Department of

Electrical & Electronics Engineering

# Abdullah Gül University

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## Project Report

## EE1200 Electronic System Design (ESD) Capsule

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**Submitted on:** 16.06.2023

**Submitted by:** Serkan KIYAKLI 2111011078

**Group Number/Name:** ASH

**Group Partner:**

Aliye Birgül
2111011070

Hasbi Mert Beyaz
2111011020

**Grade: / 100**

## OBJECTIVE

In this project, we are required to fabricate cylindrical and toroidal inductors. For the cylindrical inductors, wind one around a dielectric material and the other around a ferromagnetic material. Similarly, for the toroidal inductors, wind one around a dielectric material and the other around a ferromagnetic material. We took clear photographs of the fabricated inductors and provide information such as winding number, length, diameter, and an educated guess of the relative permeability of the core material. Next, design circuits to measure the current passing through both types of inductors and report the measured values. Additionally, we designed a circuits to measure the inductance values of the solenoids and toroid's and report those values as well. Then, we compare the theoretical inductance values with the experimental results obtained in the experimental part. In a hypothetical part, we are given a solenoid wound around a core material with a time-dependent relative magnetic permeability and wire density. We calculate the total inductance of the solenoid as a function of time and determine the voltage on the inductor for a given current waveform. Also, we calculate the voltage at an arbitrary point on the solenoid as a function of position and time, analyzing its critical points. Lastly, we consider a finite solenoid and compute the magnetic field along its central axis at a specific point, given the relevant parameters. We determine the point at which the magnetic field has the maximum value. Additionally, we provide a comprehensive report detailing our findings, including photographs, experimental measurements, theoretical calculations, and analysis of discrepancies, as well as the mathematical analysis of the hypothetical scenarios.

## BACKGROUND

In this project, we fabricate and make analysis of cylindrical and toroidal inductors are explored. For the cylindrical inductors, known as solenoids, we used magnet wire in order to wind around cardboard(dielectric material) cylinder and metal(ferromagnetic material) cylinder to provide solenoid. On the other hand metal washer are used and attached together to give toroid thickness for the ferromagnetic toroid we and for the dielectric toroid we used plastic ring which has a thickness as metal washer. Also, in our experiments we used 10 ohm resistor in order to make our circuit.

## ANALYTICAL AND SIMULATION PROCEDURES

### Part 1 – Fabrication of cylindrical inductors

For this task, we fabricated two different solenoid inductors. We used insulator-coated conductive wires, cardboard and ferrous material. We wound materials with wires.

*Figure 1: non-Ferro solenoid*

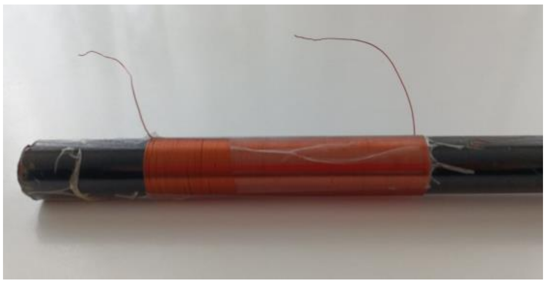

*Figure 2 : Ferro Solenoid*

Their properties are as follows,

| Type | Winding | Diameter | $\mu_r$ | $l$ength |
|---|---|---|---|---|
| Non-Ferro | 90 | 2 cm | | 10 cm |
| Ferro | 270 | 1.8 cm | | 11cm |

To find relative permeability of materials that we used, we calculated their inductance by using LCR meter, and we compared their experimental values and theoretical values.


*Figure 3 and 4 for measuring inductance of ferro solenoid*

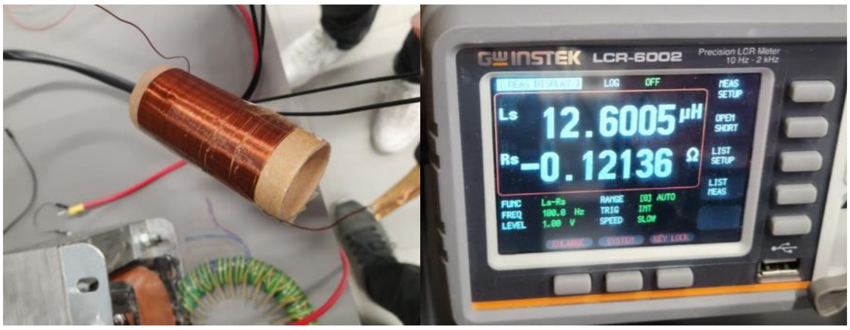


*Figure 5 and 6 for measuring inductance of non-ferro solenoid*

For the theoretical value of inductance of solenoids, we can use the following formula,

$$L = \frac{(\mu_r)\mu_0 N^2 A}{l} \tag{1.1}$$

| Type | Theoretical Value of Inductance | Experimental Value of Inductance |
|---|---|---|
| Ferro | 0.00021192373 H | 3.002 $mH$ |
| Non-Ferro | 0.00003197751 H | 12.60 $\mu H$ |

## Part 2 – Fabrication of toroidal inductors

For this task, we fabricated two different toroid inductors. We used insulator-coated conductive wires, a plastic circular material and ferrous material as circular . We wound materials with wires.

*Figure 7 : non-Ferro toroid*

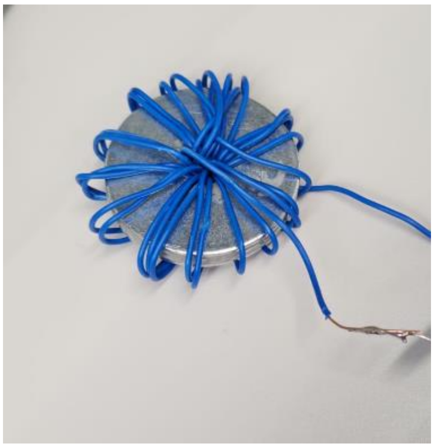

*Figure 8 : Ferro toroid*

Their properties are as follows,

| Type | Winding number | Inner Radius | Outer Radius | $\mu_r$ | Thickness |
|---|---|---|---|---|---|
| Non-Ferro | 208 | 1 cm | 1.5 cm | | 0.4cm |
| Ferro | 30 | 0.2 cm | 2.3cm | | 0.5cm |

To find relative permeability of materials that we used for the fabrication of toroids, we calculated their inductance by using LCR meter, and we compared their experimental values and theoretical values.

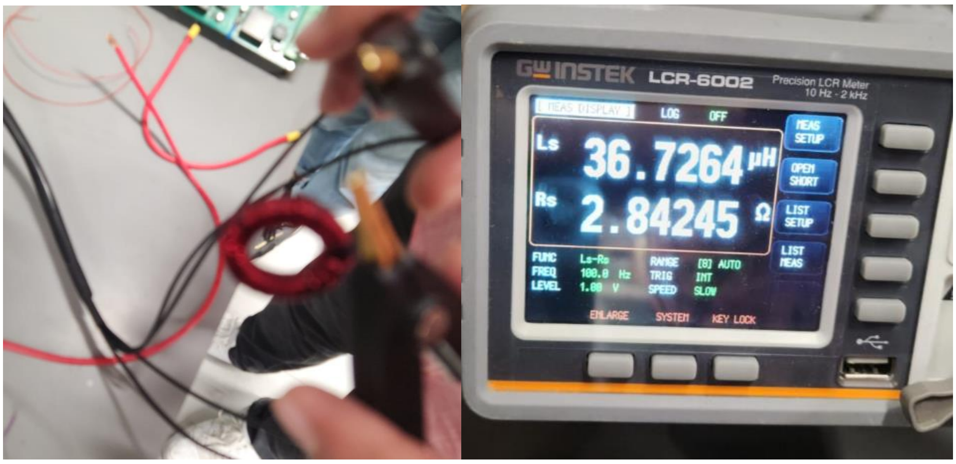


*Figure 9 and 10 for measurement of non-ferro toroid*

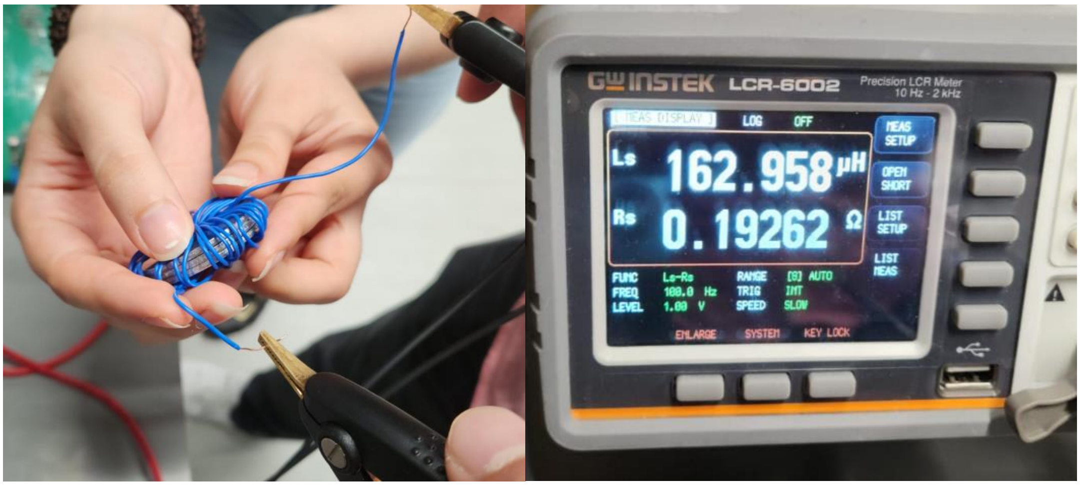


*Figure 11 and 12 for measurement of ferro toroid*

For the theoretical value of inductance of toroids, we can derive the formula,

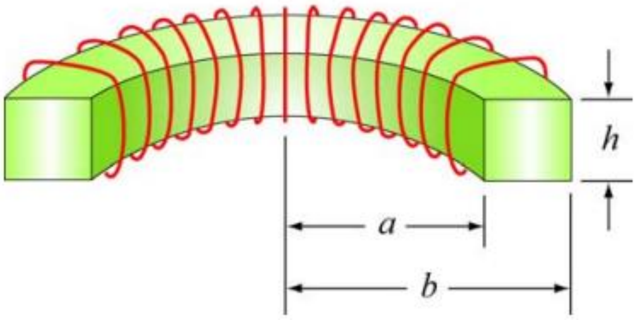


*Figure 13 : A toroid*

To find self-inductance, first we should look at its magnetic field. Due to the symmetry, magnetic field must be circular. Thus applying Ampere's Law,

$$\oint \overrightarrow{B}.d\vec{s} = \mu_r\mu_0 I_{enc} \quad 2.1$$

$$B(2\pi r) = \mu_r\mu_0 NI \quad 2.2$$

This gives us,

$$B = \frac{\mu_r\mu_0 NI}{2\pi r} \quad 2.3$$

The magnetic flux of one turn can be obtain by integrating over the cross section, with $dA = hdr$

$$\phi_B = \int \overrightarrow{B}.d\vec{A} \quad 3.1$$

$$\phi_B = \int \frac{\mu_r\mu_0 NI}{2\pi r} hdr \quad 3.2$$

$$\phi_B = \frac{\mu_r\mu_0 NIh}{2\pi} \int_a^b \frac{1}{r} dr \quad 3.3$$

As a result we get,

$$\phi_B = \frac{\mu_r\mu_0 NIh}{2\pi} \ln\left(\frac{b}{a}\right) \quad 3.4$$

And the total inductance for N turn is $N\phi_B$. The self-inductance is,

$$\frac{N\phi_B}{I} = \frac{\mu_r\mu_0 N^2 h}{2\pi} \ln\left(\frac{b}{a}\right) \quad 3.5$$

$$L = \frac{(\mu_r)\mu_0 N^2 h}{2\pi} \ln\left(\frac{b}{a}\right) \quad 3.6$$

| Type | Theoretical Value of Inductance | Experimental Value of Inductance |
|---|---|---|
| Non-Ferro | 14.01753 uH | 36.72 $\mu H$ |
| Ferro | 2,82743 uH | 162.9 $\mu H$ |

## Part 3

### Sub-Section A – Measurement of current passing through inductors

To measure the current passing through inductors, we use the method that is giving sine signal through pure inductive circuit and measuring maximum current via AC Ammeter.

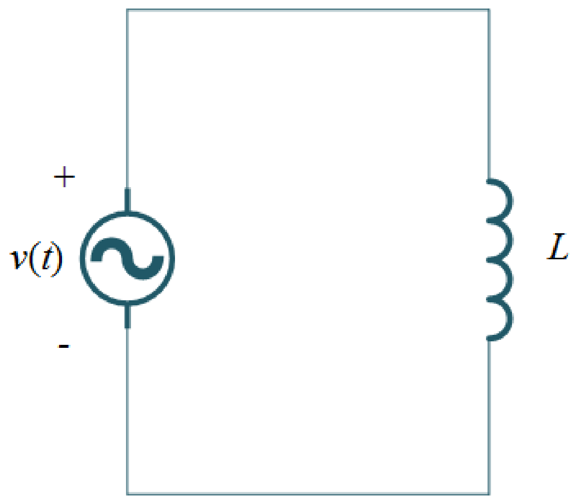


*Figure 14 : Pure inductive circuit*

Assume that $v(t) = V_m \sin \omega t$, applying KVL we get,

$$V_m \sin \omega t - L\frac{di}{dt} = 0 \qquad 4.1$$

$$V_m \sin \omega t = L\frac{di}{dt} \qquad 4.2$$

$$\frac{di}{dt} = \frac{V_m}{L} \sin \omega t \qquad 4.3$$

$$\int di = \int \frac{V_m}{L} \sin \omega t \, dt \tag{4.4}$$

$$i(t) = \frac{V_m}{\omega L}(-\cos \omega t) \tag{4.5}$$

We can write $\sin \omega t - \frac{\pi}{2} = -\cos \omega t$

$$i(t) = \frac{V_m}{\omega L} \sin \omega t - \frac{\pi}{2} \tag{4.6}$$

Here maximum current is,

$$I_m = \frac{V_m}{\omega L} \tag{4.7}$$

And $\omega L$ is inductive reactance as $X_L$.

In the Lab, we found something interesting. First we directly applied sine signal to our inductors, and we measured the current by using AC Ammeter. The AC Ammeter measures the RMS value of current. So that our RMS value of voltage is nearly 0.707 V.

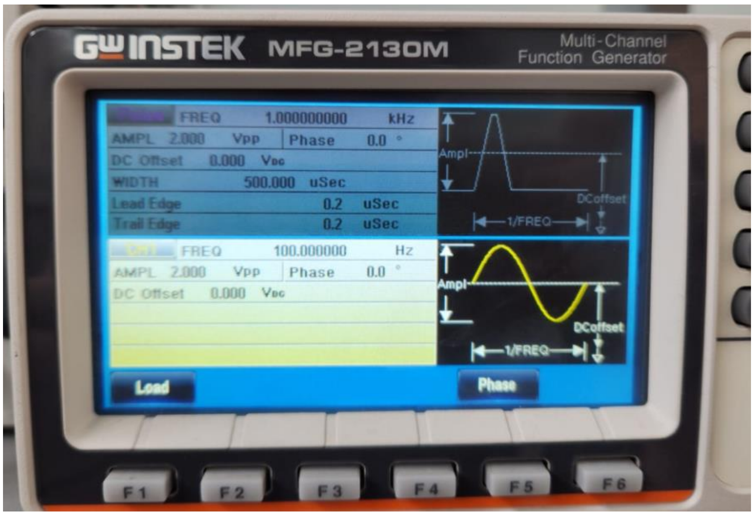


*Figure 15 : Properties of signal generator for the circuit*

First we measured the current passing through the ferro solenoid. From the formula 4.7 we should have seen that a current which is, (100 Hz frequency and our $X_L$ is 1.89Ω)

$$I = \frac{0.707}{1.89} \quad 5.1$$

$$I = 0.374\ A \quad 5.2$$

But we did not see this value on the ammeter.

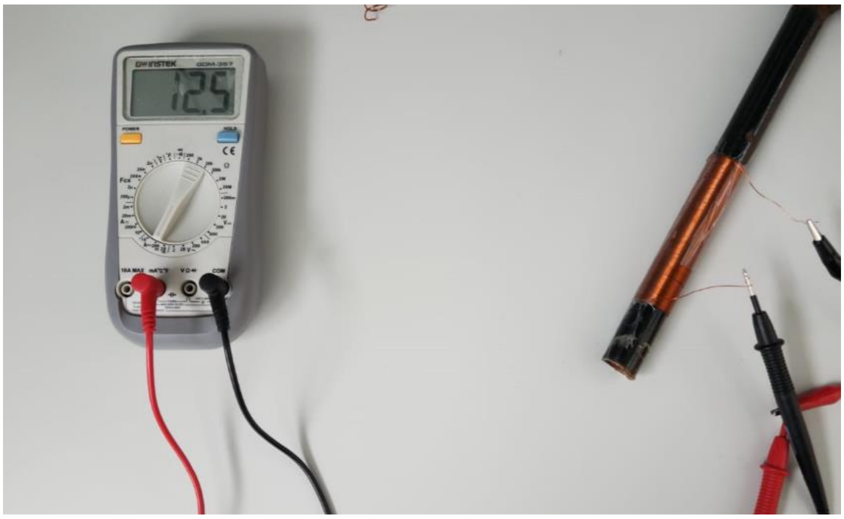


*Figure 16 : Current measurement of Ferro solenoid*

From this suspicion we decided to simulate the same circuit on the Proteus.

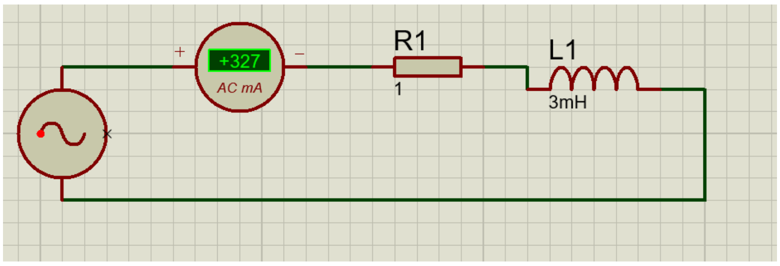


*Figure 3*

We should have seen this figure on the AC Ammeter. But in Proteus we saw 327mA. Then we consider inner resistance as 50 ohm. Then we change the resistance, we saw this figure

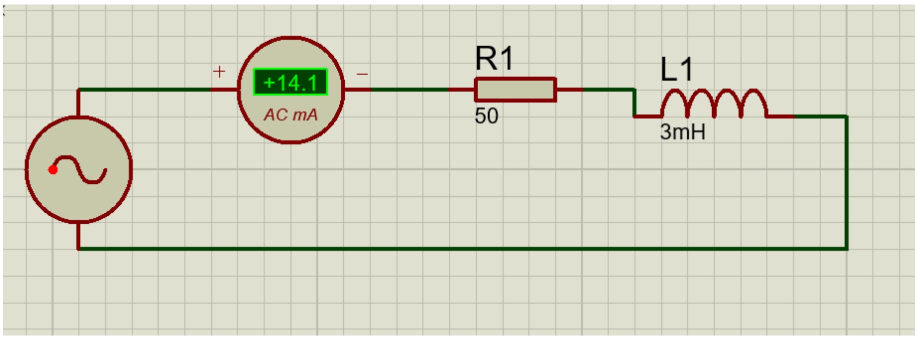


*Figure 17: Simulation representation of current measurement*

As we saw close number.

Other measurements are as follows,

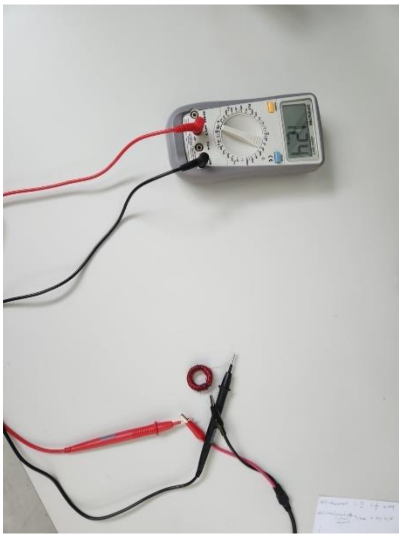

*Figure 18*

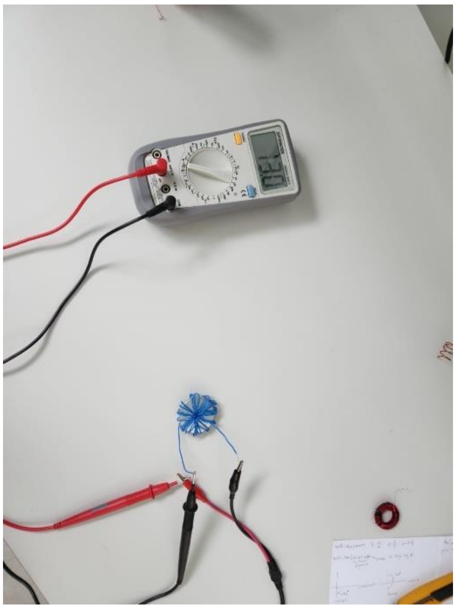

*Figure 19*

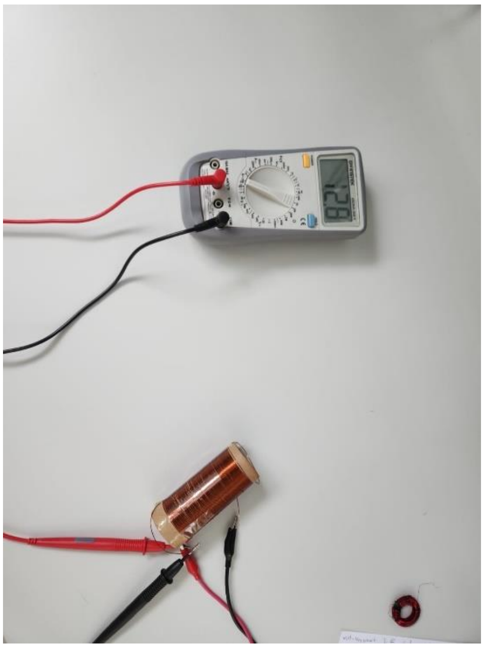

*Figure 20*

To measure the inductances, we use transient analysis in small segments of square wave signals.

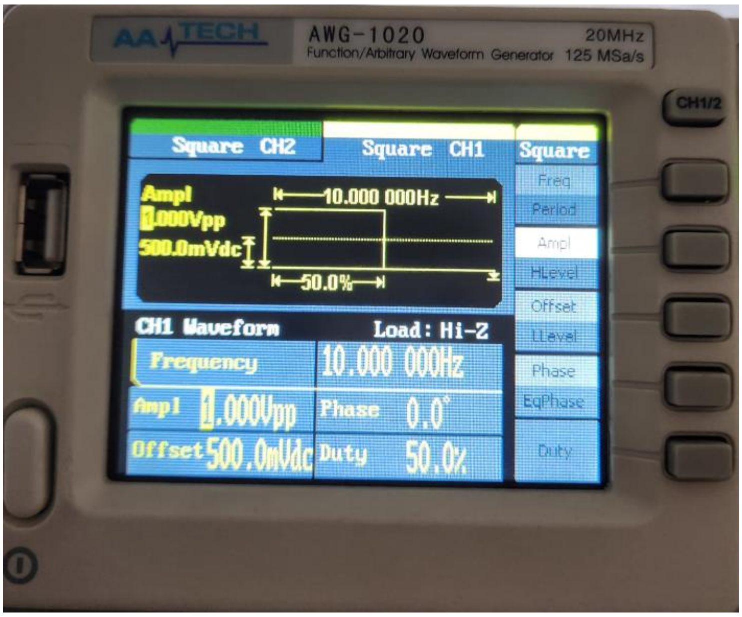


*Figure 21 : Square wave signal used for measuring*

After doing experiments, measurements on the oscilloscope are as follows:

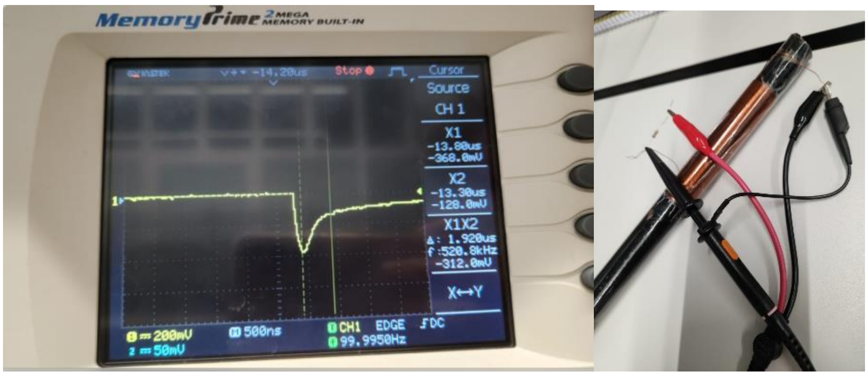


*Figure 22 and 23*

For the ferro solenoid we used 1.5k resistor (its real value is 1489). And our graph value increased with one time constant, we know that

$$\tau = \frac{L}{R} \tag{6.1}$$

$$1.9us = \frac{L}{1489} \tag{6.2}$$

As a result the inductance value is 2.8mH

If we do the same process for the others, we get

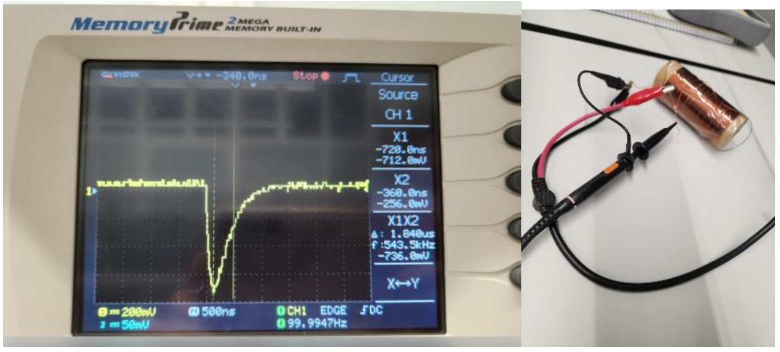


*Figure 24 and 25 : Measurement of inductance with 550 ohm resistor*

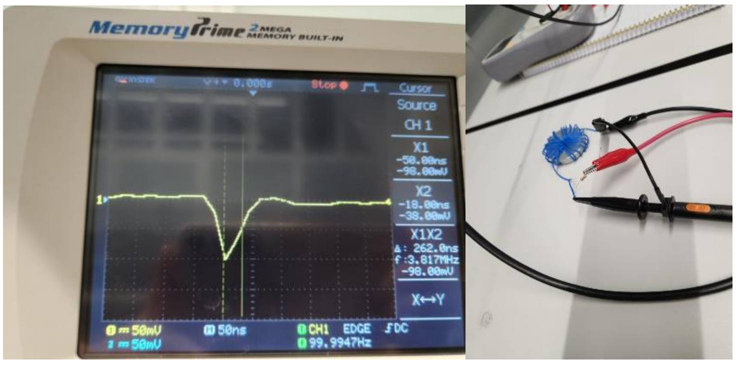


*Figure 26 and 27 Measurement of inductance with 1.5kohm resistor*


*Figure 28 and 29 : Measurement of inductance with 550 ohm resistor*

We used the same value of resistance. From time constants,

| Type | Time constant | Resistance | Inductance |
|---|---|---|---|
| Ferro Solenoid | 1.9us | 1489Ω | 2.8mH |
| Non-Ferro Solenoid | 1.84us | 550Ω | 1mH |
| Ferro Toroid | 262ns | 1489Ω | 390uH |
| Non-Ferro Toroid | 1.310us | 550Ω | 720uH |

## Part 5A

### Sub-Section A – Computing Inductance of a Solenoid

The inductance per unit length of a solenoid with a varying relative magnetic permeability can be expressed as:

$$L(z,t) = \frac{\mu_0 \mu_r N^2 A}{l} \qquad 7.1$$

where $\mu_0$ is the vacuum permeability ($4\pi \times 10$^(-7) T·m/A), $\mu r(t)$ is the relative magnetic permeability as a function of time, $A$ is the cross-sectional area, and $l$ is the length of the solenoid.

We can calculate the total inductance by integrating over the length of the solenoid. However, the number of turns N should be represented as a total number along the solenoid length, not a density. Given N(z, t) = 2z as a density, we can express total number of turns as from your given, the relative magnetic permeability μr is a function of space and time given by μr(z,t) = 4t + 5z and the density of the wires (number of turns per unit length) N(z,t) = 2z

$$N_T = \int_0^L N(z,t)dz \qquad 7.2$$

$$N_T = \int_0^L 2zdz \qquad 7.3$$

$$N_T = L^2 \qquad 7.4$$

The total inductance $L_t(t)$ as a function of time $t$ is given by:

$$L_t(t) = \int_0^l L(z,t)dz \qquad 7.2$$

Integration over $dz$ can be explain as this,

The integration over z (represented as z = 0 to z = L) in the calculation of the total inductance is performed because we are considering the contribution of each small segment of the solenoid along its length.

In the context of a solenoid, the inductance per unit length L(z,$t$) is a function that can vary with position z along the solenoid. By integrating L(z, t) over the length of the solenoid, we are essentially summing up the contributions of these small segments to obtain the total inductance.

The integral in 4.7 is performed to add up the inductance contributions from z = 0 (the starting point of the solenoid) to z = L (the end point of the solenoid). This integration takes into account the varying inductance values at different positions along the solenoid, which arise from the function $L(t, z)$ or $\mu_r(t)$ at each position $z$.

Substituting the expression for $L(t)$, we have:

$$L_t(t) = \int_0^l \frac{\mu_0\mu_r N^2 A}{l} dz \qquad 7.3$$

Since the density of wires $N(z,t)$ = 2$z$, we can express the cross-sectional area $A$ as:

$$A = 2z\left(\pi\frac{d^2}{4}\right) \qquad 7.4$$

Now, we can calculate the total inductance:

$$L_t(t) = \int_0^l \frac{\mu_0(4t+3z)L^4\left(\pi\frac{d^2}{4}\right)}{l} dz \qquad 7.5$$

$$L_t(t) = \frac{\pi\mu_0 d^2 L^4}{4l}\int_0^l (4t+3z)2z\, dz \qquad 7.6$$

$$L_t(t) = \frac{\pi\mu_0 d^2 L^4}{4l}\left(4tz^2 + \frac{6z^3}{3}\right)\Bigg|_0^l \qquad 7.7$$

Evaluating the definite integral, we have:

$$L_t(t) = \frac{\pi\mu_0 d^2 L^4}{4l}(4tl^2 + 2l^3) \qquad 7.8$$

Sub-Section B - If the current passing through this circuit is i(t) = 3, what is the voltage on the inductor?

We know that the relation between voltage and current on the Inductor,

$$V_L = L\frac{di(t)}{dt} \qquad 8.1$$

After arranging we get,

$$V_L = L\frac{d}{dt}\big(i(t)\big) \qquad 8.2$$

$$V_L = \frac{d}{dt}Li(t) \qquad 8.3$$

We know L and i(t),

$$V_L = \frac{d}{dt}\frac{3\pi\mu_0 d^2 L^3}{4}(4tL^2 + 2L^3) \qquad 8.4$$

$$V_L = 6\pi\mu_0 d^2 L^5 \qquad 8.5$$

Simplifying we get voltage on inductor,

$$V_L = 6\pi\mu_0 d^2 L^5 \qquad 8.6$$

Sub-Section C - Calculate the voltage at an arbitrary point on the inductor as a function z and t. Analyze its critical points as the functions of z and t.

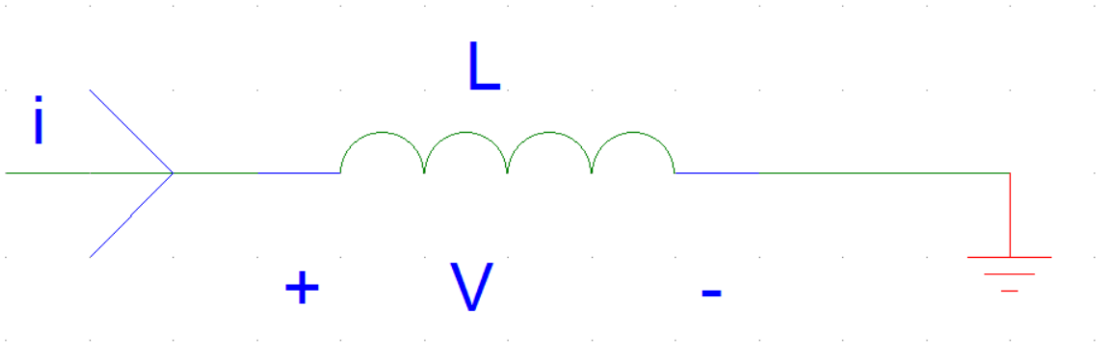


*Figure 30 : Inductor*

To obtain the inductance formula with respect to time and space, you would integrate the inductance per unit length over the spatial domain of time and space as multiple integrals. To express the inductance formula, you would integrate $L(t, z)$ over the desired range of positions. The integration with respect to space can be expressed as: (the reason for integral border is 0 to z is thinking that inductor's end is at origin and other end is at the arbitrary point on z)

$$L(z,t) = \int_0^t \int_0^z \mu_0 (4t + 3z) L^3 \left(\pi \frac{d^2}{4}\right) dzdt \quad 9.1$$

$$L(z,t) = \int_0^t tz\mu_0 \pi d^2 L^3 + \frac{3}{8}\mu_0 \pi d^2 L^3 z^2 dt \quad 9.2$$

After calculation we get,

$$L(z,t) = \frac{t^2 z \mu_0 \pi d^2 L^3}{2} + \frac{3}{8} t \mu_0 \pi d^2 L^3 z^2 \quad 9.3$$

From figure 17, we can think that the z axis is parallel to the inductor, it is like placed on z axis. An arbitrary point on inductor will divide inductor two different part.

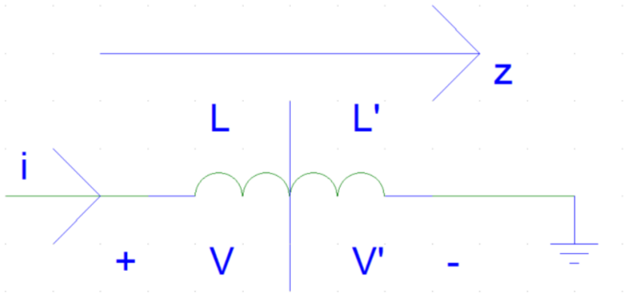


*Figure 31 : Inductor on z axis, and demonstration of voltage division*

We know that the total Voltage is $V_L = 3\pi\mu_0 d^2 l$. And the total inductance is $L_T = L + L'$

Now we can write the voltage on arbitrary point as,

$$V - V_z = L\frac{di(t)}{dt} \qquad 9.4$$

Arranging and simplifying we get,

$$6\pi\mu_0 d^2 L^5 - V_z = \frac{dLi(t)}{dt} \qquad 9.5$$

$$3\pi\mu_0 d^2 l - V_z = \frac{d}{dt}\frac{t^2 z\mu_0\pi d^2 L^3}{2} + \frac{3}{8}t\mu_0\pi d^2 L^3 z^2 \qquad 9.6$$

$$3\pi\mu_0 d^2 l - V_z = tz\mu_0\pi d^2 L^3 + \frac{3}{8}\mu_0\pi d^2 L^3 z^2 \qquad 9.7$$

As a result the voltage on arbitrary point on inductor,

$$V(z,t) = 3\pi\mu_0 d^2 l - tz\mu_0\pi d^2 L^3 + \frac{3}{8}\mu_0\pi d^2 L^3 z^2 \qquad 9.8$$

Finding its critical values we should look at first derivatives,

$$V_z = \frac{3}{2}\mu_0\pi d^2 L^3 z \qquad 9.8$$

$$V_t = -z\mu_0\pi d^2 L^3 \qquad 9.8$$

We can see that the derivative with respect to t cannot be zero or cannot fail to exist. So that it does not have critical points.

## Part 5B

Solenoids are commonly used in experimental research requiring magnetic fields. There are some factors which affect the magnetic field that produced by the solenoid like consisting of N turns of wire tightly wound over a length L. A current I is flowing along the wire of the solenoid.

In our question we have a wire, and this wire is wound over a L which is length. So we will produce a current we show it as

$$dI = \frac{NI}{L}\,\mathrm{dy} \qquad 10.1$$

$\frac{N}{L}$=The number of turns per unit length.

We used dy because the number of turns in an infinitesimal length dy are (N/L)dy turns.

We need to calculate the magnetic field at the P point. Firstly we know that the center of solenoid is equal to our P point.

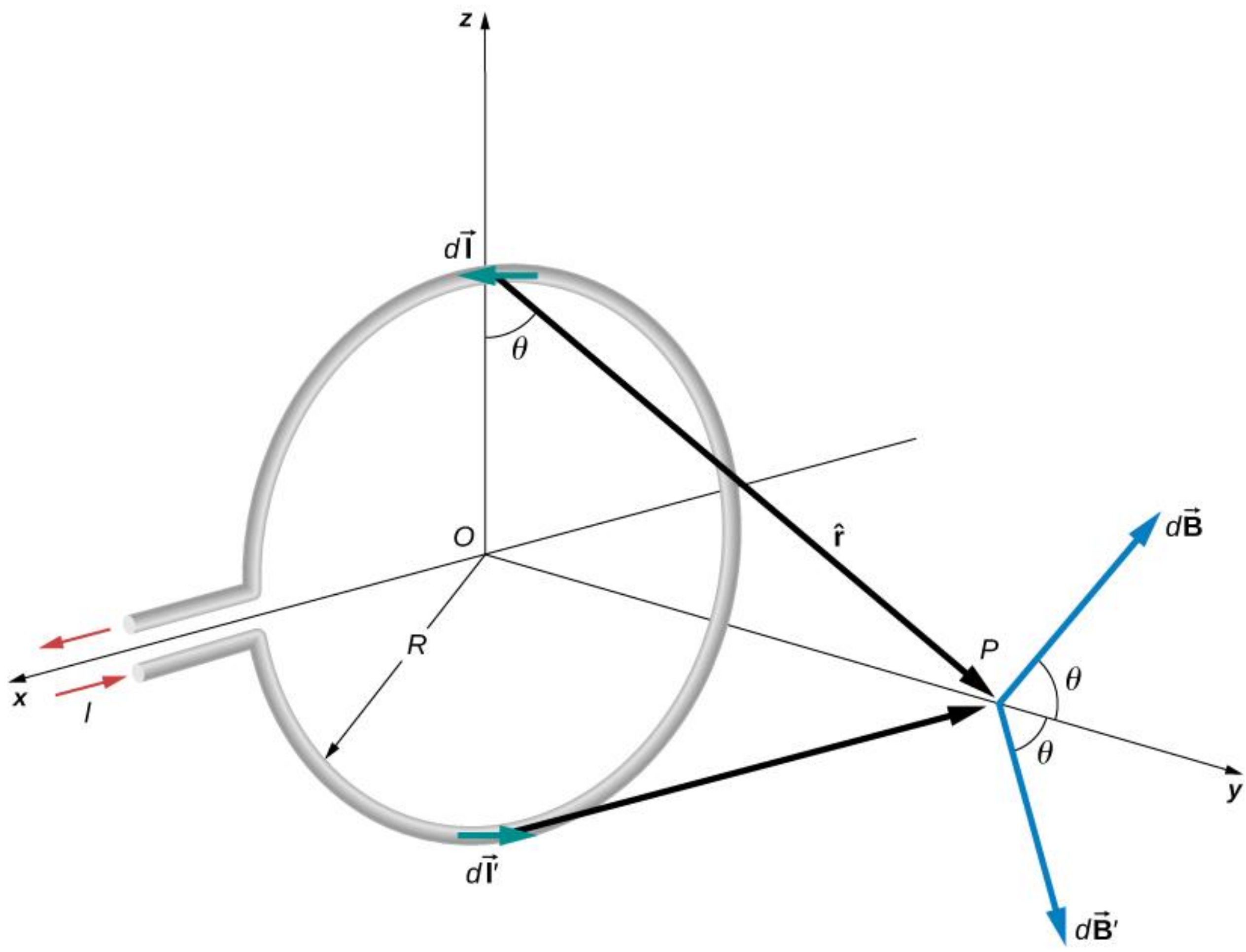


*Figure 32*

Let P be a distance y from the center of the loop. From the right-hand rule, the magnetic field $dB$at P, produced by the current element $I\ d\ l$ is directed at an angle θ above the y-axis as shown.

P point we know that because its infinitely long solenoid.

We know that dB is equal to:

$$dB = \frac{\mu}{4\pi}.\frac{IdLxr}{r^2} \qquad 10.2$$

$$r = y^2 + R^2 \qquad 10.3$$

We know r is a unit vector so we can write it as 1 and according to the cross product we get:

$$dB = \frac{\mu}{4\pi}.\frac{Idlsin\theta}{r^2} \quad 10.4$$

$$dB = \frac{\mu}{4\pi}.\frac{Idlsin\theta}{y^2 + R^2} \quad 10.5$$

$$dB = \frac{\mu}{4\pi}.\frac{Idl}{y^2 + R^2} \quad 10.6$$

Now we need to consider magnetic field dB due to the current element IdI so dB will be:

$$B = j \int_0^{2\pi} dB.cos\theta \quad 10.7$$

$$j\,\mu \frac{I}{4\pi} \int \frac{cos\theta dl}{y^2} + R^2 \quad 10.8$$

But we need to consider about one more thing that is the angle:

$$cos\theta = \frac{R}{\sqrt[2]{y^2 + R^2}} \quad 10.9$$

So we get

$$B = j\,\mu \frac{IR}{4\pi \sqrt[\frac{3}{2}]{y^2 + R^2}} \int dl \quad 10.10$$

$$\int dl = 2\pi r \quad 10.11$$

Also we know that if we have a closed loop a magnetic dipole of moment

$$\mu = IAn \tag{10.12}$$

$$A=\pi R^2 \text{ and } j = n \tag{10.13}$$

So according to those information magnetic field on the P will be

$$B = \mu 0 \mu \frac{j}{2\pi (y^2 + R^2)^{\frac{3}{2}}} \tag{10.14}$$

We will use those equations to change the $dl$ .When we put the μ in this equation we get

$$B = \mu 0 \frac{jIR^2N}{2L(y^2 + R^2)^{\frac{3}{2}}} dy \tag{10.15}$$

This integral by changing the independent variable from *y* to θ. From inspection of the figure which is blow , we have:

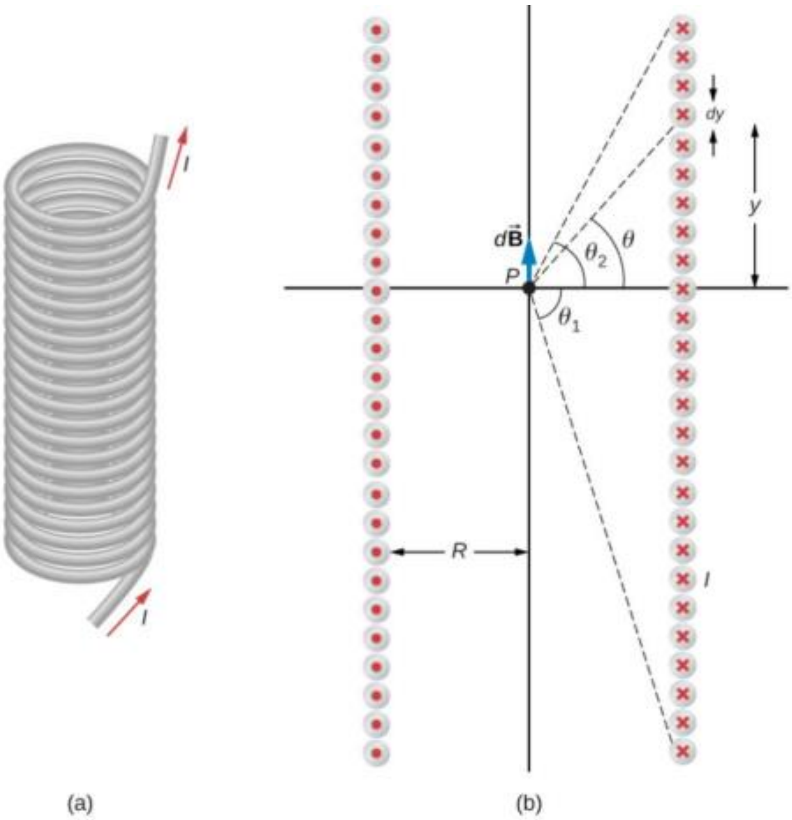


*Figure 34*

$$\sin\theta = \frac{y}{\sqrt{y^2 + R^2}} \qquad 10.16$$

Now we will take the derivative of both side and we get:

$$\cos\theta = -\frac{y^2}{y^2 + R^{2\frac{3}{2}}} + \frac{1}{\sqrt{y^2 + R^2}}dy \qquad 10.17$$

$$= \frac{R^2 dy}{(y^2 + R^2)^{\frac{3}{2}}} \qquad 10.18$$

When this is substituted into the equation for dB we will get :

$$B = \mu \frac{I0N}{2L} \int_{Q1}^{Q2} cos\theta d\theta = \qquad 10.19$$

$$B = \mu \frac{I0N}{2L} . (\sin(\theta 2) - \sin(\theta 1))\mathrm{j} \qquad 10.20$$

Behavior of the solenoid when **L** goes to $\boldsymbol{infinity}$ we can easily think that L≥R. In that case according to this information we can say that $Q1 = -\frac{\pi}{2}$ and $Q2 = \frac{\pi}{2}$

So equation will be

$$B = \mu \frac{I0N}{2L} . \left(\sin\left(\frac{\pi}{2}\right) - \sin\left(-\frac{\pi}{2}\right)\right)\mathrm{j} \qquad 10.21$$

$$B = \mu 0 . n . I . j \qquad 10.22$$

**RESULTS AND DISCUSSION**

Part 1, Part 2 and Part 4)

In these parts of the project, we fabricated two solenoids and two toroids inductors. As it is known, fabrication of inductor is difficult in terms of winding process, so we were careful about it. After getting experimental value of the inductances, we calculated the inductance theoretically by using the formulas which is for the solenoid inductance and toroid inductance.

| Types | Theoretic value of inductances with educated guess | Experimental value of inductances |
|---|---|---|
| Ferromagnetic solenoid | 21,19mH | 3.002 $mH$ |

| | | |
|---|---|---|
| Non-ferromagnetic solenoid | 32.60 $\mu H$ | 12.60 $\mu H$ |
| Ferromagnetic toroid | 2,82743 uH | 162.9 $\mu H$ |
| Non-ferromagnetic toroid | 14.01753 uH | 36.72 $\mu H$ |

For the fabrication of ferromagnetic solenoid, we paid attention about the material we will use as a core should be ferromagnetic. So, we used iron bar, and it was attracted by the magnet. However, we are thinking that it is not a pure iron bar.

As it can be seen, there are differences between the theoretic and experimental values of inductances. For the ferromagnetic solenoid, the difference may be due to the structure of iron bar. The iron bar we used was painted and a little rusty. In the sources, the relative permeability of iron is 20 * $10^5$ but it has 99.95% pure. Since we did not think the bar is not pure iron, we made an educated guess, and it is nearly 100. By taking this value and write, we calculated theoretic value of inductance. It is a ferrite material but most probably it is mixture with some materials such as nickel zinc. This situation is also valid for ferromagnetic toroid. For the fabrication of toroid, we used scale which is attracted by the magnet. We determined its $\mu r$ as nearly 1500 with educated guess and we calculated theoretically.

For the nonferromagnetic solenoid and toroid, since these are non-ferromagnetic material, our $\mu r$ value is nearly 1.

These differences also may depend on windings irregularity and radius, length measurement margin of error.

Part 3)

In this part of the project, we were asked to design a circuit in order to measure the inductance values of solenoids and toroids and to measure the current passing through inductors. To measure current, by giving sine signal and applying KVL to the circuit, we obtained current equation.

First, we applied sine signal to pure inductive circuit that has AC ammeter in series. Then we saw the figure which is 12.5 mA. Then, from theoretical figure which is 374 mA, we get the susception that function generator has a resistance as 50 ohms. Then, from Figure 17, we designed a circuit on proteus to prove the signal generator has a resistance. We proved 0 ohms resistance in front of the inductor, and we applied sine signal to it. Then we saw the figure which is 12.5 mA. Our susception was correct.

After that, we obtained other current values. The current values are nearly close to each other because the impedance of the circuit is nearly 50 ohms.

To measure the inductance values, we generated RL circuits with different resistor values. We used oscilloscope to obtain our $\tau$ values by using cursors. Then we calculated L values.

Part 5A)

For this of the project, we were asked to calculate total inductance of a solenoid that has changing parameters such as relative magnetic permeability and density of the wires as function of space and time. First, we considered that to find total winding number we should integrate the function of the density of the wires through inductor (0 to L). after that the total inductance L(t) as a function of time we integrated inductance formula over z direction . Because we thought the contribution of each small segment.

Secondly, to find the voltage on inductor we used the formula 8.1. In a standard circuit with a constant inductor, Ohm's law takes the form V = L di/dt, where V is the voltage across the inductor, L is the inductance, and di/dt is the rate of change of the current with respect to time. However, the inductance is not constant and instead changes with time so that we must arrange the formula. And we take both derivatives of the inductance and current as a function of time.

Finally, to calculate the voltage at an arbitrary point on the inductor as a space of time to obtain the inductance formula with respect to time and space we integrated the inductance over domain of time and space as multiple integrals. To express inductance formula we integrated L(z,t) over the desired range.

## CONCLUSIONS

In conclusion, the fabrication and analysis of inductors, specifically cylindrical and toroidal configurations, have been explored in this project. The cylindrical inductors and toroidal inductors are components used in a wide range of electronic systems. The choice of core material, such as dielectric or ferromagnetic, significantly impacts the inductance and magnetic properties of the inductors. Through the design and fabrication process, important parameters including winding number, length, diameter, and core material permeability were considered. Experimental measurements of current and inductance were performed to evaluate the performance of the fabricated inductors. The comparison between theoretical and experimental results in the analysis of inductors allowed for the identification of any discrepancies and potential sources of error. Factors such as variations in wire thickness or core material properties could be evaluated to understand their impact on the performance of the inductors. Theoretical analysis using mathematical formulas provided insights into the behavior of inductors and facilitated the calculation of expected inductance values.

Having a theoretical foundation served as a reference point for comparison with the experimental measurements, enabling a deeper understanding of how the fabricated components performed. Hypothetical scenarios were also considered, which involved exploring the behavior of inductors under specific conditions.

By engaging in this project, a comprehensive understanding of inductor fabrication, measurement techniques, theoretical calculations, and analysis of hypothetical scenarios was achieved. This knowledge can be utilized to optimize the design and performance of inductors for various applications in the field of electronics.

## REFERENCES


http://www.phys.boun.edu.tr/~burcin/Flux.pdf

https://en.wikipedia.org/wiki/Permeability_(electromagnetism)

http://physics.wku.edu/harper/files/apps/pla/examples/04-magnetic-field-solenoid.pdf