IMPROVING EFFICIENCY OF WIRELESS POWER TRANSFER VIA MAGNETIC RESONANCE COUPLING

by

Tan Lean Huat

Dissertation

Dissertation is submitted in partial fulfillment of

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Bachelor of Engineering (Hons)

(Electrical and Electronics Engineering)

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Universiti Teknologi PETRONAS

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CERTIFICATION OF APPROVAL

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Approved by,

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January 2014

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 in the references and acknowledgments, and that the original work contained herein have been undertaken or done by unspecified sources or persons.

TAN LEAN HUAT

ABSTRACT

Described herein is wireless energy transmission via magnetic resonant coupling for author's FYP project. The idea is based on two resonant coils, with one acting as transmitter, which consist of source and circuit, and the other as receiver connected to load, such as low power LED, having strong coupling electromagnetic resonant for wireless energy transmission from transmitter to receiver over a certain distance. The working principle operates as traditional inductance magnetic coupling devices, where Faradays' Law states that, a time varying magnetic field of a coil of wire, voltage (emf) will be induced in the coil. However, these principles will limit the efficiency and distance transfer between transmitter and receiver. Thus, by applying resonant concept, which tunes both objects operating frequencies into resonant frequency, we can transfer energy wirelessly with greater efficiency and longer distance. This paper will emphasize on the fundamental principle in order to realize the concept until the design of the prototype itself. The basic theory such as magnetic induction, resonant frequency as well as magnetic resonant coupling will be further explained for better understanding and clarification. Apart from that, further analysis will also discussed and compared with the achievement and work done by others in comprehensive literature review chapter. In the design of prototype, a number of calculations have been done in order to get the resonance frequency which can be applied to both coils to function and the process of designing the circuit and building it through exclusive studies, will also be explained in detail. Last but not least, author will further analyze the circuit comprehensively by studying on three most important results, which are voltages, magnetic field intensities, and power with respect to different parameter setting. The author compared the finding by using theoretical calculation and measurement by using spectrum analyzer and multi-meter. All the measurement will be tabulated in tables and graphs.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF GRAPHS

CHAPTER 1

INTRODUCTION

1.1 Background Study

Since 1899, Nikola Tesla, introduced the world to a new concept, which he developed a resonant transformer, Tesla Coil to transport energy over certain distances wirelessly. He has built a huge tower, Wardenclyffe or called Tesla Tower, in order to transmit energy within a city. However, due to reasons of safety hazard of radiation emitted by the tower to human body, as well as disastrous to electrical equipment, the project has been languishing. Besides, such method tends to more energy wasted to free space rather than transmit to useful load or energy demand by customer, in short term, its efficiency is very low [1].

Wireless power transmission is the means to power devices without built in power source such as generator or battery. There are multiple need and uses for such technology in a number of applications. For instance, by eliminating the battery in a small device likes cell phone and laptops, it would be possible to compact the device even further. Furthermore, on a larger scale as consumable energy sources on the planet are dwindling in number it remains an important task to look after in the future. In 2006, Massachusetts Institute of Technology (MIT) researchers lead by Prof. Marin Soljacic, worked toward this topic. They patented such technology and developed a few mid-range prototypes which using wireless energy transmission principle and the project has now created the WiTricity Corp with several products are in market [2]. Witricity technology is different than traditional magnetic induction in term of efficiency and distance of transmission can be done.

In traditional magnetic charging, the two coils must be very close together for usage and the efficiency drop when the distance increases. This working principle being study and enhance by WiTricity Corp using resonant design in magnetic induction.

There will be two coil, which having same resonant frequency will act to wireless energy transmission by several circuit application such as oscillator. The alternating current at transmitter circuit will create a time varying magnetic field. The flux generated by the time varying magnetic field will induce a voltage on a receiver coil closed loop system. Besides, this technology is a non-radiation power transfer which differentiates from any other radiation techniques transmission such as Infra-red and any electromagnetic wave likes microwave or light radiation. It won't pose any harm or hazard to human being as well as animal health. With highly resonant strong magnetic coupling technology, it can benefit to high efficiency over distance and safe for human health for wireless energy transmission.

1.2 Problem Statement

One can't deny the vital role of electricity in our daily life. Imagine, what will happen to a country, where there is no electricity supply. All the industries will face great loss, human unable to use any electrical or electronics gadget such as mobile phone or laptop to carry on their routine activities. Thus, one of the major issues highly discussed is energy transmission from one place to another place. Due to the increasing high demand for electricity by citizen, a numbers of problems and limitation of energy transmission have been discussed and shown in Figure 1.

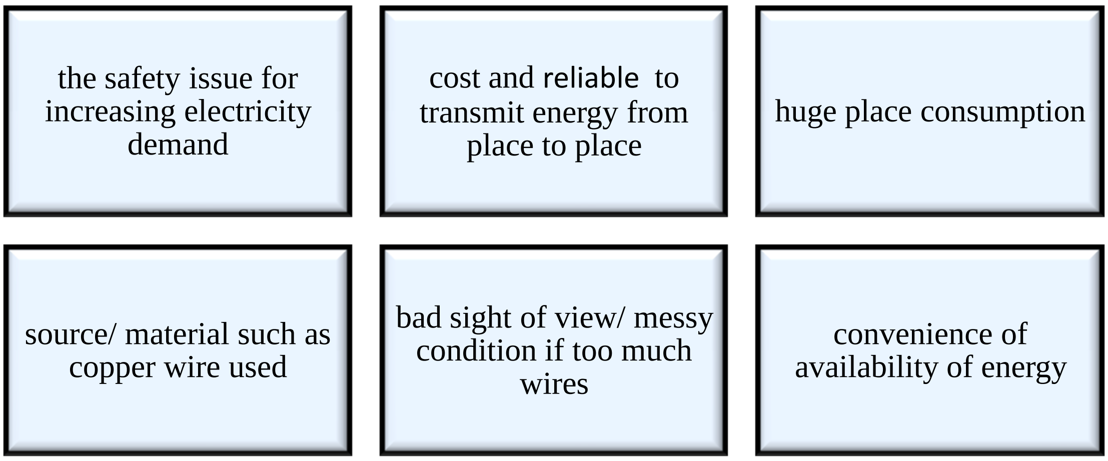


Figure 1: Problems and limitation of energy transmission

Traditional plug and socket which use wire between source and load should be replaced by wireless energy transmission which can take place in anywhere and anytime. Witricity or strong magnetic resonance coupling is a new principle and idea as ideal solutions for high efficiency and better distance wireless energy transmission for any applications.

1.3 Objectives

The purpose of this project is;

- to analyze magnetic resonance coupling for wireless energy transmission
- to study on parameter which effect the efficiency of magnetic resonance coupling principle
- to test and verify magnetic resonance coupling for wireless energy transmission through stimulation and prototype

The idea begin with tuning transmitter and receiver coils or objects to resonate to increase the magnetic coupling to improve wireless energy transmission in term of efficiency and distance compare to traditional magnetic induction principle. One of these coils is connected to power source and the other is to load such as LED or bulb. The main concern of this study is emphasized on resonant frequency of transmitter and receiver coupling, where a lot of stimulation and calculation need to be done to achieve resonant coupling throughout the project study. This research further studied on the distance and efficiency energy can be transmitting without any medium between power source and load. In the end of the project, prototype will be shown and prove the principle of the research.

1.4 Scope of Study

In this project, the main subject consists of research and analysis works. The research is vital for better understanding for fundamental principle and theory applied to achieve this technology. In order to achieve the objectives, the followings are scope of work of this project that was carried out;

- to study on magnetic induction which evolved from Faradays' Law
- to study on resonant frequency and its application nowadays
- to study on magnetic resonance coupling and how the wireless energy transmission can be achieved
- to study on power measurement at transmitter coil against power reading at receiver coil at difference distance
- to study on magnetic field measurement using Spectrum Analyzer with theoretical calculation

1.5 Relevance of the Project

The main purpose of this project is to understand and study on how the principle and theory of magnetic resonance coupling work for wireless energy transmission. As we know the important of electricity in our daily life, energy transmission which acts as a medium from energy generation, to distribution to customers or end users or gadgets, plays an important role in order to meet the requirement. Thus, it is important to understand the dynamic of wireless energy transmission. Wireless energy transmission has been commercialize in few industries for gadgets which under categories of low and medium power source. From sophisticated gadgets such as cell phone and laptop batteries charging to our daily equipments likes brush tooth and table lamp, it definitely ease our busy routine life.

1.6 Feasibility of the Project

This project need to be completed for a given time frame and period of study. Besides, the feasibility of this research is within the scope of studies while maintain substance to this project. The details for scope of study during FYP I and FYP II as shown in Figure 2 and Figure 3 respectively.

During FYP I, the scope of study will include;

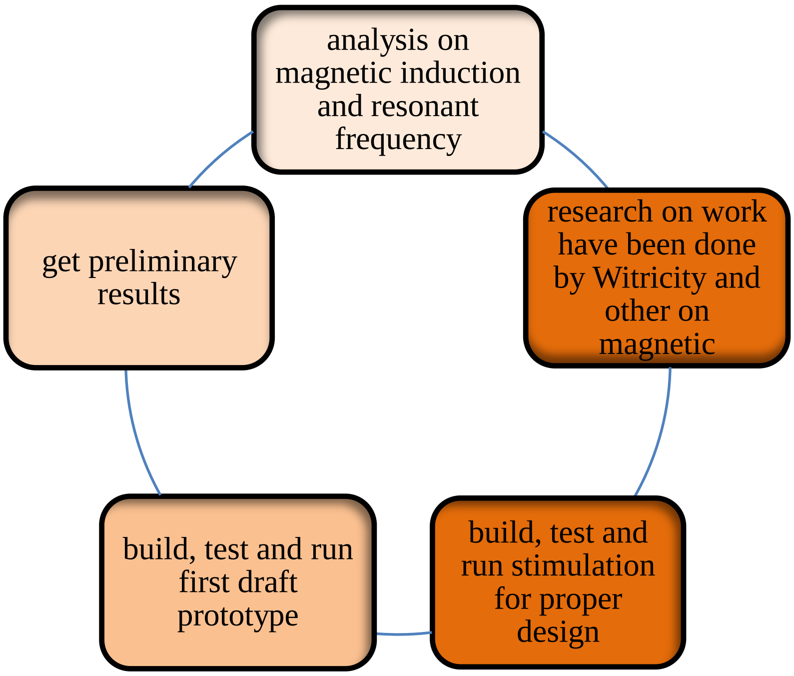


Figure 2: Scope of study in FYP I

During FYP II, the scope of project progress will cover;

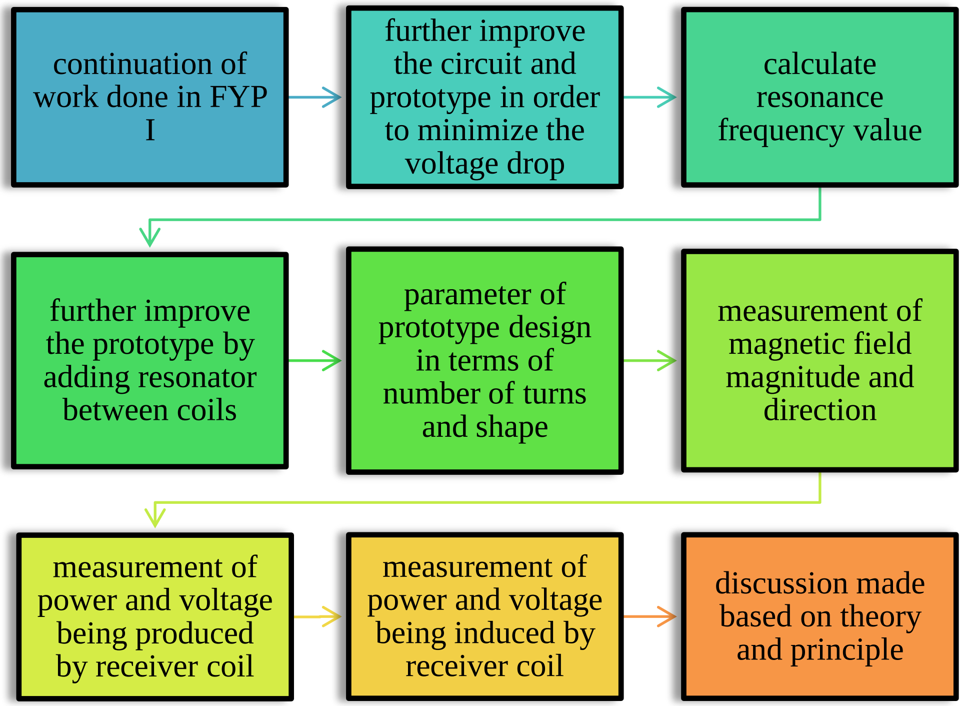


Figure 3: Scope of study in FYP II

CHAPTER 2

LITERATURE REVIEW

2.1 Critical Analysis and Relevancy

Theories play important role in order for one to fully understand the flow of project to kick off and how to accomplish the final achievement. Thus, the author will describe comprehensively few most important principles which include definition of time-varying magnetic field, magnetic induction evolved from Faradays' Law, important of resonant frequency and combination of magnetic induction with resonant frequency, namely magnetic resonance coupling.

2.1.1 Time-varying magnetic field

The charge density ρ and current density **J** are generalized to be varying with time. The charge conservation law states that,

$$\frac{d\rho}{dt} + \nabla . \boldsymbol{J} = 0 \qquad (1)$$

imposes a constraint between the two quantities namely charge density and current density. Likewise, a time varying electric field induces a magnetic field through the displacement current,

$$\oint_c B . dl = u_0 \epsilon_0 \frac{d}{dt} \int_s E . dS \qquad (2)$$

As is well known, the displacement current played a crucial role in Maxwell's prediction that electromagnetic waves can propagate through vacuum. There are four generalized set of Maxwell's equations,

$$\nabla . \boldsymbol{E} = \frac{\rho}{\epsilon_0} \tag{3}$$

$$\nabla \times E = -\frac{dB}{dt} \tag{4}$$

$$\nabla . B = 0 \tag{5}$$

$$\nabla \times B = \mu_0 (\mathbf{J} + \epsilon_0 \frac{dE}{dt}) \tag{6}$$

2.1.2 Magnetic Induction

Magnetic induction consist of a transmitter coil and receiver coil, which using magnetic fields to produce voltage and current in a complete circuit. As indicate in Figure 4 shown as below, when a magnet moves back and forth, an electromagnetic induction (emf) will induced in the wire (transmitter) which obeys Faradays Law, and its direction of voltage is obeyed Lenz Law principle. From Lenz Law principle, it states that, the direction of the induced emf and the change in flux has opposite signs [3] as equation below;

$$\oint E . dl = -\frac{d}{dt} \int_s B . dS \tag{7}$$

When a second conducting wire (receiver) is brought near to the first, some of the oscillating magnetic field will be captured in second wire. The secondary coils must be a complete or closed circuit, so that voltage can be induced and current can flow in a complete circuit. This is the most fundamental principle which will play crucial roles for this overall project. Thus, this will result generation of another emf in the second coil and turn on the load/bulb as shown in Figure 5 below.

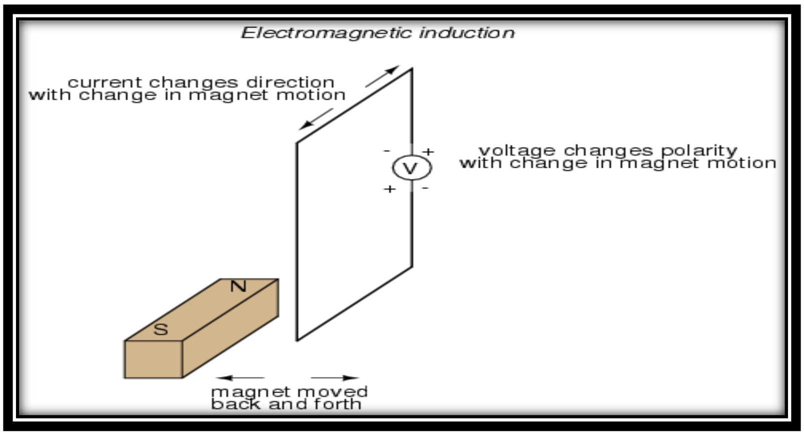


Figure 4: Magnetic induction

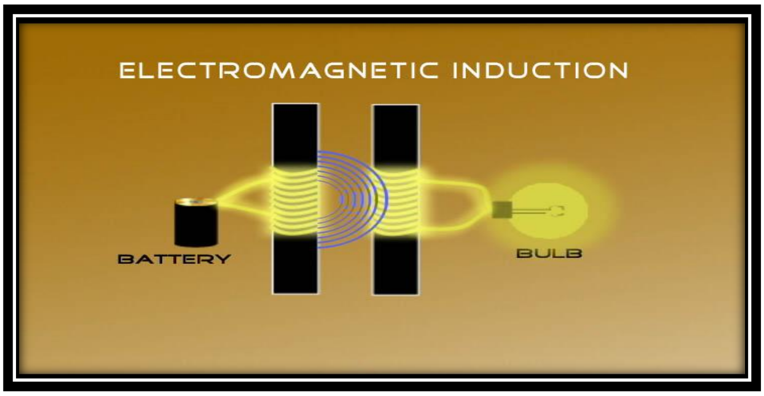


Figure 5: Electromagnetic Induction

2.1.3 Resonant Frequency

Every object has its own natural frequency. Resonant frequency is when the object vibrates at its natural frequency, and it will produce oscillating at maximum amplitude. For instance, a swinging child in a playground swing is a resonant system, where is amplitude force to produce forth and back direction is zero, when the speed in resonant which the swing itself as shown in Figure 6 [4]. Resonance can use to transfer energy in without any medium. When two objects having same frequency, an object vibrate can cause the other vibrate too. This principle has been applicable in certain frequency such as musical to create large organ, high speed locomotive and nuclear power plant.

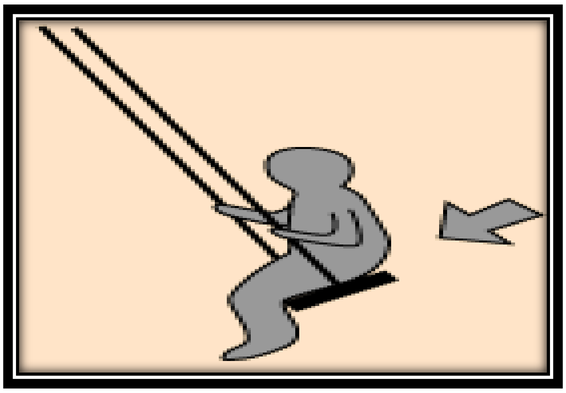


Figure 6: Concept of resonance frequency in swinging

2.1.4 Magnetic Resonance Coupling

By using concept of magnetic induction and resonance frequency, we can magnify the amplitude of magnetic flux produced in an electromagnetic system. Resonant power transmission can overcome the basic magnetic induction by increase the system efficiency and distance of power transmission. Theoretical analysis, electromagnetic wave contains energy. The transmitter generates oscillating magnetic field from source supply to surrounding and to be capture by receiver coil which connected to load, at same resonance. The resonator in transmitter and receiver in resonance magnetic coupling system consist of the transmitter and receiver inductance and a capacitor respectively. Resonance frequency can be calculated from following equation;

$$F = \frac{1}{2\pi\sqrt{LC}} \tag{8}$$

where;

F= resonance frequency of two objects,

L is inductance

C is capacitor value

Function of resonant capacitors it to cancel out the stray inductance in the receiver and the magnetizing inductance in the transmitter. The Figure 7 below show the principle of magnetic resonance coupling by using function generator connected to primary/ transmitter source and secondary coil/ receiver with a capacitor to project the frequency. Calculation which involved determining the resonance frequency value will comprehensively derived in the methodology chapter.

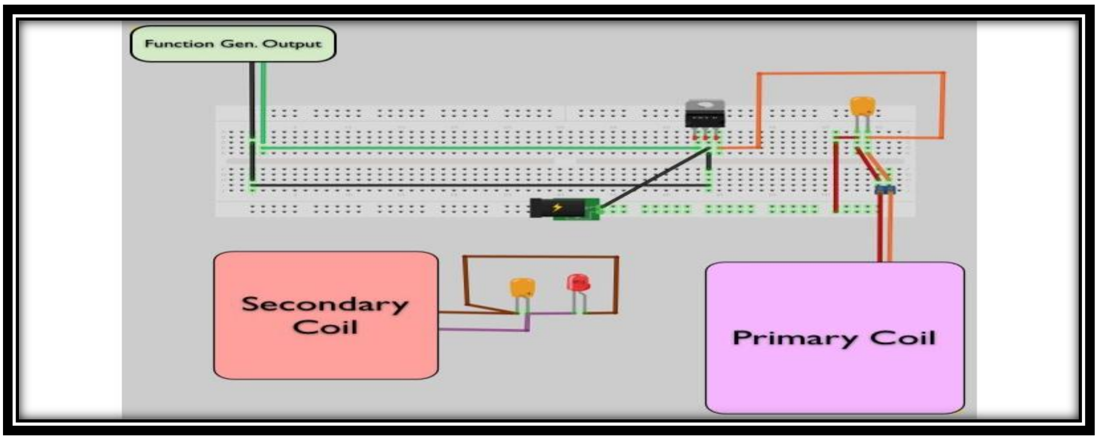


Figure 7: Idea and concept for Primary and Secondary Coil in Bread Board

2.2 Comparison between technologies

There are a few technology and principle for wireless energy transmission have been widely implemented in our nowadays technology before the Witircity introduced. For instance, one of the most common wireless technologies implemented in electronics gadget is using the traditional magnetic induction. At first glance, WiTricity's technology for power transfer appears to be traditional magnetic induction, such as is used in power transformers, which conductive coils will able to transmit power to each other wirelessly, over very short distances. For instance, in a transformer, an electric current running in a primary coil induces another current in a receiving coil by using Faradays' Law as described in this article [5]. However, the efficiency of the power exchange in traditional magnetic induction systems drops by orders of magnitude when the distance between the coils increases and until a distance, where it becomes larger than their sizes, the efficiency will be very low. In addition to electric transformers which use for step-up or step-down voltage purpose, other devices which based on traditional magnetic induction are rechargeable electric toothbrushes and inductive charging pads for dry cell or cell-phone which require that the object being charged are placed directly on top of, or very close to, the base of power supply. Traditional magnetic induction for wireless energy transfer is improved by utilizing resonant circuits [6]. WiTricity's founding technical team, lead by Professor Marin Soljacic, was the first to discover that by specially designing the magnetic resonators. This technology applies strong coupling to magnetic induction and achieved a high efficient energy transmission over a larger distances.

Apart from that, magnetic resonant coupling technology for wireless power transfer is non-radiative and relies on near-field magnetic coupling principle. There are a number of techniques for wireless power transfers rely on radiative techniques, such as broadcasted shown in Figure 8and 9 for transmission of radio wave and laser pointer which based on light waves technology. This technology exists since a few decades ago, and plays a very important role for radio and television as the most important ways for communication and information transmission. This technology commonly travelled by broadcasted radiation of radio frequency energy around 3 kHz to 300 GHz depends on the data or information to be transferred. The power received by each radio or wireless receiver end must be amplified in a receiving unit using an external power supply because the value is too miniscule. Due to the majority of radiated power is wasted into free space, radio transmission is considered to be an inefficient means of power transfer between two distances.   Note that while more energy can be supplied to the receiver by cranking up the power of the transmitters in these systems, such high power levels will cause a safety hazard and may interfere with other radio frequency devices which are nearby [7].

Figure 8: Microwave applications in our daily life

Directed radiation, using highly directional antennas, is another method of using radio transmission to beam energy from a source to a receiver. However, this method which in particular microwave radiation, may interact strongly with living organisms and certain metallic objects. Thus, this energy transfer methods may pose safety hazards to people or objects that obstruct the line-of-sight between the transmitter and receiver. These limitations make directed radio transmission impractical for delivering substantial levels of wireless power in a typical consumer, commercial, or industrial application. In fact, defense researchers are exploring the use of directed energy systems to deliver lethal doses of power to targets in space and on the battlefield [8].

In addition to radio waves, visible and invisible light waves can also be used to transfer energy. The sun is an excellent radiative source of light energy, and industry and academia are working hard to develop photovoltaic technologies to convert sunlight to electrical energy. A laser beam is a form of directed light radiation, in which visible or invisible light waves may be formed into a collimated beam, delivering energy in a targeted way. However, as in the case of directed radio waves, safe and efficient transmission of laser power requires a clear line of sight between the transmitter and receiver [9]. As mentioned at the beginning of this section, magnetic resonant coupling technology is based on non-radiative energy transfer. It does not require a clear line of sight between the power sources and capture devices and it is safe for use in typical home, hospital, office, or industrial environments.

Figure 9: Satellite which use radiation for wireless energy transmission

Besides, people assume that Witricity technology similar to magnetic resonance imaging (MRI) technology as Figure 10; however, the technologies are similar in name only. MRI is, as its name suggests, a technology which apply magnetism as a basis for diagnostic imaging purpose of soft tissue in the human body. MRI manipulate those atoms in a selective way by utilizes a strong DC magnet to orient the magnetic fields of atoms within tissues, and radio frequency fields, so that tissues and structures can be imaged clearly. The resonance referred to in MRI refers to the resonance of atomic structures. MRI is not considered to be a method for wireless power transfer. Last but not least, In the late 1800's and early 1900's, at the dawn of the electrification of the modern world, some scientists and engineers believed that using wires to transfer electricity from every place it was generated to every place that it could be used would be too expensive to be practical. Tesla Tower, as shown in Figure 11, one of the most well known achievements of Nikola Tesla scientist, had a vision for a wireless world in which wireless electric power and communications would reach around the world, delivering information and power to ships at sea, factories, and every home on the planet [10]. Tesla contributed significantly to our understanding of electricity and electrical systems and is credited with inventing three-phase AC power systems, induction motors, fluorescent lamps, radio transmission, and various modes of wireless electric power transfer. Magnetic resonant coupling technology for power transfer is different than the technologies proposed by Tesla, but his work is referenced and acknowledged in the scientific articles published by WiTricity's founding technical team.

Figure 10: MRI machine

Figure 11: Tesla Tower

2.3 Recentness of Literature

Rohan Bhutkar and Sahil Sapre [11] stated that, the interaction between magnetic field resonating at MHz frequencies with resonant nature frequency of the process of transmit energy ensures strong interaction between the sending and receiving unit. Besides, there is a relation between radius and distance between the coils, r and electromagnetic radiation, λ. It is defined that, the amount of energy per unit area at a distance r from the primary coil is proportional to

$$\lambda = 1/r^2 \quad (9)$$

They do also derived a formula to calculate self-resonant frequency of the coils for helical antennas by

$$F = \frac{29.85*(H/D)^{(1/5)}}{N*D} \quad (10)$$

where,

F=self resonant frequency in MHz of coil,

H= coil height in meters

D= coil diameter in meters

N= total number of turns

Ho, Wang, Fu, and Sun [12] conduct an experiment about transmit energy in a mid-range by using 9MHz resonant frequency which obeys two coupled mode operation;

$$\frac{da_s(t)}{dt} = (iw_s - \tau_s)a_s(t) + ik_{SD}a_D(t) + F_s(t) \quad (11)$$

$$\frac{da_D(t)}{dt} = (iw_D - \tau_D)a_D(t) + ik_{DS}a_S(t) - \tau_L a_D(t) \quad (12)$$

where,

$a_s(t)$= field amplitude of source

$a_D(t)$= field amplitude of device

w_s= source resonant angular frequency

w_D= device resonant angular frequency

k_{DS}=k_{SD}= coupling coefficient

τ_s=τ_D= decay rate

Their achievements are the design circuit able to transfer energy wirelessly up to 30W and efficiency is more than 60 and the maximum distance between source and device is around 45cm.

Duccio Gallichi Nottiani and Fabio Leccese [13] conduct a different experiment to study the effect of the coil itself by manipulate the shape into a spiral coil for wireless energy transmission. They use several method calculation and derivation formula in order to implement planar resonant coils in the shape of linear spiral. They basically use Neumann's formula for induction value calculation and simplified into;

$$L_{c_i c_j} = u_0[-1.5589 - 1.3765\ln(\log(k))]\sqrt{\frac{r_i r_j}{8}}H \quad (13)$$

where;

i, j= number of turns respectively

H= height of coil

k= constant, index value

u_0= permeability constant, $4\pi e^{-7}$

Besides, they also derived a formula for capacitance value per unit length of a pair of parallel conductor by study the geometry as;

$$C = \frac{\pi\epsilon}{ln\frac{D}{2r}+\sqrt{\frac{D^2}{2r^2}-1}} \quad (14)$$

where D is distance of coil; r is radius of coil and ϵ is permittivity constant, $8.854e^{-12}$. They evaluate resonant frequency from inductor and capacitor value by using equation (8).

Lin, J.C [14] conducted a testing which contributes to immerse success on solar-power satellites (SPS) by using wireless power transmission. The concept of SPS envisions the generations of power by solar energy in space, and transmitted for the use on Earth. The system consists of a platform, which will orbit around the Earth and gather solar energy. A power receiving antenna on the Earth will convert and collect the transmitted energy in a form of microwave.

Heha Bagga, Joshua Gruntmeir, Samuel Lewis [15] conducted experiment on wireless power transmission by using inductive coupling theory at several operating frequency for within low, medium and high frequency range. They compared and analyze the efficiency and feasibility for the means of using wireless power transmission and considering the cost for every design.

Apart from that, there are also some researches done by different company for this technology worldwide such as Intel. Intel lead by Prof. John Boys used the same basic principle of resonant magnetic coupling to conduct an experiment named Seattle, and able to transfer more than 60W energy with 75% efficiency with more than 1metre distance [16]. Besides, Wireless Power Consortium Company established in 2009 in order to produce several products which use the same technology for small electronic gadgets.

2.4 Advantages and Disadvantages of wireless energy transmission

Wireless energy transmission will help to reduce or completely eliminates the existing high-tension power transmission medium, such as copper wire cables which will rid the landscape for such towers, and sub-stations between the generating station and end of consumers. Furthermore, it facilitates the interconnection of electrical generation plants on a global scale becomes a smaller size. Thus, the system will overall reduce the cost of electrical energy drastically. Besides, wireless energy transmission means a more efficient energy distribution systems and sources are needed by both developed and under developed nations. It can transmit wireless power to any distance without limitation or barrier such as country-side or rural area. In term of transmission and distribution loss, wireless energy transmission definitely gives a more significant lower value compare to wired transmission, and overall can be more economically transmitted. Last but not least, the power failure such as short circuit and fault on cables which frequently happened will never exist in the transmission and power theft would be not possible at all.

However, wireless energy transmission does bring negative sides. One can't deny the capital cost for implementation of wireless energy transmission seems to be very high. Besides, such newly technology require a number of expert authorities in order to achieve success in this project. Nevertheless, the interference of microwave signal or radiation around the globe may disrupt and bring menace to such technologies and communication systems.

2.5 Project Description

The primary goal is to achieve wireless power transmission by stimulation and prototype using magnetic resonance coupling concept. As per discussion, magnetic induction principle for energy transmission has limitation in term of efficiency and distance between transmitter and receiver. For instance, in order to charge cell phone by using inductive coupling gadgets, one must place his or her cell phone near enough to the source or tablet provided. In order to enhance and improve the efficiency and have greater distance, resonance concept will apply to magnetic induction, to produce magnetic resonance coupling between transmitter and receiver. In order to achieve it, a detail analysis and design need to be done in term of understanding, calculation and stimulation before build a prototype. Magnetic resonance coupling can be achieved when two objects exchange energy by vary magnetic fields at natural frequencies or both objects have same frequencies. The Figure 12 shows the project description for the circuit explanation and Figure 13 shows the basic concept of matching circuit.

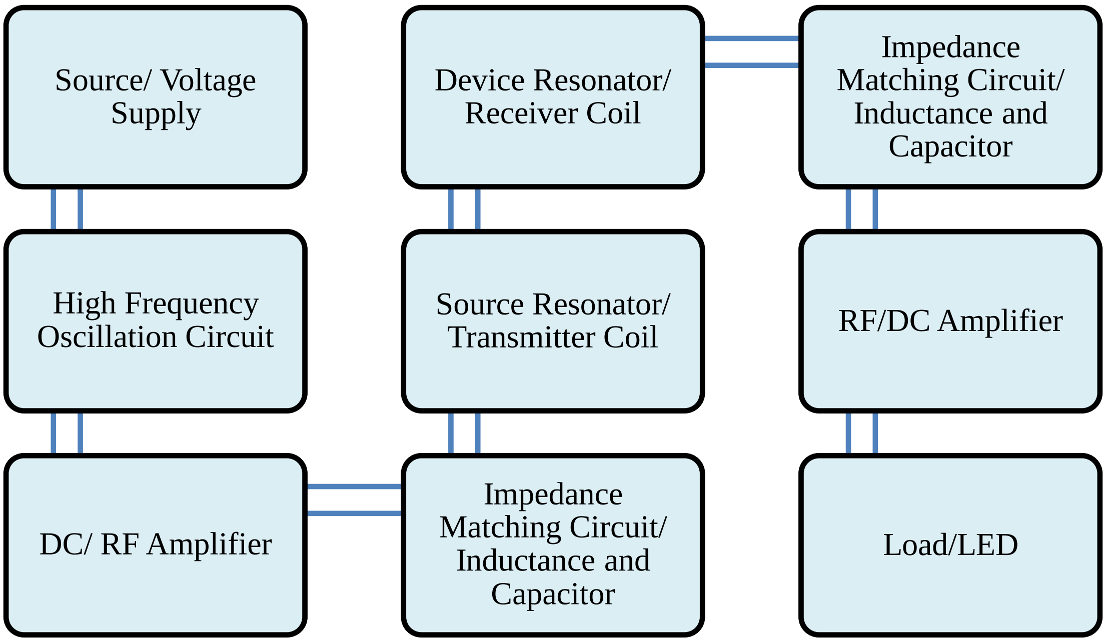


Figure 12: Project description for transmitter circuit

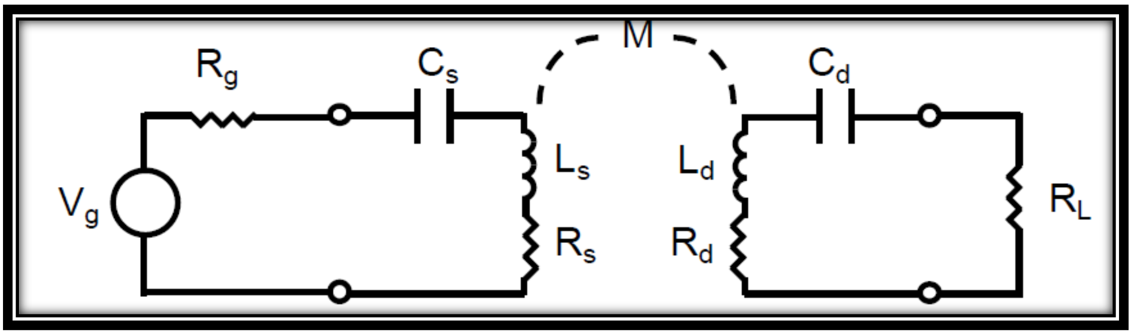


Figure 13: Basic Concept of impedance matching circuit

Efficiency will be measure with vary distance. When increase the distance between transmitter and receiver, it will reduce the amount of magnetic received in receiver coil generated by source in transmitter coil. The coupling factor, K is the measurement of the grade of magnetic coupling. The K value is manipulate or change with the distance between coils, the size/ diameter of coils, as well as the angle placement and shape of the coils.

On the other hand, quality factor is corresponding to shape and size of the coil. When the magnetic field capture in receiver coil, emf/ voltage being induced will affected by the shape and size of the coil, where value of inductance, L and resistance, R can be calculated in the coil. Thus, quality factor is the ratio of inductance to resistance of the coil,

$$Q = \frac{\omega L}{R} \quad (15)$$

As shown in the Figure 14 below, the author had stimulated the desire circuit on PSpice software for transmitter circuit. As per circuit shown, there are few basic important components which are used for the circuit such as MOSFET, capacitor and inductor as well.

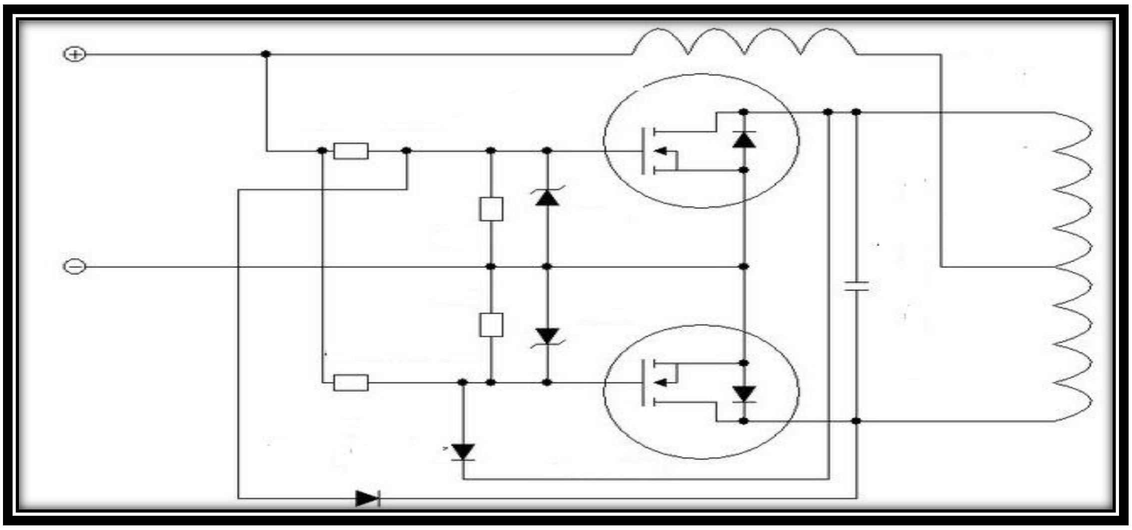


Figure 14: First Draft of Transmitter Circuit

Meanwhile, Figure 15 below is the receiver circuit which consists of receiver coil, capacitor as well as load or LED. For the design of resonators, it consists of loop of coil, which connected to capacitor acts as resonator.

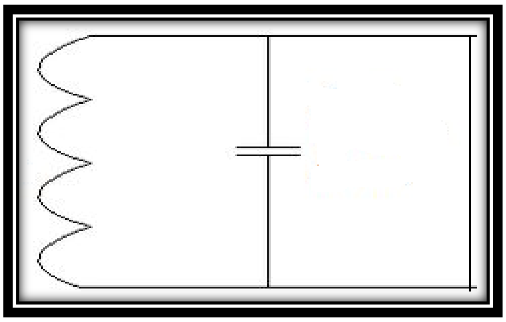


Figure 15: First Draft of Receiver Circuit

2.5.1 MOSFET

Function as power amplifier, which will operate under saturation mode in order to allow voltage across or current flow through. When the upper MOSFET is turn on, current flow through and the circuit is conducting. This will turn off the SCR diode, while current flows through the resistor to lower MOSFET for complete the circuit. Thus, the transmitter coil is conducting and function to generate magnetic field/ flux in the circuit. Since we can't neglect the effect of inductor in transmitter coil, we must allow current to discharge. The time for current discharge will determine by the coil inductor as well as capacitor value which function to store charge. When the MOSFET is off, the current will discharge by pass through the SCR diode for a complete circuit.

2.5.2 Coil Inductor

Coil inductor plays a very important role as a whole circuit. The value will change which will greatly affect the efficiency of the whole circuit. It can be manipulate by its shape of turn; whether is circular, square or so on, the number of turns, the size and diameter of the wire used, the type of wire used and diameter of the coil. Thus, a detail analysis is needed in further to achieve the highest efficiency. The author will use enameled copper wire as resonator coil and fiber-glass insulated copper wire as transmitter and receiver coil. The design will be elaborated in methodology chapter.

2.5.3 Capacitor

Value of capacitor is basically related to the coil inductor to produce resonance frequency within the coil, based on equation (8). The main function of capacitor in the circuit is to produce a resonant coupling frequency for transmitter coil and receiver coil. Thus, the value must be in coherence with the coil inductor to allow the whole circuit to function and work properly. From derivation,

$$C = \frac{1}{4\pi^2 f^2 L} \tag{16}$$

CHAPTER 3

KEY MILESTONES

3.1 Key Milestones

This project should be defined in detail for ease understanding and work can be done on time as shown in Figure 16.

Problem Statement and Objective of the project

Identify the purpose and main aim and target of this project to overcome the problem

↓

Background Study

Understand and differentiate work and analysis done by previous research by other related to the project

↓

Literature Review

Gather and analysis information which have been carried by others from various sources such as journals and publish articles and understand the principle and theory which applicable in the project

↓

Identify Tools and Instrument Needed

List all the necessary tools and instrument for achieve this project

↓

Experiment Process

Identify steps and main objective of experiment work that need to be investigated and gather all result from experiment

↓

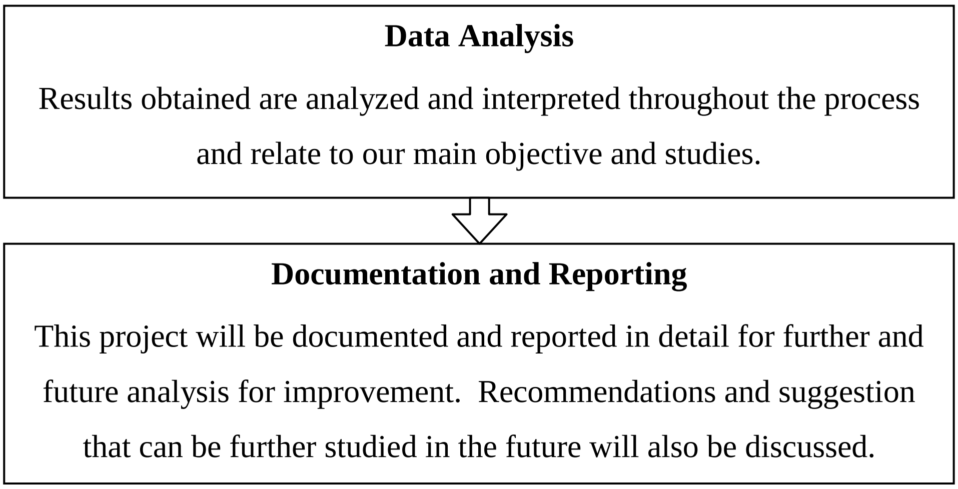


Figure 16: Key milestone of the project

3.2 Project Flow and Planning

Experimental study on resonant magnetic coupling in order to achieve wireless energy transfer is a tedious project. Gantt chart acts as a guideline for the author to complete his work successfully. In FYP I, the author focus on preliminary research and literature studies for better clarification. Before conducting the experiment, scope and methodology of the project need to be specified in order to have a clear direction on what to be achieving throughout the whole project. Besides, the author takes the initiative to familiarize himself with the lab setup and the component.

In FYP II, experiment work will be emphasized and analysis by finalized the circuit design and prototype. Besides, manipulation on design of the coil will be done by using resonator in experiment work and data will be taken as analysis for the project. After getting all the data from experiment, data will be analyzed and interpreted before reporting and documentation and the details shown in Figure 17 below.

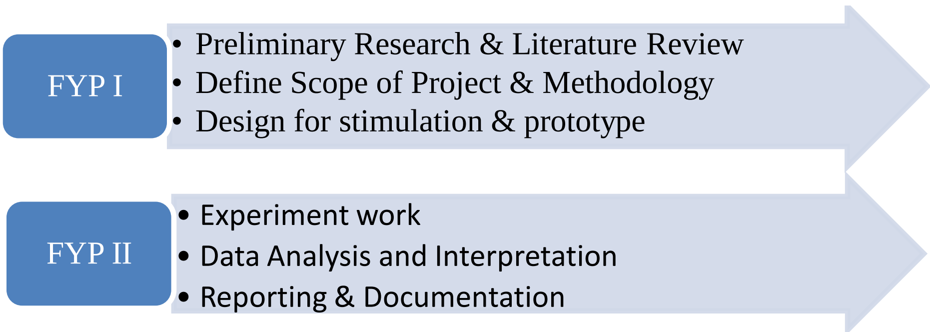
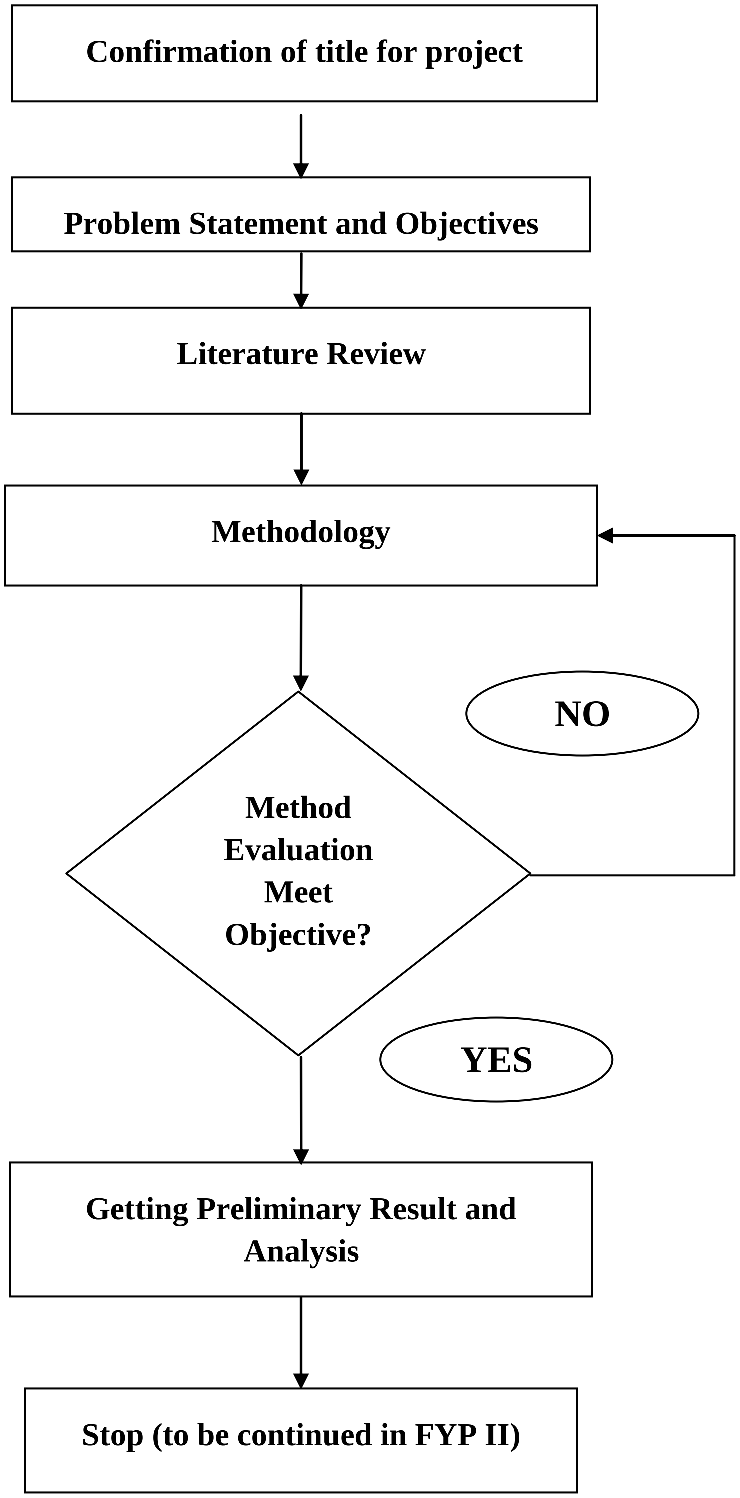
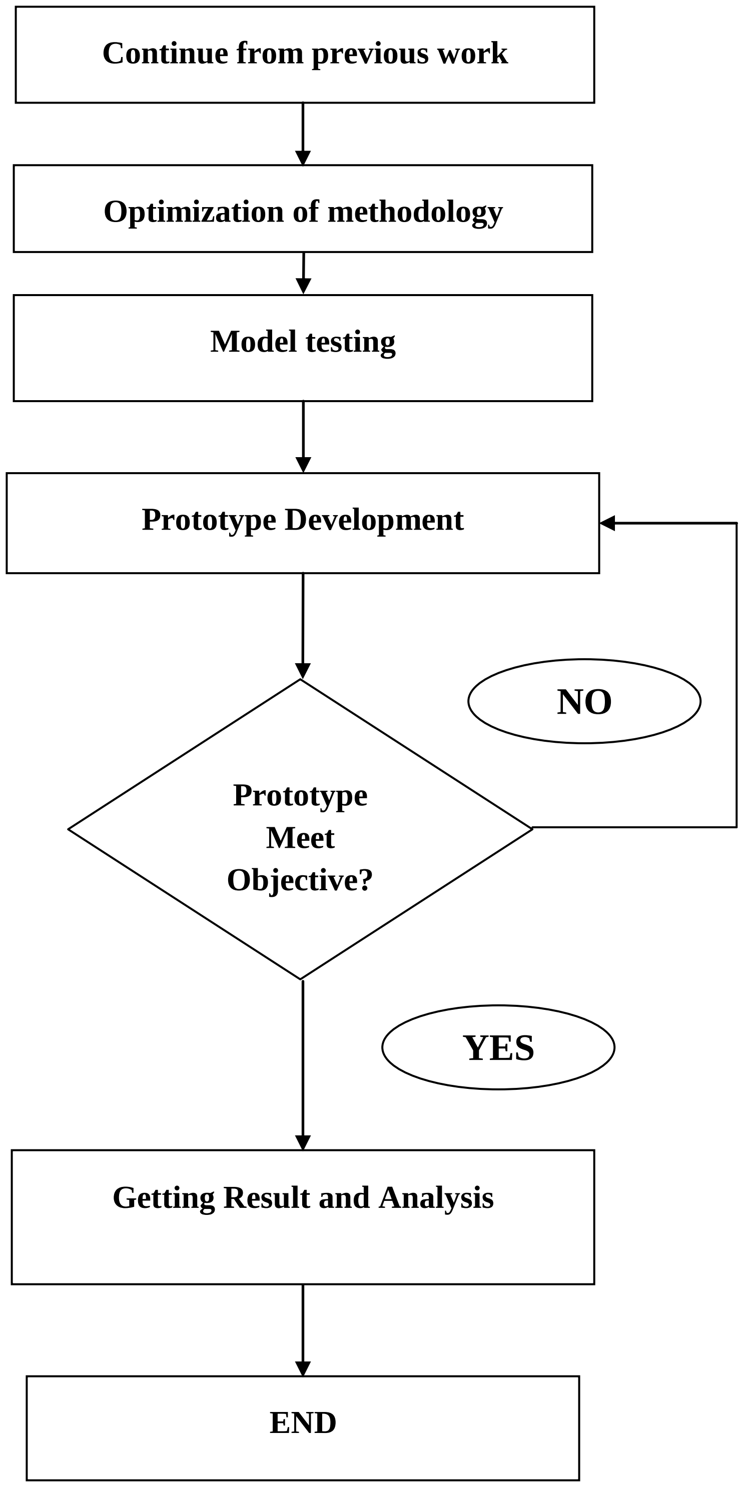


Figure 17: Project Flow in FYP I and FYP II

3.3 Project Flowchart for Final Year Project I



3.4 Project Flowchart for Final Year Project II



3.5 Gantt Chart for FYP I

No	Topic / WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Finalized Selection Project Topic for FYP	■	■												
2	Research Work and Literature Review for Project		■	■	■	■									
3	Attend FYP Talk	■	■	■	■	■									
4	Learn to use experiment set up				■	■	■	■	■	■	■	■	■		
5	Purchase tem and component				■	■	■								
6	Build stimulation and prototype				■	■	■	■	■	■	■	■	■		
7	Test, run and modified circuit				■	■	■	■	■	■	■	■	■		
8	Online Submission of Extended Proposal Defence						■								
9	Preparation for Oral Proposal Defence							■	■						
10	Viva: Proposal Defence and Progress Evaluation									■					
11	Detailed Literature Review								■	■	■	■	■		
12	Preparation of Interim Report			■	■	■	■	■	■	■	■	■	■		
13	Submission of Interim Draft Report													■	
14	Online Submission of Interim Final Report														■

3.6 Gantt Chart for FYP II

No	Topic WEEK	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	Experiment work -manipulate and fix parameters of design circuit -measure and tabulate all the result get														
2	Analysis the changes in result														
3	Writing Progress Report														
4	Data analysis														
5	Writing of final draft report														
6	Completion of dissertation (soft bound)														
7	Writing technical paper														
8	Preparation for Oral Presentation														
9	Completion of dissertation (hard bound)														

CHAPTER 4

METHODOLOGY

4.1 Research Methodology-System Design

The ultimate goal of this project is to design and build a prototype which obeys the principle of magnetic resonance coupling for transmitter and receiver circuits, to transmit energy wirelessly. In this chapter, author will explain comprehensively the way to design and carry out testing for proving the theoretical calculation with experimental works.

4.1.1 High Frequency Oscillator

There are two commonly used oscillators in electronics field, which are for relaxation and sinusoidal applications. For sinusoidal oscillators, Op-Amp operates under unstable state, which result output to oscillate back and forth at a continuous rate. Meanwhile, relaxation Op-Amp operates with some combination of capacitor and resistor, to produce oscillation. To produce high frequency oscillators, relaxation oscillator will be chosen to meet the requirement and ease for design.

4.1.2 DC/RF Amplifier

DC/RF amplifier is used to produce larger output signal which can support the system. When the current is large, the amount of flux which is induced around the coil of transmitter will increase too, and induce the voltage on the receiver coil. There are several types of amplifier which can be used, such as MOSFET which operate in saturation mode.

4.1.3 Impedance Matching Circuit

As shown in Figure 13, impedance matching circuits consist of inductance and capacitor. In order to produce magnetic resonance coupling for transmitter and receiver coils, a number of calculation and formula have been studied and analyzed for further analysis and discussion. For instance, the formula which used to determine the resonance frequency is based on equation (8) and Q, quality factor is based on equation (15). When we use a high frequency power source, the transmitter coil must work in coherence in order to produce resonant frequency within the coils. All the factor must be determine and fix for proper design. We can manipulate by changing the value of impedance of transmitter circuit/ coil, as well as capacitor so the circuit will produce or act as resonator. When the capacitor is fully charged during the ON time of MOSFET, alternating current will flow through the two components and magnetic field will be induced in transmitter coil [16]. During the OFF time, after the capacitor is fully discharged, the energy of magnetic field will generate voltage and convert into electricity [17].

4.1.4 Transmitter and Receiver Coils

Transmitter coil will act as flux supplier, where the flux will be produce from source or voltage supply, while receiver coil will act to capture the flux from transmitter coil and induce emf voltage. This two coils combined is called coupling circuit, where wireless energy transmission will take place. As per discussion above, all the factors parameters such as number of turns, diameter of coil and turn, types of material used as well as the shape will affect the efficiency of the output. The author will change two parameters which are, number of turns and shape, in order to analyze the significant. The result will be tabulated and discuss in the following chapter.

4.2 Procedure/ Steps:

1. **The concept-** One must understand the fundamental principle of induction magnetic such as Faradays' Law and Ampere's Law for a proper design of the circuit.
2. **The circuit**- As discussed in previous section, understanding the whole circuit function is important in order to build a prototype or hardware part. Each component used must be justified by understanding its function properly. In order to enhance the circuit or maintain its functionality, choice of component can vary. For instance, function generator can be replaced by Colpitts Oscillator or any chip which functions similar to it. Besides, calculation part play important role for determining the exact value of resonant frequency, which are related to coil inductor and capacitor value as a whole circuit.
3. **Parts/ Component**- List down all necessary components as materials such as capacitor and IC required. However, the most important part is the wire used to form the transmitter coil and receiver coil. It will play as starting material for every calculation such as resonant frequency, inductance as well as the capacitor value used. As discussed above, there are a number of factor which affect the design of the coil, thus a detail analysis and calculation is needed in this section.
4. **Build Prototype-** After completing the calculation and analysis, proceed to build the prototype according to the design. Bear in mind, no circuit will work at first time, thus a lot of effort and hard work is needed in order to complete to design.
5. **Theoretical Calculation-** In order to prove the efficiency of the circuit designed, the author will conduct several manually calculation based on literature review and equation proven by scientist and professor involved in order to get the measurement needed such as magnetic field, resonant frequency, as well as power and voltage transferred.
6. **Testing/ Experiment-** Experiment work will be conducted in order to get reading using supplicated and high technology equipment such as spectrum analyzer and compare with theoretical value.

4.3 Project Activities-First Draft Design

The author started the first design based on the research and studies and the details is shown in Figure 18 below.

Transmitter and Receiver Coil	Colpitt Oscillator	Power Amplifier	Capacitor
• Enamelled copper wire • Diameter of the wire- ECW0.5, 0.5mm, 25AWG • Number of turn- 20 or 10 turns for each coil • Diameter of turn- 5cm • Shape- Circular	• At first design, Colpitt Oscillator will be used since it is more easy for design and control • For improvement, will be replaced by function generator or IC	• BJT- BD139 • Power amplifier for circuit	• Value will be manipulated by adjusting to produce resonator coherence with coil inductor value • WIMA manufacture company is the best choice, because there are more variety of values and cheaper

Figure 18: List of components and description for first draft design

4.4 Project Activities, Tools and Equipment-Finalized Design

Transmitter and Receiver Coil

Table 1: Parameters of coils

Material	Fiber-glass enameled copper wire
Number of turns for each coils	Five
Diameter of turns	7cm
Diameter of coil	0.09cm
Shape of turns	Circular

Voltage Regulator-79L12

One of the main functions of voltage regulator in the circuit is to maintain the stable output voltage at specific value. It operate by detect the output voltage which set and compare it against an internal reference voltage. The output or error produced by this chip is inverted and compensated. The value of output in this design project is fixed by value of external capacitor and resistor. Besides, it also used to reduce the noise and interference in the design circuit [17].

Power Amplifier-IRF 530

The design of power amplifier in this circuit has been undergone a number of changes and modification. This is due to the failure and significant of important in order to maximize and stabilize the value of output from NE-555 Timer. Thus, at the end of the circuit design, the author use IRF 530 chip, instead of BJT which can minimize the voltage drop and ease to control in amplify mode operation [18].

Trimmer/ Rheostat

The importance of rheostat in this project design is to adjust voltage of the Threshold Pin and Output Pin in the NE-555 Timer. This chip allow author to have more flexible to control the value of output voltage in order to match the circuit design [19].

Inductor

One of the functions of external inductor in transmitter circuit is to get a better and smooth oscillating output from NE-555 Timer. It connect parallel with a capacitor and operate by charging when current pass in on cycle and discharge current when in off cycle.

Resistor

Resistor function as a coherence with capacitor to match inductance value in the coils in order to produce desired resonant frequency value.

Capacitor

The value of capacitor must be determined during the circuit design in order to match the resonant frequency produced in the Trigger Pin in NE-555 Timer chip. Besides, there are also two capacitors used to reduce the noise and smooth the oscillating output voltage in the output of voltage regulator chip and output of NE-555 Timer.

Oscillator-NE555 Timer

In order to produce an oscillator by using 555-Timer chip shown is Figure 19, the author turn run it in astable mode operation. By definition, it means that, the chip will produce a high state (output high), then switch to low state (output low) and continuous this process infinitum, which will produce a square wave signal in a period of time. The following explain how NE-555 Timer works [20];

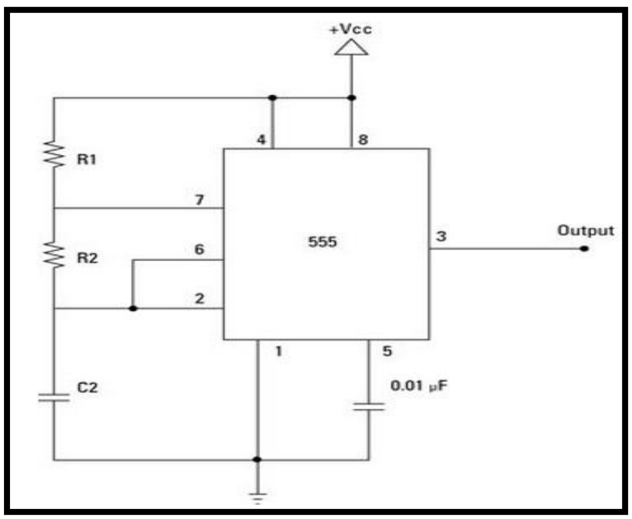


Figure 19: NE 555 Timer

1. During the high state cycle, Discharge Pin (Pin 7) will open circuit connectivity, thus the current will pass through resistor (R2) and capacitor (C1) will charge during this period.
2. As the C1 keeps charging, the voltage at Threshold Pin (Pin 6) and Trigger Pin (Pin 2) will increase.

3. Due to the connectivity of Pin 2, 6 and 7 in series, when the Pin 6 voltage value reaches two-thirds of the supply voltage, the Output Pin (Pin 3) voltage will go to low state.
4. When the Pin 3 is low state, C1 will start to discharge through R2, thus the voltage at Pin 2 and 6 starts to decrease.
5. The trigger circuitry then will cause Pin 3 to go high after the Pin 2 voltage drop to one third of the supply voltage.
6. The cycle will start over and continuously without end as long as there is voltage supply.

Multimeter- Measure voltage value

Oscilloscope- Measure frequency

Spectrum Analyzer with Near Field Probe Set (RF-E and RF1) - Measure magnetic field density, power in decibel value as shown in Figure 20.

Figure 20: Spectrum Analyzer

4.5 Manually Calculation Method and Equation

4.5.1 Resonance frequency

In transmitter circuit, the charging and discharging of the oscillator which based on the design circuit discussed above, effectively causes an oscillating signal to the output. The value and equation greatly affected by the value of time constant, capacitor and resistor in the circuit. The general equation for charing a capacitor is given by [21];

$$q = CV \left(1 - e^{-\frac{t}{RC}}\right) + q_0 e^{-t/RC} \tag{17}$$

where,

$$V = -V_{out} \tag{18}$$

$$q_0 = CV_{out} \tag{19}$$

thus,

$$q = -CV_{out} \left(1 - e^{-\frac{t}{RC}}\right) + \lambda CV_{out} e^{-t/RC} \tag{20}$$

Solve for T,

$$T = 2RC * \ln[\frac{1+\lambda}{1-\lambda}] \tag{21}$$

where $$\lambda = \frac{R_2}{R_2+R_1} \tag{22}$$

From the circuit design, the calculation for frequency at transmitter circuit is shown as below based on equation (21) and (22);

$$T = 2(100k)(270p)\ln[\frac{1+8.4e^{-3}}{1-8.4e^{-3}}] \tag{23}$$

$$= \mathbf{9.07e^{-7}}\textbf{seconds}$$

$$f = 1/T \tag{24}$$

$$= \mathbf{1.1 MHz}$$

The circular loop coil which used in this resonance system which based on Neumann's equation (14), the inductance at receiver coil can be calculated in simplified of equation (13) which is;

$$L = N^2 R u_0 [\ln(\frac{8R}{a} - 1.75)] \tag{25}$$

where, N is number of turns, R is radius of coil, u_0 is permeability constant and a is radius of conductor.

thus,

$$L = 5^2(0.035)4\pi e^{-7}[ln\frac{8(0.035)}{0.0009} - 1.75] \tag{26}$$

$$L = \mathbf{2.015e^{-6}H}$$

$$C = \mathbf{10nF}$$

from equation (8),

$$f = \frac{1}{2\pi\sqrt{(2.015e^{-6})(10e^{-9})}}$$

$$f = \mathbf{1.1MHz}$$

From the calculation shown above, the resonance frequency for this project design is approximate to 1.1MHz. This is definitely a high frequency range to transmit energy between two coils.

4.5.2 Magnetic Flux Density

In this project demonstration, the magnetic flux density will be measured dependent on distance from the source. In a current loop from transmitter coil, the magnetic flux density equation is;

$$B = \frac{u_0 2\pi r^2 I}{4\pi(z^2+r^2)^{3/2}} \tag{27}$$

The result will be calculated from 1cm to 10cm, and tabulated in the following chapter.

4.5.3 Power

One of the most important result in this project is power measurement at transmitter coil, and the power being transfer at receiver coil at difference distance. From the studies conducted by Prof. Marin Soljacic and his team, they concluded that [2], the efficiency of energy transfer for coupled-theory equation is;

$$\frac{da_d}{dt} = -i\left(w - i\Gamma_{d[e]}\right)a_d + ik_{[e]}a_s - \Gamma_{work}\,a_d \tag{28}$$

From energy conservation theorem, the total time-varying power entering the system is;

$$P_{total} = P_{work} + P_{rad} + P_s + P_d + P_e \tag{29}$$

Thus, the working efficiency is then;

$$n_{work} = \frac{P_{work}}{P_{total}} = \frac{1}{1+\frac{\Gamma_{d[e]}}{\Gamma_{work}}.[1+\frac{1}{form\ ^2_{[e]}}(1+\frac{\Gamma_{d[e]}}{\Gamma_{work}})^2]} \tag{30}$$

The result and calculation will done for different parameters of coil and two different value of power setup measurement from 1cm to 10cm. The calculation value will tabulate and compare with the measurement reading by using spectrum analyzer.

4.5.4 Voltage

The value of voltage being induced by secondary coil can be manually calculated by using Maxwell equation (7). Besides, it is proved that, the value does also obeys Ohm's Law.

4.6 Experiment Work

One must prove the theoretical value from calculations are correct by meeting the value measurement from equipment used. Thus, the author has conducted several number of testing and measurement, by using multimeter, oscillator and spectrum analyzer in order to get the reading.

4.6.1 Resonance frequency Measurement

Oscillating frequency can be measure by using oscilloscope. The Figure 21 below show the reading from oscilloscope.

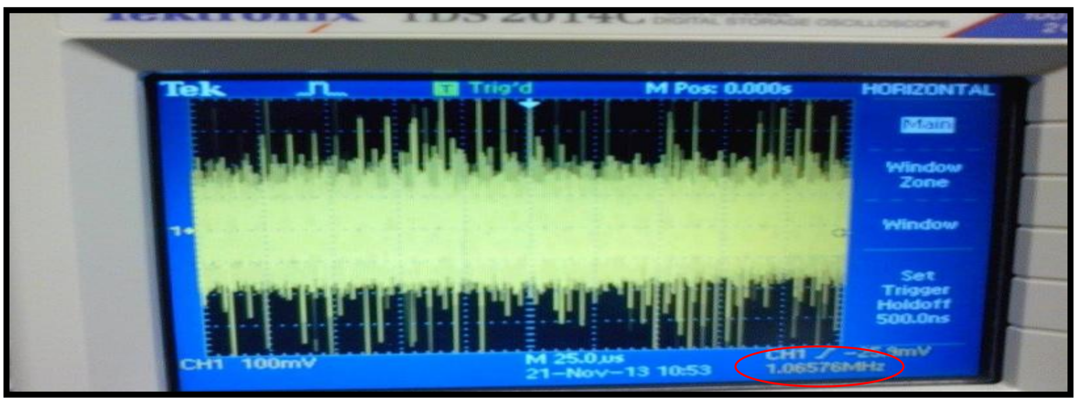


Figure 21: Reading of frequency from oscilloscope

4.6.2 Magnetic Flux Density Measurement

Magnetic flux density can be measured by using spectrum analyzer with Near Field Probe Set-RF1. The Figure 22 and Figure 23 below show the way to measure magnetic flux density at transmitter coil and receiver coil at difference distance respectively. While Figure 24 shows the reading and graph signal from spectrum analyzer display. All the readings are in decidel and will tabulated in the following chapter.

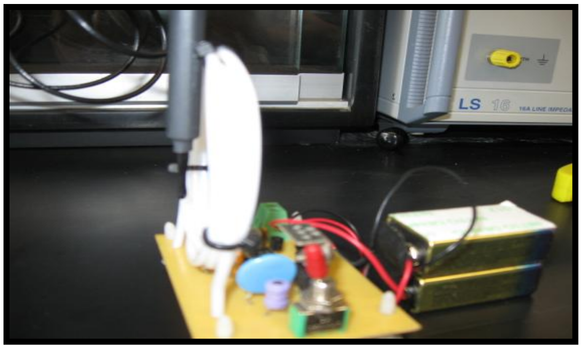


Figure 22: Magnetic flux at transmitter

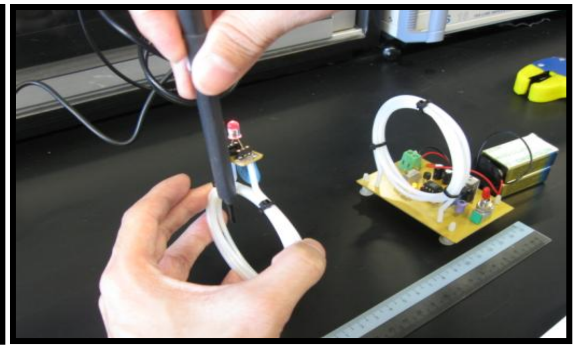


Figure 23: Magnetic flux at receiver

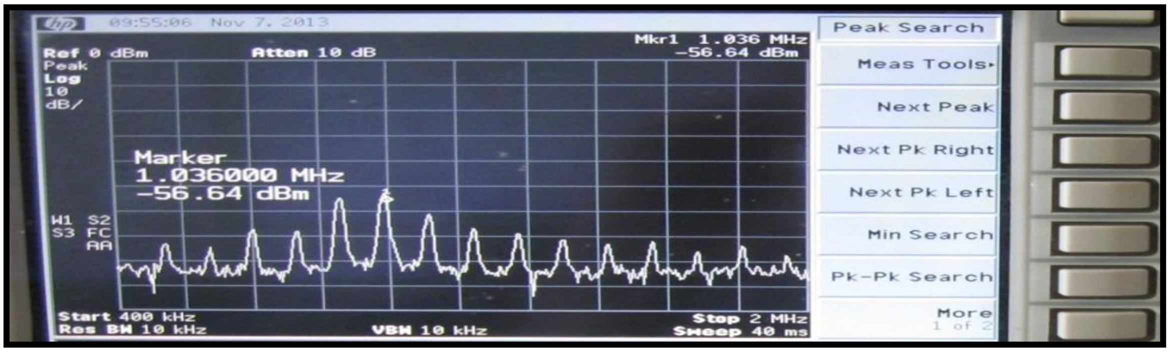


Figure 24: Reading and signal from Spectrum Analyzer display

4.6.3 Power Measurement

Power can also be measured by using spectrum analyzer by using Near Field Probe Set (RF 4-E). The author will measure the power for few different cases such as coil parameter changes and power setup starting from 1cm till 10cm. Figure 25 below shows the reading of power transmitter by using resonator at between the coils.

Figure 25: Power measurement at receiver coil

4.6.4 Voltage Measurement

Voltages can be measure by using multi-meter. Figure 26 below show the voltage reading of receiver coil at 2cm from the transmitter coil.

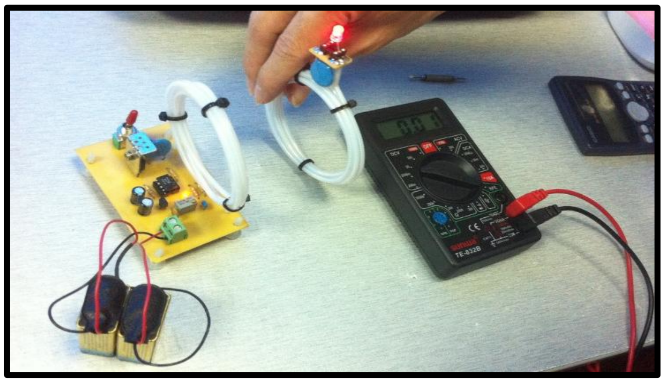


Figure 26: Voltage reading of receiver coil at 2cm from the transmitter coil

CHAPTER 5

RESULT AND DISCUSSION

5.1 Result

Based on the literature review research and analysis, the author has tried several numbers of designs in stimulation in order to build a complete working prototype. A comprehensive and detail overall understanding of the principle and theory work is the main key behind the success of the design.

5.1.1 Stimulation

Firstly, the author used PSpice stimulation to design a transmitter circuit and receiver circuit and run it as shown in the Figure 27 and Figure 28 below respectively. Calculations have been done in order to figure out the value to resistor, capacitor and inductor used in the circuit based on the study from research paper. However, when build the prototype, due to a high voltage drop in the circuit and chips, this design can’t function as desired. Besides, there is also an issue regard the voltage amplifier used in the design circuit. It caused a lot of noise and interference in the process to produce sinusoidal waveform of frequency to transmitter coil. Thus, the overall efficiency is very low and voltage received in receiver coil is less than 2% within a 3cm distance. Due to this reason, the first design circuit needs to languish and a new design and more detail analysis must carry out to overcome all the problems.

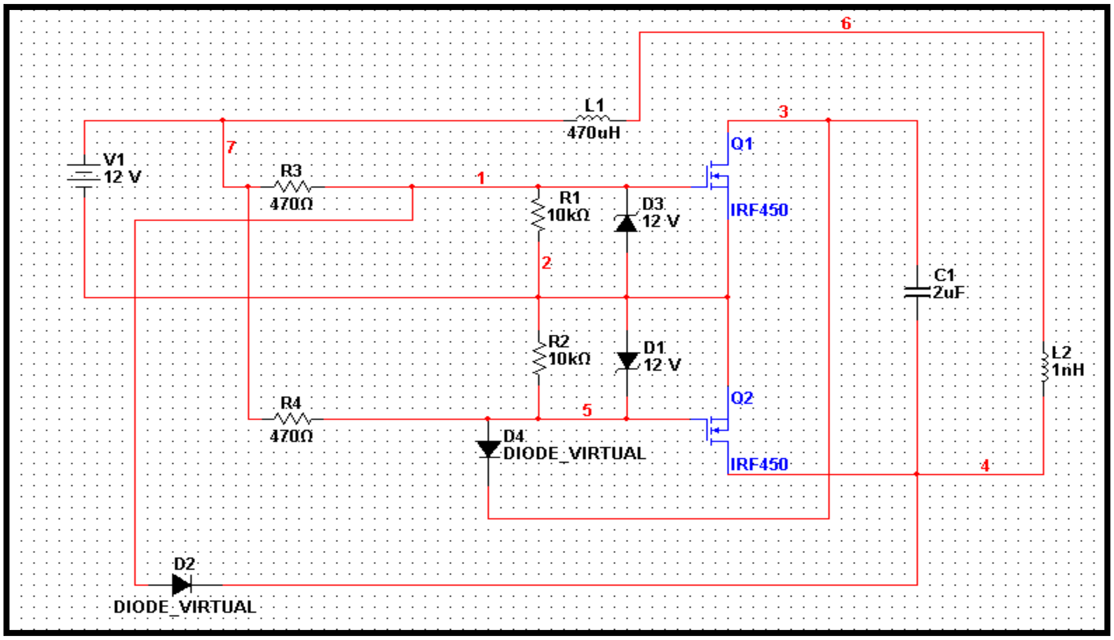


Figure 27: First Draft of Transmitter Circuit in PSpice stimulation

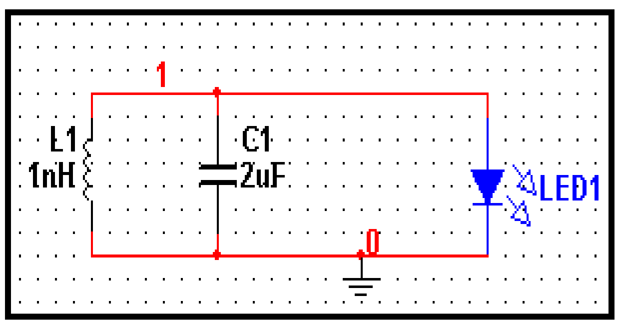


Figure 28: First Draft of Receiver Circuit

Consultation and guidance from supervisor continuously since early stage improve the design circuit from time to time. After a number of efforts and works, the author has modified the design circuit from PSpice into Proteus, and use number of chips such as NE 555 Timer and voltage regulator in order to design a well functioning prototype. As per discussion in methodology chapter above, Figure 29 and Figure 30 shown below are the finalized design for transmitter and receiver circuits respectively. Figure 31 shown below is the finalized prototype of the project after mounting into PCB.

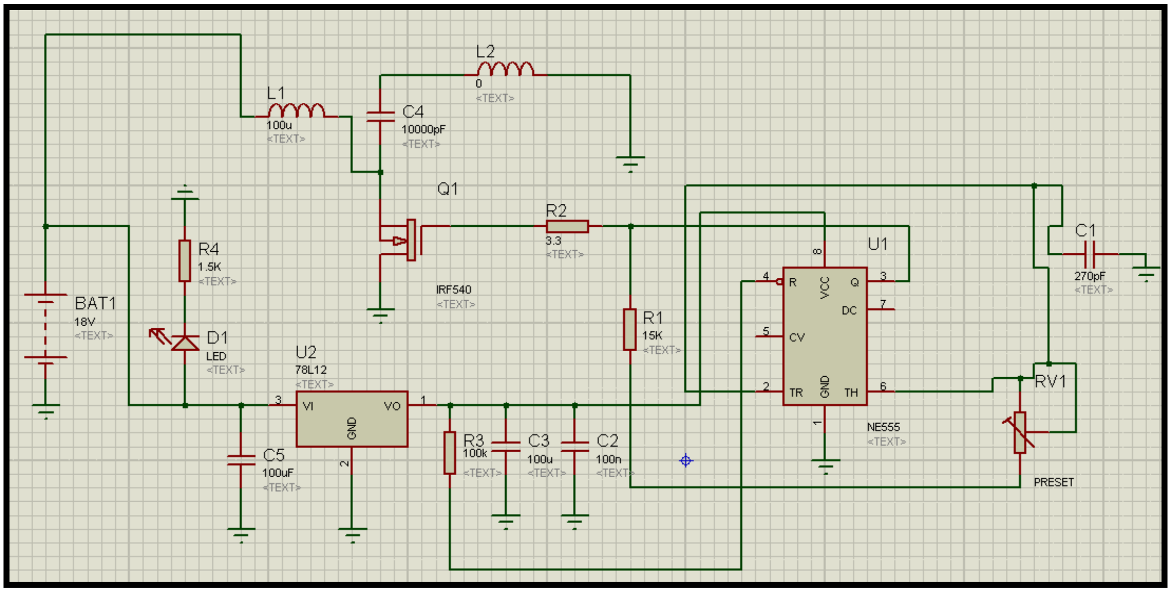


Figure 29: Final design of Transmitter Circuit in Proteus stimulation

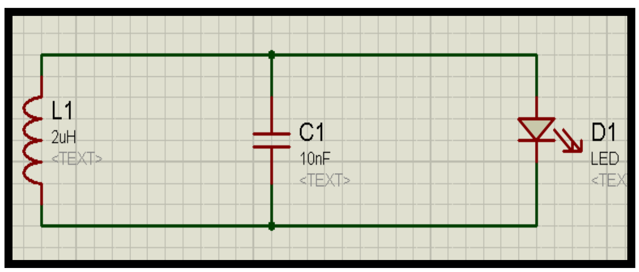


Figure 30: Final design of Receiver Circuit in Proteus stimulation

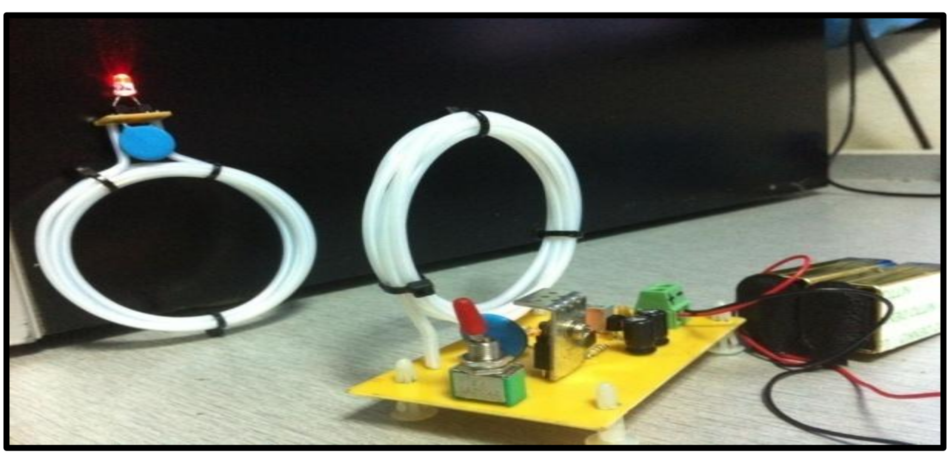


Figure 31: Finalized prototype

5.1.2 Resonance Frequency

From the calculation method and measurement by using oscilloscope, the reading of frequency is around **1.05MHz to 1.10MHz**, which they are both matching each other. It is important to determine the resonance frequency at transmitter and receiver coils because the following result of data will be taken at that particular frequency.

5.1.3 Magnetic Flux Density

The analyses conducted on magnetic flux density are based on standard measurement between transmitter coil and receiver coil starting from 1cm to 10cm distance. The following are the calculation value based on theory and measurement reading by using spectrum analyzer.

Calculation Method and Measurement Reading

The value of magnetic flux density can be manually calculated by using equation (27). The following show the calculation for transmitter coil magnetic flux density;

$$B = \frac{4\pi e^{-7}[2\pi(0.035)^2(0.005)]}{4\pi(0^2 + 0.035^2)^{3/2}}$$

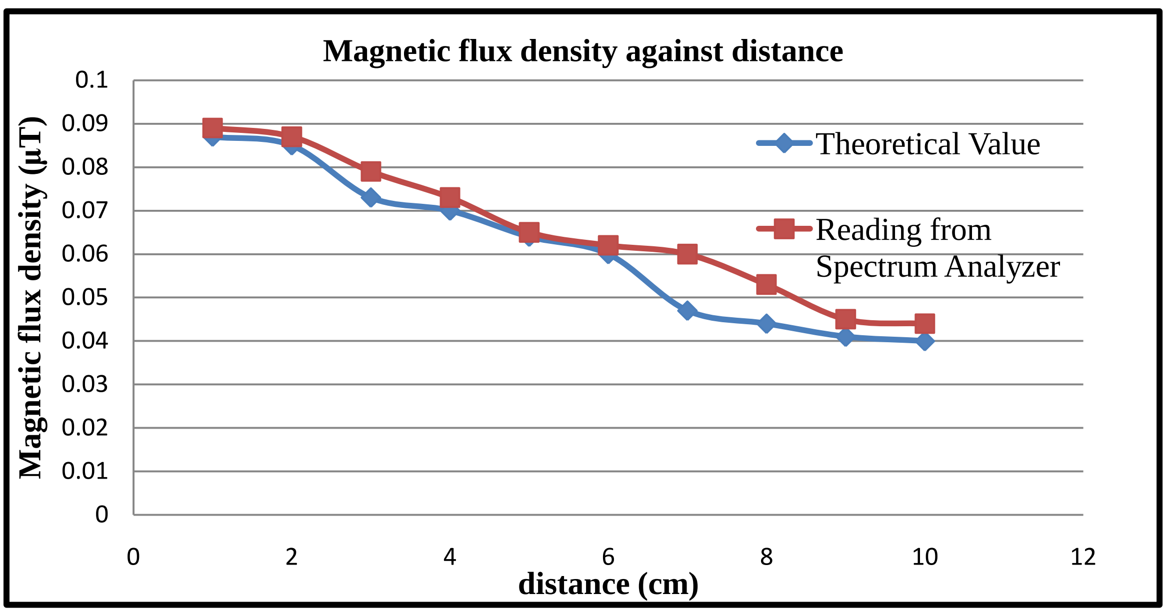
$$= \mathbf{0.09\mu T}$$

Meanwhile the reading of magnetic flux density at transmitter coil (distance=0cm) by using spectrum analyzer is -40.45dBm which equivalent to **0.09μT**. The values of magnetic flux density, at receiver coil at different distance from transmitter coil by using equation (27) and reading from spectrum analyzer will be tabulated in the following Table 2.

Table 2: Magnetic flux density data for calculation method and reading from spectrum analyzer

Distance/cm	Magnetic flux density		
	Calculation/µT	Spectrum Analyzer/ dBm	Spectrum Analyzer/ µT
1	0.087	-40.52	0.089
2	0.085	-40.62	0.087
3	0.073	-41.01	0.079
4	0.070	-41.34	0.073
5	0.064	-41.86	0.065
6	0.060	-42.06	0.062
7	0.047	-42.21	0.060
8	0.044	-42.74	0.053
9	0.041	-43.46	0.045
10	0.040	-43.58	0.044

In order to compare two results vividly, the following Graph 1 shows the comparative result;



Graph 1: Comparison between theoretical calculation and reading from spectrum analyzer for magnetic flux density with respect to distance

The result and graph above illustrate that value from theoretical value and measurement by spectrum analyzer are matching each other. This proves that, the prototype is well designed for the analysis and study of this project.

5.1.4 Power

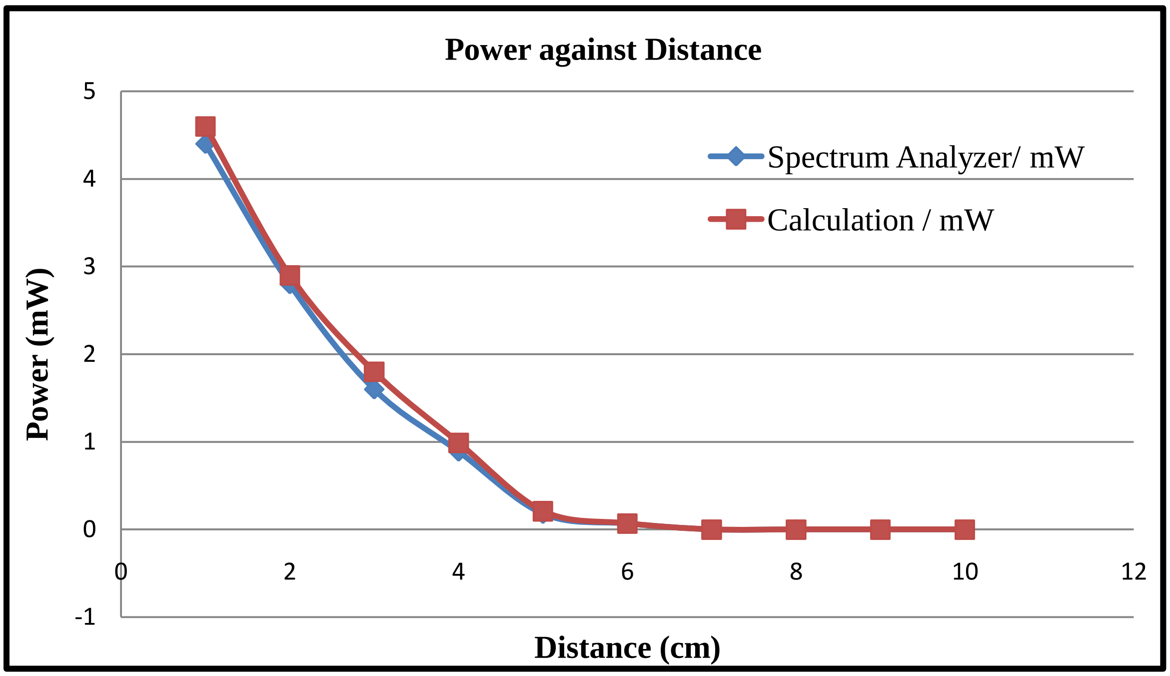
There is several comparison and experimental works done in order to put higher emphasize on power measurement. The followings are four different experiment works comparing theoretical calculation value against reading measured by using spectrum analyzer, power setting at transmitter circuit for two cases which are at resonance and not resonance coupling, and last but not least, by changing the number of turns and shape of resonators in order to carry out the experimental work.

Analysis on theoretical calculation against reading by using spectrum analyzer

The power being transmitted by transmitter coil can be calculated by using equations (28) and (30). The Table 3 and Graph 2 below shows the comparison of calculation value with reading using spectrum analyzer with respect to 1cm till 10cm distance of receiver coil from transmitter coil.

Table 3: Power data by using calculation method and reading from spectrum analyzer

Distance/cm	Power		
	Calculation/ mW	Spectrum Analyzer/ dBm	Spectrum Analyzer/ mW
1	4.641	6.450	4.421
2	2.972	4.490	2.864
3	1.851	2.020	1.628
4	0.992	-0.470	0.891
5	0.211	-7.390	0.183
6	0.069	-11.74	0.067
7	0.0001043	-40.03	0.0000993
8	0.0000279	-46.63	0.0000217
9	0.0000140	-48.72	0.0000134
10	0.0000112	-49.70	0.0000107



Graph 2: Comparison between theoretical calculation and reading from spectrum analyzer for power with respect to distance

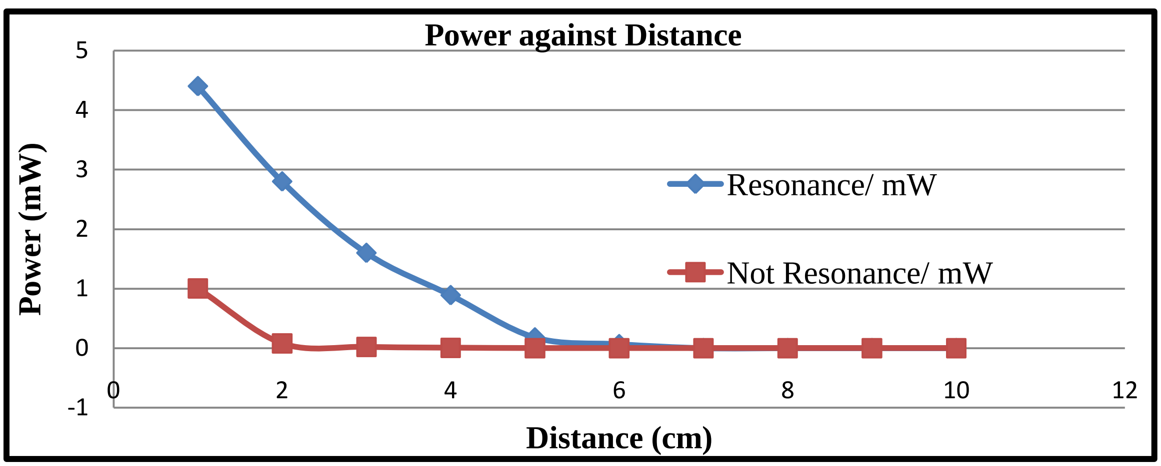
The graph above vividly shows the power transfer decrease exponentially with distance and theoretical calculation well match with result using spectrum analyzer. Both results show power transmission is maximum at 1cm distance with 4.5mW and almost zero when distance increases 5cm apart.

Analysis resonance and non-resonance circuits

In order to prove the significant of resonance coupling principle for wireless energy transmission, the author has set the transmitter circuit into resonance and non-resonance transmitter circuit by adjusting the trimmer. Table 4 and Graph 3 below show power measured at receiver coil with respect to different distance from transmitter coil.

Table 4: Result for power based on two power setup

Distance/cm	Power			
	Resonance/ dBm	Resonance/ mW	Not Resonance/ dBm	Not Resonance/ mW
1	6.450	4.400	0.020	1.005
2	4.490	2.800	-10.97	0.080
3	2.020	1.600	-16.89	0.0205
4	-0.470	0.890	-22.07	0.00621
5	-7.390	0.180	-38.38	0.000145
6	-11.74	0.067	-47.98	0.000016
7	-40.03	0.0000993	-59.37	0.000001
8	-46.63	0.0000217	-70.38	9.162E-08
9	-48.72	0.0000134	-89.05	1.244E-09
10	-49.70	0.0000107	-106.97	2.011E-11



Graph 3: Result for power based on two power setup

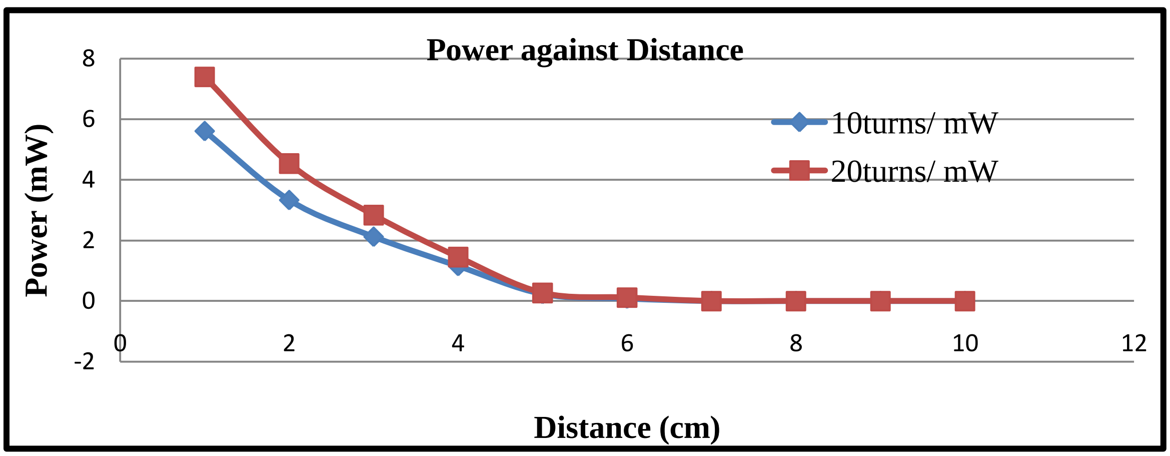
The graph above shows power able to transfer much efficiency when the coils are tuned at resonance frequency. At 1cm distance, resonance circuit able to transfer 4.4mW while non-resonance circuit just around 1mW.

Analysis on number of turns of resonators

As discussed in literature review, the number of turns of the coils will affect greatly on the wireless energy transmission. Thus, the author compares the measurement of power by using 10turns and 20turns number of turns of resonators. The following Table 5 and Graph 4 show the result by using spectrum analyzer.

Table 5: Result for power based on numbers of turns of resonators

Distance/cm	Power			
	10turns/dBm	10turns/ mW	20turns/ dBm	20turns/ mW
1	7.490	5.610	8.690	7.396
2	5.230	3.334	6.570	4.539
3	3.270	2.123	4.530	2.838
4	0.630	1.156	1.620	1.452
5	-6.310	0.234	-5.70	0.269
6	-10.90	0.081	-9.390	0.115
7	-38.35	0.000146	-37.07	0.000196
8	-44.07	0.000039	-43.35	0.000046
9	-46.03	0.000025	-44.97	0.000032
10	-48.05	0.000016	-47.14	0.000019



Graph 4: Result for power based on numbers of turns of resonators

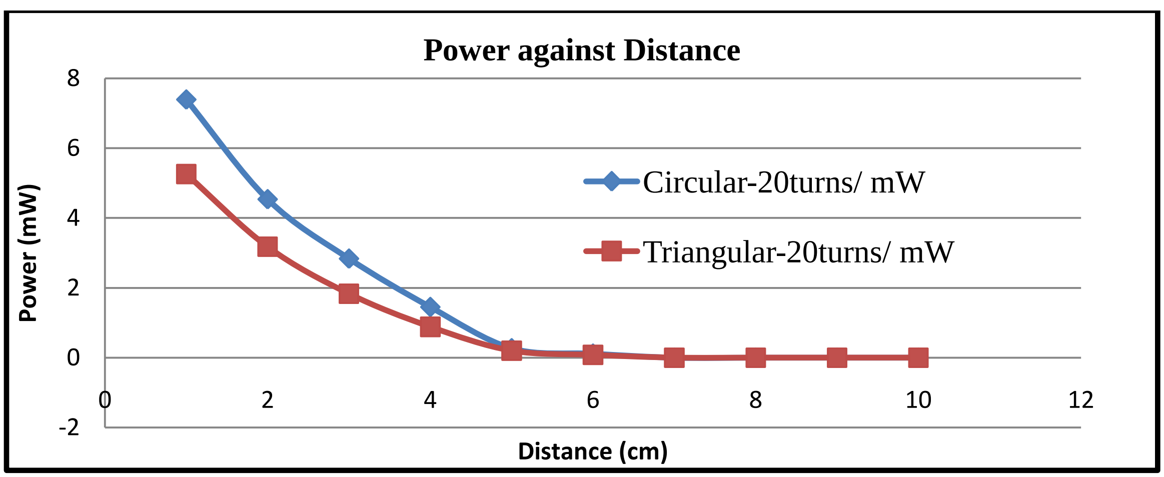
The result above shows, the greater number of turns of coils, the higher amount of power can be transfer efficiency. 10turns and 20turns of coils able to transmit 5.6mW and 8.7mW respectively at 1cm, but both reach zero at 5cm distance.

Analysis on shape of resonators

The shapes of coils do also affect the efficiency of this project. Table 6 and Graph 5 show the result of using circular and triangular shape of resonators.

Table 6: Result for power based on the shapes of resonators

Distance/ cm	Power			
	Circular-20turns/ dBm	Circular-20turns/ mW	Triangular-20turns/ dBm	Triangular-20turns/ mW
1	8.690	7.396	7.210	5.260
2	6.570	4.539	5.020	3.177
3	4.530	2.838	2.630	1.832
4	1.620	1.452	-0.540	0.883
5	-5.70	0.269	-6.990	0.200
6	-9.390	0.115	-10.98	0.080
7	-37.07	0.000196	-39.06	0.000124
8	-43.35	0.000046	-44.92	0.000032
9	-44.97	0.000032	-46.92	0.000020
10	-47.14	0.000019	-48.51	0.000014



Graph 5: Result for power based on two shapes of resonators

The result above illustrates circular shape able to transfer power more efficiently compare to triangular shape of coils. Both graphs show power transmission decrease exponentially as distance increase.

5.1.5 Voltage

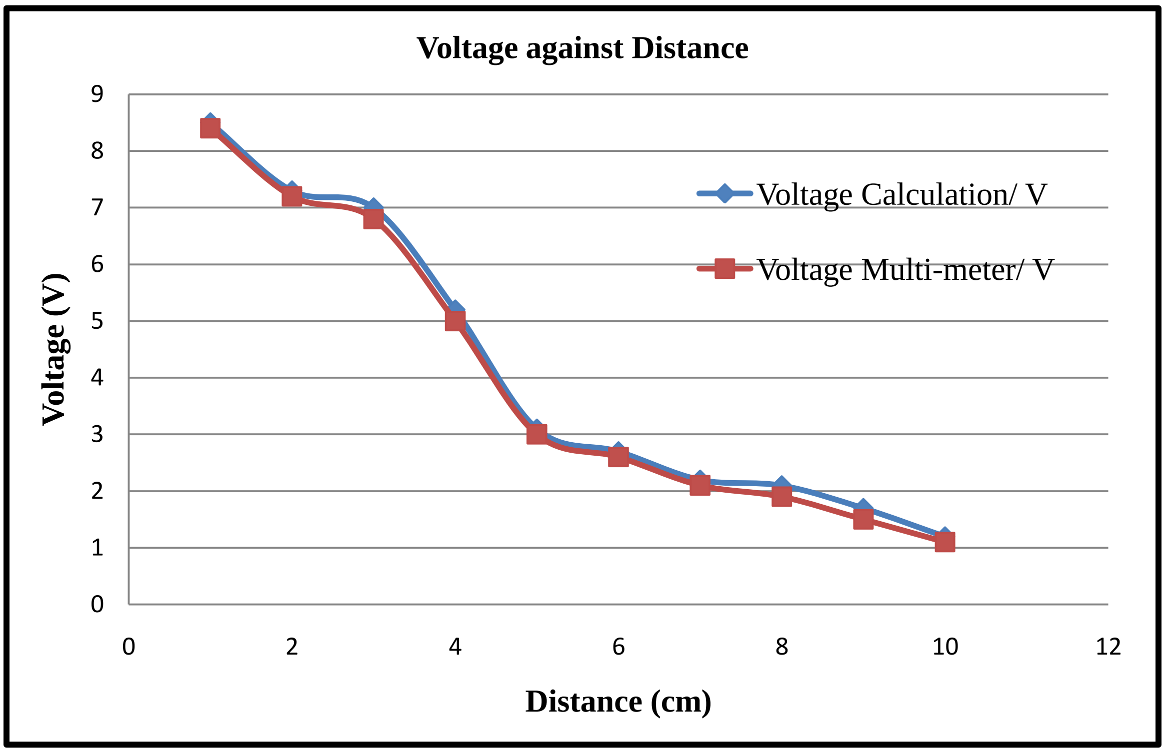
In this section, the author will emphasize on the voltage induced in the secondary coil. In order to measure voltage, the author replaced LED with resistor as load. The followings are four different experiment works which are theoretical calculation value against reading measure by using multimeter, comparison between resonance and non-resonance circuits, and last but not least, by changing the number of turns and shape of resonators in order to carry out the analysis work. The data and result is tabulated in tables and graphs below.

Analysis on theoretical calculation against reading by using spectrum analyzer

Theoretical calculation for voltage can be calculated by using Maxwell equation, equation (7). The Table 7 and Graph 6 below shows the comparison of calculation value with reading using multi-meter with respect to 1cm till 10cm distance of receiver coil from transmitter coil.

Table 7: Voltage results by calculation and reading using multimeter

Distance/cm	Voltage	
	Calculation/ V	Multi-meter/ V
1	8.5	8.4
2	7.3	7.2
3	7.0	6.8
4	5.2	5.0
5	3.1	3.0
6	2.7	2.6
7	2.2	2.1
8	2.1	1.9
9	1.7	1.5
10	1.2	1.1



Graph 6: Result for voltage based on manually calculation and reading using multimeter

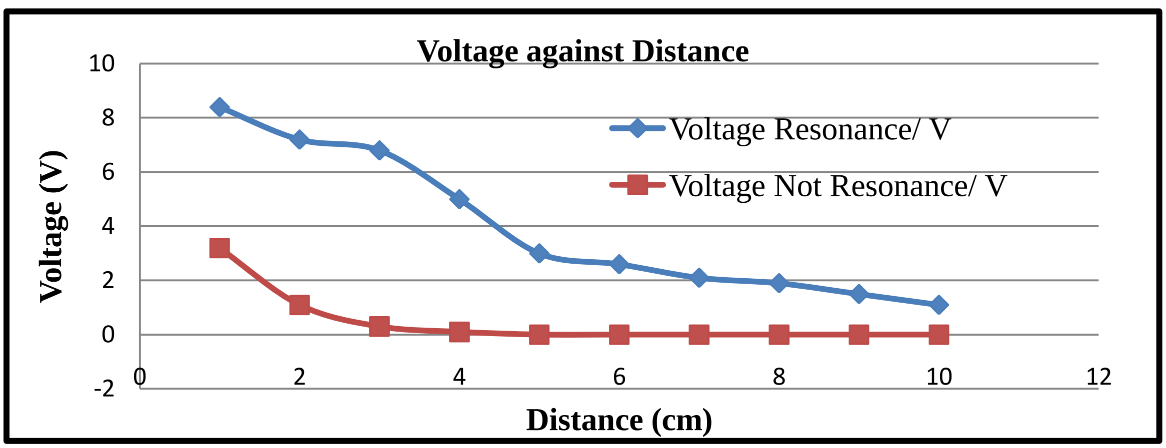
The result above illustrates the method for theory calculation and measurement using multimeter well match each other. Voltage can be induced at 8.5V at 1cm distance but decrease exponentially with distance increase between transmitter and receiver coils.

Analysis on resonance and non-resonance circuits

As per discussion in power measurement, the author do also measure voltage values to show the comparison and significant of resonance setting. The Table 8 and Graph7 below shows the comparison of two power setting of transmitter circuit and measure voltage induced in receiver coil at 1cm till 10cm distance of receiver coil from transmitter coil.

Table 8: Voltage results based on resonance and non-resonance transmitter circuit

Distance/cm	Voltage	
	Resonance/ V	Not Resonance/ V
1	8.4	3.2
2	7.2	1.1
3	6.8	0.3
4	5.0	0.1
5	3.0	0.0
6	2.6	0.0
7	2.1	0.0
8	1.9	0.0
9	1.5	0.0
10	1.1	0.0



Graph 7: Result for voltage based on resonance and non-resonance circuit

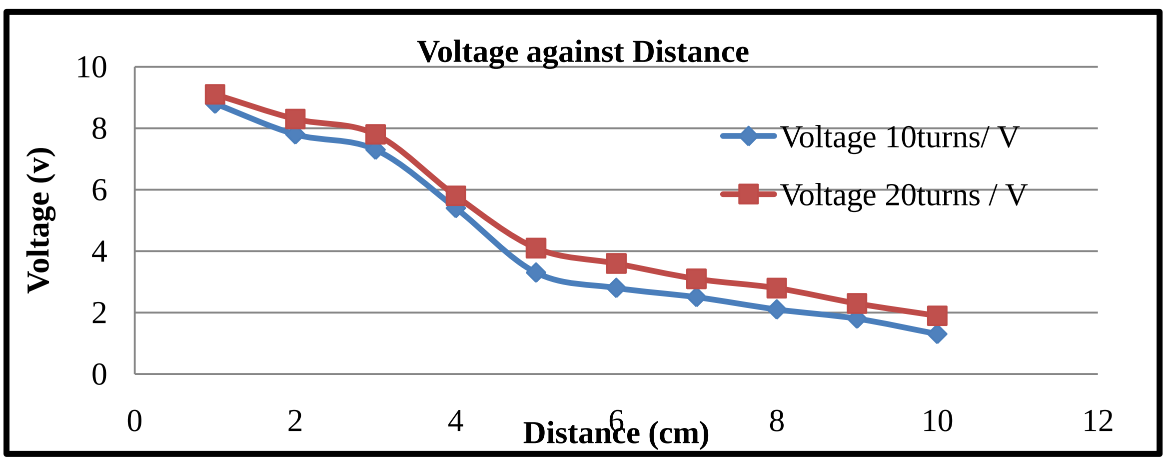
Results above vividly show resonance coils able to reach a higher efficiency to transmit voltage. Resonance circuit can transmit 8.4V while non-resonance just only transmits 3.2V at 1cm distance. This directly shows the significant of Witricity's concept to overcome the traditional magnetic induction principle.

Analysis on number of turns of resonators

As discussed in literature review, the number of turns of the coils will affect greatly on the wireless energy transmission. Thus, the author compares the measurement of voltage by using 10turns and 20turns number of turns of resonators. The following Table 9 and Graph 8 show the result of using 10 and 20turns resonators by using multi-meter.

Table 9: Voltage data for 10turns and 20turns of resonators

Distance/cm	Voltage	
	10turns/ V	20turns / V
1	8.8	9.1
2	7.8	8.3
3	7.3	7.8
4	5.4	5.8
5	3.3	4.1
6	2.8	3.6
7	2.5	3.1
8	2.1	2.8
9	1.8	2.3
10	1.3	1.9



Graph 8: Voltage results based on number of turns of resonators

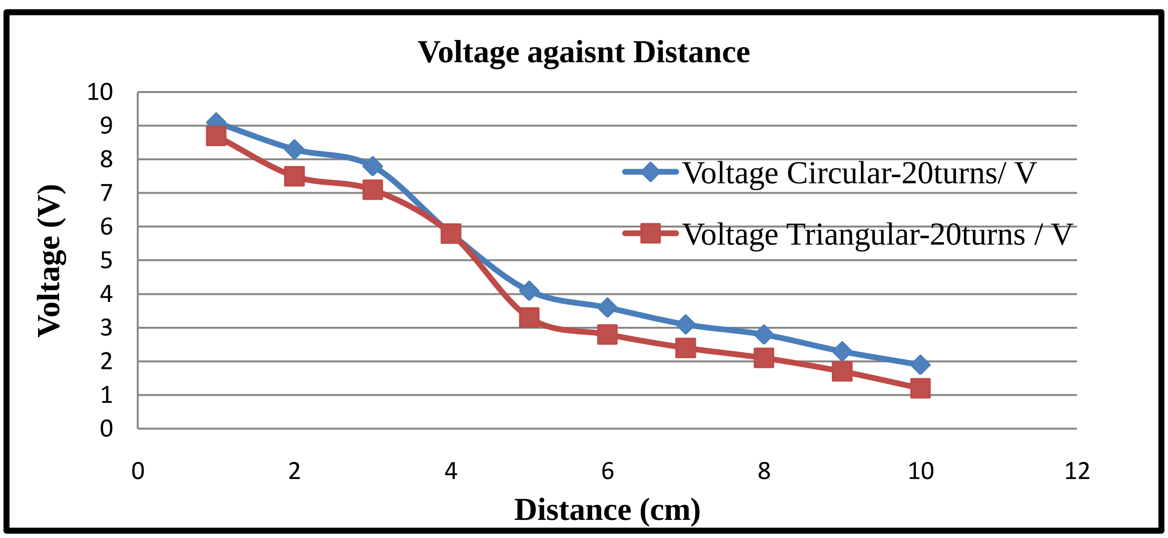
The result above shows, the more number of turns of coil, the better efficiency of voltage can be transfer. Coil with 10turns able transfer 8.8V while 20tunrs able to transfer 9.1V at 1cm, and both transfer around 2V when approaching 10cm distance apart.

Analysis on shape of resonators

The shapes of coils do also affect the efficiency of this project. The followings Table 10 and Graph 9 are the result taken.

Table 10: Result of voltage based on shape of resonators

Distance/cm	Voltage	
	Circular-20turns/ V	Triangular-20turns / V
1	9.1	8.7
2	8.3	7.5
3	7.8	7.1
4	5.8	5.8
5	4.1	3.3
6	3.6	2.8
7	3.1	2.4
8	2.8	2.1
9	2.3	1.7
10	1.9	1.2



Graph 9: Result of voltage based on shape of resonators

The result above illustrates circular shape of coils can transfer voltage more efficiently compare to triangular shape with 9.1V compare to 8.7V at 1cm distance.

5.2 Discussion

Analysis from the studies on four most important findings which are resonance frequency, power, voltage and magnetic field carry out in order to achieve this project. From the experiment work done and result from data taken, it obviously shows that, magnetic resonance coupling theory gives a better result for wireless power transfer in term of efficiency and distance covered. Such technology can also be worked even there is an obstacle between the two coils, which directly prove resonance plays an important roles to transmit energy wirelessly in a more wide application. However, when the distance is further increased, the efficiency will decrease which it happens by the output value decay exponentially as the distance between the coils is increased up to a certain value. Although the input source is 18V, due to some voltage drop in transmitter circuit, the efficiency will be less than 100%.

The method of proof in which the fact and known truth is sought as consequences by theoretical calculation works done through theoretical analysis are matching to value obtained from measurement using spectrum analyzer for power measurement and multimeter for voltage readings. This proves that, the fundamental principles are correct in this project design. Apart from that, analysis and interpretation of magnetic flux density prove magnetic resonance coupling direct energy in a single direction in order to minimize the power loss to environment. The results show, the magnitude to magnetic flux density almost remains constant even though the distances between the coils are increasing. At 10cm distance apart, the magnitude of magnetic flux density just deflects approximately by 50% only. While from other directions, the result or value of magnetic flux density remain constant approximate zero magnitude.

Besides, a more detail and comprehensive experiment work done by dissection of coils parameter which are number of turns and shape of coil itself. The results prove, as the number of turns increase, the higher efficiency of energy transmission. This directly involves the fundamental principle of Maxwell equation, where magnetic field directly proportional to number of turns and current flows. The results show, there is an approximately increase by 5% in higher efficiency for wireless energy transmission by using 20turns of coil compare to 10turns. The author can conclude the same shape of coils will give a better efficiency as shown from the results. The overall efficiency is increase approximately by 40% if circular shape of resonator used instead of triangular. However, the findings show the power transmission approximately zero when the distance increase to 5cm. The reason behind is due to power loss to environment increase as the distance increase. As the magnitude of magnetic flux density deflects much less than voltage when the distance increases, the current assume to be remain constant. However, as a fact, power loss to environment is increase directly proportional to square of current. Thus, this directly contributes to a higher power loss when the current is higher compare to voltage.

CHAPTER 6

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

As a conclusion, the aim and target of this project is to create a comprehensive study of resonant magnetic coupling for wireless energy transmission in a greater efficiency and distance. The intense literature review has been gone through to analyze the principle and theory for this project to achieve the objectives. Project Gantt chart as well activities flow act as a guideline for the author to complete the task and project successfully within the time frame. The result from the experiment has proved the principle of the resonance magnetic to transfer energy wirelessly more efficiently and over a longer distance.

The parameters of the transmitter coil and receiver coil such as number of turns and its shape have been controlled and set in the studies for brief interpretation of Witricity concept. The author varied them in order to have a more detail and comprehensive analysis and research on this technology to come out with different result and data for better well-rounded study. Besides, the resonance frequency value can be manipulated by trimmer used in transmitter circuit as well as the factors that determine the inductance value in the coil.

All in all, this paper comprehensively analyzes and interprets the research on wireless energy transmission via magnetic resonance coupling by using prototype demonstration and experiment work done. The theory analysis and the experimental result proved that energy transfer is feasible using the technology of magnetic coupling resonance and which will excite more application in the future.

6.2 Recommendation and Future Work

Research work and progress for this new technology will never end, since there are a lot of spaces for further development. After a comprehensive analysis of theory and principle, the author too also designed circuits and built prototype in order to test and prove the principle of wireless energy transmission by using resonant magnetic coupling. As a venue of future study, research and experimental work such as impedance matching, critical coupling, and power efficiency can be carried out to make this technology more practical and minimize the power loss to environment. Besides, analysis and work can be further carry on the way to manipulate and control the direction of magnetic flux density and magnitude by more detail and comprehensive studies. Furthermore, the range of applicability could be extended to acoustic systems, where this technology is applicable to more usage.

REFERENCES

[1] Teck Chuan Beh, Masaki Kato, Takehiro Imura, and Yoichi Hori, *Wireless power transfer system via magnetic resonant coupling at restricted frequency range- Fixing resonance frequency with impedance matching,* University of Tokyo, Departments of Electrical Engineering and Advanced Energy, 2010

[2] Andre Kurs, Aristeidis Karalis, Robert Moffatt, J.D. Joannopoulos, Peter Fisher, and Marin Soljacic, *Wireless power transfer via strongly coupled magnetic resonances.*Science 317 (5834): 83-86 (July 2007)

[3] C.Zhu, K.Liu, C.YU, R.Ma, and H.Cheng, "*Stimulation and experimental analysis on wireless energy transfer based on magnetic resonances,"* in Vehicle Power and Propulsion Conference, 2008. VPPC'08. IEEE, Sept.2008, pp.1-4

[4] A.Karalis, A.Kurs, R.Moffatt, J.D.Joannopoulos, P.H.Fisher, and M.Soljacic, United States Patent: *Wireless Power Transfer,* Patent no US7825543B2, Nov. 2, 2010.

[5] Alanson P. Sample, David A. Meyer, and Joshua R. Smith, *Analysis*, *experimental result and range adaptation of magnetically coupled resonator for Wireless Power Transfer*,IEEE Transactions on industrial electronics vol 58, no2, febbraio 2011.

[6] H.L.Chan, K.W.E Cheng, and D.Sutanto, *Calculationsof inductances of high frequency air-core transformers with superconductor windings for DC-DC converters*, IEEE Proceedings Electric Power Application, vol 150, no4, luglio 2003.

[7] S.Suzuki, T.Katane, H.Saotome and O.Saito, *Electric power generating system using magnetic coupling for deeply implanted medical electronics devices,*IEEE Trans.Magnetic, vol 38, pp. 3006-3008, Sep.2002

[8] Z.Tang, R.J.Sclabassi, C.Sun,S.A.Hackworth, J.Zhao, X.Cui, and M.Sun, *Tramscutaneous battery recharging by volume conduction and its circuit modeling,* IEEE Int. Conf. of Eng. in Medicine and Biology Society, pp.644-647, Sep.2006

[9] Aristeidis Karalis, J.D. Joannopoulos, and Marin Soljacic, *Efficient wireless non-radiative mid-range energy transfer,* 2008.

[10] Arthur Charych, *System and method for wireless electrical power transmission,* US patent no6,798,716

[11] Rohan Bhutkar and Sahil Sapre, *Wireless energy transfer using magnetic resonance*, Second International Conference on Computer and Electrical Engineering, 2009

[12] S.L. Ho, Junhua Wang, W.N.Fu, and Mingui Sun, *A comparative study between novel Witricity and traditional inductive magnetic coupling in wireless charging*, IEEE Transactions on Magnetics, Vol. 47, No.5, May, 2011

[13] Duccio Gallichi Nottiani, and Fabio Leccese, *A simple method for calculating lumped parameters of planar spiral coil for wireless energy transfer*, IEEE, 2012

[14] Lin, J.C *Space Solar Power Stations, Wireless Power Transmissions, and Biological Implications,* Microwave Magazine, IEEE, vol 3, Issue 1, page 36-42, March 2002

[15] Neha Bagga, Joshua Gruntmeir, Samuel Lewis, *Wireless Power Transmission,* Dec.2004

[16] B.Jiang, J.R.Smith, M.Philipose, S.Roy, K. Sundara-Rajan, and A.V. Mamishev, *Energy scavenging for inductively coupled passive RFID systems,* IEEE Trans.Instrum. Meas., vol 56, no 1, pp.118-125, Feb. 2007

[17] RamRakhyani, A.Kumar, Mirabbasi, Shahriar, and Chiao.Mu, *Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants*, IEEE Transactions on biomedical circuits and system, Jan 24, 2011

[18] J. Hirai, T.W. Kim, and A.Kawamura, *Wireless transmission of power and information for cable less linear motor drive,* IEEE Trans. Power Electron., vol 15, no. 1, pp. 21-27, Jan. 2000

[19] A. Kurs, R.Moffatt, and M. Soljacic, *Simultaneous mid-range power transfer to multiple devices,* Appl. Phys. Lett., vol 96, no. 4, p. 044102 Jan.2010

[20] W.Fu, B.Zhang, D.Qiu, and W.Wang, *Analysis of transmission mechanism and efficiency of resonance coupling wireless energy transfer system,* in Proc. Int. Conf. Elect. Mach. Syst., Wuhan, China, Oct. 17-20, 2008, pp. 2163-2168

[21] Q.Yuan, Q.Chen, L.Li, and K.Sawaya, *Numerical analysis on transmission efficiency of evanescent resonant coupling wireless power transfer system,* IEEE Trans. Antennas Propag., vol. 58, no.5, pp. 1751-1758, May 2010

[22] J.S. Mandip, and H. Joey, *Wireless Power Transmission Using Magnetic Resonance*, Cornell College PHY312, Dec 2011

[23] Witricity Electricity Company [Online] Available: http://www.witricity.com/