Faculty of Engineering and Technology

Electrical and Computer Engineering Department

ENEE2103

Circuits and Electronics Lab

Experiment No.4

Sinusoidal Steady State Circuit Analysis

Report No.3

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Abstract

The aim of this experiment is to determine the impedance, the current, and the voltage for the elements in the specified circuits, examine capacitive and inductive behavior, verify the effectiveness of the Circuit theorems in the sinusoidal steady-state, and to measure the power of sinusoidal steady-state circuits.

The method used in this experiment is that all the specified circuits were connected to the board, and Function Generator was used to generate different types of electrical waveforms over a different range of frequencies, the Oscilloscope was used to test and display voltage and current signals to measure the phase shift, and the Digital Multimeter (DMM) was used to measure the voltage and the current.

Table of Contents

Table of Figures

List of Tables

Theory

1. AC circuits and DC circuits:

Electric current flows in two different ways, as an **Alternating Current** (AC) or **Direct Current** (DC). In the Alternating current circuits, the current keeps switching directions periodically, in forward or backward. While in Direct current circuits, the current flows in one single direction which is forward only.

- In the AC circuits, the alternating current can be identified in waveform called a **sine wave**. In other words, it can be referred as a curved line. These curved lines represent electric cycles and are measured per second and the measurements are read in Hz.

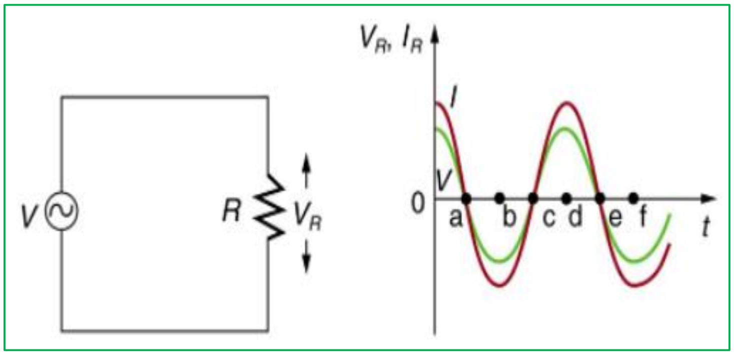

Figure 1: AC circuit

- While in DC circuits, the direct current does not change periodically, the current flows in a single direction, and it does not have frequency, while the AC has. The major of use of DC is to supply power to electrical devices and to charge batteries.

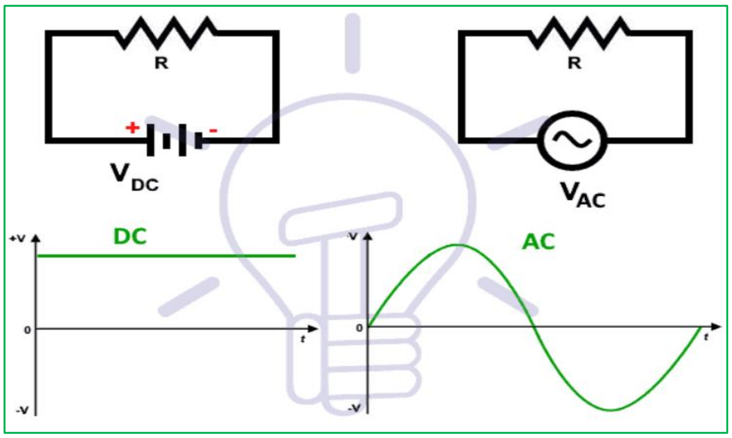

Figure 2: The difference between AC and DC circuits

2. Impedance:

The **Impedance** defined as the opposition to current flowing around the circuit. In the **Alternating Current** circuit, which is known as AC Circuit, the Impedance is a value calculated in **Ohms** that is the combined effect of the circuit's current limiting components within it, for instance the resistance(R), capacitance (C), and inductance (L).

While in the **Direct Current** circuit, or DC circuits, the opposition to current flow is called **Resistance** and donated by the letter **R,** but in an AC circuit, it's called as mentioned before Impedance, which is the result of both the circuits **resistive** (R), and **reactive** (X) components and donated by the letter **Z**.

2.1 Impedance in simple circuits:

In the simple circuits, which contains the three basic elements, the voltage source, current, and resistors, and the impedance in this case consists of **only real part** while the imaginary part (**reactance**) equals to **zero (zero phase shift Θ = 0).** The real part will be equal to the value of the equivalent **resistors (R)** in the circuit.

$$Z = R + 0\,j \qquad (1)$$

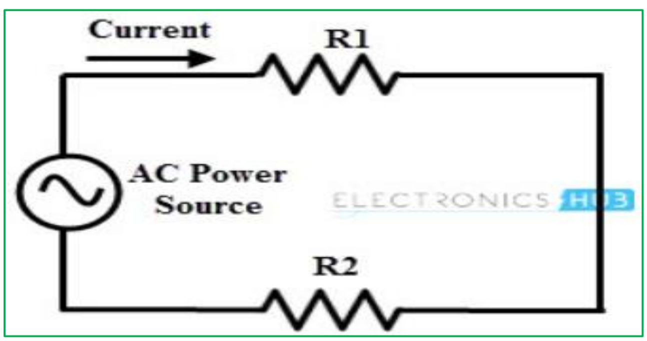

Figure 3: Simple Alternating Current (AC) circuit

Resistors connected in series:

When resistors are connected in series their combined resistance is equal to the individual resistances added together.

$$\boldsymbol{Req = R1 + R2 + R3 + \cdots + Rn} \qquad (2)$$

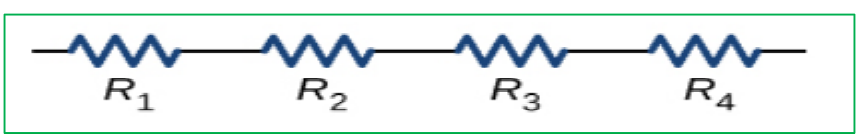

Figure 4: R in series

Resistors connected in parallel:

When resistors are connected in parallel their combined resistance is less than any of the individual resistances.

$$\frac{1}{Req} = \frac{1}{R1} + \frac{1}{R2} + \frac{1}{R2} + \cdots + \frac{1}{Rn} \qquad (3)$$

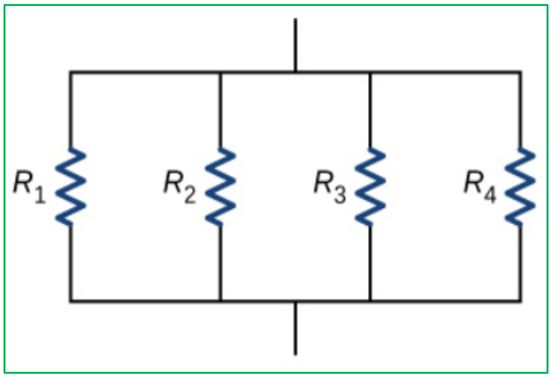

Figure 5: R in parallel

2.2 Impedance in RC circuits:

The impedance in the series of RC circuit consists of two parts, the **Resistance(R)** and **Capacitive Reactance (Xc)** as shown in the following equation:

$$Z = R - j\,Xc \quad , where\ Xc = \frac{1}{2\pi f C} \qquad (4)$$

And the **magnitude** of the impedance (Z) is :

$$|Z| = \sqrt{R^2 + XC^2} \qquad (5)$$

While the **phase shift** is:

$$\theta = tan^{-1}(\frac{-Xc}{R}) \qquad (6)$$

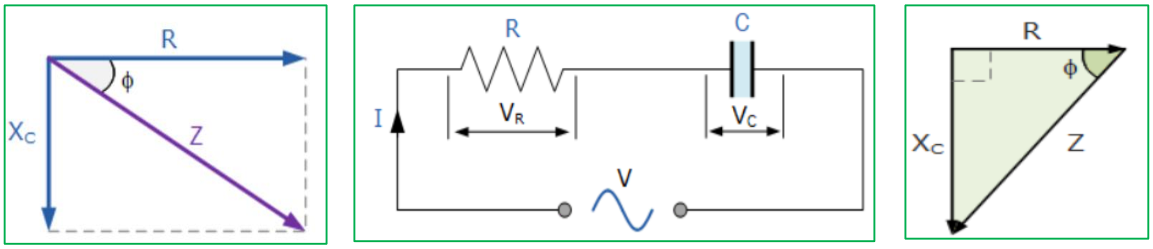

Figure 6: The impedance of series RC circuit

2.3 Impedance in RL circuits:

The impedance in the series of RL circuit is the same as the RC circuit includes two parts, the **Resistance(R)** and **Inductive Reactance (XL)** as shown in the following equation:

$$Z= R + j\,Xl \quad , where\ Xl= 2\pi f L \qquad (7)$$

And the **magnitude** of the impedance (Z) is :

$$|Z| = \sqrt{R^2 + XL^2} \qquad (8)$$

While the **phase shift** is:

$$\theta = tan^{-1}(\frac{Xl}{R}) \qquad (9)$$

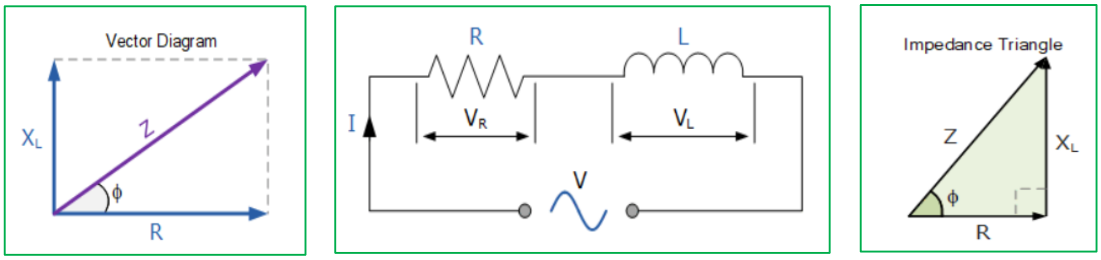

Figure 7: The impedance of series RL circuit

Note That: The electrical relationship between voltage, current, and impedance is called Ohm's law. The following equation represents Ohm's Low:

$$V = ZI \qquad (10)$$

Note That: The phase shift of the simple circuit is **zero**, which means that the voltage and the current waves are **in phase**, while in capacitive circuits is negative (negative angle) which means that the **current leads the voltage**, and in the inductive circuits is positive (positive angle), in other words, the **current lags the voltage** as shown in the following figures:

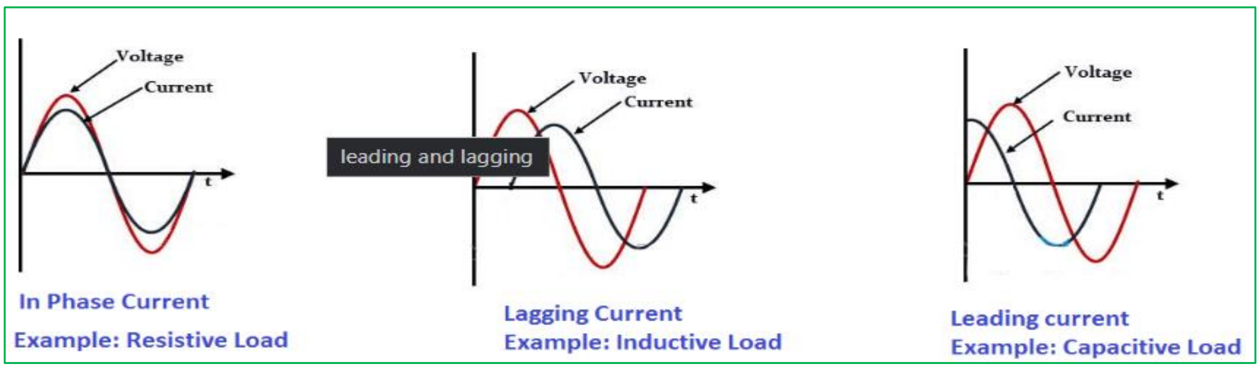

Figure 8: The phase shift of simple, capacitive, and inductive circuits.

3. Capacitive and inductive behavior:

For series RLC circuit, the impedance can be found by the sum of the resistance (R), the **Inductive Reactance (XL),** the **Capacitive Reactance (Xc).**

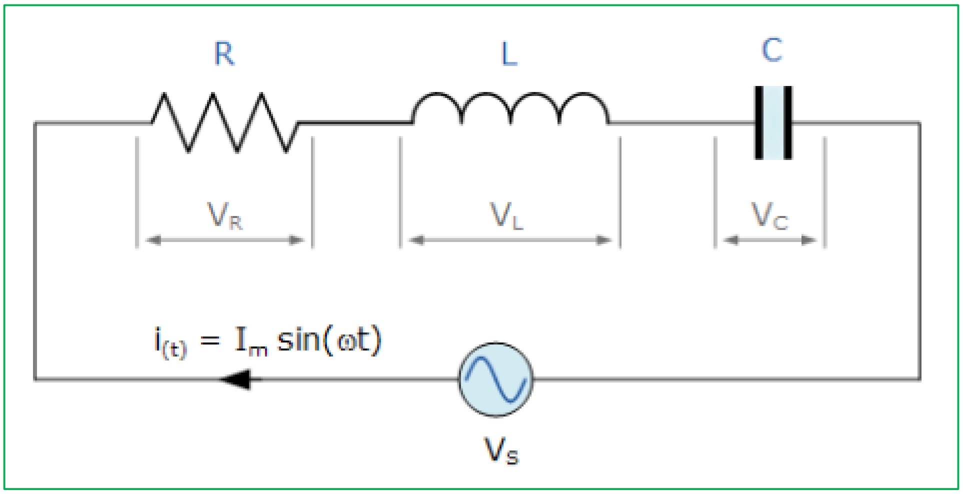

Figure 9: Series RLC circuit

The **impedance equation** as the following:

$$Z = R + j\,(Xl - Xc) \quad , \text{where } Xl = 2\pi f L \text{ and } Xc = \frac{1}{2\pi f C} \qquad (11)$$

And the **magnitude** of the impedance (Z) is :

$$|Z| = \sqrt{R^2 + (XL - Xc)^2} \qquad (12)$$

While the **phase shift** is:

$$\theta = \tan^{-1}\left(\frac{Xl - Xc}{R}\right) \qquad (13)$$

If the phase shift of the impedance is negative**,** this means that **current leads the voltage,** in other word, **capacitive circuit**. While if the phase shift is positive, the circuit considered as **inductive circuit**.

4. Sinusoidal steady state power:

In the DC circuits, the voltage and the current are generally constant, that is not varying with time as there is no sinusoidal waveform associated with the supply. But in the AC circuits, the voltage and current waveforms are sinusoidal so their amplitudes are constantly changing over time.

4.1 Average Power:

The average power, also known as **real power** or **active power** perform the "real work" within an electrical circuit. Average power is measured in **watts**, and defines the power consumed by the resistive part of a circuit. The equation of the average power is the following:

$$P_{avg} = \frac{1}{2} V_m I_m \cos(\theta) \text{ , where } \theta\text{: between the } V \text{ \& } I \quad (14)$$

Since the $V_{rms} = \frac{Vm}{\sqrt{2}}$ and $I_{rms} = \frac{Im}{\sqrt{2}}$, we can represent the average power as:

$$P_{avg} = V_{rms} I_{rms} \cos(\theta) \quad (15)$$

Note: The average power of the capacitor or inductor in the AC circuit is equals to **Zero**.

4.2 Reactive Power:

Reactive power (Q), (sometimes called **wattless power**) is the power consumed in an AC circuit that does not perform any useful work but has a big effect on the phase shift between the voltage and current waveforms. Reactive power is linked to the reactance produced by inductors and capacitors and counteracts the effects of real power. **Reactive power does not exist in DC circuits.**

Reactive Power in an AC Circuit is as the following:

$$P_{avg} = \frac{1}{2} V_m I_m \sin(\theta) \text{ , where } \theta\text{: between the } V \text{ \& } I \quad (16)$$

We can represent the Reactive power in terms of V_{rms} and I_{rms} as the following:

$$P_{avg} = V_{rms} I_{rms} \sin(\theta) \quad (17)$$

4.3 Power Factor:

Power factor is an important part of an AC circuit that can also be expressed in terms of circuit impedance or circuit power. Power factor is defined as the ratio of real power (P) to apparent power.

$$\text{Power Factor} = \frac{P_{avg}}{VI} = \cos(\theta) \quad (18)$$

Procedure and Data analysis

1. Impedance:

The objective of this part is to measure the impedance in different types of AC circuits, such as simple circuit, RC circuit and RL circuit using **DMM** by measuring the total voltage and current. In addition, to find the phase shift between the total voltage and current by using **Oscilloscope**.

1.1 Impedance in simple circuit:

- **Experimental Results:**

  Initially, the circuit in (Figure 10) was connected on the board, and the value of resistor set to Rx =2.2 kΩ.

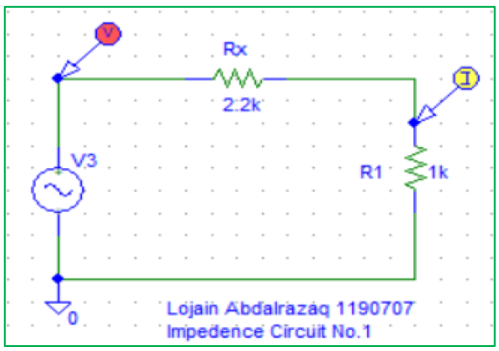

Figure 10: Series simple circuit, with Rx=2.2k.

✓ **When f=500 Hz:**

When the frequency is equals to 500 Hz, the waves of the total voltage and current were in phase. In other word, the **phase shift was equals to zero** as shown in the following figure:

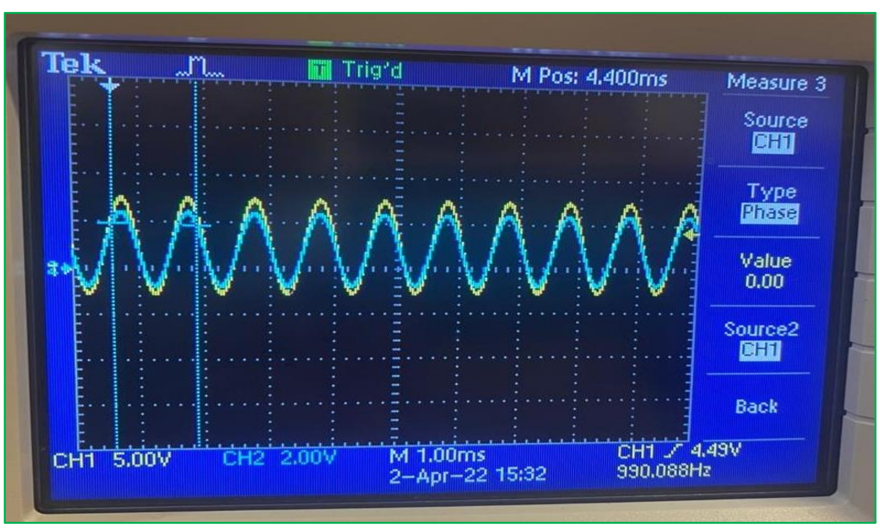

Figure 11: The total voltage and current waves in Oscilloscope when F=500 Hz

The total voltage and current in the circuit which is $V_{rms} = 3.58\,V$ and $I_{rms} = 1.107\,mA$ as shown:

Figure 12: The total voltage and current values of the simple circuit using DMM, f=500 Hz

In order to calculate the **total impedance** for this AC circuit, the total impedance can be calculated as:

$$Z_{eq} = \frac{V}{I} = \frac{3.58}{1.107 * 10^{-3}} = 3.233\ Kohm.$$

- ✓ **When f=1000 Hz:**

  When the frequency was changed to 1000Hz, the waves of the total current and the voltage still in phase with **zero phase shift,** and the value of the total voltage and current **still the almost same** , $V_{rms} = 3.51\,V$ and $I_{rms} = 1.107\,mA$**, and the total impedance is as the following:**

$$Z_{eq} = \frac{V}{I} = \frac{3.51}{1.107 * 10^{-3}} = 3.1707 Kohm.$$

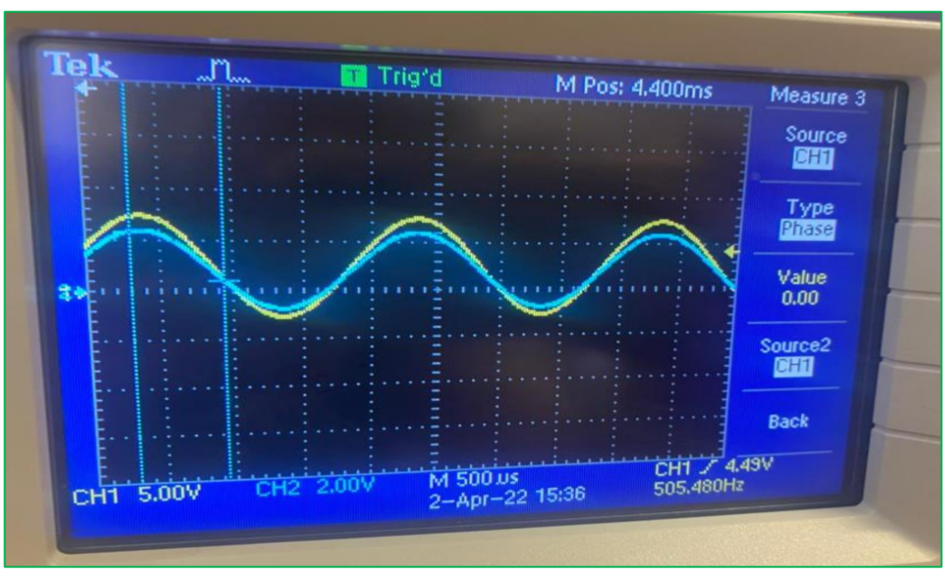

Figure 13: The total voltage and current waves in Oscilloscope when F=1000 Hz

✓ **When f=1500 Hz:**

When the frequency was changed to 1500Hz, the waves of the total current and the voltage did not change ,still in phase with **zero phase shift,** and the value of the total voltage and current still the **almost same,** $\boldsymbol{V_{rms} = 3.54\ V}$ and $\boldsymbol{I_{rms} = 1.107\ mA}$**, and the total impedance** is as the following**:**

$$\boldsymbol{Z_{eq} = \frac{V}{I} = \frac{3.54}{1.107 * 10^{-3}} = 3.197Kohm.}$$

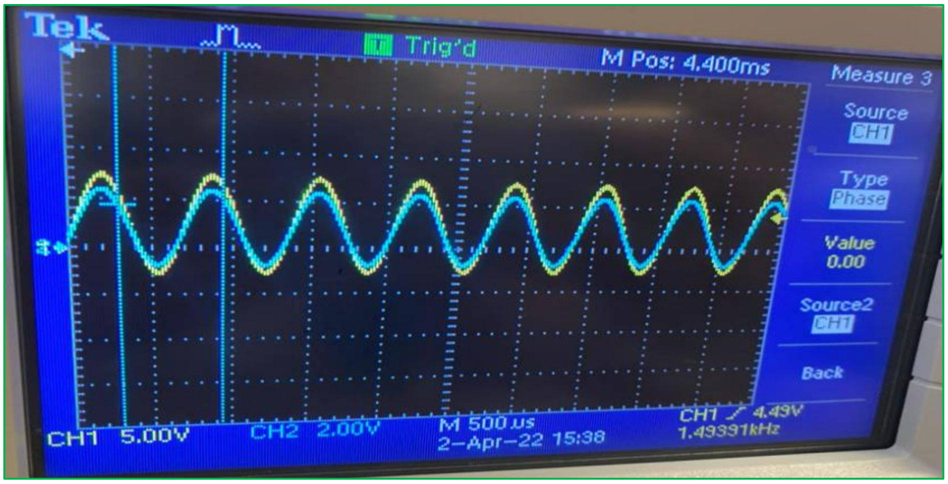

Figure 14: The voltage and current waves of simple circuit when f=1500 Hz

In summary, it is noticed that the **total impedance** of the AC circuit still the **same** when changing the value of the frequency **(500 Hz, 1 kHz, and 1.5 kHz)** using the function generator. Since when changing the frequency, we change the number of periods per unit of time not the value of the current or voltage which the total impedance depends on. The **total impedance** of the circuit is:

1. Frequency = 500 Hz → Z= $\boldsymbol{3.233\ Kohm}$.
2. Frequency = 1000 Hz → Z= $\boldsymbol{3.1707Kohm.}$
3. Frequency = 1500 Hz → Z= $\boldsymbol{3.197Kohm}$.

In addition, the **phase shift** was equal to zero in all cases, since the waves of total voltage and current were **in phase** because the circuit contains only resistors without any inductors or capacitors.

Table 1: Impedance of the simple circuit practical results.

f [Hz]	$\boldsymbol{V_{rms}}$	$\boldsymbol{I_{rms}}$	$\boldsymbol{\Delta t}$	Phase Shift
500	3.58 V	1.107 mA	0	0
1k	3.51 V	1.107 mA	0	0
1.5k	3.54 V	1.107 mA	0	0

- **Theoretical Results:**

In the simple circuits which contain only the basic components, without any capacitors and inductors, the total impedance will be the equal to the equivalent resistor of the circuit. Since the circuit in (***Figure 10)*** has resistors in series, then the equivalent resistor will be the sum of the resistors with zero phase shift as the following:

$$\boldsymbol{Total\ impedance\ Z = R_{eq} = Rx + R1 = 2.2k + 1k = 3.2\ Kohm}$$

Table 2: Comparison between experimental the theoretical results in the simple circuit.

	Frequency	Impedance	Phase Shift
Theoretically	*500 Hz*	*3.2 K ohm*	0
Experimentally		3.233 $Kohm$	0
Theoretically	*1000 Hz*	*3.2 K ohm*	0
Experimentally		3.1707$Kohm$	0
Theoretically	*1500 Hz*	3.2 K ohm	0
Experimentally		3.197$Kohm$	0

1.2 Impedance of RC circuit:

- **Experimental Results:**

Firstly, the circuit was connected in the board, it was the same circuit, but a capacitor with 100 nF was connected in series with the circuit, and the value of Rx = 2.2 K ohm as shown:

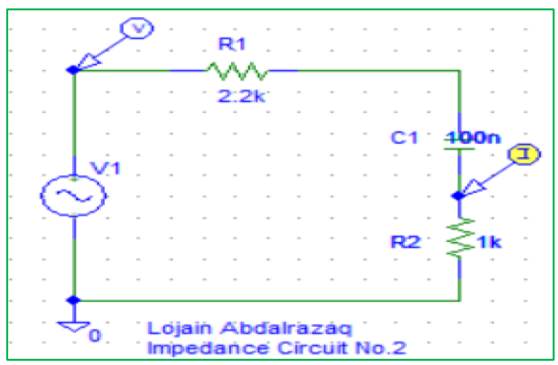

Figure 15: Series RC circuit

In the series RC circuit, the impedance of the circuit will be the sum of the **resistors (R)** and the **capacitive reactance (Xc).** In addition, the phase shift will be negative which means that the current leads the voltage.

- ✓ **When f=500 Hz:**

  When the frequency equals to 500 Hz, the total current equals to 0.779 mA, while the total voltage equals to 3.57 V. The **phase shift** of the circuit is -44.3 degree, the current **leads** the voltage. The **total impedance** is measured as the following:

$$Z_{eq} = \frac{V}{I} = \frac{3.57}{0.779 * 10^{-3}} = 4.58\ Kohm$$

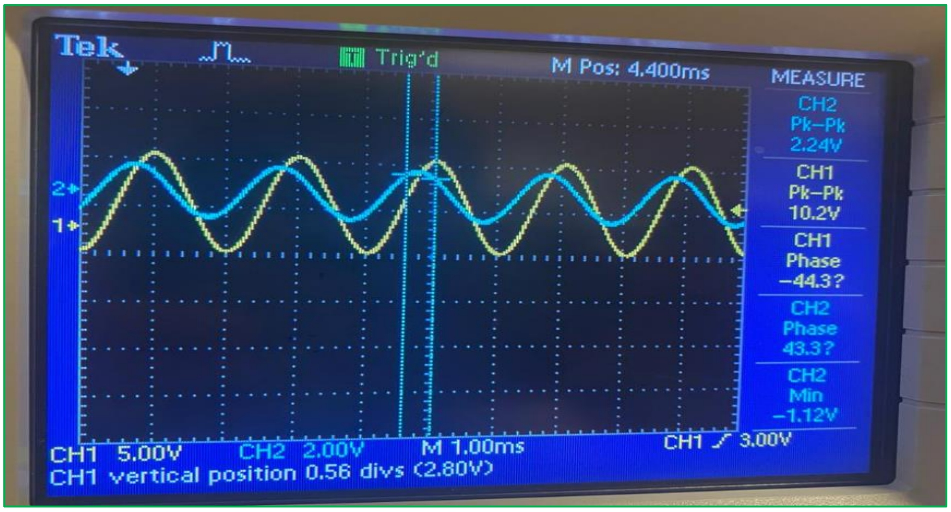

Figure 16: The voltage and current waves of RC circuit when F=500 Hz

The total voltage and current in the RC circuit, $V_{rms} = 3.57\ V$ and $I_{rms} = 0.779\ mA$ as shown:

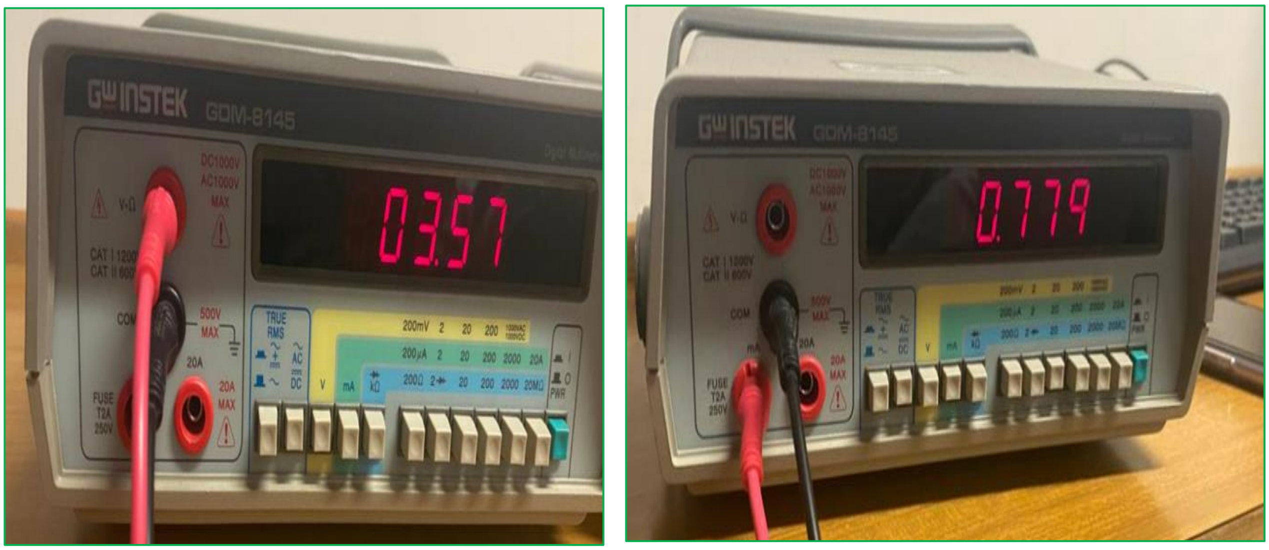

Figure 17: The total voltage and current of RC circuit values using DMM, f=500 Hz

✓ **When f=1000 Hz:**

When the frequency was changed to 1 kHz, the **total current** and **voltage** were changed to 3.56 V and 0.993 mA, and **phase shift** became -25.8 degree. The **total impedance** calculated as the following:

$$Z_{eq} = \frac{V}{I} = \frac{3.56}{0.993 * 10^{-3}} = 3.585\ Kohm$$

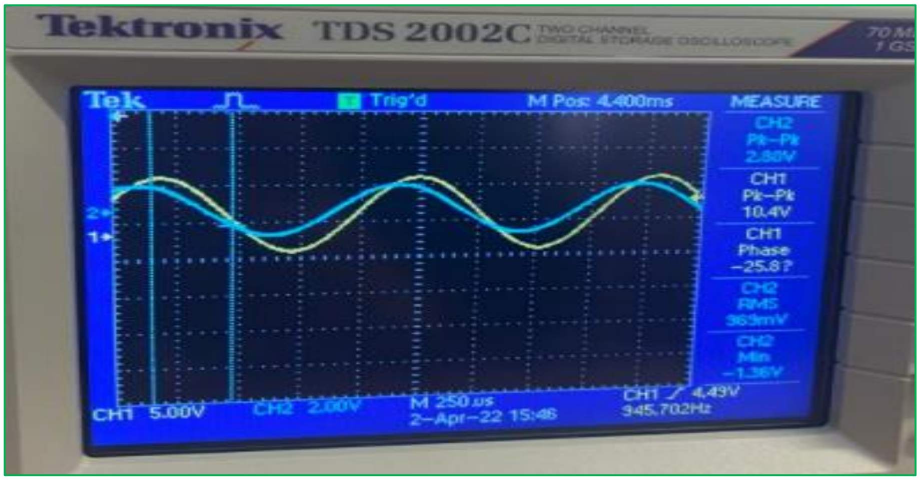

Figure 18: The voltage and current waves of RC circuit when F=1000 Hz

✓ **When f=1500 Hz:**

When the frequency was changed to 1500Hz, the **total voltage** and **current** were also changed to 3.53 V and 1.045 mA respectively. While the **phase shift** became -17.3 degree. The **total impedance** measured as:

$$Z_{eq} = \frac{V}{I} = \frac{3.53}{1.045 * 10^{-3}} = 3.37\ Kohm$$

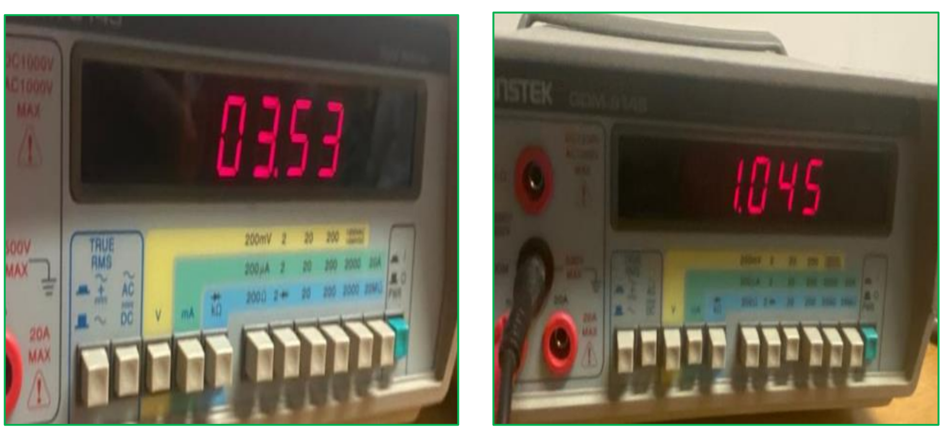

Figure 19: The total voltage and current of RC circuit values using DMM, f=1500 Hz

From the experimental results, it is noticed that the total impedance changed once the frequency change **(500 Hz, 1 kHz, and 1.5 kHz)** using the function generator. Since in the RC circuits, the impedance calculated by the sum of the resistors and the capacitive reactance (Xc) which depends on the frequency of the circuit as the following:

$$Z = R - j\,Xc \quad , \text{where } Xc = \frac{1}{2\pi f C}$$

The **total impedance** of the RC circuit is:

1. Frequency = 500 Hz → Z= $\mathbf{4.58\ Kohm}$.
2. Frequency = 1000 Hz → Z= $\mathbf{3.585\ Kohm}$.
3. Frequency = 1500 Hz → Z= $\mathbf{3.585\ Kohm}$.

Also, the **phase shift** is negative in all cases since its capacitive circuit. In other word, the current leads the voltage.

1. Frequency = 500 Hz → Phase Shift = **-44.3 degree.**
2. Frequency = 1000 Hz → Phase Shift = **-25.8 degree.**
3. Frequency = 1500 Hz → Phase Shift = **-17.3 degree.**

Table 3: Impedance of the RC circuit practical results.

f [Hz]	V_{rms}	I_{rms}	Δt	Phase Shift
500	3.57 V	0.779 mA	-	-44.3 degree
1k	3.56 V	0.993 mA	-	-25.8 degree
1.5k	3.53 V	1.045 mA	-	-17.3 degree

- **Theoretical Results:**

  As mentioned before, In the AC circuits, the total impedance can be calculated by the using the following:

$$R_{eq} = 2.2\,K + 1\,K = 3.2\,K\ ohm.$$

1. **Frequency = 500 Hz:**

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(500) * 100 * 10^{-9}} = \mathbf{3.18\ K\ ohm}.$$

So, the **total impedance**:

$$Z = \boldsymbol{R - j\,Xc} = 3.2 - j\,3.18\,Kohm.$$

While the **magnitude** of the total impedance is:

$$|Z| = \sqrt{\boldsymbol{R^2 + XC^2}} = \sqrt{3.2^2 + 3.18^2} = \mathbf{4.511\ Kohm}.$$

And the **phase** is:

$$\boldsymbol{\theta = tan^{-1}(\frac{-Xc}{R}) = tan^{-1}\left(\frac{-3.18}{2.2}\right) = -44.84\ degree}.$$

2. **Frequency = 1000 Hz:**

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(1000) * 100 * 10^{-9}} = \mathbf{1.59\ K\ ohm}.$$

So, the **total impedance**:

$$Z = \boldsymbol{R} - \boldsymbol{j\ Xc} = 3.2 - j\ 1.59\ Kohm.$$

While the **magnitude** of the total impedance is:

$$|Z| = \sqrt{\boldsymbol{R^2} + \boldsymbol{XC^2}} = \sqrt{3.2^2 + 1.59^2} = \mathbf{3.57\ Kohm}.$$

And the **phase** is:

$$\boldsymbol{\theta = tan^{-1}(\frac{-Xc}{R}) = tan^{-1}\left(\frac{-1.59}{2.2}\right) = -26.4\ degree}.$$

3. **Frequency = 1500 Hz:**

$$X_C = \frac{1}{2\pi f C} = \frac{1}{2\pi(1500) * 100 * 10^{-9}} = \mathbf{1.06\ K\ ohm}.$$

So, the **total impedance**:

$$Z = \boldsymbol{R} - \boldsymbol{j\ Xc} = 3.2 - j\ 1.06\ Kohm.$$

While the **magnitude** of the total impedance is:

$$|Z| = \sqrt{\boldsymbol{R^2} + \boldsymbol{XC^2}} = \sqrt{3.2^2 + 1.06^2} = \mathbf{3.37\ Kohm}.$$

And the **phase** is:

$$\boldsymbol{\theta = tan^{-1}(\frac{-Xc}{R}) = tan^{-1}\left(\frac{-1.06}{2.2}\right) = -18.32\ degree}.$$

Table 4: Comparison between experimental the theoretical results in the RC circuit.

	Frequency	**Impedance**	**Phase Shift**
Theoretically	*500 Hz*	*4.511 K ohm*	*-44.8 degree*
Experimentally		4.58 $Kohm$	*-44.3 degree*
Theoretically	*1000 Hz*	*3.573 K ohm*	*-26.4 degree*
Experimentally		3.585 $Kohm$	*-25.8 degree*
Theoretically	*1500 Hz*	*3.37 K ohm*	*-18.3 degree*
Experimentally		3.37 $Kohm$	*-17.3 degree*

Note: From the above table, it is noticed that the results of theoretical part is **so close** from the experimental ones, which leads us to know that the **results are true**.

1.3 Impedance of RL circuit:

- **Experimental Results:**

First of all, the series RL circuit was connected to the board, an inductor with 400 mH was connected in series with two resistors, and the value of Rx changed to **0.47 k ohm** as shown the next figure:

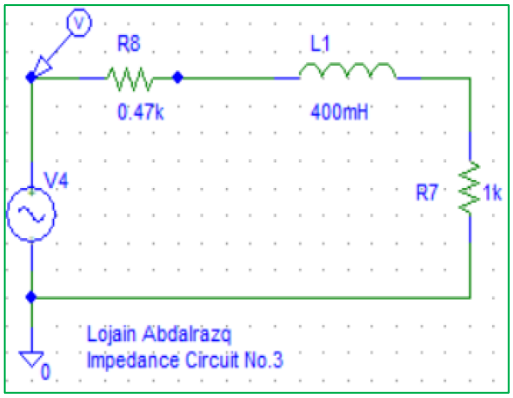

Figure 20: Series RL circuit

In the series RL circuit, the impedance of the circuit will be the sum of the **resistors (R)** and the **inductive reactance (XL).** In addition, the phase shift will be positive which means that the current lags the voltage.

✓ **When f=500 Hz:**

When the frequency was set to 500 Hz by the function generator, the total current equals to 1.807 mA while the total voltage 3.57 V. The phase shift of the series RL circuit is equals to 41.2 degree, which means that the **current lags the** voltage by 41.2 degree.

And the total impedance can be measured as the following:

$$Z_{eq} = \frac{V}{I} = \frac{3.57}{1.807 * 10^{-3}} = 1.97 \ Kohm$$

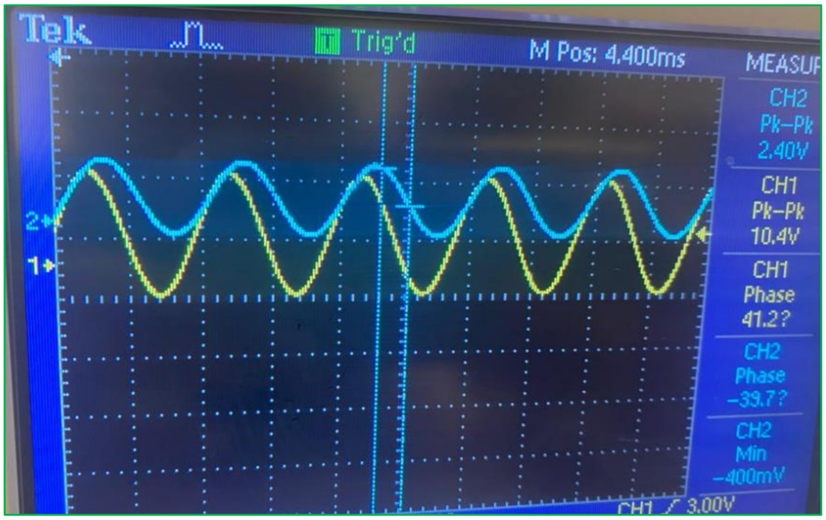

Figure 21: The voltage and current waves of RL circuit when F=500 Hz

✓ **When f=1000 Hz:**

When the frequency is changed to 1000 Hz, both voltage and current have changed to 3.56 V and 1.215 mA respectively. While the phase shift was equals to 62.8 degree (**current lags the** voltage by 62.8 degree).

To measure the **total impedance**:

$$Z_{eq} = \frac{V}{I} = \frac{3.56}{1.215 * 10^{-3}} = 2.95\ Kohm$$

.

✓**When f=1500 Hz:**

When the frequency is changed to 1000 Hz, both voltage and current have changed to 3.54 V and 0.882 mA respectively. While the phase shift was equals to 69.9 degree (**current lags the** voltage by 69.9degree).

To measure the **total impedance**:

$$Z_{eq} = \frac{V}{I} = \frac{3.54}{0.882 * 10^{-3}} = 4.01\ Kohm$$

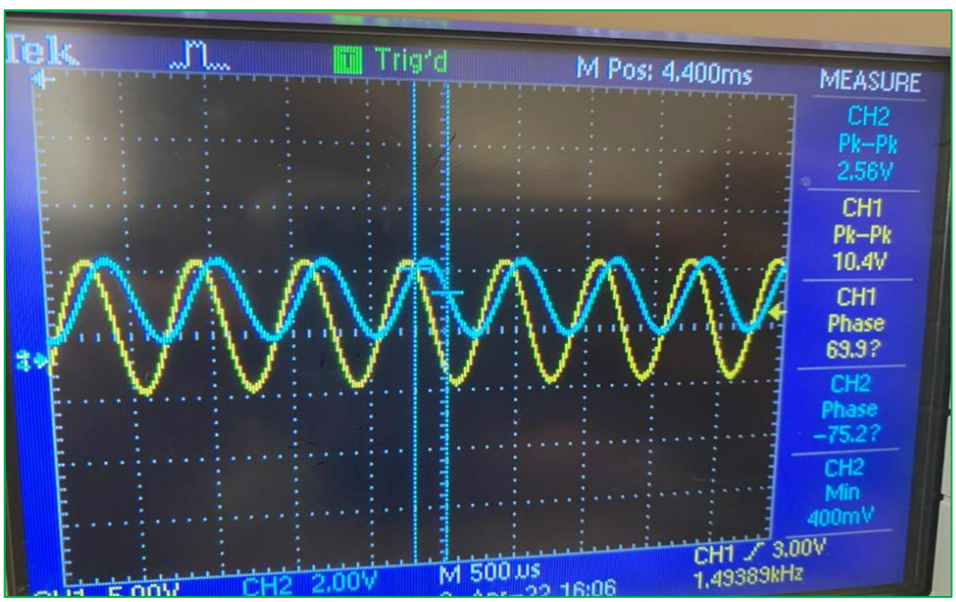

Figure 22: The voltage and current waves of RL circuit when F=1500 Hz

From the experimental results, it is noticed that the total impedance changed once the frequency change **(500 Hz, 1 kHz, and 1.5 kHz)** using the function generator, because in the RL circuits, the total impedance calculated by the inductive reactance(XL), which also depends on the value of the frequency as shown. In other words, when changing the frequency, the total impedance will be changed automatically:

$$\boldsymbol{Z= R + jXl \ \ , where\ Xl=2\pi f L}$$

The **total impedance** of the RC circuit is:

4. Frequency = 500 Hz → Z= $\boldsymbol{1.97\ Kohm}$.
5. Frequency = 1000 Hz → Z= $\boldsymbol{2.95\ Kohm}$.
6. Frequency = 1500 Hz → Z= $\boldsymbol{4.01\ Kohm}$.

While the **phase shift** is:

4. Frequency = 500 Hz → Phase Shift = **41.2 degree.**
5. Frequency = 1000 Hz → Phase Shift = **62.8 degree.**
6. Frequency = 1500 Hz → Phase Shift = **69.9 degree.**

Table 5: Impedance of the RL circuit practical results.

f [Hz]	V_{rms}	I_{rms}	Δt	Phase Shift
500	3.57 V	1.807 mA	-	41.2 degree
1000	3.56 V	1.215 mA	-	62.8 degree
1500	3.54 V	0.882 mA	-	69.9 degree

- **Theoretical Results:**
  Calculating the value of the total impedance:

$$R_{eq} = 0.47\ K + 1\ K = 1.47\ K\ ohm.$$

1. **Frequency = 500 Hz:**

$$X_l = 2\pi f L = 2\pi * 500 * 400 * 10^{-3} = 1.25\ \boldsymbol{K\ ohm}.$$

So, the **total impedance**:

$$Z = \boldsymbol{R} + \boldsymbol{j\ Xl} = 1.47 + j\ 1.25\ Kohm.$$

While the **magnitude** of the total impedance is:

$$|Z| = \sqrt{\boldsymbol{R^2 + Xl^2}} = \sqrt{1.47^2 + 1.25^2} = \boldsymbol{1.934\ Kohm}.$$

And the **phase** is:

$$\boldsymbol{\theta = tan^{-1}(\frac{Xl}{R}) = tan^{-1}\left(\frac{1.25}{1.47}\right) = 40.5\ degree}.$$

2. **Frequency = 1000 Hz:**

$$X_l = 2\pi f L = 2\pi * 1000 * 400 * 10^{-3} = 2.512\ \boldsymbol{K\ ohm}.$$

So, the **total impedance**:

$$Z = \boldsymbol{R} +\ \boldsymbol{j\ Xl} = 1.47 + j\ 2.512\ Kohm.$$

While the **magnitude** of the total impedance is:

$$|Z|\ =\ \sqrt{\boldsymbol{R^2} + \boldsymbol{XC^2}} = \sqrt{1.47^2 + 2.512^2} = \boldsymbol{2.91\ Kohm}.$$

And the **phase** is:

$$\boldsymbol{\theta = tan^{-1}\left(\frac{Xl}{R}\right) = tan^{-1}\left(\frac{2.512}{1.47}\right) = 59.66\ degree}.$$

3. **Frequency = 1500 Hz:**

$$X_l = 2\pi f L = 2\pi * 1500 * 400 * 10^{-3} = 3.77\ \boldsymbol{K\ ohm}.$$

So, the **total impedance**:

$$Z = \boldsymbol{R} +\ \boldsymbol{j\ Xl} = 3.2 + j\ 3.77\ Kohm.$$

While the **magnitude** of the total impedance is:

$$|Z|\ =\ \sqrt{\boldsymbol{R^2} + \boldsymbol{XC^2}} = \sqrt{1.47^2 + 3.77^2} = \boldsymbol{4.04\ Kohm}.$$

And the **phase** is:

$$\boldsymbol{\theta = tan^{-1}(\frac{Xl}{R}) = tan^{-1}\left(\frac{3.77}{2.2}\right) = 68.9\ degree}.$$

Table 6: Comparison between experimental the theoretical results in the RL circuit.

	Frequency	Impedance	Phase Shift
Theoretically	*500 Hz*	1.934 $Kohm$	*40.5 degree*
Experimentally		1.97 $Kohm$	*41.2 degree*
Theoretically	*1000 Hz*	2.91 $Kohm$	59.66 $degree$
Experimentally		2.95 $Kohm$	*62.8 degree*
Theoretically	*1500 Hz*	4.04 $Kohm$	68.9 $degree$
Experimentally		4.01 $Kohm.$	*69.6 degree*

Note: From the above table, it is noticed that the results of theoretical part is also very close and almost the same of theoretical one, which means the **results are true**.

2. Capacitive and inductive behavior:

The aim of this part is to find the phase shift between the total voltage and current, and to determine the behavior of the RLC circuit in relation to the capacitive, inductive or resistive circuit.

Initially, the RLC circuit in (Figure 23) was connected in the board, and a sinusoidal waveform with amplitude 5 volts was generated using the function generator.

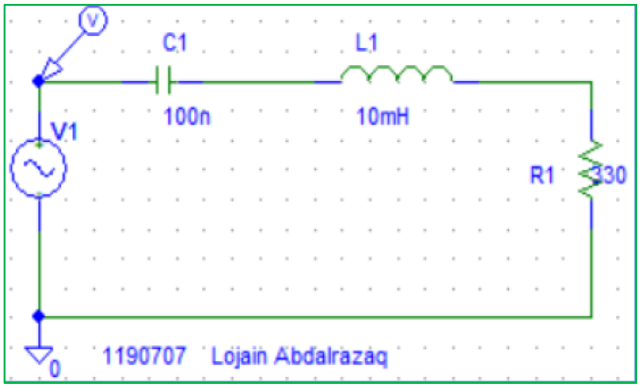

Figure 23: Series RLC circuit

- **Experimental Results:**

  ✓ **Frequency = 1000Hz:**

  When the frequency is 1000 Hz, the phase shift between the voltage and frequency is -76.8 degree, which means that the circuit is **capacitive.**

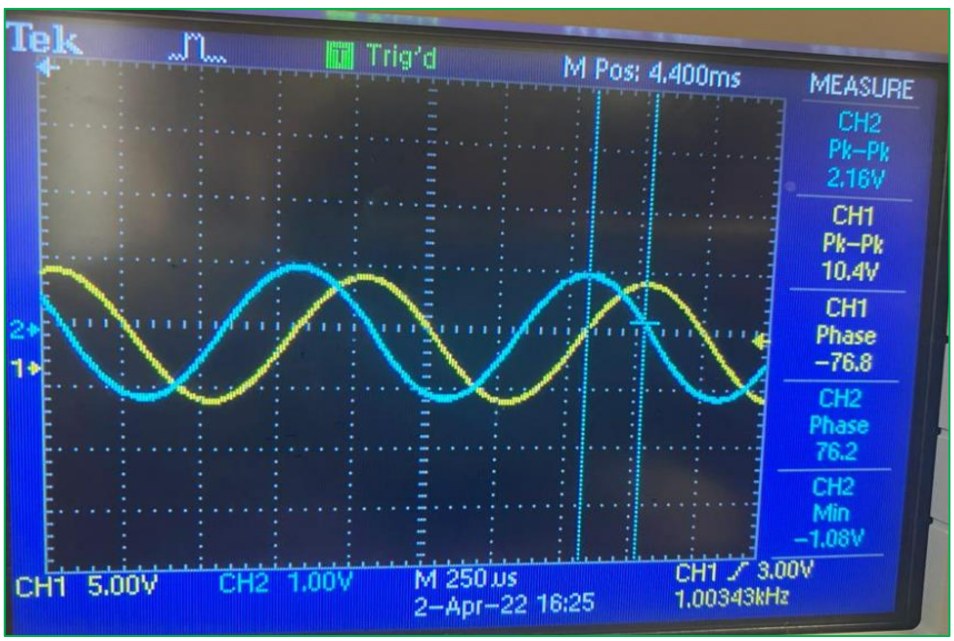

Figure 24: The voltage and current waves of RLC circuit when F=1000 H

- ✓ **Frequency = 2000Hz:**
  When Frequency equals to 2000 Hz, the phase shift changed to -63.6 degree, but still **capacitive** circuit.

- ✓ **Frequency = 4000Hz:**
  The phase shift changed to -21.5 degree, and still **capacitive** circuit.

- ✓ **Frequency = fo:**
  When the frequency equals to the resonance frequency, the phase shift between the voltage source and the current becomes almost zero, in other words, the phase shift will be in phase:

$$F_O = \frac{1}{2\pi\sqrt{LC}} = \frac{1}{2\pi\sqrt{10m * 100n}} = 5033\ Hz$$

So, the phase shift in this situation is equals to 0.279 degree, which is so close to zero.

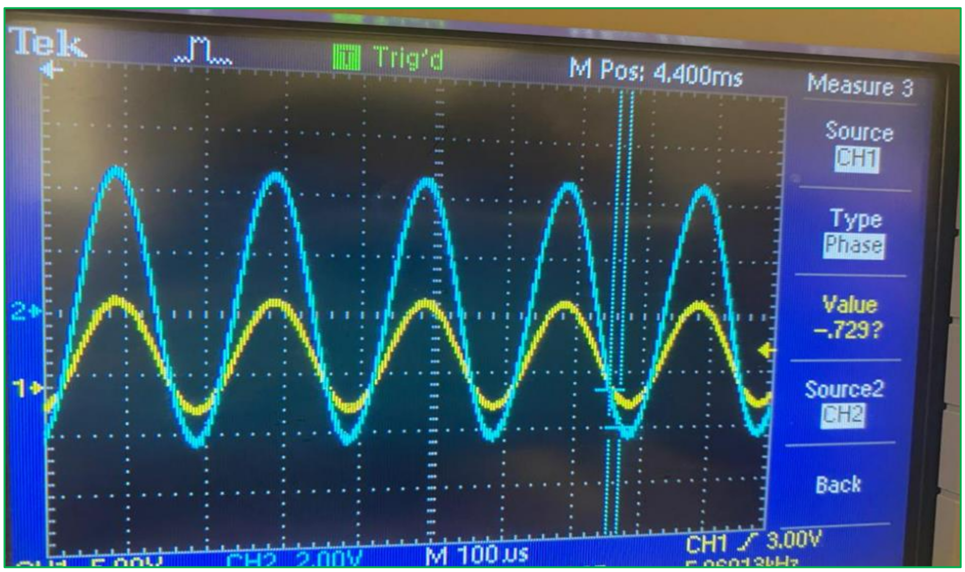

Figure 25: The voltage and current waves of RLC circuit when F=5033Hz

- ✓ **Frequency = 6000Hz:**
  When the frequency is 6000 Hz, which is greater than the resonance frequency, the circuits became **inductive** circuit, with phase shift equals to 18.2 degree.

- ✓ **Frequency = 8000Hz:**
  When the frequency is 8000 Hz, the circuit still **inductive** with 43.7 degree.

- ✓ **Doubling the capacitor:**
  When doubling the value of the capacitor, by connecting another capacitor **in parallel** to the original one, the phase shift between the total voltage and current became 23.5 degree, which means the circuit is **inductive.**

- ✓ **Doubling the inductor:**
  When doubling the value of the inductor, by connecting another inductor in series with the original one, the phase shift became 43.3 degree, the circuit still **inductive**.

- **Theoretical Results:**

To find the phase shift among different values of frequencies, we have to find the reactance part, and apply the following:

$$X = \boldsymbol{Xl - Xc = 2\pi f L - \frac{1}{2\pi f C}, \theta = tan^{-1}\left(\frac{Xl - Xc}{R}\right) = tan^{-1}\left(\frac{X}{R}\right)}$$

1. **Frequency=1000Hz:**

   Calculating the reactance:
   $$X = 2\pi f L - \frac{1}{2\pi f C} = 62.8 - 1592.35 = -1529.5\ ohm.$$
   Then the phase shift:
   $$\theta = \tan^{-1}\left(\frac{X}{R}\right) = \tan^{-1}\left(\frac{-1529.5}{330}\right) = -77.8\ degree$$

2. **Frequency=2000Hz:**

   Calculating the reactance:
   $$X = 2\pi f L - \frac{1}{2\pi f C} = 125.6 - 796.1 = -670.5\ \ ohm.$$
   Then the phase shift:
   $$\theta = \tan^{-1}\left(\frac{X}{R}\right) = \tan^{-1}\left(\frac{-670.5}{330}\right) = -63.7\ degree$$

3. **Frequency=4000Hz:**

   Calculating the reactance:
   $$X = 2\pi f L - \frac{1}{2\pi f C} = 251.2 - 398.08 = -146.889\ ohm.$$
   Then the phase shift:
   $$\theta = \tan^{-1}\left(\frac{X}{R}\right) = \tan^{-1}\left(\frac{-146.889}{330}\right) = -23.99\ degree$$

4. **Frequency=6000Hz:**

Calculating the reactance:

$$X = 2\pi f L - \frac{1}{2\pi f C} = 376.8 - 265.39 = 111.4\ ohm.$$

Then the phase shift:

$$\theta = \tan^{-1}\left(\frac{X}{R}\right) = \tan^{-1}\left(\frac{111.4}{330}\right) = 18.65\ degree$$

5. **Frequency=8000Hz:**

Calculating the reactance:

$$X = 2\pi f L - \frac{1}{2\pi f C} = 502.4 - 19.904 = 482.49\ ohm.$$

Then the phase shift:

$$\theta = \tan^{-1}\left(\frac{X}{R}\right) = \tan^{-1}\left(\frac{482.49}{330}\right) = 55.62\ degree$$

6. **Frequency=fo:**

Calculating the reactance:

$$X = 2\pi f L - \frac{1}{2\pi f C} = 316.07 - 316.38 = -0.313\ ohm.$$

Then the phase shift:

$$\theta = \tan^{-1}\left(\frac{X}{R}\right) = \tan^{-1}\left(\frac{-0.313}{330}\right) = -0.054\ degree$$

As shown in the following table, it is noticed that the results of both experimental and theoretical calculations are so close which leads us to know that the results are true.

Table 7: Comparison between experimental the theoretical results in the RLC circuit.

Freq (Hz)	1000	2000	4000	6000	8000	fo
Experimental	*-76.8 deg*	*-63.6 deg*	*-21.5 deg*	*18.2 deg*	*43.7 deg*	*0.279 deg*
Theoretical	$-77.8\ deg$	$-63.7\ deg$	$-23.99\ deg$	$18.65\ deg$	$55.62\ deg$	$-0.054\ deg$

3. Sinusoidal steady state power:

In this part, the following circuit was connected on the board with 2.5 V voltage source amplitude and 2000 Hz frequency.

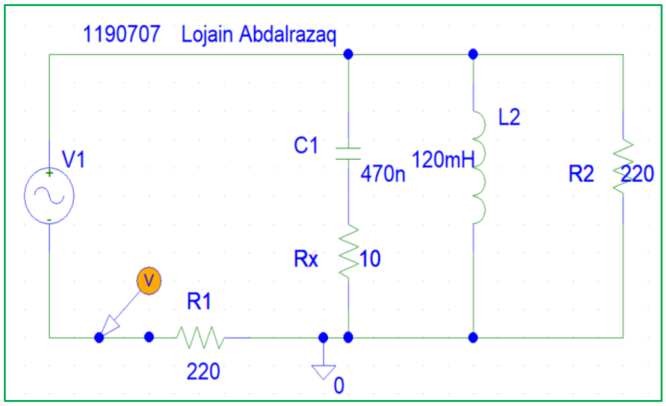

Figure 26: Steady state power RLC circuit

1. **Measuring the Vrms and Irms for R1,R2, L and C:**

   From the practical results, the values of the rms voltage and current are the following:

   The values of **Vs=1.74 Volt** and **Is=5.021 mA**.

Table 8: Vrms and Irms for the circuit elements.

	R1	R2	L	C
V rms	1.009	0.645	0.645	1.74
I rms	5.021	3.164	0.48	6.302

Note: The rms voltage of the inductor is equal to the value in the resistor R2 since they are connected in parallel. Also, the rms current of the resistor R1 is equals to the Is.

2. **Measuring the phase shift between Vs and Is ,and Vc and Ic:**

   The phase shift between **Vs and Is → -39.9 degree.**
   The phase shift between **Vc and Ic → 88.9 degree.**

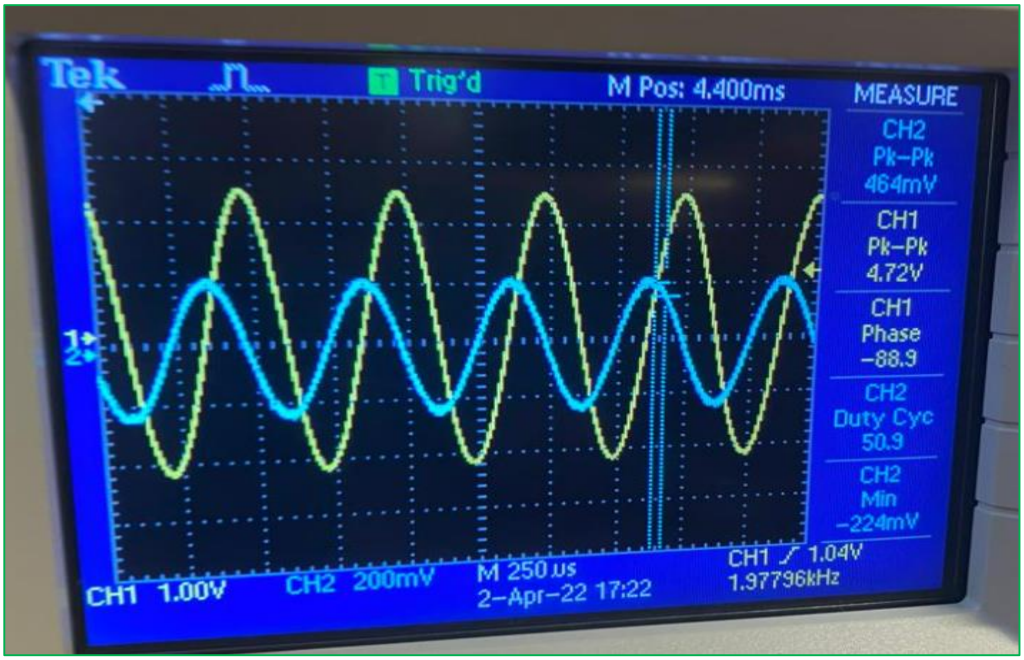

Figure 27: The phase shift between Vs and Is

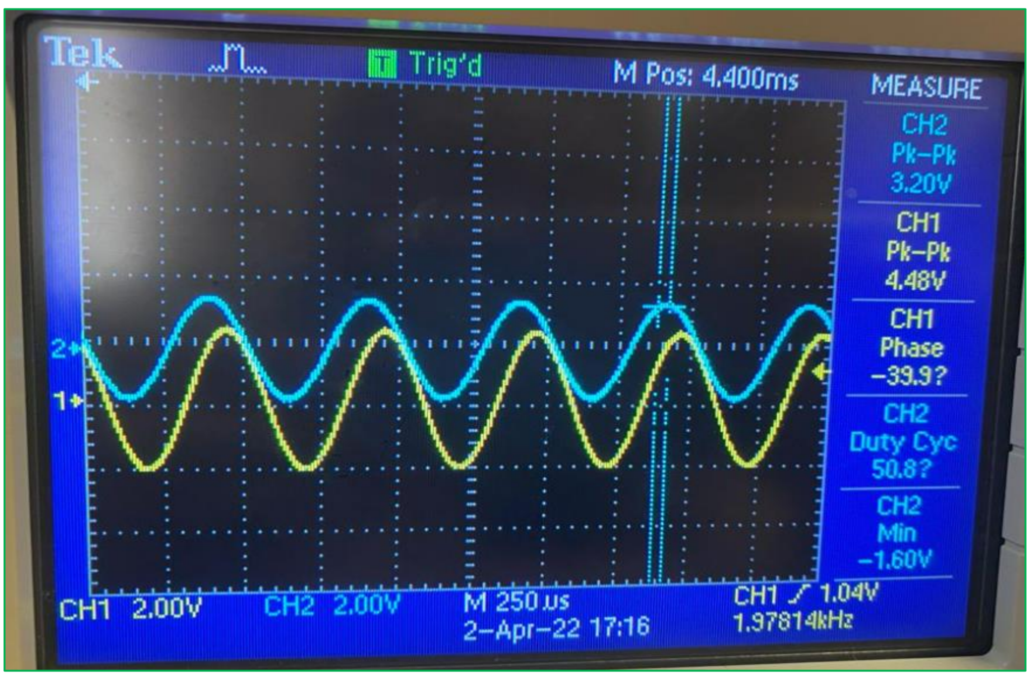

Figure 28: The phase shift between Vc and Ic

3. **Computing the active power (Average power, reactive power, and power factor):**

- To calculate the values of active power:

$$P_{avg} = V_{rms} I_{rms}\, cos(\theta)$$

1. For R1 $= \mathbf{1.009 * 5.021 * cos(-39.9) = 3.88\, mWatt}$.
2. For R2 $= \mathbf{0.645 * 3.164 * cos(-39.9) = 1.56\, mWatt}$.

Note: The average power of the capacitor and inductor is zero.

Note: I have forgot to take the data of the voltage across Rx.

- To calculate the values of reactive power:

$$P_{avg} = V_{rms} I_{rms}\, sin(\theta)$$

1. For C $= \mathbf{1.74 * 6.302 * sin(-39.9) = -7.048\, mWatt}$.
2. For L $= \mathbf{0.645 * 0.48 * sin(-39.9) = -0.1985\, mWatt}$.

- To calculate the values of power factor:

$$P_{factor} = cos(\theta) = cos(-39.9) = 0.767$$

Conclusion

This experiment has covered many concepts such as determining the impedance for different types of AC circuits, the current, and the voltage for the elements in the specified circuits. The capacitive and inductive behavior was examined. In addition, power of the sinusoidal steady-state circuits was calculated.

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Appendix

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Table 4.1

f [Hz]	Vrms	Irms	Δt	Phase shift
500	3.58	1.107mA	0	0
1k	3.51	1.207mA	0	0
1.5k	3.~~?~~4	1.107mA	0	0

Table 4.2

f [Hz]	Vrms	Irms	Δt	Phase shift
500	3.57	0.779	—	−43.5
1k	3.56	0.9893	110mF	−26.90
1.5k	3.53	1.045	—	−17.3

Table 4.3

4.79

f [Hz]	Vrms	Irms	Δt	Phase shift
500	3.57	2.807	—	40.8°
1k	3.56	1.215°	—	62.8°
1.5k	3.54	0.882°	—	69.90

Table 4.4

$f_0 = \frac{1}{2\pi\sqrt{LC}}$

f	1k	2k	4k	6k	8k	(fo)
			14	5	8	
Δt	240 Ms	904	16Ms	12Ms	16Ms	5033
$(\Theta_{Vs} - \Theta_{Is})$	−76.8	−63.6	21.5	−18.2	−13.7	0.729 ≈ 0

practical

~~56~~

Table 4.5

$V_{(R1)}$	$V_L = V_{(R2)}$	I_L	I_{R2}	V_s	I_s	$(\Theta_{Vs} - \Theta_{Is})$	V_c	I_c	$(\Theta_{Vc} - \Theta_{Ic})$
1.009	0.645	0.48	3.164	2.74	5.021	−39.9°	1.74	6.302	88.9

90

2.42 5.15 −18.2 4.24

1.15 0.71 1.742

0.47 9. 0.01

|Page 18