International University

School of Electrical Engineering

Principles of EE I Laboratory Lab 5 & 6

AC Circuits

Submitted by

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Nomenclature

V_{DD} = DC Voltage Source

V_{dd} = AC Volatge Source

I_{ref} = Reference Current

Etc.

Theoretical Background

1. The Sinusoidal Source:

A sinusoidal voltage or current source (independent or dependent) produces a voltage or current that varies sinusoidally with time. Using the cosine function as a base, we can write a sinusoidally varying voltage as follows:

$$\boldsymbol{v(t) = V_m Cos(\omega t + \varphi)} \quad \textbf{(Eq. 1)}$$

where $\mathbf{V_m}$ is the maximum amplitude of the sinusoidal voltage,
$\omega = 2\pi\mathbf{f} = 2\pi/\mathbf{T}$ is the angular frequency of the sinusoidal signal in rad/sec.
(**f** is the frequency of the sinusoid in Hz,
T is the period of the sinusoid in seconds)
and φ is the phase angle of the sinusoidal voltage.

Notes: 1- Since the cosine function is bounded by ±1, the amplitude is bounded by $\pm\mathbf{V_m}$. This is clearly shown in Fig. 1.

2- Changing the phase angle φ shifts the sinusoidal function along the time axis, but has no effect on either the amplitude $\mathbf{V_m}$ or the angular frequency ω.

3- If φ is positive, the sinusoidal function shifts to the left.
If φ is negative, the sinusoidal function shifts to the right.

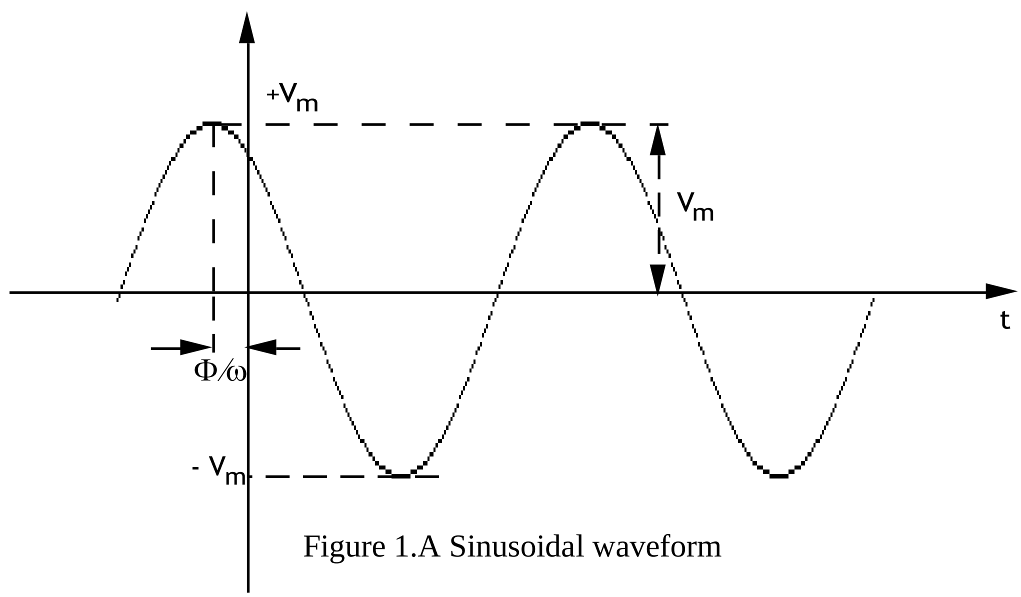


Figure 1.A Sinusoidal waveform

2. Phasor Representation of a Sinusoid:

Using Euler identity. $e^{\pm j\theta} = \cos(\theta) \pm \sin(\theta)$

Equation can be written as follows:

$$v(t) = V_m \,\mathrm{Re}\{e^{j(\omega t+\theta)}\} = V_m \,\mathrm{Re}\{e^{j\omega t} e^{j\theta}\}\ v(t)$$
$$= \mathrm{Re}\{(V_m e^{j\theta})e^{j\omega t}\}$$

The complex number $\mathbf{V_m e^{j\theta}}$ is called the phasor representation or the phasor transform. Eq. 1 can be represented in the phasor domain as follows:

$$\mathbf{V} = \mathbf{V_m} < \theta$$

3. The passive Circuit Elements In Phasor Domain:

a-Across a resistors: V=RI

b- Across a inductor: $\mathbf{V = (j\omega L)I}$

c- Across a capacitor: $\mathbf{V = (1/j\omega C)I = -(j/\omega C)I}$

where where $\mathbf{I = I_m} < \boldsymbol{\theta}$ is the sinusoidal current $\mathbf{i(t)}$ in phasor domain.

4. Phasor Diagram:

Consider a series **RLC** circuit with an input sinusoidal voltage $\mathbf{V_s}$ as shown in fig. 2.

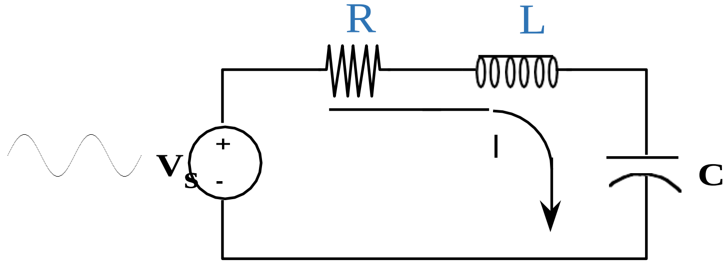


Fig. 2 A Series RLC Circuit

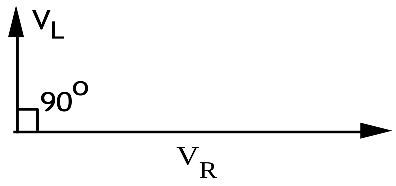
In the phasor domain, $\mathbf{V_s = V_R + V_L + V_C = RI + (j\omega L)I + (-j/\omega C)I.}$

To draw the phasor diagram of Fig. 2, for ideal circuit elements, we do the following:

(1) Choose a reference voltage, say $\mathbf{V_R}$

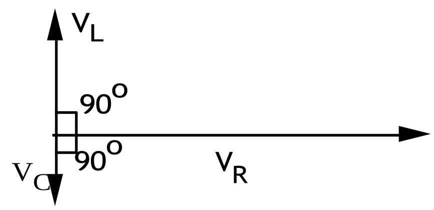
(1)

(2) From Eqs. 2 & 3 we see that $\mathbf{V_L}$ will lead $\mathbf{V_R}$ by 90°



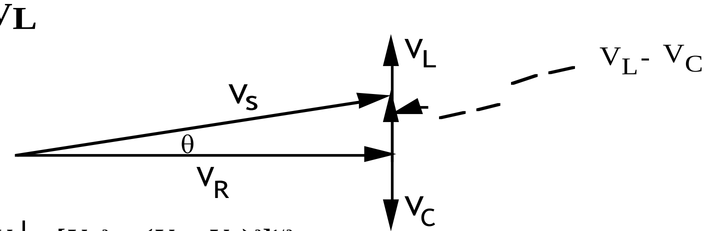
(2)

(3) From Eqs. 2 & 4 we see that $\mathbf{V_C}$ will lag behind $\mathbf{V_R}$ by 90^o



(3)

(4) $V_s = \mathbf{V_R} + \mathbf{V_L} + \mathbf{V_C}$



The magnitude of $\mathbf{V_s}$ is: $|\mathbf{V_s}| = [\mathbf{V_R}^2 + (\mathbf{V_L} - \mathbf{V_C})^2]^{1/2}$

The phase angle of $\mathbf{V_s}$ is: $\theta = \tan^{-1}[(\mathbf{V_L} - \mathbf{V_C})/\mathbf{V_R}]$

Experimental Procedure and Results:

1. RC circuit

Circuit Design and Layout:

Following is a RC circuit, we consider that the input voltage $v(t)$ has form $v(t) = \boldsymbol{V_P}\sin(\boldsymbol{\omega}.\boldsymbol{t} + \boldsymbol{\varphi})$, with $\boldsymbol{\varphi}$ the phase shift between $v(t)$ and $i(t)$.

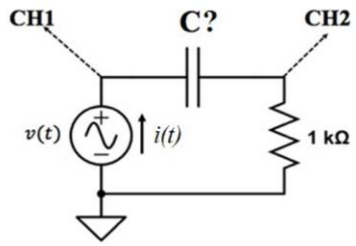


Figure 3. A RC circuit

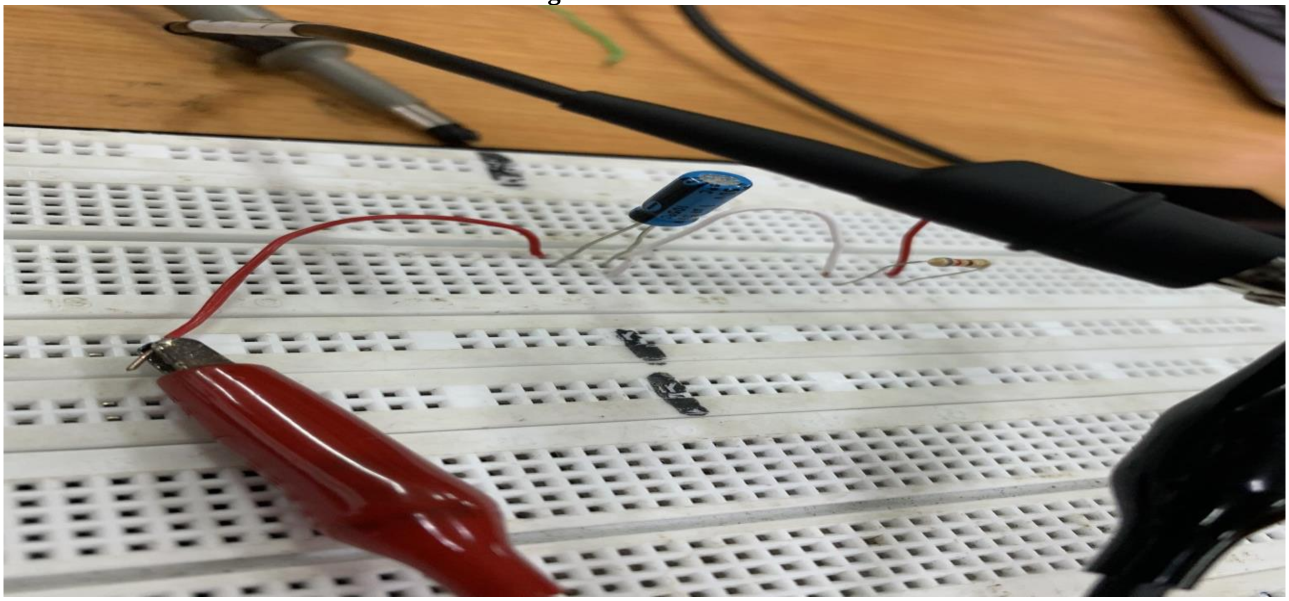


Figure 4. Constructed RC circuit

1.1 Determine value of a capacitor by measuring the phase shift

In this section, our objective is to ascertain the phase shift ($\boldsymbol{\varphi}$) between the overall voltage ($\boldsymbol{v}(\boldsymbol{t})$) and the voltage across the resistor ($\boldsymbol{vR}(\boldsymbol{t})$) within an RC circuit setup. To accomplish this, we use an oscilloscope to monitor $\boldsymbol{vR}(\boldsymbol{t})$ at the resistor (R), which serves as our reference voltage on Channel 2 (CH2) of the oscilloscope, while the function generator creates the sinusoidal input voltage $\boldsymbol{v}(\boldsymbol{t})$.

Each team receives a capacitor with unknown capacitance for the practical component of the experiment. We initiate a sinusoidal $\boldsymbol{v}(\boldsymbol{t})$ with a maximum amplitude Vp of 2 V and a frequency f of 500 Hz. Subsequently, we assemble the RC circuit as illustrated in Figure 1, ensuring that the oscilloscope's connections are correct for phase shift measurement.

Upon constructing the circuit, we have our setup verified by the instructor. With the frequency set to 500 Hz, we determine the time difference $\Delta \boldsymbol{t}$ and either calculate or directly measure the phase shift $\boldsymbol{\varphi}$ (expressed in degrees) using the oscilloscope. This data is recorded in the first column of the provided table. We perform the same procedure for frequencies of 750 Hz and 1000 Hz.

To wrap up the experiment, we deduce the capacitance value of the undetermined capacitor (C) using our collected data, and fill out the remaining parts of the table accordingly.

Following the setup and data collection as per the circuit in Figure 1, we obtained the following results:

$$V_R = v_{in} \times \frac{R}{Z_c + R}$$

$$Z_C + R = \frac{v_{in}}{V_R} \times R$$

$$\frac{1}{2\pi f C} = R\left(\frac{v_{in}}{v_R} - 1\right)$$

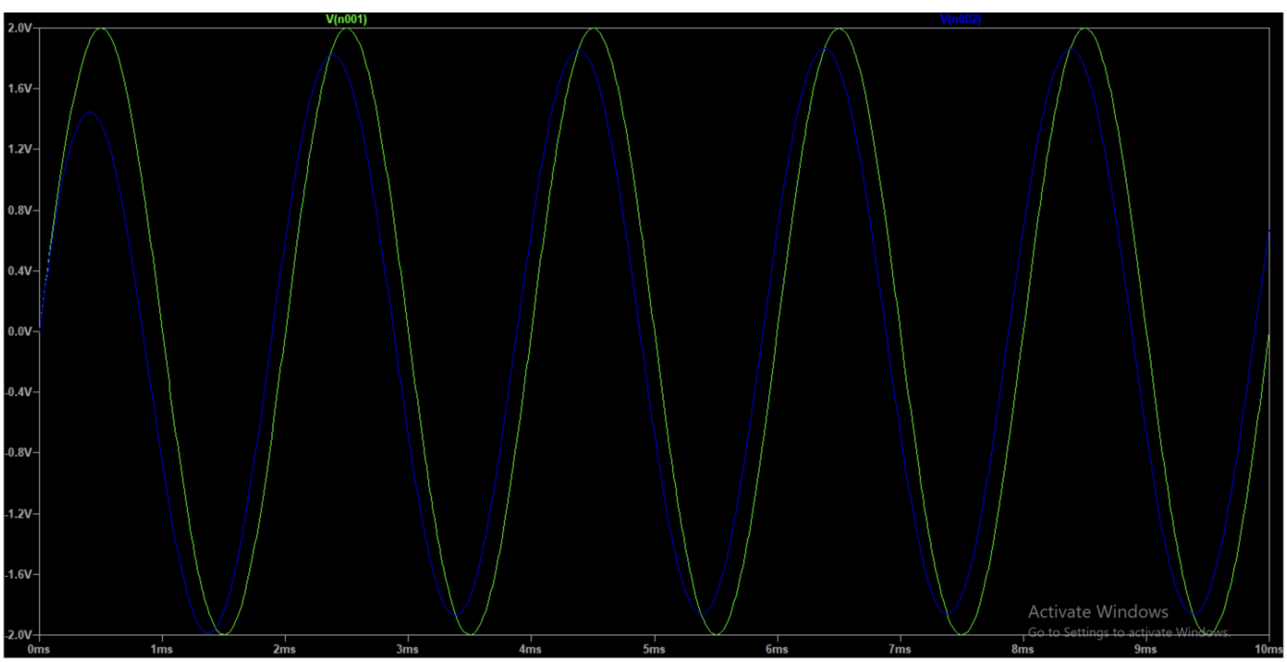


Figure 5. Simulated result for f=500 Hz

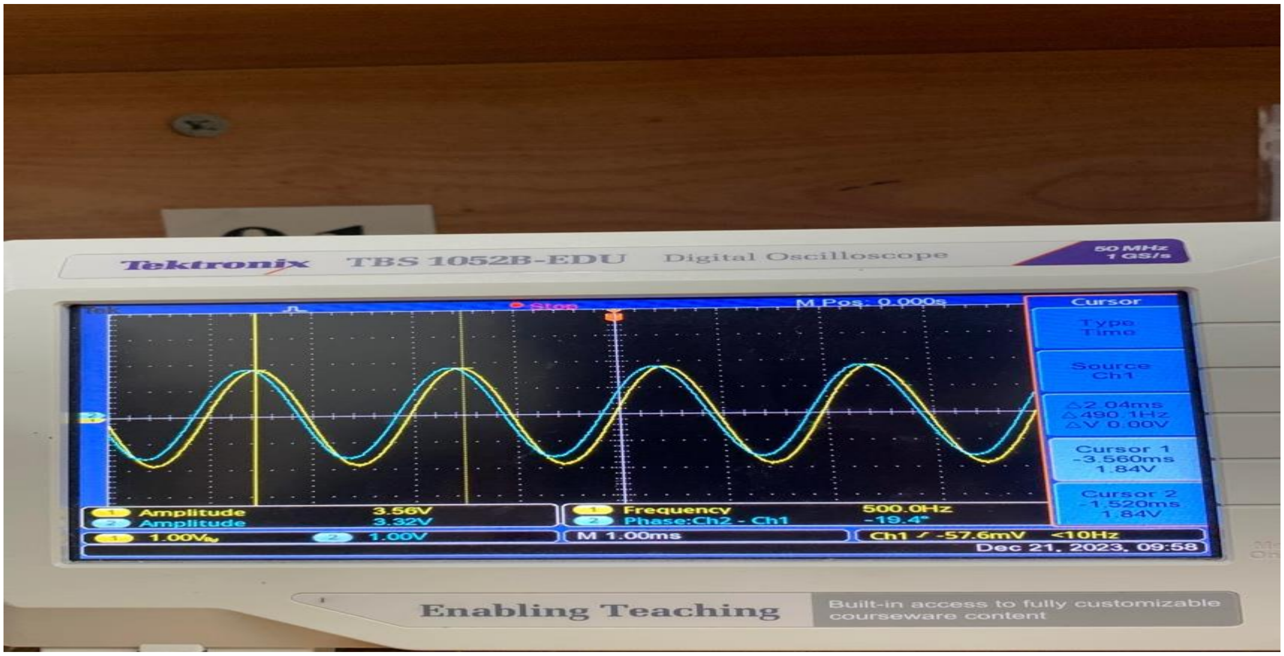


Figure 6. Measurement result for f=500Hz

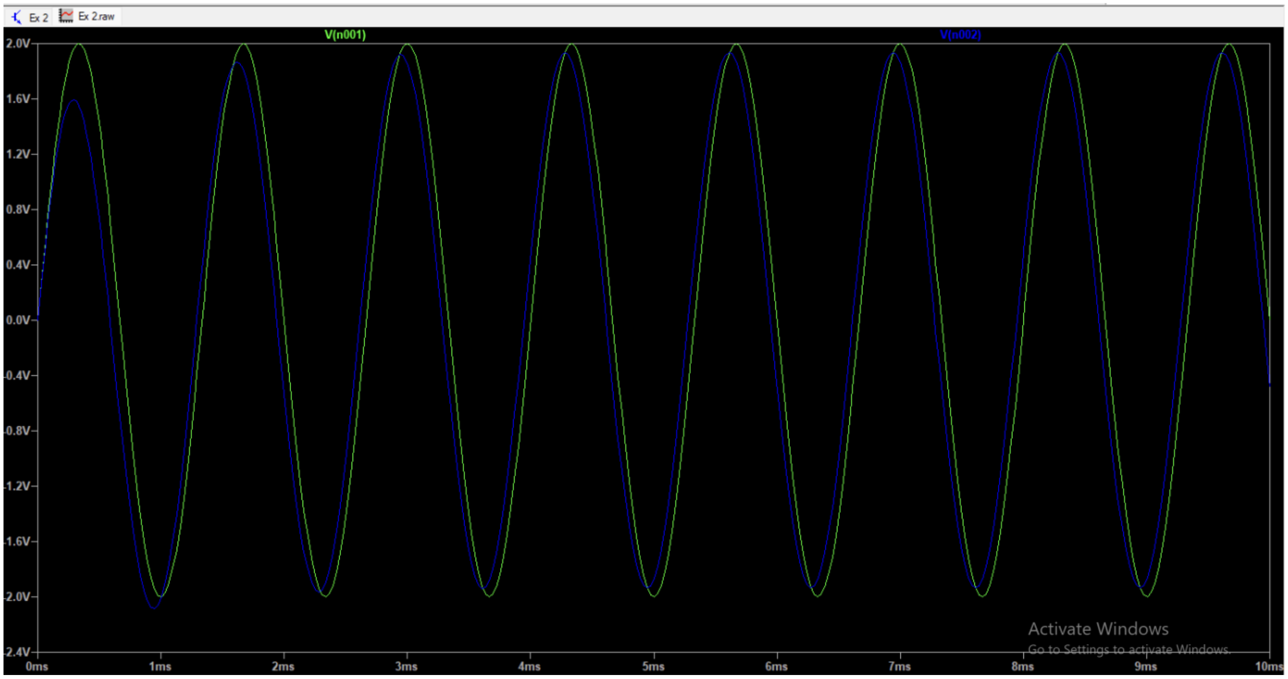


Figure 7. Simulated result for f= 750Hz

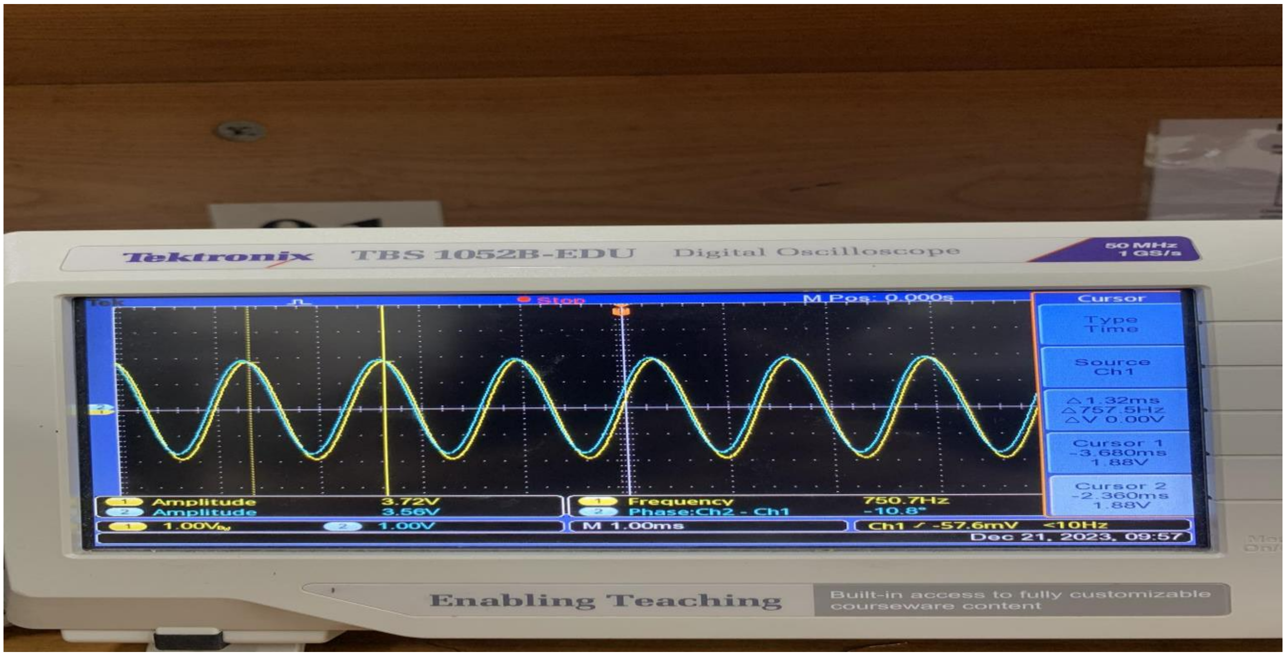


Figure 8. Measurement result for f= 750Hz

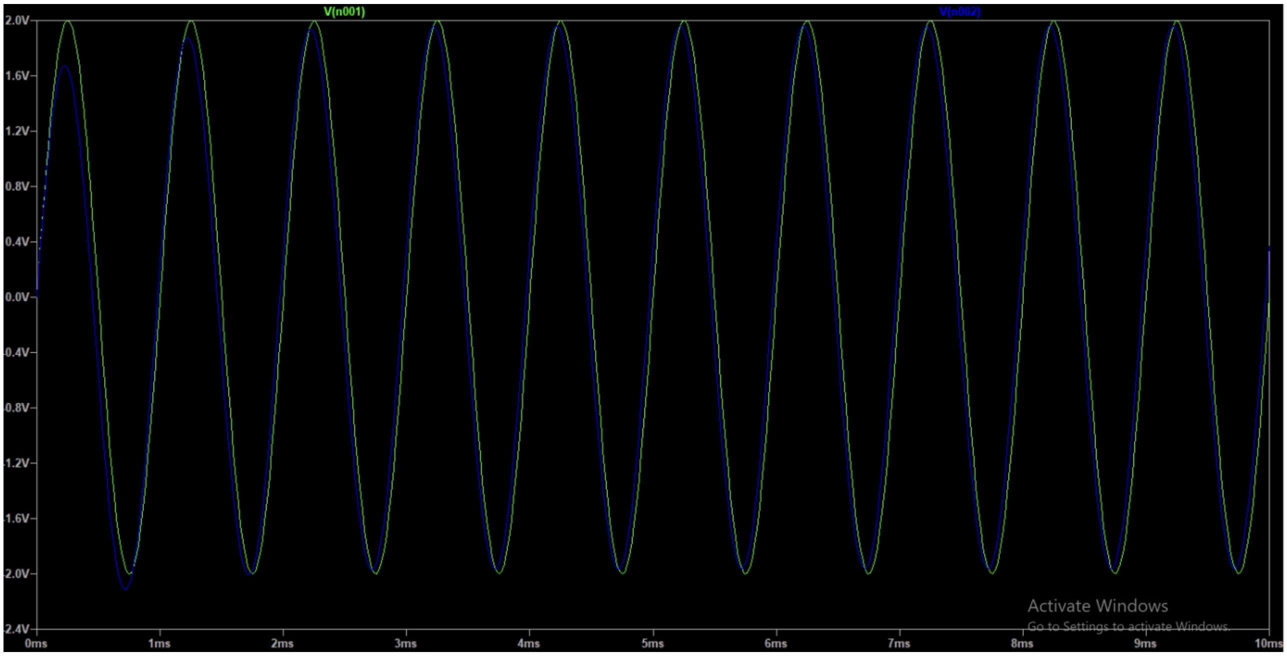


Figure 9. Simulated result for f=1000 Hz

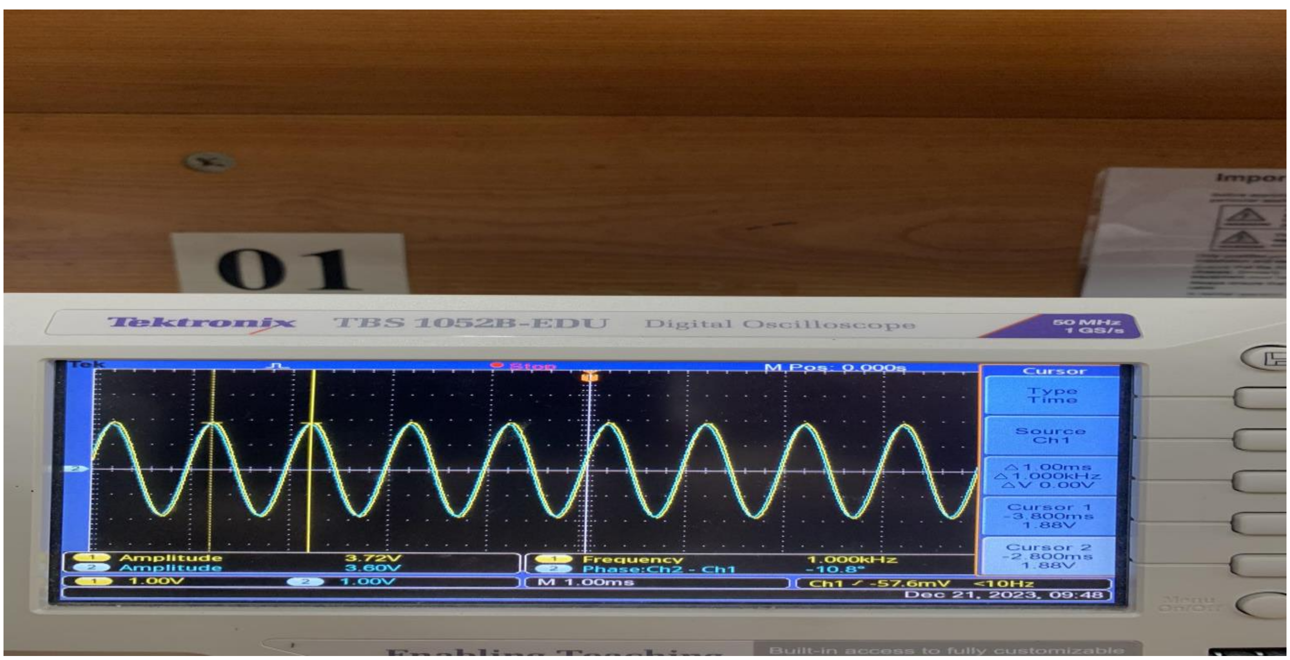


Figure 10. Measurement result for 1000 Hz

Table 1. Result collection for the circuit in figure 3.

	Simulated	Measured	Simulated	Measured	Simulated	Measured
f (Hz)	500		750		1000	
Period: **T** (ms)	2	2	1.33	1.33	1	1
Time delay $\Delta \boldsymbol{t}$ (μs)	80	107	37	40	25	50
Phase shift $\boldsymbol{\varphi}$ (°)	14.4°	19.4°	9.99°	10.8°	9°	10.8°
C (μF)	1.04	2.11	1.02	1.99	1.01	1.85

1.1.1 **Considering the values in the table I, what can we conclude:**

a. As the frequency increases, the phase shift $\boldsymbol{\varphi}$ decreases. This is because higher frequencies result in shorter delay times, leading to smaller phase shifts.

b. The calculated values for capacitance (C) decrease as frequency increases. This suggests that the capacitor becomes less effective at storing charge as frequency increases.

c. The difference between the nominal and measured capacitance value could be due to a number of factors including tolerances in manufacturing, environmental conditions, or variations in the measurement method. However, the general trend is that the measured capacitance is higher than the simulated one, which could suggest a systematic error in the measurement method or equipment.

1.2 Determine value of a capacitor by measuring its impedance

We use the same previous circuit.

Experimental work:

Objective: To measure the RMS voltage across the capacitor's terminals using multimeters within the same circuit configuration.

1.2.1 At a frequency of 1000 Hz:

a. Confirm on oscilloscope that sinusoidal voltage v(t) maintains a constant Peak Amplitude of 2 V.

b. Fill out Table 2 by first measuring the RMS voltage (Vrms) across the capacitor using a multimeter set to measure true RMS values. Then, determine the RMS current (Irms) through the circuit. Finally, compute the impedance magnitude $|Zc|$ and from this value, infer the capacitor's capacitance (C).

$$|Z_c| = \frac{V_{c.rms} \sim V}{I_{c.rms} \sim mA}$$

$$|Z_c| = \frac{1}{2\pi f C} => C =$$

Table 2. Simulated-Measurement collection result for 1.2

	Simulated	Measured	Simulated	Measured	Simulated	Measured
f (Hz)	1000		250		100	
Vrms (mV)	289	192.741	889.357	650.023	1258.916	1055.385
Irms (mA)	1.817	1.911	1.397	1.455	0.791	0.872
$\lvert \boldsymbol{Z_c} \rvert = \frac{\boldsymbol{V_{rms}}}{\boldsymbol{I_{rms}}}$ (Ω)	159.155	100.859	636.620	446.751	1591.550	1210.304
C (μF)	1	1.578	1	1.425	1	1.315

1.2.5 Comment on the result:

The measured values of capacitance are consistently higher than the simulated and nominal values across all frequencies tested. This could indicate systematic errors in measurement or issues with the experimental setup. It may also suggest that the real-world behavior of the capacitor is not perfectly captured by the simulation, possibly due to factors not considered in the model such as temperature effects, dielectric absorption, or parasitic inductances and resistances in the actual capacitor.

1.2.6 Conclusion

The results show that the theoretical models used to simulate capacitor behavior may not fully account for real-world conditions and component variances. The consistently higher measured capacitance values suggest that in practical applications, the actual performance of capacitors can deviate from ideal predictions, emphasizing the importance of empirical testing in circuit design and analysis. It's important to consider these discrepancies in critical applications where precise capacitance values are crucial. Further investigation to pinpoint the cause of the discrepancies could lead to a better understanding of the factors affecting capacitor behavior in this specific setup.

2. RL Circuit:

I initiated my experiment with the specified lab circuit and added my own signal generator input as outlined in part 1.1.

I then constructed the RL circuit following the method used for the RC circuit in Figure 1, ensuring the resistor had a value of 1 kΩ, as shown in Figure 11.

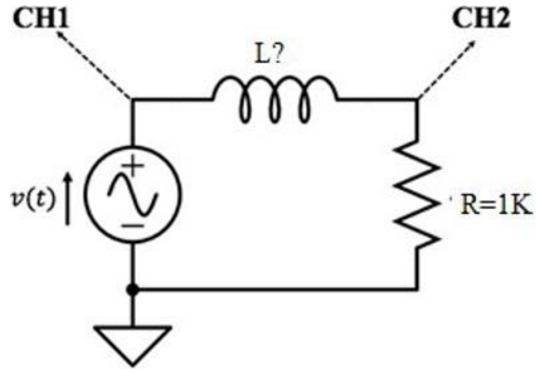


Figure 11. A RL circuit

In the RL circuit depicted in Figure 11, I noted the input voltage v(t) takes the form of a sine wave, VP sin(ωt + φ), where φ is the phase shift between v(t) and i(t).

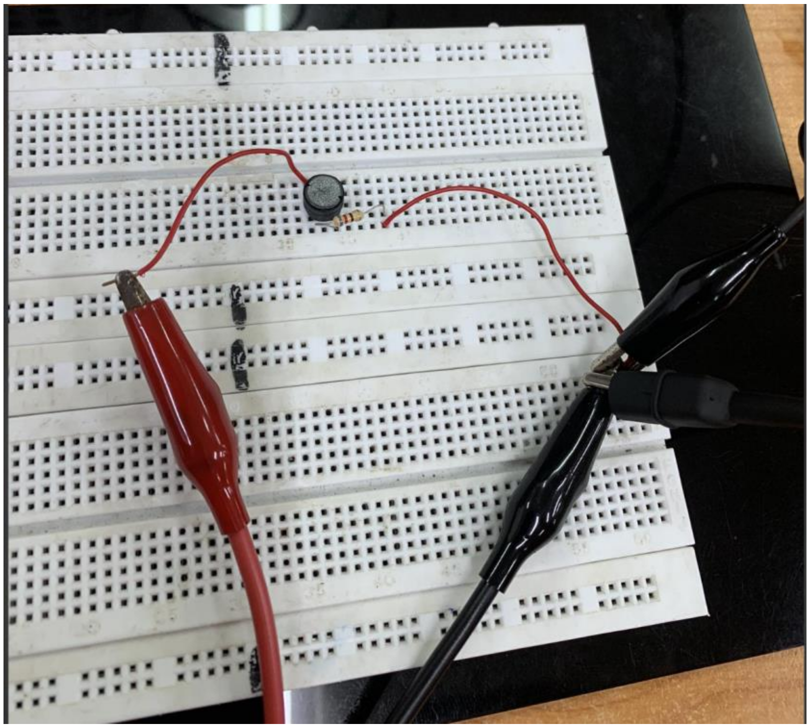


Figure 12. A constructed RL circuit

2.1 etermine the inductor’s value by measuring the phase shift..

In this section, my goal was to evaluate the phase angle (φ) between the total voltage (v(t)) and the voltage across the resistor (vR(t)) in an RL circuit arrangement. For this purpose, I utilized the oscilloscope to trace vR(t) at the resistor (R), which I designated as the reference voltage on Channel 2 (CH2) of the oscilloscope. Meanwhile, the function generator was responsible for producing the sinusoidal input voltage v(t).

For the experimental part, I was provided with an inductor whose inductance was unknown. I started by generating a sinusoidal v(t) with a peak voltage **Vp of 2 V** and a frequency **f of 1 kHz**. Following that, I assembled the RL circuit as displayed in Figure 11, paying close attention to the connections of the oscilloscope to ensure accurate phase angle measurements.

After constructing the circuit, I sought approval from my instructor to confirm the correctness of my setup. With the frequency maintained at 1 kHz, I proceeded to measure the time difference Δt and calculated or directly measured the phase angle φ (expressed in both degrees and radians) using the oscilloscope. I then recorded this information in the designated column of the table provided. I repeated these measurements for increased frequencies of 2 kHz and 4 kHz.

Concluding the experiment, I analyzed the collected data to infer the inductance value of the unknown inductor (L) and completed the necessary sections of the table.

Based on the procedure and data gathered following the circuit in Figure 11, I derived the following conclusions:

$$V_R = v_{in} \times \frac{R}{Z_L + R}$$

$$Z_L + R = \frac{v_{in}}{V_R} \times R$$

$$2\pi f L = R(\frac{v_{in}}{v_R} - 1)$$

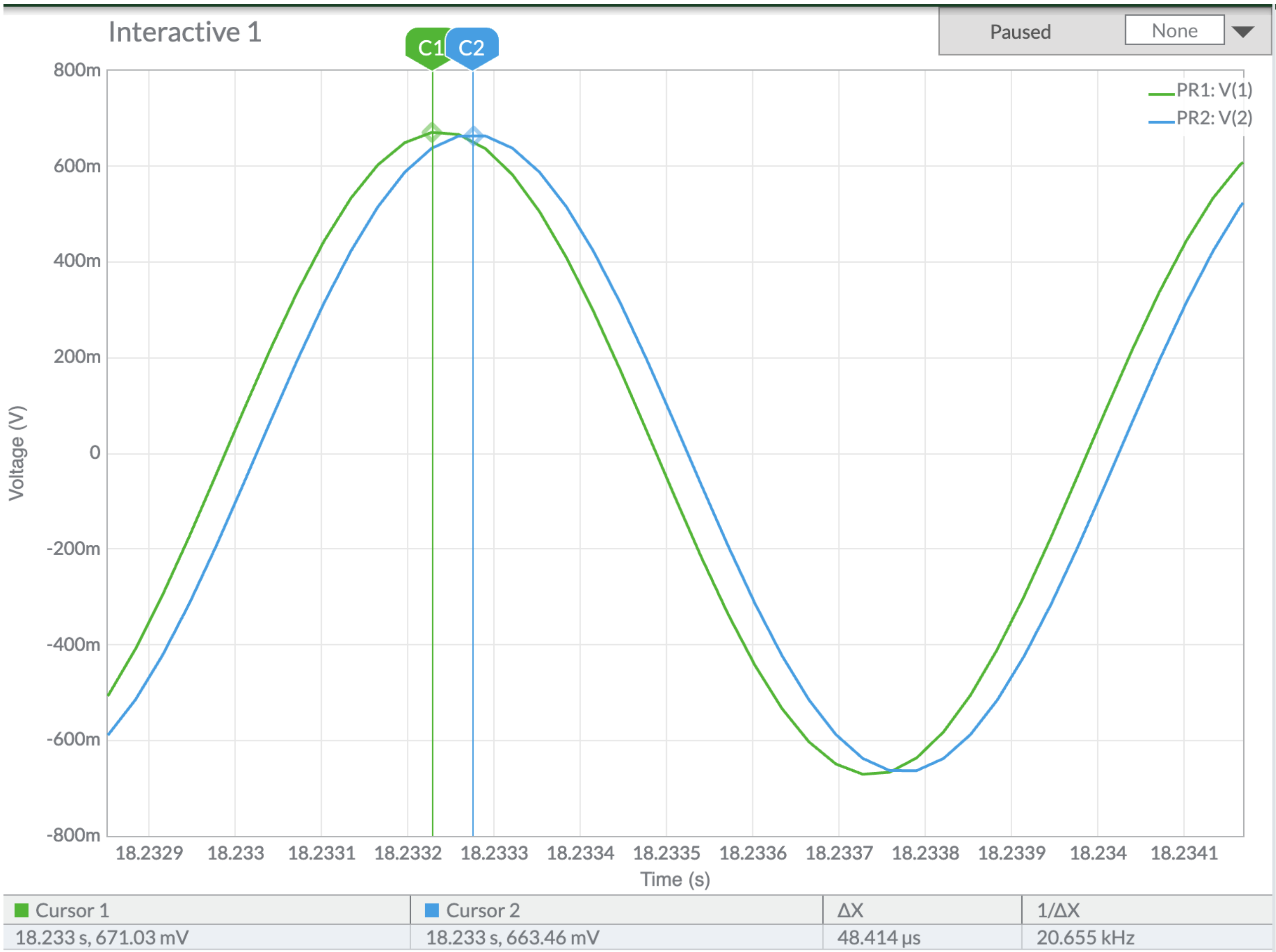


Figure 13 . Simulation result for 1000 Hz

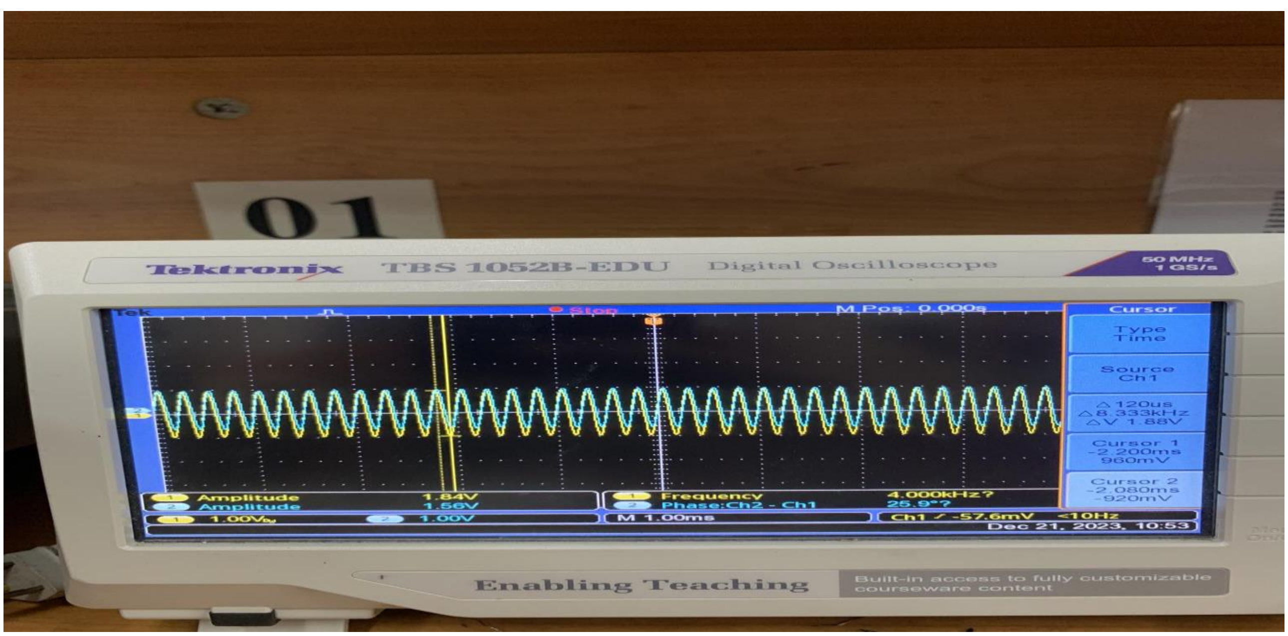


Figure 14 . Measurement result for 1000 Hz

Figure 15 . Simulation result for 2000 Hz

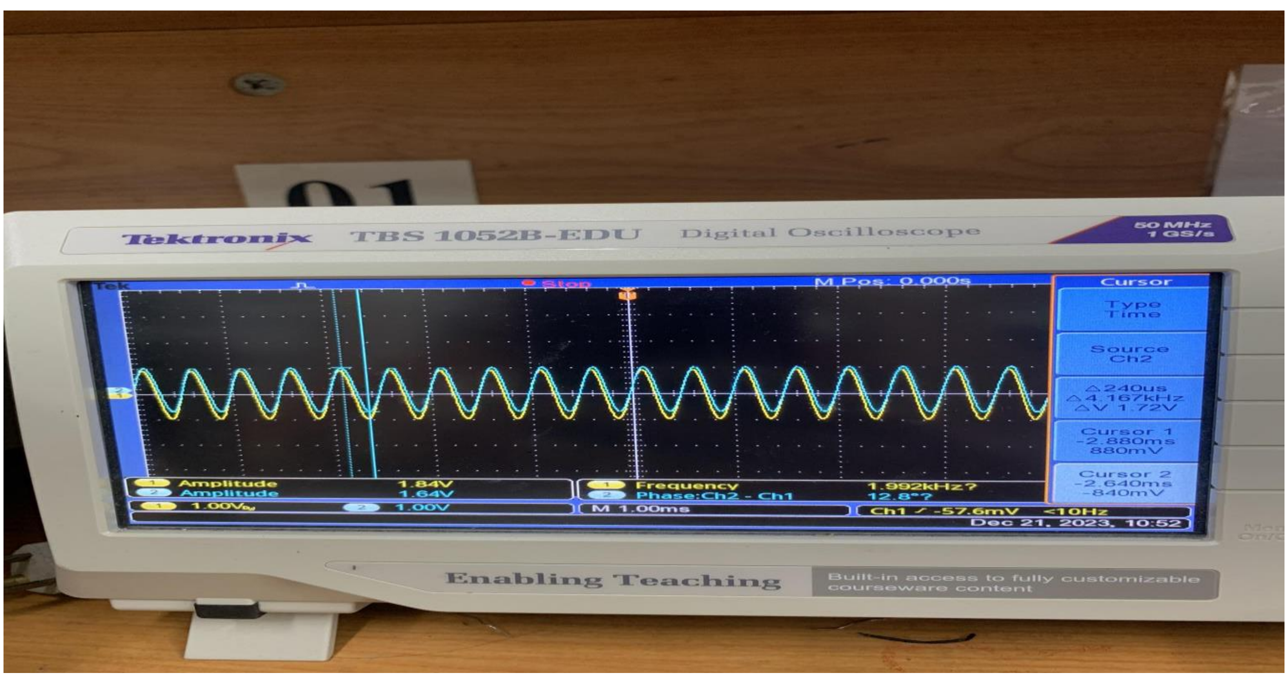


Figure 16 . Measurement result for 2000 Hz

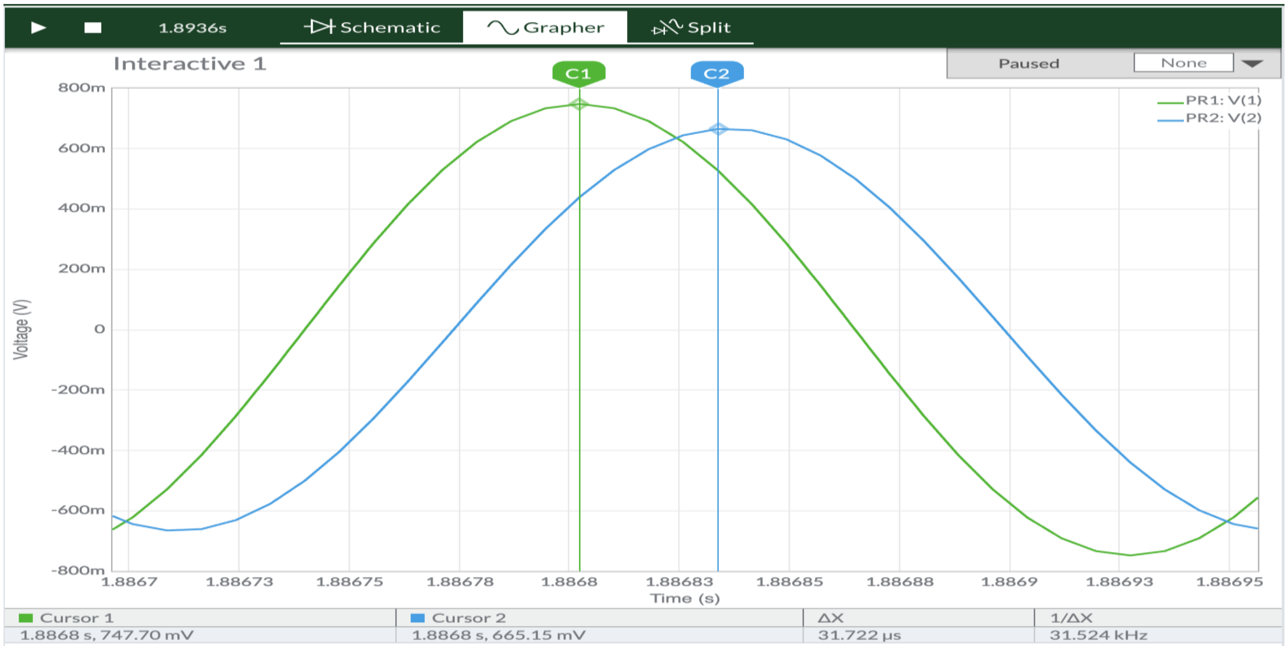


Figure 17 . Simulation result for 4000 Hz

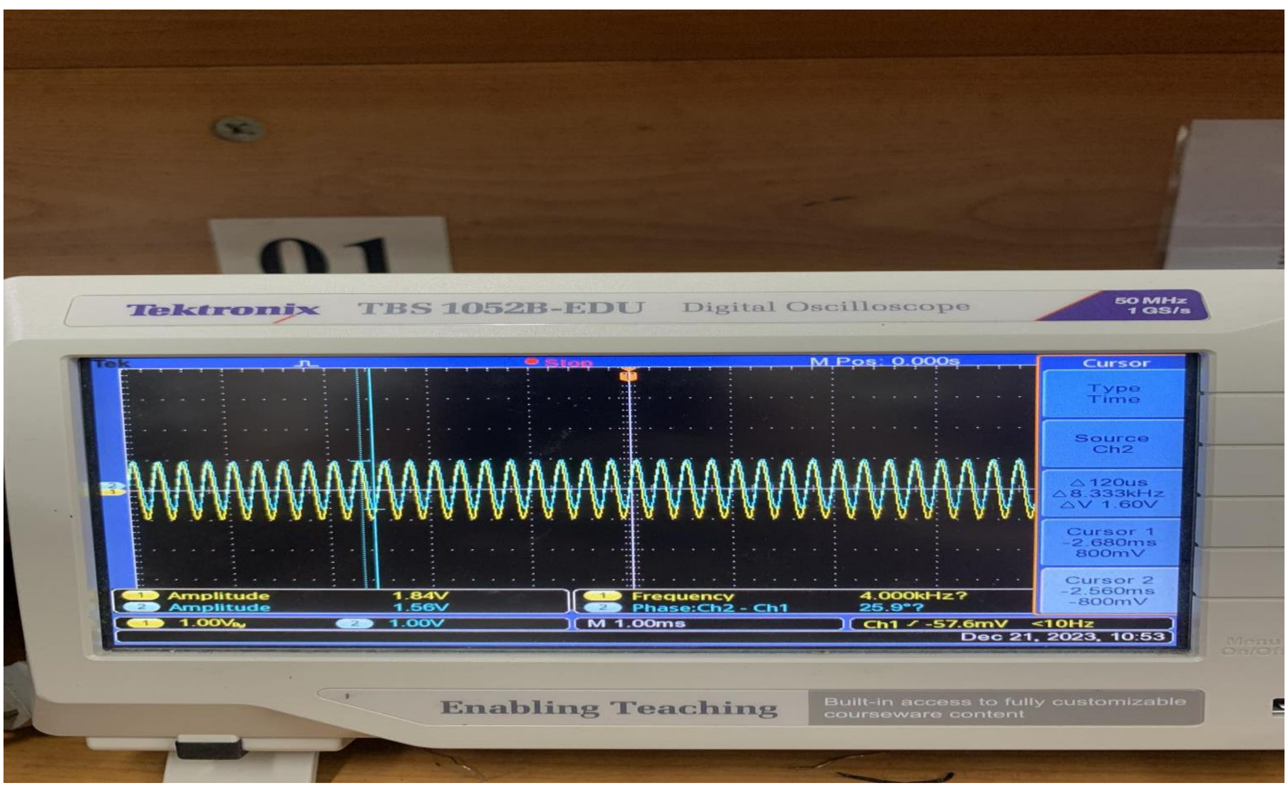


Figure 18 . Measurement result for 4000 Hz

Table 3. Simulation and measurement result by measuring phase shift

	Simulated	Measured	Simulated	Measured	Simulated	Measured
f (Hz)	1000		2000		4000	
Period: **T** (ms)	1	1.04		0.54		0.26
Time delay $\Delta \boldsymbol{t}$ (us)	48.414	16	36.45	9	36.452	19
Phase shift $\boldsymbol{\varphi}$ (°)	12.96	17.43	27.887	12.8	45.679	25.9
L (mH)	10.05	9.551	11.2	9.882	9.9	10.405

2.2 Determine value of an inductor by measuring its impedance

We use the same previous circuit.

2.2.1 Use the same circuit in order to measure the amplitudes **Vrms** in the terminals of the inductor by using multi-meters.

2.2.2 For **f = 1 k**Hz

a. Verify at the Oscilloscope that the Peak Amplitude of $\boldsymbol{v}(\boldsymbol{t})$ stays constant at **2 V**.

b. Complete Table 4 after measuring the voltage **Vrms**, then calculating **Irms**, by using a multi-meter in position (measuring effective values - rms: root-mean-square). At last, calculate the value $|Z_L|$ and deduce the value of the inductance L.

$$|Z_L| = \frac{V_{c.rms} \sim V}{I_{c.rms} \sim mA}$$

$$|Z_L| = 2\pi f L => L =$$

	Simulated	Measured	Simulated	Measured	Simulated	Measured
f (Hz)	1000		2000		4000	
Vrms (V)	108.07	88.95	216	156.23	432	402
Irms (A)	1.72	1.35	1.72	1.256	1.72	1.024
$\boldsymbol{|Z_c|} = \frac{\boldsymbol{V_{rms}}}{\boldsymbol{I_{rms}}}$ (Ω)	62.832	64.834	125.66	124.203	251.327	392.578
L(mH)	10	10.89	10	10.453	10	10.56

Table 4: Simulation and measurement result its impedance

Comment on the results:

The experiment aimed to determine the inductance (L) of an inductor by measuring its impedance across varying frequencies. The results closely aligned with theoretical expectations and the nominal inductance value, affirming the relationship between inductive reactance and frequency. Minor discrepancies can be attributed to practical factors such as measurement precision and real-world inductor properties. Overall, the experiment validated the method for calculating inductance in an RL circuit and reinforced the theoretical principles governing inductors in AC circuit

Discussion of Results

1. **For RC circuit:**

In this section, we aimed to measure the unknown capacitance of a capacitor using phase shift and impedance methods. The observed trend of decreasing phase shift with increasing frequency aligns with theoretical expectations. However, both methods yielded measured capacitance values consistently higher than the simulated predictions across all frequencies.

The discrepancies between measured and simulated values may be attributed to several factors, including the inherent tolerances of the capacitor, environmental influences, and potential systematic errors in our measuring equipment. Additionally, the real-world performance of the capacitor could be affected by parasitic elements and non-idealities not considered in the simulation model.

The consistency in the variance of measured values across different frequencies and methods suggests that our experimental setup and the calibration of measurement instruments may need refinement. Moreover, this highlights the divergence between theoretical models and actual component behavior, emphasizing the necessity of empirical validation in circuit design.

In conclusion, the experiment underscores the importance of accounting for practical variables and potential measurement inaccuracies when determining the characteristics of electronic components.

2. **For RL circuit:**

In our experiment, we aimed to identify the inductance of an unknown inductor using two methods: phase shift measurement and impedance calculation. The phase shift method involved recording the time delay at various frequencies to determine the phase angle. The impedance method involved measuring the RMS voltage across the inductor to calculate its impedance and, subsequently, its inductance.

The results obtained from both methods showed some inconsistencies with the simulated values, particularly at higher frequencies. These discrepancies could be due to various factors such as equipment calibration issues, measurement errors, or the inductive reactance's frequency dependence.

Despite these variations, the data consistently indicated an inductance value in close proximity to the theoretical expectations. This reinforces the effectiveness of using phase shift and impedance measurements to determine the inductance of an inductor within an RL circuit.

The experiment highlights the importance of practical validation in circuit analysis and the need to account for potential deviations when working with real-world components. The slight differences between simulated and measured values remind us of the complexities involved in electronic design and the necessity of empirical testing to complement theoretical studies.