Class: First Stage
Subject: Electrical Tech. Laborotory
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Laboratory Manual

for

DC Electrical Circuit Analysis

(Part one)

Supervised by:

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Zainulabdeen.J (ENG)

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The Electrical Laboratory

Objective

The laboratory emphasizes the practical, hands-on component of this course. It complements the theoretical material presented in lecture, and as such, is integral and indispensible to the mastery of the subject. There are several items of importance here including proper safety procedures, required tools, and laboratory reports. This exercise will finish with an examination of scientific and engineering notation, the standard form of representing and manipulating values.

Lab Safety and Tools

If proper procedures are followed, the electrical lab is a perfectly safe place in which to work. There are some basic rules: No food or drink is allowed in lab at any time. Liquids are of particular danger as they are ordinarily conductive. While the circuitry used in lab is normally of no shock hazard, some of the test equipment may have very high internal voltages that could be lethal (in excess of 10,000 volts). Spilling a bottle of water or soda onto such equipment could leave the experimenter in the receiving end of a severe shock. Similarly, items such as books and jackets should not be left on top of the test equipment as it could cause overheating.

Each lab bench is self contained. All test equipment is arrayed along the top shelf. Beneath this shelf at the back of the work area is a power strip. All test equipment for this bench should be plugged into this strip. None of this equipment should be plugged into any other strip. This strip is controlled by a single circuit breaker which also controls the bench light. In the event of an emergency, all test equipment may be powered off through this one switch. Further, the benches are controlled by dedicated circuit breakers in the front of the lab. Next to this main power panel is an A/B/C class fire extinguisher suitable for electrical fires. Located at the rear of the lab is a safety kit. This contains bandages, cleaning swaps and the like for small cuts and the like. For serious injury, the Security Office will be contacted.

A lab bench should always be left in a secure mode. This means that the power to each piece of test equipment should be turned off, the bench itself should be turned off, all AC and DC power and signal sources should be turned down to zero, and all other equipment and components properly stowed with lab stools pushed under the bench.

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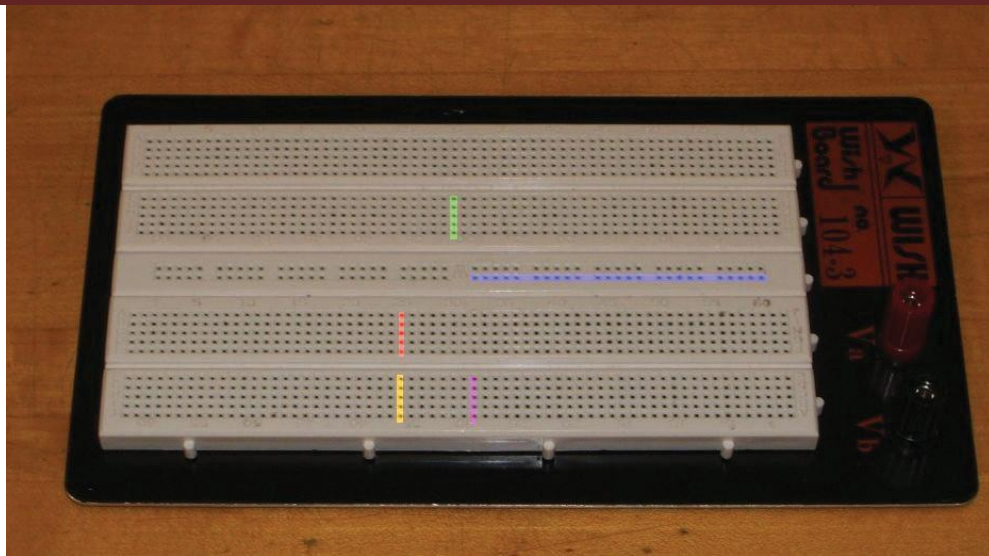**E-mail: Zain.alabdeen@uomus.edu.iq**

It is important to come prepared to lab. This includes the class text, the lab exercise for that day, class notebook, calculator, and hand tools. The tools include an electronic breadboard, test leads, wire strippers,and needle-nose pliers or hemostats. A small pencil soldering iron may also be useful. A basic DMM (digital multimeter) rounds out the list.

A typical breadboard or protoboard is shown below:

This particular unit features two main wiring sections with a common strip section down the center. Boards can be larger or smaller than this and may or may not have the mounting plate as shown. The connections are spaced 0.1 inch apart which is the standard spacing for many semiconductor chips. These are clustered in groups of five common terminals to allow multiple connections. The exception is the common strip which may have dozens of connection points. These are called *buses* and are designed for power and ground connections. Interconnections are normally made using small diameter solid hookup wire, usually AWG 22 or 24. Larger gauges may damage the board while smaller gauges do not always make good connections and are easy to break.

In the picture below, the color highlighted sections indicate common connection points. Note the long blue section which is a bus. This unit has four discrete buses available. When building circuits on a breadboard, it is important to keep the interconnecting wires short and the layout as neat as possible. This will aid both circuit functioning and ease of troubleshooting.

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Laboratory Reports

Unless specified otherwise, all lab exercises require a non-formal laboratory report. Lab reports are individual endeavors not group work. The deadline for reports is one week after the exercise is performed. A letter grade is subtracted for the first half-week late and two letter grades are subtracted for the second half-week late. Reports are not acceptable beyond one week late. A basic report should include a statement of the Objective (i.e., those items under investigation), a Conclusion (what was found or verified), a Discussion (an explanation and analysis of the lab data which links the Objective to the Conclusion), Data Tables and Graphs, and finally, answers to any problems or questions posed in the exercise.

Scientific and Engineering Notation

Scientists and engineers often work with very large and very small numbers. The ordinary practice of using commas and leading zeroes proves to be very cumbersome in this situation. Scientific notation is more compact and less error prone method of representation. The number is split into two portions: a precision part (the mantissa) and a magnitude part (the exponent, being a power of ten). For example, the value 23,000 could be written as 23 times 10 to the 3rd power (that is, times one thousand). The exponent may be thought of in terms of how places the decimal point is moved to the left. Spelling this out is awkward, so a shorthand method is used where "times 10 to the X power" is replaced by the letter E (which stands for exponent). Thus, 23,000 could be written as 23E3. The value 45,000,000,000 would be written as 45E9. Note that it would also be possible to write this number as 4.5E10 or even 0.45E11. The

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only difference between scientific notation and engineering notation is that for engineering notation the exponent is always a multiple of three. Thus, 45E9 is proper engineering notation but 4.5E10 isn't. On most scientific calculators E is represented by either an "EE" or "EXP" button. The process of entering thevalue 45E9 would be depressing the keys 4 5 EE 9.

For fractional values, the exponent is negative and may be thought of in terms how many places the decimal point must be moved to the right. Thus, 0.00067 may be written as 0.67E−3 or 6.7E−4 or even 670E−6. Note that only the first and last of these three are acceptable as engineering notation.

Engineering notation goes one step further by using a set of prefixes to replace the multiples of three for the exponent. The prefixes are:

E12 = Tera (T)	E9 = Giga (G)	E6 = Mega (M)	E3 = kilo (k)
E−3 = milli (m)	E−6 = micro (µ)	E−9 = nano (n)	E−12 = pico (p)

Thus, 23,000 volts could be written as 23E3 volts or simply 23 kilovolts.
Besides being more compact, this notation is much simpler than the ordinary form when manipulating wide ranging values. When multiplying, simply multiply the precision portions and add the exponents. Similarly, when dividing, divide the precision portions and subtract the exponents. For example, 23,000 times 0.000003 may appear to be a complicated task. In engineering notation this is 23E3 times 3E−6. The result is 69E−3 (that is, 0.069). Given enough practice it will become second nature that kilo (E3) times micro (E−6) yields milli (E−3). This will facilitate lab estimates a great deal. Continuing, 42,000,000 divided by 0.002 is 42E6 divided by 2E−3, or 21E9 (the exponent is 6 minus a negative 3, or 9).

When adding or subtracting, first make sure that the exponents are the same (scaling if required) and then add or subtract the precision portions. For example, 2E3 plus 5E3 is 7E3. By comparison, 2E3 plus 5E6 is the same as 2E3 plus 5000E3, or 5002E3 (or 5.002E6).

Perform the following operations. Convert the following into scientific and engineering notation.

1. 1,500	2. 63,200,000
3. 0.0234	4. 0.000059
5. 170	

Convert the following into normal longhand notation:

6. 1.23E3	7. 54.7E6
8. 2E−3	9. 27E−9
10. 4.39E7	

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Use the appropriate prefix for the following:

11. 4E6 volts   12. 5.1E3 feet
13. 3.3E–6 grams

Perform the following operations:

14. 5.2E6 + 1.7E6   15. 12E3 – 900
16. 1.7E3 • 2E6   17. 48E3 / 4E6
18. 20 / 4E3   19. 10 M • 2 k
20. 8 n / 2 m

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Resistor Color Code

Objective

The objective of this exercise is to become familiar with the measurement of resistance values using a digital multimeter (DMM). A second objective is to learn the resistor color code.

Theory Overview

The resistor is perhaps the most fundamental of all electrical devices. Its fundamental attribute is the restriction of electrical current flow: The greater the resistance, the greater the restriction of current. Resistance is measured in ohms. The measurement of resistance in unpowered circuits may be performed with a digital multimeter. Like all components, resistors cannot be manufactured to perfection. That is, there will always be some variance of the true value of the component when compared to its nameplate or nominal value. For precision resistors, typically 1% tolerance or better, the nominal value is usually printed directly on the component. Normally, general purpose components, i.e. those worse than 1%, usually use a color code to indicate their value.

The resistor color code typically uses 4 color bands. The first two bands indicate the precision values (i.e. the mantissa) while the third band indicates the power of ten applied (i.e. the number of zeroes to add). The fourth band indicates the tolerance. It is possible to find resistors with five or six bands but they will not be examined in this exercise. Examples are shown below:

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It is important to note that the physical size of the resistor indicates its power dissipation rating, not itsohmic value.

Each color in the code represents a numeral. It starts with black and finishes with white, going through the rainbow in between:

0 Black	1 Brown	2 Red	3 Orange	4 Yellow
5 Green	6 Blue	7 Violet	8 Gray	9 White

For the fourth, or tolerance, band:
5% Gold   10% Silver   20% None

For example, a resistor with the color code brown-red-orange-silver would correspond to 1 2 followed by 3 zeroes, or 12,000 ohms (more conveniently, 12 k ohms). It would have a tolerance of 10% of 12 k ohms or 1200 ohms. This means that the actual value of any particular resistor with this code could be anywhere between $12,000 - 1200 = 10,800$, to $12,000 + 1200 = 13,200$. That is, 10.8 k to 13.2 k ohms. Note, the IEC standard replaces the decimal point with the engineering prefix, thus 1.2 k is alternately written 1k2.

Similarly, a 470 k 5% resistor would have the color code yellow-violet-yellow-gold. To help remember the color code many mnemonics have been created using the first letter of the colors to create a sentence. One example is the *picnic mnemonic* **B**lack **B**ears **R**obbed **O**ur **Y**ummy **G**oodies **B**eating **V**arious **G**ray **W**olves.

Measurement of resistors with a DMM is a very straight forward process. Simply set the DMM to the resistance function and choose the first scale that is higher than the expected value. Clip the leads to the resistor and record the resulting value.

Equipment

 (1) Digital multimeter   model:_____srn:_____

Procedure

1. Given the nominal values and tolerances in Table 3.1, determine and record the corresponding color code bands.

2. Given the color codes in Table 3.2, determine and record the nominal value, tolerance and the minimum and maximum acceptable values.

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3. Obtain a resistor equal to the first value listed in Table 3.3. Determine the minimum and maximum acceptable values based on the nominal value and tolerance. Record these values in Table 3.3. Using the DMM, measured the actual value of the resistor and record it in Table 3.3. Determine the deviation percentage of this component and record it in Table 3.3. The deviation percentage may be found via: Deviation = 100 * (measured − nominal)/nominal. *Circle the deviation if the resistor is out of tolerance.*

4. Repeat Step 3 for the remaining resistor in Table 3.3.

Data Tables

Value	Band 1	Band 2	Band 3	Band 4
27 @ 10%				
56 @ 10%				
180 @ 5%				
390 @ 10%				
680 @ 5%				
1.5 k @ 20%				
3.6 k @ 10%				
7.5 k @ 5%				
10 k @ 5%				
47 k @ 10%				
820 k @ 10%				
2.2 M @ 20 %				

Table 3.1

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Colors	Nominal	Tolerance	Minimum	Maximum
red-red-black-silver				
blue-gray-black-gold				
brown-green-brown-gold				
orange-orange-brown-silver				
green-blue-brown –gold				
brown-red-red–silver				
red-violet-red–silver				
gray-red-red–gold				
brown-black-orange–gold				
orange-orange-orange–silver				
blue-gray-yellow–none				
green-black-green-silver				

Table 3.2

Value	Minimum	Maximum	Measured	Deviation
22 @ 10%				
68 @ 5%				
150 @ 5%				
330 @ 10%				
560 @ 5%				
1.2 k @ 5%				
2.7 k @ 10%				
8.2 k @ 5%				
10 k @ 5%				
33 k @ 10%				
680 k @ 10%				
5 M @ 20 %				

Table 3.3

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Questions

1. What is the largest deviation in Table 3.3? Would it ever be possible to find a value that is outside the stated tolerance? Why or why not?

2. If Steps 3 and 4 were to be repeated with another batch of resistors, would the final two columns be identical to the original Table 3.3? Why or why not?

3. Do the measured values of Table 3.3 represent the exact values of the resistors tested? Why or why not?

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Ohm's Law

Objective

This exercise examines Ohm's law, one of the fundamental laws governing electrical circuits. It states that voltage is equal to the product of current times resistance.

Theory Overview

Ohm's law is commonly written as V = I * R. That is, for a given current, an increase in resistance will result in a greater voltage. Alternately, for a given voltage, an increase in resistance will produce a decrease in current. As this is a first order linear equation, plotting current versus voltage for a fixed resistance will yield a straight line. The slope of this line is the conductance, and conductance is the reciprocal of resistance. Therefore, for a high resistance, the plot line will appear closer to the horizontal while a lower resistance will produce a more vertical plot line.

Equipment

(1) Adjustable DC power supply   model:_____ srn:_____
(1) Digital multimeter   model:_____ srn:_____
(1) 1 kΩ resistor   _____
(1) 6.8 kΩ resistor   _____
(1) 33 kΩ resistor   _____

Schematic

Figure 4.1

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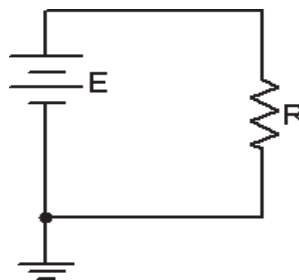**E-mail: OmarAhmed@uomus.edu.iq**
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Procedure

1. Build the circuit of Figure 4.1 using the 1 kΩ resistor. Set the DMM to measure DC current and insert it in-line between the source and resistor. Set the source for zero volts. Measure and record the current in Table 4.1. Note that the theoretical current is 0 and any measured value other than 0 would produce an undefined percent deviation.

2. Setting E at 2 volts, determine the theoretical current based on Ohm's law and record this in Table 4.1. Measure the actual current, determine the deviation, and record these in Table 4.1. Note that Deviation = 100 * (measured − theory) / theory.

3. Repeat step 2 for the remaining source voltages in Table 4.1.

4. Remove the 1 kΩ and replace it with the 6.8 kΩ. Repeat steps 1 through 3 using Table 4.2.

5. Remove the 6.8 kΩ and replace it with the 33 kΩ. Repeat steps 1 through 3 using Table 4.3.

6. Using the measured currents from Tables 4.1, 4.2, and 4.3, create a plot of current versus voltage. Plot all three curves on the same graph. Voltage is the horizontal axis and current is the vertical axis.

Data Tables

E (volts)	I theory	I measured	Deviation
0	0		
2			
4			
6			
8			
10			
12			

Table 4.1 (1 kΩ)

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E (volts)	I theory	I measured	Deviation
0	0		
2			
4			
6			
8			
10			
12			

Table 4.2 (6.8 kΩ)

E (volts)	I theory	I measured	Deviation
0	0		
2			
4			
6			
8			
10			
12			

Table 4.3 (33 kΩ)

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Questions

1. Does Ohm's law appear to hold in this exercise?

2. Is there a linear relationship between current and voltage?

3. What is the relationship between the slope of the plot line and the circuit resistance?

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Series-Parallel DC Circuits

Objective

This exercise will involve the analysis of basic series-parallel DC circuits with resistors. The use of simple series-only and parallel-only sub-circuits is examined as one technique to solve for desired currents and voltages.

Theory Overview

Simple series-parallel networks may be viewed as interconnected series and parallel sub-networks. Each of these sub-networks may be analyzed through basic series and parallel techniques such as the application of voltage divider and current divider rules along with Kirchhoff's voltage and current laws. It is important to identify the most simple series and parallel connections in order to jump to more complex interconnections.

Equipment

(1) Adjustable DC power supply   model:_____ srn:_____
(1) Digital multimeter   model:_____ srn:_____
(1) 1 kΩ   _____
(1) 2.2 kΩ   _____
(1) 3.3 kΩ   _____
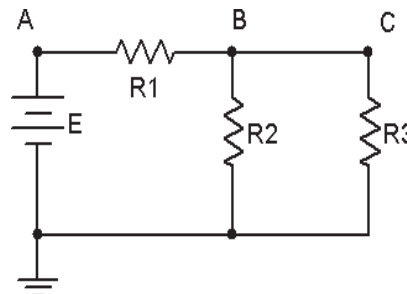(1) 4.7 kΩ   _____
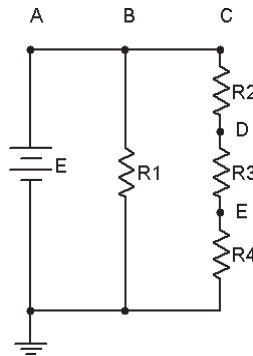(1) 6.8 kΩ   _____

Schematics

Figure 7.1

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Figure 7.2

Procedure

1. Consider the circuit of Figure 7.1 with R1 = 1 k, R2 = 2.2 k, R3 = 4.7 k and E = 10 volts. R2 is in parallel with R3. This combination is in series with R1. Therefore, the R2, R3 pair may be treated as a single resistance to form a series loop with R1. Based on this observation, determine the theoretical voltages at points A, B, and C with respect to ground. Record these values in Table 7.1. Construct the circuit. Set the DMM to read DC voltage and apply it to the circuit from point A to ground. Record this voltage in Table 7.1. Repeat the measurements at points B and C, determine the deviations, and record the values in Table 7.1.

2. Applying KCL to the parallel sub-network, the current entering node B (i.e., the current through R1) should equal the sum of the currents flowing through R2 and R3. These currents may be determined through Ohm's law and/or the current divider rule. Compute these currents and record them in Table 7.2. Using the DMM as an ammeter, measure these three currents and record the values along with deviations in Table 7.2.

3. Consider the circuit of Figure 7.2. R2, R3 and R4 create a series sub-network. This sub-network is in parallel with R1. By observation then, the voltages at nodes A, B and C should be identical as in any parallel circuit of similar construction. Due to the series connection, the same current flows through R2, R3 and R4. Further, the voltages across R2, R3 and R4 should sum up to the voltage at node C, as in any similarly constructed series network. Finally, via KCL, the current exiting the source must equal the sum of the currents entering R1 and R2.

4. Build the circuit of Figure 7.2 with R1 = 3.3 k, R2 = 2.2 k, R3 = 4.7 k, R4 = 6.8 k and E = 20 volts. Using the series and parallel relations noted in Step 3, calculate the voltages at points B, C, D and E. Measure these potentials with the DMM, determine the deviations, and record the values in Table 7.3.

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5. Calculate the currents leaving the source and flowing through R1 and R2.
    Record these values in Table 7.4. Using the DMM as an ammeter, measure those same currents,
    compute the deviations, and record the results in Table 7.4.

Simulation

6. Build the circuit of Figure 7.1 in a simulator. Using the virtual DMM as a voltmeter determine the
    voltages at nodes A, B and C, and compare these to the theoretical and measured values recorded
    in Table 7.1.

7. Build the circuit of Figure 7.2 in a simulator. Using the DC Operating Point simulation function,
    determine the voltages at nodes B, C, D and E, and compare these to the theoretical and measured
    values recorded in Table 7.3.

Data Tables

Voltage	Theory	Measured	Deviation
V_A			
V_B			
V_C			

Table 7.1

Current	Theory	Measured	Deviation
R_1			
R_2			
R_3			

Table 7.2

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Voltage	Theory	Measured	Deviation
V_B			
V_C			
V_D			
V_E			

Table 7.3

Current	Theory	Measured	Deviation
Source			
R1			
R2			

Table 7.4

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Questions

1. Are KVL and KCL satisfied in Tables 7.1 and 7.2?

2. Are KVL and KCL satisfied in Tables 7.3 and 7.4?

3. How would the voltages at A and B in Figure 7.1 change if a fourth resistor equal to 10 k was added in parallel with R3? What if this resistor was added in series with R3?

4. How would the currents through R1 and R2 in Figure 7.2 change if a fifth resistor equal to 10 k was added in series with R1? What if this resistor was added in parallel with R1?

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Superposition Theorem

Objective

The objective of this exercise is to investigate the application of the superposition theorem to multiple DC source circuits in terms of both voltage and current measurements. Power calculations will also be examined.

Theory Overview

The superposition theorem states that in a linear bilateral multi-source DC circuit, the current through or voltage across any particular element may be determined by considering the contribution of each source independently, with the remaining sources replaced with their internal resistance. The contributions are then summed, paying attention to polarities, to find the total value. Superposition cannot in general be applied to non-linear circuits or to non-linear functions such as power.

Equipment

(1) Adjustable dual DC power supply   model:_____srn:_____
(1) Digital multimeter   model:_____srn:_____
(1) 4.7 kΩ   _____
(1) 6.8 kΩ   _____
(1) 10 kΩ   _____
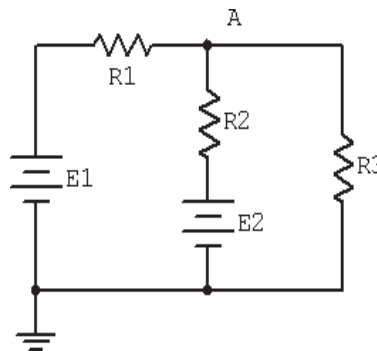(1) 22 kΩ   _____
(1) 33 kΩ   _____

Schematics

Figure 10.1

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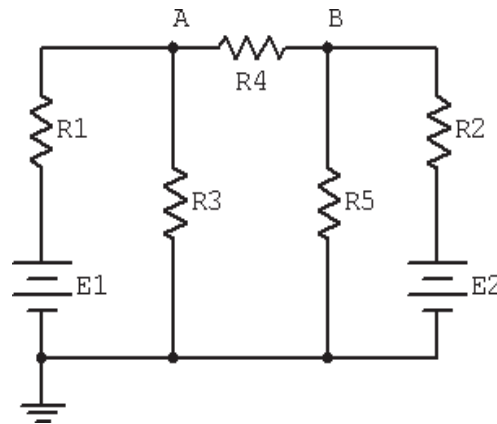**E-mail: OmarAhmed@uomus.edu.iq**
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Figure 10.2

Procedure

Voltage Application

1. Consider the dual supply circuit of Figure 10.1 using E1 = 10 volts, E2 = 15 volts, R1 = 4.7 k,
    R2 = 6.8 k and R3 = 10 k. To find the voltage from node A to ground, superposition may be used.
    Each source is considered by itself. First consider source E1 by assuming that E2 is replaced with its
    internal resistance (a short). Determine the voltage at node A using standard series-parallel techniques
    and record it in Table 10.1. Make sure to indicate the polarity. Repeat the process using E2 while
    shorting E1. Finally, sum these two voltages and record in Table 10.1.

2. To verify the superposition theorem, the process may be implemented directly by measuring the
    contributions. Build the circuit of Figure 10.1 with the values specified in step 1, however, replace E2
    with a short. Do **not** simply place a shorting wire across source E2! This will overload the power
    supply.

3. Measure the voltage at node A and record in Table 10.1. Be sure to note the polarity.

4. Remove the shorting wire and insert source E2. Also, replace source E1 with a short. Measure the
    voltage at node A and record in Table 10.1. Be sure to note the polarity.

5. Remove the shorting wire and re-insert source E1. Both sources should now be in the circuit. Measure
    the voltage at node A and record in Table 10.1. Be sure to note the polarity. Determine and record the
    deviations between theory and experimental results.

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6. Consider the dual supply circuit of Figure 10.2 using E1 = 10 volts, E2 = 15 volts, R1 = 4.7 k, R2 = 6.8 k, R3 = 10 k, R4 = 22 k and R5 = 33 k. To find the current through R4 flowing from node A to B, superposition may be used. Each source is again treated independently with the remaining sources replaced with their internal resistances. Calculate the current through R4 first considering E1 and then considering E2. Sum these results and record the three values in Table 10.2.

7. Assemble the circuit of Figure 10.2 using the values specified. Replace source E2 with a short and measure the current through R4. Be sure to note the direction of flow and record the result in Table 10.2.

8. Replace the short with source E2 and swap source E1 with a short. Measure the current through R4. Be sure to note the direction of flow and record the result in Table 10.2.

9. Remove the shorting wire and re-insert source E1. Both sources should now be in the circuit. Measure the current through R4 and record in Table 10.2. Be sure to note the direction. Determine and record the deviations between theory and experimental results.

10. Power is not a linear function as it is proportional to the square of either voltage or current. Consequently, superposition should not yield an accurate result when applied directly to power. Based on the measured currents in Table 10.2, calculate the power in R4 using E1-only and E2-only and record the values in Table 10.3. Adding these two powers yields the power as predicted by superposition. Determine this value and record it in Table 10.3. The true power in R4 may be determined from the total measured current flowing through it. Using the experimental current measured when both E1 and E2 were active (Table 10.2), determine the power in R4 and record it in Table 10.3.

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Simulation

11. Build the circuit of Figure 10.2 in a simulator. Using the virtual DMM as an ammeter, determine the current through resistor R4 and compare it to the theoretical and measured values recorded in Table 10.2.

Data Tables

Source	V_A Theory	V_A Experimental	Deviation
E1 Only			
E2 Only			
E1 and E2			

Table 10.1

Source	I_{R4} Theory	I_{R4} Experimental	Deviation
E1 Only			
E2 Only			
E1 and E2			

Table 10.2

Source	P_{R4}
E1 Only	
E2 Only	
E1 + E2	
E1 and E2	

Table 10.3

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Questions

1. Based on the results of Tables 10.1, 10.2 and 10.3, can superposition be applied successfully to voltage, current and power levels in a DC circuit?

2. If one of the sources in Figure 10.1 had been inserted with the opposite polarity, would there be a significant change in the resulting voltage at node A? Could both the magnitude and polarity change?

3. If both of the sources in Figure 10.1 had been inserted with the opposite polarity, would there be a significant change in the resulting voltage at node A? Could both the magnitude and polarity change?

4. Why is it important to note the polarities of the measured voltages and currents?

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Thévenin's Theorem

Objective

The objective of this exercise is to examine the use of Thévenin's Theorem to create simpler versions of DC circuits as an aide to analysis. Multiple methods of experimentally obtaining the Thévenin resistance will be explored.

Theory Overview

Thévenin's Theorem for DC circuits states that any two port linear network may be replaced by a single voltage source with an appropriate internal resistance. The Thévenin equivalent will produce the same load current and voltage as the original circuit to any load. Consequently, if many different loads or sub-circuits are under consideration, using a Thévenin equivalent may prove to be a quicker analysis route than "reinventing the wheel" each time.

The Thévenin voltage is found by determining the open circuit output voltage. The Thévenin resistance is found by replacing any DC sources with their internal resistances and determining the resulting combined resistance as seen from the two ports using standard series-parallel analysis techniques. In the laboratory, the Thévenin resistance may be found using an ohmmeter (again, replacing the sources with their internal resistances) or by using the matched load technique. The matched load technique involves replacing the load with a variable resistance and then adjusting it until the load voltage is precisely one half of the unloaded voltage. This would imply that the other half of the voltage must be dropped across the equivalent Thévenin resistance, and as the Thévenin circuit is a simple series loop then the two resistances must be equal as they have identical currents and voltages.

Equipment

(1) Adjustable DC power supply   model:_____ srn:_____
(1) Digital multimeter   model:_____ srn:_____
(1) 2.2 kΩ   _____
(1) 3.3 kΩ   _____
(1) 4.7 kΩ   _____
(1) 6.8 kΩ   _____
(1) 8.2 kΩ   _____
(1) 10 k potentiometer or resistance decade box

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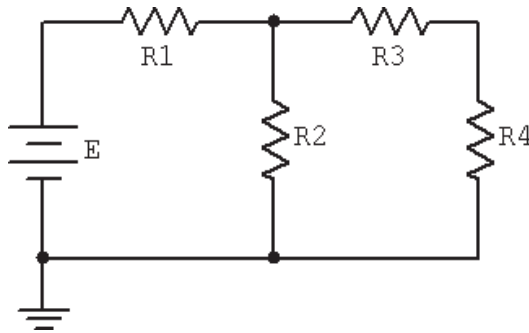
Schematics

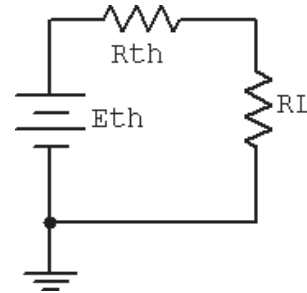Figure 11.1   Figure 11.2

Procedure

1. Consider the circuit of Figure 11.1 using E = 10 volts, R1 = 3.3 k, R2 = 6.8 k, R3 = 4.7 k and R4 (R_{Load}) = 8.2 k. This circuit may be analyzed using standard series-parallel techniques. Determine the voltage across the load, R4, and record it in Table 11.1. Repeat the process using 2.2 k for R4.

2. Build the circuit of Figure 11.1 using the values specified in step one, with R_{Load} = 8.2 k. Measure the load voltage and record it in Table 11.1. Repeat this with a 2.2 k load resistance. Determine and record the deviations. Do not deconstruct the circuit.

3. Determine the theoretical Thévenin voltage of the circuit of Figure 11.1 by finding the open circuit output voltage. That is, replace the load with an open and calculate the voltage produced between the two open terminals. Record this voltage in Table 11.2.

4. To calculate the theoretical Thévenin resistance, first remove the load and then replace the source with its internal resistance (ideally, a short). Finally, determine the combination series-parallel resistance as seen from the where the load used to be. Record this resistance in Table 11.2.

5. The experimental Thévenin voltage maybe determined by measuring the open circuit output voltage. Simply remove the load from the circuit of step one and then replace it with a voltmeter. Record this value in Table 11.2.

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6. There are two methods to measure the experimental Thévenin resistance. For the first method, using the circuit of step one, replace the source with a short. Then replace the load with the ohmmeter. The Thévenin resistance may now be measured directly. Record this value in Table 11.2.

7. In powered circuits, ohmmeters are not effective while power is applied. An alternate method relies on measuring the effect of the load resistance. Return the voltage source to the circuit, replacing the short from step six. For the load, insert either the decade box or the potentiometer. Adjust this device until the load voltage is half of the open circuit voltage measured in step five and record in Table 11.2 under "Method 2". At this point, the load and the Thévenin resistance form a simple series loop as seen in Figure 11.2. This means that they "see" the same current. If the load exhibits one half of the Thévenin voltage then the other half must be dropped across the Thévenin resistance, in other words $V_{RL} = V_{RTH}$. Consequently, the resistances have the same voltage and current, and therefore must have the same resistance according to Ohm's law.

8. Consider the Thévenin equivalent of Figure 11.2 using the theoretical E_{TH} and R_{TH} from Table 11.2 along with 8.2 k for the load (RL). Calculate the load voltage and record it in Table 11.3. Repeat the process for a 2.2 k load.

9. Build the circuit of Figure 11.2 using the measured E_{TH} and R_{TH} from Table 11.2 along with 8.2 k for the load (RL). Measure the load voltage and record it in Table 11.3. Also determine and record the deviation.

10. Repeat step nine using a 2.2 k load.

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Data Tables

Original Circuit

R_4 (Load)	V_{Load} Theory	V_{Load} Experimental	Deviation
8.2 k			
2.2 k			

Table 11.1

Thévenized Circuit

	Theory	Experimental
E_{TH}		
R_{TH}		
R_{TH} Method 2	X	

Table 11.2

R_4 (Load)	V_{Load} Theory	V_{Load} Experimental	Deviation
8.2 k			
2.2 k			

Table 11.3

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Questions

1. Do the load voltages for the original and Thévenized circuits match for both loads? Is it logical that this could be extended to any arbitrary load resistance value?

2. Assuming several loads were under consideration, which is faster, analyzing each load with the original circuit of Figure 11.1 or analyzing each load with the Thévenin equivalent of Figure 11.2?

3. How would the Thévenin equivalent computations change if the original circuit contained more than one voltage source?

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Maximum Power Transfer

Objective

The objective of this exercise is to determine the conditions under which a load will produce maximum power. Further, the variance of load power and system efficiency will be examined graphically.

Theory Overview

In order to achieve the maximum load power in a DC circuit, the load resistance must equal the driving resistance, that is, the internal resistance of the source. Any load resistance value above or below this will produce a smaller load power. System efficiency (η) is 50% at the maximum power case. This is because the load and the internal resistance form a basic series loop, and as they have the same value, they must exhibit equal currents and voltages, and hence equal powers. As the load increases in resistance beyond the maximizing value the load voltage will rise, however, the load current will drop by a greater amount yielding a lower load power. Although this is not the maximum load power, this will represent a larger percentage of total power produced, and thus a greater efficiency (the ratio of load power to total power).

Equipment

(1) Adjustable DC power supply   model:_____ srn:_____
(1) Digital multimeter   model:_____ srn:_____
(1) Resistance decade box
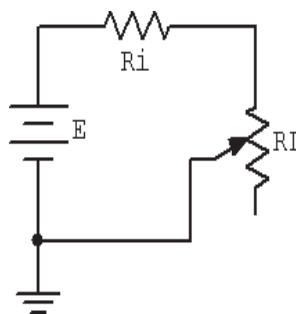(1) 3.3 kΩ _____

Schematics

Figure 12.1

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Procedure

1. Consider the simple the series circuit of Figure 12.1 using E = 10 volts and Ri = 3.3 k. Ri forms a simple voltage divider with RL. The power in the load is VL^2/RL and the total circuit power is $E^2/(Ri+RL)$. The larger the value of RL, the greater the load voltage, however, this does not mean that very large values of RL will produce maximum load power due to the division by RL. That is, at some point VL^2 will grow more slowly than RL itself. This crossover point should occur when RL is equal to Ri. Further, note that as RL increases, total circuit power decreases due to increasing total resistance. This should lead to an increase in efficiency. An alternate way of looking at the efficiency question is to note that as RL increases, circuit current decreases. As power is directly proportional to the square of current, as RL increases the power in Ri must decrease leaving a larger percentage of total power going to RL.

2. Using RL = 30, compute the expected values for load voltage, load power, total power and efficiency, and record them in Table 12.1. Repeat for the remaining RL values in the Table. For the middle entry labeled Actual, insert the measured value of the 3.3 k used for Ri.

3. Build the circuit of Figure 12.1 using E = 10 volts and Ri = 3.3 k. Use the decade box for RL and set it to 30 ohms. Measure the load voltage and record it in Table 12.2. Calculate the load power, total power and efficiency, and record these values in Table 12.2. Repeat for the remaining resistor values in the table.

4. Create two plots of the load power versus the load resistance value using the data from the two tables, one for theoretical, one for experimental. For best results make sure that the horizontal axis (RL) uses a log scaling instead of linear.

5. Create two plots of the efficiency versus the load resistance value using the data from the two tables, one for theoretical, one for experimental. For best results make sure that the horizontal axis (RL) uses a log scaling instead of linear.

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Data Tables

R_L	V_L	P_L	P_T	η
30				
150				
500				
1 k				
2.5 k				
Actual=				
4 k				
10 k				
25 k				
70 k				
300 k				

Table 12.1

R_L	V_L	P_L	P_T	η
30				
150				
500				
1 k				
2.5 k				
Actual=				
4 k				
10 k				
25 k				
70 k				
300 k				

Table 12.2

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Questions

1. At what point does maximum load power occur?

2. At what point does maximum total power occur?

3. At what point does maximum efficiency occur?

4. Is it safe to assume that generation of maximum load power is always a desired goal? Why/why not?

Laboratory Manual

for

AC Electrical Circuit Analysis

(Part Two)

Supervised by:

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1

The Oscilloscope

Objective

This exercise is of a particularly practical nature, namely, introducing the use of the oscilloscope. The various input scaling, coupling, and triggering settings are examined along with a few specialty features.

Theory Overview

The oscilloscope (or simply *scope*, for short) is arguably the single most useful piece of test equipment in an electronics laboratory. The primary purpose of the oscilloscope is to plot a voltage versus time although it can also be used to plot one voltage versus another voltage, and in some cases, to plot voltage versus frequency. Oscilloscopes are capable of measuring both AC and DC waveforms, and unlike typical DMMs, can measure AC waveforms of very high frequency (typically 100 MHz or more versus an upper limit of around 1 kHz for a general purpose DMM). It is also worth noting that a DMM will measure the RMS value of an AC sinusoidal voltage, not its peak value.

While the modern digital oscilloscope on the surface appears much like its analog ancestors, the internal circuitry is far more complicated and the instrument affords much greater flexibility in measurement. Modern digital oscilloscopes typically include measurement aides such as horizontal and vertical cursors or bars, as well as direct readouts of characteristics such as waveform amplitude and frequency. At a minimum, modern oscilloscopes offer two input measurement channels although four and eight channel instruments are increasing in popularity.

Unlike handheld DMMs, most oscilloscopes measure voltages with respect to ground, that is, the inputs are not floating and thus the black, or ground, lead is **always** connected to the circuit ground or common node. This is an extremely important point as failure to remember this may lead to the inadvertent short circuiting of components during measurement. The standard accepted method of measuring a non-ground referenced potential is to use two probes, one tied to each node of interest, and then setting the oscilloscope to subtract the two channels rather than display each separately. Note that this technique is not required if the oscilloscope has floating inputs (for example, in a handheld oscilloscope). Further, while it is possible to measure non-ground referenced signals by floating the oscilloscope itself through defeating the ground pin on the power cord, this is a safety violation and should not be done.

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Equipment

(1) DC power supply   model:_____ srn:_____
(1) AC function generator   model:_____ srn:_____
(1) Digital multimeter   model:_____ srn:_____
(1) Oscilloscope, Tektronix MDO 3000 series   model:_____ srn:_____

Components

(1) 10 kΩ   actual:_____
(1) 33 kΩ   actual:_____

Schematics and Diagrams

Figure 3A.1

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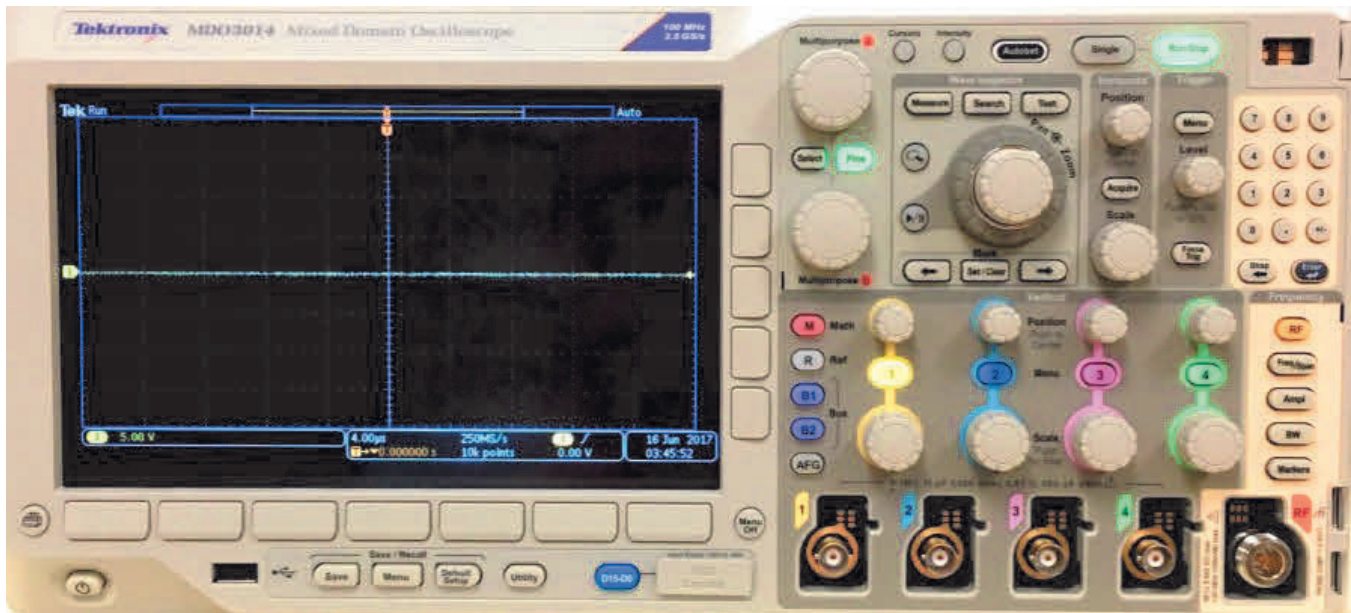E-mail: **OmarAhmed@uomus.edu.iq**
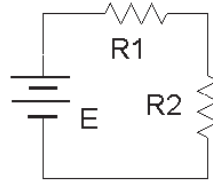E-mail: **Zain.alabdeen@uomus.edu.iq**

Figure 3A.2

Procedure

1. Figure 3A.1 is a photo of the face of a Tektronix MDO 3000 series oscilloscope. Compare this to the bench oscilloscope and identify the following elements:
   - Channel one through four BNC input connectors.
   - RF input connector and settings section.
   - Channel one through four select buttons.
   - Horizontal Scale (i.e., Sensitivity) and Position knobs.
   - Four Vertical Scale (i.e., Sensitivity) and Position knobs.
   - Trigger Level knob.
   - *Math* and *Measure* (in *Wave Inspector*) buttons.
   - *Save* button (below display).
   - *Autoset* button.
   - *Menu Off* button.

2. Note the numerous buttons along the bottom and side of the display screen. These menu buttons are context-sensitive and their function will depend on the most recently selected button or knob. Menus may be removed from the display by pressing the *Menu Off* button (multiple times for nested menus). Power up the oscilloscope. Note that the main display is similar to a sheet of graph paper. Each square will have an appropriate scaling factor or weighting, for example, 1 volt per division vertically or 2 milliseconds per division horizontally. Waveform voltages and timings may be determined directly from the display by using these scales.

3. Select the channel one and two buttons (yellow and blue) and also press the *Autoset* button. (Autoset tries to create reasonable settings based on the input signal and is useful as a sort of "panic button"). There should now be two horizontal lines on the display, one yellow and one blue. These traces may be moved vertically on the display via the associated Position knobs. Also, a trace can be removed by deselecting the corresponding channel button. The Vertical and Horizontal Scale knobs behave in a similar fashion and **do not** include calibration markings. That is because the settings for these knobs show up on the main display. Adjust the Scale knobs and note how the corresponding values at the bottom of the display change. Voltages are in a 1/2/5 scale sequence while Time is in a 1/2/4 scale sequence.

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4. When an input is selected, a menu will pop up allowing control over that input's basic settings. One of the more important fundamental settings on an oscilloscope channel is the *Input Coupling*. This is controlled via one of the bottom row buttons. There are two choices: *AC* allows only AC signals through thus blocking DC, and *DC* allows **all** signals through (it does **not** prevent AC).

5. Set the channel one Vertical Scale to 5 volts per division. Set the channel two Scale to 2 volts per division. Set the Time (Horizontal) Scale to 1 millisecond per division. Finally, set the input Coupling to DC for both input channels and align the blue and yellow display lines to the center line of the display via the Vertical Position knob (note that pushing the vertical Position knobs will automatically center the trace).

6. Build the circuit of figure 3A.2 using E=10 V, R1=10 kΩ and R2= 33kΩ. Connect a probe from the channel one input to the power supply (red or tip to the positive terminal, black clip to ground). Connect a second probe from channel two to R2 (again, red or tip to the high side of the resistor and the black clip to ground).

7. The yellow and blue lines should have deflected upward. Channel one should be raised two divisions (2 divisions at 5 volts per division yields the 10 volt source). Using this method, determine the voltage across R2 (remember, input two should have been set for 2 volts per division). Calculate the expected voltage across R2 using measured resistor values and compare the two in Table 3A.1. Note that it is not possible to achieve extremely high precision using this method (e.g., four or more digits). Indeed, a DMM is often more useful for direct measurement of DC potentials. Double check the results using a DMM and the final column of Table 3A.1.

8. Select AC Coupling for the two inputs. The flat DC lines should drop back to zero. This is because AC Coupling blocks DC. This will be useful for measuring the AC component of a combined AC/DC signal, such as might be seen in an audio amplifier. Set the input coupling for both channels back to DC.

9. Replace the DC power supply with the function generator. Set the function generator for a one volt peak sine wave at 1 kHz and apply it to the resistor network. The display should now show two small sine waves. Adjust the Vertical Scale settings for the two inputs so that the waves take up the majority of the display. If the display is very blurry with the sine waves appearing to jump about side to side, the Trigger Level may need to be adjusted. Also, adjust the Time Scale so that only one or two cycles of the wave may be seen. Using the Scale settings, determine the two voltages (following the method of step 7) as well as the waveform's period and compare them to the values expected via theory, recording the results in Tables 3A.2 and 3A.3. Also crosscheck the results using a DMM to measure the RMS voltages.

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10. To find the voltage across R1, the channel two voltage (V_{R2}) may be subtracted from channel one (E source) via the *Math* function. Use the red button to select the *Math* function and create the appropriate expression from the menu (ch1 – ch2). This display shows up in red. To remove a waveform, press its button again. Remove the math waveform before proceeding to the next step.

11. One of the more useful aspects of the oscilloscope is the ability to show the actual waveshape. This may be used, for example, as a means of determining distortion in an amplifier. Change the waveshape on the function generator to a square wave, triangle, or other shape and note how the oscilloscope responds. Note that the oscilloscope will also show a DC component, if any, as the AC signal being offset or "riding on the DC". Adjust the function generator to add a DC offset to the signal and note how the oscilloscope display shifts. Return the function generator back to a sine wave and remove any DC offset.

12. It is often useful to take precise differential measurement on a waveform. For this, the bars or cursors are useful. Select the *Cursors* button toward the top of the oscilloscope. From the menu on the display, select *Vertical Bars*. Two vertical bars will appear on the display (it is possible that one or both could be positioned off the main display). They may be moved left and right via the Multipurpose knobs (next to the Cursors button). The *Select* button toggles between independent and tandem cursor movement. A read out of the bar values will appear in the upper portion of the display. They indicate the positions of the cursors, i.e., the location where they cross the waveform. Vertical Bars are very useful for obtaining time information as well as amplitudes at specific points along the wave. A similar function is the Horizontal Bars which are particularly useful for determining amplitudes. Try the Horizontal Bars by selecting them via the Cursors menu again (holding the *Cursors* button will bring up the menu).

13. For some waveform parameters, automatic readings are available. These are accessed via the *Measure* button. Press *Measure*, select *Add Measurement*, and page through the various options using the Multipurpose b knob. Select *Frequency*. Note that a small readout of the frequency will now appear on the display. Multiple measurements are possible simultaneously. **Important:** There are specific limits on the proper usage of these measurements. If the guidelines are not followed, erroneous values may result. **Always** perform an approximation via the Scale factor and divisions method even when using an automatic measurement!

14. Finally, a snap-shot of the screen may be saved for future work using the USB port and a USB memory stick via the *Save Menu* button. The pop up menu has options for saving the image as well as the trace data or setup info. Select *Save Screen Image* to save a bit mapped graphics file that can be used as is or processed further in a graphics program (for example, inverting the colors for printing). The .PNG format is recommended.

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Data Tables

V_{R2}	Scale (V/Div)	Number of Divisions	Voltage Scope	Voltage DMM
Oscilloscope				
Theory	X	X		

Table 3.1

	Scale (V/Div)	Number of Divisions	Voltage Peak	Voltage RMS
E Oscilloscope				
E Theory	X	X		
V_{R2} Oscilloscope				
V_{R2} Theory	X	X		

Table 3A.2

	Scale (S/Div)	Number of Divisions	Period	Frequency
E Oscilloscope				
E Theory	X	X		

Table 3A.3

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2

Capacitive Reactance

Objective

Capacitive reactance will be examined in this exercise. In particular, its relationship to capacitance and frequency will be investigated, including a plot of capacitive reactance versus frequency.

Theory Overview

The current – voltage characteristic of a capacitor is unlike that of typical resistors. While resistors show a constant resistance value over a wide range of frequencies, the equivalent ohmic value for a capacitor, known as *capacitive reactance*, is inversely proportional to frequency. The capacitive reactance may be computed via the formula:

$$X_c = -j\,\frac{1}{2\pi fC}$$

The magnitude of capacitive reactance may be determined experimentally by feeding a capacitor a known current, measuring the resulting voltage, and dividing the two, following Ohm's law. This process may be repeated a across a range of frequencies in order to obtain a plot of capacitive reactance versus frequency. An AC current source may be approximated by placing a large resistance in series with an AC voltage, the resistance being considerably larger than the maximum reactance expected.

Equipment

(1) AC function generator   model:_____ srn:_____
(1) Oscilloscope   model:_____ srn:_____

Components

(1) 1 µF   actual:_____
(1) 2.2 µF   actual:_____
(1) 10 kΩ   actual:_____

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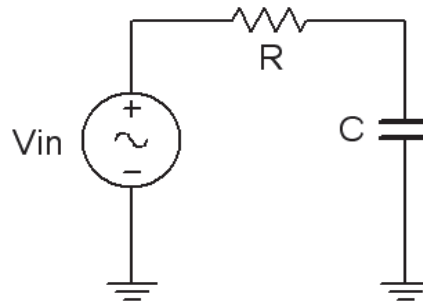**E-mail: Zain.alabdeen@uomus.edu.iq**

Schematics

Figure 4.1

Procedure

Current Source

1. Using figure 4.1 with Vin=10 V p-p and R=10 kΩ, and assuming that the reactance of the capacitor is much smaller than 10k and can be ignored, determine the circulating current using measured component values and record in Table 4.1.

Measuring Reactance

2. Build the circuit of figure 4.1 using R=10 kΩ, and C=1 µF. Place one probe across the generator and another across the capacitor. Set the generator to a 200 Hz sine wave and 10 V p-p. Make sure that the *Bandwidth Limit* of the oscilloscope is engaged for both channels. This will reduce the signal noise and make for more accurate readings.

3. Calculate the theoretical value of Xc using the measured capacitor value and record in Table 4.2.

4. Record the peak-to-peak capacitor voltage and record in Table 4.2.

5. Using the source current from Table 4.1 and the measured capacitor voltage, determine the experimental reactance and record it in Table 4.2. Also compute and record the deviation.

6. Repeat steps three through five for the remaining frequencies of Table 4.2.

7. Replace the 1 µF capacitor with the 2.2 µF unit and repeat steps two through six, recording results in Table 4.3.

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8. Using the data of Tables 4.2 and 4.3, create plots of capacitive reactance versus frequency.

Data Tables

$i_{source \ (p-p)}$	

Table 4.1

Frequency	X_C Theory	$V_{C(p-p)}$ Exp	X_C Exp	% Dev
200				
400				
600				
800				
1.0 k				
1.2 k				
1.6 k				
2.0 k				

Table 4.2

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Frequency	X_C Theory	$V_{C(p-p)}$ Exp	X_C Exp	% Dev
200				
400				
600				
800				
1.0 k				
1.2 k				
1.6 k				
2.0 k				

Table 4.3

Questions

1. What is the relationship between capacitive reactance and frequency?

2. What is the relationship between capacitive reactance and capacitance?

3. If the experiment had been repeated with frequencies 10 times higher than those in Table 4.2, what would the resulting plots look like?

4. If the experiment had been repeated with frequencies 10 times lower than those in Table 4.2, what effect would that have on the experiment?

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3

Inductive Reactance

Objective

Inductive reactance will be examined in this exercise. In particular, its relationship to inductance and frequency will be investigated, including a plot of inductive reactance versus frequency.

Theory Overview

The current – voltage characteristic of an inductor is unlike that of typical resistors. While resistors show a constant resistance value over a wide range of frequencies, the equivalent ohmic value for an inductor, known as *inductive reactance*, is directly proportional to frequency. The inductive reactance may be computed via the formula:

$$X_L = j2\pi fL$$

The magnitude of inductive reactance may be determined experimentally by feeding an inductor a known current, measuring the resulting voltage, and dividing the two, following Ohm's law. This process may be repeated a across a range of frequencies in order to obtain a plot of inductive reactance versus frequency. An AC current source may be approximated by placing a large resistance in series with an AC voltage, the resistance being considerably larger than the maximum reactance expected.

Equipment

(1) AC function generator   model:_____ srn:_____
(1) Oscilloscope   model:_____ srn:_____
(1) DMM   model:_____ srn:_____

Components

(1) 1 mH   actual:_____
(1) 10 mH   actual:_____
(1) 10 kΩ   actual:_____

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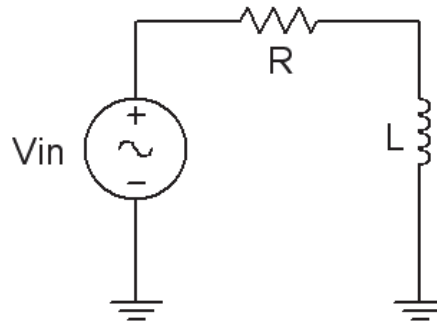**E-mail: Zain.alabdeen@uomus.edu.iq**

Schematics

Figure 5.1

Procedure

Current Source

1. Using figure 5.1 with Vin=10 V p-p and R=10 kΩ, and assuming that the reactance of the inductor is much smaller than 10k and can be ignored, determine the circulating current using measured component values and record in Table 5.1. Also, measure the DC coil resistances of the inductors using an ohmmeter or DMM and record in Table 5.1.

Measuring Reactance

2. Build the circuit of figure 5.1 using R=10 kΩ, and L=10 mH. Place one probe across the generator and another across the inductor. Set the generator to a 1000 Hz sine wave and 10 V p-p. Make sure that the *Bandwidth Limit* of the oscilloscope is engaged for both channels. This will reduce the signal noise and make for more accurate readings.

3. Calculate the theoretical value of X_L using the measured inductor value and record in Table 5.2.

4. Record the peak-to-peak inductor voltage and record in Table 5.2.

5. Using the source current from Table 5.1 and the measured inductor voltage, determine the experimental reactance and record it in Table 5.2. Also compute and record the deviation.

6. Repeat steps three through five for the remaining frequencies of Table 5.2.

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7. Replace the 10 mH inductor with the 1 mH unit and repeat steps two through six, recording results in Table 5.3.

8. Using the data of Tables 5.2 and 5.3, create plots of inductive reactance versus frequency.

Data Tables

$i_{source(p-p)}$	
R_{coil} of 10 mH	
R_{coil} of 1 mH	

Table 5.1

Frequency	X_L Theory	$V_{L(p-p)}$ Exp	X_L Exp	% Dev
1 k				
2 k				
3 k				
4 k				
5 k				
6 k				
8 k				
10 k				

Table 5.2

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Frequency	X_L Theory	$V_{L(p-p)}$ Exp	X_L Exp	% Dev
10 k				
20 k				
30 k				
40 k				
50 k				
60 k				
80 k				
100 k				

Table 5.3

Questions

1. What is the relationship between inductive reactance and frequency?

2. What is the relationship between inductive reactance and inductance?

3. If the 10 mH trial had been repeated with frequencies 10 times higher than those in Table 5.2, what effect would that have on the experiment?

4. Do the coil resistances have any effect on the plots?

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4

Series R, L, C Circuits

Objective

This exercise examines the voltage and current relationships in series R, L, C networks. Of particular importance is the phase of the various components and how Kirchhoff's voltage law is extended for AC circuits. Both time domain and phasor plots of the voltages are generated.

Theory Overview

Each element has a unique phase response: for resistors, the voltage is always in phase with the current, for capacitors the voltage always lags the current by 90 degrees, and for inductors the voltage always leads the current by 90 degrees. Consequently, a series combination of R, L, and C components will yield a complex impedance with a phase angle between +90 and -90 degrees. Due to the phase response, Kirchhoff's voltage law must be computed using vector (phasor) sums rather than simply relying on the magnitudes. Indeed, all computations of this nature, such as a voltage divider, must be computed using vectors.

Equipment

(1) AC function generator   model:_____ srn:_____
(1) Oscilloscope   model:_____ srn:_____

Components

(1) 10 nF   actual:_____
(1) 10 mH   actual:_____
(1) 1 kΩ   actual:_____

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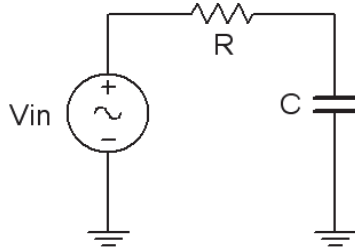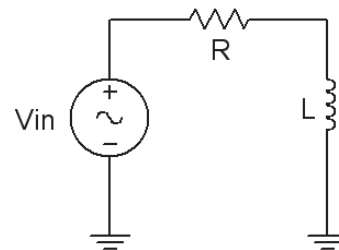**E-mail: Zain.alabdeen@uomus.edu.iq**

Schematics

Figure 6.1

Figure 6.2
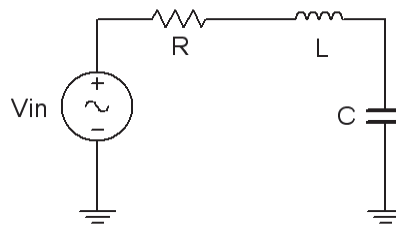

Figure 6.3

Procedure

RC Circuit

15. Using Figure 6.1 with Vin=2 V p-p sine at 10 kHz, R=1 kΩ, and C=10 nF, determine the theoretical capacitive reactance and circuit impedance, and record the results in Table 6.1 (the experimental portion of this table will be filled out in step 5). Using the voltage divider rule, compute the resistor and capacitor voltages and record them in Table 6.2.

16. Build the circuit of Figure 6.1 using R=1 kΩ, and C=10 nF. Place one probe across the generator and another across the capacitor. Set the generator to a 10 kHz sine wave and 2 V p-p. Make sure that the *Bandwidth Limit* of the oscilloscope is engaged for both channels. This will reduce the signal noise and make for more accurate readings. Also, consider using *Averaging* for the acquisition mode, particularly to clean up signals derived using the *Math* function.

17. Measure the peak-to-peak voltage across the capacitor and record in Table 6.2. Along with the magnitude, be sure to record the time deviation between V_C and the input signal (from which the phase may be determined). Using the *Math* function, measure and record the voltage and time delay for the resistor ($V_{in} - V_C$). Compute the phase angle and record these values in Table 6.2.

18. Take a snapshot of the oscilloscope displaying V_{in}, V_C, and V_R.

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19. Compute the deviations between the theoretical and experimental values of Table 6.2 and record the results in the final columns of Table 6.2. Based on the experimental values, determine the experimental Z and X_C values via Ohm's law ($i=V_R/R$, $X_C=V_C/i$, $Z=V_{in}/i$) and record back in Table 6.1 along with the deviations.

20. Create a phasor plot showing V_{in}, V_C, and V_R. Include both the time domain display from step 4 and the phasor plot with the technical report.

RL Circuit

21. Replace the capacitor with the 10 mH inductor (i.e. Figure 6A.2), and repeat steps 1 through 6 in like manner, using Tables 6.3 and 6.4.

RLC Circuit

22. Using Figure 6.3 with both the 10 nF capacitor and 10 mH inductor, repeat steps 1 through 6 in similar manner, using Tables 6.5 and 6.6. **Using a four channel oscilloscope:** To obtain proper readings, place the first probe at the input, the second probe between the resistor and inductor, and the third probe between the inductor and capacitor. Probe three yields V_C. Using the *Math* function, probe two minus probe three yields V_L, and finally, probe one minus probe two yields V_R. Assigning *Reference* waveforms can be useful to see all of the signals together. **Using a two channel oscilloscope:** Unfortunately, it will be impossible to see the voltage of all three components simultaneously with the source voltage using a two channel oscilloscope. To obtain proper readings, place the first probe at the input and the second probe across the capacitor in order to see the phase and magnitude of V_C. Then, swap C and L (placing the second probe across the inductor) to see V_L, and finally, swap L and R (with the second probe across R) in order see V_R.

Data Tables

RC Circuit

	Theory	Experimental	% Deviation
X_C			
Z Magnitude			
Z θ			

Table 6.1

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	Theory Mag	Theory θ	Exp Mag	Exp Delay	Exp θ	% Dev Mag	% Dev θ
V_C							
V_R							

Table 6.2

RL Circuit

	Theory	Experimental	% Deviation
X_L			
Z Magnitude			
Z θ			

Table 6.3

	Theory Mag	Theory θ	Exp Mag	Exp Delay	Exp θ	% Dev Mag	% Dev θ
V_L							
V_R							

Table 6.4

RLC Circuit

	Theory	Experimental	% Deviation
X_C			
X_L			
Z Magnitude			
Z θ			

Table 6.5

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	Theory Mag	Theory θ	Exp Mag	Exp Delay	Exp θ	% Dev Mag	% Dev θ
V_C							
V_L							
V_R							

Table 6.6

Questions

1. What is the phase relationship between R, L, and C components in a series AC circuit?

2. Based on measurements, does Kirchhoff's voltage law apply to the three tested circuits (show work)?

3. In general, how would the phasor diagram of Figure 6.1 change if the frequency was raised?

4. In general, how would the phasor diagram of Figure 6.2 change if the frequency was lowered?

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5

AC Superposition

Objective

This exercise examines the analysis of multi-source AC circuits using the superposition theorem. In particular, sources with differing frequencies will be used to illustrate the contributions of each source to the combined result.

Theory Overview

The superposition theorem can be used to analyze multi-source AC linear bilateral networks. Each source is considered in turn, with the remaining sources replaced by their internal impedance, and appropriate series-parallel analysis techniques employed. The resulting signals are then summed to produce the combined output signal. To see this process more clearly, the exercise will utilize two sources operating at different frequencies. Note that as each source has a different frequency, the inductor and capacitor appear as different reactances to the two sources.

Equipment

(2) AC function generators   model:_____ srn:_____

                                   model:_____ srn:_____

(1) Oscilloscope   model:_____ srn:_____

Components

(1) 100 nF   actual:_____
(1) 10 mH   actual:_____
(1) 1k Ω actual:_____
(1) 50 Ω actual:_____

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Schematics
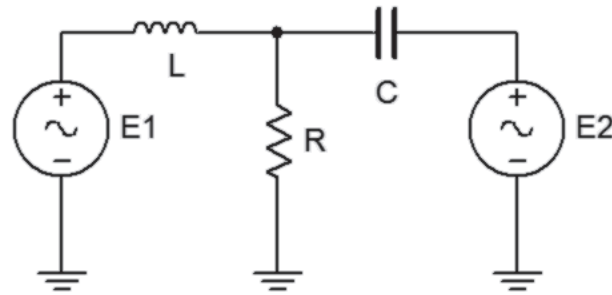

Figure 10.1

Procedure

1. Typical function generators have a 50 Ω internal impedance. These are not shown in the circuit of Figure 10.1. To test the superposition theorem, sources *E1* and *E2* will be examined separately and then together.

Source One Only

2. Consider the circuit of Figure 10.1 with C=100 nF, L=10 mH, R=1 kΩ, using only source *E1*=2 V p-p at 1 kHz and with source *E2* replaced by its internal impedance of 50 Ω. Using standard series-parallel techniques, calculate the voltages across *E1*, R, and *E2*. Remember to include the 50 Ω internal impedances in the calculations. Record the results in Table 10.1.

3. Build the circuit of Figure 10.1 using C=100 nF, L=10 mH, and R=1 kΩ. Replace *E2* with a 50 Ω resistor to represent its internal impedance. Set *E1* to 2 V p-p at 1 kHz, unloaded. Make sure that the *Bandwidth Limit* of the oscilloscope is engaged for both channels. This will reduce the signal noise and make for more accurate readings. Place probe one across *E1* and probe two across R. Measure the voltages across *E1* and R, and record in Table 10.1. Record a copy of the scope image. Move probe two across *E2* (the 50 Ω), measure and record this voltage in Table 10.1.

Source Two Only

4. Consider the circuit of Figure 10.1 using only source *E2*=2 V p-p at 10 kHz and with source *E1* replaced by its internal impedance of 50 Ω. Using standard series-parallel techniques, calculate the

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voltages across *E1*, R, and *E2*. Remember to include the 50 Ω internal impedances in the calculations. Record the results in Table 10.2.

5. Replace the 50 Ω with source *E2* and set it to 2 V p-p at 10 kHz, unloaded. Replace *E1* with a 50 Ω resistor to represent its internal impedance. Place probe one across *E2* and probe two across R. Measure the voltages across *E2* and R, and record in Table 10.2. Record a copy of the scope image. Move probe two across *E1* (the 50 Ω), measure and record this voltage in Table 10.2.

Sources One and Two

6. Consider the circuit of Figure 10.1 using both sources, *E1*=2 V p-p at 1 kHz and *E2*=2 V p-p at 10 kHz. Add the calculated voltages across *E1*, R, and *E2* from Tables 10.1 and 10.2. Record the results in Table 10.3. Make a note of the expected maxima and minima of these waves and sketch how the combination should appear on the scope

7. Replace the 50 Ω with source *E1* and set it to 2 V p-p at 1 kHz, unloaded. **Both sources should now be active.** Place probe one across *E1* and probe two across R. Measure the voltages across *E1* and R, and record in Table 10.3. Record a copy of the scope image. Move probe two across *E2*, measure and record this voltage in Table 10.3.

Computer Simulation

8. Build the circuit of Figure 10.1 in a simulator. Using Transient Analysis, determine the voltage across the resistor and compare it to the theoretical and measured values recorded in Table 10.3. Be sure to include the 50 Ω source resistances in the simulation.

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Data Tables

Source One Only

	Theory	Experimental	% Deviation
E_1			
E_2			
V_R			

Table 10.1

Source Two Only

	Theory	Experimental	% Deviation
E_1			
E_2			
V_R			

Table 10.2

Sources One and Two

	Theory	Experimental	% Deviation
E_1			
E_2			
V_R			

Table 10.3

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Questions

1. Why must the sources be replaced with a 50 Ω resistor instead of being shorted?

2. Do the expected maxima and minima from step 6 match what is measured in step 7?

3. Does one source tend to dominate the 1 kΩ resistor voltage or do both sources contribute in nearly equal amounts? Will this always be the case?

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6

AC Thevenin's Theorem

Objective

Thevenin's theorem will be examined for the AC case. The Thevenin source voltage and Thevenin impedance will be determined experimentally and compared to theory. Loads will be examined when driven by both an arbitrary circuit and that circuit's Thevenin equivalent to determine if the resulting load potentials are indeed identical. Both resistive and complex loads will be examined as well as well source impedances that are inductive or capacitive.

Theory Overview

Thevenin's theorem states that any linear single port (i.e., two terminals) network can be replaced by a single voltage source with series impedance. While the theorem is applicable to any number of voltage and current sources, this exercise will only examine single source circuits for the sake of simplicity. The Thevenin voltage is the open circuit output voltage. This may be determined experimentally by isolating the portion to be Thevenized and simply placing an oscilloscope at its output terminals. The Thevenin impedance is found by replacing all sources with their internal impedance and then applying appropriate series-parallel impedance simplification rules. If an impedance meter is available, an easy method of doing this in the lab is to replace the sources with appropriate impedance values and apply the impedance meter to the output terminals of the circuit portion under investigation.

Equipment

(1) AC function generator	model:_____	srn:_____
(1) Oscilloscope	model:_____	srn:_____
(1) Variable frequency impedance meter	model:_____	srn:_____
(1) Decade resistance box	model:_____	srn:_____

Components

(1) 100 nF	actual:_____
(1) 470 nF	actual:_____
(1) 10 mH	actual:_____
(1) 50 Ω	actual:_____

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(1) 1.0 kΩ   actual:_____

(1) 1.5 kΩ   actual:_____
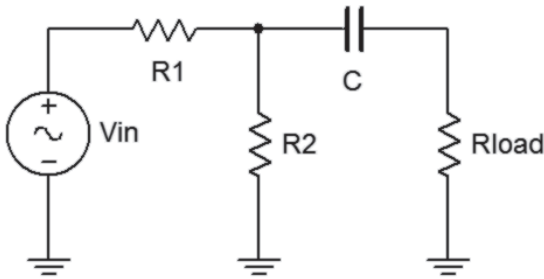
(1) 2.2 kΩ   actual:_____

Schematics

Figure 11.1
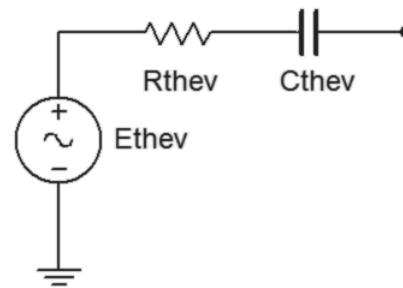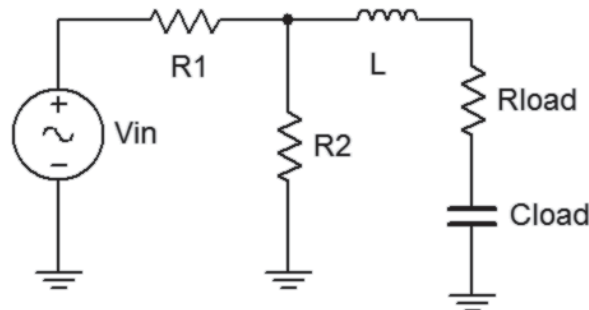

Figure 11.2

Figure 11.3

Procedure

1. For the circuit of figure 11.1, calculate the voltage across the 1 kΩ load using R1=1.5 kΩ, R2=2.2 kΩ, and C=470 nF, with a 2 V p-p 1 kHz source. Record this value in Table 11.1. Also calculate the expected Thevenin voltage and Thevenin impedance. Record these values in Table 11.2.

2. Build the circuit of figure 11.1 using R1=1.5 kΩ, R2=2.2 kΩ, Rload=1 kΩ and C=470 nF. Set the generator to a 1 kHz sine wave at 2 V p-p. Make sure that the *Bandwidth Limit* of the oscilloscope is engaged. This will reduce the signal noise and make for more accurate readings. Measure the load voltage and record in Table 11.1 as V$_{Load}$ Original.

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3. Remove the load and measure the unloaded output voltage. This is the experimental Thevenin voltage. Record it in Table 11.2.

4. Replace the voltage source with a 50 Ω resistor to represent its internal impedance. Set the impedance meter to 1 kHz and measure the resulting impedance at the open load terminals. This is the experimental Thevenin impedance. Record these values in Table 11.2 and compare with the theoretical values.

5. Using the decade resistance box and capacitor, build the Thevenin equivalent circuit of figure 11.2 and apply the 1 kΩ load resistor. Measure the load voltage and record in Table 11.1. Compare with the values of the original (non-Thevenized) circuit and determine the deviation between the original and Thevenized circuits.

6. To verify that Thevenin's theorem also works with an inductive source and a complex load, repeat steps 1 through 5 in like manner but using figure 11.3 with R1=1.5 kΩ, R2=2.2 kΩ, L=10 mH, Rload=1 kΩ with Cload=100 nF. Set the generator to a 10 kHz sine wave at 2 V p-p. Record results in Tables 11.3 and 11.4.

Data Tables

V_{load} Theory	
V_{load} Original	
V_{load} Thevenin	
% Deviation	

Table 11.1

	Theory	Experimental	% Deviation
$E_{Thevenin}$			
$Z_{Thevenin}$			

Table 11.2

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V_{load} Theory	
V_{load} Original	
V_{load} Thevenin	
% Deviation	

Table 11.3

	Theory	Experimental	% Deviation
$E_{Thevenin}$			
$Z_{Thevenin}$			

Table 11.4

Questions

1. How does the AC version of Thevenin's theorem compare with the DC version?

2. Would the Thevenin equivalent circuits be altered if the source frequency was changed? If so, why?

3. Based on the results of this exercise, would you expect Norton's theorem for AC to behave similarly to its DC case?

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7

AC Maximum Power Transfer

Objective

In this exercise, maximum power transfer to the load will be examined for the AC case. Both the load's resistive and reactive components will be independently varied to discover their effect of load power and determine the values required for maximum load power.

Theory Overview

In the DC case, maximum power transfer is achieved by setting the load resistance equal to the source's internal resistance. This is not true for the AC case. Instead, the load should be set to complex conjugate of the source impedance, the complex conjugate having the same magnitude as the original but with the opposite sign for the angle. By using the complex conjugate, the load and source reactive components will cancel out leaving a purely resistive circuit similar to the DC case. When calculating the true load power, care must be taken to remember that the load voltage appears across a complex load impedance. Only the real portion of this voltage appears across the resistive component, and only the resistive component dissipates power.

Equipment

(1) AC function generator   model:_____ srn:_____
(1) Oscilloscope   model:_____ srn:_____
(1) Decade resistance box   model:_____ srn:_____
(1) Impedance meter   model:_____ srn:_____

Components

(1) 10 mH   actual:_____
(1) 1k Ω   actual:_____
(1) 50 Ω   actual:_____
(1) 100 nF   actual:_____
(1) 47 nF   actual:_____
(1) 33 nF   actual:_____
(1) 22 nF   actual:_____
(1) 10 nF   actual:_____   Assorted capacitors in the 1 nF region

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Schematics
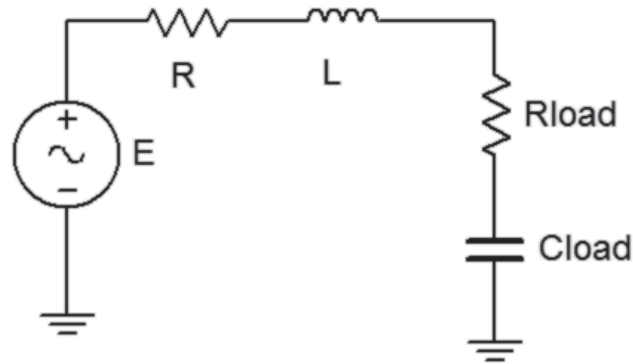

Figure 12.1

Procedure

1. Build the circuit of figure 12.1 using R=1 kΩ and L= 10 mH, but leaving off the load components. Replace the generator with a 50 Ω resistor and determine the effective source impedance at 10 kHz using the impedance meter. Record this value in Table 12.1, including both magnitude and phase. Determine the load impedance which should achieve maximum power transfer according to the theorem and record in Table 12.1. Finally, determine values for R_{load} and C_{load} to achieve this load impedance and record in Table 12.1, also copying the resistance value to the first R_{load} entry of Table 12.2.

Testing R_{load}

2. Replace the 50 Ω resistor with the generator. Insert the decade resistance box in the position of R_{load} and set it to the value calculated in Table 12.1. For C_{load}, use the value calculated in Table 12.1. Use multiple capacitors if necessary to achieve a close value. Set the generator to 10 volts peak at 10 kHz, making sure that the amplitude is measured on the oscilloscope with the generator loaded by the circuit. Make sure that the *Bandwidth Limit* of the oscilloscope is engaged for the channel. This will reduce the signal noise and make for more accurate readings.

3. Measure the magnitude of the load voltage and record in Table 12.2. Also compute the expected load voltage from theory and the load power based on the measured load voltage and record in Table 12.2. Repeat these measurements and calculations for the remaining load resistance values in the table.

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Testing C_{load}

4. Return the decade box to the value calculated in Table 12.1. For C_{load}, insert the first capacitor listed in Table 12.3. Repeat step four for each load capacitance in Table 12.3, calculating and recording the required results using Table 12.3.

5. Generate a plot of P_{load} with respect to R_{load} and another of P_{load} with respect to C_{load}.

Data Tables

Z_{source}	
Z_{load}	
R_{load}	
C_{load}	

Table 12.1

Variable R_{load}

R_{load}	V_{load} Theory	V_{load} Exp	P_{load} Exp
100			
400			
600			
800			
1.2 k			
1.8 k			
3 k			
10 k			

Table 12.2

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Variable C_{load}

C_{load}	V_{load} Theory	V_{load} Exp	P_{load} Exp
1 nF			
3.3 nF			
10 nF			
33 nF			
47 nF			
100 nF			

Table 12.3

Questions

1. In general, given a certain source impedance, what load impedance will achieve maximum load power?

2. Will achieving maximum load power also achieve maximum efficiency? Explain.

3. If the experiment was repeated using a frequency of 5 kHz, how would the graphs change, if at all?

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8
Series Resonance

Objective

This exercise investigates the voltage relationships in a series resonant circuit. Of primary importance are the establishment of the resonant frequency and the quality factor, or Q, of the circuit with relation to the values of the R, L, and C components.

Theory Overview

A series resonant circuit consists of a resistor, a capacitor, and an inductor in a simple loop. At some frequency the capacitive and inductive reactances will be of the same magnitude, and as they are 180 degrees in opposition, they effectively nullify each other. This leaves the circuit purely resistive, the source "seeing" only the resistive element. Consequently, the current will be at a maximum at the resonant frequency. At any higher or lower frequency, a net reactance (the difference between X_L and X_C) must be added to the resistor value, producing a higher impedance and thus, a lower current. As this is a simple series loop, the resistor's voltage will be proportional to the current. Consequently, the resistor voltage should be a maximum at the resonant frequency and decrease as the frequency is either increased or decreased. At resonance, the resistor value sets the maximal current and consequently has a major effect on the voltages developed across the capacitor and inductor as well as the "tightness" of the voltage versus frequency curve: The smaller the resistance, the tighter the curve and the higher the voltage seen across the capacitor and inductor. The Q of the circuit can be defined as the ratio of the resonant reactance to the circuit resistance, $Q=X/R$, which also corresponds to the ratio of the resonant frequency to the circuit bandwidth, $Q=F_0/BW$.

Equipment

(1) AC function generator   model:_____ srn:_____
(1) Oscilloscope   model:_____ srn:_____

Components

(1) 10 nF   actual:_____
(1) 10 mH   actual:_____

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(1) 47 Ω   actual:_____
(1) 470 Ω   actual:_____

Schematics
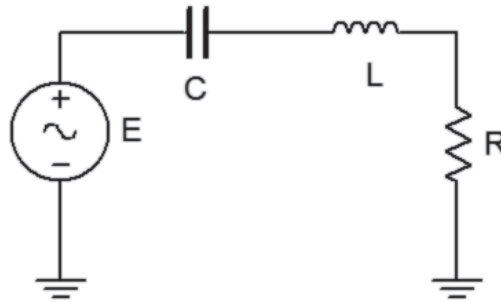

Figure 13.1

Procedure

Low Q Circuit

1. Using Figure 13.1 with R=470 Ω, L= 10 mH, and C=10 nF, determine the theoretical resonance frequency and Q, and record the results in Table 13.1. Based on these values determine the upper and lower frequencies defining the bandwidth, f_1 and f_2, and record them in Table 13.1.

2. Build the circuit of Figure 13.1 using R=470 Ω, L=10 mH and C=10 nF. Place a probe across the resistor. Set the output of the generator to a 1 V p-p sine wave. Set the frequency to the theoretical resonance frequency of Table 13.1. Make sure that the *Bandwidth Limit* of the oscilloscope is engaged for both channels. This will reduce the signal noise and make for more accurate readings.

3. Adjust the frequency in small amounts, up and down, until the maximum voltage is found. This is the experimental resonance frequency. Record it in Table 13.1. Note the amplitude (it should be approximately equal to the source voltage of 1 V p-p). Sweep the frequency above and below the resonance frequency until the experimental f_1 and f_2 are found. These will occur at a voltage amplitude of approximately 0.707 times the resonant voltage (i.e., the half-power points). Record these frequencies in Table 13.1. Also, determine and record the experimental Q based on the experimental f_0, f_1, and f_2.

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4. Transcribe the experimental frequencies of Table 13.1 to the top three entries of Table 13.2. For all of the frequencies in Table 13.2, measure and record the voltage across the resistor. Also measure and record the inductor and capacitor voltages. Note that the inductor and capacitor will have to be swapped with the resistor position in order to maintain proper ground reference with the oscilloscope.

5. Based on the data from Table 13.2, plot V_R, V_C, and V_L as a function of frequency.

6. Change R to 47Ω and repeat steps 1 through 5 but using Tables 13.3 and 13.4 for high Q.

Computer Simulation

7. Build the circuit of Figure 13.1 in a simulator. Using AC Analysis, plot the voltage across the resistor from 1 kHz to 100 kHz for both the high and low Q cases and compare them to the plots derived from Tables 13.2 and 13.4. Be sure to include the 50 Ω source resistance and coil resistance in the simulation.

Data Tables

Low Q Circuit

	Theory	Experimental	% Deviation
f_o			
Q			
f_1			
f_2			

Table 13.1

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Frequency	V_R	V_C	V_L
$f_0=$			
$f_1=$			
$f_2=$			
1 kHz			
5 kHz			
8 kHz			
12 kHz			
20 kHz			
30 kHz			
50 kHz			
100 kHz			

Table 13.2

High Q Circuit

	Theory	Experimental	% Deviation
f_o			
Q			
f_1			
f_2			

Table 13.3

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Frequency	V_R	V_C	V_L
$f_0=$			
$f_1=$			
$f_2=$			
1 kHz			
5 kHz			
8 kHz			
12 kHz			
20 kHz			
30 kHz			
50 kHz			
100 kHz			

Table 13.4

Questions

1. What is the effect of changing resistance on Q?

2. Are the V_C and V_L curves the same as the V_R curves? If not, why?

3. In practical terms, what sets the limit on how high Q may be?