Real circuit elements are approximate physical implementation of ideal circuit elements. In this experiment, you become familiar with the main limitations of the conventional real circuit elements such as resistors, capacitors, and diodes.

MANDATORY EXPERIMENTS

Experiment 1

Consider the circuit shown in Fig. 1

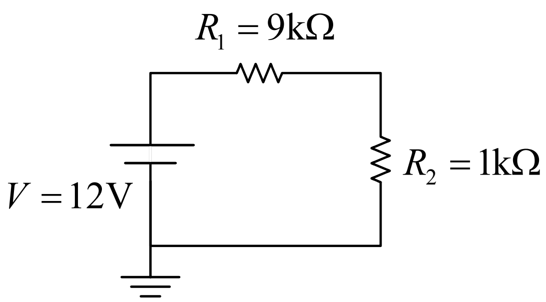


Figure 1: A voltage divider circuit.

(a) Build the circuit on a breadboard. Can you find a 9 kΩ resistor in the stackable element storage box?

We used two parallel $18k\Omega$ resistors to obtain $9k\Omega$. The $9k\Omega$ resistor is not available in the stackable element storage box since it's not a standard value in the E12 series.

(b) Which resistor is a suitable replacement for a 9 kΩ resistor? Pick that resistor and read its color code.

We used two parallel $18k\Omega$ resistors to obtain $9k\Omega$. We could also use an $8k\Omega$ because E12 resistors have 5% error.

(c) Measure the voltage across each resistor. Is there any difference between the measured and analytical values?

Experiment 1 continued on next page...

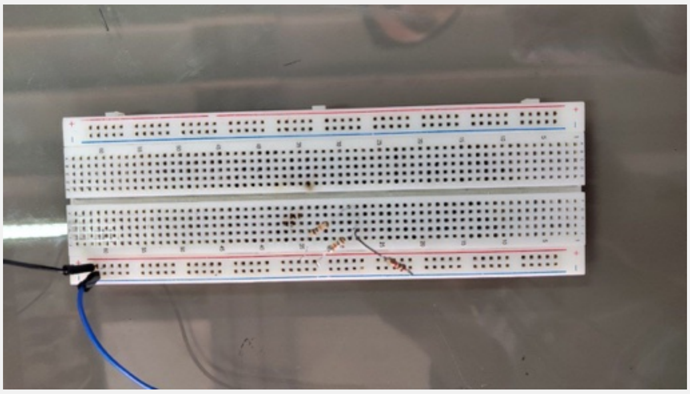


Figure 2: The circuit.

Figure 3: measured voltage value.

Yes, there is a difference between the values and the reason is the tolerance of the resistors.

Experiment 2

Each real circuit element has a nominal value within a tolerance band.

(a) Pick up ten E12 $1\ k\Omega$ resistors and measure their resistance. Calculate the maximum, minimum, mean, variance, and standard deviation of the measured values and interpret them considering the nominal and tolerance values.

We used E24 resistors instead.
values: $1.0103, 0.9940, 1.0027, 1.0018, 1.0012, 1.0015, 0.9964, 0.9996, 0.9979$ and $1.0135\ k\Omega$.

(b) Repeat the previous part for ten E12 $10\ \mu F$ capacitors.

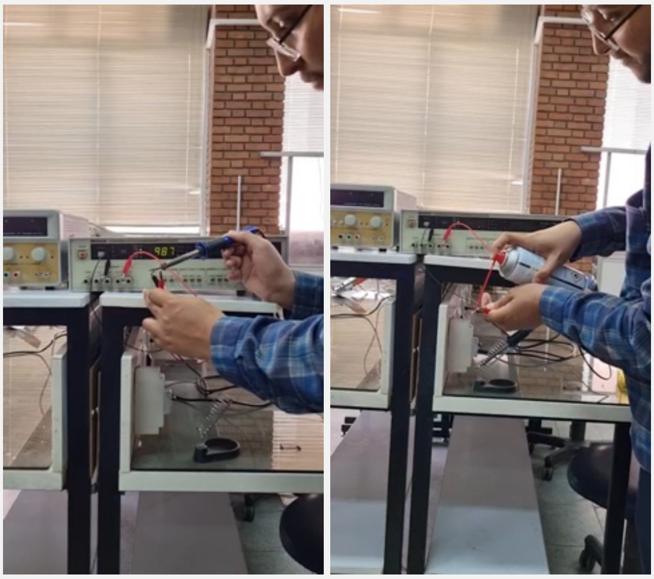
values: $9.76, 9.64, 9.05, 9.49, 9.19, 9.32, 9.61, 9.73, 9.37$ and $9.31\ \mu F$

Experiment 3

This experiment should be done by the lab supervisor. Dependency of the value of a real circuit element on temperature is characterized by a specified temperature coefficient.

Experiment 3 continued on next page...

(a) Measure the resistance of a carbon resistor in room temperature. Redo the measurement when the resistor is heated by a soldering iron and when is cooled by a cooling spray.



Lab supervisor used $1k\Omega$ resistor.
The resistance decrease by warming resistor(964Ω).
The resistance increase by cooling resistor(1033Ω).

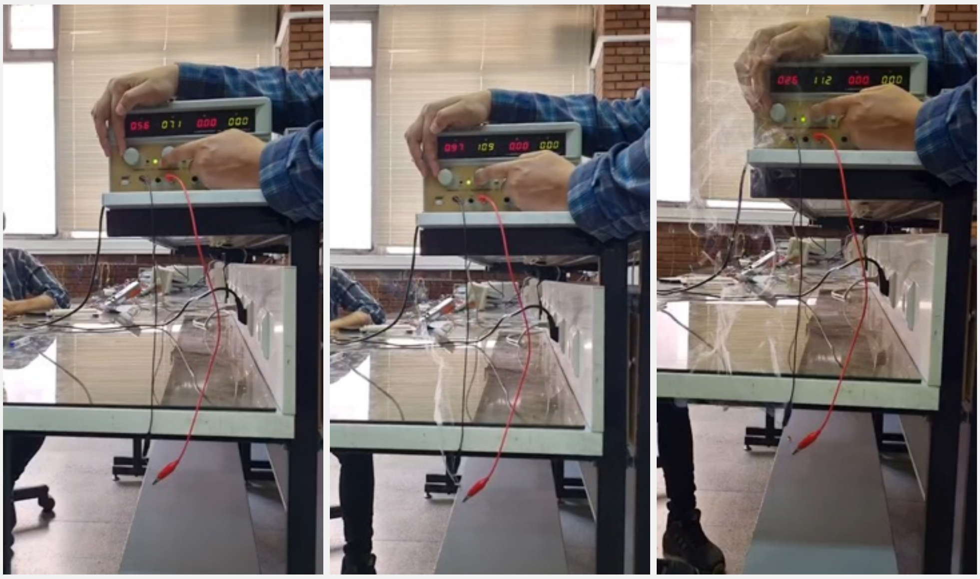
(b) Repeat the previous part for a metal film resistor, a ceramic capacitor, and a multi-layer capacitor.

Lab supervisor used $340pC$ ceramic capacitor. The capacity decrease by warming capacitor($310pC$).

The capacity increase by cooling capacitor($350pC$).
It seems that the capacitor is more sensitive to temperature increase than temperature decrease

Experiment 4

This experiment should be done by the lab supervisor. Each resistor has a specific maximum power rating. Connect a 0.25 W $10\ \Omega$ resistor to a DC power supply using an alligator clip wire. Sweep the voltage from 0 to 5 V and observe the results.



When a 0.25 W, $10\ \Omega$ resistor is connected to a DC power supply and the voltage is swept from 0 to 5 V, the current through the resistor increases linearly with the voltage, as per Ohm's law ($I = \frac{V}{R}$).
However, the power dissipated by the resistor, given by $P = IV = V^2/R$, also increases with the square of the voltage. If the power exceeds the resistor's power rating of 0.25 W, the resistor can overheat and potentially fail.
In this case, at 5 V, the power dissipated by the resistor would be $P = V^2/R = 5^2/10 = 2.5$ W, which exceeds the resistor's power rating.

Experiment 5

This experiment should be done by the lab supervisor. Each capacitor has a specific maximum voltage. Further, a capacitor may have a specific voltage polarity.

Experiment 5 continued on next page...

(a) Connect a 16 V aluminum electrolytic capacitor directly to a 30 V DC voltage and observe the results.

As can be seen, when a 16 V aluminum electrolytic capacitor is connected directly to a 30 V DC voltage, it exceeds the capacitor's rated maximum voltage. This can lead to a breakdown of the dielectric material inside the capacitor, causing capacitor failure(explosion).

(b) Connect a 16 V aluminum electrolytic capacitor inversely to a 16 V DC voltage and observe the results.

When a 16 V aluminum electrolytic capacitor is connected inversely (i.e., with reversed polarity) to a 16 V DC voltage, it can also lead to a breakdown. Electrolytic capacitors are polarized, meaning they have a positive and a negative terminal. If they are connected in reverse, the oxide layer on the anode, which acts as the dielectric, can break down, leading to a short circuit. This can cause the capacitor to heat up, potentially leading to an explosion or leakage of the electrolyte. In short, although the voltage limit is not exceeded, the polarity of the capacitor must be observed to prevent damage.

Experiment 6

Build the circuit shown in Fig. 4 on a breadboard, where $r = 1$ kΩ denotes a resistor allowing to measure the current indirectly.

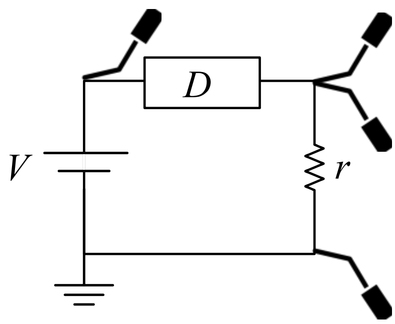


Figure 4: A test circuit for extracting the characteristic curve of a resistive element using multimeter.

Experiment 6 continued on next page...

(a) Replace D with a 1 kΩ resistor. Sweep the DC voltage over negative and positive ranges and record the voltage and current of the resistor using a multimeter. Use the recorded data to plot the characteristic curve of the resistor.

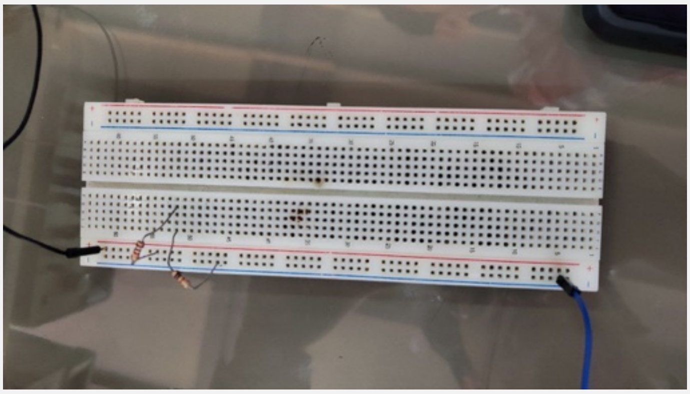


Figure 5: The circuit.

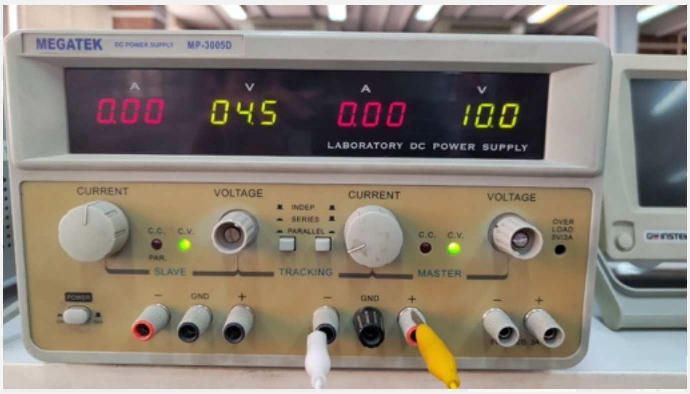


Figure 6: DC power supply set to $10V$ and $-10V$.

Figure 7: First image is for D and $10V$, second image is for r and $10V$.
Third image is for D and $-10V$, last image is for r and $-10V$.

Experiment 6 continued on next page...

Figure 8: DC power supply set to $5V$ and $-5V$.

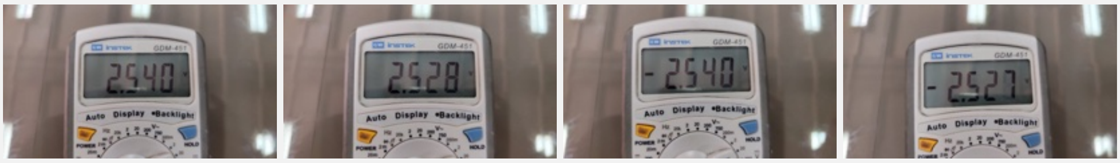


Figure 9: First image is for D and $5V$, second image is for r and $5V$.
Third image is for D and $-5V$, last image is for r and $-5V$.

Figure 10: DC power supply set to $2.5V$ and $-2.5V$.

Figure 11: First image is for D and $2.5V$, second image is for r and $2.5V$.
Third image is for D and $-2.5V$, last image is for r and $-2.5V$.

The points for D element are:

V	-10	-5	-2.5	0	2.5	5	10
V_d	-5.02	-2.54	-1.26	0	1.26	2.54	5.04

The exact value of r resistance was $0.991k\Omega$ (using a multimeter). Using the Ohm's law, we can calculate the current flowing through the circuit, and then, since we already know the voltage of D element, we can plot the characteristic curve of the D element. The points (V, V_r) for r resistor are:

V	-10	-5	-2.5	0	2.5	5	10
V_r	-4.99	-2.52	-1.25	0	1.25	2.52	5.00

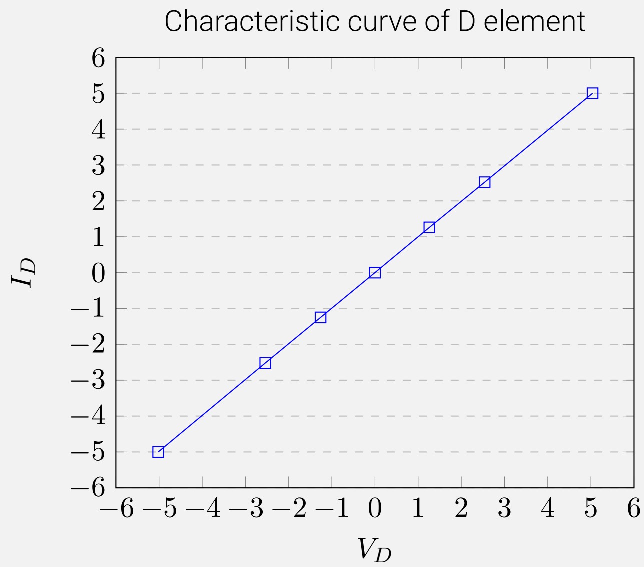
So the current flowing through the circuit based on V is:

V	-10	-5	-2.5	0	2.5	5	10
I	$-5.00mA$	$-2.52mA$	$-1.25mA$	0	$1.26mA$	$2.52mA$	$5.00mA$

So the $(V_D - I)$ points for D element are:

V_D	-5.02	-2.54	-1.26	0	1.26	2.54	5.04
I	$-5.00mA$	$-2.52mA$	$-1.25mA$	0	$1.26mA$	$2.52mA$	$5.00mA$

Using the points, the plot will be:



(b) Repeat the previous part for a diode.

Experiment 6 continued on next page...

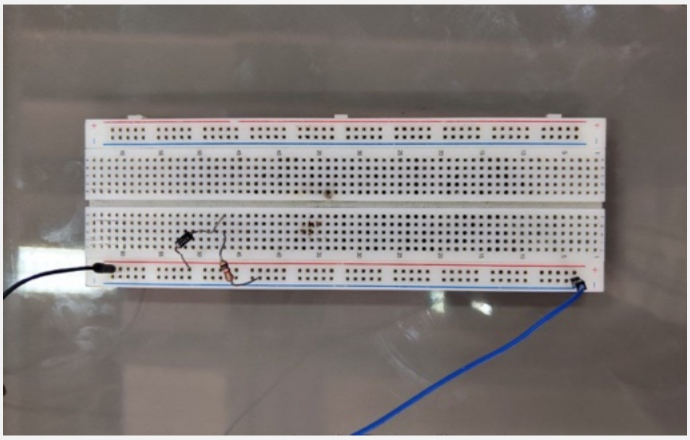


Figure 12: The circuit.

Figure 13: DC power supply set to $10V$ and $-10V$.

Figure 14: First image is for D and $10V$, second image is for r and $10V$.
Third image is for D and $-10V$, last image is for r and $-10V$.

Experiment 6 continued on next page...

Figure 15: DC power supply set to $5V$ and $-5V$.

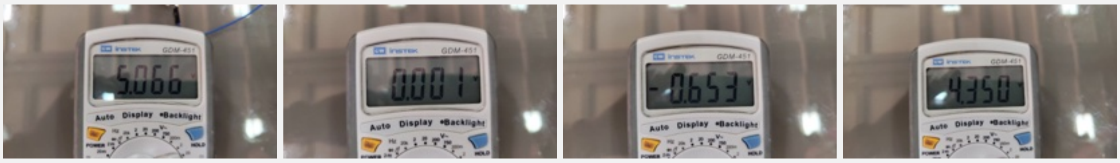


Figure 16: First image is for D and $5V$, second image is for r and $5V$.
Third image is for D and $-5V$, last image is for r and $-5V$.

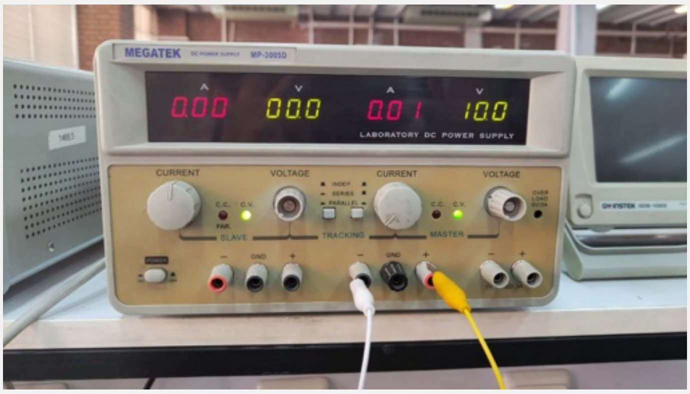
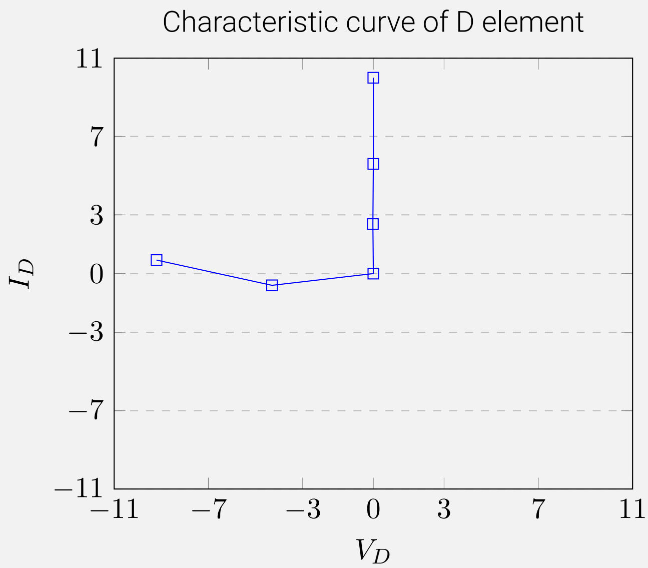


Figure 17: DC power supply set to $2.5V$ and $-2.5V$.

Figure 18: First image is for D and $2.5V$, second image is for r and $2.5V$.
Third image is for D and $-2.5V$, last image is for r and $-2.5V$.

Similar to previous part, we can plot the characteristic curve of the D element in the same way. It will look like:

Experiment 6 continued on next page...



Experiment 7

The experimental setup of Fig. 19 is used to display the Lissajous curve constructed by $v_x(t)$ and $v_y(t)$, where D is a basic circuit element and $r = 1$ kΩ.

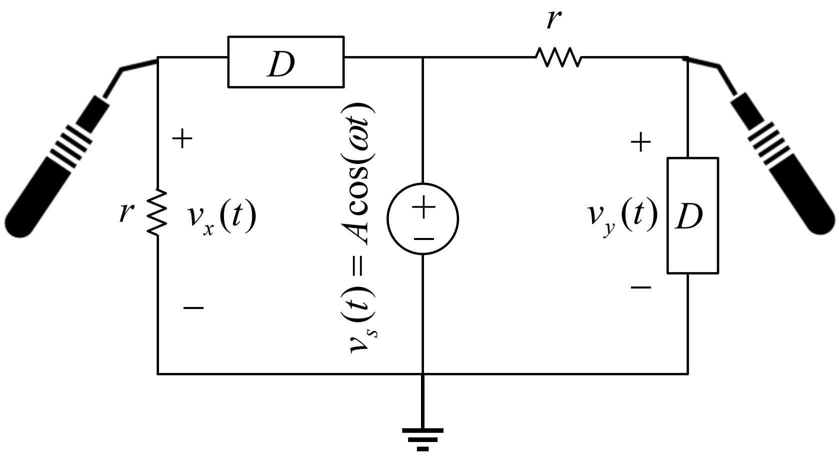


Figure 19: A test circuit for extracting the characteristic curve of a resistive element using oscilloscope.

(a) How can the displayed Lissajous curve be used to obtain the characteristic curve of a resistive element?

The Lissajous curve is a curve that is obtained by plotting the voltage of one element versus the voltage of another element. The slope of the curve is the ratio of the two voltages. The characteristic curve of a resistive element can be obtained by plotting the voltage of the resistive element versus the current flowing through it.In this circuit the first output shows

Experiment 7 continued on next page. . .

the desired voltage of the element. Since the left side (resistor and D element) is parallel to the right side (resistor and D element), the right output is equivalent to the current flowing through the element. So the Lissajous curve can be used to obtain the characteristic curve of a resistive element.

(b) Can the characteristic curve be extracted using the circuit of Fig. 4 and an oscilloscope?

yes, same as the previous question, if the value of the D element is equal to r resistor, the characteristic curve can be extracted using the circuit of Fig. 4 and an oscilloscope.

(c) Replace D with a $1\ \mathrm{k}\Omega$ resistor and see the corresponding characteristic curve on the oscilloscope screen.

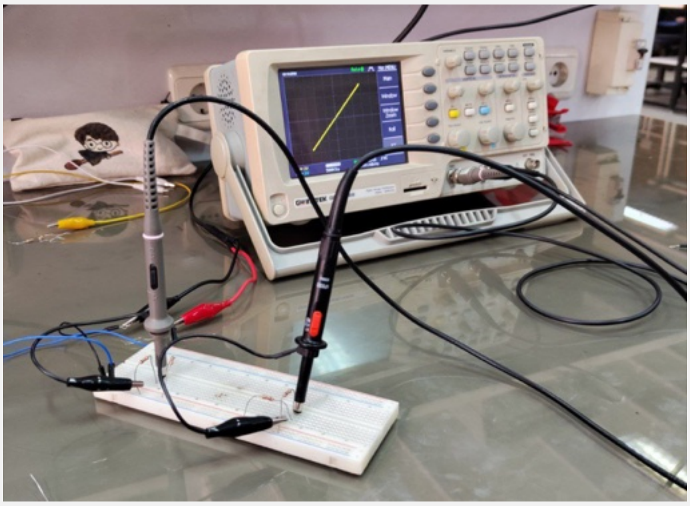


Figure 20: A photo of setup.

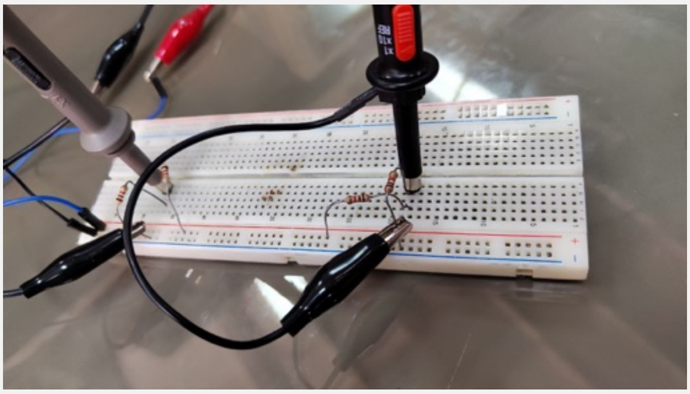


Figure 21: The circuit.

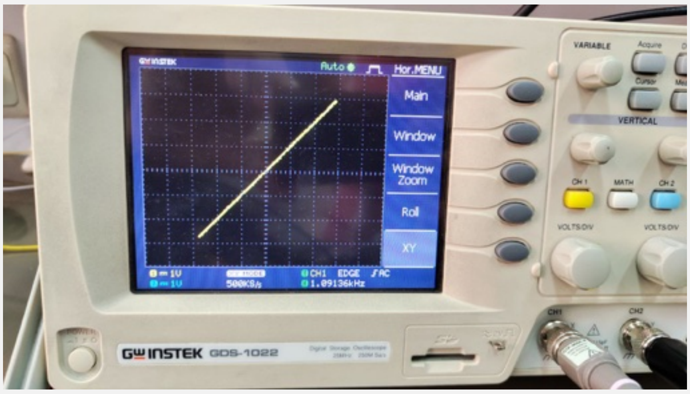


Figure 22: The oscilloscope showing resistor characteristic curve.

As can be seen, the characteristic curve of a resistor is a straight line with a slope of 1.

(d) Repeat the previous part for a diode.

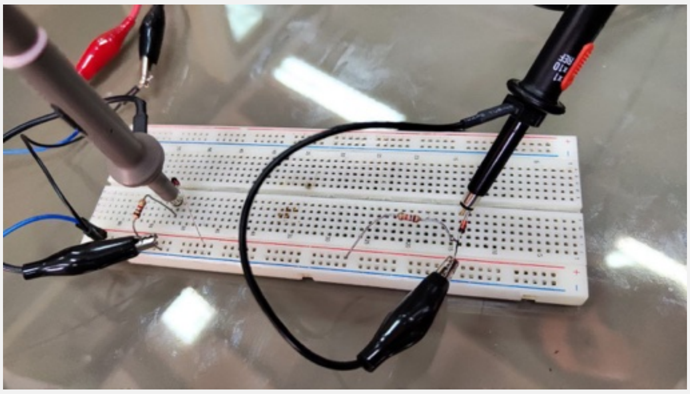


Figure 23: The circuit.

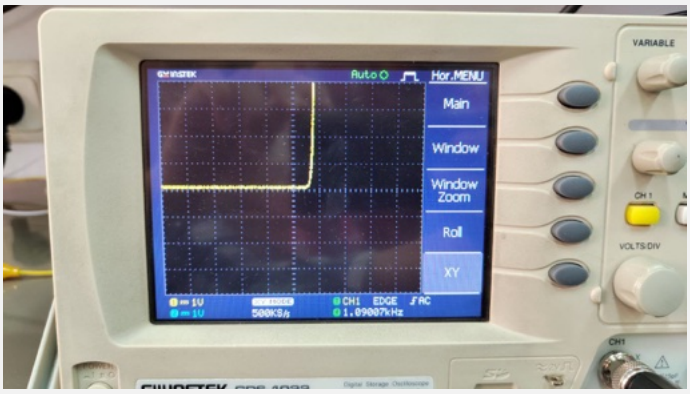


Figure 24: The oscilloscope showing diode characteristic curve.

As can be seen, the diode has non-linear characteristic curve. It passes current only in one direction and has a voltage drop of almost $0.7V$ when it's forward biased.

Experiment 8

Consider the real capacitor modeled in Fig. 25.

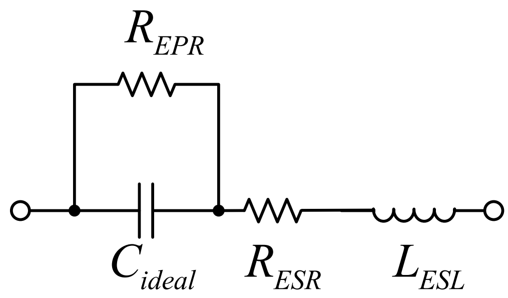


Figure 25: Real capacitor model.

(a) Assume that the sinusoidal voltage $v_C(t) = A\cos(\omega t + \theta)$ is applied to the capacitor. Find the corresponding capacitor current $i_C(t)$ for ideal values of R_{EPR}, R_{ESR}, and L_{ESL} and show that it has sinusoidal form.

For an ideal capacitor, the current $i_C(t)$ is related to the voltage $v_C(t)$ by the equation:

$$i_C(t) = C\frac{dv_C(t)}{dt}$$

Given $v_C(t) = A\cos(\omega t + \theta)$, we can find the derivative:

$$\frac{dv_C(t)}{dt} = -A\omega\sin(\omega t + \theta)$$

Substituting this derivative into the equation for $i_C(t)$, we get:

$$i_C(t) = C\frac{dv_C(t)}{dt} = -A\omega C\sin(\omega t + \theta)$$

Using the trigonometric identity $\sin(x) = \cos(x - \frac{\pi}{2})$, we can rewrite the equation as:

$$i_C(t) = -A\omega C\cos\left(\omega t + \theta - \frac{\pi}{2}\right)$$

Therefore, the current $i_C(t)$ has a sinusoidal form:

$$i_C(t) = A\omega C\cos\left(\omega t + \theta - \frac{\pi}{2}\right)$$

Experiment 8 continued on next page...

(b) Use PSpice AC sweep analysis to plot the amplitude and phase of the capacitor current versus $f = \frac{\omega}{2\pi}$ *when the capacitor voltage is* $v_C(t) = \cos(\omega t + \theta)$ *and* R_{EPR}, R_{ESR}, *and* L_{ESL} *have ideal values.*

Here is how the circuit looks like in PSpice:

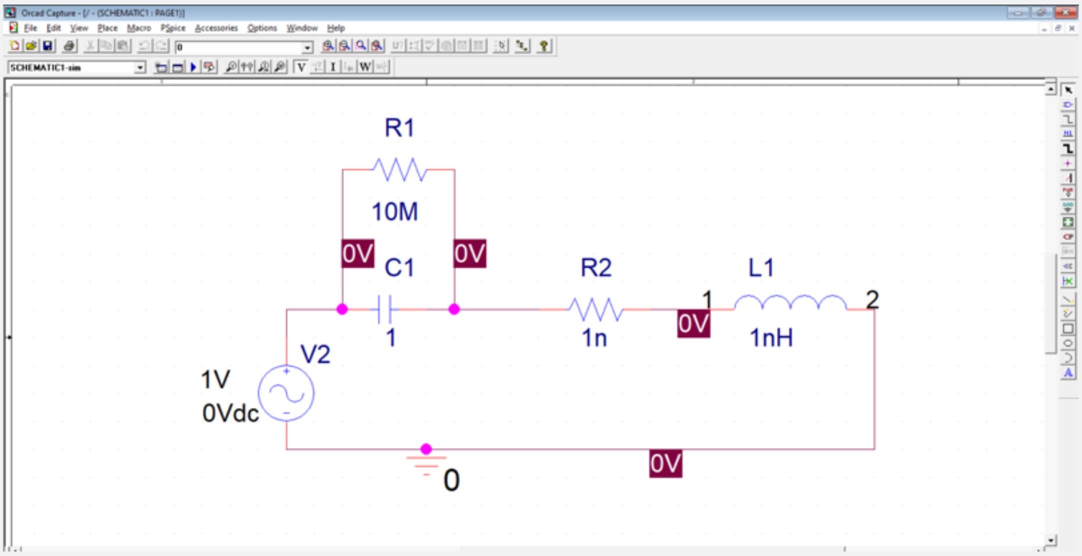


Figure 26: The circuit in PSpice.

The output of the simulation is:

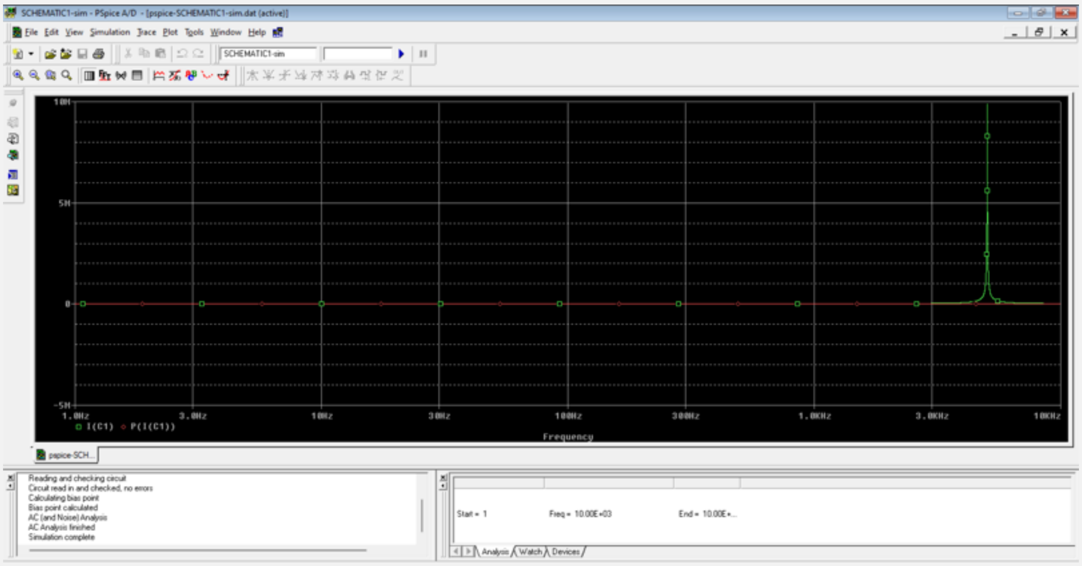


Figure 27: The output of the simulation.

Experiment 8 continued on next page...

(c) Use PSpice parametric analysis to plot the amplitude and phase of the capacitor current versus $f = \frac{\omega}{2\pi}$ for the capacitor voltage $v_C(t) = \cos(\omega t + \theta)$ and different suitably selected values of R_{EPR}, R_{ESR}, and L_{ESL}. Discuss how the parasitic parameters R_{EPR}, R_{ESR}, and L_{ESL} affect the performance of the capacitor.

Here is how the circuit looks like in PSpice:

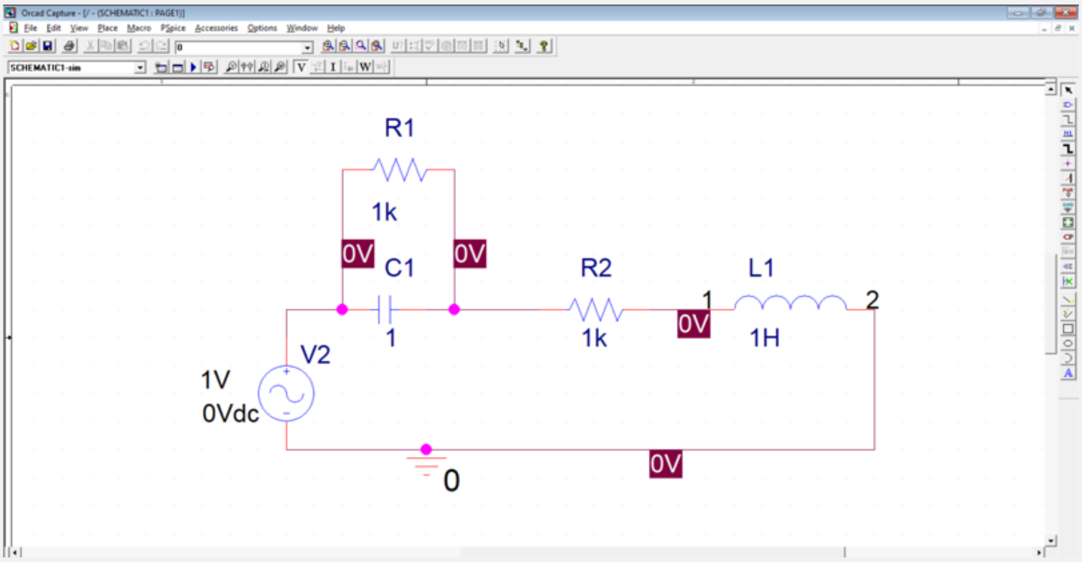


Figure 28: The circuit in PSpice.

The output of the simulation is:

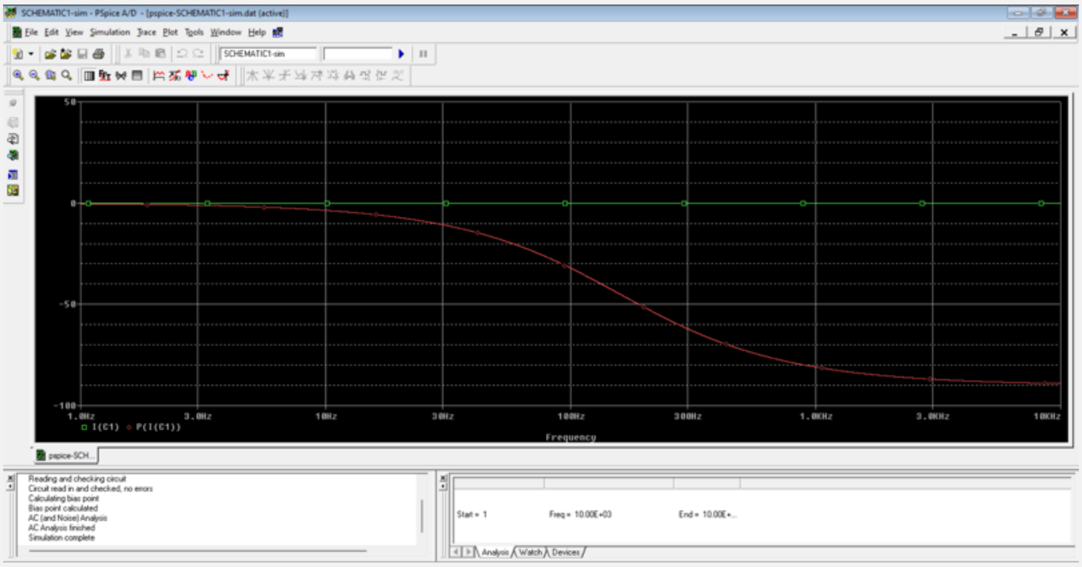


Figure 29: The output of the simulation.

It can be observed that the parasitic parameters R_{EPR}, R_{ESR}, and L_{ESL} have a significant impact on the performance of the capacitor. These parasitic parameters introduce additional resistance and inductance to the circuit, which can affect the behavior of the capacitor. For example, the presence of resistance can lead to energy losses and reduce the efficiency of the capacitor. Similarly, the presence of inductance can introduce impedance to the circuit, affecting the current flow and the phase relationship between the voltage and current. Therefore, it is important to consider these parasitic parameters when designing and analyzing circuits involving capacitors to ensure optimal performance and accuracy.

BONUS EXPERIMENTS

Experiment 9

Write a MATLAB/Python code to plot the Lissajous curve corresponding to the voltage signals $v_x(t) = A_x \cos(\omega_x t + \theta_x)$ and $v_y(t) = A_y \cos(\omega_y t + \theta_y)$.

(a) Use the developed code to plot sample Lissajous curves for various values of A_x, A_y, ω_x, ω_y, θ_x, and θ_y.

The Matlab code:

```
A_x = 0.9; % amplitude of x signal
A_y = 1.1; % amplitude of y signal
omega_x = 5.1; % frequency of x signal
omega_y = 4.5; % frequency of y signal
theta_x = 0; % phase of x signal
theta_y = pi/2; % phase of y signal

t = linspace(0, 3*pi, 1000); % time vector
v_x = A_x * cos(omega_x * t + theta_x); % x signal
v_y = A_y * cos(omega_y * t + theta_y); % y signal
figure;
plot(v_x, v_y);
xlabel('v_x(t)');
ylabel('v_y(t)');
title('Lissajous Curve');
grid on;
```

The result of the code (for entries which are shown in the code):

Experiment 9 continued on next page. . .

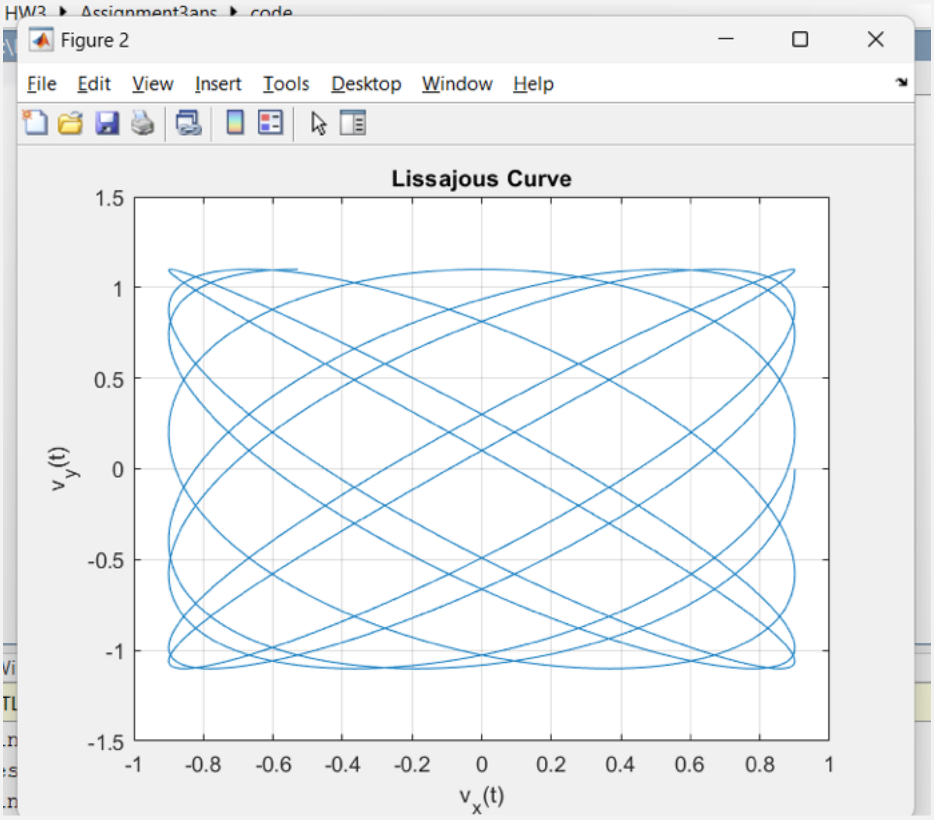


Figure 30: The Lissajous curve.

(b) Assume that $\frac{\omega_x}{\omega_y} = \frac{m}{n}$, where $\frac{m}{n}$ is a fractional number. Discuss how the ratio $\frac{\omega_x}{\omega_y}$ can be found from the corresponding Lissajous curve?

When the ratio of the angular frequencies, $\frac{\omega_x}{\omega_y}$, is a fractional number, the resulting Lissajous curve provides a visual representation of this ratio. The Lissajous curve is formed by plotting the voltage signals $v_x(t)$ and $v_y(t)$ as a parametric curve in the xy-plane.
Specifically, when $\frac{\omega_x}{\omega_y} = 1$, the Lissajous curve takes the shape of an ellipse. This ellipse can degenerate into a line when the phase difference between the two signals, $\theta_x - \theta_y$, is zero.
When $\frac{\omega_x}{\omega_y} = 2$, the Lissajous curve forms a figure-eight pattern. This pattern occurs when the two signals have a phase difference of $\frac{\pi}{2}$.
In general, for $\frac{\omega_x}{\omega_y} = \frac{m}{n}$, where m and n are integers, the Lissajous curve will have m horizontal lobes and n vertical lobes. The lobes represent the number of times the curve intersects the x-axis and y-axis, respectively.
By visually inspecting the Lissajous curve and counting the number of lobes, one can determine the ratio $\frac{\omega_x}{\omega_y}$ and gain insights into the relationship between the two signals.

Experiment 10

Return your work report by filling the LaTeX template of the manual. Include useful and high-quality images to make the report more readable and understandable.