Harvesting EM Energy to Produce Electrical power

By

Loguya Michael Loku

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronic Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

AP. Dr. Varun Jeoti

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Your Supervisor's Name
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

December 2012

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Loguya Michael Loku

ABSTRACT

The desire to transfer power wirelessly is not a new phenomenon in today’s world. The idea has been driven by the need to diversify the traditional methods of using wires to transfer energy from one point to another. Wireless power transfer also plays a very important role in such a way that electronic devices such as cell phones and laptops could be charged wirelessly. The advancement in technology, the influx of electronic devices and the cost of cables is an alarm to influence the work on wireless power transfer. Wireless power transfer is mostly dependant on the property of magnetic induction. By selecting a specific resonant frequency of an induction circuit, energy can be transferred wirelessly from one circuit to another of the same resonating frequency. The result of this project shows that very little power can be transferred wirelessly using electromagnetic induction. However, improvements can be made to the circuits to obtain better results in the future.

ACKNOWLEDGEMENTS

First and foremost, I would like to thank God the almighty, the Most Merciful for keeping me in better health and giving me knowledge to complete this project work. And I also thank him for being my strength and guide in the writing of this report. Without him, I would not have had the wisdom or the physical ability to do so.

My grateful thanks also go to my supervisor, AP Dr Varun Jeoti. Without whose guidance, I wouldn't have accomplished the objective of this project. He was very instrumental and always there for me whenever I needed him. His advice and ideas were the corner stone to the success of this project.

I offer my heartfelt thanks to my family/parents although far away. They were always close to me in their thoughts and hearts, for their encouragement, faith, support, and love, and for always being there for me. I also thank Miss. Audrey Atukunda for being very encouraging and supportive during my final year of undergraduate studies.

At last, I would like to express my great appreciation to Universsiti Teknologi Petronas for giving me the chance to study in such an amazing environment with excellent infrastructure and staff and all levels.

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CHAPTER 1 INTRODUCTION

1.1-Background of study

Wireless power transfer is a new technology where power can be transferred over a distance from one point to another using coupled magnetic resonance. [1]

A group of research team from MIT was able to experiment this aspect of wireless power transfer and was able to get some promising result. Their result showed that power was able to be transferred from one point to another wirelessly. Up to 60W of power was transferred in their experiment and about 40% efficiency. [2]

1.2- Problem statement

This paper addresses the idea of how best to transfer the power available in the Electromagnetic waves generated by a source. And the other question is; can magnetically resonant circuits help in transferring power wirelessly?

Wireless power transfer is a better way to transfer power compared to the traditional methods of using wires or cables to transfer power, this is a better way since it will be cheaper than having to buy cables. With wireless power transfer, the need for cables is eliminated. Therefore, with this device installed in various appliances, one can be located at any point and be able to get power wirelessly assuming distance is not a problem.

1.3- Objective and scope

The objectives of this project are:

To attempt wireless power transfer from one point to another

To prove that electrical power can be transferred by magnetic resonance

To conduct dynamic tests for the system

1.4- Relevance of the project

This project is relevant in way that once successful, it makes it easier and simple to transfer energy from one point to another. Devices such as laptops can be powered from a remote location without having to use a power cable.

1.5- Feasibility of the project

This project is feasible in the sense that magnetic coupling exists and as such can be used to transfer power wirelessly.

By using the principle of mutual inductance, two inductors are capable exchanging electrical power between themselves. If an inductive coil is connected to a power source, an electric field will be generated in its surrounding. Therefore by principle if a second inductive coil is brought close to the first coil, it may have a voltage induced in it by capturing the magnetic field given off by the first coil. The current generated in the second coil may be used to power devices. This method of electrical power transfer from one loop or coil to another is based on the principle of magnetic induction. Some common examples or devices that base their functioning on this principle of magnetic induction are transformers and electric generators.

CHAPTER 2: LITERATURE REVIEW

Studies show that there are some promising results in this area of research. For wireless power transfer to take place. More current should be accumulated in the primary coil. It is this current that will create more electric field in its vicinity so as for sympathetic interaction to occur between the first and second coil. This high current will also produce more power in the primary coil and thus leading to more power in the secondary so as to have high efficiency. Electro-magnetic resonant coupling for wireless power transfer satisfies the above mentioned requirements for transmitting power based on strongly coupled magnetic resonance [2]

2.1- Basics of wireless power transfer

The basics of electricity and magnetism will make us understand better the theory of wireless power transfer

2.1.1-- Electricity:

Electricity or electric current is the flow of electric charge from one place to another. Often the charge is carried by electrons moving through a metal wire/conductor, or through space. This is how energy can be transferred from one point to another.

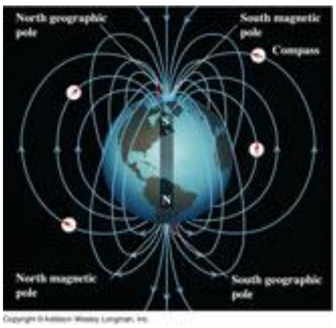


Figure 1: An illustration representing the earth's magnetic field

2.1.2- Magnetism

The study of magnetism usually leads us to think of certain objects (magnets) behave around each other. The effects f magnetism has been known for a very long time. Our very first experience with magnets always refers to the exploration of Permanent magnets or in other words bar magnets, how they can attract each other or repel. Also the earth's magnetic field; these are examples of objects having *constant* magnetic fields.

However, varying magnetic fields changes with change in time. When current is passed through a coil, it generates an electric field as shown below. Assuming that we change the direction of the current, the direction of the electric field will also change.

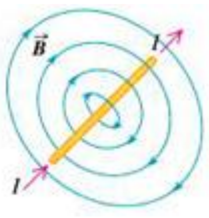


Figure 2: Magnetic field lines

2.1.3-Electromagnetism:

This is the scenario in which an electric field interacts with a magnetic field with variation in time. A variation in time of one produces the other. Say a varying magnetic field produces an electric field and a varying electric field produces a magnetic field.

2.1.4-Magnetic Induction:

Magnetic induction is the process by which a magnetic material becomes magnetized by a magnetic field. It is fair to say that for every electrical device that has wire windings in it, there is bound to be a magnetic induction process taking place in it for its operation. Take an example of a transformer, the transformer has primary and secondary windings in it but in close proximity, though there is no electrical connection between the two windings. It uses the property of magnetic induction for its operation. As mentioned earlier, when current is passed through a coil, it generates an electric field. Magnetic induction was discovered first in the 1830's by the physicist Michael Faraday. Faraday studied the fact that, if an electric current can generate a magnetic field then a magnetic field should also be able to generate an electric current. It is therefore this phenomenon that leads to the interaction between two coils, since the electric field generated in first coil will generate current in a second coil near by.

When we consider a coil of conducting wire with cross sectional area A, and placing it in an area of a known magnetic field B at a certain angle.[3] From the article published by Shakro Trubeckoi, The magnetic flux Φ_B through the coil is given by

$$\Phi_B = A B_\perp = A B \cos\theta. \qquad (1)$$

Where,

Φ_B= magnetic flux

A=cross-sectional area of the coil

B=magnetic field

If we make several loops of the coil (N turns), then the number of turns in the coil will have an effect on the resultant magnetic flux and is given by

$$\Phi_B = N\,A\,B_{\perp}. \tag{2}$$

On the other hand, if the loop does not have a uniform magnetic field, then the magnetic flux will determined by taking the integral of the magnetic field B.

$$\Phi_B = \int_S \mathbf{B} \cdot d\mathbf{S}. \tag{3}$$

Where S is the surface area attached to the magnetic field. For N turns, the magnetic flux will be the product of the integral value and the number of turns. Magnetic flux is measured in Weber.

Generally, magnetic flux is the measure of the number of magnetic field lines that cross a given area.

2.1.5-Faraday's Law

After looking at magnetic flux, it is easier to understand better Faraday's experiments. Faraday's experiment on magnetic induction revealed that when two coils interact, an emf is induced in a second coil. The induced emf causes a current in the secondary coil. According to R. Fitzpatric, Faraday finally discovered that an emf is generated around a loop which rotates in a uniform magnetic field of evenly distributed strength [5]. However he found out that the secondary coil only experiences an induced emf only when the magnetic flux through it changes with time. Furthermore, the induced emf is found to be proportional to the rate at which the flux changes with time.

Faraday's law states that;

The emf induced in a circuit is proportional to the time rate of change of the magnetic flux linking the circuit.

$$\mathcal{E} = \frac{d\Phi_B}{dt}. \tag{4}$$

2.1.6-Lenz's Law

Lenz's law is a modification of Faraday's law. It indicates the direction taken by the emf generated by the magnetic field between the two circuits. The diagram below shows the direction taken by the current as the magnetic field lines passes by.

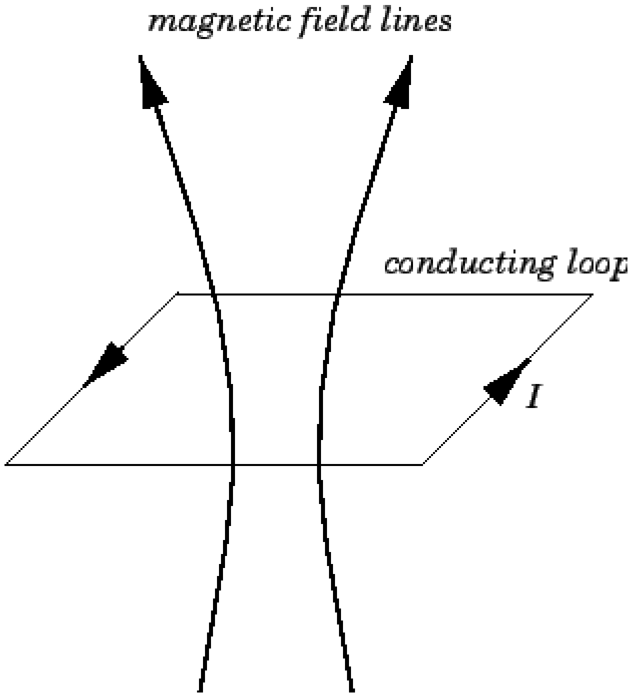


Figure 3: Magnetic field generated by a planar current-carrying loop.

Lenz's law was specified by a Russian scientist called Heinrich Lenz, hence Lenz's law. It states that;

The emf induced in an electric circuit always acts in such a direction that the current it drives around the circuit opposes the change in magnetic flux which produces the emf.

$$\mathcal{E} = -\frac{d\Phi_B}{dt}. \qquad (5)$$

The minus sign indicates that the emf always acts to oppose the change in magnetic flux which generates the emf. However, the minus has no effect since we are only concerned with the magnitude.

2.1.7-Self Inductance

Self inductance is when a coil is able to generate a magnetic flux by itself. As mentioned in the earlier sections, when current flows through a coil it tend to generate a magnetic field. And the resultant magnetic field generates a magnetic flux. The magnetic flux depends solely on the amount of current that passes through the coil. It is given by;

$$\Phi = L\, I, \tag{6}$$

Where L is the self inductance of the coil measured in Henries. The self inductance depends on the number of turns of coil and its length.

If the magnetic flux changes with time, then

$$d\Phi = L\, dI. \tag{7}$$

However from Faraday's law, (eqn 4)

$$\mathcal{E} = -\frac{d\Phi}{dt}$$

Therefore, ussing the above two eequations, the induced emf can be wrtten as,

$$\mathcal{E} = -L\,\frac{dI}{dt}. \tag{8}$$

If we have a coil of N turns and length L, with current I flowing through it, then the magnetic flux will be given by,

$$\Phi = N\,B\,A = \frac{\mu_0\, N^2\, A\, I}{l}. \tag{9}$$

We also know that the self inductance of a coil is given by L=Φ/I, therefore, it reduces to

$$L = \frac{\mu_0\, N^2\, A}{l}. \tag{10}$$

2.1.8-Mutual Inductance

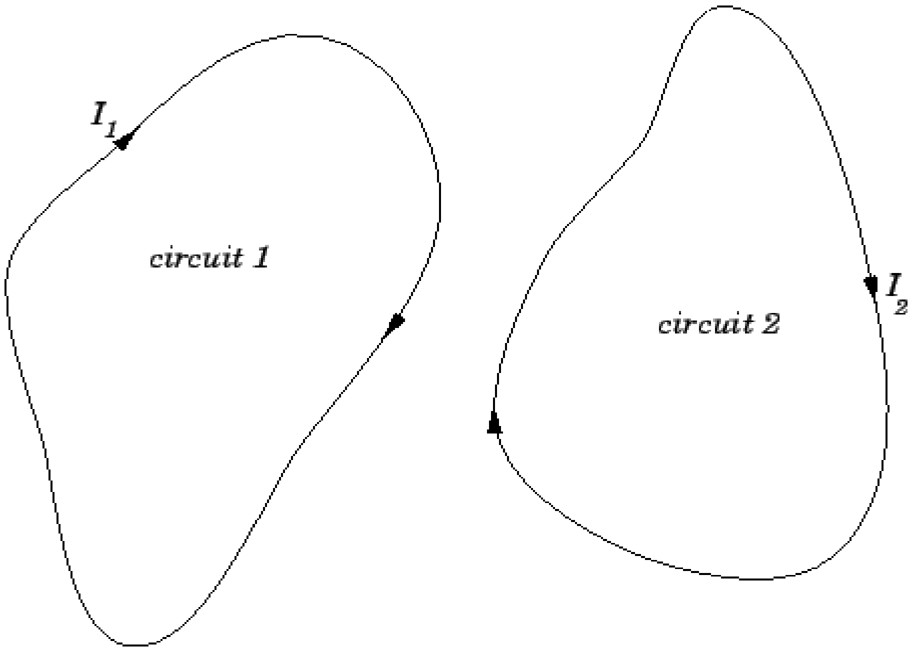


Figure 4: *Two inductively coupled circuits.*

Mutual inductance is generally the interaction between two inductive circuits. If current I_1 flows through the first circuit, it generates a magnetic field B_1. This magnetic field will then sympathetically link to the second circuit generating a second magnetic flux Q_2 [12]. The flux in the second coil depends on what happens in the first coil. It follows that the flux Φ_2 through the second circuit is directly proportional to the current I_1 flowing around the first circuit.[12] Therefore

$$\Phi_2 = M_{21}\, I_1, \tag{11}$$

Where M_{21} is the mutual inductance of second circuit with respect to the first circuit

It follows that,

$$\Phi_1 = M_{12}\, I_2, \tag{12}$$

Where M_{12} is the *mutual inductance* of circuit 1 with respect to circuit 2

When we consider a case where both mutual inductances with respect to each coil are the same, say; $M_{12}=M_{21,}$ then,

$$M_{12} = M_{21} = M, \tag{13}$$

Where M is the mutual inductance of the two coils, It is also is also measured in *Henries* similar to self inductance

If the current in the first coil changes by dI_1 in the interval dt, Suppose that the current flowing around circuit 1 changes by an amount dI_1 in a time interval dt, it follows from Eqs.(11) and (13) that the flux linking the second coil changes by $d\Phi_2=MdI_1$. From Faraday's law, an emf

$$\mathcal{E}_2 = -\frac{d\Phi_2}{dt}$$

(14)

is generated around the second coil. Since, $d\Phi_2 = M dI_1$, then the emf can also be written

$$\mathcal{E}_2 = -M\frac{dI_1}{dt}.$$

And similarly, (15)

$$\mathcal{E}_1 = -M\frac{dI_2}{dt}.$$

(16)

2.1.9-Energy/Power Coupling:

Energy coupling occurs when an energy source has a means of transferring power from one object to another via mutual inductance.

2.1.10-The Transformer

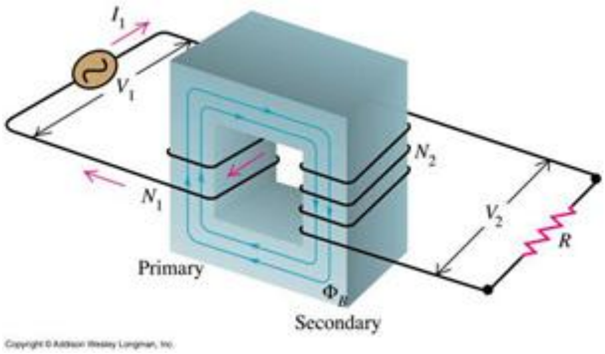


Figure 5: Circuit diagram of a transformer

A transformer is a device used to change voltage. It can be step up or step down transformer. In other words it either changes the voltage from a lower value to a higher value or from higher to lower value respectively [6]. As mentioned in section 2.1.4, the transformer consists of a primary and secondary side. However, the two sides are not electrically connected. They depend on the property of mutual inductance for energy to be transferred from the primary to the secondary side.

The magnetic field induced in the primary winding interacts with a second winding inducing an electric current in it. This way electric energy can be transferred one object to another without the two objects touching each other [6].

Figure 5 above shows the diagram of a transformer.

If an alternating voltage

$$v_1 = V_1 \cos(\omega t) \tag{17}$$

Is supplied to the primary coil, the current produced in the primary coil will be

$$i_1 = I_1 \sin(\omega t), \tag{18}$$

The current in the primary coil I_1 will then generate a magnetic field which will link with the secondary coil hence inductively generating the alternating emf in the secondary coil. The secondary emf is given by

$$v_2 = V_2 \cos(\omega t) \tag{19}$$

This voltage then drives an alternating current I_2 in the secondary coil given by

$$i_2 = I_2 \sin(\omega t) \tag{20}$$

The primary coil has the following equation,

$$v_1 - L_1 \frac{di_1}{dt} - M \frac{di_2}{dt} = 0, \tag{21}$$

Which gives

$$V_1 = \omega \left(L_1 I_1 + M I_2\right), \tag{22}$$

Since

$$\frac{d \sin(\omega t)}{dt} = \omega \cos(\omega t). \tag{23}$$

Similarly,

$$v_2 = L_2 \frac{di_2}{dt} + M \frac{di_1}{dt}. \tag{24}$$

And Equations (17), (18), (19), (20), and (24) yield

$$V_2 = \omega \left(L_2 I_2 + M I_1\right). \tag{25}$$

Therefore the external power supplied to the primary side will be given by

$$P_1 = i_1 v_1. \tag{26}$$

Similary

$$P_2 = i_2 v_2. \tag{27}$$

Assuming zero losses, then

$$i_1 v_1 = i_2 v_2, \tag{28}$$

Which gives

$$I_1 V_1 = I_2 V_2. \tag{29}$$

Equations (22), (25), and (29) will give

$$I_1 V_1 = \omega \left(L_1 I_1{}^2 + M I_1 I_2\right) = \omega \left(L_2 I_2{}^2 + M I_1 I_2\right) = I_2 V_2, \tag{30}$$

Which yields,

$$\omega L_1 I_1{}^2 = \omega L_2 I_2{}^2, \tag{31}$$

And hence,

$$\frac{I_1}{I_2} = \sqrt{\frac{L_2}{L_1}}. \tag{32}$$

Equations (29) and (32) can be combined to give

$$\frac{V_1}{V_2} = \sqrt{\frac{L_1}{L_2}}. \tag{33}$$

As stated earlier that the transfer of energy from the first to the second coil depends on the mutual inductance of the two coils, the peak voltages and currents are however determined by the self inductances of the individual coils.

We know that the self inductance of the coils are given by L1= $\mu_0 N_1^2 A/L$ and L2= $\mu_0 N_2^2 A/L$, respectively. Then

$$\frac{L_1}{L_2} = \left(\frac{N_1}{N_2}\right)^2, \tag{34}$$

And

$$\frac{V_1}{V_2} = \frac{I_2}{I_1} = \frac{N_1}{N_2}. \tag{35}$$

We can say that the ratio the turns of primary to seconday coil determines the ratio of the peak voltages and peak currents.

2.1.11-Resonance:

Whenever a physical system has a natural frequency, we expect it to find resonance when it is driven near that frequency. Resonance does exist in many different physical systems. It is that natural frequency at which energy can be transferred onto an oscillating system

2.1.12-Resonant Magnetic Coupling:

Two coils are expected to have magnetic coupling if they both have the same natural frequency. This happens when the two coils exchange energy via their magnetic fields. [3]

The figure below shows two similar resonant magnetic coils.

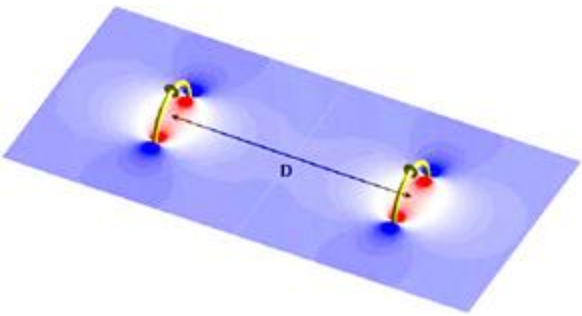


Figure 6: magnetic coupling between two loops

2.2-Theory of wireless power transfer system

Wireless power transfer is entirely dependant on coupled magnetic resonance utilizing the principle of electromagnetic induction. It consists of mainly two resonant coils. The two coils must have the same resonating frequency for coupling to take place. As shown on the block diagram in figure 7, there other parts that make up the wireless transfer system.

Source

This is an Ac power source that supplies the energy for the system. It can be an in house power source or a car battery in case the device is installed in cars.

Oscillator

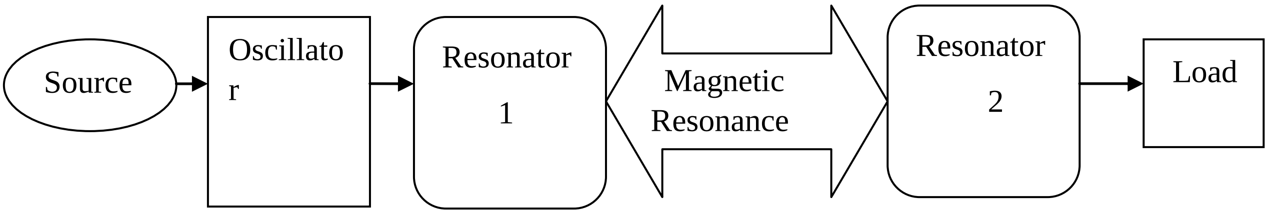
The oscillator is used to determine the natural frequency of the resonator/coil without which it would be hard to coupling to take place.

Resonator

There are two resonators/coils in the system. The first coil is connected to the oscillator so as to obtain the necessary energy. The second coil is then coupled inductively to the first coil for power transfer to take place. Both coils should however resonate at the same frequency.

Load

The load in this case can be any battery device that needs to be



Driving circuit Output circuit

Figure 7: Block diagram for wireless power transfer system

CHAPTER 3: METHODOLOGY

In this part, methodology and approach is being discussed in order to obtain the objective of this project. All the way through this semester, several activities have be done to accomplish the objectives of this project, from the work planning to the fabrication process in laboratory and testing.

Research is done by taking into account the literature reviews related to this project.

3.1-Project Activities

In the early stage of the project, research was done to gather information, facts, theories and fundamentals regarding the project. By studying books, journals, internet information and thesis, any relevant information is collected. The importance of the research activities is to have more understanding of what the project is all about.

3.2-Key milestones

a) Final year project I

- Extended proposal. (Week 6)
- Proposal defense. (Week 9)
- Interim draft report. (Week 13)
- Interim final report (week 14)

b) Final year project II

- Progress report due (week 8)
- Pre-EDX (week 11)
- Draft report due (week 13)
- Final Report due (week 14)
- Viva (week 15)

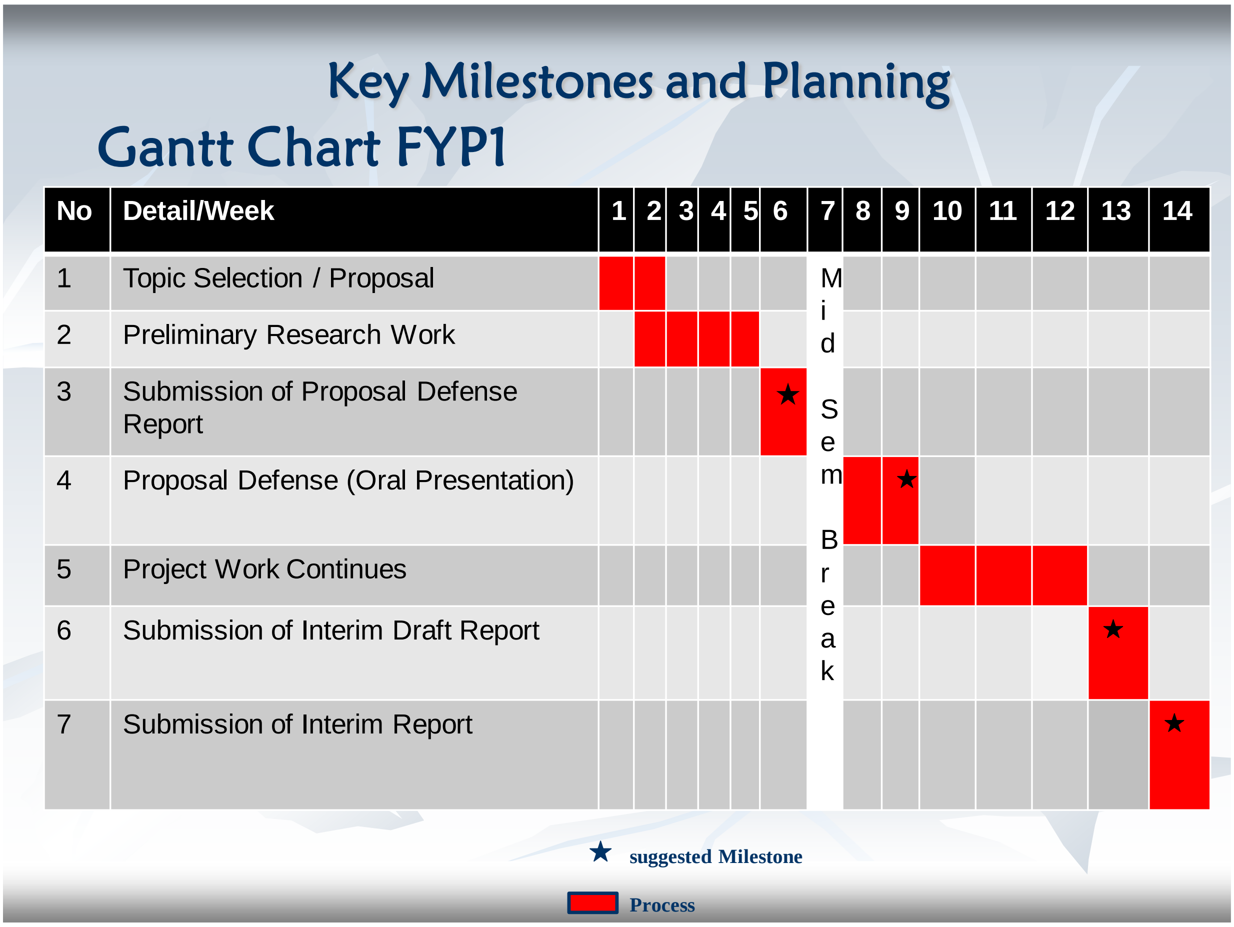


Figure 8: Project Gantt chat for FYP1

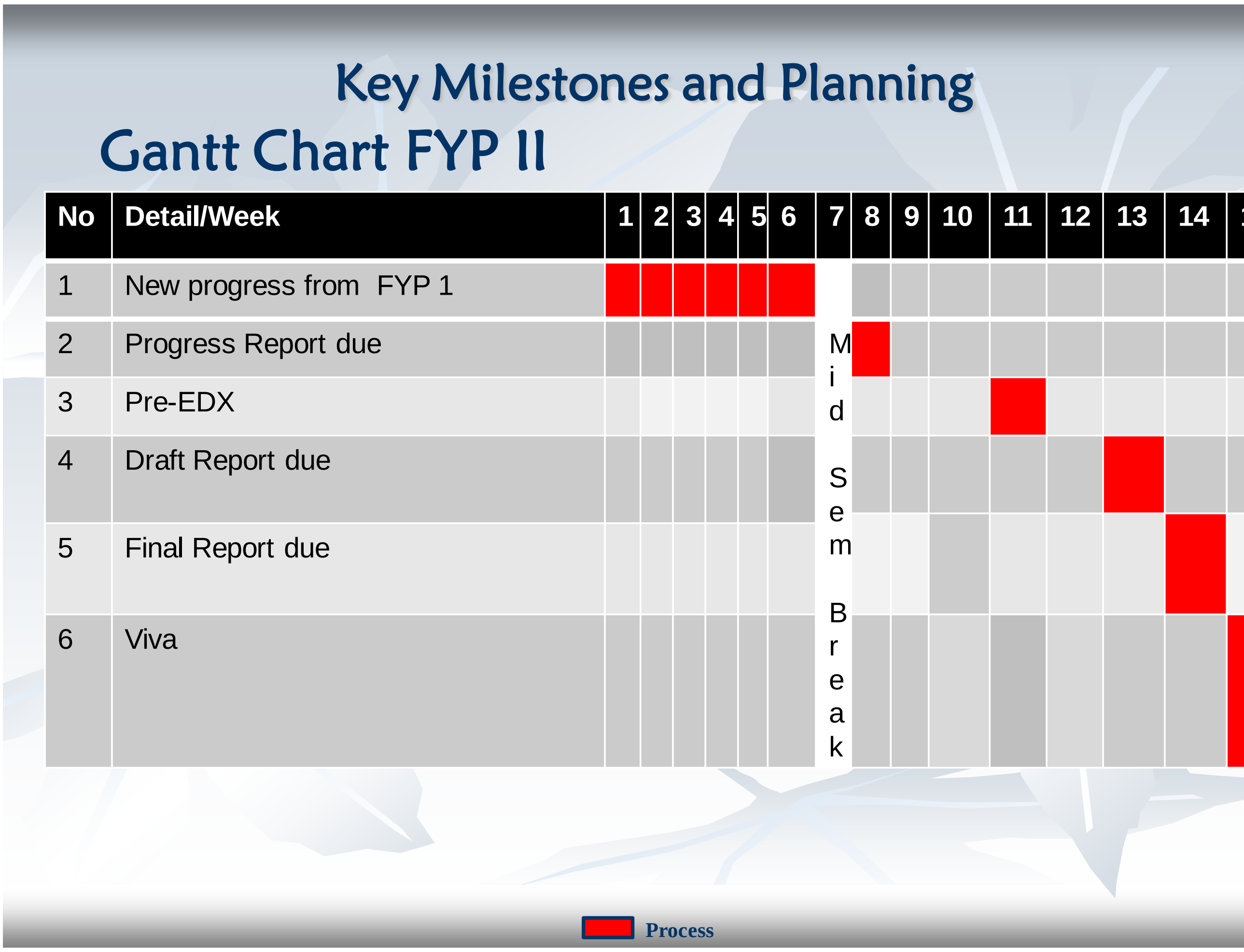


Figure 9: Project Gantt chat for FYP II

3.3 Tools and equipment required

The following components and equipment are used for the success of this project most of which are found in the University's Electrical and Electronics lab.

- Enameled copper wire
- Capacitors
- Resistors
- Frequency generator
- Voltage source
  Oscilloscope

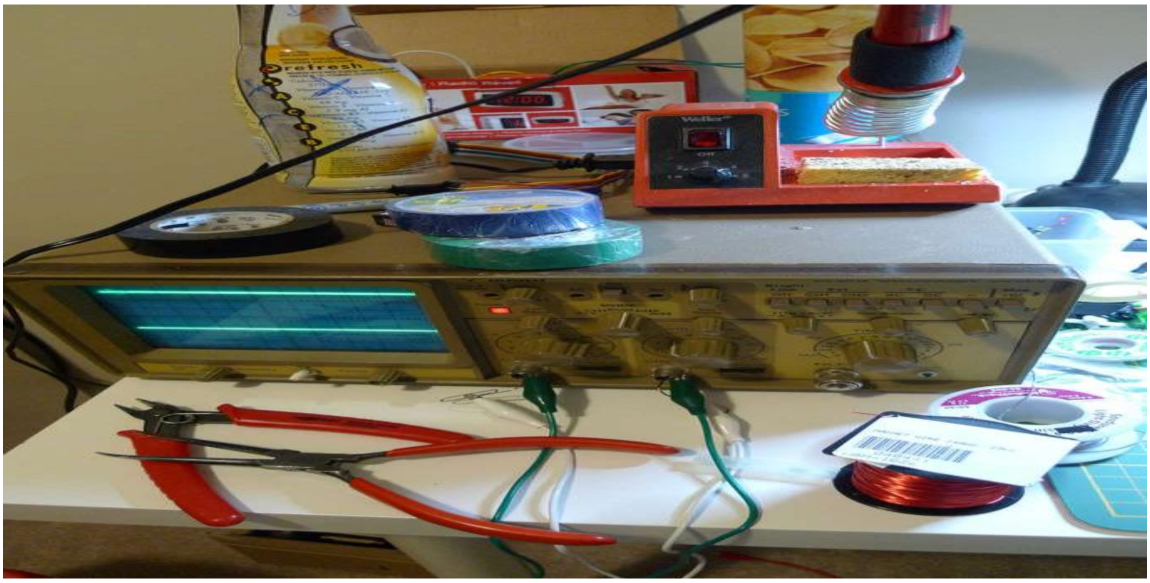


Figure 10: Required tools and equipment

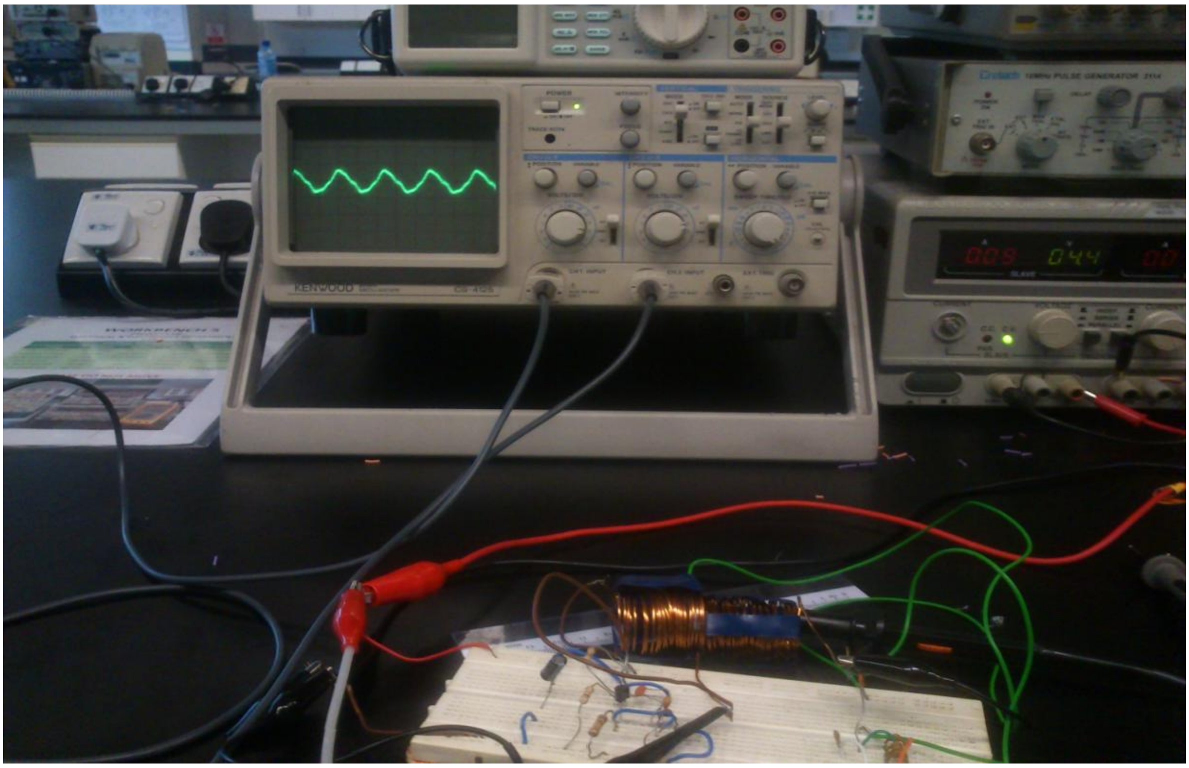
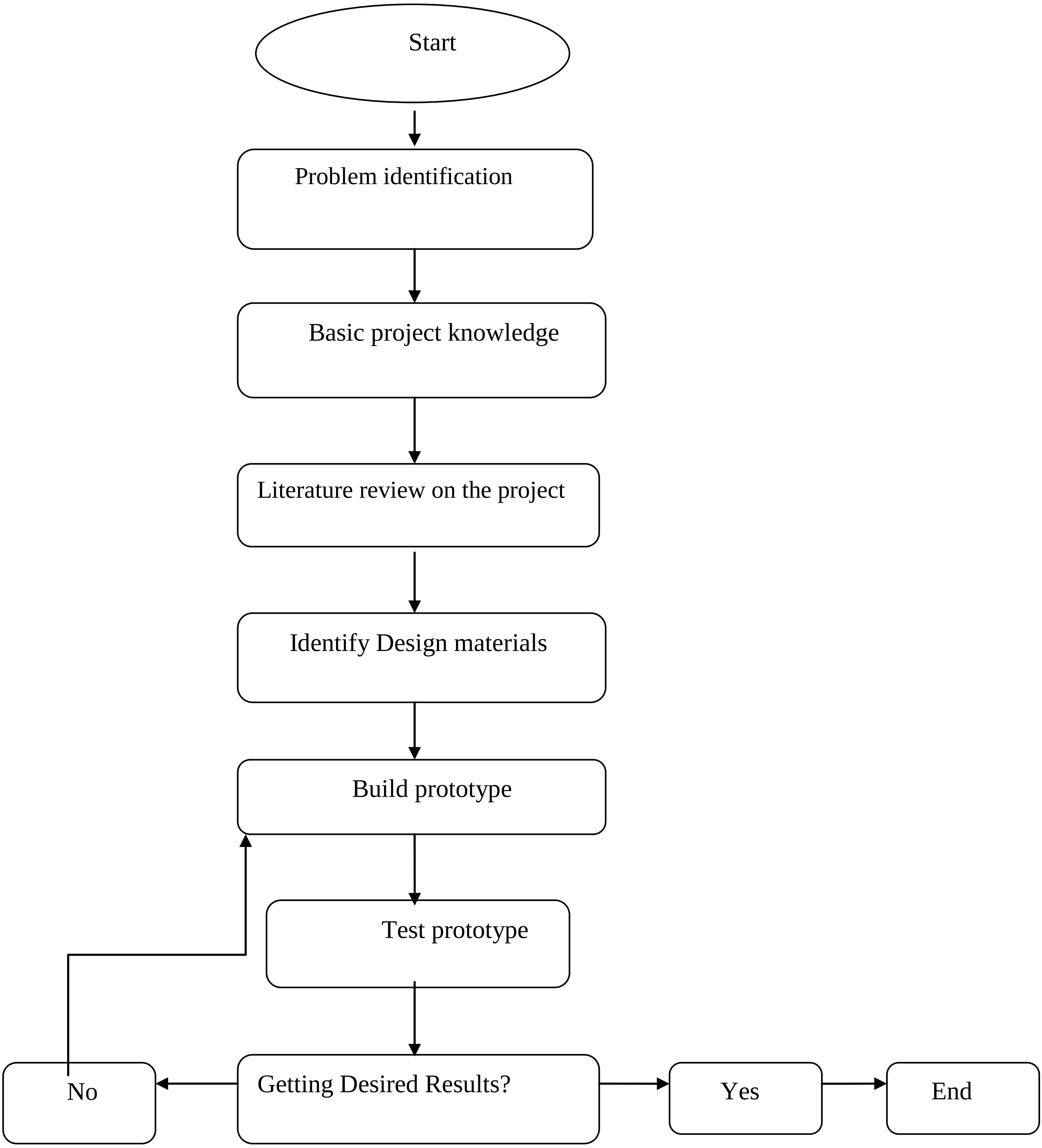


Figure 11: Building the system/labsetup

3.4- Project Activities and progress



CHAPTER 4: RESULTS

4.1 Results

After building the primary coil and running a preliminary test as follows

By applying a heavy AC current to the primary coil in the range of MHz which is connected to an oscillator, a certain amount of voltage was detected on the primary coil. The voltage and current on the coil were both measured and recorded. The primary coil was made to resonate at its oscillating frequency based on its value of inductance and the charging capacitance connected to it. The formula below was used to determine the resonant frequency

$$F = \frac{1}{2\pi\sqrt{(LC)}}$$

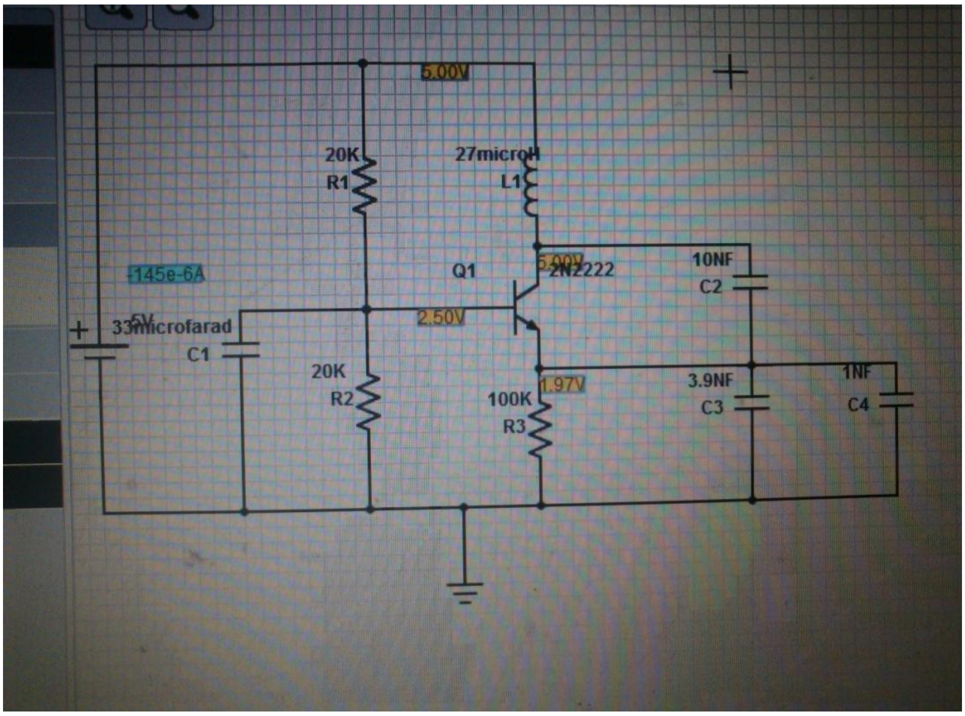


Figure 12: Oscillating circuit used

The above circuit resonated at about 165 KHZ by calculation. However, from experimental result, the frequency is about 178 KHZ. And a voltage of about 4.875 V peak to peak and about 0.023 Amperes current.

Using the values above, the average power in the coil was found using the following formula;

$P_{in,ave} = V_{rms}I_{rms} = \frac{4.875V}{2\sqrt{2}} X0.023$ = 0.0396W

Secondary Coil

The secondary coil was designed to have a similar inductance value by taking into account, the number of turns, the area and its length. The formula below was used to determine the inductance of the secondary coil.

$$L = \frac{\mu_0 N^2 A}{l}$$

Where,

L=Inductance

μ_o=permeability of free space

N= number of turns

A= area of the circular coil

l = length of the coil

The tricky part was in making the secondary coil resonate at a similar frequency as that of the primary coil. Here a capacitor is used to adjust it to have a resonant frequency of 165 KHZ.

To find the value of the capacitor, the formula below was used;

$$C = \frac{1}{4\pi^2 f^2 L}$$

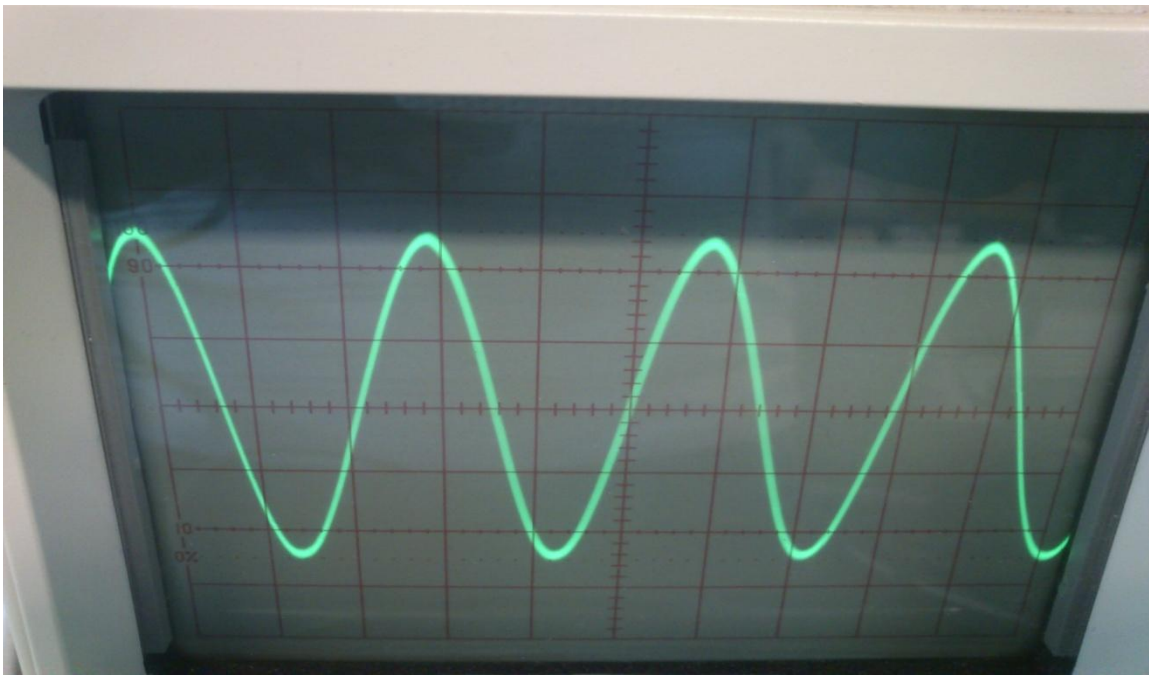


Figure 13: Output of the oscillator

After this test, the next attempt is to try and see if this voltage from the primary coil can be transferred to the secondary coil and how much of it for that matter.

The figure below shows the waveform produced by the second coil after the two coils were paired.

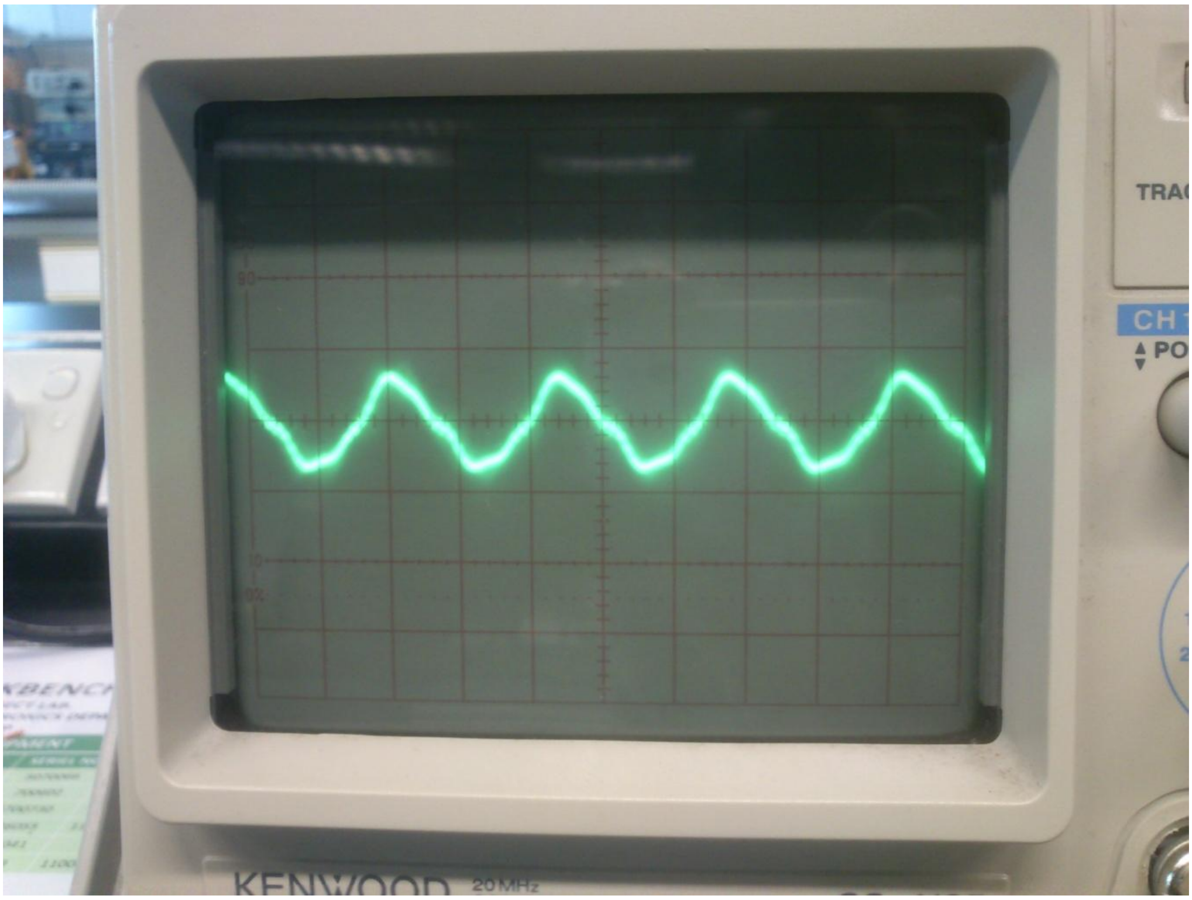


Figure 14: Waveform of received signal

However, the signal was seen to die off when the secondary coil was moved further away from the primary coil. This shows that the electric field generated in the secondary coil reduces as the distance between the two coils increases.

This could also be caused by the quality factor, to have better transfer, the coils should have high quality factors given by

$$Q = \frac{\omega L}{R}$$

Where L is the coil inductance and R is the coil impedance. The quality factor therefore depends on the resonant frequency. However the resonant frequency decreases as the coil area and turns increases

The table below shows the result after the two coils were connected by mutual inductance.

Separation distance(cm)	V_{in}(Vpp)	I_{in} (A)	P_{in} (W)	V_{out}(Vpp)	I_{out}(A)	P_{out}(W)
Inside	4.875	0.023	0.0396	1.778	0.012	0.0075
1	4.875	0.023	0.0396	0.0413	0.0062	0.00009
2	4.875	0.023	0.0396	0	0	0
3	4.875	0.023	0.0396	0	0	0
4	4.875	0.023	0.0396	0	0	0
5	4.875	0.023	0.0396	0	0	0

Table 1: Experimental results for power transfer

However, the result obtained above after pairing the two coils together were not as promising as expected. With very low output power for the various distances. We can see that at a distance of about 4cm and above, the voltage in the secondary coil becomes zero. The respective current value after that distance shown on the table is actually the original value as when only the leads of the ammeter are connected by themselves only.

4.2 Discussion

4.2.1 The Tesla coil

As already mentioned, for power to be transmitted, Tesla utilized a second Tesla Coil as a receiver to collect it. For efficient power transfer, the receiver needs to be in resonance with the transmitter.

4.2.2 Resonance

There are a few ways of accomplishing resonance; one way is by making the receiver the same as the transmitter. However, if both receivers and transmitters are of different sizes, they can also resonate together.

Another factor as stated by Nikola Tesla was that the mass of the primary and secondary coils work best if identical. This makes for the difference in diameters between the primary and secondary coils.

4.2.3 Coupling factor (k)

The coupling factor determines how fast energy is transferred between the primary coil and the secondary coil.
K is defined by the formula:

$$k = \frac{M}{\sqrt{l1l2}}$$

Where $l1 \text{ and } l2$ are the inductance of the primary and secondary coils and M the mutual inductance between both coils.

We can see that the coupling factor is dependant on the both the mutual inductance and self inductances of the coils. The coupling factor is usually expected to be in the range of zero to unity. For a unity coupling factor, it shows that there is perfect/faster transfer of energy [13]. However, this might not be possible due to the placing of the coils and their make up.

CHAPTER 5: CONCLUSION/RECOMMENDATIONS

This section acts as a reference for what has been presented in this paper. This paper has basically looked at some of the theories behind wireless power transfer and some previous studies on the subject matter. As in theory, it takes two mutually inductive coils to wirelessly transfer power from one coil to the other.

The result of this project are however not as expected, with only very little power being able to be transferred between the two coils. This could due to the following reasons.

Coil

This could be due to the coil sizes. Further testing could provide a better result for this project in order to have higher efficiency for power transfer. In my project, coils of the same size did not yield any result. However with a receiving coil smaller in area, I was able to find some results.

Frequency

With continued testing, the frequency value tends to change. This is probably due to the inductance values of the coils that changes since their lengths tend to change due to any slight disturbance.

When such problems are solved, it would be easier to transfer power wirelessly. In such a case, wireless charging devices can be made.

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APPENDIX A

Experimental values used

N1=30

N2=36

l1=l2=0.03m

r1=0.015m

r2=0.0125m

L1=L2=27μH

Resonant frequency F=178KHZ

Average Power, P = $I_{rms}V_{rms} = (\frac{V_{pp}}{2\sqrt{2}})I_{rms}$

APPENDIX B

Project progress