that they can make connections to their conductors.
5. All resistors in the box are 5% and between 560 and 5.6 kΩ.
6. One more **5%** resistor is part of the circuit but it is completely hidden inside the box.
7. The circuit does not necessarily include all 5 resistors in a complete circuit.

Here are some suggestions for proceeding with the analysis:

- You can completely identify the mystery circuit by measuring resistance at every possible node on the circuit. Use the ohmmeter to identify shorts, and resistors arranged in series and parallel.
- The first step in the analysis is to make a sketch of the box layout and record the box number, color code and value of each of the 4 resistors in your lab journal.
- Next, include a diagram with all of the visible nodes labeled, as shown in Figure 4.

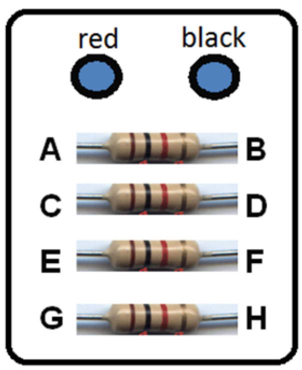


Figure 4: Mystery Box Nodes

- Then, use the ohmmeter to measure between each of these nodes, and record your data in Table 1 (in your lab journal).
- Identify all of the shorts in the table (circle them). Any resistance less than 50 ohms represents a short and shows where two or more elements touch. Make a preliminary sketch of the disputed circuit based on these shorts.
- Use the table to determine which resistors are in series based upon your measurements (put a box around them). Use this information to refine your preliminary sketch of the disputed circuit.
- Use the measured value of the resistors to determine which resistors are in parallel with something and use this information to refine the preliminary sketch of the disputed circuit and identify possible locations of the internal resistor.
- Finally, calculate the value of the internal resistor in the box. All of the resistors are 5% so the proposed value must be one from the table on page 8 of lab 0.5.

- Verify your circuit is correct by making two different measurements (ideally red post to black post and the terminals directly across the internal resistor). Include these measurements in your lab journal and perform an appropriate error analysis.
- Have someone else in the class independently verify your circuit is correct.

Table 1: Mystery Box Resistance Data Table

	Red	Black	A	B	C	D	E	F	G	H
Red										
Black										
A										
B										
C										
D										
E										
F										
G										
H										

Results

You should now have enough information about the box to be able to prepare appropriate circuit diagrams and drawings to illustrate your testimony in court. Remember that you are being paid well and will be expected to present quality work. Also keep in mind that you would like the quality of your work to make you a candidate for further expert engagements. The lab journal should include the schematic circuit (Figure 5) and the physical layout (Figure 6) which helps a lay person to see how the circuit is organized. The lab journal also must include all of your measurements and calculations, as well as the two independent measurements you made (with error analysis) to confirm your circuit is accurate. You and your partner should end your analysis by signing and dating your lab journal. The student who verifies your circuit should write a statement indicating so and also sign and date your journal.

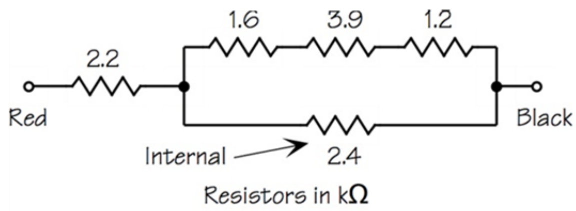


Figure 5: Schematic Circuit

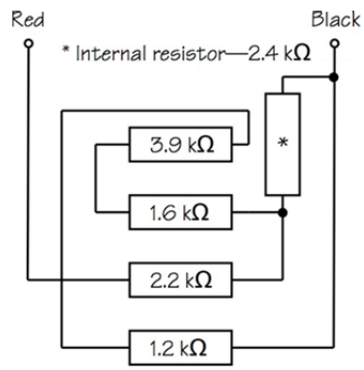


Figure 6: Physical Layout

The memo and lab notebook will be due at the beginning of the <u>second</u> class following the completion of the lab. Please make sure you follow all of the guidelines in the following checklists.

Submission Checklist

- Review Lab 0 for memo and journal specifications, guidelines and standards for writing assignments
- Complete the Table of Contents including lab number, lab title and page number
- Number all of the pages of the lab write up
- Include a title page at the beginning of the lab write up with lab number, title, date, partner names, and bench number
- Label the heading for each part of the lab procedure
- Write a procedure sentence for each part of the lab procedure
- Include a diagram of the schematic circuit and physical layout , with all resistor values clearly indicated (**using 5% resistor values**)
- Tabulate all measured data and include appropriate error analysis
- Sign and date the last page of the lab write up (both partners)
- Verification statement and signature

Lab Memo Checklist

✓ Format
  - Begins with Date, To , From, Subject
  - Font must be 12 point or smaller
  - Spacing cannot be greater than double-spaced
  - Includes computer generated drawings that are professional
  - All drawings include a figure # and caption and are referenced correctly in the memo
  - All tables include a table # and caption and are referenced correctly in the memo
  - Follows memo format outlined in the standards document
  - Includes handwritten initials at the top of the memo next to name(s)
  - Written as a paragraph not bulleted list

- No longer than one page of text
- ✓ Writing
  - Memo is organized in a logical order
  - Starts with a statement of purpose
  - Gives an overview of the tests and methods performed
  - States the results including error analysis
  - Ends with a clear conclusion statement
  - Writing is direct, concise and to the point
  - Written in first person from ***one*** person
  - Grammatically correct and void of spelling errors
- ✓ Content
  - Has an informative subject which states the box number
  - Acknowledges lab partner in the written text
  - States the results (meas, nom) including error analysis for $R_{red\text{-}black}$ (i.e. data table)
  - States the results (meas, nom) including error analysis for R_X (i.e. data table)
  - States who verified the circuit
  - Has schematic and physical layout with 5% resistor values including hidden resistor
  - DO NOT include full data table from lab
  - DO NOT include calculations
  - No references to lab journal; include relevant content in memo

Laboratory 4

Kirchhoff's Voltage and Current Laws

Purpose

Kirchhoff's laws are the basic laws that describe the performance of electrical systems. The primary purpose of this lab is to gather data on voltages and currents in circuits and compare these results with the predictions of Kirchhoff's Voltage and Current Laws. Note that the voltage and current divider are derived from KVL and KCL and these concepts will be explored as well. Lastly, students will explore two different techniques for creating a current source.

Prelab

Read the entire lab procedure and sections 2.4, 3.3 and 3.4 of your textbook on Kirchhoff's Laws, and Voltage and Current Division. Submit the answers to the following questions on engineering paper at the beginning of the class before the lab.

1. Use a combination of Ohm's law and Kirchhoff's voltage and current laws to find all of the voltages and currents in the circuit in Figure 1 and create a power table to confirm that it obeys the law of conservation of energy.

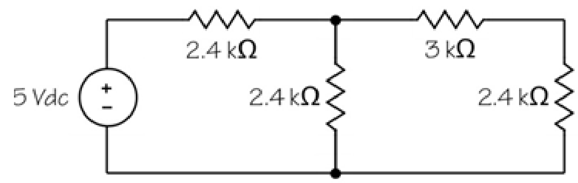


Figure 1: KVL and KCL Circuit

2. Use the voltage divider to find the voltage across the 4 resistors in the circuit in Figure 2.

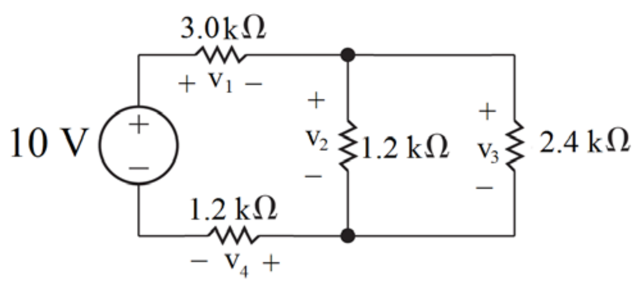


Figure 2: Voltage Divider Circuit

3. Use the current divider to find the current through the 3 resistors in the circuit in Figure 3.

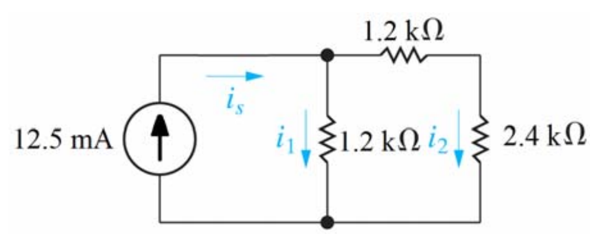


Figure 3: Current Divider Circuit

4. Use the mesh-current method to determine the mesh currents for the circuit in Figure 4.
5. Use the node-voltage method to determine the node voltages for the circuit in Figure 4.

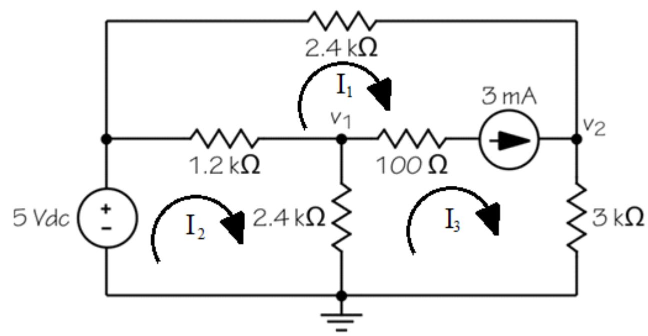


Figure 4: Node-voltage and Mesh-current Circuit

If necessary, review the videos on the DMM, power supply, resistors and breadboard on the BEEM website. If you have any questions, please ask your instructor.

Equipment

1 – 100 Ω resistor

2 – 1.2 kΩ resistor

3– 2.4 kΩ resistors

1 – 3.0 kΩ resistor

1 – LM 317 voltage regulator

2 pair – BNC-to-alligator leads for the power supply

2 – BNC-to-probe adapters

2 pair – red and black meter leads for the voltmeter and ammeter

Procedure

In this lab, you will build several circuits and measure current and voltage, therefore you should verify that both ammeters do not have blown fuses. Refer to lab 1 if you don't recall how to "ohmmeter the ammeter". You should also limit the current to 100 mA for each power supply that you use so that you don't accidentally blow the ammeter fuse.

Part I – KVL and KCL

Build the circuit in Figure 1, and then measure and tabulate all of the branch voltages and currents. Don't forget that you must break the circuit to measure current through an element! Use the measured data to demonstrate KCL at the top-middle node and KVL around both of the meshes. Since you will be comparing your results with the theoretical values computed in the prelab, you should include a data table and appropriate error analysis.

Part II – Voltage Divider

Construct the circuit in Figure 2 and measure the voltage across the source and each of the four resistors. Create a data table to compare your results to the theoretical values computed in the prelab. Next, use the ohmmeter to measure each of the four resistors in the circuit. Use the measured data (resistances and voltages) to demonstrate the voltage divider relationship for the 3.0-kΩ resistor.

Part III – Current Divider

Construct the circuit in Figure 3, ***excluding*** the current source. For this circuit, the LM 317 voltage regulator will be used to create the current source. The LM317 develops a nominal 1.25V between the output (V_{out}) and the adjustment (ADJ) terminal. Since this voltage is constant, a constant current I_1 then flows through the output resistor R_2. The current I_1 is set by the resistor, R_1. The LM317 pin out (left) and voltage regulator constant current source wiring diagram (right) is shown in Figure 5. (Note that the front of the LM 317 has writing on it.)

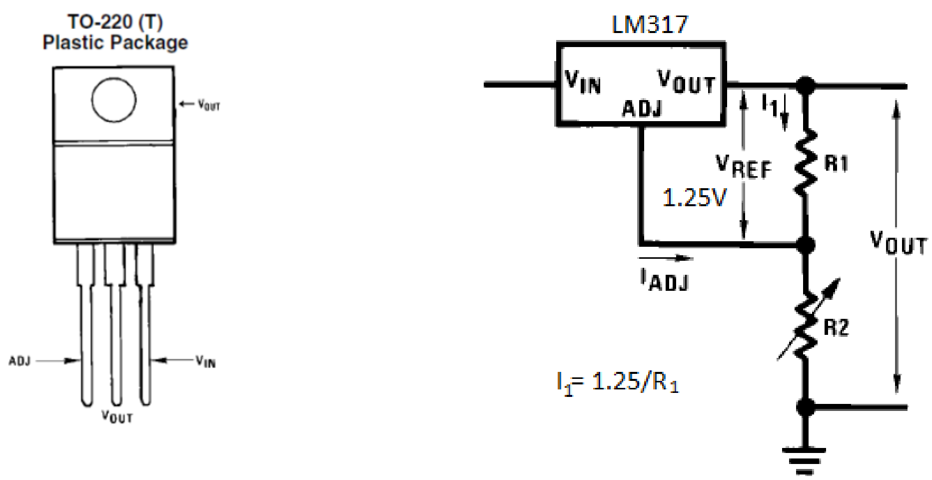


Figure 5: LM 317 pin out and current source wiring diagram

Add the LM317 voltage regulator to the breadboard. Don't short out the device! (i.e. make sure that each terminal of the LM317 is in a different node (row) on the breadboard). Set the **+**25V power supply to 15 V and connect it to the LM317 V_{in} terminal. Use the 100 Ω resistor to connect the V_{out} and ADJ terminals on the LM317. Finally, complete the circuit as shown in Figure 6. In this configuration, the LM317 effectively acts as a 12.5 mA current source (since 1.25 V, the nominal voltage that develops between V_{out} and the ADJ terminal, divided by 100 Ω (R_1 in Figure 5) is 12.5 mA).

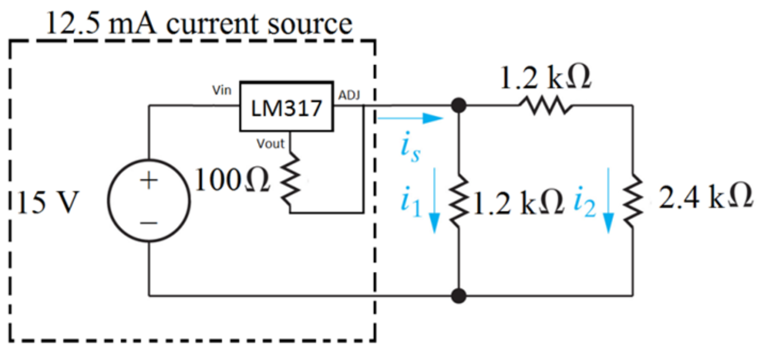


Figure 6: Current divider circuit with LM 317 current source

Finally, use the ammeter to measure the source current (i_s), as well as the current through each of the resistors. Create a data table to compare your results to the theoretical values computed in the prelab. Use an ohmmeter to measure each of the 3 resistors in the current divider circuit. Use the measured data (currents and resistances) to demonstrate the current divider relationship for the 2.4-kΩ resistor.

Part IV – Node-voltage method

Construct the circuit in Figure 4, except for the current source. Use the 6-V power supply to generate the 5-V source. This circuit is a little more complicated than the other ones because it has a current source and a voltage source, and we don't really have current source at our lab bench. This means you will have to make one! For this circuit, the voltage source or power supply, not a voltage regulator, will be used to make the current source. Here's how:

1. Put a second power supply (+25 V) in the branch with the 100-Ω resistor. The polarity of the voltage source should be consistent with driving current in the direction of the 3-mA current source as shown in Figure 4.
2. Put an ammeter **in series** with this source and set it to measure current flowing in the direction of the source's current arrow. Remember that current flowing ***into*** the red ammeter terminal yields a positive reading!
3. Turn on both power supplies and confirm that the 6-V supply is set to 5 V. Increase the +25V power supply voltage until the ammeter reads 3 mA of current flowing through the 100-Ω resistor (in the desired direction—"right-to-left").

Measure the node voltages and compare your measured results to the theoretical results computed in the prelab.

Part V – Mesh-Current Method

Measure the mesh currents for the circuit in Figure 4. Compare your measured results to the theoretical results computed in the prelab.

Submission:

The lab journal is due at the conclusion of the lab period. Please review the checklist from prior weeks to determine what constitutes an acceptable record of your laboratory work.

Laboratory 5

Circuit Theorems

Purpose

Kirchhoff's laws are the basic essentials for circuit analysis, but there also are some other important tools that are used for circuit analysis and simplification. These theorems and techniques provide more powerful insight into circuit operation. They include superposition, linearity, and Thevenin's and Norton's theorems. In this lab, you will verify the application of superposition, and Thevenin's and Norton's theorems to circuit analysis.

Prelab

Read the entire lab procedure and section 4.10 – 4.13 in your textbook on Thevenin and Norton Equivalents, maximum power transfer and superposition. Submit the answer to the following questions on engineering paper in class the day before the lab.

1. For the circuit in Figure 1, use the node-voltage or mesh-current method to find v_o and *i*.

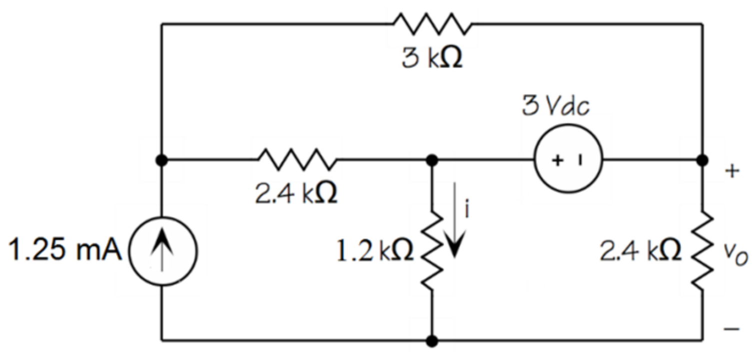


Figure 1: Superposition Circuit

2. Now use superposition to find v_o and *i* for the circuit in Figure 1.

   a. First, "deactivate" the voltage source (i.e., replace it with a wire to make its voltage zero) and calculate v_o and *i*.
   b. Next, "deactivate the current source (i.e., replace it with an open circuit to make its current zero) and calculate v_o and *i*.
   c. Sum your answers from the above two parts to finish this "superposition".

3. For each of the three results in step 2, calculate the power delivered to the rightmost 2.4-kΩ resistor. Does superposition work for power? Why or why not?

4. For the circuit in Figure 2, calculate the Thevenin and Norton equivalent circuits to the left of terminals a and b. Include a diagram of each equivalent circuit.

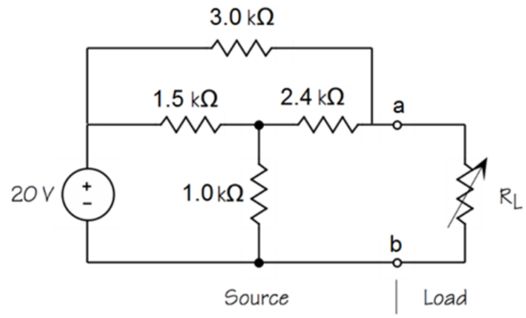


Figure 2: Thevenin Circuit

5. For the circuit in Figure 2, find the value of the load resistor R_L that will absorb maximum power from the source. What is the value of the maximum power R_L can absorb?

6. Use the Thevenin equivalent circuit to determine the power delivered to a 500 Ω resistor and a 2.0 kΩ resistor.

If necessary, review the videos on breadboards, resistors, power supplies, and the DMM on the BEEM website.

Equipment

1 - 100 Ω resistor

1 - 240 Ω resistor

1 – 1.0 kΩ resistor

1 – 1.2 kΩ resistor

2– 2.4 kΩ resistors

1 – 3.0 kΩ resistor

1 – 7361 lamp rated at 5V @ 60mA

1 – decade resistance box

2 pair – red and black meter leads for the voltmeter and ammeter

2 pair – BNC-to-alligator leads for the power supply

2 – BNC-to-banana adapters

Procedure

Since you will measure current in this lab procedure, you should confirm that both ammeters do not have a blown fuse and record the results of the check in your lab journal. If you do not recall how to use the ohmmeter to check the ammeter, please review Lab 1. In addition, you should limit the current on every power supply you use to 100 mA so that you don't accidentally blow a fuse in the ammeter.

Part I – Superposition

- Build the circuit in Figure 1. Recall that you do not have a current source in the lab so you will use the voltage regulator with a resistor to create the source. Review part III of Lab 4 if you don't remember how to create the current source. What size resistor should you put between the *ADJ* and V_{out} terminals on the voltage regulator?
- After you confirm that the circuit is built correctly, measure v_o and *i* and compare these results to the theoretical values found in the prelab.
- "Deactivate" the voltage source, which means to replace it with a wire—not just to turn it off. Measure v_o and *i*. Compare these results to the theoretical values found in the prelab.
- Turn the voltage source back on and "deactivate" the current source, which means to results to the theoretical values found in the prelab.
- Confirm superposition by showing that the sum of v_o and *i* measured with each source acting alone is the same as the value of v_o and *i* measured when both sources are turned on.
- Use the measured voltage v_o in all three cases (i.e., one source on at a time and both sources on together) to calculate the power absorbed by the rightmost 2.4-kΩ resistor. Compare your power measurements to their theoretical values found in the prelab. Does superposition work for power? Why or why not?

Part II – Thevenin's Theorem

- Build the circuit in Figure 2 without the load resistor.
- Measure the open-circuit voltage (V_{th}) and the short-circuit current (I_N). Compare these results to the theoretical values found in the prelab. Use these measured values to calculate the Thevenin resistance (R_{th}), and compare this result to the theoretical value found in the prelab.
- Deactivate the voltage source by replacing it with a wire (just like you did in part I), and use the ohmmeter to measure the resistance, R_{th}, between terminals a and b. Compare this result to the theoretical value found in the prelab.
- Set the decade resistance box to the value of R_L found in the prelab for maximum power transfer. (Use the ohmmeter to confirm the value of R_L is what you intended.) After the resistance is set, connect it to the circuit as the load resistor and use the voltmeter and ammeter to measure v_L and i_L. Use the voltage and current measurements to find the measured power delivered to the load resistor, and compare the result to the theoretical value for the maximum power absorbed by R_L that you found in the prelab.

Part III – Maximum Power

- Use the same setup as in the previous part to measure the voltage across the load resistor and the current through the load resistor. Create a data table and record v_L and i_L as you vary the load resistor from 10 Ω to 10 kΩ. Make a third column in the table for the measured power for each resistance setting. Since you will be plotting the results on semi-log paper, you should take data points that make sense. For example, a step interval of 1, 2, 4, 7 of the decades would be approximately equidistant. Note that the graph in Figure 3 is a sample for a different circuit and your numerical values may not be similar.

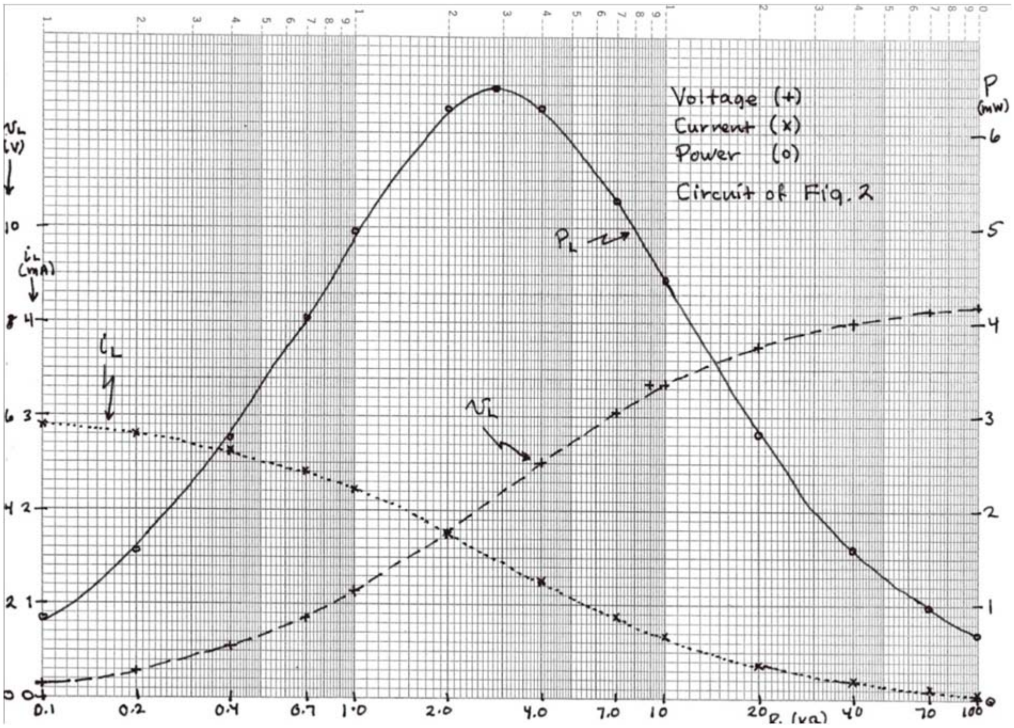


Figure 3: Maximum Power Graph

- Plot all three sets of data (v_L, i_L, and p) on the same semi log graph as shown in Figure 3.
- This graph requires three different sets of y-axes scales. Be sure to label your curves so that the graph is readable. This graph should be properly attached to your lab journal. (There is semi log paper included at the end of this lab handout.
- What value of R_L corresponds to when i_L equals i_N?
- What value of R_L corresponds to when $V_L = v_{th}$?

Part IV – Non-linear circuit

- Build the circuit in Figure 4 using the 7361 lamp. Make sure to put the lamp leads in two different nodes of the breadboard to avoid shorting out the lamp!
- Use the DMM to measure the voltage across and current through the lamp. Use the measured voltage and current to compute the apparent resistance of the lamp and the measured power delivered to the lamp.
- Deactivate the 4-V source (remember what it means to deactivate a source) and remeasure these parameters (v_{lamp}, i_{lamp}, p and apparent resistance).
- Then, turn the 4-V source back on and deactivate the 8-V source. Once again, measure v_{lamp}, i_{lamp}, p and apparent resistance).
- Use these data to test superposition for v_{lamp}, i_{lamp}, and p. Does superposition hold for any of these electrical quantities? Is the circuit in Figure 4 a linear circuit? How do you know?

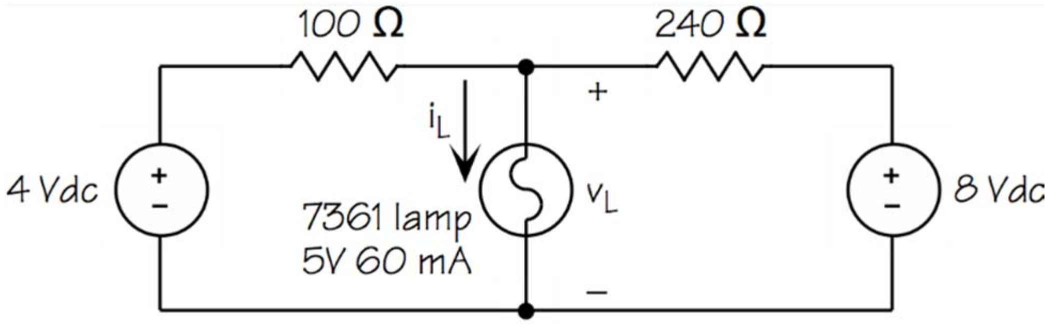
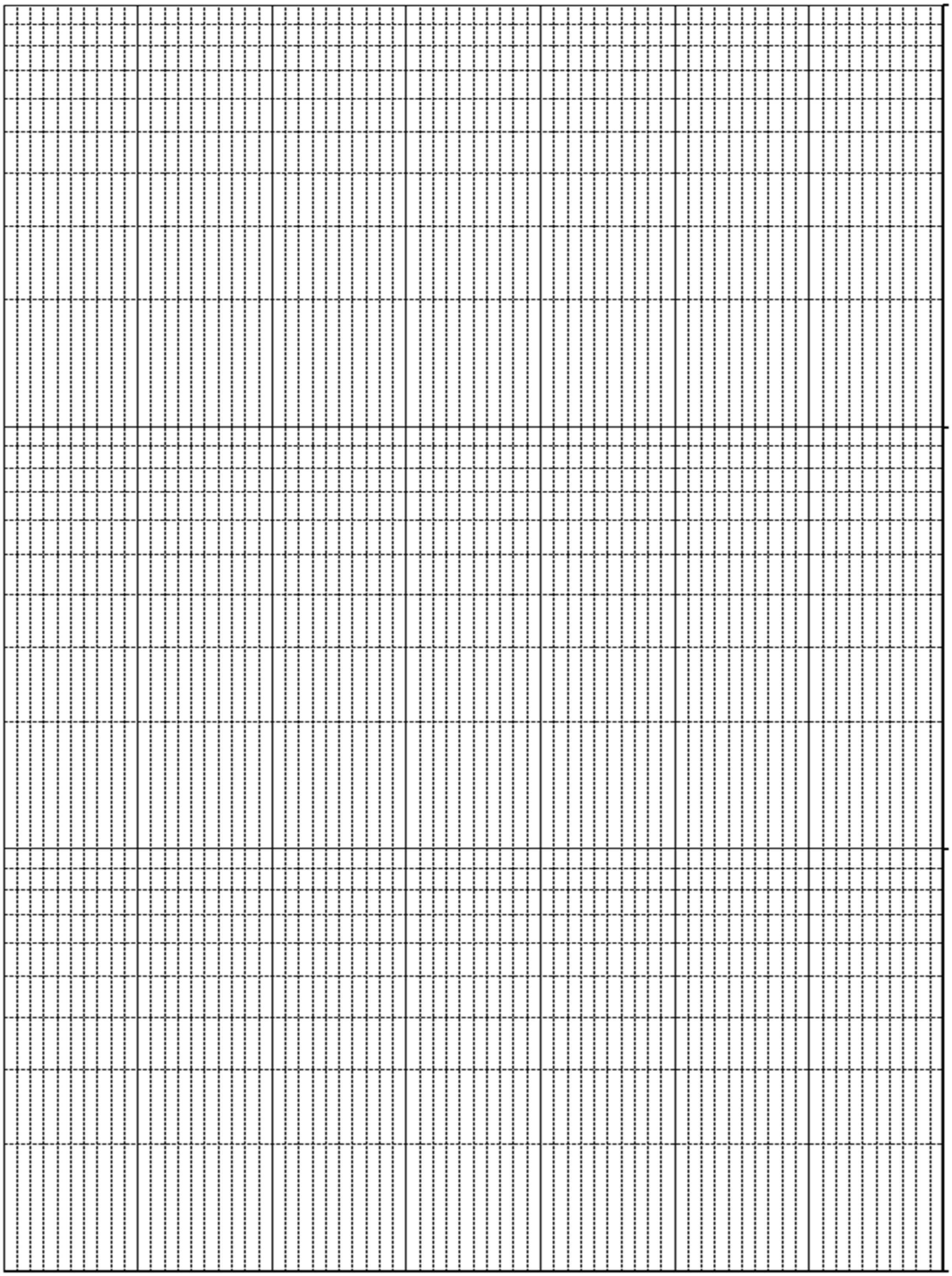
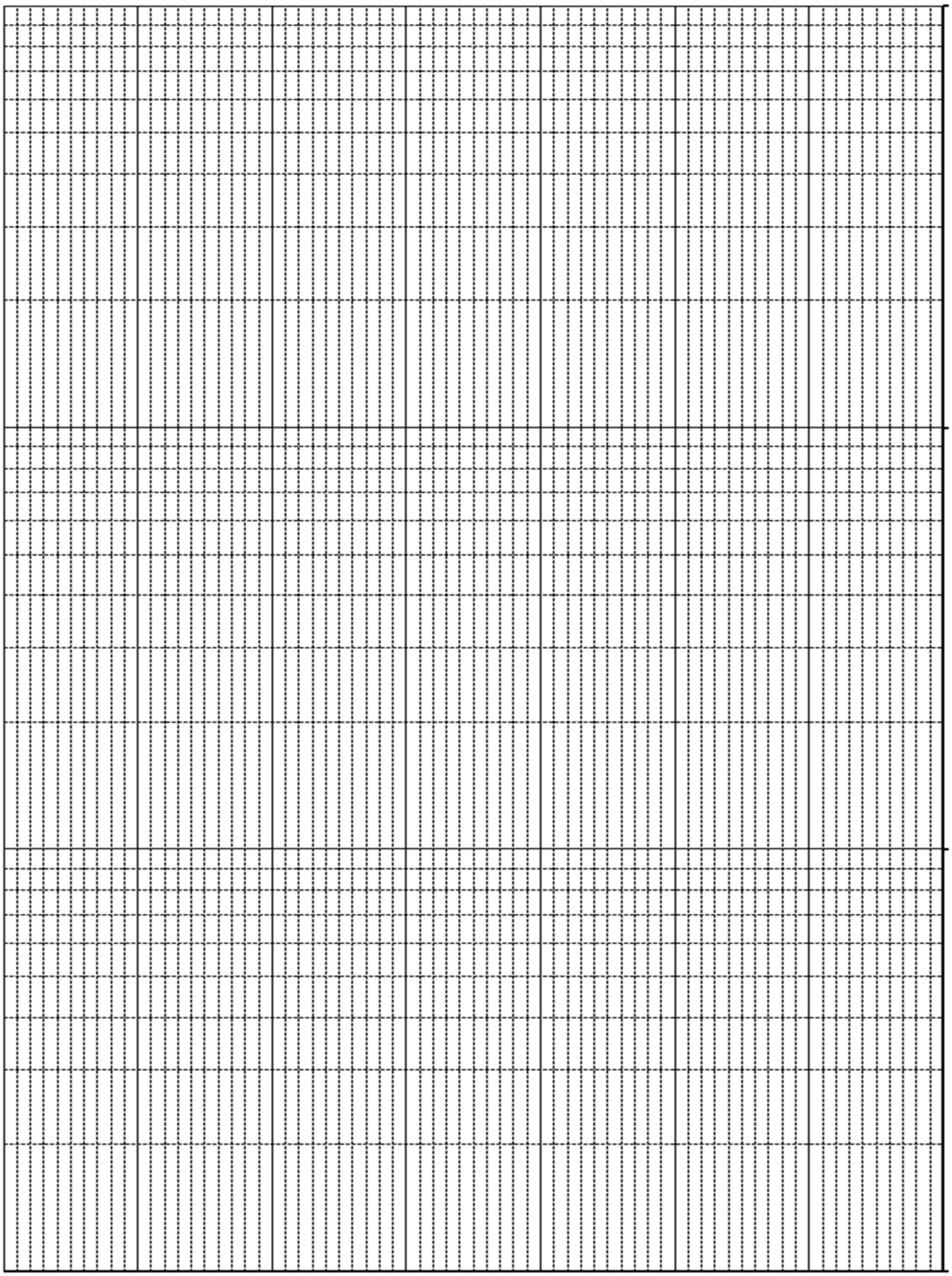


Figure 4: Lamp Circuit

Submission:

The lab journal is due at the conclusion of the lab period. Please review the checklist from prior weeks to determine what constitutes an acceptable record of your laboratory work.





Laboratory 6

Operational Amplifier Measurements

Purpose

The operational amplifier (op-amp) is useful in circuits for many applications including amplifying a signal, integrating, differentiating and summing. It can also be used to condition a signal, to change its voltage level or its power. Additionally, it can filter a signal to suppress or enhance certain frequencies such as in a radio, bass, woofer or tweeter. In this lab you will construct an inverting and non-inverting amplifier and use it to amplify a microphone signal. You will also examine a third method for creating a current source using an operational amplifier.

Prelab

Read the entire lab procedure and review operational amplifiers in chapter 5 of your textbook. Submit the answer to the following questions on engineering paper in class the day before the lab session.

1. For the circuits in Figures 1 and 2, what type of op amp is it? What is the gain? What is the output for v_{in} = 2 V? What is the output for v_{in} = 6.5 V?

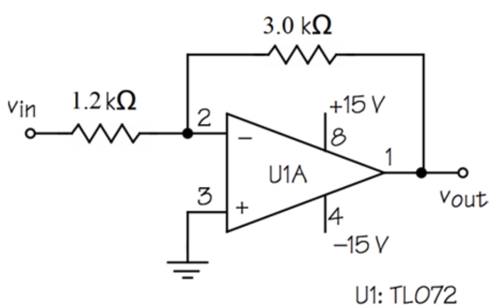


Figure 1: Operational Amplifier Circuit 1

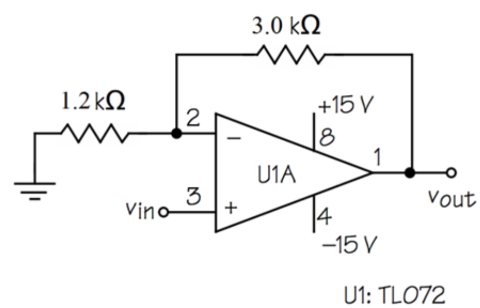


Figure 2: Operational Amplifier Circuit 2

2. For the circuit in Figures 3, what type of op amp is it? What is the gain? What is the output for $v_a = v_b$ = 2 V? What is the output for v_a = 6.5 V, v_b = 3.0 V? What is the output for v_a = 1.0 V, v_b = 8.0 V?

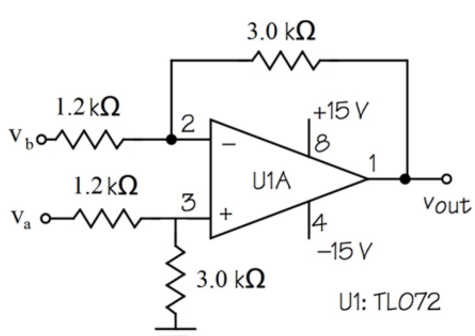


Figure 3: Operational Amplifier Circuit 3

3. The operational amplifier circuit in Figure 4 is a difference amplifier and an alternate method for generating a constant current through a load. Use KCL, to calculate the load current i_L.

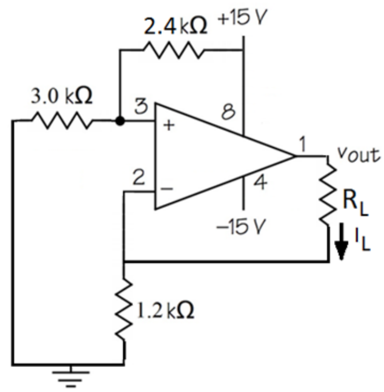


Figure 4: Operational Amplifier Current Source Circuit

In addition, log into the BEEM website, and review the following videos under the *How_to_Videos* link:

- *How_to_use_function_generator*
- *How_to_FG_HighZMode (C115)*
- *How_to_power_op_amp*
- *How_to_adjust_scope_display*

If you have any questions, please ask your instructor.

Equipment

1 – TL072 op-amp

1 – 100 kΩ resistor

1 – 240 Ω resistor

2 – 1.2 kΩ resistor

1 – 2.4 kΩ resistor

1 – 3.0 kΩ resistor

1 pair – red and black meter leads for the voltmeter

3 pair – BNC to alligator leads for the power supply and function generator

1 – single red meter lead for the -25V power supply

2 – BNC-to-probe adapters for the power supply

2 pair – oscilloscope leads from the bench drawer

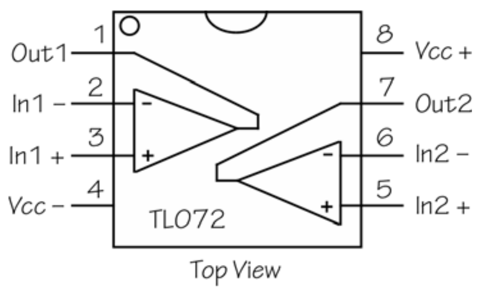
1 – BNC-to-banana adapter from the bench drawer

Procedure

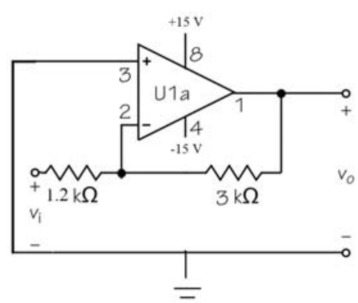
In this lab you will build an inverting and non-inverting amplifier and compare the different outputs as you vary the input voltage. You will also observe the effect of saturation on the output voltage. Lastly, you will build an operational amplifier circuit to model a constant current source.

Part I – Gain

An operational amplifier is an integrated circuit, and it must be powered similar to a television. You will use the positive and negative (**±25V**) supplies for the op amp power and the **+6V** power supply for the input, v_i. Set up the positive and negative 25-V power supplies to provide **+15V** (VCC+) and **-15V** (VCC-). You can set both of them at the same time by holding the **track button.** In order to keep from destroying the op amp and blowing a fuse on the ammeter, you should also limit the current on both power supplies to 100 mA. Make sure that the tab on the BNC-to-banana adapter is in the COM jack! Connect the leads to the op amp next. You can use the BNC-to-alligator lead for the +25V supply and a single banana lead for the -25 V supply. Figure 5 shows the TL072 pin out and the power connections for your circuit.



TL072 pinout



Circuit Connections

Figure 5: Inverting Amplifier

Connect the power supply COM or ground socket (black) to the breadboard buss (red or blue line). Connect the +15V (red) terminal to pin 8 on the op amp and the -15V (red) terminal to pin 4 on the op amp.

Connect the 3-kΩ feedback resistor between pins 1 and 2 of the op amp. Connect the 1.2-kΩ input resistor to pin 2 of the op amp. You should use your wires from the kit to spread out the connections to enable quick debugging and to confirm that the circuit is built correctly. See Figure 6 for an example of a properly wired operational amplifier circuit.

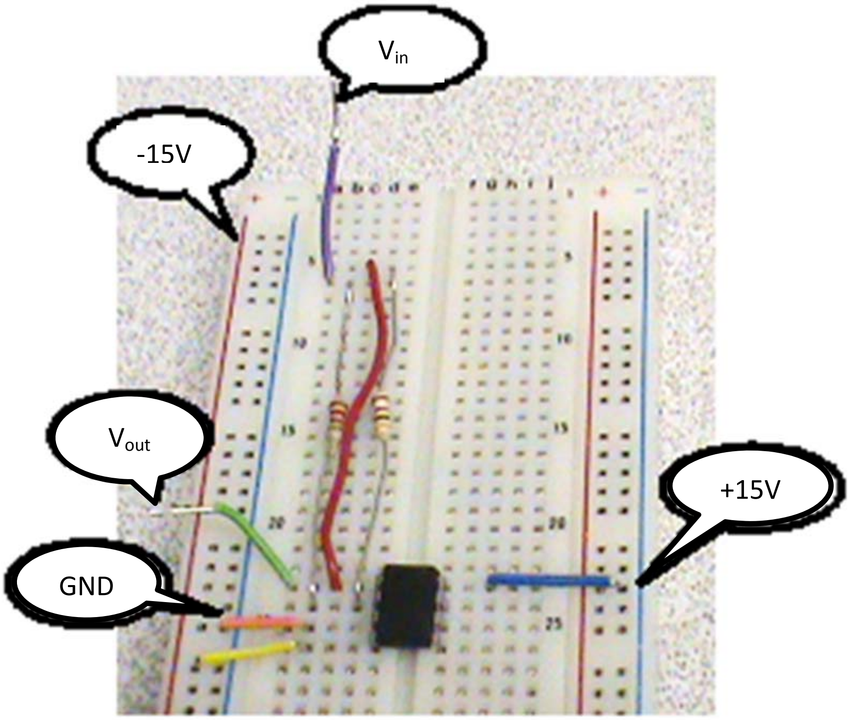


Figure 6: Operational Amplifier properly wired circuit

Set the **+6V** power supply to **1 V** and limit the current to 100 mA. Make sure the tab on the BNC-to-banana adapter is in the COM tab, and connect the black jack to the same ground buss (red or blue line) established on the breadboard (from the previous step). Connect the postive terminal of the +6V supply to the input voltage on the left side of the 1.2 kΩ input resistor.

Set both DMMs to measure voltage, and put one across the input voltage (from the 1.2-kΩ resistor to ground). Place the other voltmeter across the output voltage (between the output pin (1) and ground. Press **output** on the power supply and measure the DC gain for the inverting amplifier. Compare this measured value to the theoretical value found in the prelab. If these values are not within 8%, do not go on to the next part until you debug and correct your circuit (or perhaps correct your prelab calculation)!

Part II – Saturation

In order to observe the effects of saturation, you will vary the input voltage and measure the output voltage for the inverting amplifier. Create a data table and record the input voltage, output voltage and gain as the input voltage is varied from 0 to 6 V. Make sure you collect enough data points to capture the transition from the linear region of your plot to the saturation region (i.e., the "corner point). Use the grid of your lab journal to create a graph of the output voltage versus input voltage, and clearly label the region of the plot that corresponds to saturation. Make sure that the graph covers at least half of the page, has an appropriate figure legend, and labeled axes with units.

Remove the +6V power supply and both DMMs from the operational amplifier circuit. You will now use the function generator and oscilloscope to observe the effects of saturation on an op amp circuit. Connect the BNC-to-alligator cable to the function generator ***output*** terminal. Collect two oscilloscope leads from the bench drawer and connect one to Ch. 1 and one to Ch. 2 of the oscillsocope.

Connect the function generator probes to Channel 1 of the oscilloscope and turn both devices on. Make sure to press the **output** button on the function generator. Set the function generator to supply a 1 V peak-to-peak sine wave at 1 kHz. Press **auto scale** on the oscilloscope and press **quick measure** to measure the peak to peak voltage on Channel 1. (Note that the function generator assumes a low impedance load, and thus the peak-to-peak value it displays may be half of the actual value, as correctly measured by the oscillscope.) You should then adjust the function generator amplitude until the ***scope*** reads 1 V peak-to-peak. ALWAYS USE THE OSCILLOSCOPE TO CONFIRM THE CORRECT SETTINGS FROM THE FUNCTION GENERATOR. Also note that the larger the waveform appears on the scope screen, the more accurate the voltage measurement will be. Now that the function generator and oscilloscope are set up correctly, connect the function generator leads and Channel 1 of the scope to the input of the op amp circuit (between the left side of the 1.2-kΩ resistor (red and grey leads) and ground (black leads)). Connect Channel 2 of the scope to the output of the op amp circuit (between pin 1 and ground). In the future, this is how you should always set up the scope for measurement (i.e. the input of the circuit on Channel 1 and the output of the circuit on Channel 2).

Turn on the power supply and display both the input and output of the circuit on the oscilloscope. Confirm that the gain is correct and use the grid of your lab journal to create a sketch of the scope display in your lab manual. In your sketch, you should superimpose the input and output on top of each other and make them as large as possible. Also, make sure that you label the axes with the volts/division and seconds/division to make it clear that the gain and frequency are correct. *Why are the input and output waveforms out of phase by exactly 180°?*

Increase the function generator amplitude until the output first becomes distorted. *Explain why the shape of the waveform has changed.* Use the grid of your lab journal to create a sketch of the scope display showing both the input and output waveform. (Remember to label your axes!) *For what gain does the op amp begin to saturate? Is this what you expected? Explain.*

Remove the function generator and oscillscope from the circuit.

Part III – Constant Current Source Operational Amplifier

In this part, you will verify that an op amp can be used to create a constant current source. Build the circuit in Figure 4 with R_L = 100 Ω, and measure the current through the load. Next, change the load resistor to a 240-Ω resistor and measure the current through the load. *Does this circuit appear to act as a constant current source? How do these values compare to the theoretical values found in the prelab? If there is any error, what do you think is the cause?*

Next, change the load resistor to a 1.2-kΩ resistor and measure the current through the load. *Does the circuit still appear to be an ideal current source? Why or why not? Why do you think the current through the load has changed?*

Part IV – Non-inverting Amplifier to Amplify a Microphone Signal

In this part you will use an amplifier to to strengthen the output signal from a microphone, so that it is audible in a set of earphones. The microphones that are available in the lab have an internal resistance of about 600 Ω, so they can be modeled as a voltage source in series with a 600-Ω resistor. Typical speech into a microphone produces an output voltage below 25 mV, which is much too weak to drive the earphones since they need signals on the order of hundreds of mV.

Build the circuit in Figure 7, and use the +6V power supply to deliver a voltage of 0.1 V to input pin 3. Use the DMM's two voltmeters to measure the input and output voltage of the circuit. *Is the gain of this circuit as predicted?*. Compare the measured value of the gain to the theoretical value of the gain. If the gain is not correct, debug your circuit and correct it before you move on to the next part. (Of course, it could be that your theoretical calculation is wrong.)

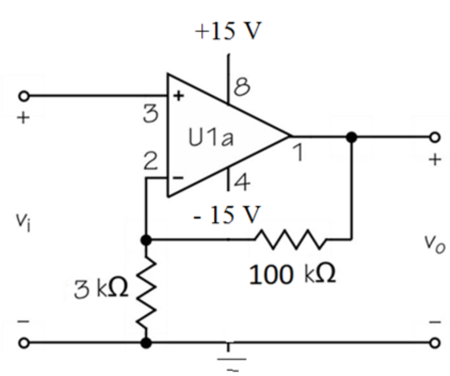


Figure 7: Non-Inverting Amplifier

Your instructor will provide you with a microphone and set of headphones to test the functionality of your circuit. Remove the +6V power supply and connect the output of the microphone to the input of the op amp using the jack provided as shown in Figure 8. Make sure that the wire from the outer shell of the microphone connects to ground in the circuit.

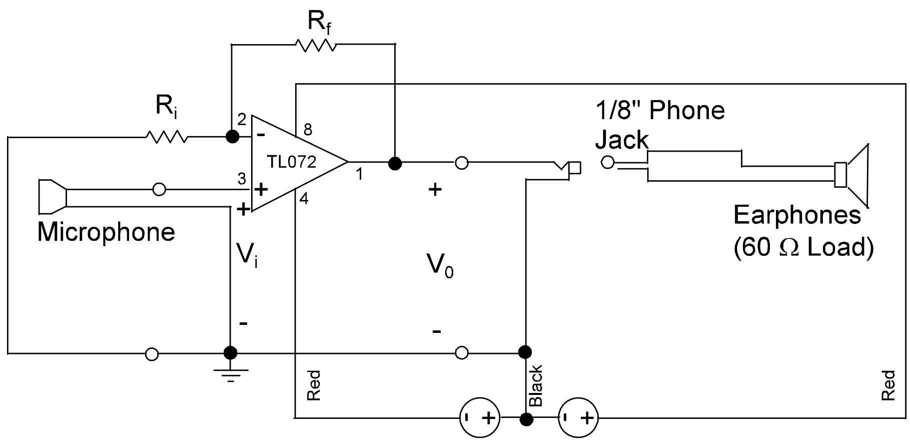


Figure 8: Non-Inverting Amplifier

Connect channel 1 of the oscilloscope across the input V_i (pin 3 to ground) and channel 2 of the oscilloscope across the output V_o (pin 1 to ground). Set channel 1 to 20 mV/div, channel 2 to 100 mV/div, and the horizontal (time) scale to 5 msec/div. Make sure that the op-amp power supplies are on. Test the circuit by having one team member speak into the microphone while the other team member wears the earphones.

Explain in your lab journal what you hear in the earphones and what you see on the oscilloscope while you lab partner hums or speaks into the microphone. Can you hum loud enough to make the amplifier output clip? Describe qualitatively how the scope signal is correlated to the frequency and intensity of your voice.

Submission:

The lab journal is due at the conclusion of the lab period. Please review the checklist from prior weeks to determine what constitutes an acceptable record of your laboratory work.

Laboratory 7

AC Measurements

Purpose

In this lab, we will use the function generator and oscilloscope to generate and measure time varying signals. Measurements also will be made using the digital multimeter on alternating current signals in circuits that have inductors and capacitors. In this lab several goals will be accomplished including:

- Measure characteristics of a sine wave using a DMM, oscilloscope and LED
- Measure characteristics of a ramp using a DMM and oscilloscope
- Measure circuit voltages and relate them to Kirchhoff's Voltage Law
- Graph data on a semi log scale

Prelab

Read the entire lab procedure and review sinusoidal sources, phasors and impedance in sections 7.1 through 7.4 of your textbook. Submit the answer to the following questions on engineering paper in class the day before the lab session.

1. Calculate the average and RMS value of the waveform in Figure 1.
2. Calculate the average and RMS value of the waveform in Figure 2.

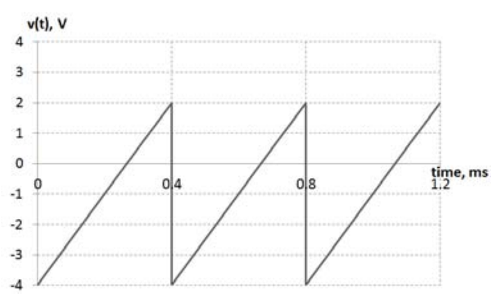


Figure 1: Ramp Signal

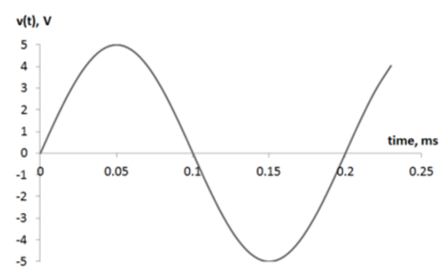


Figure 2: Sinusoid

3. Write an expression for the voltage waveform, v(t). Then write an expression for the current, i(t), with respect to the voltage waveform.

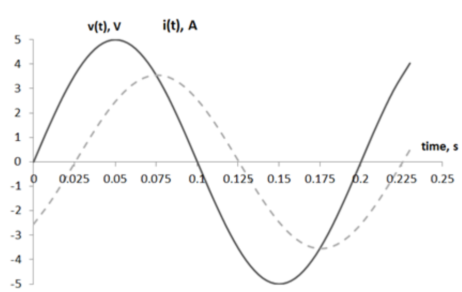


Figure 3: Voltage and current sinusoidal sources

Review the videos on "How to use a function generator", and "How to adjust the scope display" at the following link: http://www.rose-hulman.edu/~walter/labTutorials.htm

If you have any questions, please ask your instructor.

Equipment

1 – 33-mH inductor

1– 0.022-μF capacitor

1 – 1.2-kΩ resistor

1 – LED

2 pair – red and black meter leads

1 pair – BNC-to-alligator leads for the function generator

2 pair – oscilloscope leads from the bench drawer

Procedure

In this lab you will gain experience measuring AC signal parameters including amplitude, frequency, period, phase, and RMS value. You will measure AC current using the DMM in this lab so verify that the ammeters do not have a blown fuse.

Part I – Ramp waveform

a) Measuring RMS voltage with the oscilloscope

- Connect the output of the function generator to channel 1 of the oscilloscope (red clip to grey scope probe; black clip to black clip). (Either connect the clips directly, or use a short piece of wire to connect them.
- Turn on the function generator and oscilloscope. Set the function generator to produce a **6 V peak-to-peak ramp at 2.5 kHz with a -1 V DC offset**. Press **output** on the function generator. Recall that the function generator assumes a 50-Ω load so the reported amplitude by the function generator may be off by a factor of two! Use the oscilloscope to confirm the waveform amplitude is set correctly.
- Press **Auto Scale** then **Quick Measure** on the oscilloscope. Finally, use the oscilloscope to measure the **RMS** amplitude of the ramp wave.
- Compare the measured RMS value with the theoretical value found in the prelab.

b) Measuring frequency with the oscilloscope

- Use the oscilloscope to measure the frequency of the ramp waveform.
- Compare the measured frequency to its theoretical value.

c) Measuring RMS voltage with the DMM

- Disconnect the oscilloscope from the function generator.
- Connect the output of the function generator to the DMM. Make sure the meter leads are in the appropriate jacks for measuring voltage.
- Turn on the DMM and press **AC V** in order to measure the **RMS** value of the ramp signal.
- Compare the measured RMS value with the theoretical value found in the prelab.

Part II – Measuring RMS voltage for a sinusoidal waveform

Set the function generator to produce a **10 V peak-to-peak sine wave** at **100 Hz** (as verified by the *oscilloscope*). Measure the RMS value of the sinusoid on the DMM and the oscilloscope. Compare both measurements to the theoretical value found in the prelab.

Part III – Studying sinusoidal waveform characteristics with an LED

Set the function generator to produce a **10 V peak-to-peak sine wave** at **100 Hz** and build the circuit in Figure 4. Vary the frequency between 1 and 100 Hz and observe the LED response. What happens to the LED as the sinusoid frequency is increased and decreased? Reset the function generator to 100 Hz and vary the amplitude of the source between 4 and 10 V_{pp}, and observe the LED response. What happens to the LED as the sinusoid amplitude is increased and decreased?

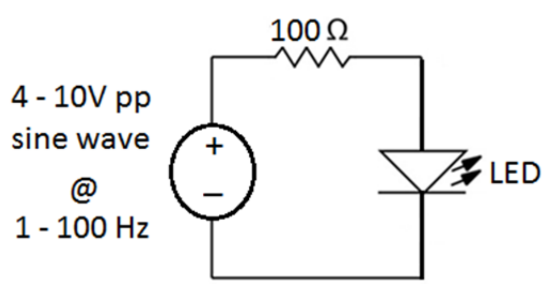


Figure 4: Voltage and current sinusoidal sources

Part IV – RL circuit

a) Using the DMM to measure voltages in an AC circuit

- Obtain a 33-mH inductor from your instructor and build the circuit shown in Figure 5.
- Set the function generator to produce a **5 V RMS sine wave** at **1.0 kHz**. Connect the DMM across the function generator and press **AC V** to confirm that the amplitude is correct. If not, adjust the function generator until the amplitude is 5 V RMS.

- Use the DMM to measure the 3 voltages v_S, v_R, and v_L, and record them in your lab journal.
- Use KVL to sum up the three voltages around the loop and explain why KVL appears not to hold.

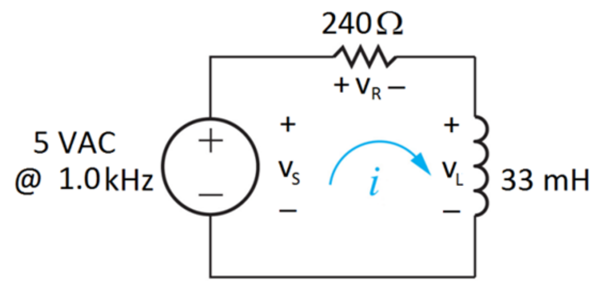


Figure 5: RL Circuit

b) Using the DMM to measure currents in an AC circuit

- Use the DMM to measure the magnitude of the current in the circuit by pressing **shift AC V** to measure AC current (**AC I**).
- Next, find the magnitude of the current by using the voltage across the resistor divided by its measured resistance. (You should remove the resistor from the circuit before you measure its resistance with the ohmmeter.) Compare these two current values.

c) Using the oscilloscope to measure voltage and current in an AC circuit

- Disconnect the DMM from the circuit and attach the oscilloscope.
- Please note that the oscilloscope does not measure current, but you can use it to measure voltages and then calculate the current from Ohm's Law.
- Measure the voltage across the source and confirm that it reads **5 VRMS** on the scope (and if not, adjust the function generator accordingly).
- Measure the voltage across the inductor and the resistor. *It turns out measuring voltage with the oscilloscope is trickier than it seems. The black clips of the probes MUST be connected to the circuit ground! Your instructor will explain to you how to measure the voltage across the 240-Ω resistor.*
- *Give the scope's voltage readings a sanity check. In other words, do they seem right? For example, channel 1's voltage should be around 5 volts, not 50 and not 0.5 V. If the readings seem to be off by a factor of 10, the "probe" setting may be wrong. To check this:*
    - *Press the "1" button above the probe connection.*
    - *In the lower right corner of the screen, press **probe.***
    - *In the lower left corner of the screen, confirm that the probe is set to "10:1"; if not, adjust the knob until it is.*

- *If necessary, repeat this procedure for channel 2.*

- Use the measured voltage across the resistor to find the current through the loop.
- Compare these values to the DMM measurements.

d) Measuring phase with the oscilloscope

- Connect Channel 1 of the oscilloscope across the source.
- Connect Channel 2 of the oscilloscope across the inductor. *Recall that the black clips of the scope probes must be connected to the circuit ground (black terminal of the function generator)*
- Use the oscilloscope to measure the phase difference between the sinusoidal output voltage and the sinusoidal input voltage (i.e., phase **2 –> 1**). Record this value in your journal.

Part V – RC Circuit

a) More DMM measurements

- Build the RC circuit in Figure 6, and set the function generator to produce a **5 V RMS sine wave** at **50 kHz**. Use the DMM or oscilloscope to confirm the amplitude is set correctly.
- Use the DMM to measure the voltage across all three elements (v_s, v_r, and v_c), and record their values in your lab journal. Sum these voltages, and explain why KVL appears to be violated.

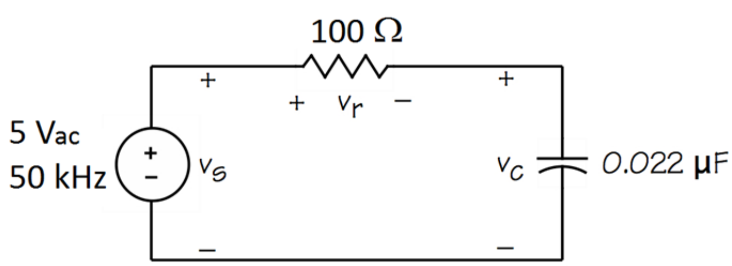


Figure 6: RC Circuit

- Use the DMM to measure the magnitude of the current in the circuit by pressing **shift AC V** to measure AC current.
- Next, find the magnitude of the current by using the voltage across the 100-Ω resistor divided by its measured resistance. (Remember to disconnect the resistor from the circuit before measuring its resistance.) How do these two current values compare?

b) More oscilloscope measurements

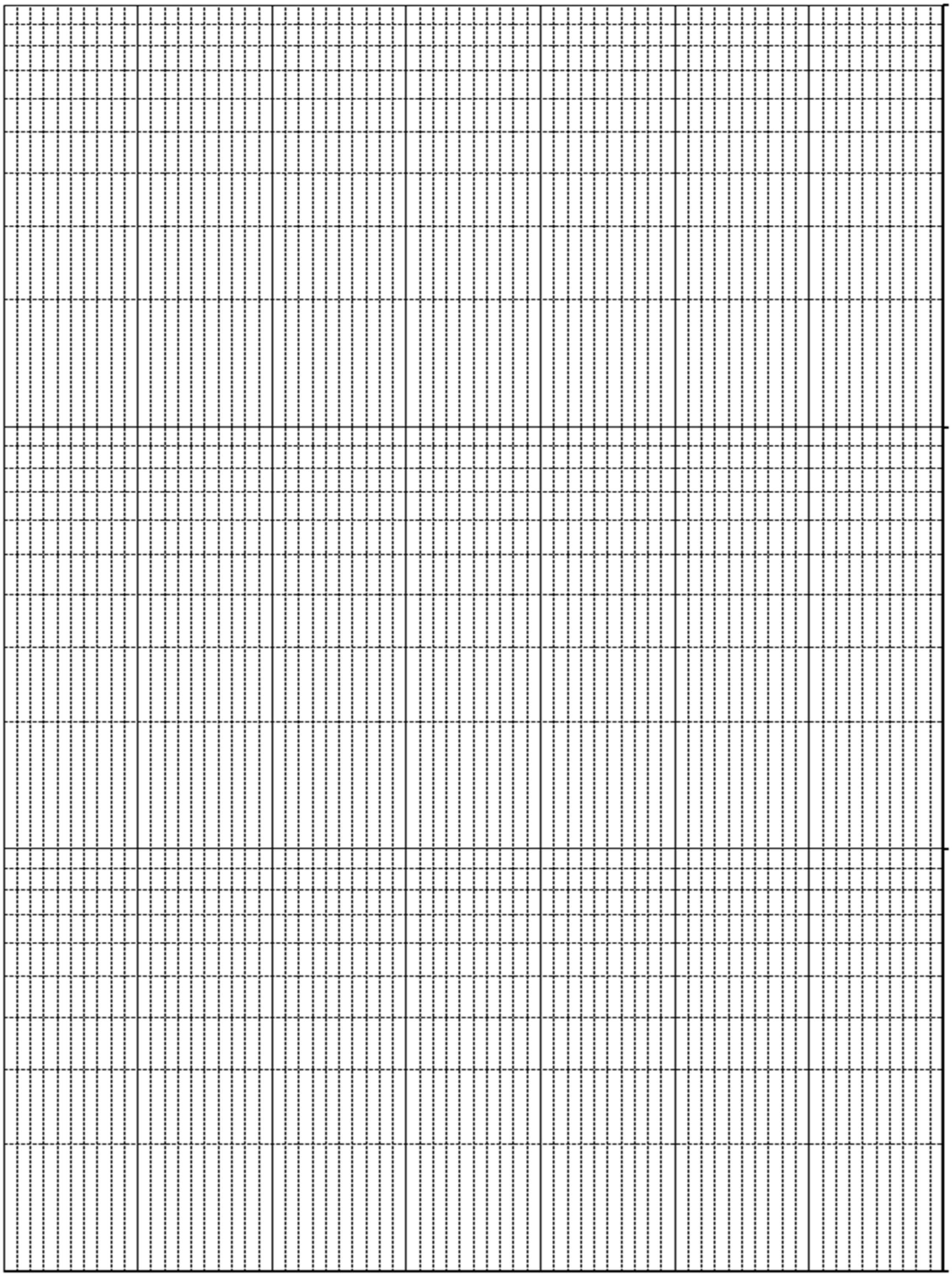
- Disconnect the DMM and connect the oscilloscope to the circuit, with channel 1 across the source and channel 2 across the capacitor. (Recall that the oscilloscope has an internal ground, so the clips on the scope probes and the black probe from the function generator must all be connected to the same node in the circuit!)
- Adjust the scope for a good display of both the input and output waveforms. (A good start is to press **Auto Scale**.) In general, it is good practice to use channel 1 to monitor the input signal and channel 2 to monitor the output signal.
- The function generator still should be set to **5 V RMS** at **50 kHz**. If it is not, adjust the function generator until its amplitude and frequency are correct.
- Measure the voltage across the capacitor in $\mathbf{V_{RMS}}$ and compare it to the DMM reading. You also can measure the phase shift between the output and input waveform by measuring phase **2 –> 1** with the scope.
- Compare the phase difference measured in this circuit (i.e., capacitor phase referenced to source) with the phase difference measured from the circuit in Figure 5 (i.e., inductor phase referenced to source).
- Record both the magnitude and phase of the voltage across the capacitor in your lab journal.

Part VI – Gain versus frequency

- Disconnect the oscilloscope from the circuit and attach the left DMM across the AC voltage input (v_s) and right DMM across the output (v_c).
- Create a data table of input frequency, input voltage, output voltage, and gain(v_c/v_s).
- Vary the input frequency from 100 Hz to 100 kHz in steps of 1, 2, 4, and 7. Record the corresponding output voltage and gain. (Note that the gain for this circuit never should exceed one. If it does, then your input voltage probably isn't 5 V RMS. Verify this voltage when the source is connected to the circuit.)
- Plot the gain versus frequency on the three-decade semi-log paper included at the end of the lab procedure. Make sure the graph has an appropriate figure legend and labeled axes with units.

Submission:

The lab journal is due at the conclusion of the lab period. Please review the checklist from prior weeks to determine what constitutes an acceptable record of your laboratory work.



Laboratory 8

Impedance

Purpose

In this lab, you will explore the concept of impedance for inductors and capacitors. Most inductors consist of coils of wire. Since these coils have an associated resistance, actual inductors have a small internal resistance. This resistance tends to vary with frequency, and it will be measured as part of the impedance.

Prelab

Read the entire lab procedure and review impedance and reactance in section 7.4 of your textbook. Submit the answer to the following questions on engineering paper in class the day before the lab session.

1. For the circuit in Figure 1, determine the voltage across and current through the inductor.

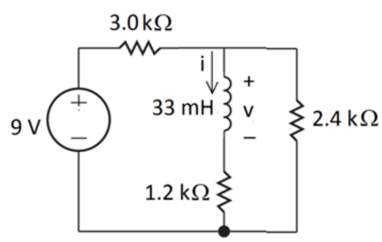


Figure 1: Inductor DC circuit

2. For the circuit in Figure 2, determine the voltage across and current through the capacitor.

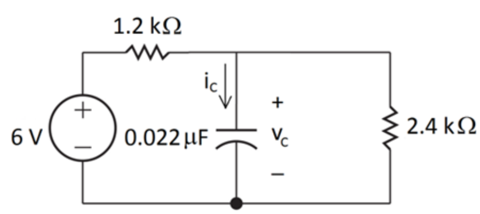


Figure 2: Capacitor DC circuit

3. For the circuit in Figure 3, if f = 600 Hz, $\mathbf{V_S} = 5\angle 0^\circ\ V_{RMS}$ and $\mathbf{V_L} = 3.64\angle 35^\circ\ V_{RMS}$, calculate the inductance L and resistance R_L.

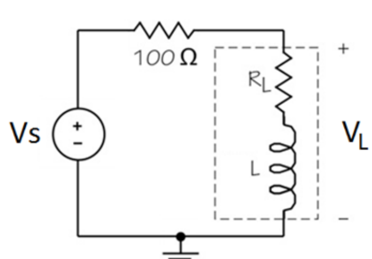


Figure 3: Inductor Impedance

4. For the circuit in Figure 4, if f = 60 kHz, $\mathbf{V_s} = 5\angle 0^\circ\ V_{RMS}$ and $\mathbf{V_C} = 3.74\angle -38^\circ\ V_{RMS}$, calculate the capacitance C and resistance R_C.

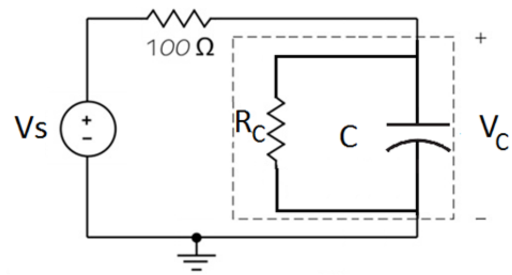


Figure 4: Capacitor Impedance

If you have any questions, please ask your instructor.

Equipment

1 – 33-mH inductor

1– 0.022-μF capacitor

1 – 100-Ω resistor

1 – 1.2-kΩ resistor

1 – 2.4-kΩ resistor

1 – 3.0-kΩ resistor

2 pair – red and black meter leads

2 pair – BNC-to-alligator leads for the function generator and power supply

1 – BNC-to-banana adapter from the bench drawer

2 pair – oscilloscope leads from the bench drawer

Procedure

In this lab you will explore inductor and capacitor impedance and compare the results to theory. Since you will use the DMM to measure current, make sure you check both ammeters for blown fuses. (Remember to record the ammeter resistance in your journal.)

Part I – Inductors under DC conditions

Retrieve a 33-mH inductor from the cabinet in the front of the classroom, and build the circuit in Figure 1. Use the +25V power supply to provide the input voltage. Use the DMMs to measure the voltage across and current through the inductor. How do these values compare to the theoretical values found in the prelab?

Part II – Capacitors under DC conditions

Build the circuit in Figure 2 using a 0.022-μF capacitor from your parts kit. Use the +25V power supply to provide the input voltage. Use the DMMs to measure the voltage across and current through the capacitor. How do these values compare to the theoretical values found in the prelab?

Part III – Inductor Impedance – DC

A DC measurement of the impedance of an inductor should yield the inductor's internal resistance. In this part, you will explore the validity of this statement. Use the ohmmeter to measure the resistance of the 33-mH inductor, and record it in a data table as the nominal value of the inductor's resistance. An ideal inductor should have zero DC resistance. Look closely at the inductor and explain why this resistance is ***not*** zero.

Build the circuit in Figure 5, and measure the voltage across the resistor and the voltage across the inductor. Remove the 100-Ω resistor from the circuit and measure its actual resistance; use this measured resistance to calculate the current in the resistor. Finally, use the voltage measured across the inductor and the current through the resistor to calculate the inductor's internal resistance (R_L). Compare this value to the nominal value.

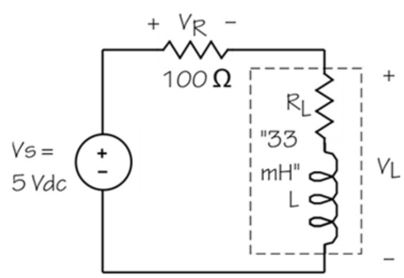


Figure 5: DC Inductor Measurement

Part IV – Capacitor Impedance - DC

Retrieve the 0.022-μF capacitor from your parts kit, and use the ohmmeter to measure its internal resistance. An ideal capacitor should have infinite DC resistance. (Why?) Does your capacitor appear to be ideal? Accurately record the resistance reported by the ohmmeter. What does this reading tell you about the capacitor's DC resistance? (BE CAREFUL TO ANSWER THIS QUESTION ACCURATELY! Hint: how large a resistance can the ohmmeter measure?)

Build the circuit in Figure 6 and measure the voltage across the resistor and the voltage across the capacitor. Based on these measurements, calculate the capacitor resistance (R_C).

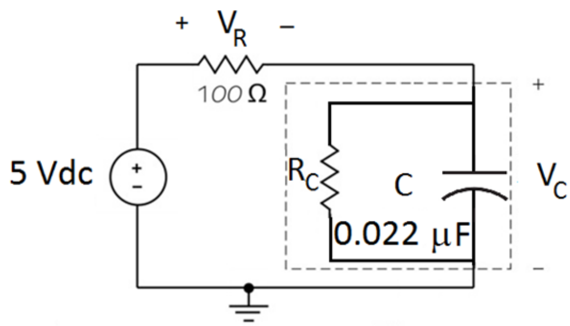


Figure 6: DC Capacitor Measurement

Part V – Inductor Impedance – AC Trial 1

Since you will use two different AC measurements to determine the inductor impedance (R_L + L), you should create a data table to compare the results for the resistance and inductance from parts V and VI. Build the circuit in Figure 7, and connect channel 1 of the scope to the input signal and channel 2 of the scope to measure v_R. Make sure that the source reads 5 V_{RMS} as measured on the oscilloscope.

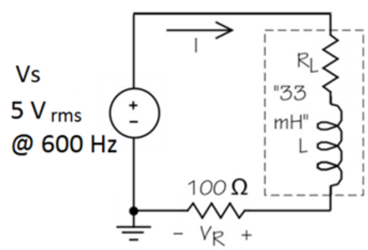


Figure 7: Inductor AC Measurement Trial 1

Display both channels on the oscilloscope and use the adjust knobs to make them both as large as possible. Also, display a little over one period for each waveform in order to collect the most accurate data. Make sure to measure the magnitude and phase of v_R (2→1) and use the measured voltages to find the inductor impedance. (Note that both grounds of the scope channels must be tied together as well as to the negative (ground) terminal of the function generator.)

Remember that Z = **V**/**I**, where **V** and **I** are Phasors and **V** is the source voltage with 0° as a phase angle. **I** =$\mathbf{V_R}/R_{100}$, where R_{100} is the measured value of the 100-Ω resistor. This impedance is the series combination of the lossy inductor and the 100-Ω resistor. Convert the measured impedance to rectangular form. Then calculate R_L by subtracting the measured resistance of the 100-Ω resistor from the real part; calculate L from the imaginary part.

Part VI – Inductor Impedance – AC Trial 2

Build the circuit in Figure 8, and measure the voltage across the source and the inductor. Display both of these voltages on the oscilloscope, and record the magnitude and phase angle of V_L. Remember to make the waveforms as large as possible and do not display more than two periods of either waveform. Use these measured voltages to calculate the inductor impedance similar to what you did in the prelab. Find the resistance, R_L and inductance, L and record them in the data table created in part V. How do the two values compare?

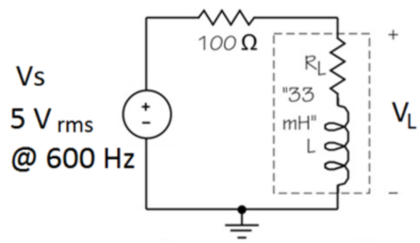


Figure 8: Inductor AC Measurement Trial 2

Part VII – Capacitor Impedance – AC Trial 1

Since you will use two different AC measurements to determine the capacitor impedance, you should create a data table to compare the results for the resistance and capacitance from parts VII and VIII. Build the circuit in Figure 9. Measure the voltage across the source (**V_S**) and resistor (**V_R**), and display both waveforms on the oscilloscope. (Note that both grounds of the scope channels must be tied together as well as to the negative (ground) terminal of the function generator.) Use the measured values to calculate R_C and C, and record them in the data table.

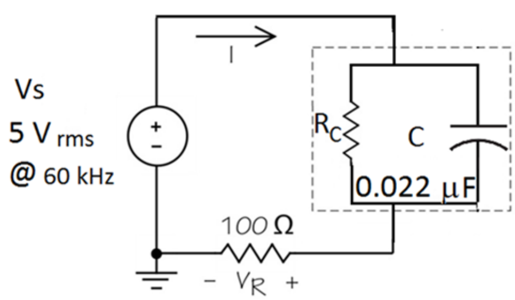


Figure 9: Capacitor AC Measurement Trial 1

Part VIII – Capacitor Impedance – AC Trial 2

Build the circuit in Figure 10, and connect channel 1 and 2 of the oscilloscope to the source and capacitor. Measure both voltages including phase angle, and calculate R_c and C. Record these values in the data table created in part VII. How do these values compare?

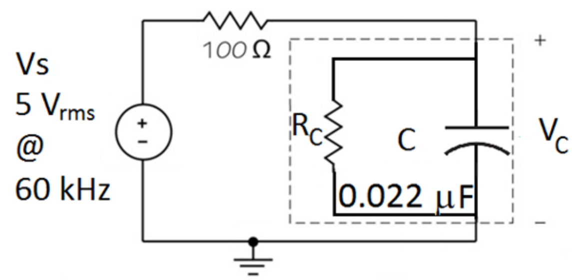


Figure 10: Capacitor AC Measurement Trial 2

Submission:

The lab journal is due at the conclusion of the lab period. Please review the checklist from prior weeks to determine what constitutes an acceptable record of your laboratory work.

Laboratory 9

AC Circuits

Purpose

In this lab, you will explore making phasor voltage and current measurements from AC circuits. Recall from the prior lab that without the magnitude and phase information, Kirchhoff's voltage law appears to fail in AC circuits. In this lab, the focus will be on using the oscilloscope to display waveforms in order to measure their magnitude and phase relationships. The goals are to perform the following AC measurements:

- Phase difference
- Phasor voltage and current
- peak-to-peak and RMS values
- AC gain in op-amp circuits

Prelab

Read the entire lab procedure and review sections 7.1 – 7.3, and 7.12 of your textbook. Submit the answer to the following questions on engineering paper in class the day before the lab session.

1. For the circuit in Figure 1, calculate $\mathbf{V_o}$.
2. For the circuit in Figure 1, calculate $\mathbf{I_s}$.
3. For the circuit in Figure 1, calculate $\mathbf{I_c}$.

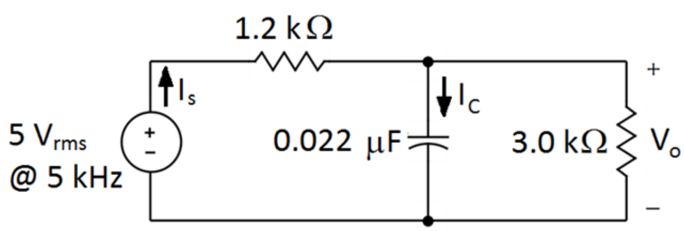


Figure 1: RC Circuit

4. For the circuit in Figure 2, calculate the DC gain.
5. For the circuit in Figure 2, calculate the AC gain (magnitude and phase) for an input with a frequency of 5 kHz.

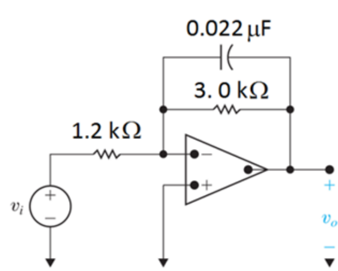


Figure 2: AC Op-Amp Circuit

If you have any questions, please ask your instructor.

Equipment

1– 0.022-µF capacitor

1 – 10-Ω resistor

1 – 1.2-kΩ resistor

1 – 3.0-kΩ resistor

1 – TL072 op amp

2 pair – red and black meter leads

3 pair – BNC-alligator-leads for the function generator and power supply

2 – BNC-to-banana adapter from the bench drawer for the power supply

2 pair – oscilloscope leads from the bench drawer

Procedure

All of the measurements in this lab will be performed using the oscilloscope and DMM. The DC voltages will be produced using the power supplies. The AC source will be generated using the function generator. Note that the oscilloscope only measures voltage not current, so we will have to a devise method for measuring AC current and phase.

Part I – Phasor Voltage Measurement

At times, a capacitor can have a capacitance significantly different from its nominal value. Use the LCR meter at the front of the room to measure the capacitance of your capacitor. Confirm that it is 0.022-µF, and compare this measured value to its theoretical value.

Set the function generate to produce a **5** $\mathbf{V_{rms}}$ sine wave at **5.0 kHz**. Use the oscilloscope to confirm that the output is correct. If it is not, adjust the function generator accordingly.

Build the circuit in Figure 1 (using the function generator as the voltage source). Use channel 1 of the oscilloscope to measure the voltage from the function generator (i.e., input voltage) and channel 2 of the oscilloscope to measure the output voltage ($\mathbf{V_o}$). Remember that both black clips from the scope probes must be connected to the ground node of your circuit.

Press **output** on the function generator and **auto scale** on the oscilloscope to display the circuit input and output signal. Press **quick measure** on the oscilloscope and the appropriate buttons in the window to measure the RMS voltage of channel 1 and channel 2 and the phase difference between channel 2 and channel 1 (2 -> 1).

Record the magnitude and phase of the output voltage (**V_o**). Compare these measured values with the theoretical values found in the prelab. Note that you used the percent error formula in prior labs to compare magnitudes. However, phase angle error is expressed as a **difference** not a percent (i.e. measured phase angle – theoretical phase angle).

Part II – Phasor Current Measurement

In the prelab you calculated the phasor current through the capacitor for the circuit shown in Figure 1. Next, you will measure this current. To begin, let's display the current on the scope and see how well it compares with theory. However, there is a problem with displaying currents on the oscilloscope; it only displays voltages! Therefore we have to calculate the current from a voltage waveform.

This is accomplished by using a shunt, which is nothing more than a small resistor placed in series with the element whose current you want to measure. The value of the resistor should be small enough that it barely alters the branch impedance, yet large enough to provide a voltage that the scope can measure. Note that the circuit in Figure 3 includes a 10-Ω resistor in series with the capacitor. The capacitor current **I_C** is the same as the current in the resistor. Thus, the *voltage* across the shunt resistor equals ten times the capacitor current.

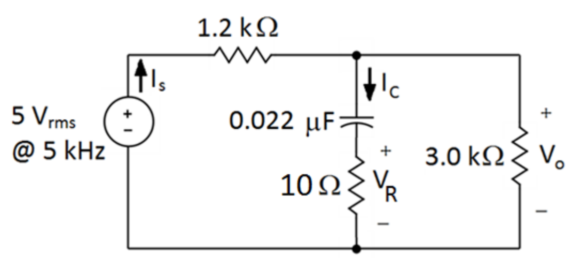


Figure 3: RC Circuit with shunt

Is the 10-Ω resistor a significant part of the impedance of the capacitor branch? Compare this 10-Ω value to the capacitor impedance at 5.0 kHz.

Why is the shunt at the bottom of the branch? This placement enables both black clips of the scope probes to be connected to the same node as the ground (negative) terminal of the function generator. If the shunt resistor came before the capacitor, then there would be no way to connect the black clips from both scope probes to the same node.

Your scope should now display **V_s** on channel 1 and the shunt voltage **V_R** on channel 2. The channel 2 signal will be very small because the current is in mA. In fact, it may be so small that it won't even be displayed when you press **auto scale** on the scope. In order to view the waveform, don't use **auto scale**. Instead press the channel 2 button, and the signal will appear as a flat line. Adjust the voltage scale of channel 2 to make the amplitude of the waveform as large as possible. Finally, have the scope "average" this waveform to cancel any random noise that is present. (To do so, press **acquire**, select **average**, and then press **quick measure**) You should now be able measure the phasor voltage for the shunt resistor.

Use Ohm's law to calculate the phasor currentf $\mathbf{I_C}$ by using the voltage across the shunt and the resistance of the shunt. Make sure that you use the actual resistance of the shunt in this calculation. Remove the 10-Ω resistor from the circuit and measure its resistance. Compare the measured value of the capacitor current to the theoretical value found in the prelab.

Part III – More current measurement

In order to measure the source current $\mathbf{I_S}$ it is not necessary to use a shunt resistor because there already is a resistor in series with the source. You will now use channel 2 of the oscilloscope to measure the voltage across this series resistor (both magnitude and phase). Similar to part II, use Ohm's law and the measured value of the 1.2-kΩ resistor to find $\mathbf{I_S}$**.** How can you manipulate the circuit in Figure 1 to measure the voltage across the 1.2-kΩ resistor and the source voltage? Think carefully‼ Remember that both black clips from the scope probes must be connected to the ground (negative) terminal of the function generator to avoid shorting out any circuit elements.

Build the circuit in the Figure 1, with the appropriate oscilloscope connections, and measure the magnitude and phase of the source current. How does the measured value of the current through the source compare to the theoretical value found in the prelab?

Part IV – Op Amp DC Gain

Build the circuit in Figure 4, and apply a **1 V** input from the +6V power supply. Use the positive and negative 25V power supplies to provide the rail voltages of ±15 V. Make sure to limit the current on all of the power supplies to 100 mA in order to protect the op amp. Use the DMM to measure the input and output voltage and calculate the DC gain. How does this measured value compare with the theoretical value found in the prelab?

Part V – Op Amp AC Gain

Set the function generator to supply a **1** $\mathbf{V_{RMS}}$ sine wave at **5 kHz** (as measured by the oscilloscope). Remove the power supply and attach the function generator to the input of the op-amp circuit. Connect channel 1 of the oscilloscope to measure the input voltage to the op-amp circuit and channel 2 to measure the output voltage. Calculate the AC gain from these voltages. How does this measured value compare to the theoretical value obtained in the prelab?

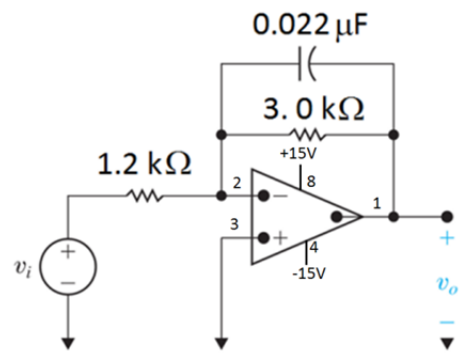


Figure 4: RC Op-Amp Circuit

Submission:

The lab journal is due at the conclusion of the lab period. Please review the checklist from prior weeks to determine what constitutes an acceptable record of your laboratory work.

Laboratory 10

Lab Practical Test

Purpose

The 75-minute lab practical will test your ability to build a circuit, calculate and measure electrical quantities and analyze the results. Because this test constitutes a significant part of your overall grade, you may want to prepare before coming to the practical.

Prelab

To prepare for the practical, you should review the prelabs, lab journal and lab manual. You may also come into the lab room after hours and practice building circuits and taking measurements. In addition, you can review a sample lab practical made available to you by your instructor.

Equipment

Bring your entire parts kit and breadboard to the lab session. You may also bring your prelabs, lab journal, lab manual and calculator (but NOT your computer).

Procedure

During the practical, you will build two simple circuits, one AC and one DC. You may be asked to measure resistance, voltage, current, and power. Since there will be AC and DC measurements, you should also be prepared to measure magnitude and phase for sinusoidal signals. You should be familiar with how to set up all 3 power supplies, the DMMs, oscilloscope and the function generator.

You will be given a sheet with instructions for what measurements to make, and a data sheet to record your results.You will be making measurements similar to those you have done most of the quarter. Your grade will be based entirely on the recorded data and analysis.

One member of each lab team will arrive at the beginning of the lab period to perform the practical. The other member of the lab team should arrive 80 minutes later. Your instructor will let you know how to decide which person shows up first. Good luck!