| **Student ID:** | | **Lab Section:** | |
|---|---|---|---|
| **Name:** | | **Lab Group:** | |

Experiment No. 6

# Verification of Thevenin's Theorem and Maximum Power Transfer Theorem

## Objective

The aim of this experiment is to validate Thevenin's Theorem for linear circuits as well as the condition for the Maximum Power to be delivered to the load of any linear two terminal circuit.

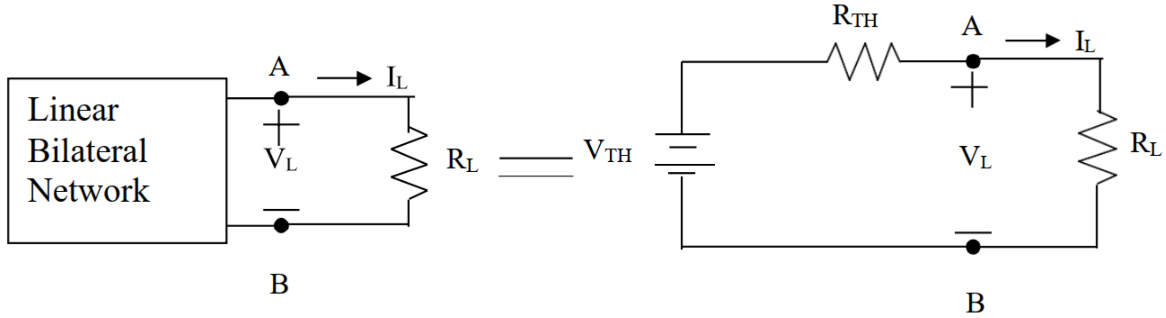
## Part 1: Thevenin's Theorem

### Theory

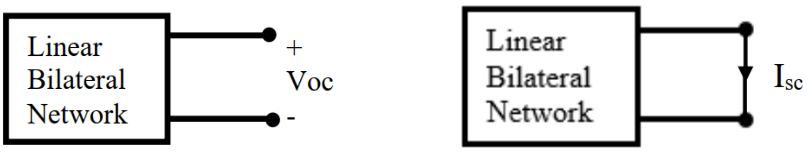
It is often desirable in circuit analysis to study the effect of changing a particular branch element while all other branches and all the sources in the circuit remain unchanged. Thevenin's theorem is a technique to this end, and it greatly reduces the number of computations that we have to do each time a change is made. Using Thevenin's theorem the given circuit except the particular branch to be studied is reduced to the simplest equivalent circuit possible and then the branch to be changed is connected across the equivalent circuit.

Thevenin's theorem states that any two-terminal linear bilateral networks containing sources and passive elements can be replaced by an equivalent circuit consisting of a voltage source ($V_{Th}$) in series with a resistor ($R_{Th}$), where,

$V_{Th}$ = The open circuit voltage ($V_{OC}$) at the two terminals A and B.
$R_{Th}$ = The resistance looking into terminals A and B of the network with all sources removed.



There are several methods for determining Thevenin resistance $R_{Th}$. An attractive method for determining $R_{Th}$ is: (1) determine the open circuit voltage, and (2) determine the short circuit current $I_{SC}$ as shown in the figure; then




$$R_{th} = \frac{Voc}{ISC}$$

## Methodology of Determining Thevenin's Circuit Parameters ($V_{OC}$, $I_{SC}$, $R_{th}$)

Procedure to determine the Thevenin's Circuit Parameters ($V_{OC}$, $I_{SC}$, $R_{Th}$) and Thevenin equivalent circuit for any linear two-terminal linear circuit is given below.

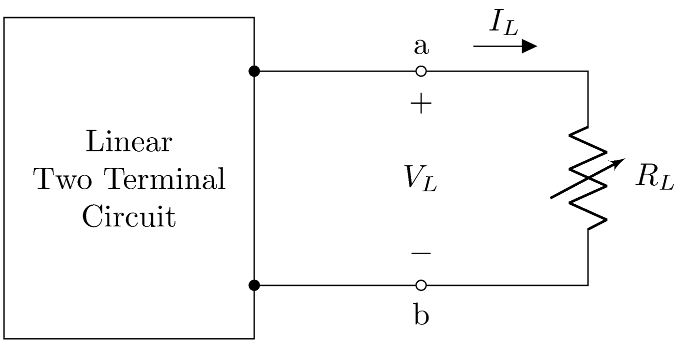



**Figure 1:** Original Circuit

### Step 1: Determining $V_{OC}$

Remove the load resistance $R_L$ and find the open circuit voltage between terminals a & b. This voltage is called Thevenin's voltage, i.e., $V_{Th} = V_{OC}$. It is also known as the Open Circuit Voltage.

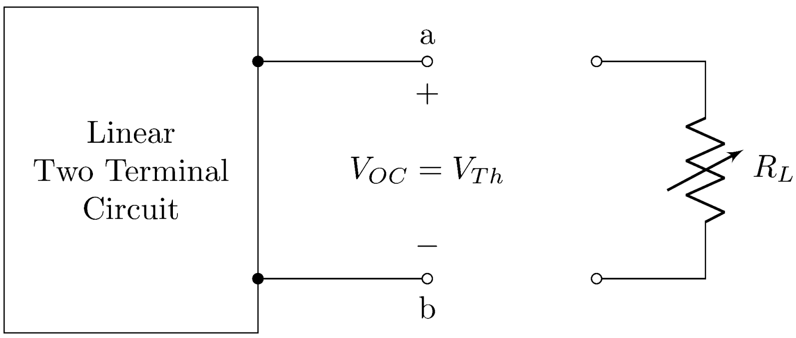



**Figure 2:** Circuit for finding $V_{OC}$

**Step 2: Determining $I_{SC}$**

Place a short circuit between terminals a and b (simply connect them through a wire). The current through the short circuit is called Norton's Current, i.e., $I_N = I_{SC}$. It is also known as the Short Circuit Current.

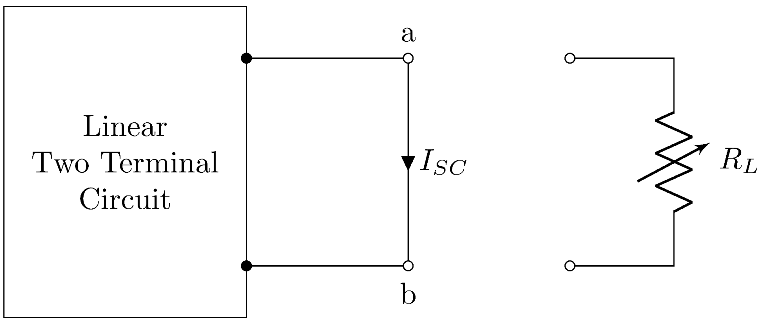



**Figure 3:** Circuit for finding $I_{SC}$

**Step 3: Determining $R_{th}$**

Divide the Open Circuit Voltage by the Short Circuit Current to determine the Thevenin's Resistance.

$$R_{Th} = \frac{V_{OC}}{I_{SC}}$$

**Alternatively,** turn off all the independent sources and determine the equivalent resistance between terminals $a - b$. This is the Thevenin resistance, that is, $R_{ab} = R_{Th}$.

**Step 4: Constructing Thevenin's Equivalent Circuit**

Construct Thevenin's equivalent circuit as shown in the following figure setting the voltage source at $V_{Th}$ volts and the series resistance at $R_{Th}$ ohms. The values shown here should closely match the corresponding values you determined from the earlier steps.

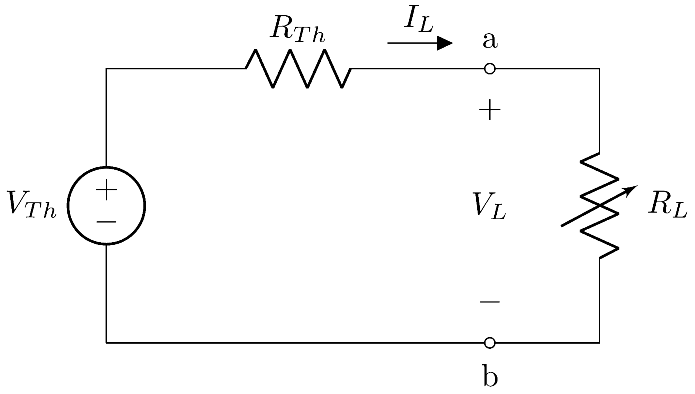


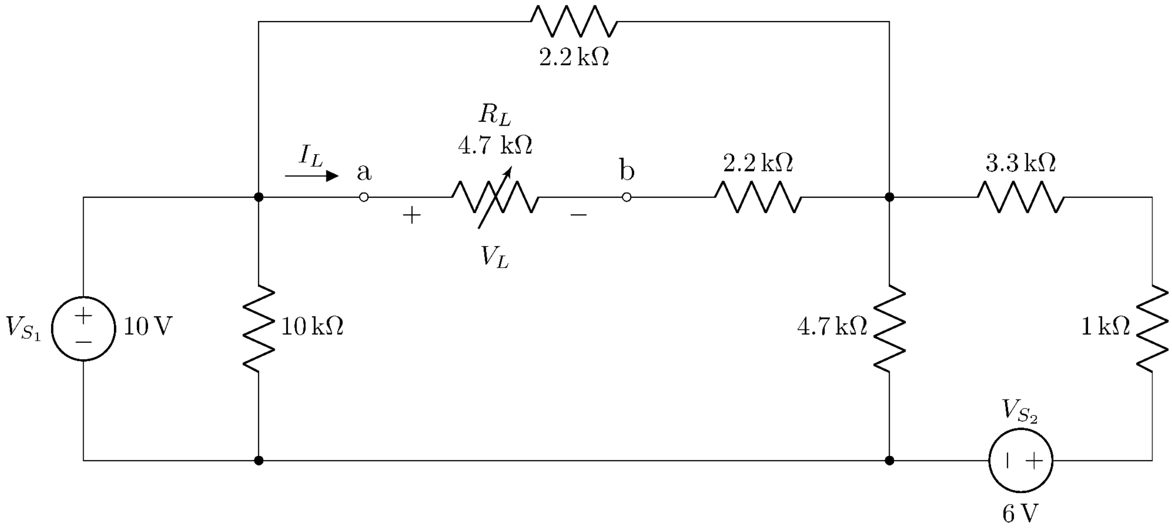

**Figure 4:** Thevenin Equivalent Circuit

## Apparatus

- ➢ Multimeter
- ➢ Resistors ($1\ k\Omega,\ 2.2\ k\Omega$ x $2,\ 3.3\ k\Omega,\ 4.7\ k\Omega$ x $2,\ 10\ k\Omega$).
- ➢ DC power supply
- ➢ Breadboard
- ➢ Jumper wires

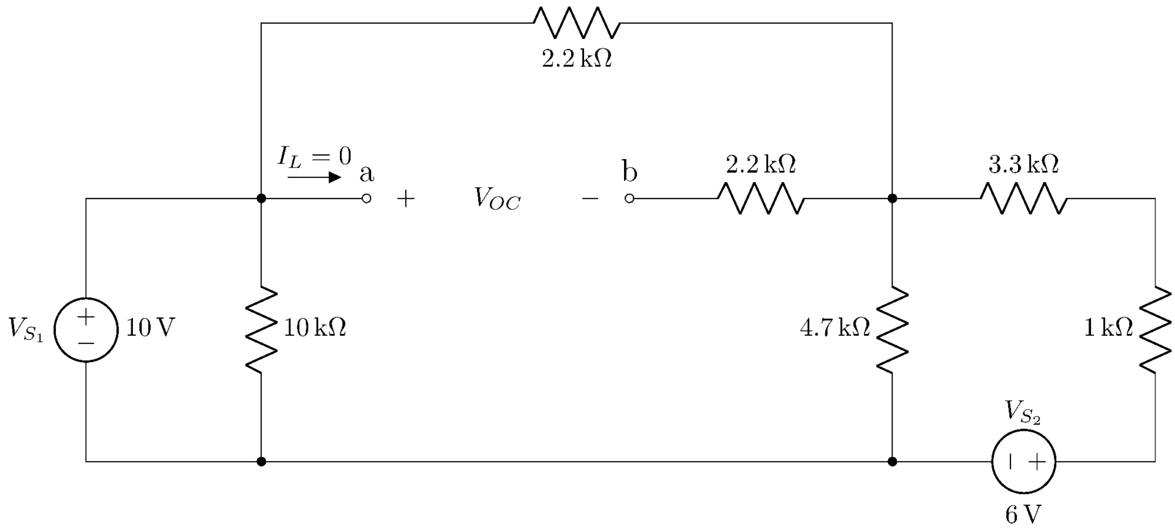
## Procedures

- ➢ Measure the resistances of the provided resistors and fill up the data table.
- ➢ Construct the following circuit on a breadboard. Try to use a minimum number of jumper wires.



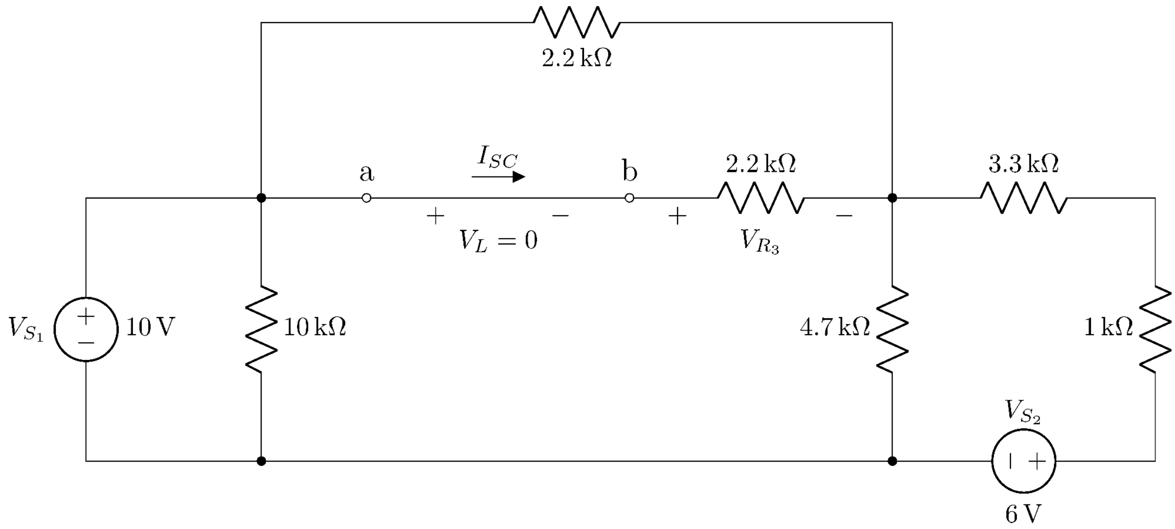

**Circuit 1**

- ➢ Connect two DC voltage sources or two channels of a DC source with voltages set to $6\ V$ and $10\ V$ as shown in the figure.
- ➢ We will model the load resistance ($R_L$) by a $4.7\ k\Omega$ resistor for simplicity. Connect a $4.7\ k\Omega$ resistor as $R_L$.
- ➢ Measure the voltage ($V_L$) across the load resistance. Measure the current ($I_L$) through the load using Ohm's law as $I_L = \frac{V_L}{R_L}$. Record the values in the corresponding data table.
- ➢ Now, disconnect the load resistor and leave the terminals $a - b$ open. The circuit should look like the one shown below.




**Circuit 2**

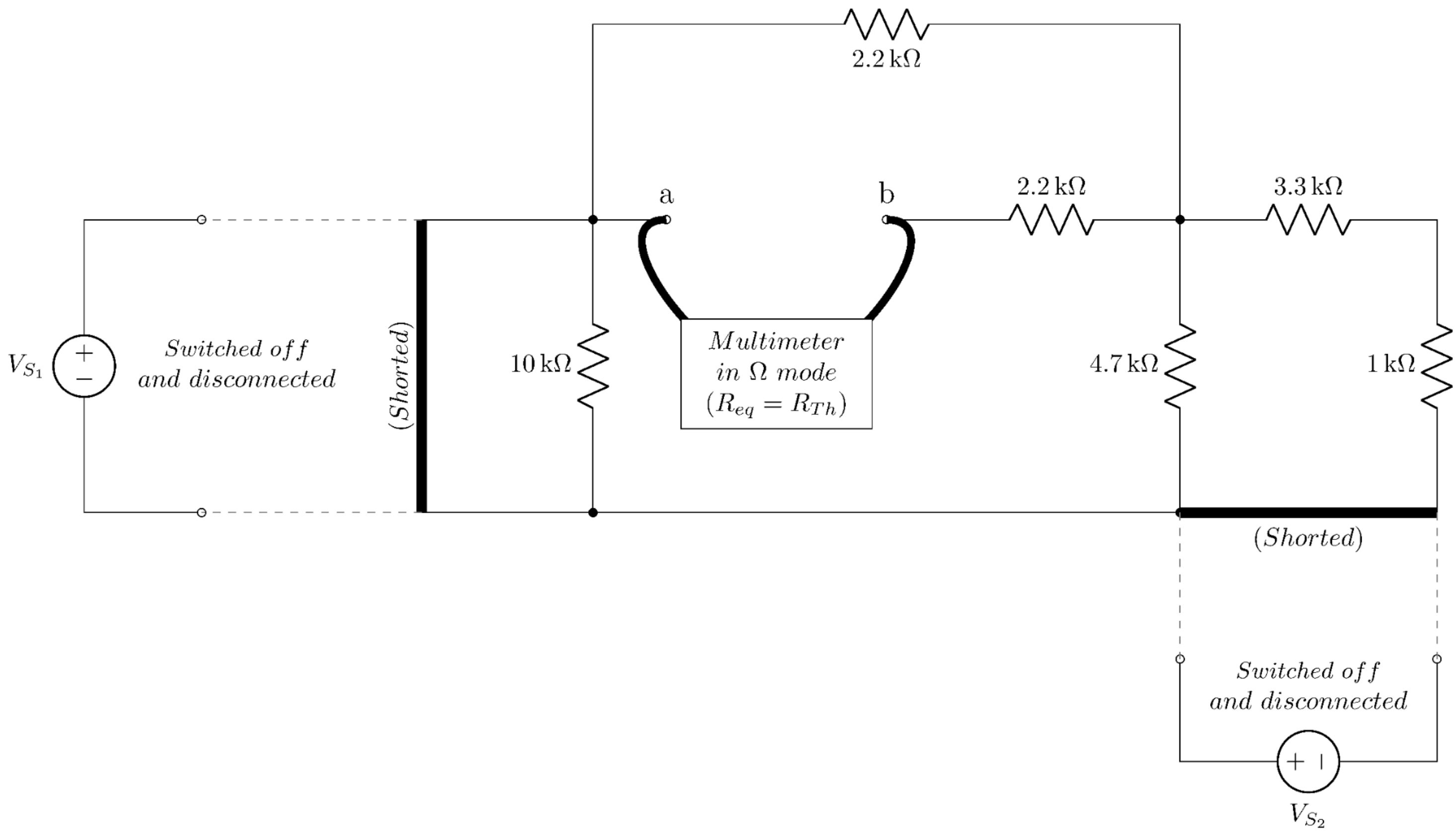
- Notice that, as the load is open circuited, the load current $(I_L)$ is zero. Measure the open circuit voltage $V_{OC}$ and record in the corresponding data table.
- Now short the terminals $a - b$ by connecting a wire between them as shown in the following diagram.




**Circuit 3**

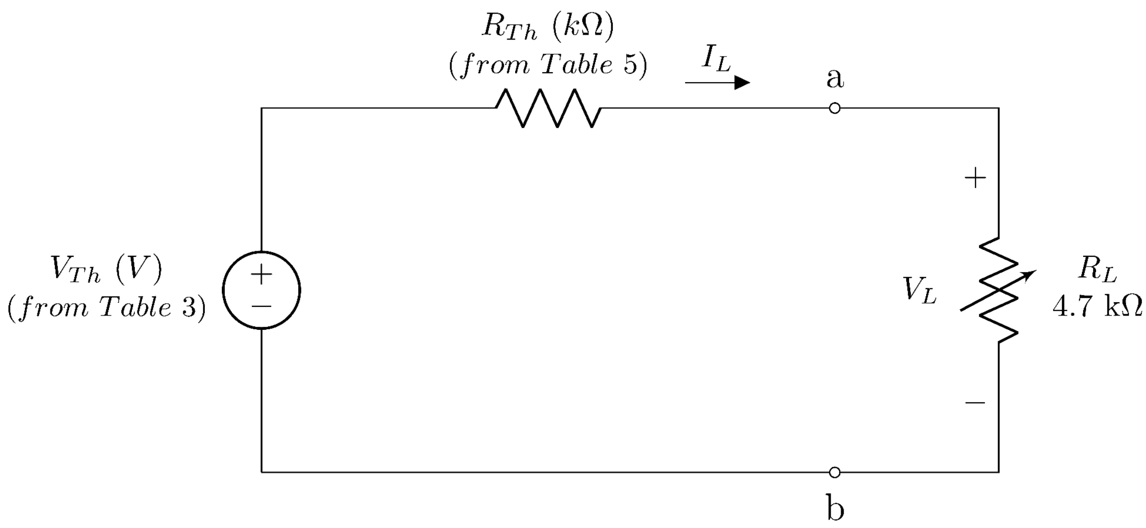
- Notice that, as the load is short circuited, the load voltage $(V_L)$ is zero. Measure the short circuit current $I_{SC}$ and record in the corresponding data table. $I_{SC}$ is the current flowing through the $R_3$ resistor, that is $I_{SC} = \frac{V_{R_3}}{R_3}$.
- Use $V_{Th}$ from **Circuit 2** and $I_{SC}$ from **Circuit 3** to calculate $R_{Th}$ as $R_{Th} = \frac{V_{Th}}{I_{SC}}$ in data Table 5.

- ➢ Now let's determine $R_{Th}$ using another method which is called the Universal Method. To do this, again open the terminals $a - b$ (remove the shorting wire in **Circuit 3**)
- ➢ Turn the switches of the voltage source(s). Replace them with short circuits as shown in the following diagram.




**Circuit 4**

- ➢ Measure the equivalent resistance between terminals $a - b$. This the Thevenin resistance $R_{Th}$.
- ➢ Now construct the following Thevenin equivalent circuit shown in the following diagram.
- ➢ Set the value of the voltage source equal to $V_{Th}$ (from Table 3). Use $R_{Th}$ from Table 5.




**Circuit 5**

➢ Measure the voltage ($V_L$) across the load resistance. Measure the current ($I_L$) through it using Ohm's law as $I_L = \frac{V_L}{R_L}$. Record the values in the corresponding data table.

## Data Tables

| **Signature of Lab Faculty:** | | **Date:** | |
|---|---|---|---|

*** **For all the data tables, take data up to three decimal places, round to two, then enter into the table.***

## Table 1: Resistance Data

For all your future calculations, please use the observed values only **(even for theoretical calculations)**.

| Notation | Expected Resistance | Observed Resistance (kΩ) | Notation | Expected Resistance | Observed Resistance (kΩ) |
|---|---|---|---|---|---|
| $R_1$ | 10 kΩ | | $R_5$ | 3.3 kΩ | |
| $R_2$ | 2.2 kΩ | | $R_6$ | 1 kΩ | |
| $R_3$ | 2.2 kΩ | | $R_L$ | 4.7 kΩ | |
| $R_4$ | 4.7 kΩ | | | | |

## Table 2: Data from Circuit 1

In the following table, $V_L$ is the voltage drop across the load resistor $R_L$ and $I_L$ is the current through the load with polarity and direction respectively as shown in **Circuit 1**. Solving the circuit and calculate theoretical $V_L$ and $I_L$. Also, calculate the percentage of error between experimental and theoretical values of $V_L$.

<table>
<tr><th>Observation</th><th>$V_{S_1}$<br>(V)<br>(from dc supply)</th><th>$V_{S_1}$<br>(V)<br>(using multimeter)</th><th>$V_{S_2}$<br>(V)<br>(from dc supply)</th><th>$V_{S_2}$<br>(V)<br>(using multimeter)</th><th>$V_L$<br>(V)</th><th>$I_L = \frac{V_L}{R_L}$<br>(mA)</th></tr>
<tr><td>Experimental</td><td></td><td rowspan="2"></td><td></td><td rowspan="2"></td><td></td><td></td></tr>
<tr><td>Theoretical</td><td></td><td></td><td></td><td></td></tr>
</table>

$$\textbf{Percentage of Error} = \left|\frac{Experimental - Theoretical}{Theoretical}\right| \times 100\%$$

Here, Percentage of Error in $V_L$ calculation = [ %]

## Table 3: Data from Circuit 2

In the following table, $V_{OC}$ is the open circuit voltage across the open terminals with $I_L = 0$. This is the Thevenin voltage $V_{Th}$. Calculate the percentage of error between experimental and theoretical values of $V_{OC}$.

<table>
<tr><th>Observation</th><th>$V_{S_1}$<br>(V)<br>(from dc supply)</th><th>$V_{S_1}$<br>(V)<br>(using multimeter)</th><th>$V_{S_2}$<br>(V)<br>(from dc supply)</th><th>$V_{S_2}$<br>(V)<br>(using multimeter)</th><th>$V_{OC} = V_{Th}$<br>(V)</th></tr>
<tr><td>Experimental</td><td></td><td rowspan="2"></td><td></td><td rowspan="2"></td><td></td></tr>
<tr><td>Theoretical</td><td></td><td></td><td></td></tr>
</table>

Here, % error in $V_{OC} = V_{Th}$ calculation = [ %]

## Table 4: Data from Circuit 3

In the following table, $I_{SC}$ is the current through the shorted terminals with $V_L = 0$. Theoretically calculate the short circuit current and calculate the percentage of error between experimental and theoretical values of $I_{SC}$.

| **Observation** | $V_{S_1}$ (V) (from dc supply) | $V_{S_1}$ (V) (using multimeter) | $V_{S_2}$ (V) (from dc supply) | $V_{S_2}$ (V) (using multimeter) | $V_{R_3}$ (V) | $I_{SC} = \frac{V_{R_3}}{R_3}$ (mA) |
|---|---|---|---|---|---|---|
| **Experimental** | | | | | | |
| **Theoretical** | | | | | | |

Here, % error in $I_{SC}$ calculation = %

## Table 5: $R_{Th}$ calculation

Comparison of the two methods to determine $R_{Th}$.
Here, $\Delta R_{Th} = (R_{Th}\ using\ V_{Th}/I_{SC}\ method) - (R_{Th}\ using\ the\ Universal\ method)$

| **Observation** | $V_{Th}$ (V) (from data Table 3) | $I_{SC}$ (mA) (from data Table 4) | $R_{Th} = \frac{V_{Th}}{I_{SC}}$ (kΩ) | $R_{Th}$ (kΩ) (using multimeter from Circuit 4) | $\Delta R_{Th}$ (kΩ) |
|---|---|---|---|---|---|
| **Experimental** | | | | | |
| **Theoretical** | | | | | |

## Table 6: Data from Circuit 5

In the following table, $V_L$ is the voltage drop across the load resistor $R_L$ and $I_L$ is the current through the load with polarity and direction respectively as shown in **Circuit 1** and **Circuit 5**. Measure the value of $V_L$ from **Circuit 5**. Then calculate $I_L$ using the measured $V_L$. Finally compare the values with those in Table 1. Here,

$\Delta V_L = (V_L\ from\ Table\ 2) - (V_L\ measured\ for\ Circuit\ 5$ in Table 6) and

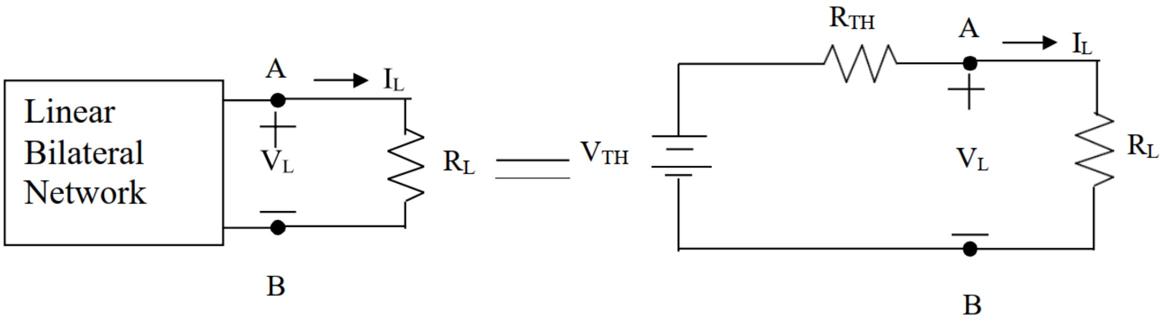
$\Delta I_L = (I_L\ from\ Table\ 2) - (I_L\ calculated\ for\ Circuit\ 5$ in Table 6).

| Observation | $V_L$ (V) (from data Table 2) | $I_L$ (mA) (from data Table 2) | $V_L$ (V) (from Circuit 5 using multimeter) | $I_L = \frac{V_L}{R_L}$ (V) (for Circuit 5) | $\Delta V_L$ (V) | $\Delta I_L$ (mA) |
|---|---|---|---|---|---|---|
| **Experimental** | | | | | | |
| **Theoretical** | | | | | | |

# Part 2: Maximum Power Transfer Theorem

## Theory

The Maximum Power Transfer Theorem is a fundamental concept in electrical engineering that relates to the transfer of maximum power from a source to a load. The Maximum Power Transfer theorem states that ***A resistive load will receive maximum power when its total resistive value is exactly equal to Thevenin's resistance of the network as "seen" by the load.***




We know that any circuit A terminated with a load $R_L$ can be reduced to its Thevenin's equivalent. Now according to this theorem, the load $R_L$ will receive maximum power when $R_L = R_{Th}$. We can calculate the Maximum Power theoretically using the formula,

$$P_{max} = \frac{V_{Th}^{2}}{4R_{Th}}$$

The theorem focuses on the transfer of power between a source and a load. In electrical circuits, power is transferred from a source (such as a generator) to a load (such as a resistor) through a transmission medium (such as wires or conductors).

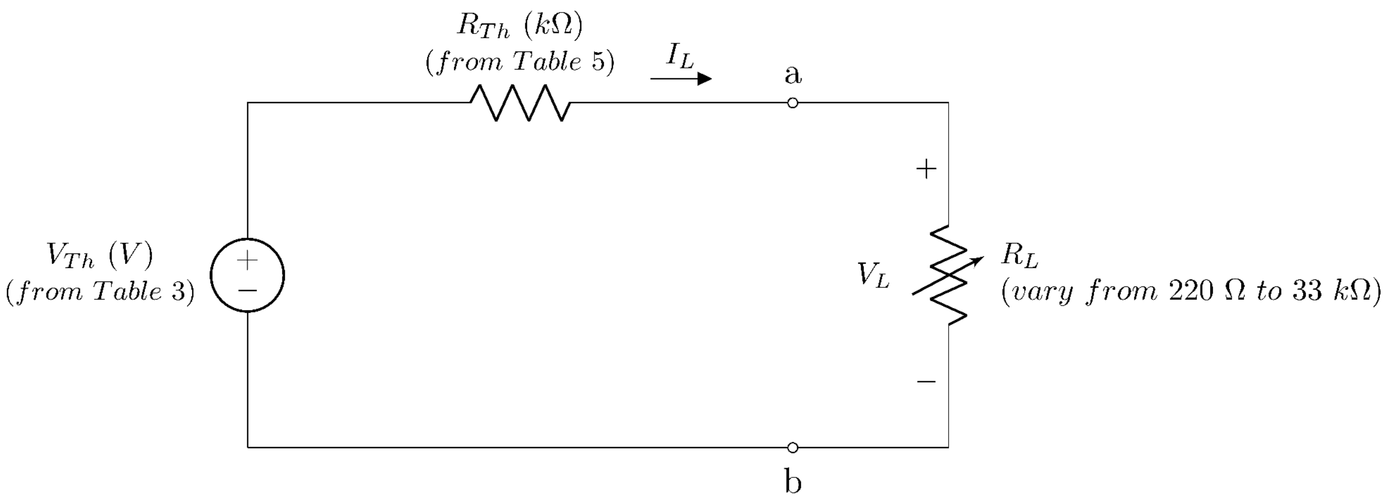
It's worth noting that the Maximum Power Transfer Theorem is a theoretical concept and is not always practical or desirable in real-world scenarios. In many practical applications, impedance matching is employed to achieve efficient power transfer, but it may not always result in maximum power transfer. Design considerations, system constraints, and other factors often influence the choice of impedance matching in electrical circuits.

## Apparatus

- Multimeter
- Resistors($220\ \Omega,\ 1\ k\Omega,\ 1.5\ k\Omega,\ 2.2\ k\Omega,\ 3.3\ k\Omega$ x $2,\ 4.7\ k\Omega,\ 5.6\ k\Omega,\ 10\ k\Omega,$ $18\ k\Omega,\ 33\ k\Omega$).
- DC power supply
- Breadboard
- Jumper wires

## Procedures

- Construct the following reduced Thevenin equivalent circuit.




**Circuit 6**

- Vary $R_L$ from $220\,\Omega$ to $33\ k\Omega$. For each resistors listed in the **Apparatus** section, measure $V_L$. Calculate $I_L$ using $I_L = \frac{V_L}{R_L}$ and record in the corresponding data table.

## Data Tables

| | | | |
|---|---|---|---|
| **Signature of Lab Faculty:** | | **Date:** | |

***** <u>For all the data tables, take data up to three decimal places, round to two, then enter into the table.</u>***

### Table 7: Data from Circuit 6

In the following table, $P_{In}$ is the power supplied by the dc source, value set equal to $V_{Th}$ and $P_{Load}$ is the power consumed by the load. η is the power efficiency. Theoretically, η is 50% at the maximum power transfer condition.

| $R_L$ (Expected) | $R_L$ (kΩ) (Measured) | $V_{Th}$ $(V)$ (using multimeter) | $V_L$ $(V)$ | $I_L = \frac{V_L}{R_L}$ $(mA)$ | $P_{In} = V_{Th} I_L$ $(mW)$ | $P_{Load} = V_L I_L$ $(mW)$ | Efficiency $\eta = \frac{P_{Load}}{P_{In}} \times 100$ (%) |
|---|---|---|---|---|---|---|---|
| 220 Ω | | | | | | | |
| 1 kΩ | | | | | | | |
| 1.5 kΩ | | | | | | | |
| 2.2 kΩ | | | | | | | |
| 3.3 kΩ | | | | | | | |
| 4.7 kΩ | | | | | | | |
| 5.6 kΩ | | | | | | | |
| 10 kΩ | | | | | | | |
| 18 kΩ | | | | | | | |
| 33 kΩ | | | | | | | |

Maximum Power found from the Table 7, $P_{max}$ = 0.707 mW

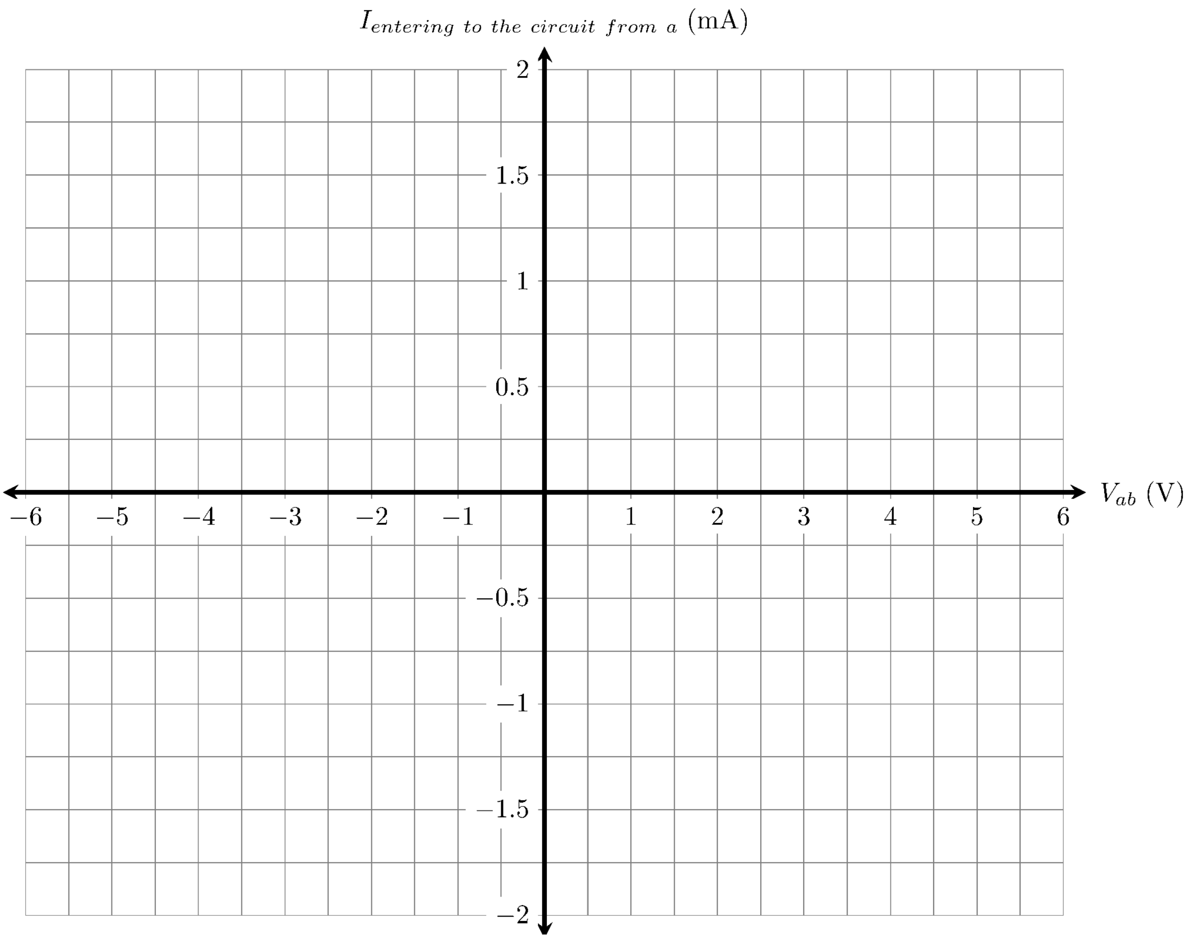
Theoretical Maximum Power, $P_{max} = \frac{V_{Th}^2}{4R_{Th}} =$ 0.881 mW

Here, percentage error in Maximum Powers calculation = 19.75 %

## Questions

**1.** Circuit equivalency:

(a) Draw the $I - V$ characteristic of the **Circuit 5** with respect to the terminals $a - b$ in the template provided below.




The straight line intersects x-axis at [ ] V

The straight line intersects y-axis at [ ] mA

**Slope** of the straight line, $m$ = [ ] $k\Omega^{-1}$

**Resistance** from the plot, $\frac{1}{m}$ = [ ] $k\Omega$

(b) Comparing the values to those measured for **Circuit 1** in Tables 3, 4, and 5, do they match?

☐ Yes ☐ No

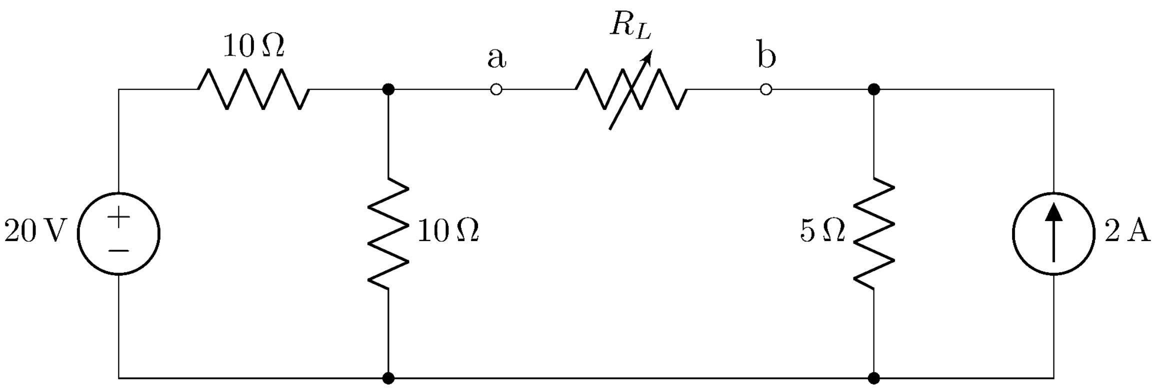
**2.** Now in the same plot provided above, plot the $I - V$ curve of **Circuit 4**.

**Slope** of the straight line, $m$ = | kΩ$^{-1}$ |

**Resistance** from the plot, $\frac{1}{m}$ = | kΩ |

Explain why there is a shift in the $I - V$ curve of Circuit 4.

**3.** Determine the open circuit voltage ($V_{OC}$) and the short circuit current ($I_{SC}$) with respect to the terminals $a - b$ for the circuit shown below.




Open circuit voltage, $V_{OC}$ = | 20 V |

Short circuit current, $I_{SC}$ = | 1.5 mA |

Have you been able to calculate the Thevenin resistance ($R_{Th}$) using $R_{Th} = \frac{V_{OC} = V_{Th}}{I_{SC}}$?

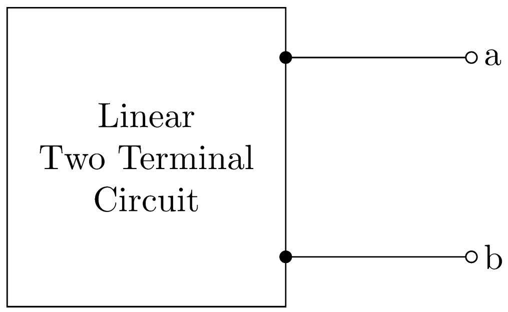
☑ Yes ☐ No

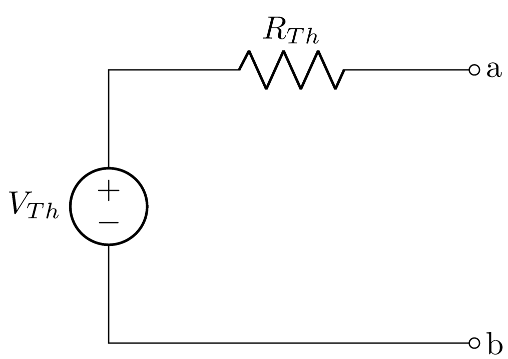
If not, suggest an alternative approach and determine $R_{Th}$.

We can determine $R_{Th}$ by

Calculation:

**4.** If the following voltage source is in series with a resistor is the Thevenin equivalent of the linear two-terminal circuit, for each of the circuit elements listed in the column 1 of the following table, write the values of $V_{Th}$ and $R_{Th}$. Write 'Unknown' if unable to specify.



| **The linear two-terminal circuit is composed of only a/an** | $V_{Th}$ (V) | $R_{Th}$ ($\Omega$) |
|---|---|---|
| Short circuit | 0 | 0 |
| Open circuit | 15 | infinite |
| $-$ 2 $V$ voltage source | -2 | 0 |
| 3 $A$ current source | unknown | infinte |
| 5 k$\Omega$ resistor | 0 | 5kohm |

**5.** Efficiency and Maximum Power:

(a) From the η and $P_{Load}$ vs. $R_L$ plot, what is the efficiency at the maximum power position?

| η = 95 % at the maximum power point position. |
|---|

(b) For a load resistance $R_L$,

we can **increase** the power efficiency of the load by –

☐ Increasing $R_L$ than $R_{Th}$ ☐ Decreasing $R_L$ than $R_{Th}$ ☐ By equating $R_{Th}$ and $R_L$

(c) We can **maximize** the power transfer of the load by –

☐ Increasing $R_L$ than $R_{Th}$ ☐ Decreasing $R_L$ than $R_{Th}$ ☐ By equating $R_{Th}$ and $R_L$

(d) "We cannot maximize both the power of a load and the power efficiency of the circuit" – justify the statement.

Impedance matching between the source and load impedances is necessary to increase the power provided to a load. By doing this, the load is guaranteed to get the most power from the source. Impedance matching enhances power transmission, although it does not always ensure the circuit's optimum power efficiency.

Power losses inside circuit components or transmission lines have an impact on efficiency. Even if the load in an impedance-matched system receives the maximum power possible, there might still be efficiency losses along the route.

On the other hand, concentrating on increasing the circuit's power efficiency can require adopting greater load resistances to reduce power losses.

6. Specify by putting × *or* ✔, what should be the first priority: maximizing the power or increasing the efficiency for the following applications –

| Application | Should Maximize the power transferred to the load | Should try to operate the load with the highest efficiency possible |
|---|---|---|
| An antenna sending signal to the Mars | | |
| A motor running to pull water to a tank placed in a higher position | | |
| A mic used to amplify voice | | |

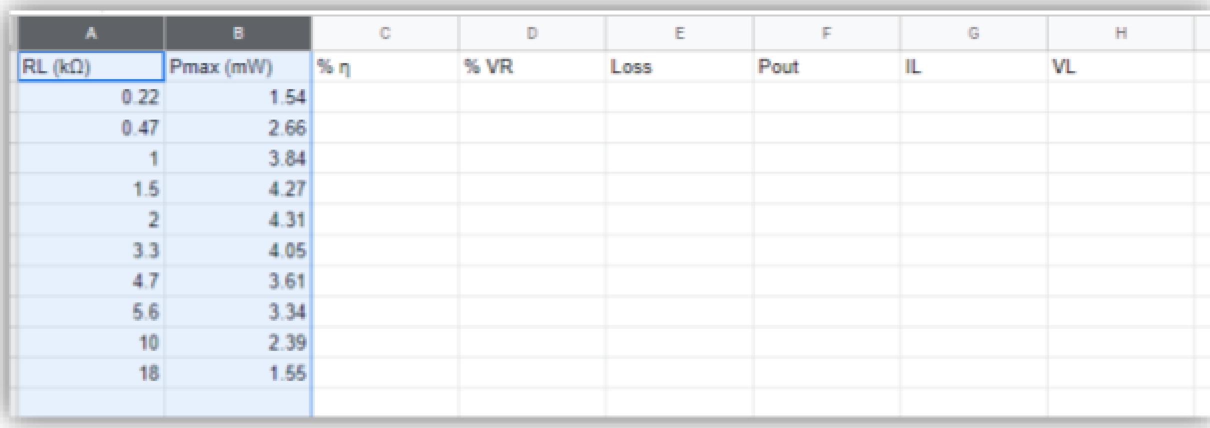
## Report

1. Fill up the theoretical parts of all the data tables.
2. Answer to the questions.
3. Attach two data plots, one should include $V_L$, $I_L$, and $P_{Load}$ vs. $R_L$ plotted together in the same pane and the other should include η and $P_{Load}$ vs. $R_L$ plotted together in the same pane. There is a guideline of plotting data using google sheet in the next page.
4. Discussion *[comment on the obtained results and discrepancies]*. Start writing below the line.

---

## Part 3: Plotting Circuit Characteristics on Google Sheets

1. Create a Google spreadsheet by visiting [https://docs.google.com/spreadsheets](https://docs.google.com/spreadsheets)
2. Fill in the spreadsheet with the data that you've collected in the lab (refer to your lab sheet). Select the column $R_L$ (kΩ) and any other column you want to plot with (to select a column, click on the column head, e.g., "A". Then hold CTRL while clicking the second column, e.g., "B", to select both columns).



| A | B | C | D | E | F | G | H |
|---|---|---|---|---|---|---|---|
| RL (kΩ) | Pmax (mW) | % η | % VR | Loss | Pout | IL | VL |
| 0.22 | 1.54 | | | | | | |
| 0.47 | 2.66 | | | | | | |
| 1 | 3.84 | | | | | | |
| 1.5 | 4.27 | | | | | | |
| 2 | 4.31 | | | | | | |
| 3.3 | 4.05 | | | | | | |
| 4.7 | 3.61 | | | | | | |
| 5.6 | 3.34 | | | | | | |
| 10 | 2.39 | | | | | | |
| 18 | 1.55 | | | | | | |

**Note**: This is sample data collected from a simulation. Your data may not match with this.

3. Select Insert → Chart. You should be getting a graph that looks like the following diagram.

4. A Chart Editor section should pop up at the right side of your screen. If it doesn't show up, then double click on the graph. Go to the setup section in the chart editor and change the "Chart type" to "Line chart". Your graph should be changed into a line plot as shown below.