Wireless Power Transmission With Brook's Coil Adaptation and Class E Power Amplifier

by

Lum Jian Kai

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

MAY 2014

Universiti Teknologi Petronas

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Electrical & Electronics Engineering Programme
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Approved:

____

IR. Dr. Perumal Nallagownden
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

MAY 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 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.

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LUM JIAN KAI

ABSTRACT

Wireless Power Transmission (WPT) via Magnetic Resonance Coupling will be the future method in transmitting electrical power. The vision of transferring power wirelessly will provide a solution to power equipments in unreachable areas. Success of WPT depends on distance of power transmission which requires great improvement. This project propose a multilayer Brook's coil design and class E power amplifier to increase transmission distance. The use of zero voltage switching MOSFET operation in a 375kHz class E power amplifier, serves to reduce power loss and increase current supplied to transmitter coil. A DC voltage of 13.34V was obtained at 30cm with 3.068mW power output at receiver end. This resulted to 15 times increased in transmission distance from previous project. Maximum output power achievable for this project was 418mW at 10cm transmission distance.

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6th -7th August 2014

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ACKNOWLEDGEMENTS

I would like to express my deepest gratitude and appreciation to IR. DR. Perumal Nallagownden for his guidance and support throughout this project. His advice in progressing this project have been a valuable knowledge and experience for me to take into my future undertakings.

My gratitude extends to all lecturers in Electrical and Electronics Engineering Department that have equipped me with all the knowledge and skills, both technical and my personal development through this 4 years of degree course. The patience and openness in advising me is greatly appreciated.

I would also like to thank all lab technicians for their full support in the completion of this project and friendliness that made this project more meaningful.

Finally, the utmost important appreciation goes to my family for their impeccable support and encouragement throughout my life.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Wireless power transmission(WPT) dates back to 1899 where Nikola Tesla designed the Wardenclyffe Tower with the sole purpose to use resonance effect in transmission of electricity [1],[2],[3],[4]. From that stand point, many research was developed and conducted to successfully transmit power wirelessly. The consideration on using antenna technology for this purpose have seen many challenges despite the long distance power transfer capability. Challenges include effects of earths atmospheric conditions and the technology's side effect on living organisms [1].

With that, the wireless technology strives for success in using magnetic resonance coupling in which is acknowledged to be the most efficient technique in WPT that are not affected by the antenna's setback, capable within the middle range transmission distance [1]. In 2007, Massachusetts Institute of Technology(MIT) have demonstrated successfully, the usage of magnetic resonance coupling by lighting a 60W bulb from a distance of 2 meters apart between transmitter and receiver coils and have since moved on in setting up Witricity, a company that develops WPT products for the commercial market. The application since then have been many which include charging electric vehicle and smart phones wirelessly to name a few [1],[3],[4],[5],[6]. However, the distance remain in the mid range level and position between the transmitter and receiver are required to be rigidly aligned for energy transfer.

There are many other research conducted since MIT's breakthrough, mostly targeted at increasing power transfer efficiency by addressing the use of power amplifiers [5], studying the frequency in which magnetic resonance operates most efficiently and the duty cycle or wave pattern in the transmitter coils have any effect on magnetic field strength generation [3],[7]. These information are useful to design an optimum level of WPT technology and this is important to address the magnetic field issue which require further insight into power losses by these circuits [6].

1.2 Problem Statement

The WPT has a wide range of application in terms of powering all electrical and electronics machines or equipments. The elimination of cables and wires used to supply electrical energy will save cost in production and installation. In developing countries, rural areas are experiencing limited access to electricity as an ongoing issue due to unviable financial setting up of conventional electricity grid [8]. With that, this technology will bring possibilities in supplying electrical power to unreachable areas where installing electric cables are expensive due to the environmental boundary. The requirement to transmit at longer distance with magnetic resonance coupling technology requires improvement to sustain reliable and feasible applications.

1.3 Objectives

To improve Magnetic Resonance Coupling Wireless Power Transmission distance by

1. implementing and matching low power dissipation class E power amplifier circuit with wireless power transmission that will overcome restriction in supplying higher power to transmitter coil.
2. implementing multilayer coil design with Brook's coil concept adaptation to cater for higher power supplied from power amplifier circuit without causing coil overheating or alteration to wireless power transmission configuration.

1.4 Scope of Study

This project study will cover :

- design and build power electronics circuit with low power dissipation for high current conduction.
- design and build multilayer coil to cater for higher power input supplied by power amplifier.
- the use of magnetic resonance coupling technology to transmit electric power wirelessly

CHAPTER 2

LITERATURE REVIEW

2.1 Magnetic Resonance Coupling

The technology behind magnetic resonance coupling lies in magnetic field propagation between a transmitter and a receiver at the same frequency called resonant frequency. The principal is focused on resonating the energy back and forth in a specified area of effect in which enables a strongly coupled magnetic field, transferring energy at the highest efficiency. The rest follows Faraday's Law and Lenz's Law for electromagnetic induction [2], [3],[7].

Based on [9], the frequency of resonance will affect the Q-factor of the resonator that is also influenced by inductance and resistance of coil. With higher Q-Factor, the power transfer efficiency will increase due to higher coupling effect [9]. Following that, the inductance and capacitor used to obtain resonance effect will produce LC cancellation that causes the resistance across the L and C to be low at resonant frequency and this increases Q-factor [6]. According to [6] and [9], the power efficiency is affected by design parameters of transmitter and receiver coil focusing on increasing Q-Factor and resonant frequency configuration.

Apart from resonant frequency selection and coil design, the waveform highlighted by [2], [3] ,[5] and [7] for magnetic field induction in accordance to Faraday's Law is a sine wave. In fact, researched done by [7] have discovered that sine wave provided highest efficiency compared to other waveforms. The sine wave input to the transmitter coil in radiating magnetic field was accomplished by using an oscillator with adjustable duty cycle to convert DC source into alternating current of significant power and frequency [2], [5]. According to [3], the wireless power transmission efficiency was inversely proportional to the duty cycle after the maximum duty cycle have been achieved. Furthermore, [2] have mentioned a 15% estimated efficiency of implemented oscillator in which [5] have resorted to using power amplifier to increase efficiency.

Despite the success of generating magnetic field, performance of WPT system as a whole is questioned by [6] with consideration on coil performance but also regarding power efficiency of power electronics circuit that generated the sine wave. [6] emphasized the need to consider power losses before the coil on the basis that a decrease in output power of circuit components will be limiting power flowing to the coil. Furthermore, based on magnetic field effect, the magnetic field strength is directly proportional to current [10] and with high power losses in circuit components, the coil will be hindered from maximum magnetic field generation in which justifies concerns of [6] in the importance of considering power electronics efficiency.

2.2 Coil Design

In designing a high efficiency coil, [6] and [9] have emphasized the requirement to have high Q-Factor by increasing inductance and reducing resistance value. The multilayer coil proposed by [11], [12], and [13] consists of stacked layers of coils on top of each other where the cross sectional area increases with each stack. Following that, the internal resistance decreases as the stack of coil increases [12]. Moreover, the inductance will increase while diameter of coil remain unchanged, contributing to high efficiency small coil design in which is suitable for WPT operation [14].

Despite the high efficiency and low internal resistance of multilayer coil, the design requires consideration in terms of skin effect, proximity effect and displacement current [13], [14]. Although a higher frequency increases Q-Factor [6], [9], the increase in frequency of operation will increase AC resistance due to skin effect and proximity effect that in fact decreases Q-Factor [13], [14]. Furthermore, [14] have discovered the increase in AC resistance is most distinct when the stacked layers are increased beyond the maximum amount.

Based on the fact that there is a maximum stacked layer in which varies for different coil dimensions, [11] and [15] demonstrates brook's coil design that is a multilayer coil orientation with a square cross sectional area and controlled dimensions by ratio, standardized the amount of stacked layer for maximum performance. This type of design enables optimum inductance value at a finite length of wire [11].

In spite of brook's coil and multilayer coil design, the use of magnetic core for WPT coil design was not effective because of core saturation [11] and negative effect to surrounding wireless devices [13]. With that, [11] and [13] have justified using air core in which is efficient and does not affect inductance with an increase in current. Therefore, consideration is required in terms of frequency of operation with number of stack layers and the application of core in coil design is crucial.

2.3 Power Electronics Circuit - Power Amplifier

Power amplifiers are categorised into linear power amplifiers such as class A, B and AB and switching amplifiers with class C, D, E and F. In the case of WPT application, the switching amplifier produces substantial improvement towards power efficiency especially related to class E power amplifier design. The design process is tedious although simple to construct with success in WPT implementation [16], [17].

Basically, the class E power amplifier uses lesser components compared to other classes in the same category and achieve higher efficiency [16]. According to [17], the calculation in design consists of long iterative methods in which is a setback to simple circuit construction. In order to fully comprehend the advantages of class E power amplifiers, a simple analytical design method was implemented by [17] to produce a high approximation design. However, the full and complete mathematical model is covered by [16].

With the design process made simple, there have been success in implementing this power amplifier in WPT system. [18] and [19] have significantly improved WPT system efficiency to above 80% by using class E power amplifier. The improvement of system efficiency was due to reduced power dissipation in power amplifier through zero voltage switching [16] that increased power transfer to coils [18], [19].

Therefore, concerns in power efficiency of circuit components by [6] was addressed by class E power amplifier application in WPT. However, the application on WPT using magnetic resonance coupling at low frequency range have not been explored and due to frequency effect on coil resistance, the research on this will be useful in developing high efficiency WPT system at low frequency range.

CHAPTER 3

METHODOLOGY

3.1 Research Methodology

This project will be divided into coil design and efficiency of power electronics circuit for higher power conduction to transmitter coil with the aim and thus longer distance of transmission to receiver coil that will consists of 3 sections :

1. Class E Power Amplifier
2. Oscillator
3. Brook's Coil design

The research methodology will address concept and design of class E power amplifier with driving circuit consisting of an oscillator. Following enhancement of power efficiency in transmitter coil, design adaptation of brook's coil concept will be developed to increase coil efficiency that will enhance power transfer capability through stronger magnetic field strength. Apart from that, magnetic field strength will be explained with reference to current through the coil to improve transmission distance.

3.2 Design Characteristics of Magnetic Resonance Coupling Circuit

A WPT system mainly consists of power source, oscillator, power amplifier, transmitter and receiver coil as summarized in Figure 1. In this section, the design criterias are highlighted before detailed project concepts are explained.

3.2.1 Power Source

A DC power supply will be used to power the circuit. The current supply will be required to range from 1 A to 3 A for high current conduction to transmitter coil.

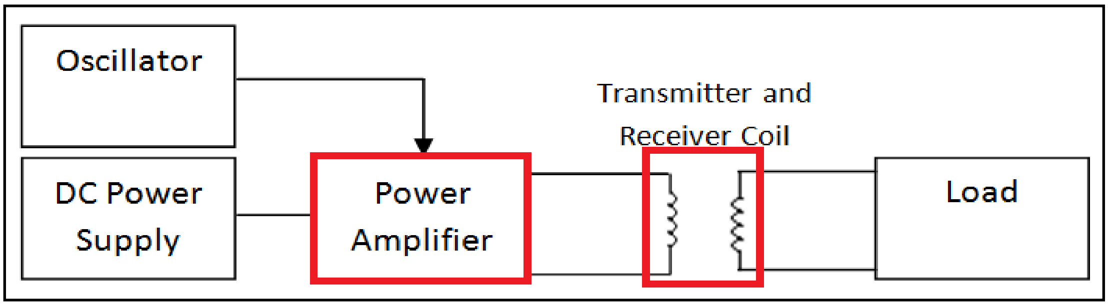


Figure 1 : Wireless Power Transmission System Summary

3.2.2 Frequency

Resonance frequency is an important factor in WPT system that was mostly done with 1Mhz up to 13.56Mhz. This includes class E power amplifier implemented in WPT system, configured to 13.56Mhz [19]. Referring to previous WPT project done in this university, 1.1Mhz resonance frequency was chosen with unjustified reason.

With that, motivation in researching a lower resonant frequency on both class E power amplifier and WPT system will provide greater insight into the effect of frequency on performance. This project will address WPT system at medium frequency range, from 300kHz to 3Mhz but confined to lower portion of the spectrum. Reason for this is an effort in maintaining variables to compare previous project at 1.1Mhz with the current project.

3.2.3 Magnetic Field Strength

The standard magnetic field intensity is given by equation (1) as proposed by [10].

$$B = \frac{\mu_0 I 2\pi r^2}{4\pi (z^2+r^2)^{\frac{3}{2}}} \qquad (1)$$

where r = radius of coil

I = current through coil

From this equation, a higher current will generate higher magnetic field intensity and larger area of magnetic coverage. Therefore, this project promotes high current conduction to transmitter coil which is made possible with class E power amplifier explained in the next section.

3.3 Class E Power Amplifier

From the determined frequency for resonance, a low power dissipation, class E power amplifier designed to operate under zero voltage switching (ZVS) mode at lower portion of medium frequency range operation will be developed. Simplified equations from [17] is used to provide a good approximation to the design introduced by [16]. The calculation is as follows :

Basic 4 equations consisting of

$$K_L(q) = 8.085q^2 - 24.53q + 19.23$$

$$K_c(q) = -6.97q^3 + 25.93q^2 - 31.071q + 12.48$$

$$K_p(q) = -11.90q^3 + 42.753q^2 - 49.63q + 19.70$$

$$K_x(q) = -2.9q^3 + 8.8q^2 - 10.2q + 5.02$$

By setting q=1.412 to get maximum power efficiency and substituting into the basic equations,

$$K_L = 0.689$$

$$K_c = 0.698$$

$$K_p = 1.355$$

$$K_x = -0.082$$

and equating with

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

$$K_c = \omega CR$$

$$K_p = \frac{P_{out} R}{V_{DD}^2}$$

$$K_x = \frac{X}{R}$$

the components value required for ZVS operation will be determined at resonance frequency as the operating frequency. These calculations will provide inductance and capacitance value responsible for MOSFET switching on and off at zero voltage, thus contributing towards low power dissipation.

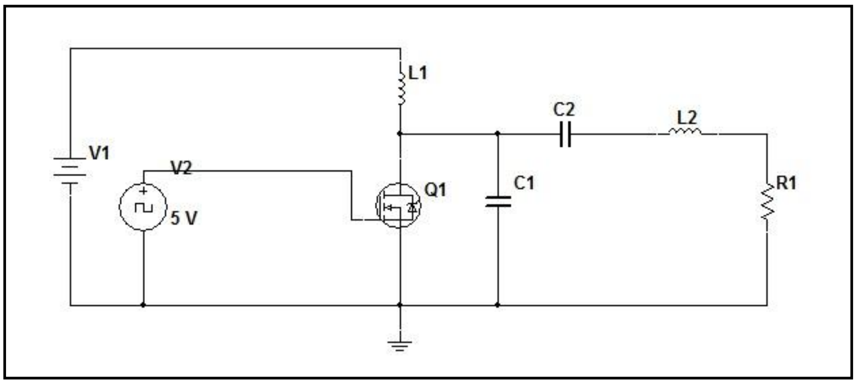


Figure 2 : Class E Power Amplifier Circuit

3.3.1 Theoretical Operation

Referring to Figure 2, the ZVS capacitor, C1 is connected in parallel to the MOSFET whereas the inductor, L1 is in series with the drain of MOSFET. During ZVS operation, the capacitor will ensure zero voltage is present during turn on to allow rise in current controlled by the inductor with low power loss associated with P=VI. At the off state, there will be maximum voltage across the switch and therefore the capacitor slowly charges, thus slowing the rise in voltage while current reduces to zero during transition from on to off. The main concept is to keep voltage and current low during on and off state respectively.

Following that the switching effect will generate a square waveform corresponding to switching of MOSFET gate by a square waveform, the output requires a low pass filter to generate a pure sine waveform. Using LC filter with resonance effect, the value of L2 and C2 are calculated using :

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

At desired resonance frequency, the Brook's coil will be used to replace the inductance and operate at resonance with capacitor connected in series. The value of capacitor is calculated using equation (2) at resonant frequency. With a lower power dissipation in the power electronics circuit, a higher current can be supplied to the coil without overheating the power MOSFET, provided that the MOSFET model is chosen with low $R_{DS(ON)}$. Total design parameters and calculated values are discussed in results section.

3.3.2 MOSFET Selection

In a class E power amplifier, the MOSFET influences ZVS performance due to parasitic capacitance and internal resistance. Therefore, a power MOSFET have the characteristic of low parasitic capacitance and internal resistance with high output power in which will operate within requirements. 2 different types of power MOSFET are evaluated and listed in Table 1.

Table 1 : MOSFET Selection

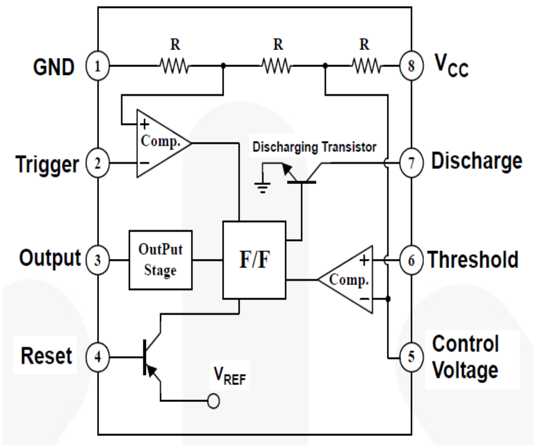
Model	IRF530	IRF540
Manufacturer	International Rectifier	International Rectifier
V_{ds} , I_d	100 V , 14 A	100 V , 44 A
C_{ds}	200 pF	210 pF
R_{ds}	0.160	0.044

From the evaluation, IRF530 MOSFET will provide a better ZVS performance due to lower C_{ds} and lower power dissipation for a class E power amplifier operation despite higher R_{ds} [18]. Furthermore, a higher current will certainly improve magnetic field of transmitter coil and a detailed explanation was covered in magnetic field strength section.

3.4 Oscillator

The class E power amplifier is categorised as a switching amplifier that requires a switching signal at the gate of power MOSFET. This oscillator will be responsible in generating a 50% duty cycle square wave as input to drive the power MOSFET. Following that the gate voltage requirement is 5V with further voltage increase will result in power dissipation, the oscillator will be configured to supply 5.5V to maintain reliable driving signal and reduced power dissipation at the gate terminal.

For this criteria, a LM555CN timer will be used to produce an approximate 50% duty cycle, 5.5V square waveform that have sufficient current to drive the power MOSFET gate. The chip diagram is as shown in Figure 3 and specifications are listed in Table 2.



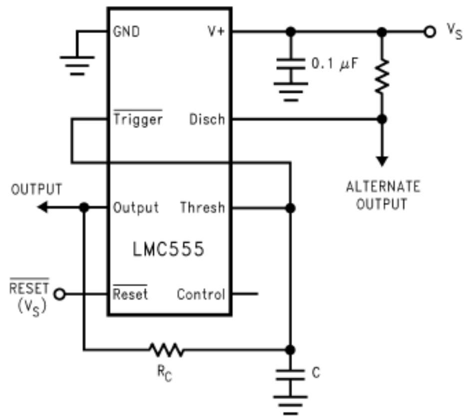


Figure 3 : 555 Timer Structure and 50% duty cycle circuit

This timer model consists of 8 pin and based on the specifications, the IC is capable of withstanding high voltage input close to the DC power supply voltage that simplifies powering it. Furthermore, this chip is designed to cater for frequency ranging up to 3Mhz which covers the desired range of frequency as explained previously.

Basically, the 555 timer operates through change in voltage with reference to supply voltage. The connection is as shown in Figure 3 with a capacitor and resistor connected to output pin in which voltage across capacitor will be responsible for changing the voltage level of trigger pin (pin 2) and threshold pin (pin 6). The operation is explained in Table 2.

Table 2 : 555 Timer Operation

Pin	Voltage Level	Output State	CR Relation
Trigger (2)	$\frac{1}{3}Vcc$	High	Output charges capacitor through resistor to $\frac{2}{3}Vcc$
Threshold (6)	$\frac{2}{3}Vcc$	Low	Capacitor discharges through resistor to $\frac{1}{3}Vcc$

The process repeats to form a square waveform with frequency controlled by capacitor and resistor value, calculated using equation (3).

$$f = \frac{1}{1.4R_C C} \tag{3}$$

3.5 Brook's Coil Design

Based on multilayer coil design with Brook's coil adaptation in terms of square cross sectional design, the multilayer coil will have the same amount of stacked layers as the number of turns in one layer as shown in Figure 4.

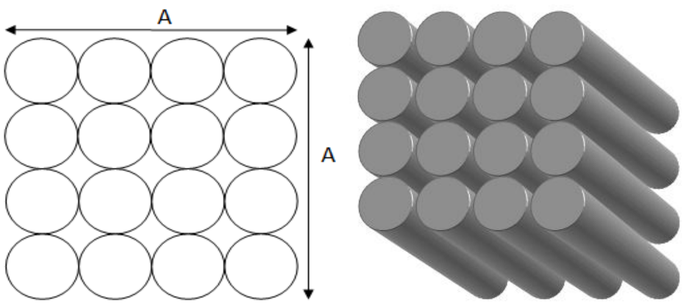


Figure 4 : Coil Cross Section

This will ensure a square cross sectional area with high inductance, calculated using equation (4) from [13].

$$L = \frac{0.8r^2N^2}{6r+9l+10d} \quad (4)$$

where r = mean radius of coil (inches)

N = number of turns of coil

l = length of coil (inches)

d = depth of coil (inches)

The coil will use air as the core which avoids magnetic saturation with the material chosen to have high conductivity and relative permeability that increases magnetic field strength. Furthermore, a circular coil shape will be designed to provide highest efficiency.

3.6 Project Activities

3.6.1 Work Breakdown Structure

<u>Level 1</u>

1. Class E Power Amplifier
2. Coil Design
3. WPT Prototype

<u>Level 2</u>

1.1 Design Calculation
1.2 Simulation
1.3 Component Selection
1.4 Testing

2.1 Coil Design Calculation
2.2 Coil Design Parameters
2.3 Coil Design Testing

3.1 Class E Power Amplifier
3.2 Oscillator
3.3 Coil
3.4 Prototype Testing

<u>Level 3</u>

1.1 Design Calculation
- 1.1.1 ZVS Component Value
- 1.1.2 Resonant Component Value

1.2 Simulation
- 1.2.1 ZVS Voltage Waveform
- 1.2.2 Coil Voltage Waveform
- 1.2.3 Resonance Frequency

1.3 Component Selection
- 1.3.1 Component Values
- 1.3.2 Component Voltage Ratings

1.4 Testing
- 1.4.1 Building actual circuit
- 1.4.2 ZVS Voltage Waveform
- 1.4.3 Coil Voltage Waveform

2.1 Coil Design Calculation
- 2.1.1 Inductance Value
- 1.1.2. Q-Factor
- 1.1.3 Magnetic Field Intensity

2.2 Coil Design Parameters
- 1.2.1 Circular Shape
- 1.2.2 Number of Coils
- 1.2.3 Multi Layer Coil
- 1.2.4 Material of Coil

2.3 Coil Design Testing
- 1.3.1 Inductance Value
- 1.3.2 Resistance Value
- 1.3.3 Cross-sectional verification

3.1 Class E Power Amplifier
- 3.1.1 Matching with coil
- 3.1.2 Ensure ZVS operation
- 3.1.3 Ensure resonance effect

3.2 Oscillator
- 3.2.1 50% duty cycle
- 3.2.2 Powering MOSFET gate

3.3 Coil
- 3.3.1 Match with power amplifier

3.4 Testing
- 3.4.1 ZVS
- 3.4.2 Resonant frequency
- 3.4.3 Distance of transmission

Month	January			February				March				April		
Task Name\Week	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Selection of Project Title														
Project Title and Scope														
Finalized Title and Scope		◊												
Coil Design														
Literature review														
Research on coil design parameters														
Inductance value, Q-Factor, magnetic field intensity										◊				
Coil design shape and size														
Decision on shape, no.of coil, coil orientation, radius												◊		
Resonance Frequency														
Calculations on resonance frequency														
Effect of frequency research														
Decision on range of frequency												◊		
Multi-directional WPT														
Research on coil orientation														
Decision on coil orientation										◊				
Research on criteria required for orientation														
Evaluation on criteria and coil design relationship													◊	
Research on mutual induction														

Figure 5 : FYP 1 Gantt Chart

Legend	
	Summary
	Timeline
◊	Key Milestone

Month	May			June				July			August			
Task Name\Week	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
Class E Power Amplifier														
Concept and Design														
Calculation on Design														
Simulation		◊												
Sourcing and Purchasing Components														
Building and Testing Circuit					◊									
Coil Design														
Concept and Design														
Inductance Calculation														
Building coil														
Testing inductance, resistance and Q-Factor				◊										
Oscillator														
Concept and Design														
Calculation on Design														
Simulation					◊									
Sourcing and Purchasing														
Building and Testing Circuit								◊						
Wireless Power Transmission Prototype														
Combine Power Amplifier with Coil														
Testing ZVS operation						◊								
Testing distance							◊							
Combine Oscillator with Power Amplifier and Coil														
Testing with PASCO									◊					
Testing with Spectrum Analyzer									◊					
Building Complete Prototype														
Enhancement														

Figure 6 : FYP 2 Gantt Chart

Legend	
	Summary
	Timeline
◊	Key Milestone

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

This project will demonstrate results for each section listed from Methodology covering :

1. Class E Power Amplifier
2. Brook's Coil Design Adaptation
3. Wireless Power Transmission Prototype

The calculation and simulation will be determined with selection of components, followed by the actual results and discussion obtained for each section. All simulations are completed using Multisim software from National Instrument while other equipment used in measuring practical circuits are highlighted at each section.

4.2 Class E Power Amplifier

4.2.1 Simulation

Based on the design concept and calculation covered in methodology, the circuit is build and simulated before practical application. Figure 7 shows the simulated circuit connection and component values from calculations.

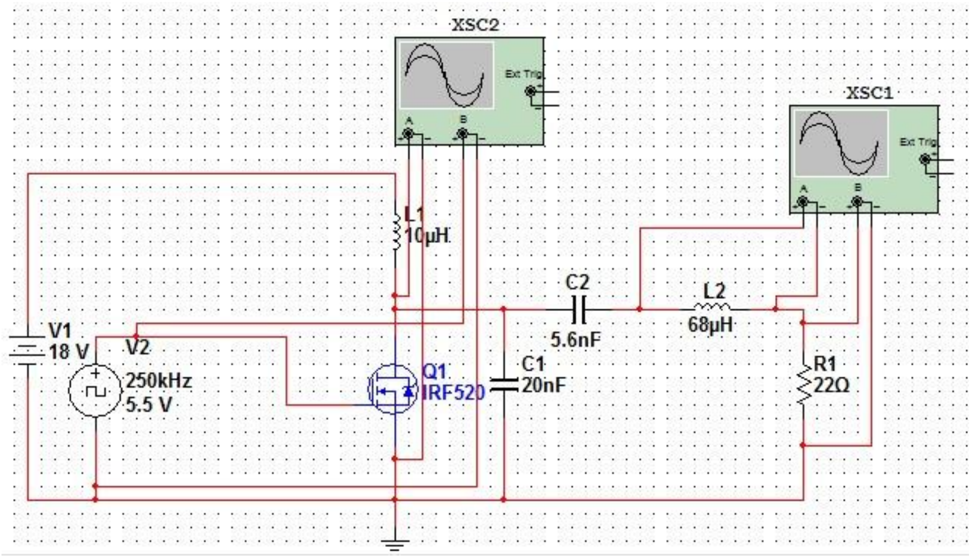


Figure 7 : Multisim Simulation Circuit

The setup for this simulation includes a 250kHz oscillating frequency square waveform with 5.5 V amplitude to drive MOSFET IRF520 in which closely resembles the MOSFET model intended for real application. The DC power supply is 18V connected directly to the drain of MOSFET. Upon simulation, the waveform across inductor that would be replaced by transmitter coil as shown in Figure 8 was observed and verified to be a sine waveform in which satisfies the condition for magnetic field induction.

Furthermore, the simulated circuit was examined for ZVS operation by observing the waveform across the MOSFET from drain to source terminals. The waveform shown in Figure 9 confirms the ZVS operation as practically no voltage is present at MOSFET turn off time. However, as highlighted in the figure, at the start of MOSFET turn on time, there was a small voltage present in which was negligible during simulation but the location was noted as prediction of significant voltage to appear during real circuit operation.

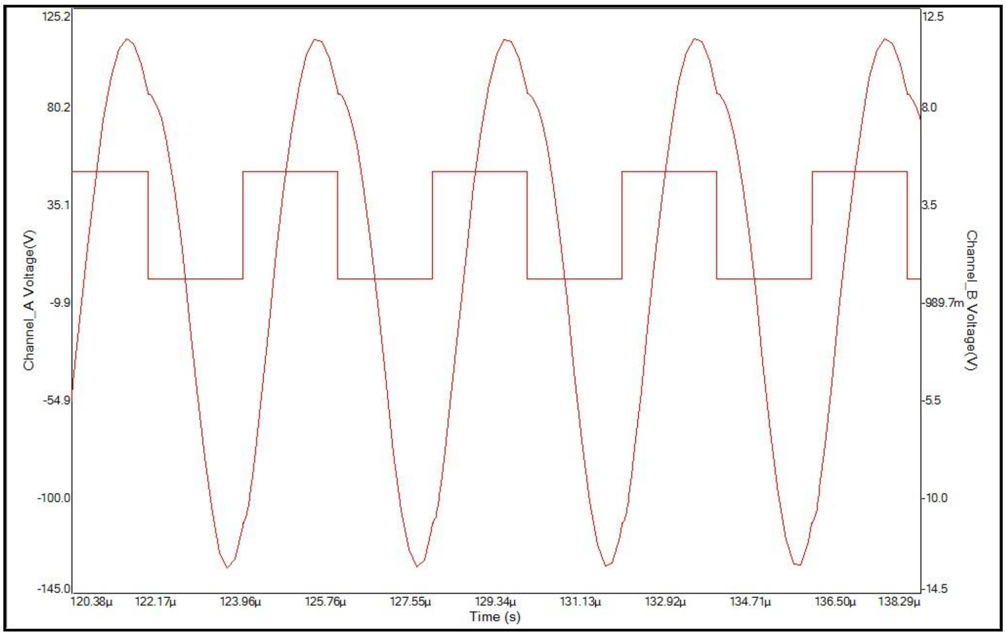


Figure 8 : Voltage across MOSFET & and 50% Square Waveform

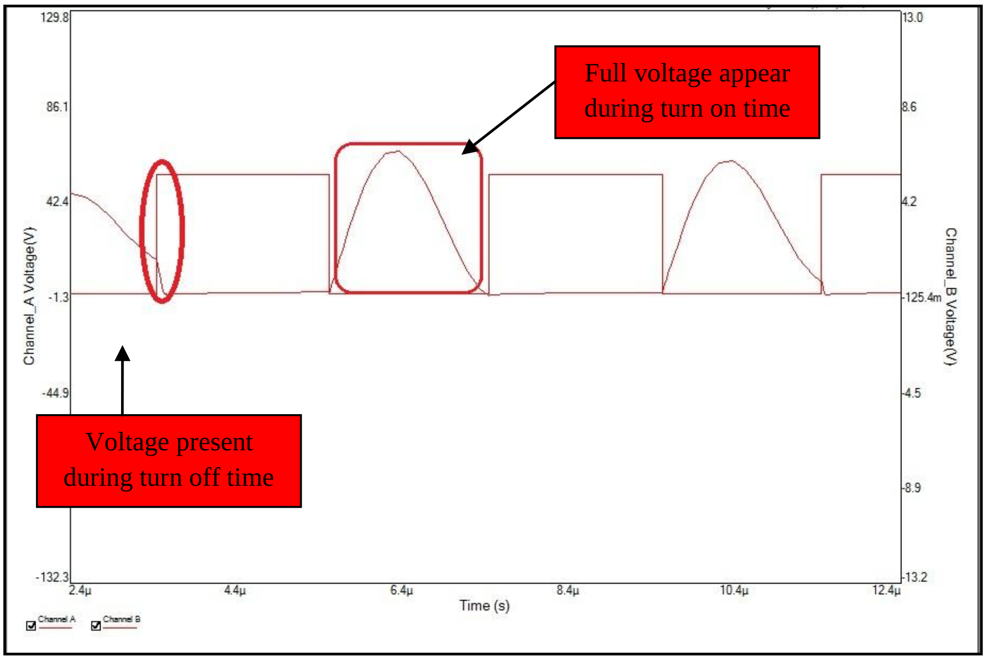


Figure 9 : ZVS Operation

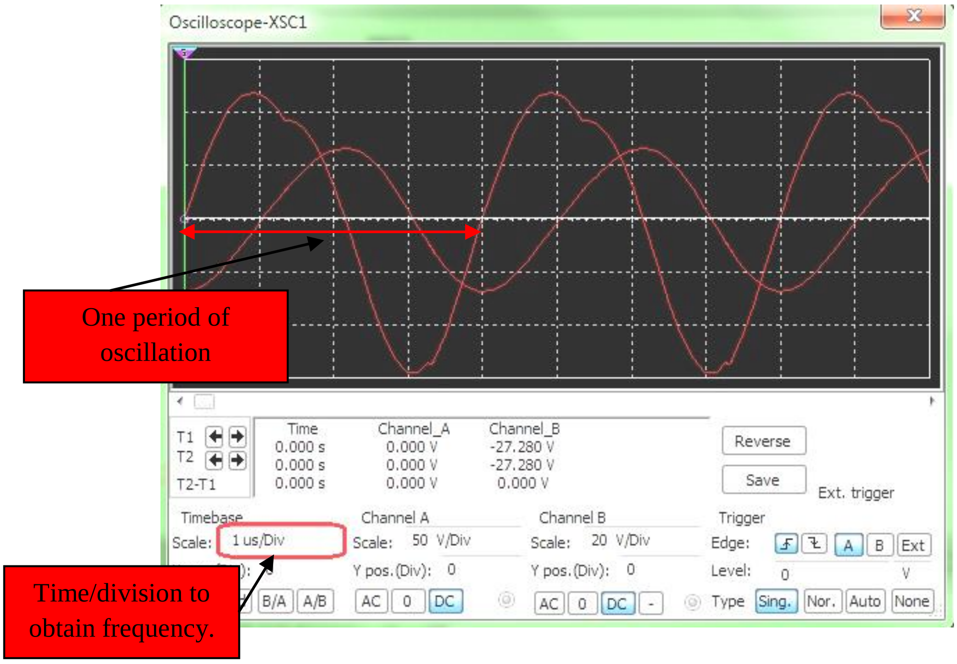


Figure 10 : Simulated waveform across inductor resembling coil

Apart from voltage waveform and ZVS operation, the resonance frequency from the LC series circuit was examined and referring to Figure 10, the frequency obtained was 250kHz. This confirms that the frequency of oscillation at the gate of MOSFET was unaltered at the drain terminal. With that, all criteria for WPT with class E power amplifier have been verified by simulation and proceeded with real application as documented next.

4.2.2 Practical Application

The circuit was constructed based on simulation circuit design in Figure 7. Component values for simulation and real operation might be different and this was taken into consideration with thorough calculations made to ensure fixed component values was given priority. However, there was variations in values in which have effect as observed from deviated results obtained from theoretical. The component values for calculated and practical circuit is listed in Table 3 for easy reference.

Table 3 : Calculated & Practical Specification

Description	q	F(Hz)	L1(μH)	C1(nF)	L2(μH)	C2(nF)	R(Ω)
Calculated	1.412	250k	9.65	20.2	68.8	5.89	22
Practical		250k	10	20	68	5.6	22

Equipments used in this test are as follows :

1. GW Instek Laboratory DC Power Supply
   – Used for 18 V DC power supply
2. Tektronix TDS 1002 Digital Oscilloscope
   – Used for reading voltage waveform
3. GW Instek Function Generator GFG-8256
   – Used for substituting oscillator circuit to drive MOSFET gate

Results obtained is shown in Figure 11 and Figure 12 for type of waveform and ZVS operation respectively. Frequency of operation was varied from 250kHz to 264kHz and finally at 370kHz. The first 2 frequency was used to test for resonance frequency and from the test, Figure 11 (left) have lower amplitude compared to Figure 11 (right) in which the latter represents resonant frequency by applying the concept that highest voltage is present at resonant frequency. Furthermore, this result clearly shows the effect of component value mismatch between calculated and available

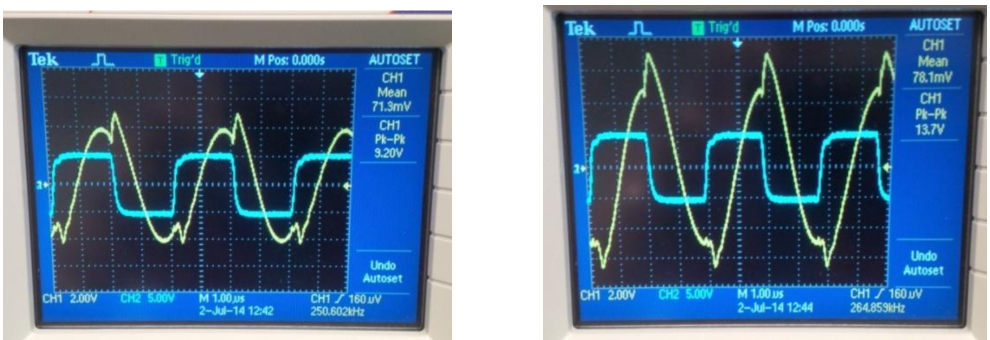


Figure 11 : 250kHz (left) & 264kHz (right) Inductor Voltage Waveform

values forms the fact that resonant frequency was affected. Despite the difference, voltage waveform conforms to simulated results with sine waveform confirmed.

Although there was a distortion at the peak of sine wave due to noise and LC effect that was not perfect taking consideration in tolerance of component values but this was similar to simulation and can be neglected since quality of sine waveform is not priority. Apart from the waveform, the ZVS operation was evaluated and result shown in Figure 12. From the results obtained, voltage was present during the start of MOSFET turn on time as predicted from simulations but this voltage level was high and became significant to MOSFET power dissipation. Effect of power dissipation was converted to heat on MOSFET in which affects MOSFET performance that requires decreasing current supplied to prevent overheating. Therefore, high current supply to transmitter coil is prevented at this stage. Despite this, the WPT prototype section will explain methods to overcome this setback.

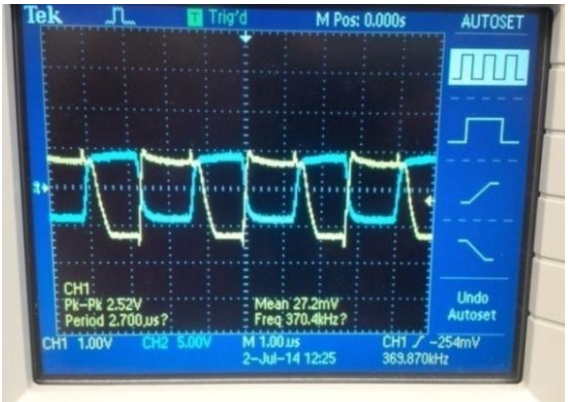


Figure 12 : ZVS Waveform at 370kHz

4.3 Brook's Coil Design Adaptation

4.3.1 Calculation

By implementing multilayer coil design and criteria of square cross section, adapted from brook's coil design, equation (4) was used to calculate inductance value. The calculated result and coil specification are listed in Table 4.

Table 4 : Coil Specification

Material	Cable Diameter (cm)	Coil Diameter (cm)	Length/Width of cross section (cm)	No. of Turns	Inductance (µH)
Enamelled Copper	0.15	8.8	0.7/0.7	16	39

4.3.2 Practical Application

Due to unavailable winding machine, the coil was wound by hand following the designed values. The coils was then tested using FLUKE PM6303A Meter as shown in Figure 13, to obtain inductance, Q-factor and resistance of the copper coil. Results are tabulated in Table 5 for 2 coils.

Figure 13 : Measuring Coil Inductance with FLUKE PM6303A

Table 5: Measured Coil Specification Result

Description		Inductance (µH)	Q-Factor	Resistance (Ω)
Measured	Coil 1	38.4	3.51	0.249
	Coil 2	33.4	3.20	0.220

According to the results, the inductance value deviated by 2% from calculated values. With that, the power amplifier circuit will be modified to accommodate this inductance value. Q-factor of 3 and above is in the high range for a coil of this configuration but the critical portion of this results is related to coil resistance.

Following that the resistance must be low to be insignificant for WPT circuit performance and since the resistance is below 1 Ω due to multilayer coil design, it is safe to assume constant performance without distinct effect. Therefore, the coil design is considered optimum within this project with high inductance and low resistance. The coil will proceed to implementation in the next section which demonstrates an air core advantage with current's effect on inductance.

4.4 Wireless Power Transmission Prototype

The wireless power transmission circuit consists of power supply, class E power amplifier with transmitter and receiver coils. The L2 inductor in class E power amplifier was replaced with the multilayer Brook's coil and functions as the transmitter.

Referring to Class E power amplifier section, matching of coil inductance and resistance with resonance frequency of amplifier circuit was completed. With that, the resonance frequency was set to 374kHz instead of previous frequency obtained for class E power amplifier. This frequency configuration was caused by changes in inductor value from 68μH component to 38μH coil. The frequency setting was ensured similar between the transmitter and receiver coil that achieved magnetic resonance coupling system configuration. The same capacitor value is used at both transmitter and receiver circuit. Prototype setup and wireless power transmission demonstration is shown in Figure 14. At this setting, the class E power amplifier have successfully obtain zero voltage switching with literally no voltage appearing during turn on at 374kHz which allows higher current supply to transmitter coil without significant overheating.

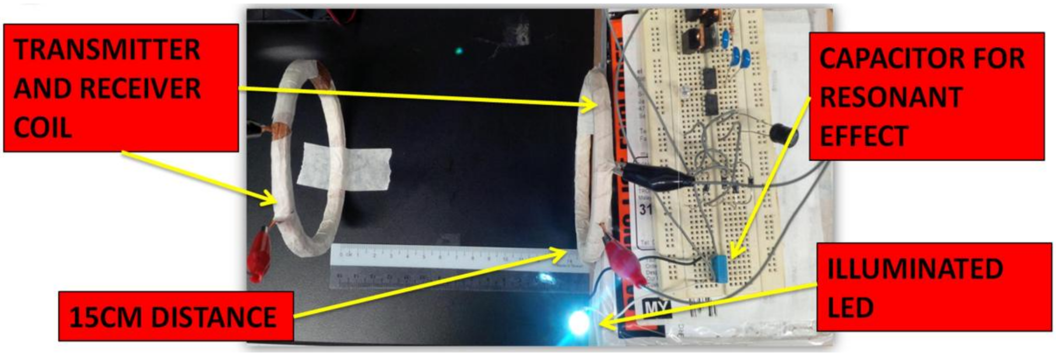


Figure 14 : Wireless Power Transmission Demonstration

Figure 15 shows voltage waveform across drain to source and square waveform for MOSFET switching at the gate terminal. This clearly demonstrates and confirms wireless power transmission at 374kHz resonant frequency with zero voltage switching operation. The voltage is maximum during the off time and at the minimum level during on time. With that, the class E power amplifier was successfully designed and implemented into wireless power transmission circuit.

With minimum power dissipation in power amplifier circuit, the voltage across transmitter coil was measured and waveform is shown in Figure 16. The waveform correlates with simulation results.

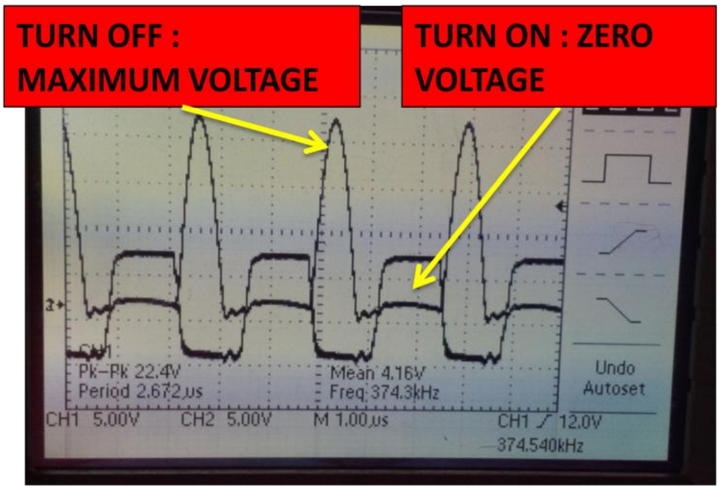


Figure 15 : Low Power Dissipation with Zero Voltage Switching

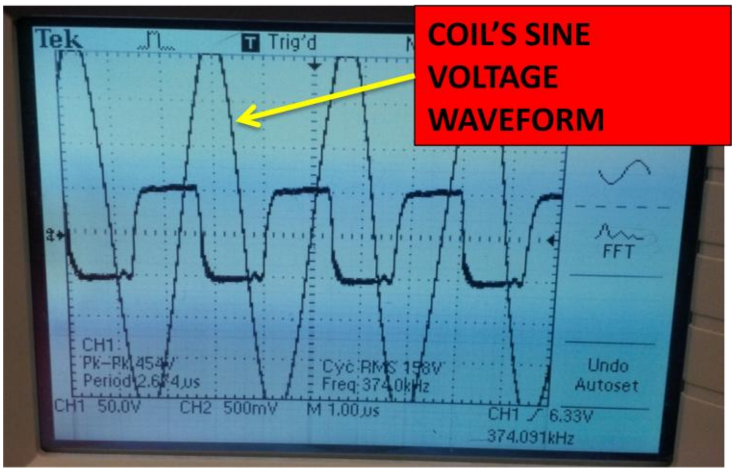


Figure 16 : Sinusoidal High Voltage Supplied to Transmitter Coil

Following that, the voltage and current was measured at receiver side for increasing distance. Referring to Figure 17, the power at receiver was highest at 10cm apart, measuring 418.34mW and decreases as distance increases. 108V DC was measured at 10cm with 3.86mA current which represents the highest achieved output as shown in Figure 18. In comparison with previous project, the distance was compared at the same output power level. As shown in Table 6, at the same output power, the distance of this project was 30cm and signifies an increase of 15 times with previous project of 2cm distance as reference.

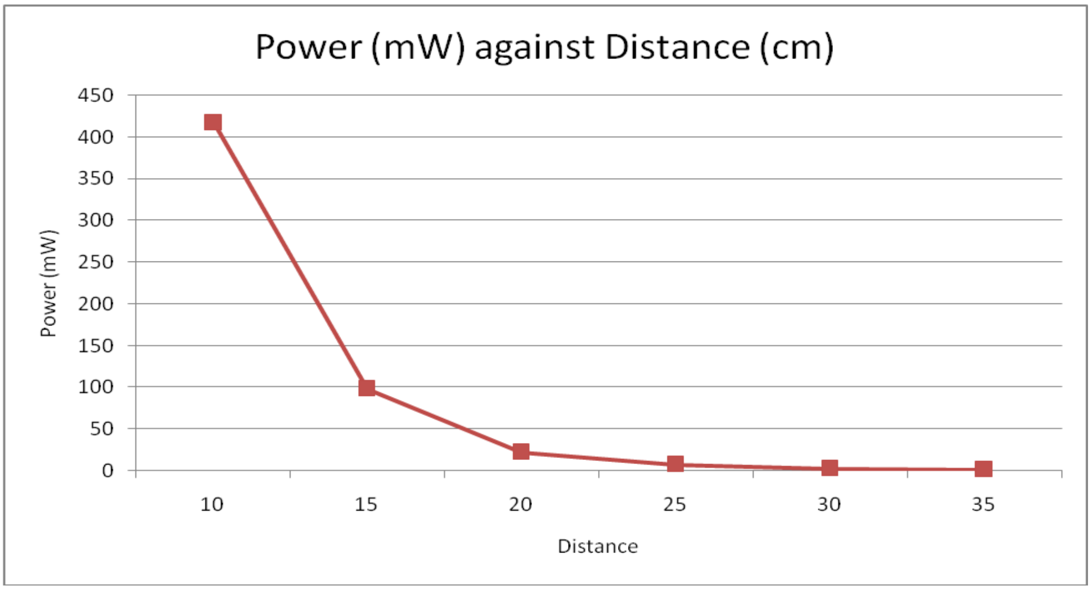


Figure 17 : Graph of Power (mW) against Distance (cm)

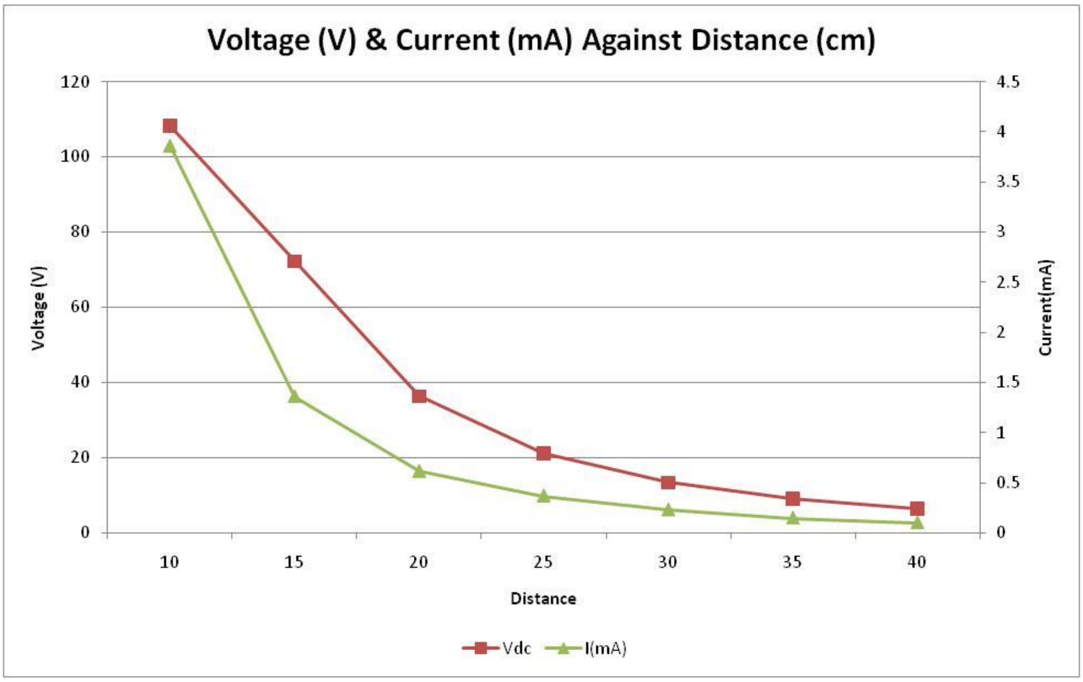


Figure 18 : Voltage(V) and Current(mA) Against Distance (cm)

Table 6 : Comparison with Previous Project

Description	Distance (cm)	Voltage (Vdc)	Current (mA)	Power (mW)
Previous Project	**2**	**7.2**	**0.40**	**2.864**
This Project	**30**	**13.34**	**0.23**	**3.068**
Maximum Power Output For This Project	**10**	**108.4**	**3.86**	**418.42**

The completed prototype is shown in Figure 19 which includes all components for wireless power transmission at resonance configuration. The handmade multilayer Brook's coil transmitter was powered at approximately 5V and 1.1A to produce similar power transmission distance to receiver coil obtained in lab environment.

A 12V dc power adapter was used instead of a 5V adapter due to high cost and availability of 5V adapters rating above 2A. In an effort to step down 12V supply to 5V, a voltage regulator L78S05 was used instead of a buck converter for accurate result and circuit simplicity. However, 1.1A current drawn from this regulator will cause heating and requires cooling. Therefore, a 12V dc fan was used to provide adequate cooling effect and with that further justifies a 12V power supply. The cooling was also a precaution for power MOSFET overheating.

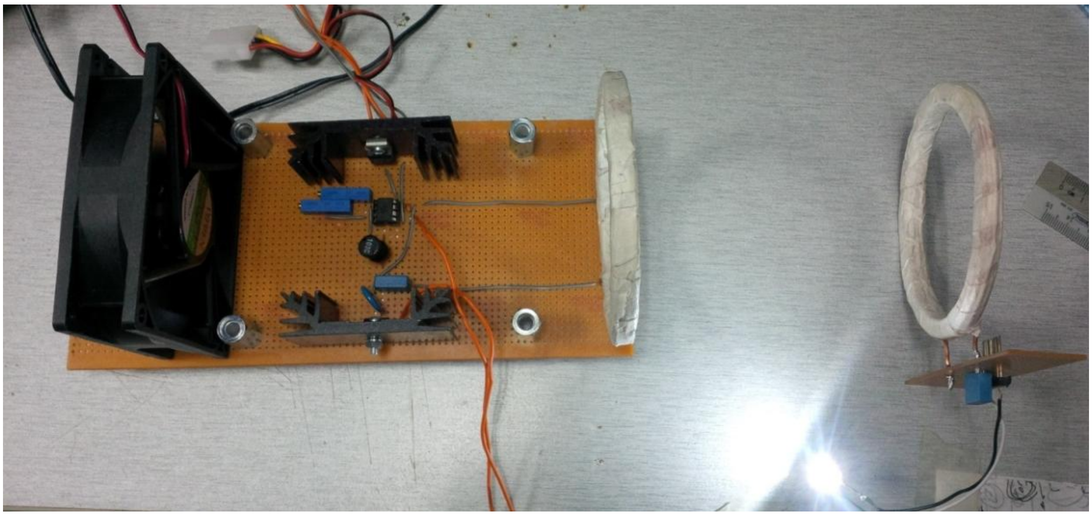


Figure 19 : Wireless Power Transmission Prototype

4.5 Wireless Power Transmission Prototype Operational Guide

The prototype was designed to have the fan operated when 12V adapter was turned ON. This will provide enhanced cooling since the circuit is cooled from beginning even when no current is drawn from voltage regulator. To begin wireless power transmission, the oscillator switch must be turned ON. Another switch was included for connecting 12V adapter power to voltage regulator that allows the user an emergency shutdown option in the event of overheating or malfunctioning for safety purposes. The fan will still be operational during this time to provide continuous cooling. Full specifications are listed in Table 7 for reference.

Table 7 : Prototype Technical Specification

Technical Specification		
Power supply	Voltage (V_{DC})	12
	Current (A)	2
Operating Frequency (kHz)		374
Output Power	Distance (cm)	10
	Power (mW)	418
Fan Rating	Voltage (V_{DC})	12V
	Current (A)	0.25
Transmitter Dimension		10 X 15 X 10
Coil Dimension	Wire Diameter (cm)	0.15
	Coil Diameter (cm)	8.8
	Cross Sectional Area (cm)	0.7 X 0.7

CHAPTER 5

CONCLUSION AND RECOMMENDATION

In conclusion, the WPT is a ground breaking technology that can be beneficial in terms of cost saving on expensive cables and reduce hassle in pulling cables or wires. Power can be available to everyone with this technology and this can be a solution to limitations of electrical and electronics application that requires portability. However, there is a need to increase power transmission distance to sustain reliable and feasible application. With that, this project have successfully increased power transmission distance through improved power amplifier application and coil design.

Class E power amplifier circuit design was implemented to reduce power dissipation in transmitter circuit. With Zero Voltage Switching (ZVS) operation, the power dissipated during MOSFET switching is substantially reduced. This allowed higher current conduction to transmitter coil for generation of higher magnetic field strength without overheating the power amplifier. Thus, higher power was transferred successfully to transmitter coil and resulted in further power transmission distance to receiver coil.

Besides class E power amplifier, coil design optimization using multi layer Brooks coil design was implemented to accommodate the higher output power from transmitter circuit. This prevented coil overheating that limited transmission distance and alter the wireless power transmission configuration. Furthermore, this coil design promotes a standardised method of designing an optimized coil for wireless power transmission in which the number of turns in each layer determines the number of layers required. This have provided a starting point for future coil design research with a sustainable design platform to improve on.

With improved power amplifier application and coil design in this project, an improvement of 15 times the transmission distance from previous project was achieved. This clearly defines the feasibility and recognition of class E power amplifier and multilayer Brook's coil for improving transmission distance of wireless power transmission via magnetic resonance coupling.

Future improvement is recommended on using different resonant frequency, coil material and diameter. Future research focused towards increasing power transfer efficiency with increased distance is advised to design power amplifier with different frequency range and more enhancement in coil material coupled with magnetic field effect study on the coil itself. This will prove to increase feasibility of this technology and widen the scope of application.

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