ECE 2080

ELECTRICAL ENGINEERING
LABORATORY I

by

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Revised January 1998
by Michael Hannan

Revision 1.4: May 2015

by Amir A. Asif

Revision Notes

1991 Authors: A. L. Duke and Dan McAuliff. Original release.

1998 Author: Michael Hannan. Reorganization, mostly with same information.

2008 Author: James Harriss. General reorganization, corrections, and update. Clarified instructions to reduce equipment damage and blown fuses. Redrew many figures. Rewrote laboratory sessions on SPICE and Oscilloscope. Added equipment list and references. Created common Appendix (A to E) for ECE 309 and ECE 212. Moved Safety and Oscilloscope background information into Appendix. Added appendix for Tektronix TDS 1002B Oscilloscope. August 2008.

2010 Author: Dr. J. E. Harriss. In Lab 5 - Oscilloscope: Add explanation of RMS and clarify purpose of the experiment; delete procedure 5, Lissajous figures. May 2010.

2015 Author: Asif Amir. Simulation lab rewritten. Appendix F added. Re-arranging the order of labs to keep pace with the co-requisite course. Alternate method added in instrument (voltmeter) characterization. Pre-lab and post-lab redefined in circuit analysis chapter.

Table of Contents

Equipment

Description	Manufacturer	Model
AC Power Supply	use *Autotransformer* or *Transformer Board*	
Ammeter-Voltmeter, Analog	Hampden	ACVA-100
Autotransformer (Variac)	Powerstat	3PN116C
Capacitance Decade Box	EICO	1180
Capacitor, 40 mfd	Square D	PFC2001C
DC Power Supply	TENMA	72-7245
Digital Designer	Digi-Designer	DD-1
Frequency Counter	Tektronix	CFC250
Function Generator	BK Precision	4011A, 5MHz
Inductor, 10 mH	ECE	
Inductor, coaxial, 36mH, 28mH, 120mH	ECE	
LCR Meter	BK Precision	878
Multimeter, Digital, True RMS	Meterman Wavetek	BDM40 BDM40
Oscilloscope, Dual Beam	Tektronix	TDS1002B or TDS1002
Resistance Load Box	ECE	
Resistance/Reactance Load Box	Hampden	RLC-100
Resistor Decade Box, High Power	Clarostat	240C
Resistor Decade Box, Low Power	Heathkit	IN-3117
Transformer Board	mounted 120V to 6.3V & 12.6V transformer	
Two-port Network	ECE	
Voltmeter, Analog	Hampden	AC3V-300
Voltmeter-Ammeter, Analog	Hampden	ACVA-100
Wattmeter, Dual Analog	Hampden	ACWM-100

References

1. Giorgio Rizzoni, *Principles and Applications of Electrical Engineering*, Fifth Edition, McGraw-Hill, December 2005.

2. Giorgio Rizzoni, *Principles and Applications of Electrical Engineering*, Revised Fourth Edition, McGraw-Hill, July 2003.

3. Mahmood Nahvi, Joseph A. Edminister, *Schaum's Outline of Electric Circuits,* Fourth Edition, December 2002.

4. James W. Nilsson and Susan Riedel, *Electric Circuits,* 8th Edition, Prentice Hall, May 2007.

5. James W. Nilsson and Susan Riedel, *Electric Circuits,* 7th Edition, Prentice Hall, May 2004.

6. Charles Alexander, Matthew Sadiku, *Fundamentals of Electric Circuits,* Second Edition, McGraw-Hill, May 2004.

Preface

This laboratory manual is composed of three parts. Part One provides information regarding the course requirements, recording the experimental data, and reporting the results. Part Two includes the laboratory experiments and problem exercises to be performed. Part Three is an appendix with sections regarding electrical safety, general equipment in the laboratory, creating a logarithmic scale for graphs, general information about oscilloscope use, and specific information about the oscilloscopes available in the laboratory.

Introduction

This laboratory course operates in co-ordination with the companion lecture course, ECE 2070, Basic Electrical Engineering. Each course complements the other: Several ECE 2080 exercises require knowledge of theory developed in ECE 2070, and several assist in understanding ECE 307 concepts.

Preliminary laboratory preparation ("Pre-Lab") is assigned for most periods. A student who understands this preliminary preparation should be able to complete the exercises during the time scheduled.

Much of the value of the laboratory exercises lies in working with the instruments and other electrical equipment; therefore, attendance is required. Since the laboratory facilities are in use almost every period of the week, it is difficult to schedule make-up periods to complete the work. If absence is unavoidable, the instructor can usually assist in arranging a meeting with another section.

The instructor of each section will inform that section of policies regarding tests, ethics, the method of determining grades, and other administrative matters during the first-period orientation.

This laboratory course has five major objectives: (1) Familiarization with basic electrical measurement techniques, (2) Enhancing ability to apply electrical theory to practical problems, (3) Practice in recording and reporting technical information, (4) Familiarization with electrical safety requirements, and (5) Laboratory verification of some elementary theorems and concepts of electrical engineering. These objectives are to be accomplished by a series of laboratory exercises and problem sessions.

The laboratory exercises are generally focused on electrical instrumentation, with one period focused on using a digital computer program to analyze electrical networks.

The problem sessions are coordinated with the theory covered in the lecture. The problem sessions involve two types of problems: (1) those that are of a more applied nature, such as application of theorems to bridge circuits, and (2) those for which the topic requires little or no lecture, such as determination of shunts and multipliers to change the scale of ammeters and voltmeters. While some assigned problems are similar to those in the text, others extend the text material in order demonstrate how the theory can be applied to basic problems encountered in general engineering practice.

Preparing the Laboratory Notebook

Laboratory-oriented engineering work, particularly research work, provides information that is usually quite detailed. Records of this work and the results specified are kept in laboratory notebooks. Laboratory notebooks must be complete and clear, since data recorded may provide a basis for calculations, conclusions, recommendations, engineering designs, patents, etc. These notebooks are given to the engineer to generate various types of reports, sometimes after long periods of time. They may be used by others to verify the work, or as a base for additional work. They also may serve as evidence in lawsuits over patents. While the format of the notebook is an individual matter, certain standards must be maintained to ensure accuracy and readability.

The requirements and procedures necessary to produce a good laboratory notebook are given in the following paragraphs. The lead page or pages of the laboratory notebook should contain general information, such as title, purpose, and laboratory location. The information recorded in the laboratory notebook should be sufficiently detailed to permit the work to be duplicated at a later date by the writer or by other knowledgeable engineers. It should include all data observed and the pertinent conditions that existed, such as instruments used, parameter settings, and so on.

Entries in the notebook should be in chronological order and should be in ink. Any erroneous or incorrect entries should not be erased, but should be lined through. Pages should be numbered consecutively, with no pages removed or torn out. No blank pages should be left. Any pages or partial pages left blank should be lined through. Each entry should be dated and signed and, if appropriate, witnessed. Dating, signing, and witnessing are especially important when pursuing or protecting patents.

Types of entries in a laboratory notebook include concise written explanations of procedures, equations used, freehand sketches and diagrams, tables, curves, charts, photographs, lists of apparatus, and references to items such as blueprints that are large or bulky to include.

The laboratory notebook normally should not contain lengthy presentation theory or reference material, or extended discussions of ordinary or routine results. Written explanations should be sufficiently detailed to permit the writer to understand what was done even after several years have elapsed, but should not be burdened by trivial details.

Any equation used in the work should be given in the notebook, along with source of the equation, if it is not a standard, well-known one.

Freehand sketches should be used liberally to illustrate laboratory experiments. These sketches should be neat. Straightedge and compass or suitable drawing templates should be used to obtain, as a minimum, straight lines and round circles. Using templates for sketching standard devices such as resistors, inductors, and capacitors also improves the appearance of the notebook. The engineer doing the recording must decide on the trade-off between the time required and the appearance and readability the notebook.

Tables should be used to list observed data as well as data calculated during laboratory work. These tables should be titled with the conditions that existed or parameters that were set. Headings for columns and rows should be given with the units used in the measurement or calculations. It is frequently desirable to separate observed data and calculated data in tables by use of a double rather than a single line. Where calculated data is tabulated, the table should be followed by representative sample calculations.

Graphs and charts are frequently used during laboratory work to determine validity of the data and to detect immediately anomalies, trends, and unexpected changes in the data; this may avoid a need for repeating the experiment later. It is much more expensive in time and material to set up the experiment a second time needlessly, rather than correcting the problem during the first run. Photographs, charts, oscillograms, diagrams, and other loose sheets are sometimes desirable in a notebook. These should be attached or affixed in the most suitable and permanent manner.

Any pertinent material, such as blueprints, which cannot be reduced sufficiently for inclusion in the notebook, should be referenced and filed so as to be available as long as the notebook is to be kept.

Instruments or other apparatus affecting the work should be listed in the notebook. The name, manufacturer, equipment type, model, rating, and serial number of the item should be recorded, as appropriate.

The instructor may or may not require a formal lab notebook in this course. If required, carbon paper will be provided.

References

1. J. N. Ulman, Jr. and J. R. Gould, *Technical Reporting*. Third Edition, Holt, Rinehart, and Winston, Inc., New York, 1972.
2. B. D. Wedlock and J. K. Roberge, *Electrical Components and Measurements*. Prentice-Hall, Inc., Englewood Cliffs, NJ, 1969.

Reports

General

The final result of almost all engineering work includes some sort of report. The information for the report usually comes from the engineer's notebook, status reports, design information, and other reports. It follows that a good engineer must be skilled at transmitting technical information, whether by a long formal report or by a short telephone conversation. Examples of the types of informational reports commonly used by engineers are:

- Routine periodic (e.g., biweekly) reports to a supervisor on activities carried out during the time period.
- Special reports on projects, investigations, etc., to a supervisor or to management.
- Informational reports to others regarding work done to provide the information needed to do the job.
- Routine (monthly, quarterly, etc.) project reports to a project director, or from you as a project director to management or to clients.
- Informational and fiscal status reports to the management and controllers.
- Informational reports needed by people being supervised.

The informational report is written to provide information on the results of specific work done. It will vary from a very short report (e.g., a telephone conversation or one-page laboratory report) to a comprehensive formal technical report that requires weeks or months and many people to prepare. The informational report is the type used in technical laboratories and in engineering design correspondence.

The major characteristics of a good technical report can be summed up as <u>conciseness</u>, <u>completeness</u>, <u>accuracy</u>, and <u>clarity</u>. <u>Conciseness</u> is important since a wordy report or one with unneeded information is often put aside and not read, or only scanned. <u>Completeness</u> is important since lack of needed information may require additional work to get the information, causing delay of a project, or it may result in wrong decisions being made. <u>Accuracy</u> is important since any error in content (or in write-up) generally makes the whole report suspect. <u>Clarity</u>, along with accuracy, is a primary requirement since ambiguities or misinterpreted statements are synonymous with errors.

Other characteristics, such as objectivity, authoritativeness, coherence, control, direction, organization, and veracity are also important, and are discussed in more detail in the references.

One of the most important but often overlooked steps in preparing a good report is the selection of the appropriate audience. A technical report addressed to a few people with similar background and knowledge of the subject can be written more easily than one addressed to an audience of varied backgrounds. In reports for people of similar backgrounds, superfluous information must be omitted. In writing to a group with different types of background knowledge, care must be used to include the required information without requiring all the readers to read and comprehend all the material. Perhaps the worst technical reports are those written to the wrong audience.

Judgment must be used in establishing sections and subsections in all types of reports. It is just as inappropriate to have a one page report with twenty section headings as it is to have a fifty-page report with only one heading. Where appropriate, elements may be combined and renamed.

In this course, two types of reports will be used: the Laboratory Report and the Memo Report. Both are described in the following paragraphs.

Memo Report

This should be a brief report limited to a single subject. It is usually limited to communication within the organization. The memo may be from one-half to five or ten pages long. In addition to the technical information, it should always have a date, a reference line, a "To" line, a "From" line, and a signature or initials. It may also have a heading (e.g., organization or company name), subject line, identification symbol, distribution notice, and attachment or enclosure notice. Most organizations, through regulations or through custom, have standard or semi-standard formats for the heading lines.

Some common types of memo reports are the progress report and the status report. These two reports are similar but the status report usually is more comprehensive and less specific. It frequently includes such things as costs and man-hours expended, while the progress report may only provide information on the work that has been done, the work being done, and the work planned. The progress report should point out problems as well as the steps being taken to overcome these problems. Unexpected progress should be presented. Recommended changes can also be included; however, such recommendations may be better addressed with a separate memorandum in order to receive more immediate attention.

Laboratory Reports

This category of report includes types of reports that vary from the standard fill-in-the-blank type (e.g., test results from standard, well-known, performance tests of transformers) to the individual comprehensive report, very similar to the formal report (e.g., one resulting from the individual laboratory testing of a large, expensive piece equipment). The format will, of course, depend on where the report lies between these extremes. However, all laboratory reports should answer the following questions in a straightforward, smooth-flowing manner:

1. What was the objective of the test or experiment?
2. How was it performed?
3. What information or data were obtained?
4. What is the result and significance of the information and data?
5. What are the conclusions to be drawn, as related to the objective of the test or experiment?

The laboratory report is the communication vehicle frequently used to combine the appropriate test or experimental data from the laboratory notebook with information from other sources and to transmit it to the person or organization that needs it. This type report is also frequently used as an undergraduate student laboratory report.

The following paragraphs give the headings and a brief description of sections of a typical laboratory report.

Heading. This varies from the title page of a formal report to the heading of a memo or letter report. It is the writer's responsibility to find out what is appropriate in each case. The heading should include the report title and the report number. Reports without numbers and names are likely to be misfiled and lost. On a student report, the date should be the date the report is due.

Objectives. This section should carefully state the objectives or purpose of the test or experiment. It should be edited very carefully to avoid vagueness and ambiguities. In a student report, the objectives should not necessarily be just a copy of the purpose or objective specified in the lab manual, but should state the objectives or purposes of the test or experiment as it was done.

Apparatus or Equipment. This should be a listing of all equipment, instruments, and devices used. General-purpose items, such as wire, resistors, or other items which do not affect the results should not be included. The listing should include name, manufacturer, model, and type number, and rating of the equipment.

Procedure. A narrative account of the method and procedures used in carrying out the laboratory work is written in chronological order, and should briefly describe the work accurately as it was done. Diagrams, sketches, and pictures should be liberally used. In beginning student exercises, the procedure is usually fully given by the instructor, but in more advanced exercises, students may be required to develop their own procedures.

Observation and Discussion. This section should contain the data or recorded observations from the laboratory work. This is usually in tabular form and may include calculated data as well as observed data. It may also include narrative comments on the significance of the data, comparison of analytical and experimental values, and answers to specific questions.

Conclusions. This section is similar to the conclusions section in the formal report. The conclusions reached should be clearly supported by specific data in the observation section, and should be closely related to the experimental objectives.

Signature. The person responsible for the work and the report should sign the report signifying acceptance of responsibility for the report. In some instances, this also requires the engineer's, registration number as a professional engineer, thus accepting legal responsibility for the work done. In shorter reports; the signature may a part of the heading section. In student reports, it signifies that the report is the students work with no unauthorized assistance from other students or reports.

The report may also include other sections, such as Analysis and Calculations, Theoretical Development, and Recommendations. The report should be organized with section headings selected to provide the reader with an organized, smoothly moving path through the report. It may be suitable to give all procedures followed by observations, then followed by all conclusions; or it may be preferable to organize the report in sections with procedure, observations, and conclusions for one part of the experiment, followed by procedure, observations, and conclusions for another part. The writer should very clearly identify the procedures, observations, and conclusions, and should never intermingle them in one paragraph; however, neither should the reader be forced to continually turn back and forth between sections.

The report should be written in relatively formal language. Technical vocabulary should be used as appropriate, but technical vocabulary that the reader could not be expected to know should be defined in a glossary, in a footnote, or by parenthetic expression, as appropriate. Avoid jargon, as it tends to obfuscate, rather than illuminate.

Laboratory #1:

Course Description and Introduction

Objectives:

1. The establishment of course procedures and policies.
2. The review of basic electricity

Policies:

Course policies on grading and coursework ethics are determined and made known by the instructor of each section.

This course will operate as a problem workshop intermingled among laboratory experiments. Occasionally the sessions will involve topics not covered in the lecture course and at other times will reinforce the topics of ECE 307. The laboratory exercises have the dual purpose of introducing students to the basics of electrical instrumentation and augmenting ECE 307 regarding some of the practical aspects of circuit analysis.

ECE 307 is a co-requisite for ECE 309, and the courses should be taken together whenever possible. Enrollment in ECE 309 cannot be maintained without maintaining enrollment or having prior credit in ECE 307.

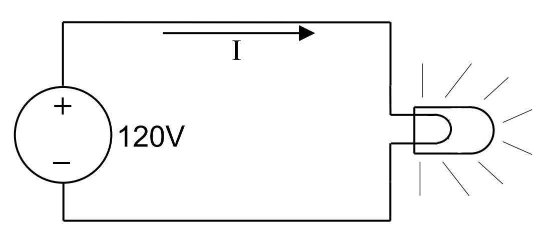
In Lab: Work the following problems.

1. State Ohm's law.

2. Write the 2 alternate forms of the equation for power, P = IV, using Ohm's law.

3. A 100Ω resistor carries a current of 2A. What is the power dissipated in the resistor?

4. Given a 100 watt light bulb in the following circuit:



   a) Find the current I.
   b) Find the resistance of the light bulb.
   c) What is the cost to operate the light bulb a $0.07 / kW-hr for 24 hours?

Laboratory #2:

Measurement of DC Voltage and Current

Objectives:

This exercise introduces the digital multimeter as an instrument for measuring DC voltage, current, and resistance.

Pre-Lab Preparation:

1. Read Appendix A: *Safety*.
2. Read Appendix B: *Equipment and Instrument Circuits* through Digital Multimeters.

Safety Precautions:

In working with electrical equipment, extreme care must be taken to avoid electrical shock to any person, and to avoid any damage to any instrument or other equipment. In this exercise, you are to investigate the circuit connections for measuring DC voltages and currents. Some important rules to remember are:

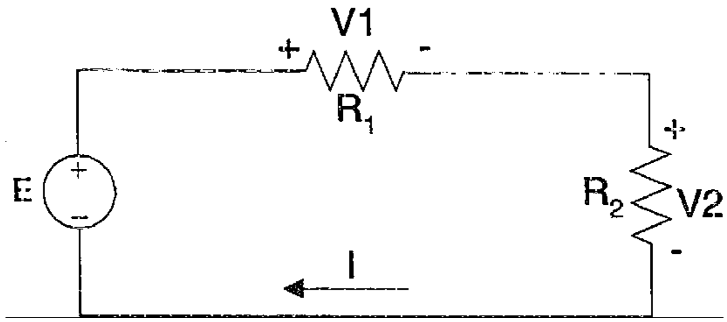
1. Always **turn off power** to the circuit when changing the circuit.
2. Only reapply power after verifying that the circuit is properly wired and that the voltage to be applied is at or below the required value.
3. Failure to turn off power when making circuit changes is a major reason for blowing fuses in the equipment, thereby rendering the equipment unusable and wasting your time and that of others. Please carefully check circuit wiring, resistor settings, and voltage settings before applying power to the circuits.
4. To avoid possible costly instrument damage, the **range of the scale** for a voltmeter or an ammeter should always be larger than the magnitude of the voltage or current being measured. When in doubt, start out with the highest scale or with an instrument known to have a higher range than the quantity you are measuring. It is important to note that one should use the smallest possible scale, without exceeding the range setting, for the most precise measurement.
5. **Polarity** must be observed on DC measurements. A voltmeter must be connected such that its positive terminal is connected to the more positive point in the circuit, and an ammeter must be connected such that current enters its positive terminal.
6. Always connect a **voltmeter in parallel** with the load or source being measured, and connect an **ammeter in series** with the load. **Never connect an ammeter across a voltage source.**
7. An ideal voltmeter would have infinite resistance and would not drain any current from the original circuit. However, real voltmeters have a finite resistance, which must be considered in a high-resistance circuit.
8. An ideal ammeter would have zero resistance, in which case there would be no voltage drop across the meter. However, real ammeters have some resistance, which becomes important in low-resistance circuits.

Equipment Needed:

- DC Power supply
- Digital multimeter
- Resistance decade boxes (2)

Procedure:

1. Series Circuit



E = 10 V
R_1 = 33kΩ
R_2 = 100kΩ

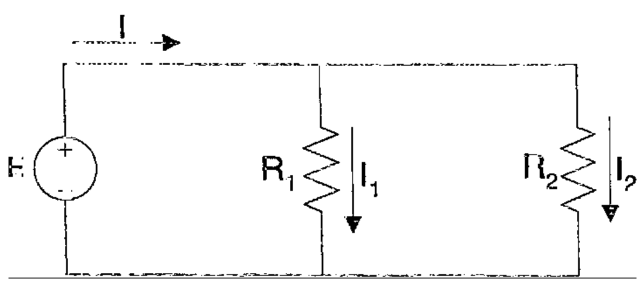
a) With the values of R_1 and R_2 provided, connect the circuit shown above. Use the digital multimeter to measure E, V1, V2, and I.

b) Check the relationships:

$$E = V1 + V2$$

$$I = \frac{E}{R_1 + R_2}$$

2. Parallel Circuit



E = 10 V
R_1 = 33kΩ
R_2 = 100kΩ

a) With the values of R_1 and R_2 provided, connect the circuit shown. Use the digital multimeter to measure E, I_1, I_2, and I.

b) Check the relationship: $\frac{I}{E} = \frac{1}{R_1} + \frac{1}{R_2}$

Laboratory #3:

Computer Analysis

Objectives:

This exercise is intended to provide familiarity with computer analysis of electrical circuits. It focuses on interpretation of results obtained from a commercial circuit analysis program.

Introduction:

The analysis of electronic circuits can be expensive in both time and money, especially as circuitry becomes complicated with many and varied components. In this course and in the parent ECE 2070 class you will be required to learn a number of robust techniques to analyze and characterize circuits. While you must learn to perform those techniques manually, there are also computer tools available to help by checking analyses or by analyzing complicated circuits.

The dominant programs of this type are referred to as SPICE (Simulation Program with Integrated Circuit Emphasis), a general purpose analog electronic circuit simulator. Such programs are commonly used in IC and board-level design to check the integrity of circuit designs and to predict circuit behavior.

The upper-level electronics courses in ECE require powerful SPICE tools from different vendors. However, in this laboratory, we will use a simpler, web browser based tool to perform simple simulations. The web based tool is known as PartSim from Digikey.

Please check the Appendix F for some more details.

Pre-Lab:

Well before the meeting of your laboratory section, you must **visit www.partsim.com.** And, create an account there. It is free, and it is not necessary to provide institutional email (you can create account with your personal email).

Familiarize yourself with the basic layout of the webpage. Check the examples, create an empty project. In a project, you can find your familiar components under **Components>Generic Parts.** The resistors, capacitors, etc. are grouped under Passives. *Ground is located under "Ports"*. Measurement tool are under "*Test Equipment",* and so on.

Procedure:

The basic procedure to use PartSim for the analysis of circuits is the following:

1. Go to the website www.parsim.com
2. Log in and open new project.
3. Draw the connecting wires
4. Set the component properties
5. Simulate the circuit
6. Save the circuit

Help can be found at http://www.partsim.com/help/

We shall use the simple circuit drawn below as an example.

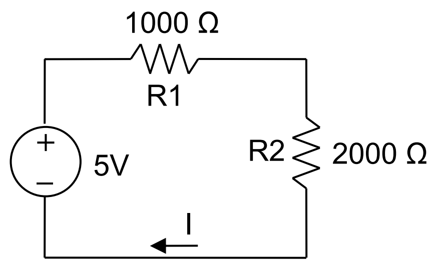


Figure 3.1: Circuit #1

1. Using the rules for adding series resistances, Kirchhoff's laws, and Ohm's law, analyze the circuit of Figure 3.1. Calculate the current I and the voltage drops across each of the resistors.

2. SPICE programs tend to use Node Analysis to analyze circuits. One node labeled '0' serves as the reference (ground) node. Number the nodes as shown below, then, using Ohm's law and Kirchhoff's laws, calculate the voltages at each of the nodes, relative to the voltage at Node 0.

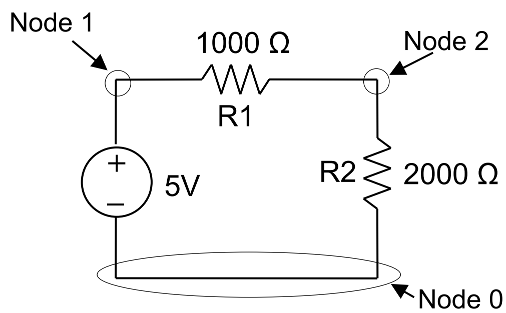


Figure 3.2: Node labels

3. Construct and measure the circuit (**in real life first**, then in simulation):
   a) Preset the DC power supply to provide 5 volts output. Switch the DC power supply's OUTPUT OFF.
   b) With the DC power supply's OUTPUT OFF, construct the circuit in Figure 3.1.
   c) Set up one of the Digital Multimeters (DMM) to measure DC current, with a scale setting of at least 20 mA. Insert the DMM in series in the circuit to measure the current.
   d) Switch the DC power supply's OUTPUT ON, and measure the current, using the lowest meter scale that is greater than the measured value. Record the reading.
   e) Set up the second DMM to measure DC voltage greater than 5 volts. Use this DMM to measure the voltage between Node 1 and Node 0. Record your reading. Then measure the voltage between Node 2 and Node 0. Record your reading.
   f) Turn the DC power supply's OUTPUT OFF.

   Now, we will do the simulation.

4. In PartSim, the circuit can look like this Figure 3.3. Click ‘Run’, then check “DC bias”, and hit “Run” (in pop up window). It will label node voltages and current.

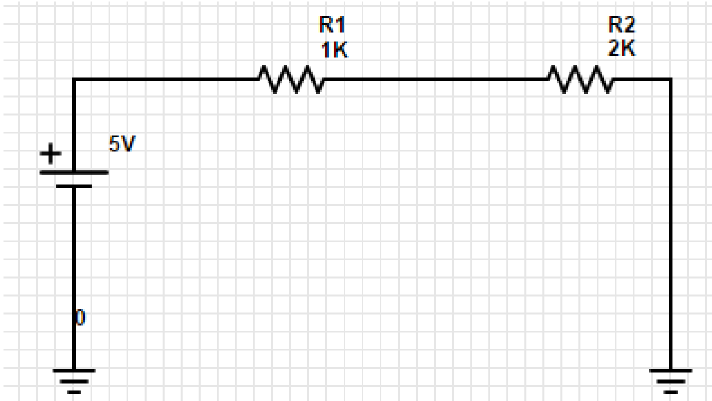


Figure 3.3: Schematic from PartSim

Create a table showing the three sets of values for currents and node voltages: (a) your calculation from Ohm’s law and Kirchhoff’s laws; (b) your measured values; and (c) the prediction from B2 SPICE. Compare the results and discuss any discrepancies.

Parameter	**Manual Calc**	**Measured**	**PartSim** (current is shown negative since it is coming out of voltage source)
Current, *I*			
Voltage, Node 1			
Voltage, Node 2			

5. Analyze another circuit by hand and again with B2 SPICE:

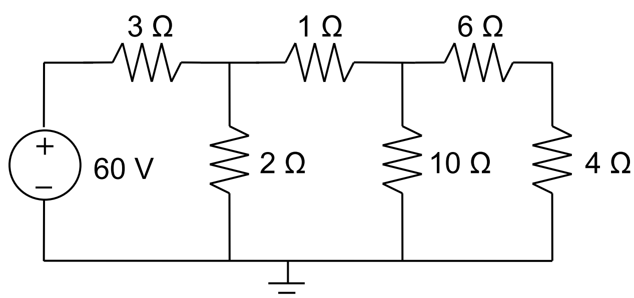


Figure 3.4: Circuit #2

a) Label the nodes in the above circuit.
b) By hand, calculate all of the node voltages and branch currents for the circuit.
c) Create the circuit in PartSim. Or , go to http://www.partsim.com/simulator#35905
d) Use PartSim to simulate the circuit. (you can do ‘Save As’ to get your own copy).
e) Compare the voltages calculated.
f) To see the currents go to http://www.partsim.com/simulator#35910
(here, dummy voltage sources are used to measure current. The ammeters have software bug)

Laboratory #4:

Instrument Characteristics

Objectives:

Understand the effect of introducing a measuring device into a circuit, and how the instrument affects the measurement.

Introduction:

One well known understanding from quantum mechanics is that the act of looking at (e.g., measuring) any system changes the system's behavior. That is certainly true for electrical and electronic systems. Thus, it is critically important for engineers to understand the characteristics of measurement equipment — how it works and how it interacts with the sample being measured — in order to make accurate and useful measurements on systems, especially in unusual circumstances. This laboratory seeks to provide such understanding and knowledge for two of the most important tools for electrical measurements: the ammeter and the voltmeter.

Pre-lab Preparation:

1. Review Appendix A: *Safety*.
2. Review Appendix B: *Equipment and Instrument Circuits* through Digital Multimeters.
3. Study the textbook's descriptions of the Voltmeter and the Ammeter.
4. Review Ohm's Law, Kirchhoff's Voltage Law, and Kirchhoff's Current Law.

Safety Precautions:

1. Always **turn off power to the circuit when changing the circuit.**
2. Only reapply power after verifying that the circuit is properly wired and that the voltage to be applied is at or below the required value.
3. Failure to turn off power when making circuit changes is a major reason for blowing fuses in the equipment, thereby rendering the equipment unusable and wasting your time and that of others. Please carefully check circuit wiring, resistor settings, and voltage settings before applying power to the circuits.

Equipment Needed:

- DC Power supply
- Digital multimeter
- Resistance decade boxes (2)

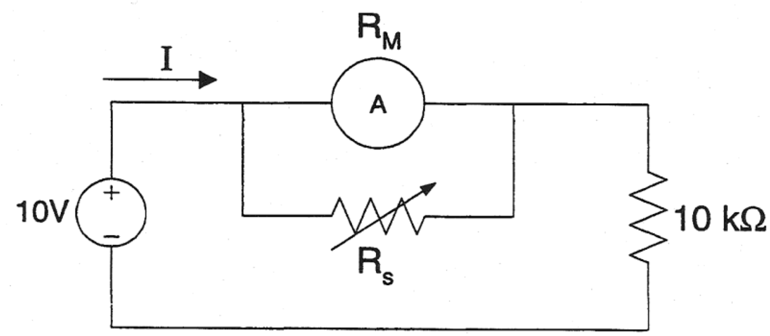
Procedure:

Ammeter

1. Determining the internal resistance of the digital ammeter.

For the following circuit, set the range of the ammeter to the 2mA scale or the closest setting to this, and do not adjust this scale at any time during the procedure. First, determine the current 'I' in the following circuit without the variable resistance in the circuit. Then connect the resistance box in the circuit as shown. Adjust the resistance until the meter reads half of its original value. The internal resistance of the ammeter is now equal to the value of the resistance box. Measure and record this value of R_S.

$$R_M = R_S \text{ when the } I_{new} = \frac{1}{2} I_{old}$$



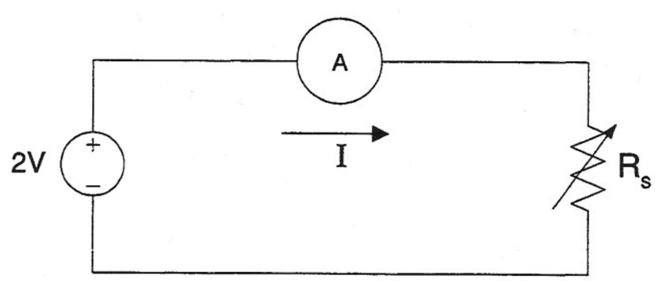
Theoretical Question: (DO NOT TEST THIS EXPERIMENTALLY!) If R_S were removed and if the 10 kΩ resistor were replaced by zero ohms (0 Ω), what would be the current I?

2. Determine the effect of the ammeter's internal resistance on the measurement of current.

   WARNING: If you are not careful to turn off the voltage when changing the circuit below (including switching values on the resistor boxes), you are likely to blow the fuse in the resistor boxes or in the ammeter. **Be sure that the resistor values are set as required before turning on the power.** Also note that **the voltage for this step is only 2 volts**.

   a) With the DC power supply disconnected from any circuit:
      1) Turn on the power supply.
      2) Turn "OUTPUT" ON.
      3) Adjust the power supply to provide 2.0 V output.
      4) **Turn "OUTPUT" OFF**.

   b) Connect the circuit shown below, using variable resistance boxes for the resistors.



   c) Set the resistance R_S to **1 kΩ**.

   d) Set the Digital Multimeter to Amps, and the scale to 200 mAmps

   e) Turn the power supply's "OUTPUT" ON. Its output should be 2.0 volts.

   f) Record the value of current indicated on the ammeter.

   g) Turn the power supply's "OUTPUT" OFF, without disturbing its voltage setting.

h) Set the resistance box to **500 Ω**.

i) Turn the power supply's "OUTPUT" ON, without disturbing its voltage setting.

j) Record the value of current indicated on the ammeter.

k) Turn the power supply's "OUTPUT" OFF.

l) Set the resistance box to **75 Ω**.

m) Turn the power supply's "OUTPUT" ON.

n) Record the value of current indicated on the ammeter.

o) Turn the power supply's "OUTPUT" OFF.

Analysis: Assuming that the internal resistance of the meter is zero, calculate the theoretical values for the three currents and compare these to your measured values. Explain any discrepancies and summarize your understanding of the influence of the ammeter on the measurements.

Voltmeter

1. Determining the internal resistance of the digital voltmeter.

Background

To minimize their effect on voltage measurements, voltmeters are designed to have very high input resistance. This is especially true of the newer digital meters. Historically, one common method of determining the internal resistance of a volt meter was to connect it in a simple series circuit with a variable resistor. First, with the variable resistor R_S set to 0 Ω, measure and record V_0, the initial voltage drop across the meter. Then, without adjusting the power supply or the scale setting on the voltmeter, increase R_S until the voltmeter indicates ½ V_0. At that point half of the applied voltage is dropped across R_S and half is dropped across the voltmeter. Assuming that the voltmeter behaves like a purely resistive load, the resistance of the voltmeter must be equal to the resistance of R_S at that setting. That is,

$$R_{Meter} = R_S \text{ when the } V_{meter} = \tfrac{1}{2} V_0$$

Modern digital voltmeters have very high resistances, often higher than the available variable resistors or resistance boxes. Thus, we must modify the above procedure accordingly.

Assume that the voltmeter in the circuit below behaves electrically like a resistor with resistance R_M. Define the following variables:

R_S = the resistance of the variable resistor,

V_0 = the output voltage of the power supply,

V_R = the voltage drop across the variable resistor R_S

V_M = the voltage drop across the voltmeter, and

I = the current flowing through the circuit.

Then, by Ohm's Law and Kirchhoff's Laws, we must have

$$V = V_R + V_M$$

where

$$V_R = I \cdot R_S \quad and \quad V_M = I \cdot R_M .$$

So

$$I = \frac{V_R}{R_S} = \frac{V_M}{R_M}$$

and

$$R_M = \frac{V_M}{V_R} R_S \quad or \quad R_M = \frac{V_M}{V_0 - V_M} R_S \qquad (4.1)$$

Thus, in the circuit shown below, if, for example, V_M is 90% of V_0, then $R_M = 9 \cdot R_S$. For accuracy, R_S should be as close to the value of R_M as possible, but in practice any reasonably large R_S that allows accurate measurements of V_0, V_M, and R_S can yield reasonably accurate measurement of R_M.

Procedure:

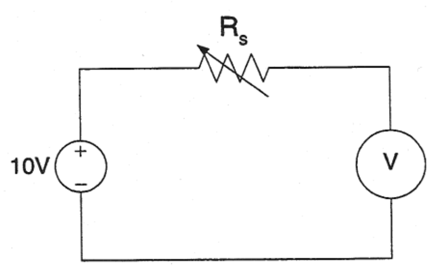
For this step of the experiment with the following circuit, do not adjust the voltmeter's scale at any time once measurements have begun.

a) Set Digital Multimeter to VOLTS and its scale to 20V. Set the AC/DC switch to DC.

b) With the DC power supply disconnected from any circuit:

   1) Turn on the power supply.
   2) Turn "OUTPUT" ON.
   3) Adjust the power supply to provide 10.0 V output.
   4) Turn "OUTPUT" OFF.

c) Connect the circuit shown below, using a variable resistance box for the resistor R_S.



d) Set the resistance box R_S to 0 Ω.

e) Turn the power supply's "OUTPUT" ON. If necessary, adjust its output voltage to 10.0 volts. This same voltage should be displayed on the digital voltmeter.

f) Record the value indicated on the voltmeter. This initial value is V_0.

g) Increase the resistance R_S as large as possible. Usually, we use two decade boxes to include 2MΩ resistance. (in most cases it comes near 8.2 ~8.4V for 2MΩ resistance)

h) Record the voltage V_M indicated on the digital voltmeter.

i) Use equation 4.1 and solve for R_M.

****Alternate method** [possible only if you have large resistances(~10 MΩ) in decade box]*

a) Connect the circuit like the previous page. Set the resistance box R_S to 0 Ω.

b) Turn the power supply's "OUTPUT" ON. If necessary, adjust its output voltage to 10.0 volts. This same voltage should be displayed on the digital voltmeter.

c) Record the value indicated on the voltmeter. This initial value is V_0.

d) Increase the resistance R_S as large as possible, as long as the voltage V_M is at least ½ V_0.

e) Record the voltage V_M indicated on the digital voltmeter.

f) Turn off the power supply.

g) Use the second digital multimeter to measure the resistance R_S. Record the value.

2. Determine the effect of the voltmeter's internal resistance on the measurement of voltages.

WARNING: Be sure resistors are set as required before applying power to the circuit.

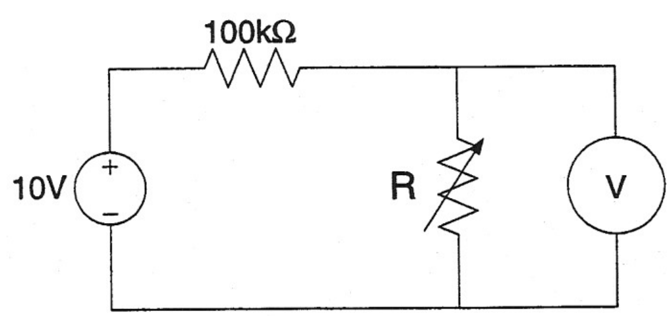
For this step of the experiment, do not adjust the voltmeter's scale or the power supply's voltage adjustment at any time once measurements have begun.

a) Set Digital Multimeter to VOLTS and its scale to 20V. Set the AC/DC switch to DC.

b) With the DC power supply disconnected from any circuit:

   1) Turn on the power supply.
   2) Turn "OUTPUT" ON.
   3) Adjust the power supply to provide 10.0 V output.
   4) Turn "OUTPUT" OFF.

c) Connect the circuit shown below, using variable resistance boxes for the resistors.



d) Set the resistance R to **10 kΩ**.

e) Switch the power supply's "OUTPUT" to ON. Its output voltage should be 10.0 volts.

f) Record the voltage value indicated on the voltmeter.

g) Switch the power supply's "OUTPUT" to OFF, without disturbing the voltage setting.

h) Set the resistance R to **500 kΩ**.

i) Switch the power supply's "OUTPUT" to ON.

j) Record the voltage value indicated on the voltmeter.

k) Switch the power supply's "OUTPUT" to OFF.

l) Set the resistance R to **1 MΩ** (or as close as you can get).

m) Switch the power supply's "OUTPUT" to ON.

n) Record the voltage value indicated on the voltmeter.

o) Switch the power supply's "OUTPUT" to OFF.

Analysis: Assuming that the internal resistance of the meter is infinite, calculate the theoretical values and compare these to your measured values. Explain any discrepancies and summarize your understanding of the influence of the voltmeter on the measurements.

Laboratory #5:

Problems: Circuit Analysis Methods

Objectives:

1. Review of mesh and nodal analysis.
2. Review of Thévenin's Theorem.
3. Review of the principle of superposition.

Pre-Lab Preparation:

Study the following topics in your textbook, *Principles and Applications of Electrical Engineering* by Giorgio Rizzoni:

- Study nodal analysis with current sources and with voltage sources.
- Study mesh analysis.
- Study Thévenin's equivalent circuit
- Study the principle of superposition.

Background:

Definitions

- A *branch* is any portion of a circuit with two terminals.
- A *node* is the junction of two or more branches in a circuit.
- A *loop* is any closed connection of branches.
- A *mesh* is a loop that does not contain other loops.

Nodal Analysis (from Rizzoni's text):

1. Select the reference node (usually ground).
2. Define the remaining n-1 node voltages as the independent or dependent variables. Each of the *m* voltage sources is associated with a dependent variable. If a node is not connected to a voltage source, then its voltage is treated as an independent variable.
3. Apply KCL at each node labeled as an independent variable, expressing each current in terms of the adjacent node voltages.
4. Solve the linear system of *n-1-m* unknowns.

Mesh Current Analysis (from Rizzoni's text):

1. Define each mesh current consistently. Unknown mesh currents will be always defined in the clockwise direction; known mesh currents (i.e., current sources) will always be defined in the direction of the current source.
2. In a circuit with *n* meshes and *m* current sources, *n-m* independent equations will result. The unknown mesh currents are the *n-m* independent variables.
3. Apply KVL to each mesh containing an unknown mesh current, expressing each voltage in terms of one or more mesh currents.
4. Solve the linear system of *n-m* unknowns.

Superposition Principle (from Rizzoni's text):

In a linear circuit containing N sources, each branch voltage and current is the sum of N voltages and currents, each of which may be computed by setting all but one source equal to zero and solving the circuit containing that single source.

Thévenin's equivalent circuit (from Rizzoni's text):

When viewed from the load, any network composed of ideal voltage and current sources, and of linear resistors, may be represented by an equivalent circuit consisting of an ideal voltage source v_T in series with an equivalent resistance R_T.

Thévenin's equivalent resistance

1. Remove the load.
2. Zero all independent voltage and current sources.
3. Compute the total resistance between load terminals, *with the load removed*. This resistance is equivalent to that which would be encountered by a current source connected to the circuit in place of the load.

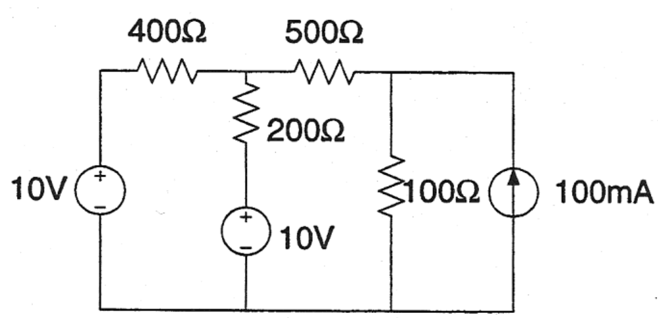
Thévenin voltage

The equivalent Thévenin voltage source is equal to the *open-circuit voltage* present at the load terminals (with the load removed).

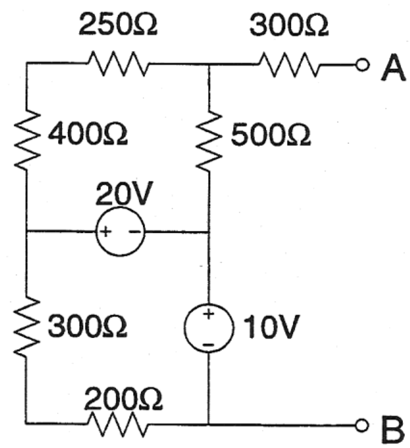
1. Remove the load, leaving the load terminals open-circuited.
2. Define the open-circuit voltage v_{OC} across the open load terminals.
3. Apply any preferred method (e.g., nodal analysis) to solve for v_{OC}.
4. The Thévenin voltage is $v_T = v_{OC}$.

In-Lab Problems: Work the following problems in lab.

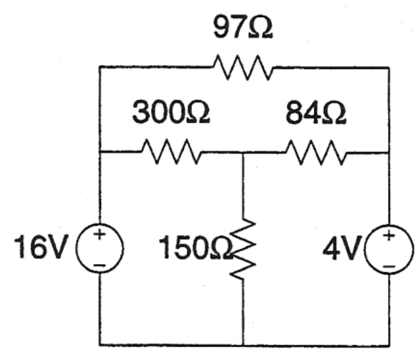
1. In the circuit below, find the current through the 200Ω resistor by:
   a) using mesh analysis
   b) using nodal analysis



2. For the circuit below, find the Thévenin equivalent circuit as seen from terminals A-B.

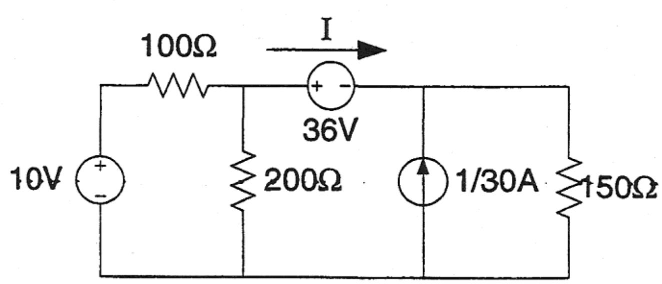


3. Use the principle of superposition to calculate the voltages across all of the resistors in the circuit below.

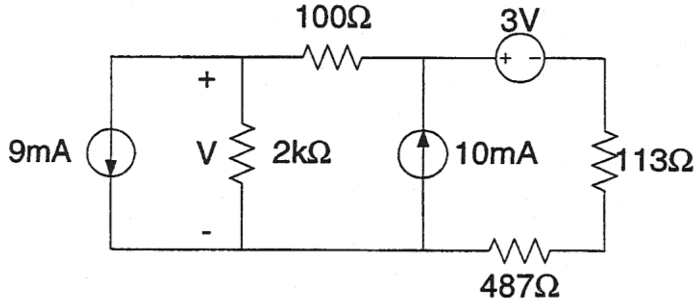


Post- Lab: Work the following problems.

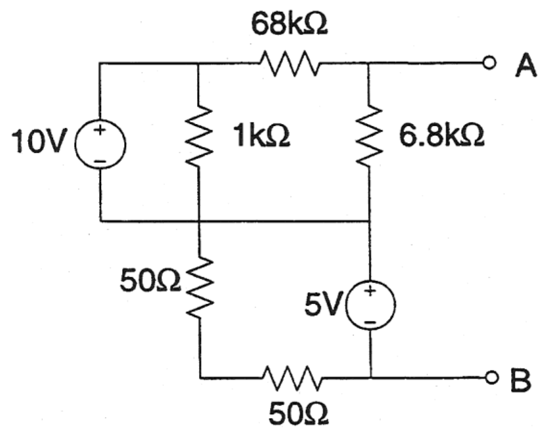
1. Write the mesh equations and determine I in the circuit below.



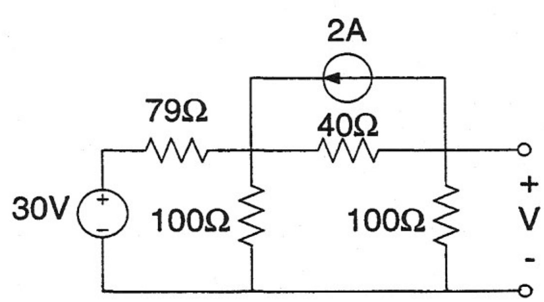
2. Apply nodal analysis to the following circuit to determine the voltage V.



3. For the following circuit below, find the Thévenin equivalent circuit as seen at A-B.



4. Use superposition to find V below.



Laboratory #6:

Network Theorems

Objectives:

The purpose of this assignment is to study certain important network theorems, which are used frequently in circuit analysis, and to improve skills in applying these to practical circuits. Experimental and analytical methods are compared.

Pre-Lab Preparation:

1. Review Thévenin's Theorems for DC circuits and for AC circuits.
2. Review the Superposition Theorem.

Safety Precautions:

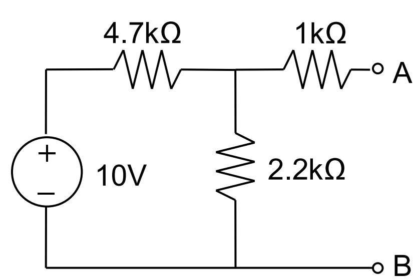
1. Set instruments to the highest scale setting before turning on power, and then adjust the scale setting to produce the most accurate reading.
2. Check your circuit for correctness before you turn on the power. Recheck if you have the slightest doubt.
3. Turn off the power before you make any circuit changes.

Equipment Needed:

- DC power supply
- Resistance decade boxes (2)
- ECE Resistance Load Box (1) or Hampden RLC-100 (1)
- Capacitance decade box
- Digital multimeter
- Function generator

Procedure:

1. **Thévenin's Theorem, DC circuit**.



a) Construct the circuit shown. Measure the voltage across A-B; this is the Thévenin voltage, V_T.

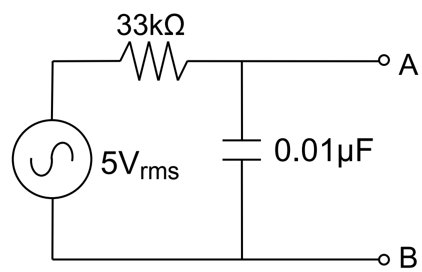
To obtain the 1kΩ, use a Resistance Load Box (either Hampden or ECE) with two switches flipped up and four switches flipped down. [Note: Use a meter to check the resistance to be sure it is correct before connecting to the circuit, since sometimes the internal contacts on the switches get dirty and give high resistance. If that happens, flip the switch a dozen times or so to clean the contacts and measure again.]

b) Set the ammeter scale to its maximum. With the power output off, connect the ammeter from A to B. Turn on the power and measure the short-circuit current, I_{SC}, from A to B, decreasing the meter's scale setting to produce the most accurate reading. You are using the ammeter's very low resistance to short A to B.

c) Compute the Thévenin resistance, R_T , by: $R_T = \frac{V_T}{I_{SC}}$

d) Construct the Thévenin equivalent circuit from this data, and compare it with the original circuit.

2. **Thévenin's Theorem, AC circuit.**

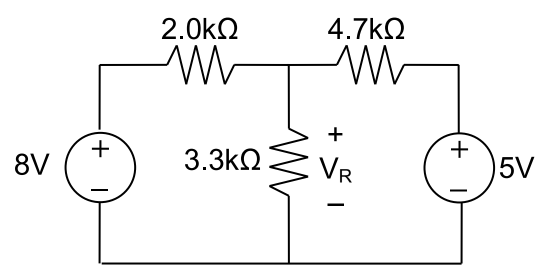


a) Construct the circuit shown. Use the function generator as the AC source, with an output of $5V_{rms}$ and a frequency of 1000Hz. Measure the voltage across A-B; this is only the rms magnitude of V_T.

b) Measure the short circuit current between A-B; this is only the rms magnitude of I_{SC}.

c) Analytically determine the Thévenin equivalent circuit, and compare the experimentally measured values of V_T and I_{SC} to the calculated values.

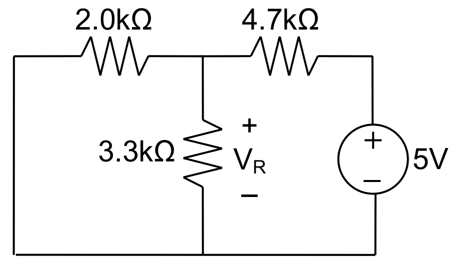
3. **Principle of Superposition**



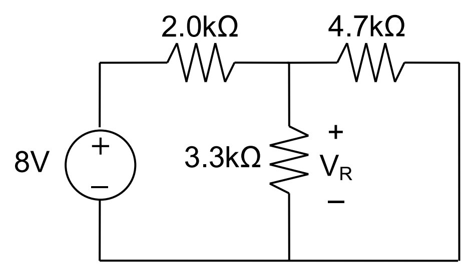
a) For the above circuit, calculate V_R, the voltage drop across the 3.3kΩ resistor, using the principle of superposition.

b) Build the above circuit and measure V_R. [To obtain the 2.0kΩ, use a Resistance Load Box (either Hampden or ECE) with one switch flipped up and the other switches flipped down. Confirm the resistance before proceeding.]

c) Remove the 8V power supply from the original circuit, such that the new circuit becomes the following, and then measure V_R.



d) Remove the 5V power supply from the original circuit such that the new circuit becomes the following, and then measure V_R.



e) Verify that the principle of superposition holds: $V_R = V_R\,(b) + V_R\,(c)$.
Compare the result to your theoretical calculation.

Laboratory #7:

Problems: Phasors

Objectives:

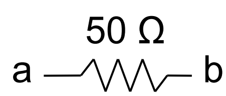
Analyze steady-state AC circuits.
Become familiar with phasors and phasor notation.

In Lab: Work the following problems.

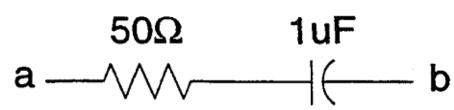
1. Convert the following:
   a) Frequency f = 8 kHz to angular frequency ω.
   b) Angular frequency ω = 0.5 krad/sec to frequency f.
   c) Polar form 10∠-45° to rectangular form.
   d) Rectangular form 3 + j2 to polar form.
   e) Sinusoidal function v(t) = 12 cos(377t) to a phasor.
   f) Phasor 15∠10° to a sinusoidal function.

2. Calculate the impedance Z_{ab} of the following combinations shown below.

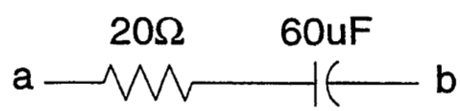
   a)



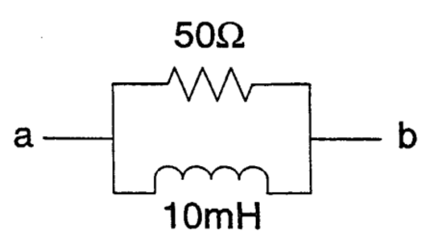
   b) frequency = 1 kHz



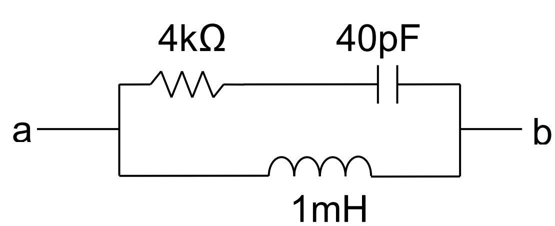
   c) frequency = 20 kHz



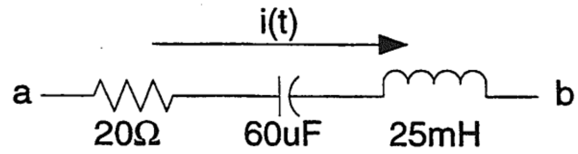
   d) frequency = 500 Hz



   e) frequency = 1 MHz



3. In the circuit below, the current i(t) = 2 cos(377t) A.

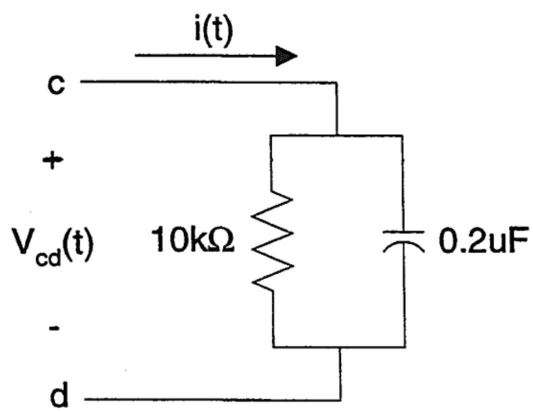


   a) Find the impedance Z_{ab}.

   b) Find the voltage V_{ab}.

   c) Draw a phasor diagram showing the current and the voltage across each element and the V_{ab}).

4. In the circuit below, the voltage $V_{cd}(t) = 25 \cos(377t + 45°)$ V.



   a) Find the admittance of the circuit.

   b) Draw a phasor diagram showing the current in each element, the voltage V_{cd}, and the phasor current I corresponding to i(t).

Laboratory #8:
Oscilloscope

Objectives:
This laboratory exercise introduces the operation and use of the oscilloscope.

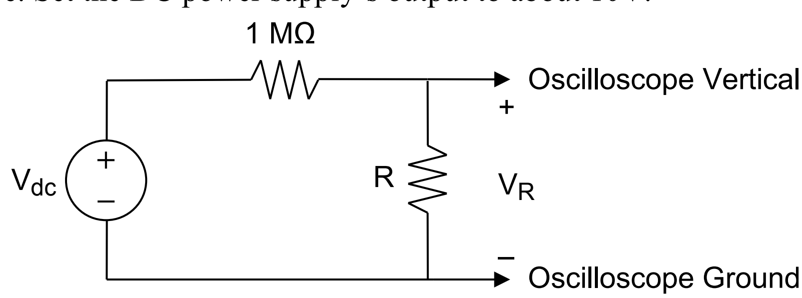
Introduction:
The oscilloscope is an instrument for the analysis of electrical circuits by observing voltage and current waves. It may be used to study wave shape, frequency, phase angle, and time, and to compare the relation between two variables directly on the display screen. Perhaps the greatest advantage of the oscilloscope is its ability to display shapes of both periodic and single-shot waveforms being studied.

Pre-Lab Preparation:
Review Appendix A: *Safety*
Read Appendix B: *Equipment and Instrument Circuits* through "Digital Storage Oscilloscope".
Pay special attention to "Oscilloscope Grounding Errors".
Read Appendix D, *Operating Instructions for a Typical Oscilloscope.*
Read Appendix E, *Tektronix TDS1002B Digital Storage Oscilloscope.*

Equipment Needed:
- AC power supply (Autotransformer)
- DC power supply
- Multimeter, Digital
- Resistance boxes (2)
- Function generator
- Oscilloscope, Dual Beam

Procedure:
1. Frequency Measurement: Adjust the function generator to have an output voltage between 5 and 10 volts. Use the oscilloscope to measure the frequencies generated by the function generator at settings of 50, 500, 5000, and 50,000 Hz, and record the results in your lab notebook. Compare the source's settings with the scope-measured values.

2. Effect of Input Resistance: Construct the following circuit, using the DC power supply for the power source. Set the DC power supply's output to about 10V.



a) Measure V_R with the oscilloscope for the following values of R: 10kΩ, 100kΩ, and 1MΩ.

b) Calculate the theoretical V_R with R_{SCOPE} = infinity (ideal).

c) Compare the measured to the calculated results.

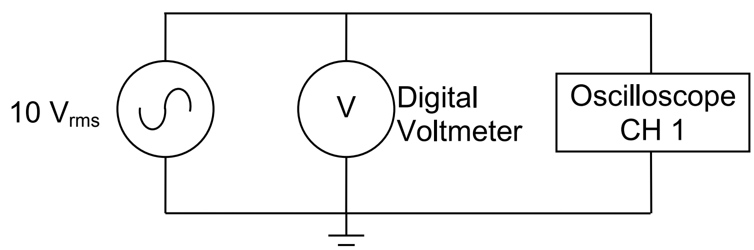
d) Calculate the oscilloscope's DC input resistance. Discuss R_{SCOPE} vs. accuracy of V_R measured on the oscilloscope.

The next steps use the autotransformer (Variac®) as an AC power supply. **When it is time to apply power,** plug the cord into the ISOLATED power outlet on the laboratory bench. **Turn off the power switch when power is not needed, such as when changing the circuit.**

3. Peak vs. RMS Voltage:

   "RMS" stands for "Root Mean Square" and is a way of expressing an AC voltage or current in terms functionally equivalent to a DC voltage or current. For example, 10 volts AC RMS is the AC voltage that would produce the same amount of heat dissipation in a resistor of given value as would 10 volts DC. The RMS value is also known as the "equivalent" or "DC equivalent" value of an AC voltage or current. The lab's digital multimeters (DMM) display the true RMS values of measured voltage and current, but to see what the actual voltage signal looks like, we turn to the oscilloscope.

   Set up the following circuit:

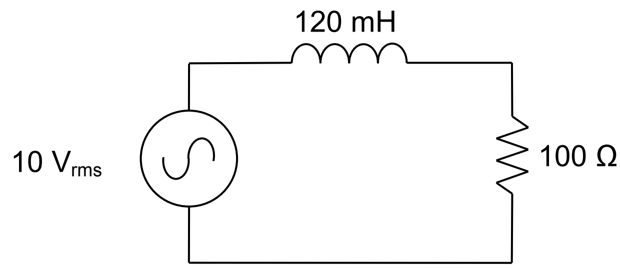


   With the autotransformer turned to zero, turn on its power switch. Gradually increase the output voltage until the digital AC voltmeter indicates the output is 10 V. Record the exact value. Observe the waveform on the oscilloscope and compare the DMM reading with the peak voltage (that is, ½ the peak-to-peak voltage) measured with the oscilloscope. For a sine wave, the peak voltage, $V_{p,}$ as seen on the oscilloscope, should be $\sqrt{2}$ times the voltmeter reading, V_{rms}:

$$V_p = \sqrt{2}\,V_{rms} \qquad \text{and} \qquad V_{p-p} = 2\sqrt{2}\,V_{rms}$$

   On the oscilloscope, set up an automatic measurement for the RMS voltage. (See Appendix E. MEASURE | CH 1 | Cyc RMS.) Compare the values for V_{rms} reported by the DMM and the oscilloscope.

4. Phase Shift through an inductor: Set up the following circuit, using the autotransformer (Variac®) as an AC power supply. Do not turn on the power until part 4b. The 120 mH inductor is a large, heavy, coaxially wound pair of coils (36 mH and 28 mH), which, because of their construction, when connected in series yield 120 mH inductance. You will need to connect a jumper from jack 2 to jack 3, then use jacks 1 and 4 for the connections to the 120 mH coil.

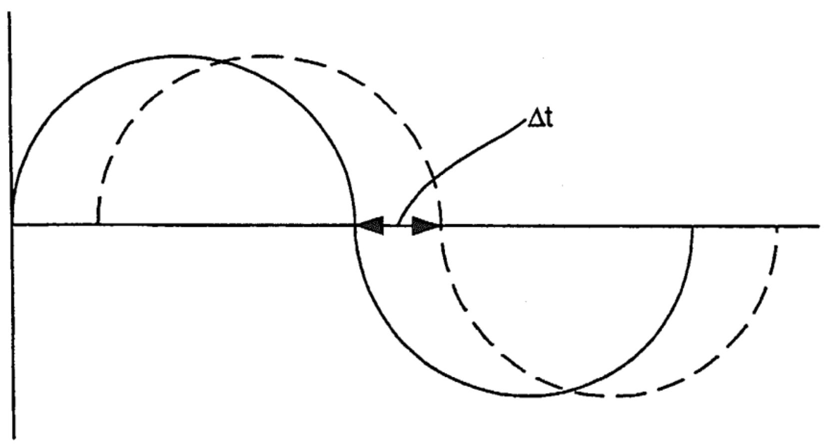


a) Estimate the worst-case RMS current that might pass through the resistor and the power dissipated in the resistor by assuming the coil is replaced by a shorting wire. The low-power resistor decade box has a ½-amp fuse, and the resistors are rated for ½ Watt. Are such ratings adequate for this circuit? If not, be sure to use the Power Resistor decade box for this circuit.

b) The 60 Hz AC voltage is approximately 10 V_{rms}. Measure the input voltage on CHANNEL 1 of the oscilloscope and compare that to the voltage drop measured across the 100Ω resistance on CHANNEL 2. What is the phase shift of the voltage waveform? The phase shift φ can be calculated in degrees by the following formula:

$$\varphi = \Delta t \cdot f \cdot 360°$$

where φ is the phase shift, f is the frequency, and Δt is the time difference between the two waveforms.



Laboratory #9:

Problems: AC Power Calculations

Objectives:

Review power in AC circuits, including power factors.

In Lab: Work the following problems

1. What is the real power with a current and voltage as follows:

$$I(t) = 2\cos(\omega t + \pi/6)\ \text{A}$$
$$V(t) = 8\cos(\omega t)\ \text{V}$$

2. An unknown impedance Z is connected across a 380 V, 60 Hz source. This causes a current of 5A to flow and 1500 W is consumed.

   Determine the following:
   a. Real Power (kW)
   b. Reactive Power (kvar)
   c. Apparent Power (kVA)
   d. Power Factor
   e. The impedance Z in polar and rectangular form

3. An industrial load consists of the following:

   - A 200 hp motor loaded to 100-hp: efficiency = 0.82, pf = 0.6 lagging
   - A 350 hp motor drawing 80 kW: pf = 0.8 lagging
   - A 500 hp motor drawing 47 kW: pf = 0.7 leading
   - A 70 kW lighting load

   Determine for the overall load:
   a. Real Power (kW)
   b. Reactive Power (kvar)
   c. Apparent Power (kVA)
   d. Power Factor

4. Three heaters and a three-phase y-connected motor are connected to a y-connected source of 208 v line-to-line. Each heater draws 10A at unity power factor (pf = 1), and each phase of the motor draws 2 A at 0.85 power factor.

   a. Find the total line current.
   b. Find the total power consumed.
   c. Determine the motor's inductive reactance per phase if the motor's R and X are considered to be in series.

Laboratory #10:

AC Measurements

Objectives:

This exercise introduces the operation and use of the AC wattmeter, as well as single-phase series circuits containing resistance, inductance, and capacitance. It uses the oscilloscope to measure the phase shift of current through reactive circuits.

Pre-Lab:

1. Study Appendix B regarding Wattmeter, especially *"Three-Phase Power Measurements"*.
2. Study Appendix D information regarding using the oscilloscope to measure phase shift.
3. Study textbook regarding calculation of *impedance* and *power factor* for reactive loads.
4. Review *phasor diagrams* for voltage and current.

Safety Precautions:

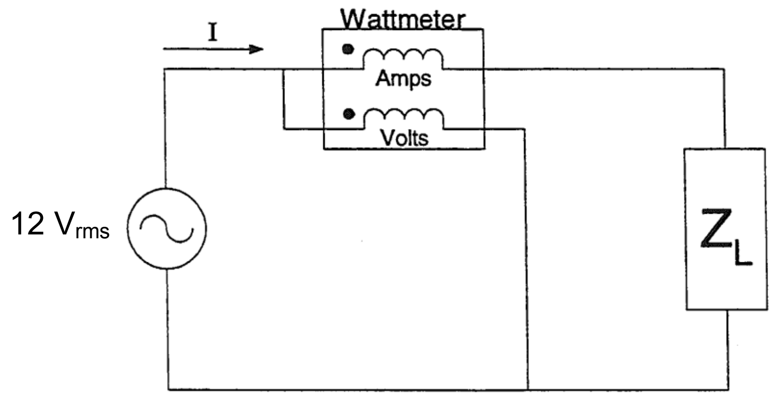
1. Care must be used in working with the autotransformer (Variac®) power supply used in this lab. Avoid touching conducting portions of a circuit when power is on. In particular, never touch two separate portions of such a circuit with both hands.
2. The ± polarity terminals of the wattmeter's voltage and current coils are usually connected together.
3. A **voltmeter** or wattmeter's voltage coil must be connected **in parallel** with the load or source being measured.
4. An **ammeter** or wattmeter's current coil must be connected **in series** with the load.

Equipment Needed:

- AC voltmeters
- AC ammeter
- Wattmeter
- Power decade resistor box
- 120 mH inductor
- 40 µF capacitor
- Autotransformer power supply

Procedure:

Connect the following AC circuit.



Change the load Z_L, as follows:

1. A resistor of R = 25Ω
2. An inductor of L = 120 mH
3. A capacitor of C = 40 μF
4. R and L in series
5. R and C in series
6. R, L, and C in series

Measurements

For each of the loads listed above:

a) Measure the wattmeter reading.
b) Measure the total current.
c) Measure the voltage drop across each element.

For loads 4-6 also measure the current *phase shift*. This is done by using the oscilloscope to measure the voltage waveform shift across the resistor on Channel 2 versus the source voltage on Channel 1. The resistor must be the last element in the series combination for the measurement to work properly.

Laboratory Notebook:

1. For each step compute the impedance and power factor for the load. Tabulate the measured and computed data.
2. Construct a phasor diagram, to scale, for each of the steps. Show all currents and voltages on each diagram in their correct relative orientations. In parts 4-6 show that the line voltage is the **phasor sum** of the voltage drops across the elements of the circuit.

Laboratory #11:

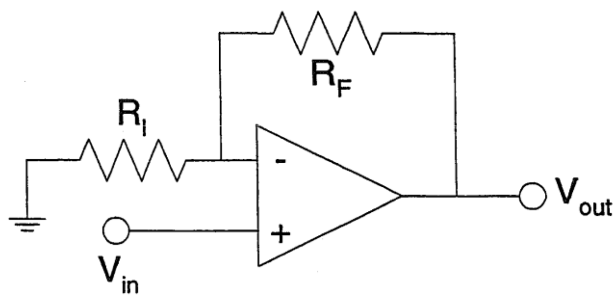
Problems: Operational Amplifiers and Digital Logic

Objectives:

1. Better understanding of networks of analog and digital devices.
2. Familiarity with amplification and digital operation of some interface devices for microprocessors.

In Lab: Work the following problems.

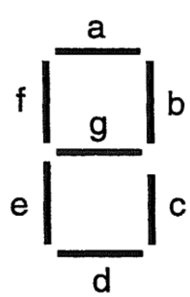
1. For the following operational amplifier circuit,



   a) Find V_{out} in terms of R_I, R_F, and V_{in}.

   b) Given $R_I = 10\Omega$, $R_F = 20k\Omega$, and $V_{in} = 3V$, what is V_{out}?

2. Consider a calculator that does computations in 8421 BCD and presents the result as decimal digits in the familiar seven-segment LED display shown below. The four-input, seven-output display decoder takes a BCD word ($B_3B_2B_1B_0$) and lights the appropriate segments of the display. Synthesize the function for one of the outputs assigned by the instructor.



Hint:

(1) For the desired output segment (a-g), make a truth table with the combinations of inputs B_3, B_2, B_1, and B_0 representing the digits 0 – 9.

(2) From the truth table, write a logical expression for the desired output segment in terms of B_3, B_2, B_1, and B_0.

(3) From the logical expression, obtain a logic diagram producing the desired output form the inputs B_3, B_2, B_1, and B_0.

Laboratory #12:

Digital Logic Circuits

Objectives:

To obtain experience with digital circuits. Implementation of BCD to seven segment decoder.

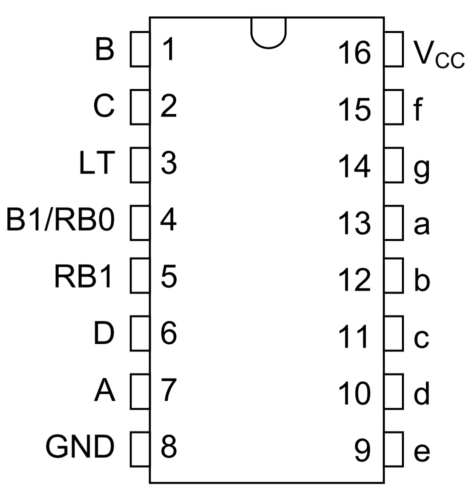
Equipment Needed:

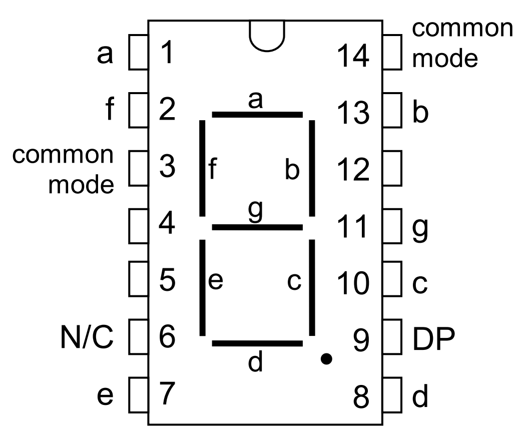
- 7447 BCD to seven segment decoder.
- Digi-trainer designer board.
- One 330 ohm resistor chip or seven 330 ohm resistors.
- Seven segment display.

Procedure:

1. **DECODER:** Connect the inputs of the decoder to the four data switches on the trainer. Use the A input of the decoder as the least significant bit.
2. **DECODER:** Make sure the V_{CC} input is connected to +5V. Also, make sure the GND input is connected to ground, and the LT input must be tied high.
3. Next **connect the a-g outputs** of the decoder through the resistors to the corresponding input on the 7-segment display. Also, connect pin 14 of the 7-segment display to +5V. **Caution!!! Do not connect any inputs of the 7-segment display to ground.**
4. Demonstrate to your instructor that the display cycles through the proper count using the corresponding inputs on the trainer.

SN5446A, SN5447A, SN54LS47, SN5448, SN54LS48 … J Package SN7446A, SN7447A, SN7448 … N Package SN74LS47, SN74LS48 … D or N Package (TOP VIEW)	DISPLAY 7-SEGMENT LED (TOP VIEW)





DP = Decimal Point

Appendix A

Safety

Electricity, when improperly used, is very dangerous to people and to equipment. This is especially true:

- in industrial environments, where large amounts of power are available, and high voltages are present;
- in environments where people are especially susceptible to electric shock, for example, where high-voltage systems must be maintained while in operation, or in hospitals where electronic equipment is used to test or control physiological functions; and
- in experimental or teaching laboratory environments, where inexperienced personnel may use electrical equipment in experimental or nonstandard configurations.

Engineers play a vital role in eliminating or alleviating the danger in all three environments. Where standard equipment is used in standard configurations, governmental agencies and insurance underwriters impose strict laws and regulations on the operation and use of electrical equipment, including switchgear, power lines, safety devices, etc. As a result, corporations and other organizations in turn impose strict rules and methods of operation on their employees and contractors. Engineers who are involved in using electrical equipment, in supervising others who use it, and in designing such systems, have a great responsibility to learn safety rules and practices, to observe them, and to see that a safe environment is maintained for those they supervise. In any working environment there is always pressure to "get the job done" and take short cuts. The engineer, as one who is capable of recognizing hazardous conditions, is in a responsible position both as an engineer and as a supervisor or manager and must maintain conditions to protect personnel and avoid damage to equipment.

Because of their non-standard activities, experimental laboratories are exempt from many of these rules and regulations. This puts more responsibility on the engineer in this environment to know and enforce the safest working procedures.

The learning necessary to develop the knowledge, the habit-forming experience to work safely around electrical equipment, and the ability to design safe electrical equipment begins with the first student laboratory experience and continues throughout life. This includes learning the types of electrical injuries and damage, the physiology of electrical injuries, ways to prevent such injuries, and steps to take when accidents occur.

Physiology of Electrical Injuries

Four main types of electrical injuries include the following:

- electric shock;
- electrical burns;
- injuries resulting from falls caused by electric shock;
- "sunburned" eyes from looking at a bright electric arc, such as that of an arc-welder. While this is very painful and may cause loss of work time, it is usually temporary.

Other injuries may be indirectly caused by electrical accidents, such as burns from exploding oil-immersed switchgear or transformers.

Although electric shock is normally associated with contact with high-voltage alternating current (AC), under some circumstances death can occur from voltages substantially less than the nominal 120 volts AC found in residential systems. Electric shock is caused by an electric current passing through a part of the body. The human body normally has a high resistance to electric currents, so a high voltage is usually required to cause lethal currents. This resistance is almost all at the skin, however, and when the skin is wet its resistance is much lower. When a person is hot and sweaty or is standing in water, contact with 120 volts or less may well cause a fatal shock.

Electric shock is not a single phenomenon but is a disturbance of the nerves by an electric current. A current through a part of the body such as the arm or leg will cause pain and muscle contraction. If a victim receives an electric shock from grasping a live conductor, a current of greater than 15 to 30 milliamperes through the arm will cause muscle contractions so severe that the victim cannot let go. Similar currents through leg muscles may cause sudden contractions that make the victim jump or fall, possibly resulting in further injuries or death. Prolonged contact of more than a minute or so may cause chest muscles to contract, preventing breathing and resulting in suffocation or brain damage from lack of oxygen.

Death by electric shock is most often attributed to **ventricular fibrillation**, which is an uncontrolled twitching or beating of the heart that produces no pumping action and therefore no blood circulation. Unless corrective action is taken, death follows quickly from lack of oxygen to the brain. While the amount of current that will cause fibrillation depends on several variables, 0.5 to 5 amperes through the body will normally cause the very small current (**approximately 1 mA**) through the heart that is sufficient to cause fibrillation in most people. Larger currents than this through the heart cause contraction or clamping of the heart muscle, resulting in death unless corrective action is taken.

Electric burns may be caused by electric currents flowing in or near parts of the body. Such bums are similar to bums from ordinary heat sources, except that those caused by high-frequency currents are generally deeper and take longer to heal the other bums. Electrocution will often leave severe burns at the points where the current entered and left the body.

Source of Electric Shock

Since electric shock is caused by an electric current flowing through a part of the body, the problem may be prevented by not allowing the body to become part of any electric circuit. For this reason, one needs to understand how a person might inadvertently become part of an electric circuit, and the most likely way is through accidental grounding.

Electric circuits may be classified as either grounded or ungrounded. Grounded circuits are safer for most conditions, since the voltages at all points in the circuit are known and it is easier to protect against fault conditions. The disadvantage of a grounded circuit is that a person standing on a non-insulated floor can receive a shock by touching only one conductor.

Almost all electric power generation, transmission, and distribution systems are grounded to protect people and equipment against fault conditions caused by windstorms, lightning, etc.

Residential, commercial, and industrial systems, such as lighting and heating, are always grounded for greater safety. Communication and computer systems, as well as general electronic equipment (e.g., DC power supplies, oscilloscopes, oscillators, and digital multimeters) are grounded for safety and to prevent or reduce electrical noise, crosstalk, and static.

Ungrounded circuits are used in systems where isolation from other systems is necessary, where low voltages and low power are used, and where obtaining a suitable ground connection is difficult or impractical. In an ungrounded circuit, contact with two points in the circuit that are at different potentials is required to produce a shock. The hazard is that, with no specific ground in such circuits, a hidden fault can cause some random point to be grounded, in which case, touching a supposedly safe conductor while standing on the ground could result in an electric shock.

Protecting People and Equipment in the Laboratory

Strict adherence to several common-sense rules, summarized below, can prevent electric shock to individuals and damage to laboratory equipment.

Protecting People

a) When building a circuit, connect the power source last, while the power is OFF.
b) Before changing a circuit, turn off or disconnect the power if possible.
c) Never work alone where the potential of electric shock exists.
d) When changing an energized connection, use only one hand. A common practice is to put one hand behind your back when touching a circuit that is possibly energized. Never touch two points in a circuit that are at different potentials.
e) Know and check that the circuit and connections are correct before applying power.
f) Avoid touching capacitors that may have a residual charge. Stored energy in a capacitor can cause severe shock even after a long period of time.
g) Insulate yourself from ground by standing on insulating mats where appropriate.

The above rules and the additional rules given below also serve to protect instruments and other circuits from damage.

Protecting Equipment

a) Set the scales of measurement instrument to the highest range before applying power.
b) When using an oscilloscope, do not leave a bright spot or trace on the screen for long periods of time. Doing so can burn the image into the screen.
c) Be sure instrument grounds are connected properly. Avoid ground loops and accidental grounding of "hot" leads.
d) Check polarity markings and connections of instruments carefully before connecting power.
e) Never connect an ammeter across a voltage source, but only in series with a load.

f) Do not exceed the voltage or current ratings of circuit elements or instruments. This particularly applies to wattmeters, since the current or voltage rating may be exceeded with the needle still reading on the scale.

g) Be sure any fuses and circuit breakers are of suitable value.

When connecting electrical elements to make up a network in the laboratory, it easy to lose track of various points in the network and accidentally connect a wire to the wrong place. One procedure to help avoid this problem is to connect first the main series loop of the circuit, then go back and add the elements in parallel.

Types of Equipment Damage

Excessive currents and voltages can damage instruments and other circuit elements. A large over-current for a short time or a smaller over-current for a longer time will cause overheating, resulting in insulation scorching and equipment failure.

Blown fuses are the most common equipment failure mode in this laboratory. The principal causes for these failures include:

- incorrectly wired circuits;
- accidental shorts;
- switching resistance settings while power is applied to the circuit;
- changing the circuit while power is applied;
- using the wrong scale on a meter;
- connecting an ammeter across a voltage source;
- using a low-power resistor box (limit ½ amp) when high power is required;
- turning on an autotransformer at too high a setting.

All of these causes are the result of carelessness by the experimenter.

Some type of insulating material, such as paper, cloth, plastic, or ceramic, separates conductors that are at different potentials in electrical devices. The voltage difference that this material can withstand is determined by design (type, thickness, moisture content, temperature, etc.). Exceeding the voltage rating of a device by an appreciable amount can cause arcing or corona, resulting insulation breakdown, and failure.

Some electrical devices can also be damaged mechanically by excessive currents. An example is the D'Arsonval meter, the indicator in most analog metering instruments. A large pulse of over-current will provide mechanical torque that can cause the needle to wrap around the pin at the top of the scale, thereby causing permanent damage even though the current may not have been on long enough to cause failure due to overheating.

After-Accident Action

Since accidents do happen despite efforts to prevent them, preparation for an accident can save valuable time and lives. This preparation should include immediate availability of first aid material suitable for minor injuries or for injuries that are likely because of the nature of the work. Knowledge of how to obtain trained assistance such as Emergency Medical Service (EMS) should be readily available for everyone.

Treating victims for electrical shock includes four basic steps, shown below, that should be taken immediately. Step two requires qualification in CPR and step three requires knowledge of mouth-to-mouth resuscitation. Everyone who works around voltages that can cause dangerous electrical shock should take advantage of the many opportunities available to become qualified in CPR and artificial respiration.

Immediate Steps After Electric Shock

1. Shut off all power and remove victim from the electric circuit. If the power cannot be shut off immediately, use an insulator of some sort, such as a wooden pole, to remove the victim from the circuit. Attempts to pull the victim from the circuit with your hands will almost always result in your joining the victim in electric shock.
2. If you are qualified in CPR, check for ventricular fibrillation or cardiac arrest. If either is detected, external cardiac massage should be started at once. Whether you are qualified in CPR or not, notify the EMS and the ECE Department at once, using the telephone numbers listed below.
3. Check for respiratory failure and take appropriate action. This may have resulted from physical paralysis of respiratory muscles or from a head injury. Sometimes many hours pass before normal respiration returns. Artificial respiration should be continued until trained EMS assistance arrives.
4. Check for and treat other injuries such as fractures from a fall or burns from the current's entry and exit sites.

Investigations are always made after accidents. As an engineer, you will be involved as a part of the investigating team or in providing information to an investigator. Information obtained and notes written immediately after the emergency will aid the investigation and assist in preventing future accidents of a similar nature.

EMERGENCY NUMBERS

All Emergencies	911
Student Health Center	656-2233
ECE Department Office	656-5650
Clemson Police	656-2222

References

1. W. F. Cooper, *Electrical Safety Engineering*. Newnes-Butterworth, London-Boston, 1978.
2. W. H. Buchsbaum and B. Goldsmith, *Electrical Safety in the Hospital*, Medical Economics Company, Oradell, NJ, 1975.
3. J. G. Webster, Editor, *Medical Instrumentation Application and Design*. Houghton Mifflin Company, Boston, 1978.

Appendix B

Equipment and Instrument Circuits

Electrical engineers measure and use a wide variety of electrical circuit variables, such as voltage, current, frequency, power, and energy, as well as electrical circuit parameters, such as resistance, capacitance, and inductance. Many instruments can be used to make such measurements, but the proper use of the instruments and interpretation of the measurements depend on a fundamental understanding of how the instruments work, their capabilities, and their limitations.

This appendix provides a brief overview of the fundamentals of the electrical equipment and instruments that you will use in this laboratory course. As you encounter more and varied types of electrical equipment and instruments in this and subsequent courses, you will find several books, in addition to your textbook, useful in developing your understanding and measurement skills. In addition, many commercial instrument manufacturers publish handbooks and application notes that provide more information on specific measurement techniques.

AC Electrical Sources

In this laboratory you will use several different types of sources for electrical voltage and current. All of those sources and all of the measurement equipment, except for a few battery-powered devices, get their power from electrical outlets on the workbench. The workbench is equipped with two duplex outlets (receptacles with two outlets) for 110 V power, but these outlets are not the same. **One duplex outlet provides NON-ISOLATED**, 120V, 60 Hz electrical power, such as you would find in your home. All of the power strips along the back of the bench also use this same power. **The second duplex outlet provides ISOLATED**, 120V, 60 Hz electrical power; the power goes through an isolation transformer, so its voltage is floating relative to earth ground. The isolation transformer has a turns ratio of one and is mounted behind the lab bench. Both sets of outlets are powered through one GFCI (Ground Fault Circuit Interrupter; a.k.a., GFI – Ground Fault Interrupter) circuit breaker in the bench. **The third power source** on the bench uses a separate circuit breaker that provides **3-phase, 208V, 60 Hz** power via banana-plug jacks.

Figure B.1 shows an equivalent circuit for the workbench's NON-ISOLATED 120 V, 60 Hz supply receptacle. The neutral (N) line carries current from the load back to the source and is connected to ground (G) at the source for purposes of personnel and equipment safety. With respect to ground, the high or "hot" (H) line varies sinusoidally at a potential that ranges from a negative maximum of about -169 Volts to a positive maximum of about +169 Volts.

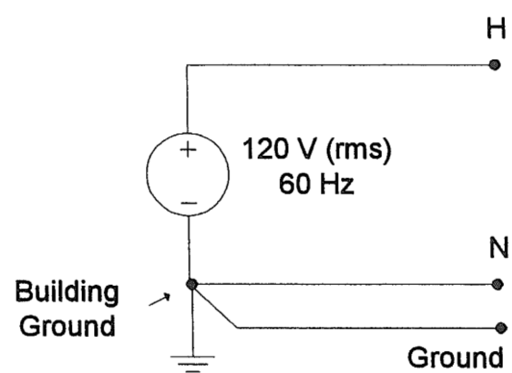


Figure B.1: Equivalent circuit for non-isolated 120 V (rms), 60 Hz power supply.

Why have a separate ground and a neutral wire? Suppose we had the scenario shown in Figure B.2, in which an electrical load is only supplied by two wires, and the supply voltage is grounded at the source. The ungrounded “hot” wire is colored black and the grounded return wire is colored white. The load is contained in a metal case. Now, consider what could happen if the ungrounded black wire came loose and made contact with the metal case. It then becomes possible that a person in contact with the ground, by contact with a metal pipe or wet concrete floor, could complete an electrical circuit, being electrocuted in the process. To prevent this from occurring, we use a third wire, often colored green, that is connected directly to ground. This is the green wire we see on some three-to-two prong adapters. By connecting this green wire to the metal case and to the building ground, we force the circuit breaker to blow if the black wire should make contact with the case, completing the circuit through the wires, instead of through people. Grounding equipment enclosures through the use of the ground wire is an important safeguard when working with high voltages.

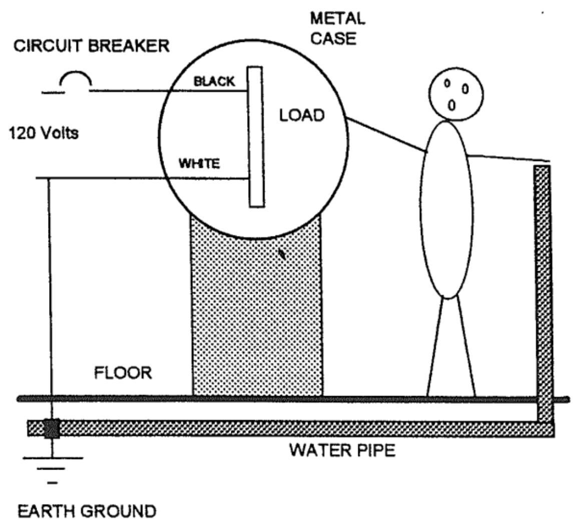


Figure B.2: Possible electrocution scenario.

Grounding and Electrical Noise

Another function of proper grounding is to eliminate or control electrical “noise”. Noise in electric systems arises from many sources, such as thermal electron movement in hot cathodes, currents induced by nearby conductors, and high-frequency electromagnetic emissions from radio or television transmitters. For most of the laboratory exercises, operation at levels of 10 or 20 volts, and at frequencies from DC to a few hundred Hertz offer few noise problems; however, as voltage or current levels are decreased, and as frequency levels are increased, extraneous signals may interfere with the desired signals and must be eliminated or reduced. This is done by grounding all items of equipment with a chassis ground and by using a coaxial conductor between equipment, as well as by eliminating the source of noise when practical.

The coaxial conductor is one in which the active or “hot” lead is enclosed within an outer metallic shield conductor that is separated by a layer of insulating material. Another layer of insulation usually surrounds the shield. The outer shield conductor is usually connected to ground. The standard laboratory connection between equipment and coaxial conductors is the “BNC” connector, a twist-lock connector that is easy to use and makes a good connection. Reasonable care must be taken to avoid breaking the connection between the BNC connector and the wires of the active conductor or the ground shield in what is commonly called a “coax cable”.

Oscilloscope Grounding Errors

The purpose of the ISOLATED supply on your workbench is to enable you to ground points in your test circuits in order to make measurements without drawing a large current through the ground connection and tripping a circuit breaker or "zapping" an instrument. Note that for personal safety, the oscilloscope ("scope") should be plugged into a NON-ISOLATED outlet. Consider now the scenario shown in Figure B.5, in which an oscilloscope is used to measure a voltage on a circuit also plugged into the NON-ISOLATED outlet. The probe ground on the oscilloscope is connected to the case ground and to the ground lead on the scope's power plug. This is the same ground lead that is connected to the neutral lead at the lab circuit breaker box. If we attempt to make a differential voltage measurement as shown in the figure, then a number of bad things can happen. First, the ground probe being connected to the circuit will create a ground path that will effectively short out the 200 Ω resistor, giving us an erroneous measurement. Second, the scope ground lead becomes part of the path that carries current, which in this example is 24 amps. This will at least cause a circuit breaker to trip and possibly blow out the scope lead. This is one reason why some of the scope leads you pull off the rack don't work properly.

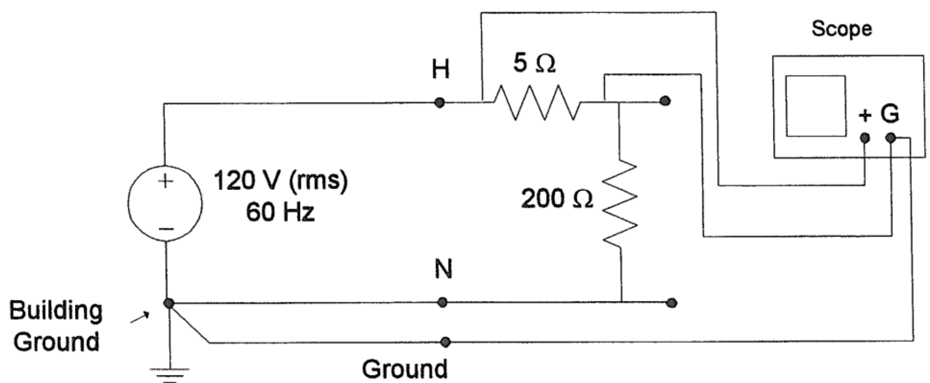


Figure B.5: Illustration of improper circuit measurement.

If instead we use an ISOLATED supply for the circuit, as illustrated in Figure B.6, then we won't have this problem. Since the resistor circuit is electrically isolated from the supply ground, the addition of the scope's ground lead has no impact. Note that if you use the isolation transformer to "float" your circuit, then you must make sure to use the scope ground lead to take the measurement. Otherwise you will get a measurement that will not make any sense.

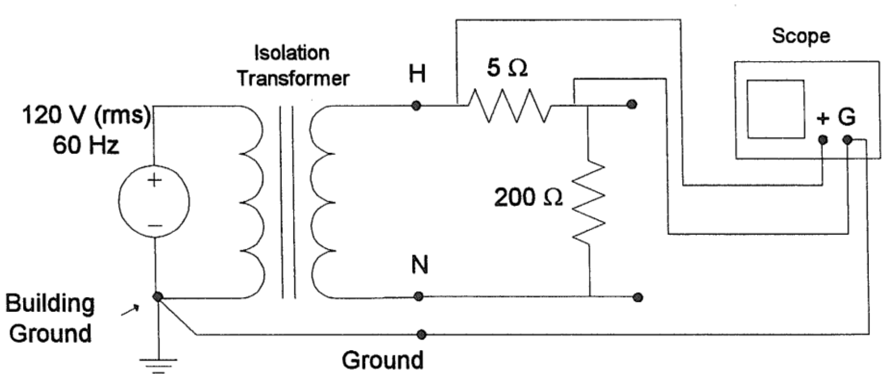


Figure B.6: Illustration of valid circuit measurement due to the use of isolation transformer.

Figure B.7 illustrates another thing you will need to watch out for when taking measurements using a scope. Both Channel 1 and Channel 2 on the scope have ground leads, and those leads are physically connected together at the scope itself. What would happen if you tried to measure both resistor voltages using the set-up shown here? The grounds on Channel 1 and Channel 2 are at the same potential and so would short the 200 Ω resistor. This would again cause a large ground loop current to flow through the scope's ground leads, causing a circuit breaker to trip, a fuse to blow if an autotransformer were also included in the circuit, and/or damage to the scope's ground leads. If you use both channels on the scope, you must make sure that the measurements will be taken with both channel grounds at the same reference point. Slight differences between probe ground leads that are supposed to be at the same potential will cause ground loop currents to flow and perhaps cause errors in your results and damage to equipment.

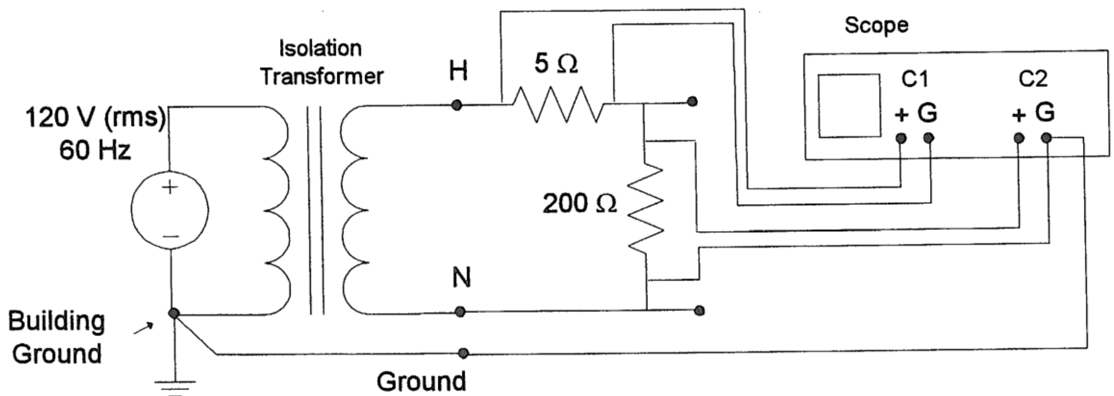


Figure B.7 Illustration of invalid circuit measurements when using isolation transformer.

Finally, another common mistake is made in the use of the scope's ground connections. When taking scope measurements on an isolated circuit, you must use the probe's ground clip from one channel in order for the measurements to make sense. At first, it might seem that you would not get any measurements at all if the ground connection on the probe were missing, as in Figure B.8. However, there is always a small amount of stray capacitance in a circuit that will tie the circuit under test back to the measuring device. Unfortunately the impedance of this ground tie is large and it will give you unpredictable and erroneous measurements.

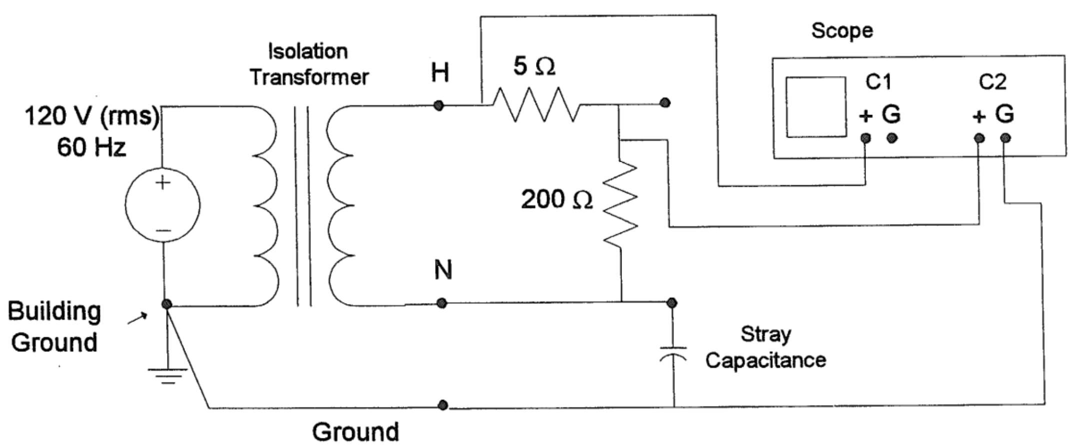


Figure B.8: Common problem with using isolation transformer.

One might be tempted to "float" the oscilloscope instead of the circuit being tested. This could be accomplished by removing the ground prong on the scope's power plug. However, doing this would create a safety hazard, since the oscilloscope's case would be at the same potential as whatever is connected to the scope probe's ground. It would then be **possible for an individual simultaneously touching the scope and an earth connection to be electrocuted.**

The 3-phase 208 V, 60 Hz, non-isolated supply

Figure B.9 shows the equivalent circuit for the 3-phase, 208 V (rms), 60 Hz, non-isolated supply, which is also available at terminals on your workbench. This supply is grounded at the source so that the potential of each of the 3 phases, the "A", "B", and "C" phase is 120 V with respect to ground, but the phase-to-phase voltage (A to B, B to C, C to A) is 208 Volts due to the 120° difference between each of the phases.

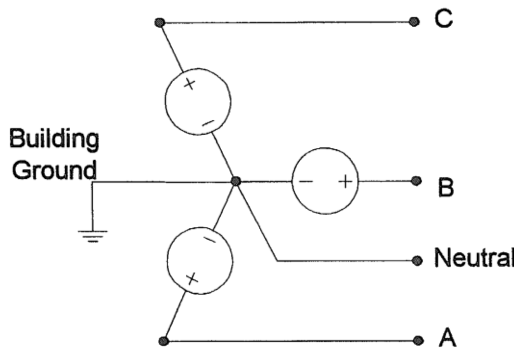


Figure B.9 Equivalent circuit for non-isolated 208 V (rms), 60 Hz 3-phase power supply.

Autotransformer

One electrical source that you will often use for experiments will be a variable transformer (autotransformer) plugged into the ISOLATED 120 V (rms), 60 Hz, electrical outlet on the workbench. This combination is represented by the equivalent circuit shown in Figure B.4. The isolation transformer itself is a transformer with a turns ratio of one. It is mounted behind the lab bench.

The autotransformer, also referred to by the brand name Variac, enables one to select a portion of the input voltage to use in a particular experiment. The autotransformer has a single winding that is connected to a voltage source. By adjusting a slider mechanism (called a wiper), one can vary the number of turns on the load side of the circuit, hence giving the user control over the magnitude of the load-side voltage, from 0 V up to 140 V.

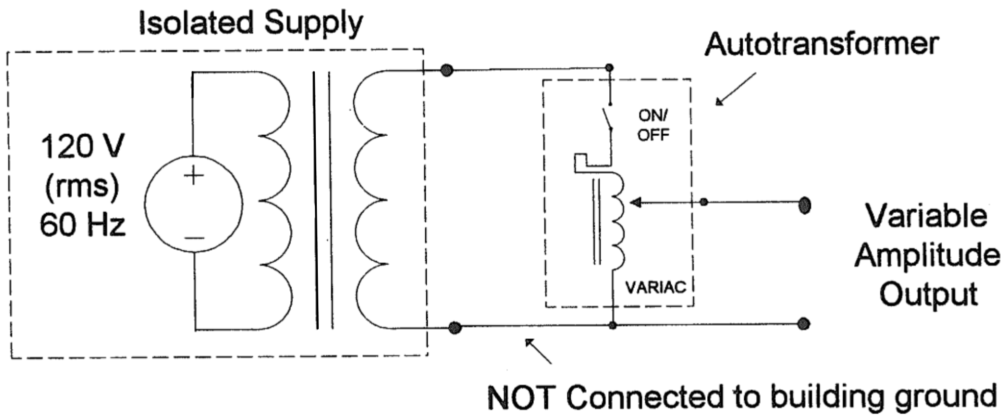


Figure B.4: Equivalent circuit for isolated 120 V, 60 Hz supply with the output voltage level controlled by an autotransformer.

Function Generator

A *function generator* is an electronic device that is capable of producing time varying voltages of sinusoidal, rectangular ("square"), or triangular shaped waveforms over a broad frequency range (1 Hz - 5 MHz). The frequency can be selected by a combination of push buttons for the frequency range and a continuously variable dial to adjust the signal within the selected range. The amplitude of the output voltage can be controlled from the front panel of the instrument. In addition, a DC component can be added to the output wave by controls on the front panel. For a particular combination of frequency, AC amplitude, and DC level settings, the equivalent circuit for this generator can be represented as shown in Figure B.3, where the internal impedance of the function generator is represented by a 50 Ω resistor.

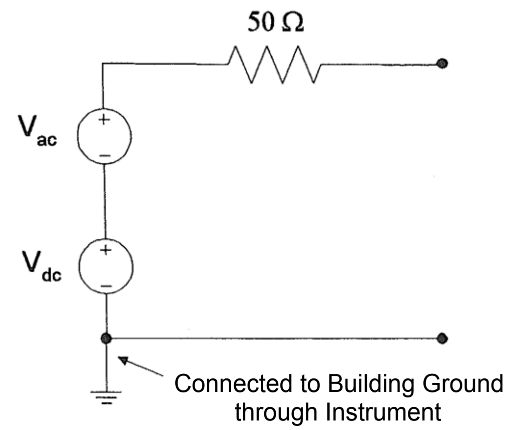


Figure B.3: Equivalent circuit for function generator.

Measurement of Current, Voltage, and Power

The basic electrical circuit variables of current and voltage are measured with ammeters (for current) and voltmeters (for voltage). These instruments may use either analog (continuous) or digital (numerical) indicators ("readouts") to report the measurement results.

Analog Meter Instruments

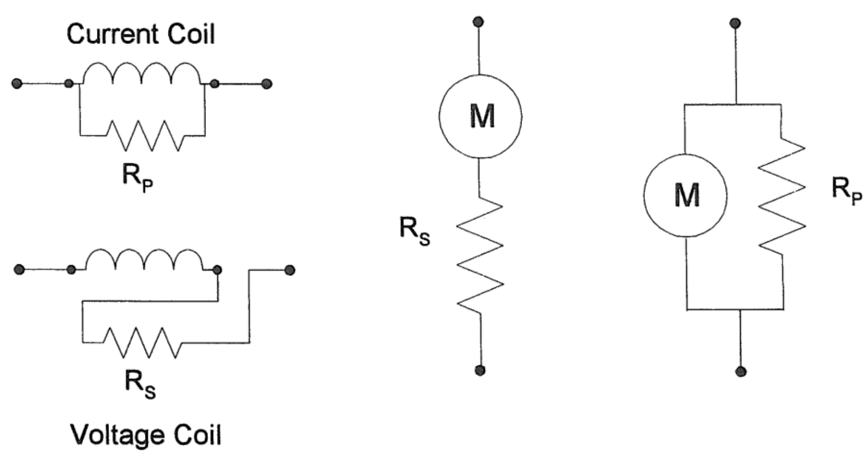
The analog meter instruments were developed early in the history of electrical science and technology. Most are based on the **d'Arsonval galvanometer** movement. A brief description of this meter movement and its use in ammeters and voltmeters is given in the textbook *Electric Circuits* by J. W. Nilsson and S.A. Riedel [B-1], on pages 78 through 80 in the Seventh Edition. More information is available in Reference B-2.

In the d'Arsonval galvanometer, current through a coil of fine wire develops a magnetic field that opposes the field of a permanent magnet, and so rotates a needle across a scale that is marked off in units of the measured variable. This type of movement is used extensively in DC analog instruments. For AC measurement, however, the d'Arsonval movement is not sufficient by itself, but must be adapted in some way:

- it must be used in conjunction with a rectifier diode that converts the AC into a waveform with a DC level to which the meter can respond, or
- it must use an electromagnet instead of the permanent magnet in the standard d'Arsonval movement, or
- it must use iron vanes [B-3].

The electromagnet form of the galvanometer is employed in the power measuring instruments (wattmeters) that you will use in this lab course.

Figure B.10 (a) shows an equivalent circuit representation of the dual-coil electrodynamometer **wattmeters** you will use to measure 60 Hz AC power in this laboratory. Because the meter deflection is proportional to the product of the current through the current-sensing coil (in series with the load) and the current through the voltage sensing coil (across the load) the response is proportional to the product of the load current and the load voltage drop. The size of the resistance in series with the voltage coil determines the voltage range of the instrument. Figure B.10 (b) shows the equivalent circuit representation of the analog voltmeter. The size of the resistor determines the voltmeter range. Figure B.10 (c) shows the equivalent circuit of the analog ammeter. The size of the shunt (parallel) resistor determines the range of the ammeter. Note that the analog instruments on the Hampden ACVA-100 console and the Hampden ACWM-100 wattmeter console all have non-linear scales.

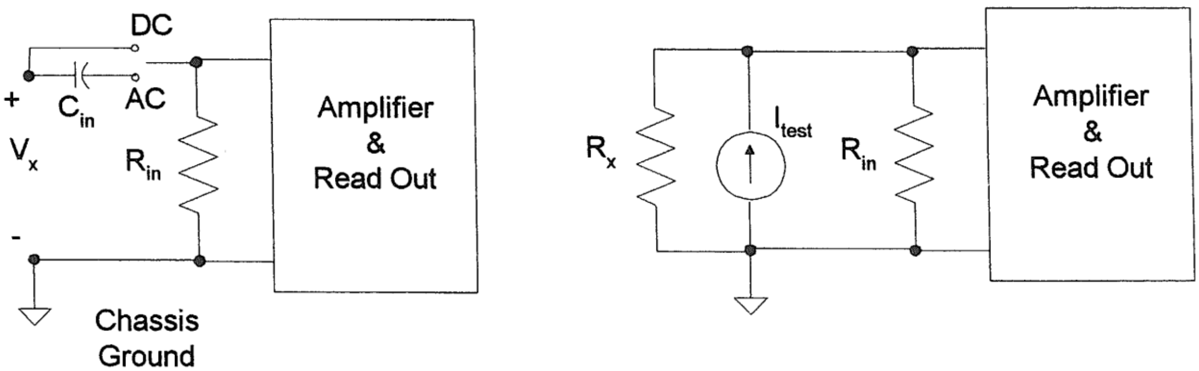


(a) (b) (c)

Figure B.10: (a) Equivalent circuit for analog wattmeter. (b) Equivalent circuit for analog voltmeter. (c) Equivalent circuit for analog ammeter.

Digital Multimeter

A multimeter is an electronic device that measures a multitude of electrical values, usually including at least AC and DC voltage and current, as well as resistance. The digital multimeter (DMM) has a digital display. The DMMs in this laboratory are powered from the non-isolated 120 V, 60-Hz supply. Figure B.11 (a) shows an equivalent circuit for the DMM when it is used to measure voltage or current. When measuring voltage, the input resistance is relatively large (10 MΩ for DC, 10 MΩ in parallel with 100pF for AC). For current measurements, the input resistance is small (1 Ω for 0.2 A DC; 0.1 Ω for 2.0 A DC). Figure B.11 (b) shows an equivalent circuit for the DMM in the resistance measuring mode. The test current, I_{test}, varies with the resistance range.



(a) (b)

Figure B.11 (a) Equivalent circuit for voltage and current measurement with the DMM.
(b) Equivalent circuit for resistance measurement with the DMM.

LCR Meter

The LCR meter is a solid-state instrument used to measure resistance, inductance, and capacitance. It replaces the impedance bridge that was used before this type of direct measuring tool became available. When first turned on, the LCR meter enters an autoranging mode, so that the appropriate scales are used in displaying the measurements. Tests can be performed using a test frequency of either 1 kHz or 120 Hz by pressing the appropriate button.

By pressing the L/C/R button until the letter L is shown in the upper-left-hand corner of the display, the user can measure inductance. The meter assumes that resistance is in series with this inductance, and the amount of this series resistance can be found from the quality factor Q displayed in the secondary display in the upper-right-hand corner. The relationship between the inductance, resistance, Q, and a dissipation factor D is given by:

$$Q = \frac{2\pi \times frequency \times L}{R} = \frac{1}{D}$$

Note that the dissipation factor is simply the inverse of the quality factor.

Pressing the *L/C/R* button until the letter *C* is shown in the upper-left-hand corner of the display allows one to measure capacitance. This time the meter assumes that the capacitance is in parallel with a resistance. The amount of resistance is related to the quality factor *Q* and dissipation factor *D* by:

$$D = \frac{1}{2\pi \times frequency \times C \times R} = \frac{1}{Q}$$

Resistance by itself can be measured by pressing the *L/C/R* button until the letter R is shown in the upper-left-hand portion of the display.

The LCR meter has many other useful features, which are described in the manual. If *CAL* is displayed in the center area, check the secondary display to see if *OPn* or *Srt* is displayed. These indicate that the leads should be either opened or shorted followed by pressing the *CAL* key, for an automatic calibration.

Dual-Beam Oscilloscope

The oscilloscope is a tool to allow engineers to look at the shape of an electrical voltage versus time or versus a second signal. Until relatively recently, oscilloscopes used a cathode ray tube (CRT) to draw the waveforms onto a screen, just like an image on a television. In fact, televisions and computer monitors also used cathode ray tubes until the advent of the new flat screens. Because of this fact, some people have referred to the laboratory oscilloscope as a CRO, short for "cathode ray oscilloscope". The oscilloscopes in this lab now use LCD screens, so the CRO reference is no longer valid. Most engineers refer to the instrument as a "scope".

The Dual-Beam Oscilloscope, which we use in this lab, has two vertical ("y") input channels and one horizontal ("x") channel. The horizontal channel can be connected either to an external AC voltage signal or to an internal time-base generator (x = time). You should become familiar with the scale options on the y input channels, the x input channel, and the time base, since you will be using these to obtain values for voltage and time. The y inputs can be either direct (1X) or through a 10X probe. Figure B.12 (a) shows the equivalent input circuit for a direct input and Figure B.12 (b) shows an equivalent circuit for the 10X probe input. Note that in both configurations one side of the input is grounded, which means that care must be used in connecting the ground clip of the probe or connector used to assure that these are not connected to a "hot" ($|V| > 0$) part of the circuit. (See the section "Oscilloscope Grounding Errors".) The calibrated time base is useful when measuring the phase difference between two waveforms (on the y_1 and y_2 inputs) by carefully lining up the zero levels for both y inputs and then using in the ac-couple mode to observe the time difference between zero crossings of the two waveforms.

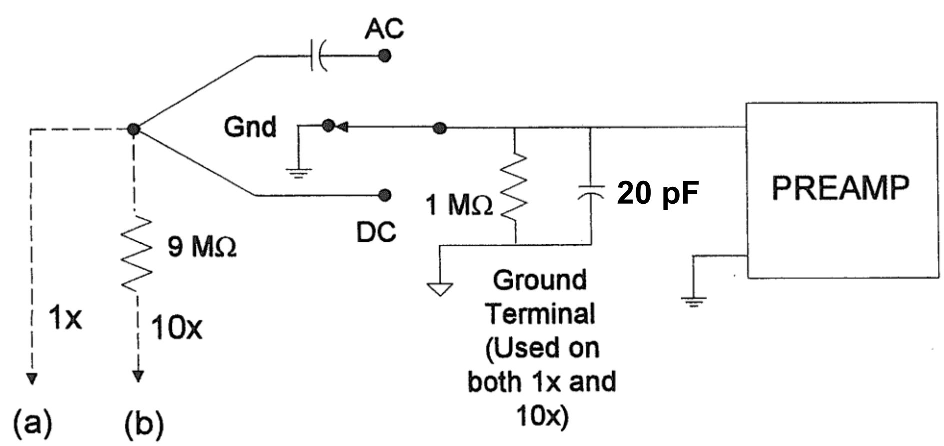


Figure B.12: (a) Equivalent circuit for oscilloscope input with 1X probe (direct input).
(b) Equivalent circuit for oscilloscope input with 10X probe.

Digital Storage Oscilloscope

The digital storage oscilloscope (DSO) is now the preferred type of oscilloscope for most industrial applications, although analog oscilloscopes are still widely used. The DSO uses digital memory to store data as long as required without degradation. The digital storage allows bringing into play the enormous array of sophisticated digital signal processing tools for the analysis of complex waveforms in today's circuitry.

Digital storage oscilloscopes come in a variety of configurations. The units in this laboratory are dual-beam oscilloscopes with two vertical inputs, as described above.

The vertical input on the oscilloscope, instead of driving the vertical amplifier, is digitized by an analog-to-digital (A-to-D) converter to create a data set that is stored in the memory of a microprocessor. The data set is processed and then sent to the display, which today is likely to be an LCD flat panel. DSOs with color LCD displays are also common. The data set can be written to a flash drive or sent over a LAN or a WAN for processing or archiving. The screen image can be directly recorded on paper by means of an attached printer or plotter, without the need for an oscilloscope camera. The scope's own signal analysis software can extract many useful time-domain features (e.g. rise time, pulse width, amplitude), frequency spectra, histograms and statistics, persistence maps, and a large number of parameters meaningful to engineers in specialized fields such as telecommunications, disk drive analysis, and power electronics.

Digital oscilloscopes are limited principally by the performance of the analog input circuitry and the sampling frequency. In general, the sampling frequency should be at least the Nyquist rate, double the frequency of the highest-frequency component of the observed signal, otherwise aliasing may occur.

Three-Phase Power Measurements

Wattmeters consist of a voltage coil and current coil that are connected to the circuit as shown in Figure B.13. Conventional AC wattmeters respond to the product of the rms voltage and rms current times the cosine of the phase difference, where $P = V_{rms} I_{rms} \cos\theta$

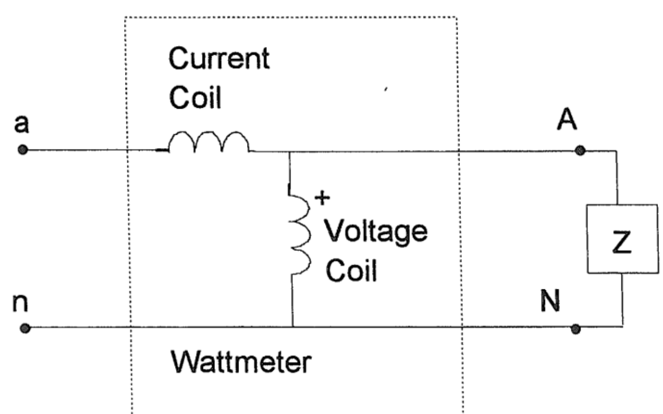


Figure B.13: Wattmeter Connection for Single-Phase Load

Notice in these schematic diagrams that the current coil and the voltage coil of the wattmeter are connected at one end. This should be done by attaching a jumper wire between the coil connectors marked with a black dot on the Hampden ACWM-100 wattmeter (Figure B.14). In the wattmeter circuit diagrams in this lab, this connection is labeled "+".

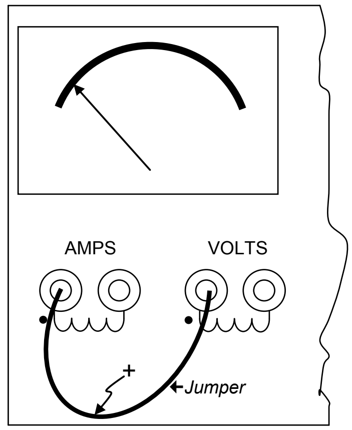


Figure B.14: Jumper on wattmeter "+" connection

To measure power on a three-phase system one could employ what is called the two wattmeter method, in which two wattmeters are connected as shown in Figure B.15. The total three-phase power is then given by the sum of the two wattmeter readings.

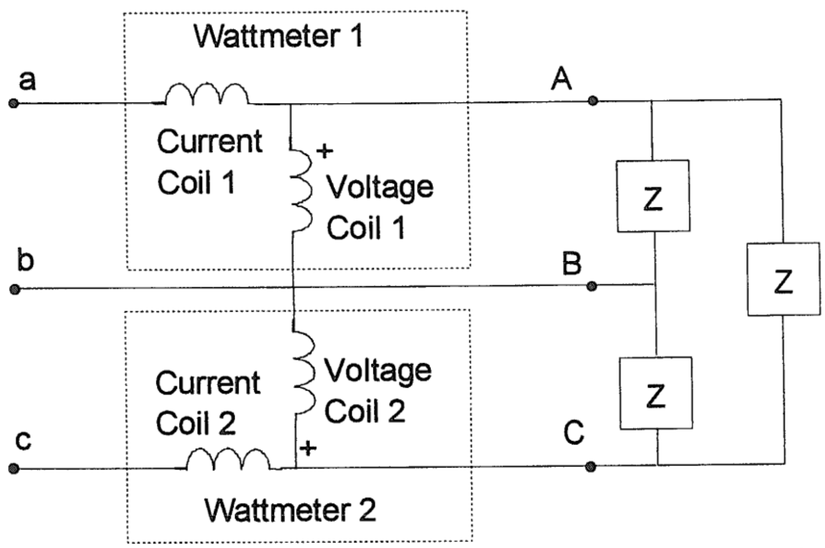


Figure B.15: Two Wattmeter Connection for Three-Phase Load

To demonstrate that the sum of the readings is the three-phase power, one can start with the definition for what each wattmeter is reading

$$W_1 = \mathrm{Re}\left(V_{ab} I_a^*\right)$$

$$W_2 = \mathrm{Re}\left(V_{cb} I_c^*\right)$$

The next step is to relate line currents to phase current

$$I_a = I_{ab} + I_{ac}$$
$$I_c = I_{ca} + I_{cb}$$

Substituting in for the currents

$$W_1 = \mathrm{Re}\left(V_{ab} I_{ab}^*\right) + \mathrm{Re}\left(V_{ab} I_{ac}^*\right)$$
$$W_2 = \mathrm{Re}\left(V_{cb} I_{ca}^*\right) + \mathrm{Re}\left(V_{cb} I_{cb}^*\right)$$

Summing the wattmeter readings results in

$$W_1 + W_2 = \mathrm{Re}\left(V_{ab} I_{ab}^*\right) + \mathrm{Re}\left(V_{ab} I_{ac}^*\right) + \mathrm{Re}\left(V_{cb} I_{ca}^*\right) + \mathrm{Re}\left(V_{cb} I_{cb}^*\right)$$

Since $I_{ac}^* = -I_{ca}^*$ then

$$W_1 + W_2 = \mathrm{Re}\left(V_{ab} I_{ab}^*\right) + \mathrm{Re}\left(\left(V_{ab} - V_{cb}\right) I_{ac}^*\right) + \mathrm{Re}\left(V_{cb} I_{cb}^*\right)$$

Finally, noting that $V_{ab} - V_{cb} = V_{ac}$

$$W_1 + W_2 = \mathrm{Re}\left(V_{ab} I_{ab}^*\right) + \mathrm{Re}\left(V_{ac} I_{ac}^*\right) + \mathrm{Re}\left(V_{cb} I_{cb}^*\right) = P_{ab} + P_{ac} + P_{cb}$$

results in an expression that is the sum of the real power dissipated in each phase. A similar argument can be made for a wye-connected load.

As an example, calculate the expected reading of each wattmeter if the line-to-line voltage is 208 V for a balanced load and the load impedance Z = 8.0+j6.0 Ohms. The load impedance in polar form is:

$$|Z| = \sqrt{8^2 + 6^2} = 10$$
$$\angle Z = 36.9°$$

The phase ab current is given by

$$I_{ab} = \frac{V_{ab}}{Z} = \frac{208\angle 0°}{10\angle 36.9°} = 20.8\angle -36.9°\ A$$

and the phase a current is given by

$$I_a = \sqrt{3} I_{ab} \angle -30° = 36.0\angle -66.9°$$

with a phase c current for a balanced load of

$$I_c = I_a \angle +120° = 36.0\angle 53.1°$$

Then

$$W_1 = |V_{ab}||I_a|\cos\theta = 208 \times 36.0 \times \cos\left(0° + 66.9°\right) = 2938\,Watts$$
$$W_2 = |V_{cb}||I_c|\cos\theta = 208 \times 36.0 \times \cos\left(\left(-120° + 180°\right) - 53.1°\right) = 7434\,Watts$$
$$P_{3\phi} = W_1 + W_2 = 2938 + 7434 = 10,372\,Watts$$

References for Appendix B

B-1. J. W. Nilsson and S.A. Riedel, *Electric Circuits, Seventh Edition*, Upper Saddle River, NJ; Pearson Prentice Hall, 2005.

B-2. H. H. Chiang, *Electrical and Electronic Instrumentation*, New York, NY: John Wiley and Sons. 1984.

B-3. Chiang, op.cit., pp 24-32.

Appendix C

Data Plots

It is often desirable to make a two-dimensional plot of data in order to examine relationships between variables, for example: voltage versus time, current versus time, output voltage versus input voltage, output voltage versus frequency, etc. When the range of both variables used in the plot is not large a linear vertical (or "y") scale and a linear horizontal (or "x") scale is often convenient, particularly if one or both of the variables can have negative values. In the cases where one of the variables may have a relatively small range while the other covers several orders of magnitude (i.e. over several powers of 10 in size) a linear versus logarithmic, or semi-log, plot is convenient. When both variables can cover a large range a logarithmic versus logarithmic, or log-log, plot is convenient.

The semi-log or log-log plots are also useful when trying to determine whether the data follows a pattern that can be described by a mathematical function. For example, the decay voltage of a capacitor discharging through a resistance follows the mathematical function

$$V(t) = V_0 \exp(-t/\tau) \qquad \text{(C.1)}$$

where τ = RC. This function can be plotted on a semi-log plot. Taking the logarithm (base 10) of both sides

$$\log\left[V(t)\right] = \log(V_0) - (t/\tau)\log(e) = \log(V_0) - (0.4343/\tau)t \qquad \text{(C.2)}$$

which is a straight line (with a negative slope) when plotted on a log[V] versus linear t plot. Note here that log[ ] is taken to be $\log_{10}$.

Another example of a semi-log plot is a (linear) phase angle versus (logarithmic) frequency Bode plot. The amplitude versus (logarithmic) frequency Bode plot is a semi-log plot when the amplitude has been converted to decibels, i.e. $20 \cdot \log_{10}(A)$. Otherwise, log(A) can be plotted versus log(*f*).

You have become accustomed to making linear versus linear plots in the past, starting in algebra and proceeding upward through various subsequent math courses. Even though taking a logarithm might seem to be a "natural" operation (i.e. "no big deal") now, the use of logarithmic plots might seem strange at first. However, a great deal of engineering information is published and exchanged in semi-log or log-log format, and even some in log(log)-log format. Thus it is useful to learn how to make and interpret such plots. You can purchase semi-log or log-log paper at a book store which deals with engineering supplies.

When you want to make a semi-log or log-log plot and you do not have any of the commercially printed plotting paper at hand, you can make your own log scale. The procedure is as follows. Refer to the scale in Figure C.1, which shows a linear scale at the top and a logarithmic scale at the bottom. The latter is calculated on the basis of log(1) = 0, log(2) = 0.301 (30% of the spacing from 1 to 10 on the bottom -log- scale), log(3) = 0.477 (47.7%), log(4) = 0.602 (about 60%), etc. Using this procedure, you can quickly construct a log scale on linear plotting paper, or on a straight line that you have used a ruler to mark off in linear increments to make your own plotting paper.

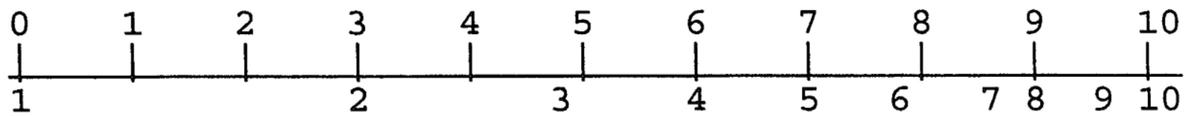


Figure C.1 Relationship of linear and logarithmic scales.

This procedure enables you to construct a set of scales to put your data points on for a quick assessment of the relationship, particularly if you want to compare a linear-linear to a semi-log to a log-log plot to see which gives the best presentation. You can use commercial paper later when you have decided the appropriate scales to use and want to make a “pretty” plot for a report.

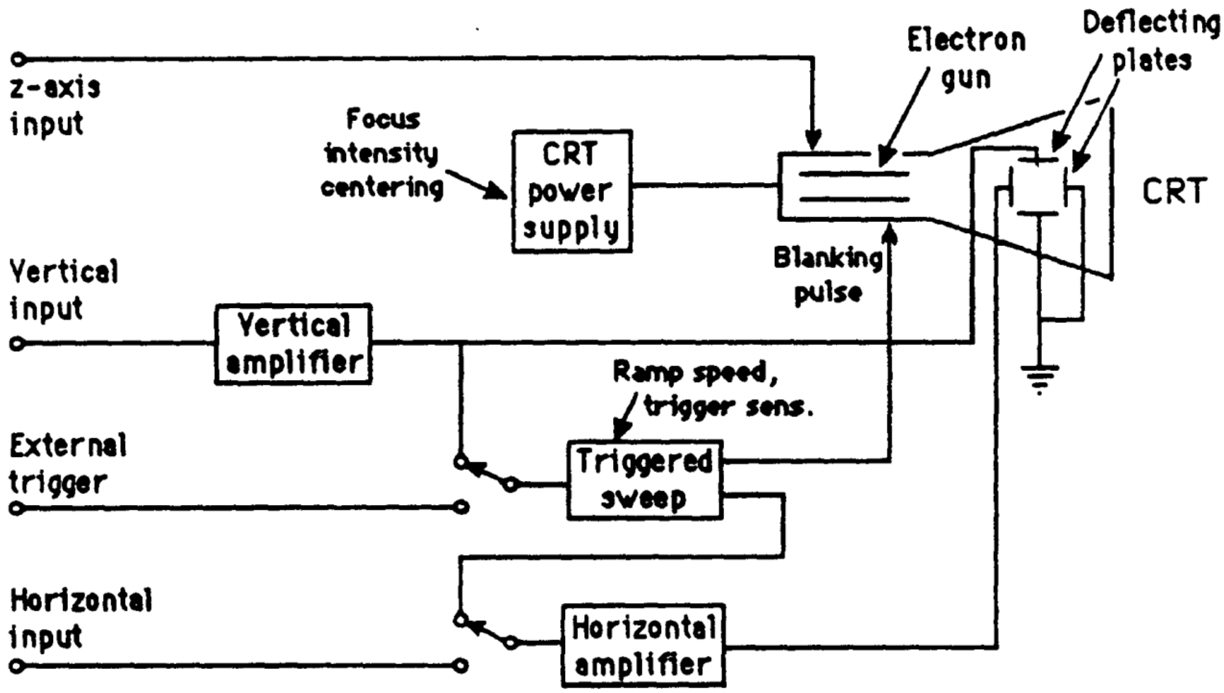
Appendix D

Operating Instructions for a Typical Oscilloscope

The oscilloscope is an instrument for the analysis of electrical circuits by observation of voltage and current waves. It may be used to study frequency, phase angle, and time, and to compare the relation between two variables directly on the display screen. Perhaps the greatest advantage of the oscilloscope is its ability to display the periodic waveforms being studied.

Until recently, oscilloscopes used a cathode-ray tube to display the signals of interest. A cathode-ray tube (CRT) contains an electron gun that directs a high-velocity beam of electrons onto a fluorescent screen. The beam is controlled by a pair of horizontal and a pair of vertical deflecting plates. When the voltage on the deflection plates is equal to zero, the beam produces a spot of light in the center of the screen. Any potential applied to the plates creates an electric field that deflects the electron beam proportionally to the applied voltage.

A simple block diagram of the cathode-ray oscilloscope is shown below.



The basic components of the traditional oscilloscope are cathode-ray tube, amplifiers, sweep or timing oscillator, and power supply. A voltage to be observed is applied to the vertical deflection plates. This signal may be amplified by the vertical amplifier in order to obtain a satisfactory vertical deflection. Meanwhile, a sweep oscillator moves the beam horizontally at a uniform rate. The simultaneous horizontal and vertical sweep of the beam across the CRT screen displays the waveform of the voltage applied to the vertical plates. The sweep oscillator blanks the CRT electron gun during its reverse sweep across the screen to switch off the electron beam.

If several voltage waveforms are to be studied and must maintain their relative phase positions, the sweep generator must be synchronized to the same voltage during the entire test. In this case, one voltage is applied to the oscilloscope as an external trigger.

An independent voltage may be applied to the horizontal input in place of the sweep oscillator voltage. In this case, two independent input voltages are displayed against one another. If the horizontal frequency is a submultiple of the vertical frequency, the trace will form a stationary pattern on the screen.

Today the traditional CRT oscilloscopes are rapidly being replaced with digital oscilloscopes that have flat-panel liquid crystal displays (LCDs), some with color displays. Instead of directly applying the incoming voltages to deflection plates, the digital oscilloscopes capture the voltage information and store it in computer memory as digital signals, which are then analyzed and displayed on the LCD. While the new digital scopes handle the incoming signal differently from the CRT-based scopes, the basic purpose and many of the operational controls remain the same. Therefore, the discussion that follows applies, for the most part, to both types of oscilloscopes.

Potential Grounding Errors With Oscilloscope

In practice the user needs to be aware that the shield or ground wire on the oscilloscope's signal input is connected to the oscilloscope's chassis ground, and therefore to the ground lead on the instrument's electrical power connection. This fact creates the possibility of grounding errors when making connections to circuits. Before proceeding, the user should review the article *"Oscilloscope Grounding Errors"* found in Appendix B of these appendices.

Preliminary Adjustment To Obtain a Trace

To operate the oscilloscope, first turn on the power switch and allow the unit to warm up and initialize. Place the HORIZONTAL CONTROL in the sweep position. Adjust the INTENSITY and FOCUS controls on a CRT scope until the desired brightness and line width are obtained. Do not leave the spot stationary on the screen, as doing so may leave a permanent burn on the screen coating.

Once a trace is obtained, some oscilloscopes must be checked for calibration and balance. For the HP 120B CRT oscilloscope (a typical example), the procedure is as follows: Place the TRIGGER LEVEL on AUTO and the TRIGGER SOURCE to INT. Turn the horizontal and vertical VERNIERS to CAL, the VERTICAL SENSITIVITY to CAL, and the HORIZONTAL DISPLAY to 1 msec/cm. With the controls in these positions, an internal calibrating signal is produced on the screen. Turn the CAL adjustment until the upper and lower peaks of the square wave are 6 cm apart.

Digital oscilloscopes often have automated setup and calibration upon power-up.

Waveform Observation

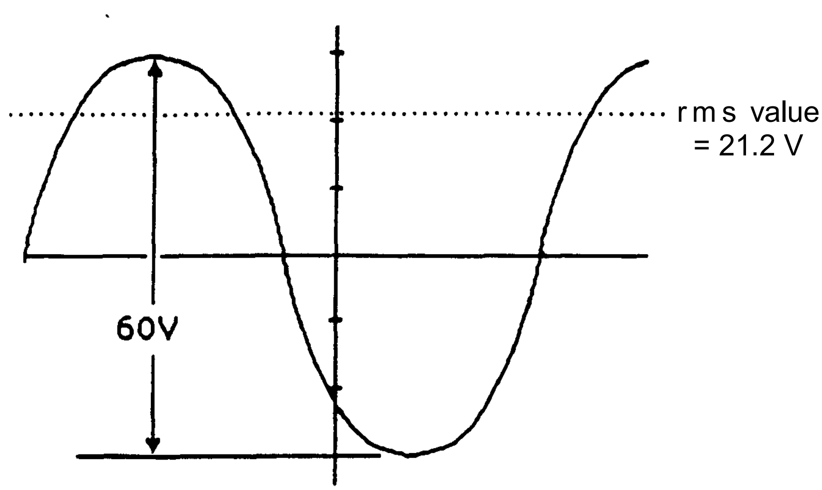
After the initial adjustments are made, the oscilloscope is ready for operation. To observe the waveform of any periodic signal, apply the signal to the vertical input terminals. Use DC coupling if the input is DC or very low in frequency or if you want to capture any DC offset. Now the signal from an oscillator, signal generator, or some component of an electrical circuit may be observed on the screen. The best resolution of the waveform is obtained when the time scale is adjusted so one or two cycles appear on the screen and when the vertical scale is adjusted so the amplitude occupies most of the graticule. If the waveform will not stabilize, adjust the

SYNC or TRIGGER just enough to cause the pattern to stop. Whenever possible, connect the oscilloscope ground to the common ground of the circuit. Exercise great care when making measurements with both terminals above ground potential, as there may be a difference in potential between two instrument cases, causing ground loop currents, faulty readings, and damaged equipment.

Voltage Measurement (AC & DC)

The oscilloscope has advantages as a voltmeter: a very high input impedance compared to an analog voltmeter;, the ability to measure voltages over a very wide frequency range; and the ability to indicate magnitude regardless of waveform. Also, scopes measure peak-to-peak values of AC voltages, whereas standard AC voltmeters measure rms values of sine wave voltages. However, the oscilloscope only has an accuracy of 2% to 5%, while the AC voltmeter's accuracy will be from 0.25% to 2%.

To use the oscilloscope as an AC voltmeter, apply the signal to the vertical input terminals, and adjust the calibrated VERTICAL SENSITIVITY (or VOLTS/DIV) so the amplitude is of suitable magnitude on the graticule. The peak-to-peak value is then the distance indicated multiplied by the vertical calibration. For example, assume that a sine wave generator is set to 1000 Hz and adjusted for maximum output voltage. A peak-to-peak value of 60V is observed on the oscilloscope. The output of the generator at 1000 Hz, therefore, is approximately 60V peak-to-peak, and 21.2 V_{rms}.

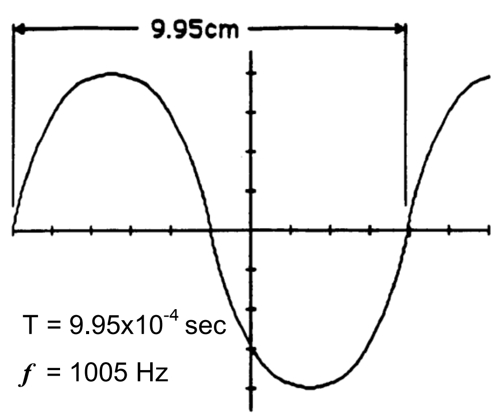


Note: $V_{rms} = \frac{1}{2\sqrt{2}} V_{p-p}$

For DC measurements, apply the voltage to the vertical input terminals, again suitably adjusting the VERTICAL SENSITIVITY. A straight line is produced with the horizontal sweep functioning. With no horizontal voltage applied, a spot will appear on the screen. In measuring DC voltages, it is necessary to remember where the trace was with 0V applied to the vertical input.

Frequency Measurement

The frequency of an unknown signal may be calculated from the oscilloscope very easily. The period of the waveform is the product of the distance along the x-axis covered by one cycle and the horizontal sweep setting. As an example, a sine-wave generator is set to 1000 Hz with the voltage applied to the oscilloscope vertical. One cycle covers 9.95 cm, with a sweep speed of



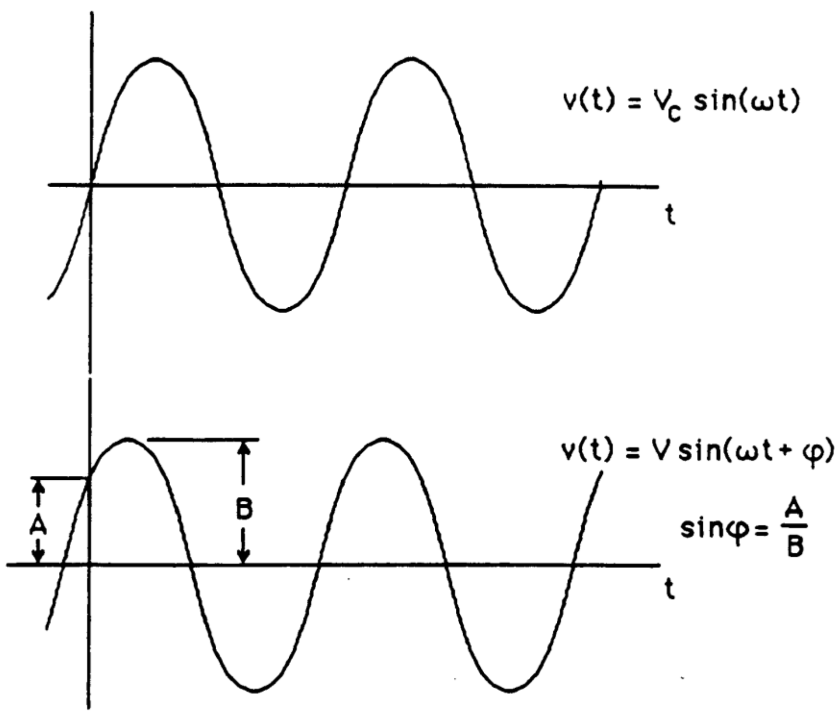
100 μsec/cm. The period is T = (9.95)·(100×10^{-6})sec. The measured frequency is f = 1/T = 1005 Hz.

Phase Angle Measurement

The difference in phase angle between two waveforms may be measured directly on the oscilloscope with little difficulty.

For an oscilloscope with only one vertical input:

One wave is chosen as the reverence and applied to the vertical input terminals. This same wave is applied to the external trigger input of the scope. Next, a convenient point on the wave is selected as a time reference, such as where the wave is zero and about to swing positive. Then, this waveform is removed from the vertical input and a second waveform is applied. The voltage of this wave at the time reference is observed. The ratio of voltage at the time reference to the maximum voltage is equal to the sine of the phase difference between the two waves. This relation is shown below.

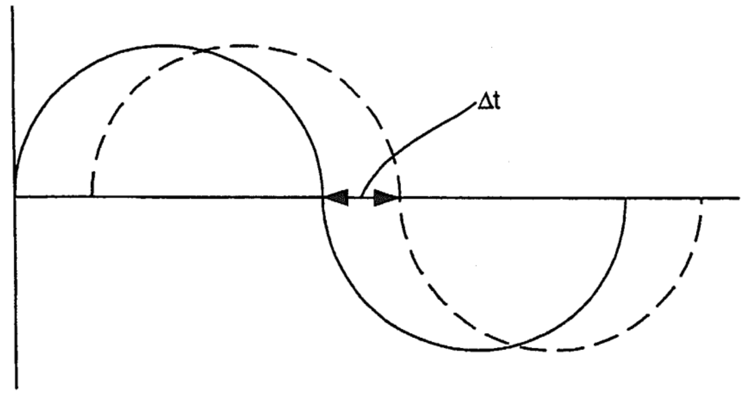


For an oscilloscope with two vertical inputs:

Connect the reference voltage to Channel 1 of the oscilloscope and connect the second voltage to Channel 2. Adjust the amplitudes so the overlapping signals look something like the figure below, where the solid curve is Channel 1 (the reference) and the dashed curve is Channel 2. (In this figure, the dashed curve is lagging the solid curve; if the dashed curve were shifted to the left so it "started" before the solid curve, then the dashed curve would be leading the solid curve.) The phase shift φ in degrees can be calculated by the following formula:

$$\varphi = \Delta t \cdot f \cdot 360°$$

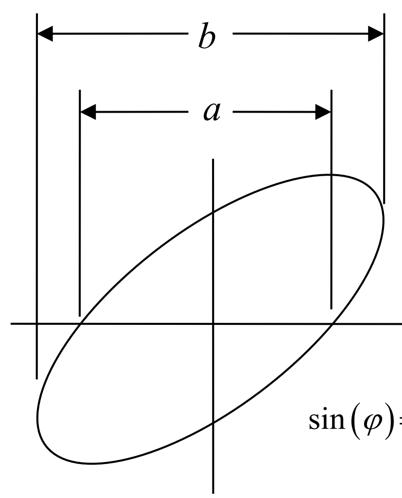
where φ is the phase shift, f is the frequency, and Δt is the time difference between the two waveforms. Many new digital scopes have cursors that allow directly marking, calculating, and displaying the time difference and perhaps even the phase shift.



Phase and Frequency Measurement by Lissajous Patterns

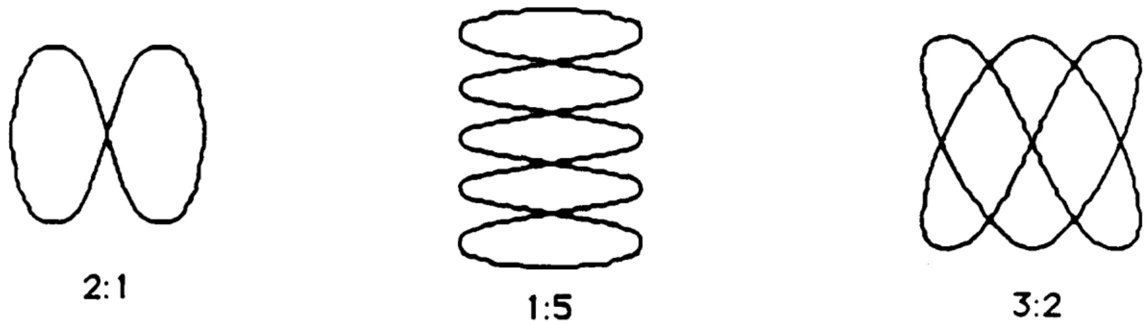
The oscilloscope may be used to compare simultaneously two separate waveforms. When two voltages of the same frequency are impressed on the oscilloscope, one on the vertical and one on the horizontal plates, a straight line results on the screen if the voltages are in phase or 180° out of phase. An ellipse is obtained for other phase angles. The pattern which results when two sine waves are applied to the oscilloscope in this way are called Lissajous patterns. They can take many forms, depending on the frequencies involved.

Phase shift (the phase angle between two waves of equal frequency) may be calculated from the pattern on the CRT screen. If the voltage applied to the vertical plates leads the voltage applied to the horizontal plates by an angle φ, a pattern such as the one at right results. The phase difference can be found by taking the ratio of the horizontal intercept to the maximum horizontal deflection. However, twice the values provide more accuracy. The phase shift is now calculated $\varphi = \arcsin(a/b)$.



$$\sin(\varphi) = \frac{a}{b}$$

Lissajous patterns may be used to compare the frequencies of voltages from two separate signal sources. If these are close to the same frequency, the pattern will slowly change back and forth from an ellipse to a straight line each half cycle of difference in frequency. For any stationary pattern, the ratio between the two frequencies may be determined by counting the number of pattern tangencies along the horizontal and vertical axes. The ratio of vertical to horizontal frequency (Y:X) equals the number of horizontal tangencies divided by the number of vertical tangencies. Lissajous patterns for three frequency ratios follow.



Y frequency **:** **X** frequency

Be warned that many presentations of Lissajous patterns report (X frequency) : (Y frequency), which would be the inverse of the ratios shown here.

To measure frequency by Lissajous patterns, the unknown signal is applied to the vertical input terminals. Then, a variable signal of known frequency is applied to the horizontal input. The HORIZONTAL DISPLAY must be on external sensitivity. The known signal is varied until a stable pattern is obtained, and the unknown frequency is calculated. The simplest way to do this, however, is just to obtain a pattern in a 1:1 ratio. Then the unknown can be read directly off the dial of the known source.

Appendix E

Tektronix TDS 1002B Oscilloscope

Introduction

Digital multimeters (DMMs) are extremely useful devices to measure and characterize electrical parameters; however, they have a number of limitations. Whether in ammeter or voltmeter mode, they give a one-number summary of the electricity. Their AC frequency range is limited to audio frequencies: 20 Hz to 20 kHz. And perhaps most significantly, they do not show to the engineer a picture of the electrical signal's shape and variation.

Oscilloscopes are useful at frequencies well above 1 MHz and some even beyond 1 GHz. Unlike the DMM, the oscilloscope (a.k.a., scope) usually measures voltage, not current. Also unlike the DMM, the oscilloscope's "common" lead is always internally connected to ground. Effectively, then, the oscilloscope displays the signal lead's voltage relative to ground. So, while a freely floating DMM can measure the 1 V potential difference between two terminals at 110 V and 111 V above ground, an oscilloscope typically cannot. (See Appendix B for potential grounding errors with oscilloscopes.) However, while a DMM converts every waveform of any shape to a single number, V_{rms}, an oscilloscope displays a graph of voltage versus time. (See Figure E.1.)

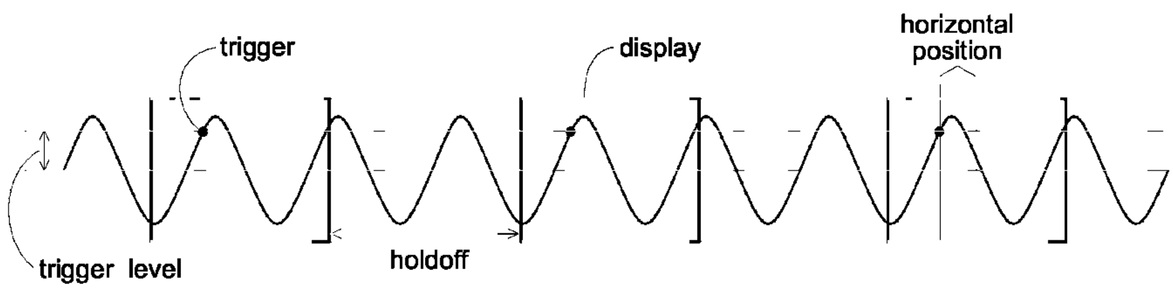


Figure E.1: An oscilloscope displays one wave section after another, making an apparently steady display. Determining when to start a new wave section is called triggering, and the trigger point is set by specifying the signal's level and slope (rising or falling). The trigger point is placed in the center of the display, but it can be moved using the horizontal POSITION knob. The holdoff is an adjustable dead time following a triggered wave section.

Oscilloscopes are generally used to display periodic signals. Every fraction of a second, a new section of the wave is displayed. If these successively displayed wave-sections match, the display will appear unchanging. Thus, the precise triggering of successive wave sections is critical for a stable display. In addition, the scales used for the HORIZONTAL and VERTICAL axes should be appropriate for the signal. That is, the signal should be neither off-scale large nor so small as to be indistinguishable from zero. A too large time (horizontal) scale will result in displaying hundreds of cycles as a blur; a too small time scale will cause just a fraction of a cycle to be displayed.

Tektronix TDS 1002B Oscilloscope

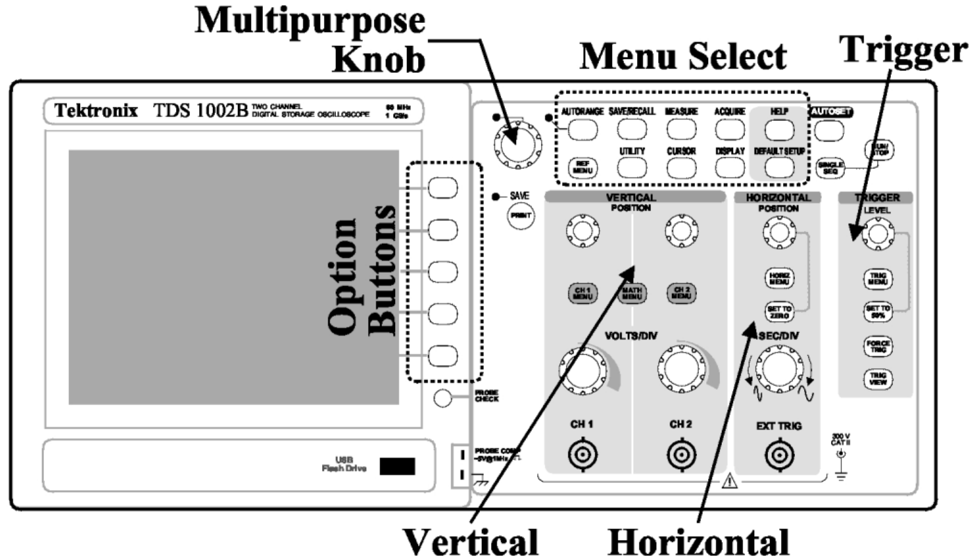


Figure E.2: Overview of Tektronix TDS 1002B. The Tektronix TDS 1002B is a two-channel digital storage oscilloscope. Pushing a button in the *Menu Select* region displays a corresponding menu on the screen adjacent to the option buttons, with the *Multipurpose Knob* allowing adjustment of continuous variables. The *Vertical* region has knobs that control the size (VOLTS/DIV) and POSITION of the vertical scales for Channel 1 (CH 1) and Channel 2 (CH 2). Push buttons in this region control the display of menus for those channels and combinations of those channels (MATH). The *Horizontal* region has knobs that control the size (SEC/DIV) and POSITION of horizontal scales. In addition to the main time-base, this dual-time-base scope can enlarge a selected portion ("Window") of the display. The controls to do this are in the HORIZ MENU. The *Trigger* region has a knob that controls the voltage LEVEL for the triggering and the TRIG MENU button allows the display of configurable options for the trigger. Note particularly the AUTOSET, DEFAULT SETUP, and HELP buttons to the right of the Menu Select region.

Figure E.2 shows an overview of the face of the Tektronix TDS 1002B oscilloscope, and a larger image is attached at the end of this appendix. The Tektronix TDS 1002 oscilloscope is identical except it lacks (1) the AUTORANGE button, (2) the MULTIPURPOSE KNOB, and (3) USB connectors at front and rear, instead using connectors for older technology. The sections below describe the scope's controls and their uses, with the name of each control printed in SMALL CAPS TEXT.

Oscilloscope Controls and Their Use

Display Section The left hand side (lhs) of the scope is dominated by the display screen. Just below the screen on the TDS 1002B is a USB port that allows saving scope data and display images on a thumb drive or sending output to a printer. There is another USB port on the back of the unit. The 1002 model has older-style connectors on the back.

Option Buttons To the right of the display are five unlabeled option buttons used to make selections from various menus that are displayed on the screen by many command buttons.

Vertical Sections To the right of the option buttons are knobs and buttons that control the vertical portions of the graph (see Figure E.3). Typically the display shows a graph of voltage (vertical) vs. time (horizontal). This scope has two channels, so the vertical section is divided into two sub-sections with identical controls for each input. The inputs are called Channel 1 (CH 1) and Channel 2 (CH 2). The scale factor for each input is determined by the corresponding VOLTS/DIV knob. The vertical location of zero volts is determined by the corresponding POSITION knobs. The scale factors and the zero level for the channel traces are set independently; therefore the graph axes cannot show values in physical units (volts). Rather, the graph is displayed on an 8 × 10 grid with units called divisions (div). Typically each division is about one centimeter.

Figure E.3: Vertical Control Section

The VOLTS/DIV knob controls the sensitivity and is similar to the range switch on a multimeter. If the knob is set to 0.5 volts/div, a 2 V signal will be displayed as 4 divisions high, since 4 div × 0.5 V/div = 2 V. These settings appear in the lower lhs of the display. For optimum resolution, you should adjust the VOLTS/DIV so that the signal displayed is at least 3 divisions peak-to-peak.

The maximum display using a 1X probe is 40V peak-to-peak, corresponding to 5V/div.

The traces of the two channels generally look identical on the screen, so the symbols 1➔ and 2➔ on the lhs of the display show the position of zero volts for each trace. If you are unsure which trace is which, moving a POSITION knob will immediately identify the corresponding trace.

MATH MENU
On the line separating the two channels is the MATH MENU button, which produces menus on the screen next to the *option buttons*. The MATH MENU is used to display combinations of CH 1 and CH 2 (+, −, ×) and Fourier transforms (FFT) of either signal.

CH MENU
The CH 1 MENU and CH 2 MENU buttons produce menus that allow controlling how the corresponding input is modified and displayed. Also, pushing these menu buttons toggles the display/non-display of the corresponding signal. The menu items are described in the next paragraphs.

Coupling
The top menu item in CH 1 and CH 2 menus, is **Coupling**, with options: **DC**, **AC**, **Ground**. These options control how the signal supplied to the BNC input is connected (coupled) to the scope's voltage measuring circuits. The **Ground** option means the scope ignores the input and displays a horizontal line at zero volts (ground) — this allows you to locate and POSITION the zero-volt reference line for that channel. When **AC** is selected a capacitor is connected between the input and the scope's electronics. This capacitor prevents any DC voltage from entering the scope's circuits, effectively subtracting any DC offset and displaying only the AC signal oscillating around a mean of zero volts. The usual selection for **Coupling** is **DC**, which means the signal displayed unmodified.

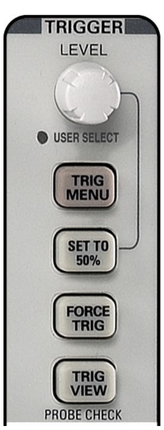
BW Limit (Bandwidth Limit)
This menu option sets the bandwidth limit of a channel at either the bandwidth of the oscilloscope (60 MHz) or 20 MHz. A lower bandwidth limit decreases the displayed noise, yielding a clearer display, and also limits the display of higher speed details on the selected signal.

Volts/Div
This menu option selects the incremental sequence of the VOLTS/DIV knob as **Coarse** or **Fine**. The **Coarse** option defines a 1-2-5 incremental sequence. The **Fine** option helps you change the resolution by small increments within the coarse settings.

Probe
Use this menu option to match a probe attenuation of 1X, 10X, 100X, or 1000X. A "Probe" is the device or wire that connects the oscilloscope to the signal source being measured, through the BNC connector. All probes have an "attenuation factor"— sort of the inverse of a magnification factor. The probe reduces the input voltage by the indicated factor, therefore to compensate, the scope must multiply what it detects by the same factor. Probes in this lab will usually be a coaxial pair of wires going to a BNC connector, so the choice should be *1X Voltage*. Unfortunately, the factory default setting is *10X Voltage*, so after turning on a scope you must check that the attenuation factor set on the scope matches the probe actually attached. If the wrong setting is used, all oscilloscope voltage measurements will be wrong. There is a PROBE CHECK button on the scope to determine the attenuation of an unlabeled probe, but usually probes are labeled and it is faster to set the probe type directly in the corresponding channel menu. **Note:** When the attenuation switch is set to 1X, the bandwidth of the oscilloscope is limited to about 7 MHz.

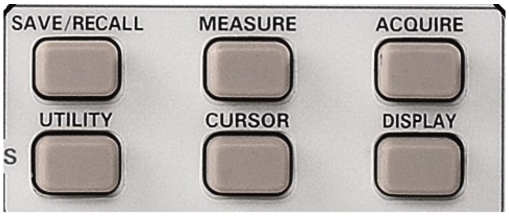
Invert
This menu option inverts the displayed waveform vertically with respect to the ground level.

Horizontal Section In the center-right of the scope face is the HORIZONTAL section. Just as in the vertical sections, knobs control the horizontal scale (SEC/DIV) and horizontal POSITION. In a single-time-base scope, all the input channels must be displayed with the same horizontal scale (unlike the vertical scale). In this dual-time-base scope, a portion of the display can be expanded in a Window. The window controls are found in the HORIZ MENU. When using the window feature the main SEC/DIV setting is labeled **M** and the Window SEC/DIV setting is labeled **W** in the display.



Trigger Section Determining when to trigger and display the next wave-section of the signal is the most complex part of an oscilloscope. Fortunately, the DEFAULT or AUTOSET settings will usually work well. Generally you will want to trigger when the wave has reached a particular LEVEL. But which wave? The TRIG MENU allows you to set the Source: CH1, CH2, EXT (the signal connected to the EXT TRIG connector in the horizontal section), EXT/5 (the same signal, but first attenuated by a factor of 5—useful for large triggering signals), or AC LINE (which uses the 60 Hz, 120 V power line as the triggering signal—useful for circuits that work synchronously with the line voltage). Just as in the vertical section, the **Coupling** of this source to the triggering electronics can occur in a variety of ways: **AC** subtracts the dc offset, **HF**

Reject filters out (removes) high frequency (> 80 kHz), **LF Reject** filters out low frequency (< 300 kHz), **Noise Reject** uses hysteresis to reduce the effects of noise, or **DC** for unfiltered. One also specifies the type of signal detail to trigger on, selecting from 11 types of measurements.



MEASURE Menu The MEASURE menu allows waveform measurements to be continuously updated and displayed. There are 11 types of available measurements, from which you can display up to five measurements at a time, one assigned to each *Option Button*. Push one of the option buttons and a new menu is displayed allowing you to set the **Source**: CH1, CH2, MATH, and the measurement **Type**: Freq, Period, Mean (voltage), Pk-Pk (peak-to-peak), Cyc RMS (the root-mean-square voltage of the first complete cycle, like V_{rms} from the DMM), Min (minimum voltage), Max (maximum voltage), Rise Time, Fall Time (10% to 90% transitions), Pos(itive) Width, Neg(ative) Width (at the waveform 50% level).

If a measurement is displayed with a question mark, try switching scales. Generally the scope wants signals that are several divisions high and that complete at least one—but not too many—cycles in the display.

CURSOR Menu The CURSOR menu enables a pair of *Amplitude* or *Time* measuring lines. With *Amplitude* cursors, a pair of horizontal lines appears. Pressing the appropriate option button allows the MULTIFUNCTION KNOB to move each cursor up or down to the required place. The voltage for each cursor is displayed along with the difference (ΔV) between them. For *Time* cursors, a pair of vertical lines appears. Pressing the appropriate option button allows the MULTIFUNCTION KNOB to move each cursor right or left to the required place. The voltage and time for each cursor is displayed along with the differences (Δt, ΔV) between them, and frequency 1/Δt.

DISPLAY Menu Use the DISPLAY menu to select the display characteristics for waveforms, such as the display type, persistence, format, and contrast.

The bottom of the display is used to report key numerical values like scale settings. For example:

CH1 500mV	CH2 2.00V	M 1.00ms	CH1 ⁄ 0.00V
		23-Nov-07 13:03	1.01407kHz

The first two numbers of the first line are the volts/div for channels CH1 and CH2, M refers to the main time-base of 1.00 ms/div, and the final sequence reports that triggering looks at Channel 1 for a positive edge at a level of 0.00 V. The second line shows the date/time and the frequency of the triggering signal.

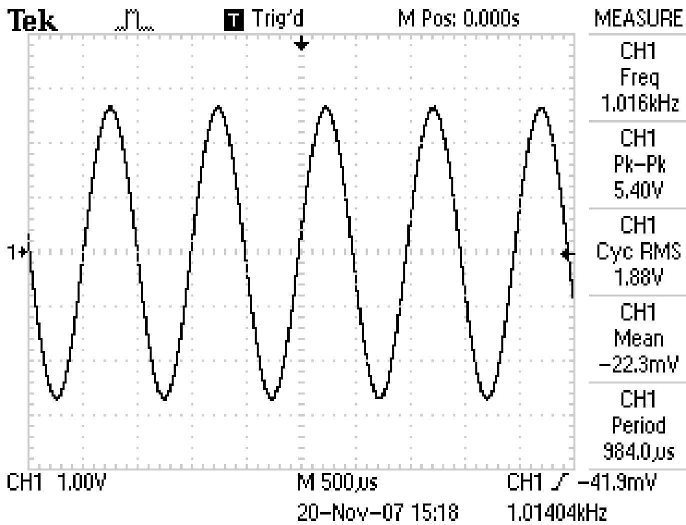


Figure E.8: Typical display. Note: MEASURE display; CH 1 V/div; horizontal time per div; trigger information; trigger point "Trig'd".

ACQUIRE Menu The ACQUIRE menu function controls the signal acquisition and processing system, allowing different types of acquisition modes for a signal.

SAVE/RECALL The SAVE/RECALL menu function allows one to save and recall up to 10 oscilloscope setups and 2 waveforms.

RUN/STOP In normal operation, the scope is constantly updating the display. It is possible to freeze the display (i.e., take a snapshot of the voltage vs. time graph) using the RUN/STOP or SINGLE SEQ buttons.

DEFAULT SETUP The scope remembers option settings between uses. Thus, unless you are the sole user of the scope, it is wise to set it to a well defined initial state before proceeding. The DEFAULT SETUP achieves this goal, but it sets the Probe to 10X Voltage, in the channel menus, which is not usually desired in this class.

AUTOSET The AUTOSET button will attempt to make rational choices for scale factors and other parameters, given the signals connected to the scope.

Further reading

On its web site Tektronix offers a number of reference texts in PDF format. Prominent among these are the following:

- TDS1000 -User_manual. Document 071-1064-00
  File name: 071106400_2008.06.16.09.53.30_9253_EN.pdf
- TDS1000 Operator Training Kit Manual. Document 071-1151-00.
  File name: 071115100_2008.06.16.10.05.20_10450_EN.pdf
- TDS1000 -Service_manual: Document 071-1076-02.
  File name: 071107602_2008.06.16.09.55.58_8979_EN.pdf

Appendix F

Simulation Tool: PartSim

Introduction

PartSim is maintained by DigiKey, a hardware vendor. It is browser based and, therefore, independent of users' platform. Anyone can use it from Windows, Mac or Linux . The web address for PartSim in www.partsim.com . Sign up is free, and PartSim allows registered users to save circuits and access those later. Once a circuit is saved in PartSim web server, it generates a unique web address (URL) that can be shared with anyone. Even without registration, one can view the circuit drawn by others by going to that specific link.

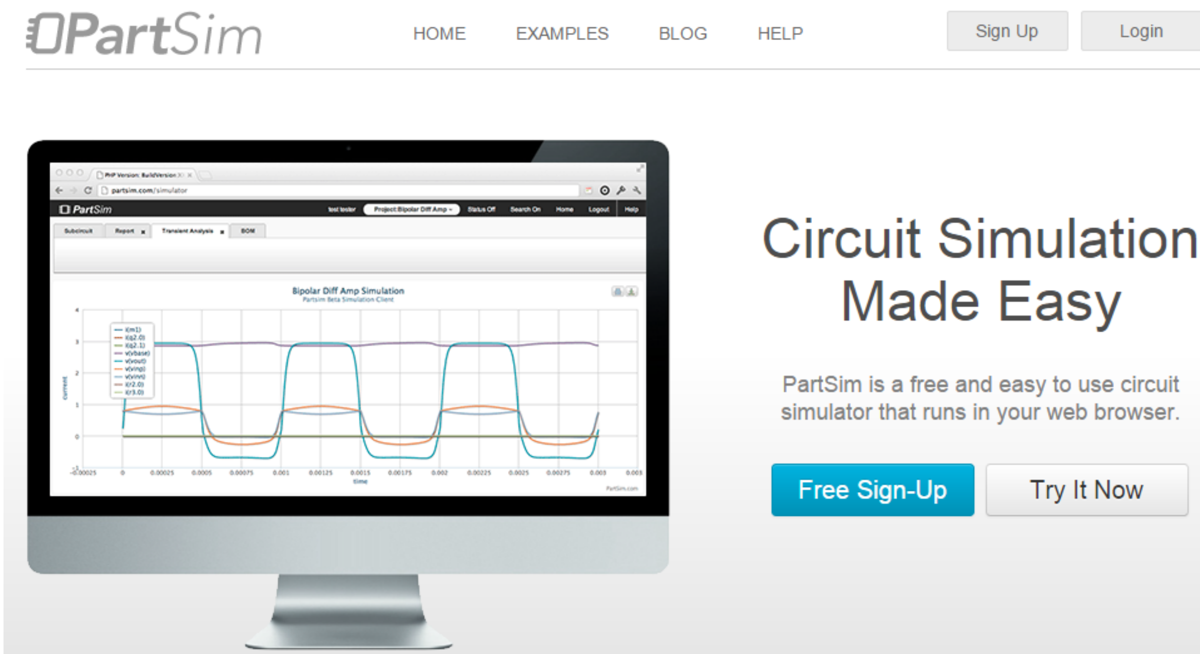
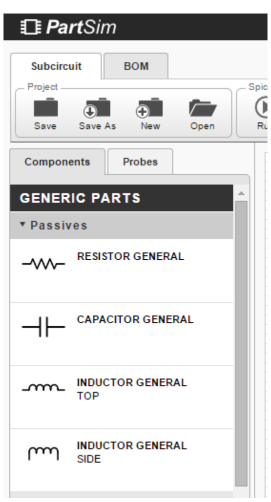


Figure F.1: Landing page of www.parstim.com

After sign up and login, you can click "New Project" to create a new blank project.

Getting the components On the left, there is the "Components" tab.



The resistors are under "Passives."
Similarly, voltage and current sources are under "Sources".
Voltmeter and Ammeter are under "Test Equipment".
Ground is located under "Ports".

Figure F.2: Resistors are under passives.

When you 'click' on a resistor, and move your mouse pointer to right, you will be able to place the circuit element by clicking it at the desired position. To rotate by 90 degrees, press 'R' in keyboard. You can double click on any node and rename it.

The resistors come with the default value of 1KΩ. Double clicking any component pops up the properties. You can easily change values there by typing in the desired number.

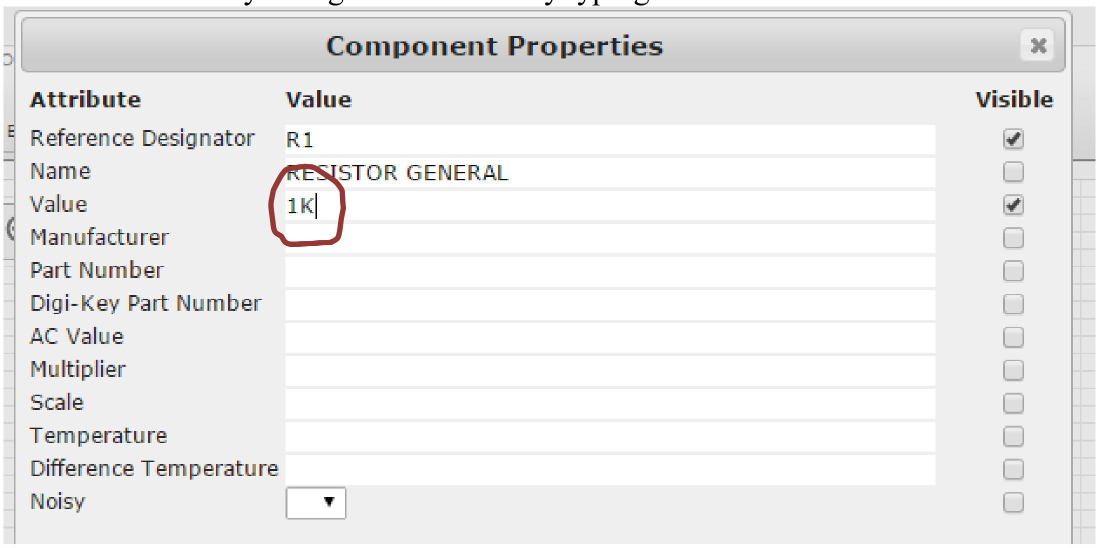


Figure F.3: Component properties for resistors.

However, there are some 'rules' that we need to follow while drawing in PartSim. Drawing wires can be a little bit difficult at the beginning. Place your mouse pointer at the terminal end of any component and move-click-move until you reach your next connection point.

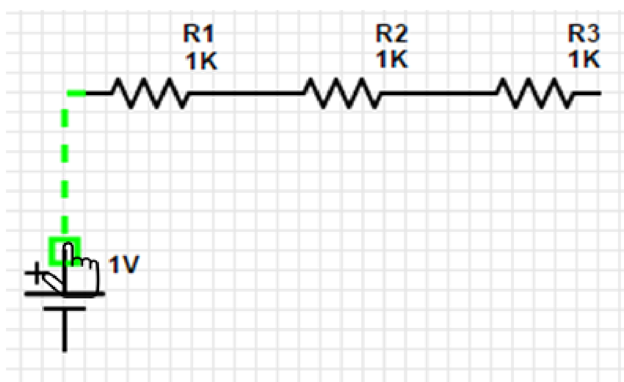


Figure F.4: Drawing wires in PartSim

Simple Circuit Simulation

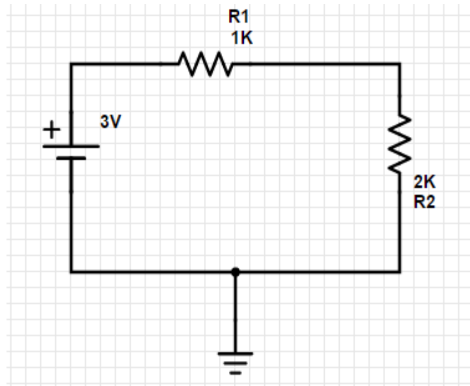
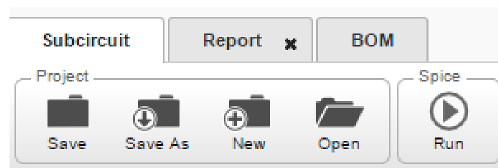
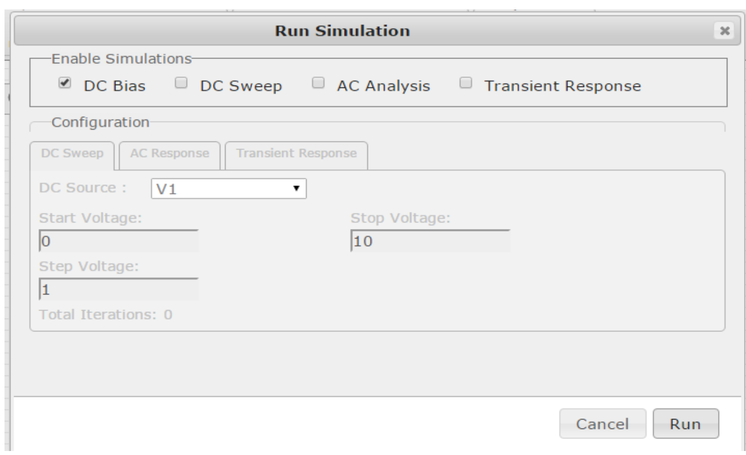


Figure F.5: Schematic of a simple circuit

After building the circuit, save it and you can click and'Run' on the top of the screen.



It will pop up the "Run Simulation" menu. Check "DC Bias" and hit "Run"



After that, the voltages and currents will be visible is different nodes and branches.

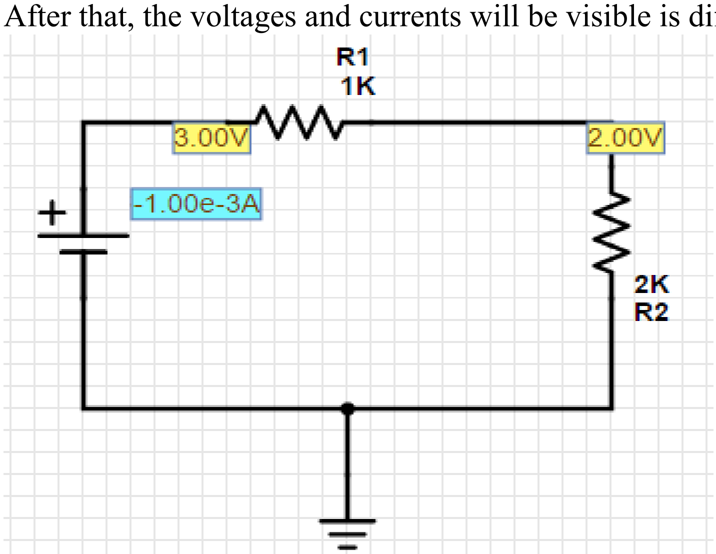


Figure F.6: We can see 2.00V and 3.00V at two nodes. The current is 1mA. The negative sign indicates that the current is coming out of the voltage source (it is delivering power).

However, sometimes PartSim gives erroneous result for some circuits if the circuit is drawn that way. Instead, drawing with multiple grounds eliminates such problems.

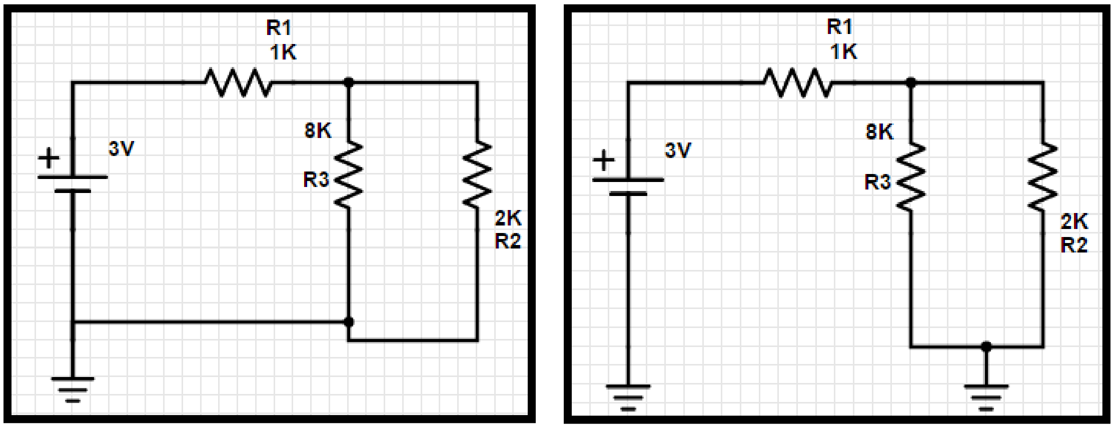


Figure F.7: The figure on the right is preferred to the one on the left.

Ensuring proper connection Make sure your components are 'connected' not just touching. See figure F.8 for details.

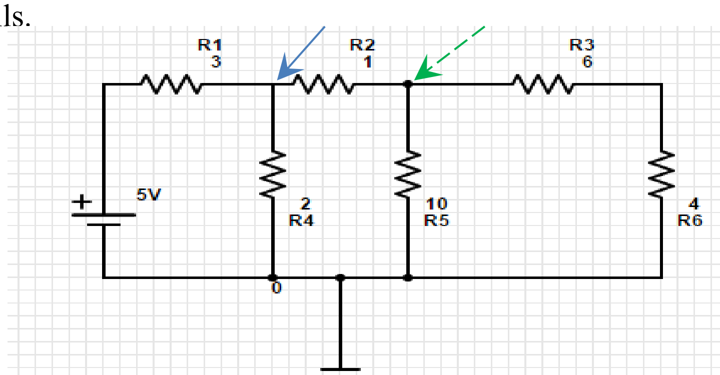
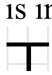


Figure F.8: The solid arrow points to a 'not properly connected' node

R4 (2Ω) is not connected at the node where R1 and R2 meets! (pointed by the solid arrow) However, R4 (10Ω) is connected properly at the node where R2 and R3 meets. (pointed by a dashed arrow). It is indicated by the black circle, and can be found by comparing the nodes' appearances. this  means not connected with three branches. This  means connected with all three branches.
Running simulation on this kind of node will produce some errors (like two voltages at one node). See Figure F.9 for such an example.

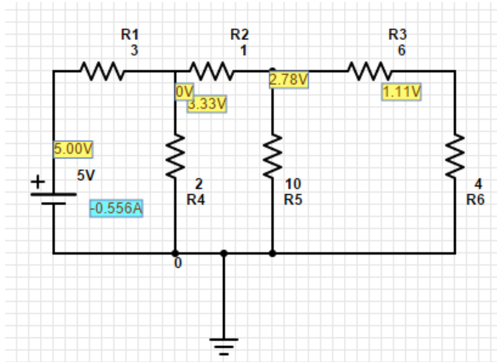


Figure F.9: Simulation run on not connected node.

Here, 0V is shown for R4, and the 3.333V is shown for the node where R1 and R2 meet. To eliminate this, we will redraw the connection from R4 to that node.

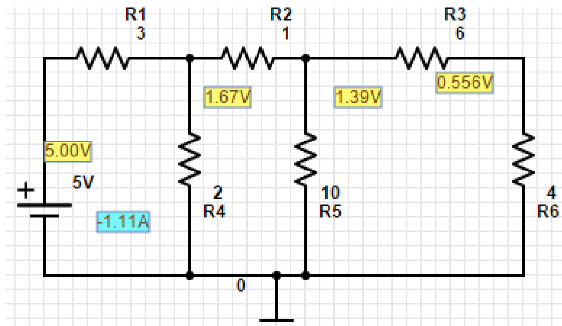


Figure F.10: R4 is properly connected.

Current Measuremnt Due to some bugs on the PartSim server, Ammeters may not work. The way around this is to put 'dummy' voltage sources (of 0V) in branches. Then, we will be able to see the currents through each branch. It might be noted that the current is shown 'positive' if it enters through the + terminal and leaves from - . If the current comes out of + , then the sign will be shown 'negative'. One such example can be found at http://www.partsim.com/simulator#35910

Further reading:

- http://www.partsim.com/help/ (This also has video demonstration)
- http://www.partsim.com/examples/