<u>EET 3086C – Circuit Analysis</u>

Summer 2024

<u>Experiment # 1</u>

DC Measurements of a Resistive Circuit and Proof of Thevenin Theorem

Performed By:

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OBJECTIVE/PURPOSE

The objective of this experiment is to analyze a given resistive circuit and verify the application of Thevenin's Theorem by constructing its Thevenin equivalent circuit. The goal is to measure the voltage and current values across specific components in the circuit and compare the theoretical, simulated, and experimental results to demonstrate the equivalency of the Thevenin equivalent circuit for different load conditions.

LIST OF EQUIPMENT/PARTS/COMPONENTS

1. Breadboard
   - Model: Elenco 9830
2. Triple Power Supply
   - Model: HM8040-3
3. Resistors (all 5% tolerance):
   - R1: 1.0 kΩ
   - R2: 2.0 kΩ
   - R3: 3.0 kΩ
   - R4: 4.7 kΩ
   - R5: 1.0 kΩ
   - R6: 2.2 kΩ
   - Pot: 5 kΩ (for R_{TH})
4. Digital Programmable Multimeter & LCR Meter
   - Model: HM8012/HM8018
5. Computer with Multisim Software

THEORETICAL BACKGROUND RESEARCH

Thevenin's Theorem

Thevenin's Theorem states that any linear bilateral network, no matter how complex, can be replaced by an equivalent circuit consisting of a single voltage source (V_{TH}) in series with a resistance (R_{TH}), connected to a load resistor (R_L). The theorem simplifies the process of analyzing the power transfer and load conditions in a circuit. To find the Thevenin equivalent circuit:

1. **Remove the load resistor** (R_L) from the original circuit.
2. **Calculate the open-circuit voltage** (V_{OC}), which is the voltage across the terminals where the load resistor was connected.
3. **Find the Thevenin resistance** (R_{TH}) by deactivating all independent sources in the circuit:
   - Replace all independent voltage sources with short circuits.
   - Replace all independent current sources with open circuits.
   - Calculate the equivalent resistance seen from the open terminals.

The Thevenin equivalent voltage (V_{TH}) is the same as the open-circuit voltage (V_{OC}), and the Thevenin resistance (R_{TH}) is the equivalent resistance seen from the terminals [2].

Procedure for Thevenin Equivalent

1. **Determine V_{TH}**:

$$V_{TH} = V_{OC}$$

   This is the voltage measured across the open terminals of the network when the load is removed [4].

2. **Determine R_{TH}:**

$$R_{TH} = \frac{V_{TH}}{I_{SC}}$$

Here, I_{SC} is the short-circuit current that flows when the terminals are shorted together [4].

Nodal Analysis

Nodal analysis is a systematic method to determine the voltage at various nodes of a circuit. It is based on the application of Kirchhoff's Current Law (KCL), which states that the sum of currents entering a node is equal to the sum of currents leaving the node. This method is particularly useful for circuits with multiple nodes and components.[2]

To perform nodal analysis:

1. **Identify all nodes** in the circuit.
2. **Choose a reference node** (ground).
3. **Apply KCL to each node** (except the reference node) to set up equations.
4. **Solve the simultaneous equations** to find the node voltages.

The equations are derived by summing the currents at each node, considering the conductance of the components connected to the node.[3]

PROCEDURE

The procedure for this experiment is adopted from the following reference[1]:

Masood Ejaz, Lab Experiments Manual for EET 3086C – Circuit Analysis, Experiment 1, Valencia College ECET Department, pp. 2-4

RESULTS AND OBSERVATIONS

In this experiment, the nominal values of each resistor were used for calculations and measurements. The actual measured values of the resistors were recorded to account for any deviations in the results due to real-world variations. The results are divided into three parts: the initial calculations and measurements for V_{R4}, I_{R3}, V_{R6}, and I_{R6}; the Thevenin equivalent circuit with resistors R_4, R_5, and R_6 as the load; and the Thevenin equivalent circuit with only R_6 as the load.

Resistor Values:

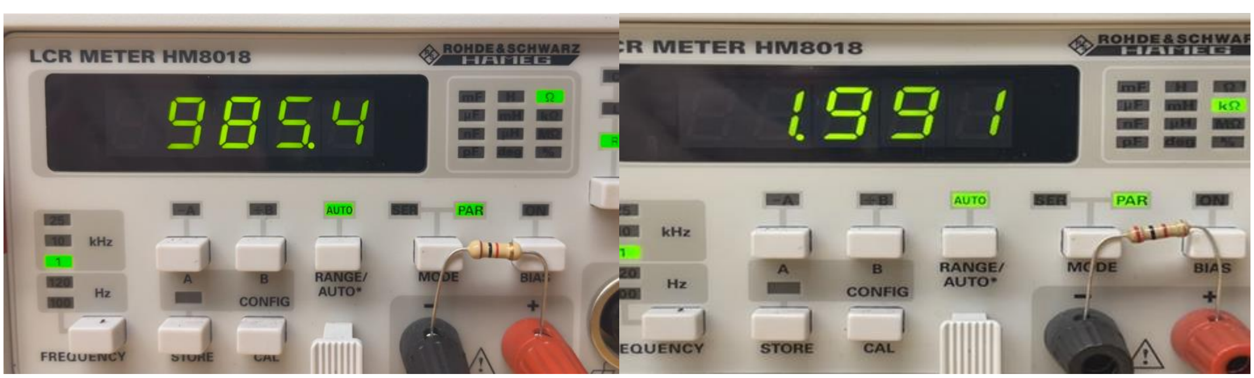

Fig. 1 – Measuring the actual values of R_1 and R_2.

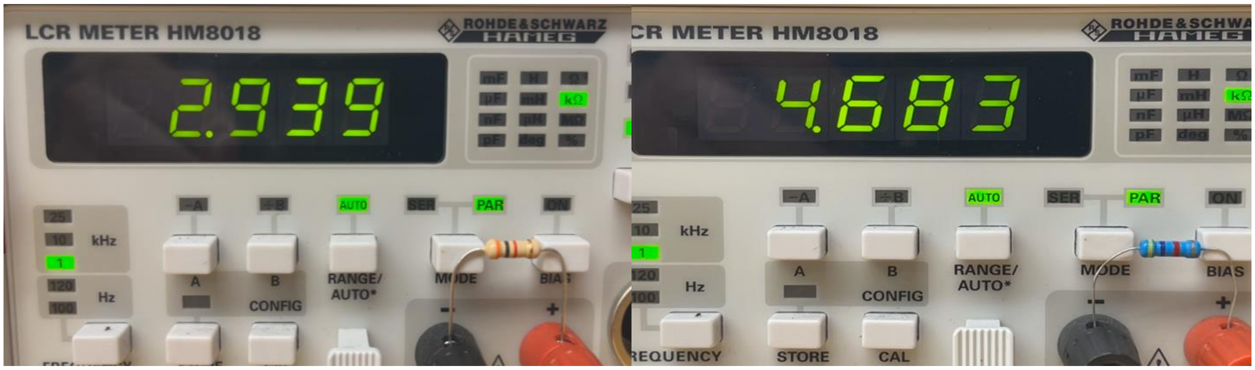

Fig. 2 – Measuring the actual values of R_3 and R_4.

Fig. 3 – Measuring the actual values of R_5 and R_6.

To ensure the accuracy of the experimental results, the actual measured values of the resistors were recorded and compared with the nominal values. This helps in understanding the discrepancies that might arise due to tolerance variations in the resistors. The table below shows the nominal and measured values of each resistor used in the experiment:

Table 1

Resistor	**Nominal Value (Ω)**	**Measured Value (Ω)**	**Percent Error (%)**
R_1	$1.0\ k\Omega$	$985.4\ \Omega$	1.47%
R_2	$2.0\ k\Omega$	$1991\ \Omega$	0.45%
R_3	$3.0\ k\Omega$	$2939\ \Omega$	2.03 %
R_4	$4.7\ k\Omega$	$4683\ \Omega$	0.36 %
R_5	$1.0\ k\Omega$	$985.3\ \Omega$	1.47 %
R_6	$2.2\ k\Omega$	$2175\ \Omega$	1.14 %

*Note: The nominal values were used for both calculations and the simulation setup. The measured values are relevant for accounting for minimal deviations in the results. *

Initial Calculations and Measurements for V_{R4}, I_{R3}, V_{R6}, and I_{R6}:

Sample Percent Error calculation (R_1):

$$\% \, Error = \left(\frac{|Measured \, Value - \, Nominal \, Value|}{Nominal \, Value}\right) \times 100$$

$$\% \text{ Error } = \left(\frac{|985.3\Omega - 1000\Omega|}{1000\Omega}\right) \times 100$$

$$\% \text{ Error } = \left(\frac{|-14.7\Omega|}{1000\Omega}\right) \times 100 = \left(\frac{14.7}{1000}\right) \times 100 = 1.47\%$$

Theoretical Calculations:

Using nodal analysis and Kirchhoff's Current Law (KCL), the following equations were derived to find V_{R4}, I_{R3}, V_{R6}, and I_{R6}:

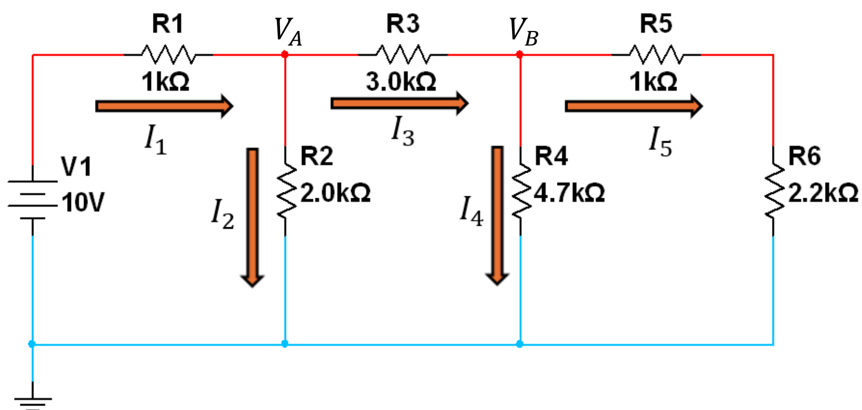

Fig. 4 – Defining the currents for Nodal Analysis.

At node V_A:

$$I_1 = I_2 + I_3$$

$$I_1 = \frac{10V - V_A}{1k\Omega}$$

$$I_2 = \frac{V_A}{2.0 \, k\Omega}$$

$$I_3 = \frac{V_A - V_B}{3.0k\Omega}$$

Equation (1):

$$-\frac{10V - V_A}{1k\Omega} + \frac{V_A}{2.0 \, k\Omega} + \frac{V_A - V_B}{3.0k\Omega} = 0$$

$$6k\Omega\left(\frac{(-10V - V_A)}{1k\Omega} + \frac{V_A}{2.0k\Omega} + \frac{(V_A - V_B)}{3.0k\Omega}\right) = 0(6k\Omega)$$

This simplifies to:

$$6V_A + 3V_A + 2V_A - 2V_B = 60$$

$$11V_A - 2V_B = 60 \ (1)$$

At node V_B:

$$I_3 = I_4 + I_5$$

$$I_3 = \frac{(V_A - V_B)}{3.0k\Omega}$$

$$I_4 = \frac{V_B}{4.7k\Omega}$$

$$I_5 = \frac{V_B}{(1.0k\Omega + 2.2k\Omega)} = \frac{V_B}{3.2k\Omega}$$

Equation (2):

$$\left(-\frac{(V_A - V_B)}{3.0k\Omega} + \frac{V_B}{4.7k\Omega} + \frac{V_B}{3.2k\Omega}\right) = 0$$

$$45.12k\left(-\frac{(V_A - V_B)}{3.0k\Omega} + \frac{V_B}{4.7k\Omega} + \frac{V_B}{3.2k\Omega}\right) = 0(45.12k)$$

This simplifies to:

$$-15.04V_A + 15.04V_B + 9.6V_B + 14.1V_B = 0$$

$$-15.04V_A + 38.74V_B = 0 \ (2)$$

Solving for V_A & V_B:

$$\begin{bmatrix} 11 & -2 \\ -15.04 & 38.74 \end{bmatrix}^{-1} * \begin{bmatrix} 60 \\ 0 \end{bmatrix} = \begin{bmatrix} V_A \\ V_B \end{bmatrix} = \begin{bmatrix} 5.869\ V \\ 2.278\ V \end{bmatrix}$$

$$V_{R4} = V_B = 2.278V$$

Using Voltage Divider:

$$V_{R6} = V_B\left(\frac{(R_6)}{(R_5 + R_6)}\right) = 2.278V\left(\frac{2.2k\Omega}{3.2\ k\Omega}\right) = 1.566\ V$$

$$I_{R6} = \frac{V_{R6}}{R_6} = \frac{1.566\ V}{2.2k\Omega} = 712.013\mu A$$

Finding I_{R3}:

$$I_3 = I_{R3} = \frac{V_A - V_B}{3.0k\Omega} = \frac{3.5475\ V}{3.0k\Omega} = 1.197\ mA$$

Simulation results:

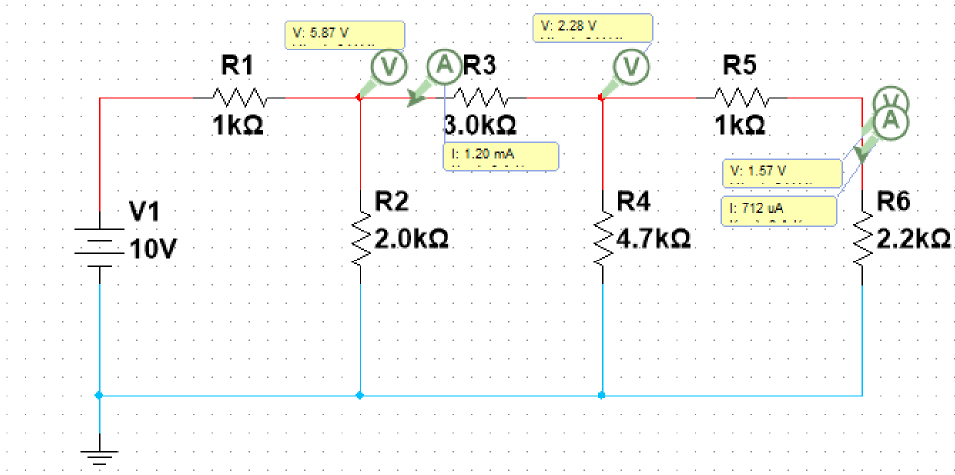

Fig. 5 – All Multisim values for V_{R4}, I_{R3}, V_{R6}, and I_{R6} using Voltage and Current Probes:

Simulations were performed using Multisim 14.3 to verify the theoretical calculations. The simulated voltages and currents closely matched the theoretical values, with only minor differences due to rounding. This confirmed the accuracy of the nodal analysis and validated the theoretical calculations. The close agreement between the simulated and theoretical values provided a reliable confirmation of the circuit's behavior (Fig. 5).

Bench results:

The bench results were obtained by constructing the circuit on a breadboard and measuring the voltages and currents using a digital multimeter. The measured values were then compared with the theoretical and simulated values. The voltages and currents across R_4, R_3 , and R_6 were found to be very close to the theoretical predictions, demonstrating the accuracy of the initial calculations. Minor discrepancies were observed, which can be attributed to the tolerances of the resistors and slight variations in the power supply voltage. These real-world deviations highlight the importance of considering component tolerances in circuit analysis and design.

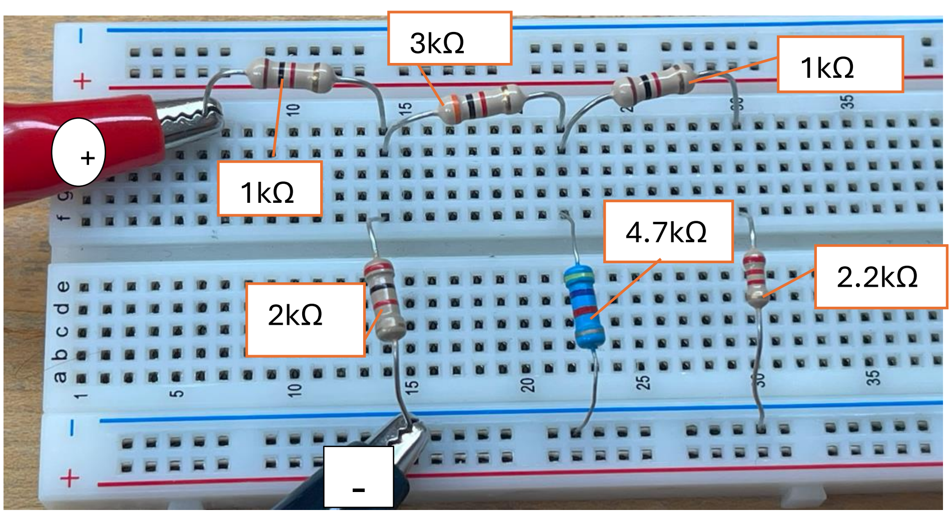

Fig. 6 – Initial Resistive Circuit on the breadboard.

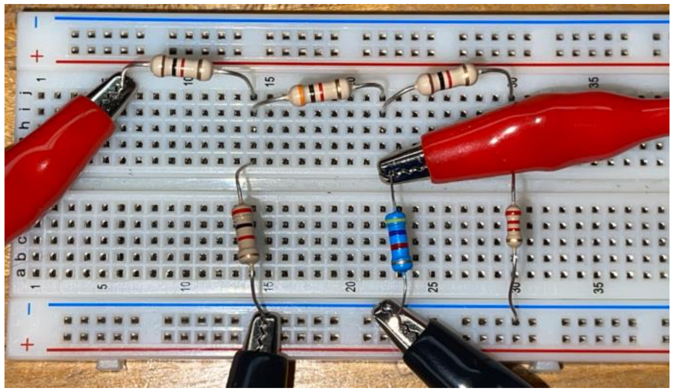

Fig. 7 – Bench Probe placement to measure voltage across R_4.

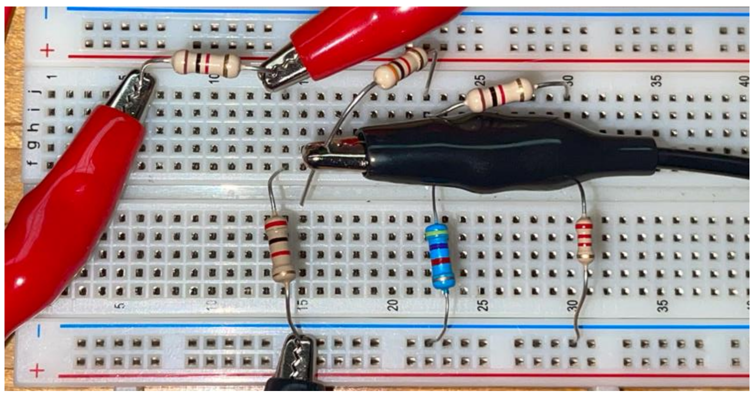

Fig. 8 – Bench Probe placement to measure current across R_3.

Fig. 9 – Value of $V_{R4}(V)$ and I_{R3} (mA) respectively.

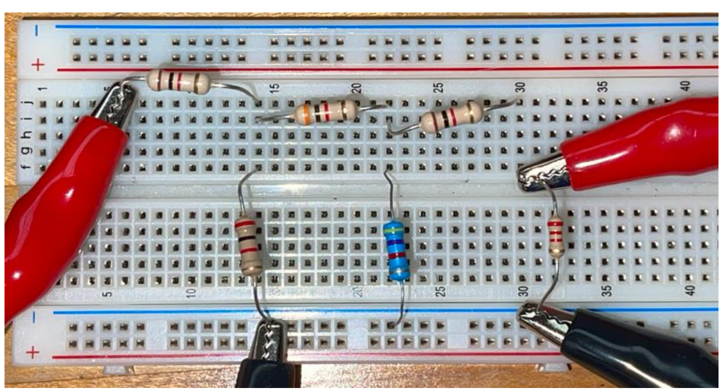

Fig. 10 – Probe placement to measure V_{R6}.

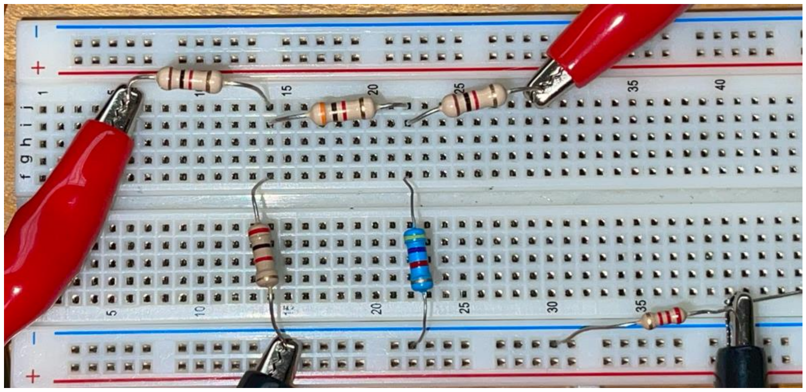

Fig. 10 – Probe placement to measure current across R_6.

Fig. 11 – Value of $V_{R6}(V)$ and I_{R6} (μA) respectively.

Theoretical, simulation, and lab results were obtained and compared for V_{R4}, V_{R6}, I_{R3}, and I_{R6}. The values were recorded in the table below:

Table 2

	$\boldsymbol{V_{R4}}$	$\boldsymbol{I_{R3}}$	$\boldsymbol{V_{R6}}$	$\boldsymbol{I_{R6}}$
Theory	$2.278\ V$	$1.197\ mA$	$1.566\ V$	$712.01\ \mu A$
Simulation	$2.28\ V$	$1.2\ mA$	$1.57\ V$	$712\ \mu A$
Lab	$2.3\ V$	$1.22\ mA$	$1.582\ V$	$713.2\ \mu A$
Percent Error (%)	0.97%	1.92%	1.02%	0.17%

Significance of Initial Measurements

The initial measurements of V_{R4}, V_{R6}, I_{R3}, and I_{R6} play a critical role in validating the nodal analysis in a real-world scenario. By comparing these measured values with the theoretical and simulated results, the accuracy of the nodal analysis is confirmed. Specifically, the voltage across R_4 (V_{R4}) will serve as the load voltage for the second part of the experiment, while the voltage across $R_6(V_{R6})$ will be the load voltage for the third part. These measurements provide a solid foundation for the subsequent parts of the experiment, where the Thevenin equivalent circuits with different loads will be analyzed. Demonstrating consistency between these initial measurements and the results from the Thevenin equivalent circuits will highlight the practical applicability of Thevenin's Theorem and nodal analysis in simplifying and solving complex circuits. This validation is essential for ensuring that theoretical concepts hold true in practical applications, thereby reinforcing their significance in real-world circuit design and analysis.

Thevenin Equivalent Circuit with Resistors $\boldsymbol{R_4}$, $\boldsymbol{R_5}$, and $\boldsymbol{R_6}$ as the Load:

For the Thevenin equivalent circuit with resistors R_4, R_5, and R_6 as the load, the following calculations were performed to determine the Thevenin resistance (R_{TH}) and Thevenin voltage (V_{TH}):

Thevenin Resistance ($\boldsymbol{R_{TH}}$)

The load resistance (R_L) for the combined resistors R_4, R_5, and R_6 is calculated as:

$$R_L = (R_5 + R_6) \parallel R_4$$

Using the parallel resistance formula:

$$R_L = \frac{3.2k\Omega * 4.7k\Omega}{3.2k\Omega + 4.7k\Omega} = 1.904k\Omega$$

The Thevenin resistance (R_{TH}) is then calculated as:

$$R_{TH} = \left(R_3 + (R_1 \parallel R_2)\right)$$

$$R_{TH} = 3.0\ k\Omega + \frac{1.0k\Omega * 2.0\ k\Omega}{1.0k\Omega + 2.0\ k\Omega} = 3.667k\Omega$$

Thevenin Voltage (V_{TH})

The Thevenin voltage (V_{TH}) is calculated using the voltage divider rule:

$$V_{TH} = \frac{V_S(R_2)}{R_1 + R_2} = \frac{10(2.0K\Omega)}{3.0k\Omega} = 6.667\ V$$

Calculating I_{RL} and V_{RL}:

$$I_{RL} = \frac{6.667\ V}{3.667\ k\Omega + 1.904\ k\Omega} = \frac{6.667}{5.571}\ mA = 1.196\ mA$$

$$V_{RL} = I_{RL} \times R_{RL}$$

$$V_{RL} = 1.196\ mA \times 1.904\ k\Omega = 1.196 \times 1.904\ V = 2.28\ V$$

Simulation Results:

The Thevenin equivalent circuit with resistors R_4, R_5, and R_6 as the load was simulated in Multisim. The circuit diagram and the simulation results provided both visual and numerical verification of the theoretical values (Fig. 12).

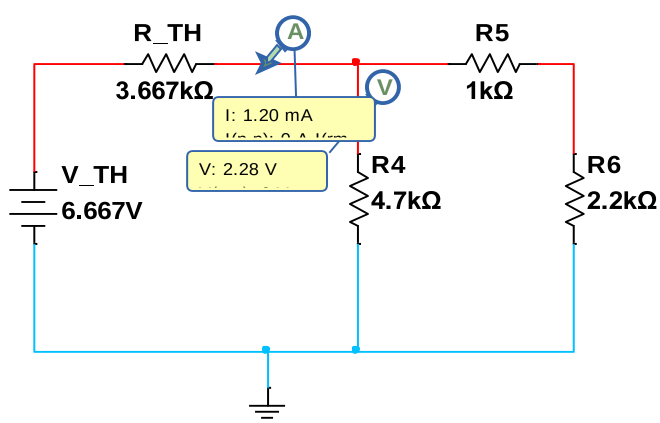

Fig. 12 – Multisim Thevenin's Equivalent Circuit for (R_L) as the combined resistors R_4, R_5, and R_6.

Bench Measurements

The circuit was constructed on a breadboard to validate the theoretical and simulated results through practical measurements (Fig.15).

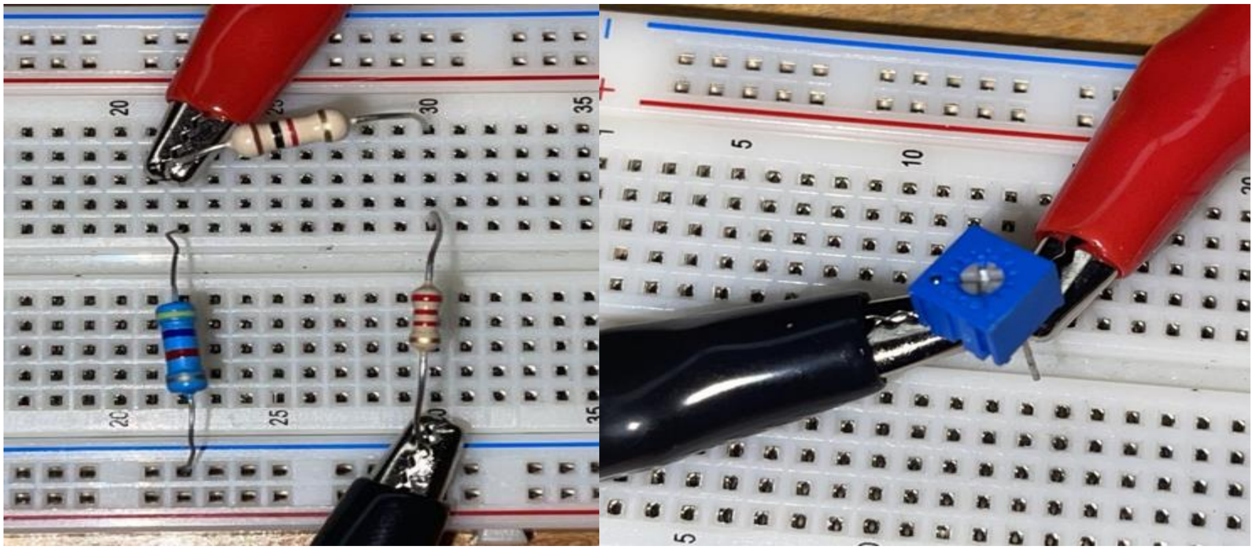

Fig. 13 – Measuring R_L and R_{TH} respectively.

Fig. 14 – Measured values of R_L and R_{TH} respectively.

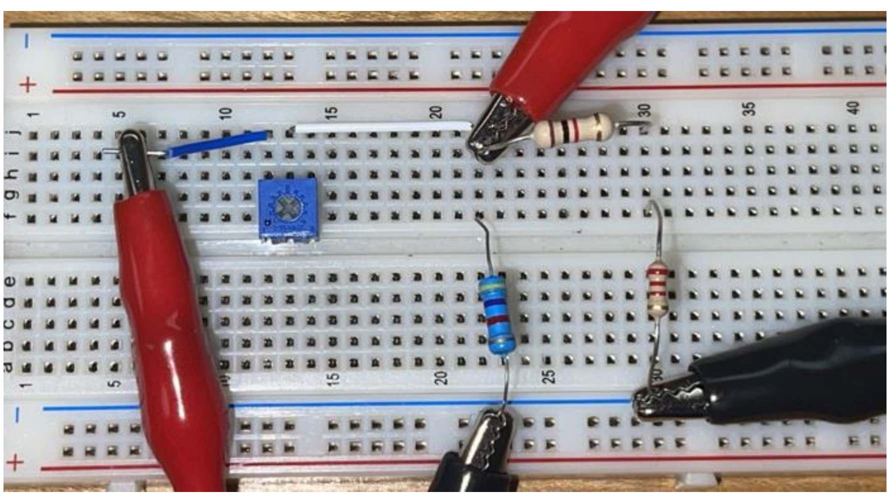

Fig. 15 – Thevenin's Equivalent circuit for (R_L) as the combined resistors R_4, R_5, and R_6. DMM Probes are placed to measure V_{RL}.

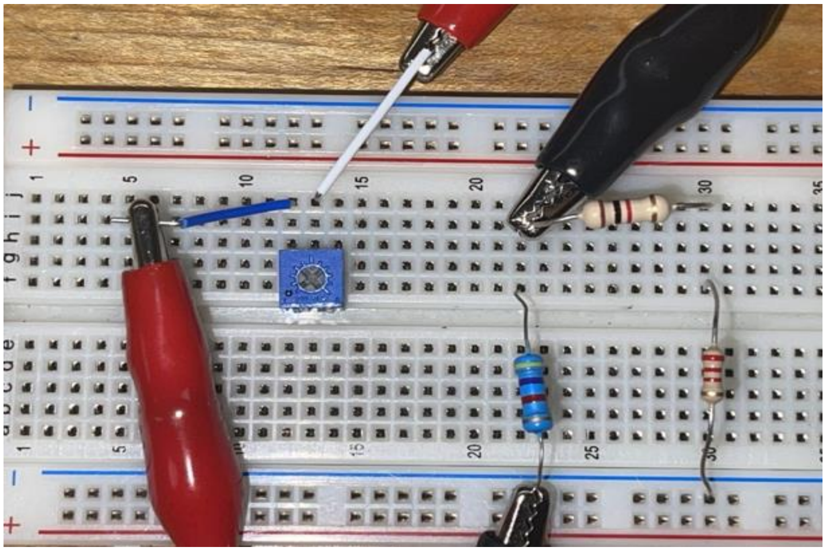

Fig. 16 - Thevenin's Equivalent circuit for (R_L) as the combined resistors R_4, R_5, and R_6. DMM Probes are placed to measure I_{RL}.

Fig. 17 – Measured values for V_{RL} (V) and I_{RL} (mA) respectively.

The measured values provided practical confirmation of the theoretical calculations and simulation results. The close agreement among the theoretical, simulated, and measured values indicated that the circuit was accurately constructed and the analysis methods were reliable. Minor discrepancies observed between the theoretical and measured values were within the expected range due to resistor tolerances and slight variations in the power supply voltage.

Table 3

	$\boldsymbol{V_{RL}}$	$\boldsymbol{I_{RL}}$
Theory	2.28 V	1.196 mA
Simulation	2.28 V	1.2 mA
Lab	2.27 V	1.18 mA
Percent Error (%)	0.44 %	1.34 %

Thevenin Equivalent Circuit with Resistor R_6 as the Load

For the Thevenin equivalent circuit with only resistor R_6 as the load, the following calculations were performed to determine the Thevenin resistance (R_{TH}) and Thevenin voltage (V_{TH}):

Thevenin Resistance (R_{TH})

The Thevenin resistance (R_{TH}) is calculated by deactivating all independent sources and calculating the equivalent resistance seen from the terminals where R_6 is connected.

Calculating R_{TH}:

$$R_{TH} = \left(\left(\left((R_1 \parallel R_2) + R_3\right) \parallel R_4\right) + R_5\right)$$

$$R_{1,2,3} = 3.0\ k\Omega + \frac{1.0k\Omega * 2.0\ k\Omega}{1.0k\Omega + 2.0\ k\Omega} = 3.667\ k\Omega$$

$$R_{1,2,3,4} = \frac{3.667k\Omega * 4.7k\Omega}{3.667k\Omega + 4.7k\Omega} = 2.0598k\Omega$$

$$R_{TH} = R_{1,2,3,4} + R_5 = 2.0598k\Omega + 1.0k\Omega = 3.06k\Omega$$

Calculating V_{TH} Using Ohms law:

$$R_{2,3,4} = (R_3 + R_4) \parallel R_2 = \frac{7.7k\Omega * 2.0k\Omega}{7.7k\Omega + 2.0k\Omega} = 1.5876k\Omega$$

$$V_{R_{2,3,4}} = 10\left(\frac{1.5876}{2.5876}\right) = 6.135\ V$$

$$V_{TH} = 6.135\left(\frac{4.7k\Omega}{7.7k\Omega}\right) = 3.745\ V$$

Current to the Load (I_{RL}):

$$I_{RL} = \frac{3.745\ \mathrm{V}}{3.0598\ \mathrm{k\Omega} + 2.2\ \mathrm{k\Omega}} = \frac{3.745}{5.2598}\ \mathrm{mA} = 712\ \mu\mathrm{A}$$

Voltage at the Load (V_{RL}):

$$V_{RL} = 0.712\ \mathrm{mA} \times 2.2\ \mathrm{k\Omega} = (0.712 \times 2.2)\mathrm{V} = 1.567\ \mathrm{V}$$

Simulation Results for Thevenin Equivalent Circuit with Resistor R_6 as the Load

The Thevenin equivalent circuit with only resistor R_6 as the load was simulated in Multisim to verify the theoretical calculations. The circuit diagram and simulation results provided both visual and numerical verification.

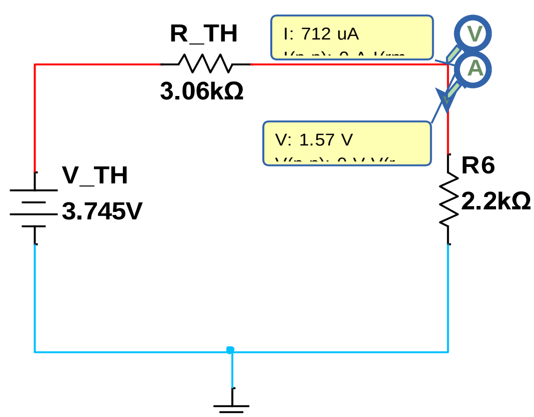

Fig. 18 - Thevenin Equivalent Circuit with Resistor R_6 as the Load.

The simulation showed that the voltage across the load resistor R_6 was the same as the previously calculated V_{R6} from the initial circuit analysis. This demonstrates that the Thevenin equivalent circuit is indeed an accurate simplification of the original circuit. By matching the voltage across R_6 in both the original and Thevenin equivalent circuits, it is confirmed that Thevenin's Theorem effectively simplifies complex circuits without altering the overall behavior and response of the load (Fig.18).

Bench Measurements for Thevenin Equivalent Circuit with Resistor R_6 as the Load

The final step involved constructing the Thevenin equivalent circuit on a breadboard and measuring the voltage and current to compare with the theoretical and simulated results.

Fig. 19 – Measured values for V_{TH} and R_{TH} respectively.

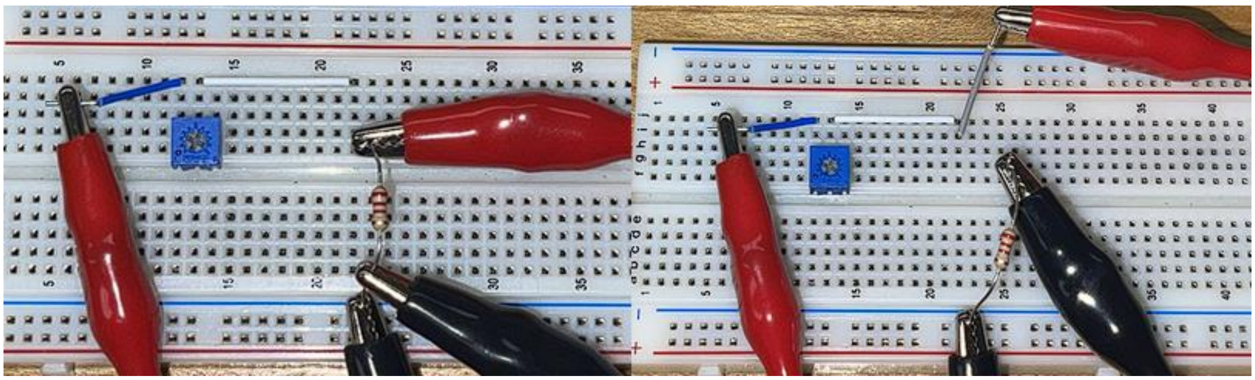

Fig. 20 – Probe placements to measure V_{RL} and I_{RL} respectively.

Fig. 21 – Measured values of V_{RL} (V) and $I_{RL}(mA)$ respectively.

These measurements were then compared to the theoretical and simulated values to ensure consistency and accuracy. The practical measurements confirmed the theoretical predictions, demonstrating that the Thevenin equivalent circuit is an accurate and simplified representation of the original circuit.

Table 4

	$\boldsymbol{V_{RL}}$	$\boldsymbol{I_{RL}}$
Theory	$1.56\ V$	$712\ \mu A$
Simulation	$1.57\ V$	$712\ \mu A$
Lab	$1.55\ V$	$713\ \mu A$
Percent Error (%)	0.64 %	0.14 %

ANSWERS TO LAB QUESTIONS

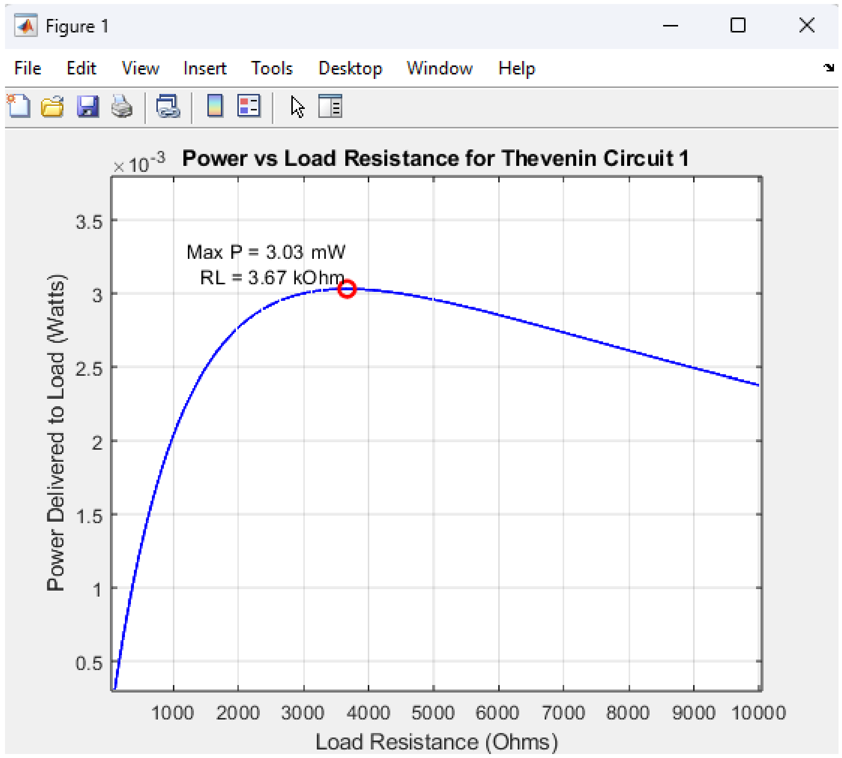

Fig. 21 – Power vs. Loas Resistance curve for the first Thevenin Circuit.

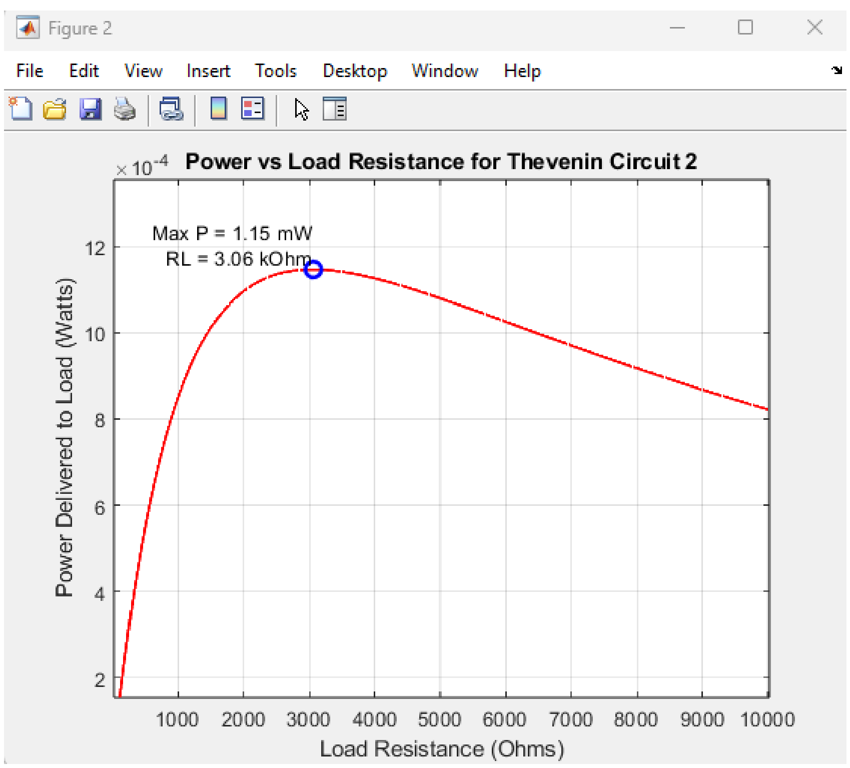

Fig. 22 – Power vs. Loas Resistance curve for the first Thevenin Circuit.

The curve of $PLPL$ (Power delivered to the load) versus $RLRL$ (Load resistance) is important because it demonstrates the principle of maximum power transfer. This principle states that maximum power is transferred to the load when the load resistance $RLRL$ is equal to the Thevenin resistance $RthRth$ of the source network.

Understanding this curve helps in designing and optimizing electrical circuits for efficient power transfer, which is crucial in various engineering applications, from power systems to electronic devices. It ensures that the load receives the highest possible power from the source, improving performance and efficiency.

DISCUSSION

Theoretical calculations were derived using nodal analysis and Thevenin's Theorem, providing a solid foundation for expected outcomes. Simulation results, obtained using Multisim, closely matched the theoretical values, with minor differences due to rounding and numerical precision. Bench measurements were conducted to validate these results and showed slight discrepancies from the theoretical and simulated values due to real-world factors.

The accuracy of measurements was influenced primarily by resistor tolerances. Resistors with a 5% tolerance led to variations in actual resistance values compared to the nominal values used in theoretical calculations. Additionally, the precision of the digital multimeter used for measurements introduced minor discrepancies. Slight variations in the power supply voltage also affected the current and voltage measurements.

These minor discrepancies, which were within the acceptable range, highlight the importance of considering practical elements in circuit design and analysis. Despite these sources of error, the experiment successfully demonstrated that the Thevenin equivalent circuit accurately represents the original circuit in a simplified form. The close agreement between the theoretical, simulated, and bench measurements validates the methods used and underscores the importance of real-world considerations in circuit design. By discussing these factors, the experiment shows a comprehensive understanding of circuit analysis techniques and the practical application of theoretical concepts.

CONCLUSION

This experiment successfully demonstrated the application of Thevenin's Theorem in simplifying circuit analysis. The theoretical, simulation, and bench measurements were closely aligned, validating the accuracy of the nodal analysis and the Thevenin equivalent circuit. The minor discrepancies observed were primarily due to resistor tolerances and measurement instrument precision, which are expected in practical scenarios.

The experiment yielded the desired results, proving that the Thevenin equivalent circuit can effectively replace a more complex circuit with a simplified version without losing accuracy. This simplification is highly beneficial in analyzing and designing electrical circuits, particularly when dealing with varying load conditions.

For future work, improvements can be made by using resistors with lower tolerance values to minimize discrepancies. Additionally, using more precise measurement instruments can further enhance the accuracy of the results. Overall, this experiment reinforced the practical applicability of Thevenin's Theorem and provided valuable insights into real-world circuit analysis and design.

REFERENCES

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2. Hayt, W. H., Kemmerly, J. E., Phillips, J. D., & Durbin, S. M. (2019). *Engineering Circuit Analysis* (Ninth Edition). McGraw-Hill Education.

3. Notash, A. (2020). *Chapter 4: Node Voltage Analysis*. Valencia College ECET Department.

4. Notash, A. (2020). *Chapter 5: TEC-NEC Circuits & Maximum Power Transfer*. Valencia College ECET Department.

APPENDIX A

```
% MATLAB code to plot Gaussian curves for two Thevenin circuits

% Thevenin parameters for the first circuit
Vth1 = 6.667; % Thevenin voltage in volts
Rth1 = 3.667 * 1000; % Thevenin resistance in ohms

% Thevenin parameters for the second circuit
Vth2 = 3.745; % Thevenin voltage in volts
Rth2 = 3.06 * 1000; % Thevenin resistance in ohms

% Define a range of load resistances (RL) from 100 to 10k ohms
RL = linspace(100, 10000, 10000); % With 10k points for a smooth curve

% Calculate power delivered to the load for the first circuit
PL1 = (Vth1^2 * RL) ./ ((Rth1 + RL).^2);

% Calculate power delivered to the load for the second circuit
PL2 = (Vth2^2 * RL) ./ ((Rth2 + RL).^2);

% Find the maximum power and the corresponding load resistance for the first circuit
[maxPL1, idx1] = max(PL1);
maxRL1 = RL(idx1);

% Find the maximum power and the corresponding load resistance for the second circuit
[maxPL2, idx2] = max(PL2);
maxRL2 = RL(idx2);

% Plot the power vs load resistance for the first circuit
figure;
plot(RL, PL1, 'b', 'LineWidth', 1.5);
hold on;
plot(maxRL1, maxPL1, 'ro', 'MarkerSize', 8, 'LineWidth', 2);
text(maxRL1, maxPL1, sprintf('Max P = %.2f mW\nRL = %.2f kOhm', maxPL1*1000,
maxRL1/1000), 'VerticalAlignment', 'bottom', 'HorizontalAlignment', 'right');
xlabel('Load Resistance (Ohms)');
ylabel('Power Delivered to Load (Watts)');
title('Power vs Load Resistance for Thevenin Circuit 1');
grid on;
hold off;

% Plot the power vs load resistance for the second circuit
```

```
figure;
plot(RL, PL2, 'r', 'LineWidth', 1.5);
hold on;
plot(maxRL2, maxPL2, 'bo', 'MarkerSize', 8, 'LineWidth', 2);
text(maxRL2, maxPL2, sprintf('Max P = %.2f mW\nRL = %.2f kOhm', maxPL2*1000,
maxRL2/1000), 'VerticalAlignment', 'bottom', 'HorizontalAlignment', 'right');
xlabel('Load Resistance (Ohms)');
ylabel('Power Delivered to Load (Watts)');
title('Power vs Load Resistance for Thevenin Circuit 2');
grid on;
hold off;
```