THE DESIGN OF WIRELESS POWER TRANSFER SYSTEM FOR DRONE CHARGING BASED ON CLASS-D CLL TOPOLOGY

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THE DESIGN OF WIRELESS POWER TRANSFER SYSTEM FOR DRONE CHARGING BASED ON CLASS-D CLL TOPOLOGY

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

Faculty of Electronic and Computer Engineering
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DECLARATION

I declare that this report entitled “The Design of Wireless Power Transfer System for Drone Charging based on Class-D CLL Topology” is the result of my own work except for quotes as cited in the references.

Signature : ………………….

Author : LOW KUAN YIK

Date : 21 JUNE 2021

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Bachelor of Electronic Engineering with Honours.

Signature : …………………………………

Supervisor Name : DR. YUSMARNITA BINTI YUSOP

Date : 25 June 2021

DEDICATION

I would like to dedicate my work to my family, my friends and my supervisor who helps me a lot.

ABSTRACT

In this paper, the concept of a wireless power transfer system has been discussed. Wireless Power Transfer (WPT) system is the communication of power source and electrical load without any medium such as cables. The project aims to design a Wireless Power Transfer system based on class-D CLL topology. The class D converter is used in this project because of the lower losses in power consumption and it can increase the efficiency to 100% theoretically. The design will first convert DC to AC and follow by the resonant circuit. The next objective is to analyse the electromagnetic field distribution of the IPT system in term of coupling distance variations and misalignment. Some calculations have been done and compare to the output results. To achieve the objectives, the idea of the designed such as how the power can be transfer through the system has been discussed. There are many techniques for power transfer such as inductive power transfer, capacitive power transfer, microwave power transfer, etc. The method used in this paper is Inductive Power Transfer (IPT) due to the electromagnetic field and inductive coupling which is not affected by dust. This paper also included several examples of power transfer systems to help everyone have a better understanding of Wireless Power Transfer. All the details are fully included in the paper.

ABSTRAK

Dalam makalah ini, konsep sistem pemindahan kuasa tanpa wayar telah dibincangkan. Sistem Pemindahan Tenaga Tanpa Wayar (WPT) adalah komunikasi sumber kuasa dan beban elektrik tanpa medium seperti kabel. Projek ini bertujuan untuk merancang sistem Pemindahan Tenaga Tanpa Wayar berdasarkan topologi CLL kelas-D. Penukar kelas D digunakan dalam projek ini kerana kehilangan penggunaan kuasa yang lebih rendah dan ia dapat meningkatkan kecekapan hingga 100% secara teori. Reka bentuk akan menukar DC ke AC terlebih dahulu dan diikuti oleh litar resonan. Objektif seterusnya adalah untuk menganalisis taburan medan elektromagnetik sistem IPT dari segi variasi jarak gandingan dan ketidaksejajaran. Beberapa pengiraan telah dilakukan dan dibandingkan dengan hasil output. Untuk mencapai objektif, idea yang dirancang seperti bagaimana kuasa dapat dipindahkan melalui sistem telah dibincangkan. Terdapat banyak teknik untuk pemindahan daya seperti pemindahan daya induktif, pemindahan daya kapasitif, pemindahan kuasa gelombang mikro, dll. Kaedah yang digunakan dalam makalah ini adalah Pemindahan Daya Induktif (IPT) kerana medan elektromagnetik dan gandingan induktif yang tidak dipengaruhi oleh habuk . Makalah ini juga menyertakan beberapa contoh sistem pemindahan kuasa untuk membantu setiap orang memahami lebih baik

mengenai Pemindahan Kuasa Tanpa Wayar. Semua butir-butir disertakan sepenuhnya di dalam kertas.

ACKNOWLEDGEMENTS

First of all, I would like to express my gratitude to the people who helped me and gave me valuable advice in the process of completing this project. In addition, I also want to appreciate my family for their support and encouragement in this project.

Next, I would like to express my deep and sincere feelings for my supervisor, Dr. Yusmarnita Binti Yusop. Thank you for your support and invaluable guidance. I am honored to have her as my supervisor. She always guides me patiently. I also very much appreciate the opportunity given by her.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

For examples:

WPT	:	Wireless Power Transfer
IPT	:	Inductive Power Transfer
UAV	:	Unmanned Aircraft Vehicle
MATLAB	:	Matrix Laboratory
API	:	Application Program Interface
DC	:	Direct Current
AC	:	Alternating Current
VSI	:	Voltage Source Inverter
CSI	:	Current Source Inverter
MOSFET	:	Metal–Oxide–Semiconductor Field-Effect Transistor
PER	:	Period
PW	:	Pulse Width

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

A drone also can know as an unmanned aircraft vehicle (UAV) which is control by a remote controller. The multiple functions enable it to have a wide range of applications, including military, agriculture, archeology, monitoring, personal use etc. Nevertheless, drones still have some limitations, one of the examples is battery life. Battery life is a key factor affecting the flight time of drones. Once the drone battery is low, it needs to be charged by replacing the battery or wired method, which is costly time-consuming, and also inconvenient. Hence, the use of the wireless power transfer system is very useful. In this chapter, background, problem statement, objectives and project scope are included.

1.1 Project Background

Nowadays, Wireless Power Transfer (WPT) has become more famous. WPT is the communication of power source and electrical load without any medium such as cables. A similar resonant frequency for two objects causes the WPT to works. One of the famous applications for wireless power transfer is drones, also known as UAV (Unmanned Aerial Vehicles). Even if the invention of drones makes things more convenient, but it still can’t change the limitations of the drones. There are several limitations for drones, one of the most important limitation is battery life. The flying time of a drone is limited by the battery life, sometimes it even takes a longer charging time than the flying time. So, in order to overcome this limitation, a wireless power transfer system will play a very important role. Due to the simple design and convenience, WPT is very suitable to overcome the battery life limitation for drones. Though WPT is very useful and convenient, but it still has some disadvantages such as high cost, more power loss etc. One of the reasons that might cause the power loss is heat dissipation. A heat dissipation that causes power loss may reduce the efficiency of the system. Therefore, in order to increase efficiency, the selection of a power amplifier is very important due to the different characteristics between different classes of power amplifiers.

The research done by Joseph Maldonado and Jeovany Vega [1] mentioned that the power amplifier can be categories into many classes such as Class A, B, AB, C, D etc. Among these classes, they are divided into two groups, which are linear or switching. The output of a linear model amplifier is proportional to their input, either fully on or fully off. This is because the heat is generated and consuming the power due to the transistors are functioning continuously, which makes them have lower efficiency than others. The example of the linear mode amplifier includes class A, B, AB and C. Each of them has different characteristics. Based on the research, class A amplifier has the least efficiency but it has the highest fidelity. It can operate 25% efficiency, 75% turns into heat but theoretically can operate a maximum 50% efficiency. For class B, it is more efficient than class A, but it is full of distortion. It can operate 50% efficiency and 78.5% theoretically. Other than that, class AB is a combination of class A and class B which consists of the characteristics of class A amplifier when low power whereas consists of the characteristics of class B amplifier when high power. The efficiency can up to 60%. Besides, class C similar to class B but it has more distortion compare to class B. The maximum efficiency that can class C reach theoretically is 78.5%.

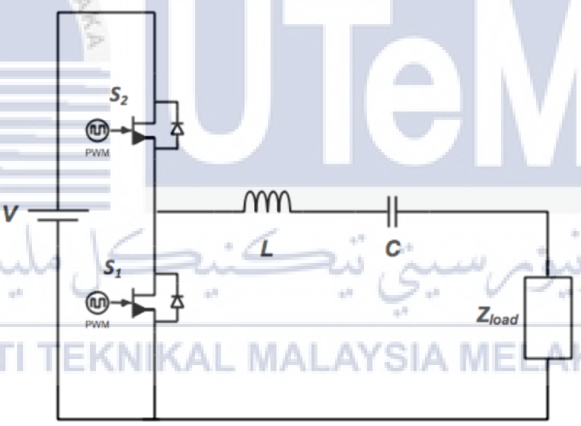

Figure 1.1: Schematic circuit for the half bridge class-D amplifier

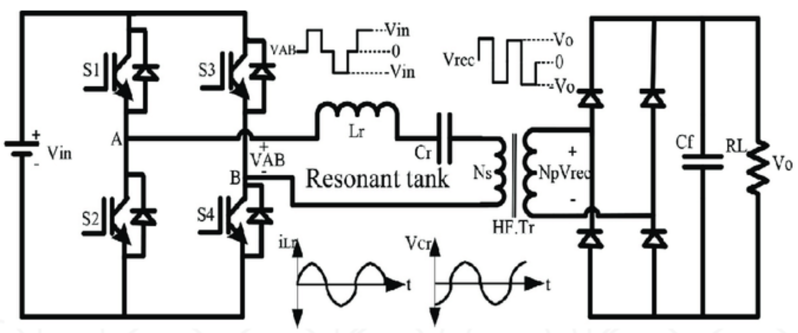

Figure 1.2: Schematic circuit for full bridge CLL resonant converter

Figure 1.1 above shows the schematic circuit for half bridge class D amplifier while figure 1.2 shows the schematic circuit for full bridge CLL resonant converter. Unlike those amplifiers, class D power amplifier is a switching amplifier which have higher efficiency theoretically. The switching amplifier will conduct current but there is no voltage flow through the switched when it is at ON state, whereas when it is in OFF state, the source voltage will flow through the MOSFETs but the switch is not consuming power due to the zero-current flow. Class D amplifier is a better selection because of the lower losses in power consumption. A class D amplifier can reach 100% efficiency theoretically. Class D amplifier categorized into two topologies, which are half-bridge and full-bridge. The difference between half-bridge and full-bridge is that the output of the half-bridge inverter is equal to one half of the supply voltage whereas the output of full-bridge is equal to the supply voltage. This difference makes the output power of full-bridge multiple times of half-bridge.

1.2 Problem Statement

In today's society, drones have become very useful applications. It can fly over the obstacles to observing the situation on the ground from a height. However, drones have some limitations that make them unable to be used for a long time. One of them is the battery life. The charging time is longer than the using time and once the drone is low battery, it needs to be recharge again which might take several times. Besides, it is also very inconvenient due to the wired charging method, which causes the drones to have to fly back. Even if we use wireless charging, there is still some problem that might occur, such as high-power losses. Heat dissipation causes high power losses may decrease the efficiency of the system. Therefore, the selection of a power amplifier also very important. Different type of power amplifier has different characteristic which will affect the efficiency of the system.

1.3 Project Objective

The aim of the project is to design a wireless power transfer system. These are the objectives of the project that required to achieved:

1. To design a wireless power transfer system based on class-D CLL topology.
2. To analyse the electromagnetic field distribution of the IPT system in term of coupling distance variations and misalignment

1.4 Project Scope

The main target of this project is to design a wireless power transfer system that is for drone charging only. The project will begin with the research of the information needed. The output power is set at 10W and the frequency is 100kHz. The distance between the coils is changed by using different values of inductance in the transformer. Then, the calculation of the value components and parameters will be done after confirming the design specification. The method used in the wireless power transfer system is class D inverter and full bridge rectifier. The power supply is selected as DC and the use of the inverter is to convert DC to AC. The charging distance will be observed by using Ansys Electronic Desktop. The use of class D is to increase efficiency. The project will then use ORCAD PSPICE as the simulation software after getting all the values. The construction of the circuit using PSPICE will be design by using the calculated parameters. Other than that, additional analysis has been done by using MATLAB Simulink software. A comparison table is done for output results and calculated results.

1.5 Project Overview

The project is categorized into five chapters which the first chapter is the introduction of the project. Then, background, objectives, and project scope will also be covered in this chapter. The next chapter is followed by the background study also known as the literature review. This chapter will discuss the technique used in the project and the existing researcher works related to this project will also be studied. Furthermore, the next chapter is project methodology. This chapter will include the method to design the project. The calculation of the project is included in this chapter. Last but not least, the fourth chapter is the result and discussion. All the results obtained no matter simulation, output or analysis of the project will be included in this chapter. Other than that, the discussion of the results will also include in this chapter. Last, the final chapter is the conclusion which the project conclusion and suggestion for future works will be found in this chapter.

CHAPTER 2

BACKGROUND STUDY

This chapter explains about the knowledge and method which is related to the project. Besides, the previous researcher works related to the project will also be discussed in this chapter.

2.1 Wireless Power Transfer

Wireless power transfer enables the power to supply through an air gap without any transmission medium. The concept of wireless transmission is carried out by Nikola Tesla. One of the basic concepts for wireless power transfer to work is according to Faraday's Law of induction which can produce AC current when the changes of the magnetic field. Not only that, when a similar resonant frequency occurs between two objects can also transfer the energy. The wireless power transfer system consists of two parts which are transmitter coil and receiver coil. The function of the coil is almost the same as a transformer that enables power to transfer from a primary coil to a secondary coil without any direct connection. Figure 2.1 below shows a basic wireless transfer system.

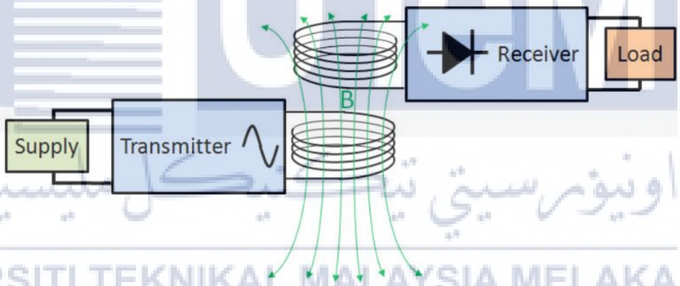

Figure 2.1: Basic wireless power transfer system

A wireless power transfer system can be divided into a few stages. For the first stage, for sure we need a source to supply energy. If AC is selected as the power supply, then the alternating current will first need to convert to direct current first, but if DC is selected as power supply, then can straightly proceed to the next stage. Then the next stage will follow by an inverter which is used to convert a direct current (DC) into an alternating current (AC). The type of the inverter will be discussing later. Next, the resonant circuit will connect with the inverter. The resonant circuit is very important in all WPT systems. Follow by the transmitter and receiver coils. The function of the coils is to generate the magnetic field so that the energy can transfer through it. After the receiver coil, the alternating current will enter the rectifier which will convert AC back to a stable DC. The direct current will then be used as a different function. The figure 2.2 below shows the block diagram of a wireless power transfer system.

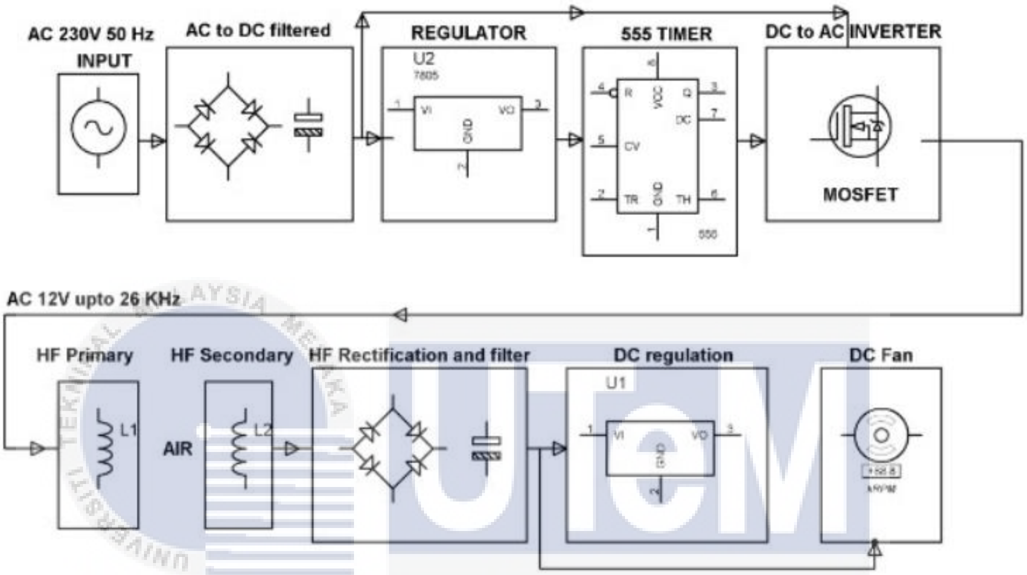

Figure 2.2: Block diagram of WPT system

Speaking of the WPT, there are some advantages and disadvantages that need to be discussed. Let's first talk about the advantage, one of the advantages is the convenience. The WPT system enables the energy to transfer wirelessly which brings convenience to users as they don't have to use any transmission medium such as cable. It is also very helpful in certain applications for instance phone charging. User doesn't have to plug in and plug out the cable, by using the WPT system they only have to put their phone on the provided tools and the power will transfer through the tools. Besides, the WPT is also easy to design as each stage of the system has clearly mentioned and also not complicated. This simple design also brings out the benefit of low cost. After some advantages, let’s focus on the disadvantages. One of the biggest problems of WPT is the high-power losses during the transmission. The loss of power is really a big problem in the WPT system which might due to the heat dissipation and resistance of wires used. Based on research, the loss percentage during transmission is approximated to 26% which is quite affect the efficiency of the system. The application of the WPT system included phone charging, transport, consumer electronics, etc.

Speaking of the WPT system, there are two categories of WPT which is near-field transfer and far-field transfer. Near-field transmission is based on the coupling of two coils within the coil size range. If the iron core is removed and separate the coils, the efficiency of transmission will drop. That is the reason why the coils must put closely in near-field transfer. For long-field transfer, the concept is based on the electromagnetic wave. The method is depending on the waveband. The concept is almost same the as the near field and far field of electromagnetic field. Figure 2.3 below shows the example for near field and far field of electromagnetic field.

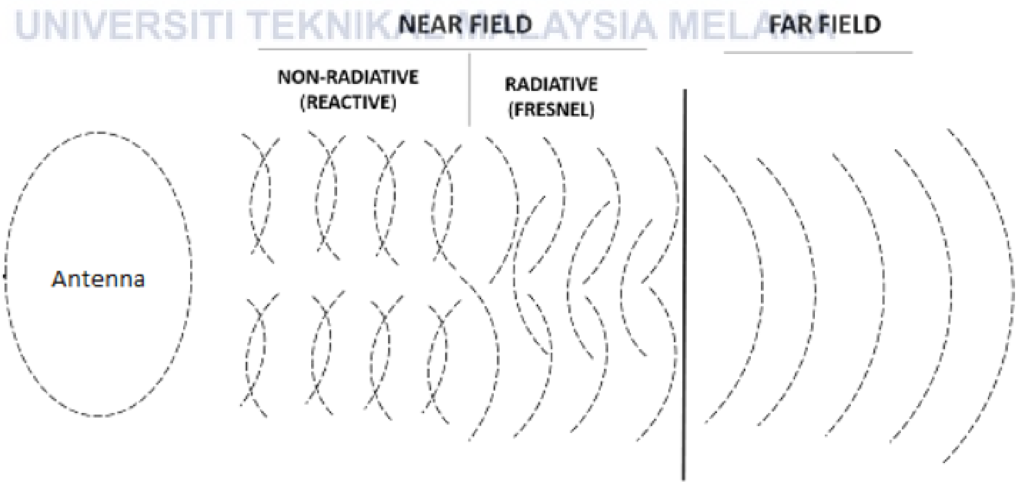

Figure 2.3: Example of near-field and far-field of electromagnetic field

Combine all near-field and far-field, the technology consists of inductive coupling, resonant inductive coupling, capacitive power transfer, microwave transfer, laser transfer, etc. Figure 2.4 below shows the summaries of wireless power transfer technology.

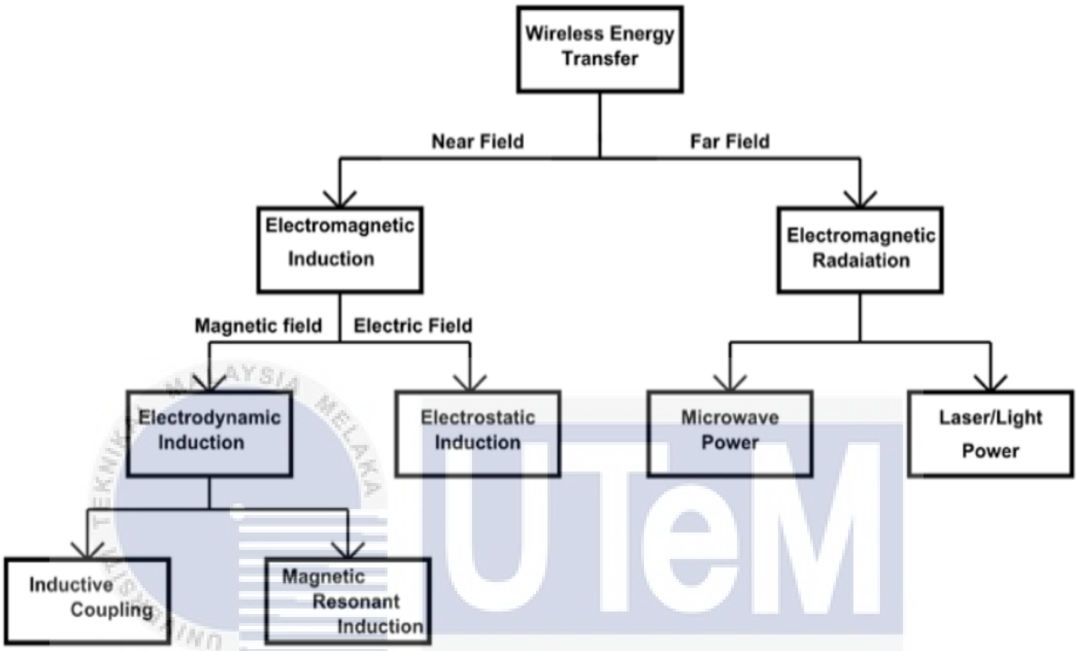

Figure 2.4: Summaries of wireless power transfer technology

2.1.1 Inductive Power Transfer

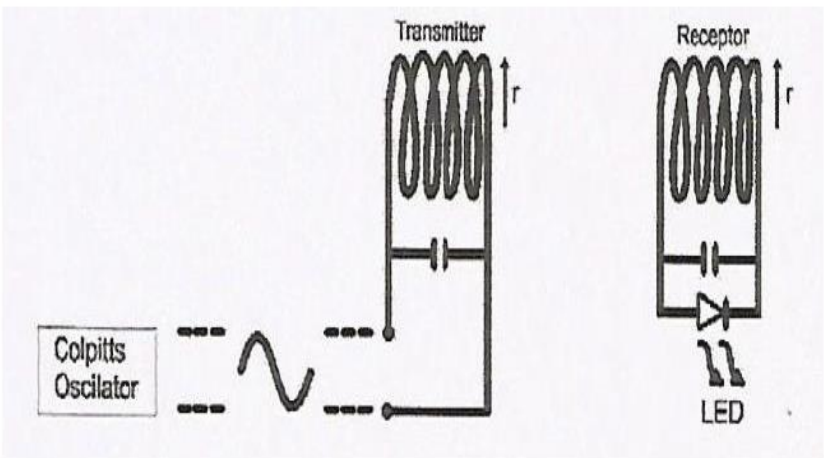

Figure 2.5: Inductive coupling

The concept of inductive coupling is based on mutual inductance. When two conductors are configured to induce a voltage at both ends of the wire through the current change of wire, they are known as inductive coupling or also known as electromagnetic coupling. Figure 2.5 above shows the inductive coupling of a wireless power transfer system.

2.1.2 Resonant Inductive Power Transfer

Resonant inductive coupling can also know as magnetic phase synchronous coupling. It is the phenomenon that the coupling is enhanced when the secondary side of the loosely coupled coil resonates. The basic principle of resonant inductive coupling includes a drive coil on the primary side and a resonant circuit on the secondary side. Figures below shows the difference between inductive coupling and resonant inductive coupling. From the figure 2.6 and figure 2.7, we can observe that the difference between two figures is the resonant circuits. The resonant inductive coupling consists of a resonant circuit which can cause the coupling to become greater while the inductive coupling is just two sides of coils for power transfer.

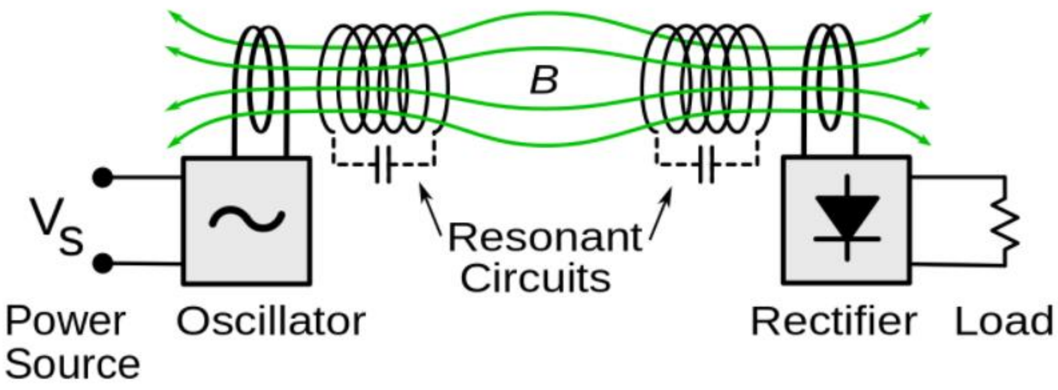

Figure 2.6: Resonant inductive coupling

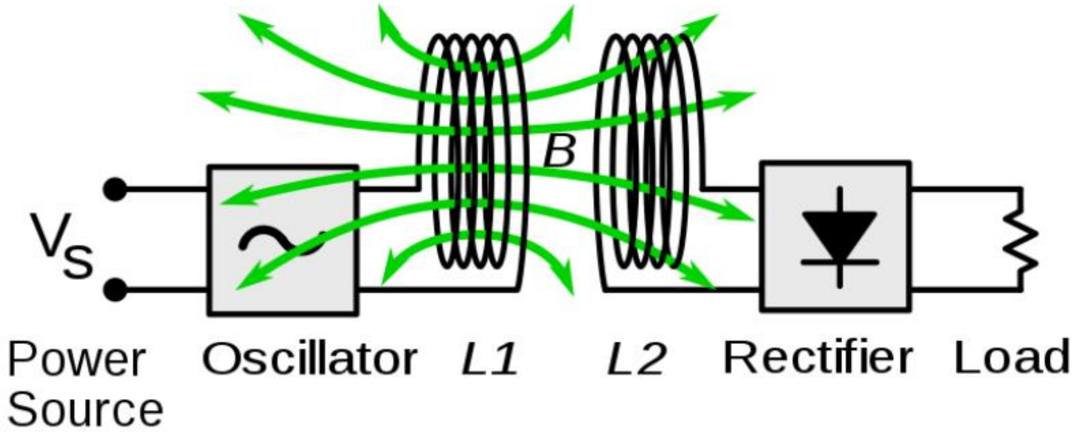

Figure 2.7: Inductive coupling

2.1.3 Capacitive Power Transfer

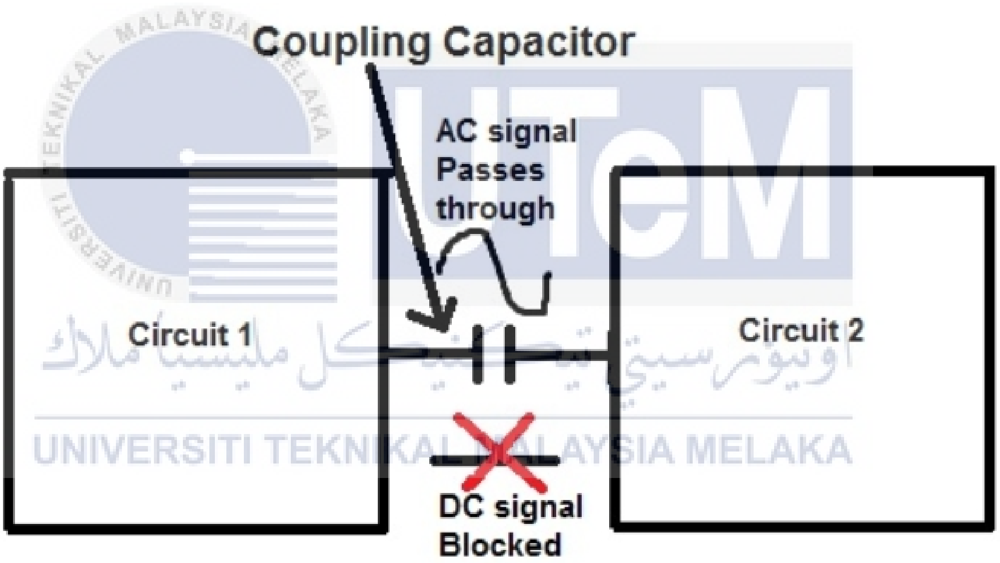

Figure 2.8: Capacitor coupling

Figure 2.8 above shows the diagram of capacitive power transfer. The capacitive coupling is also known as AC coupling which connects two circuits together with a capacitor. The capacitor blocks the low-frequency DC signal from entering the second circuit and only allows the high-frequency AC signal to pass through. For low-frequency signal, it consists of high impedance or resistance which can block low-frequency signal pass through, for high-frequency signal, it consists of low impedance or resistance which enable the high frequency to pass through. Figure above shows the example of capacitor coupling.

2.1.4 Microwave Power Transfer

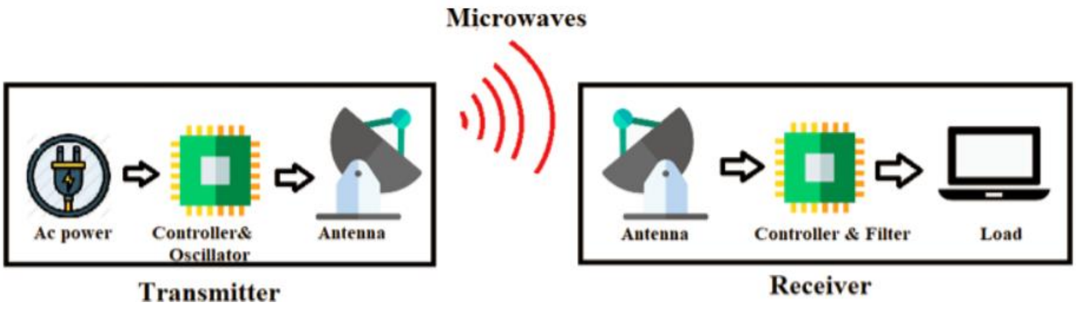

Figure 2.9: Technology of microwave WPT

Microwave power transfer use electromagnetic wave in microwave frequency range as the carrier of wireless power. A finalize microwave transmission system should include the conversion of electrical energy to microwave power, absorption antenna that can grab the waves and lastly is the conversion of microwave power back to electrical power. As we can see from the figure 2.9 above, the power source will generate electrical energy and provide the energy to the antenna. The energy will then convert to microwave radiation. the microwave will transmit through the air gap and receive by the receiver antenna. Once the receiver receives the signal, the microwave radiation will be converting back to electrical energy. That is how a microwave WPT works and due to the use of microwave radiation, the power can reach a longer distance (far-field) compare to inductive and capacitive.

2.1.5 Laser Power Transfer

Laser power transfer (LPT) is one of the far-field wireless power transfer. The characteristic of the laser is a low divergence angle when it extends from the light source. This characteristic makes it become a good selection in far-field transmission. Due to this characteristic, it can send the laser energy from space to earth and the energy can be converted into electrical energy. This transmission also depends on the wavelength. Even so, there are still somethings to pay attention to, such as the laser cannot penetrate clouds and it is susceptible to atmospheric disturbances. Figure 2.10 below shows an example of laser transmission technology.

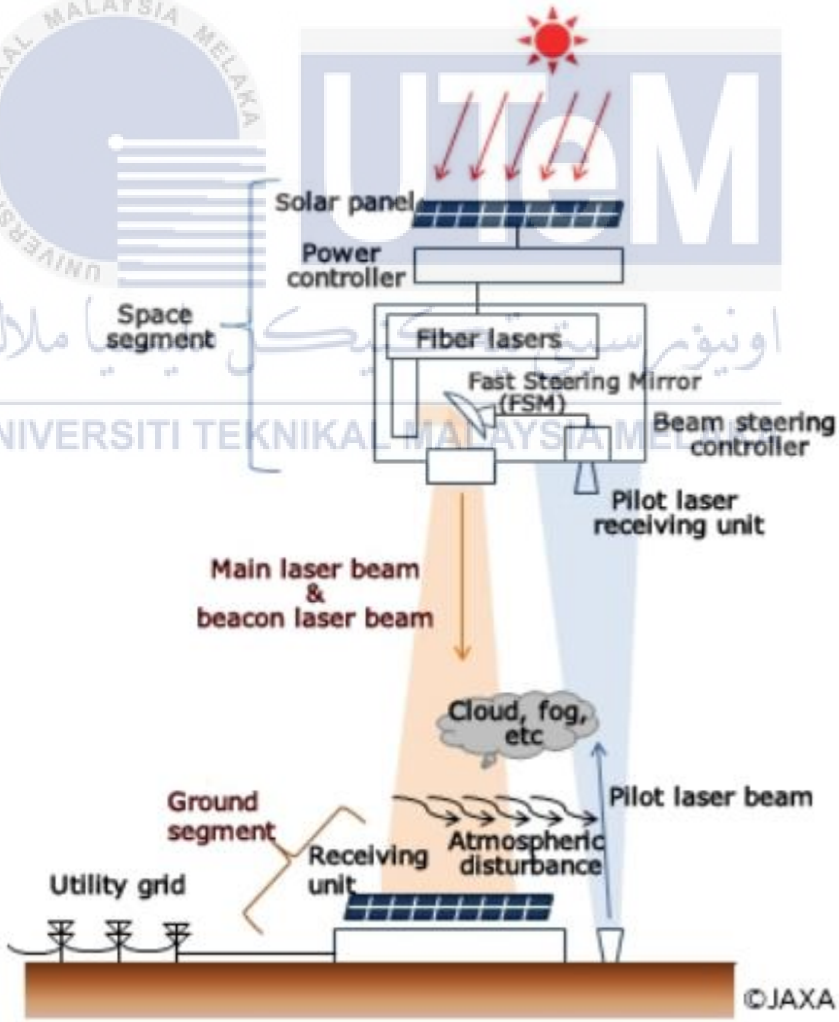

Figure 2.10: Example of laser transmission technology

2.1.6 Summary

Based on the information above, the near-field transfer has been selected. This is because the far-field transfer is not suitable for this system as this wireless power transfer system is design for drone charging only. Hence, it doesn't require a long-distance power transfer. Among the near-field transfer technique, the better option for this system is inductive power transfer. The inductive coupling is better compared to another technique as the inductive coupling can transfer energy through two coils.

2.2 Inverters

Inverter is an oscillator which can convert a DC power to high power AC output. Inverter cannot generate power by itself, it is depending on the DC source which is either a Voltage Source Inverter (VSI) or Current Source Inverter (CSI). Besides, the flow of circuit is control by transistors which is function as switches. The concept of the working principle is the transistor switched on and switched off rapidly to cause the formation of AC power. The inverter is divided into two categories which are single phase inverter and three phase inverters. This paper will only focus on the single-phase inverter. Nevertheless, speaking to a single-phase inverter, it is also divided into two groups which are half-bridge and full-bridge.

2.2.1 Half-Bridge inverter

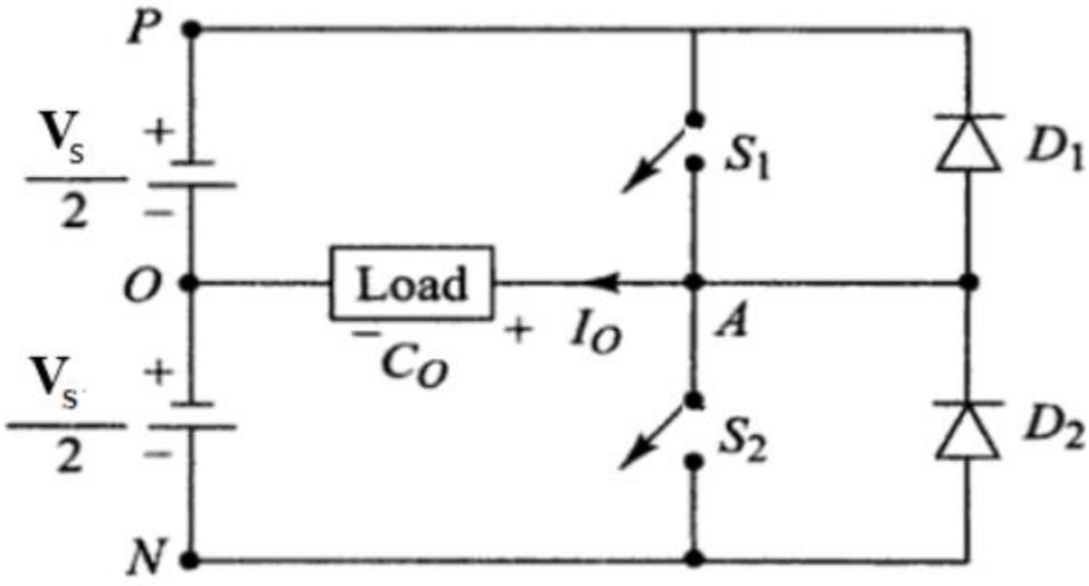

Figure 2.11: Half bridge inverter

Figure above shows the schematic circuit of half bridge inverter. The function of the inverter is also the same, converts a dc voltage into ac voltage, but the half-bridge inverter only consists of two switches and two diodes. The two switches won't open at same time due to the complementary of the two switches. Saying that, when switch 1 is ON, switch 2 will be OFF and vice versa. Let's look at the circuit, the DC voltage source is divided into two and both of them are connected to the load while load is connected to the switch. When the voltage is positive and the current is negative, switch S1 will turn on and S2 will turn on when voltage is negative and the current is positive due to the self-commutating. Same goes to diode 1 and diode 2. The inverter normally uses MOSFET to represent the switches and the diodes. the advantages of the half bridge inverter is due to the simple design and because of the simple design, the cost needed is also very low. Even so, the disadvantage of the half bridge is also critical because of the efficiency cannot compare with full bridge. The parameter of half bridge is almost same as full bridge except for the number of devices conducting simultaneously. Half bridge inverter is conducting one component at once while full bridge can conduct two simultaneously.

2.2.2 Full-Bridge inverter

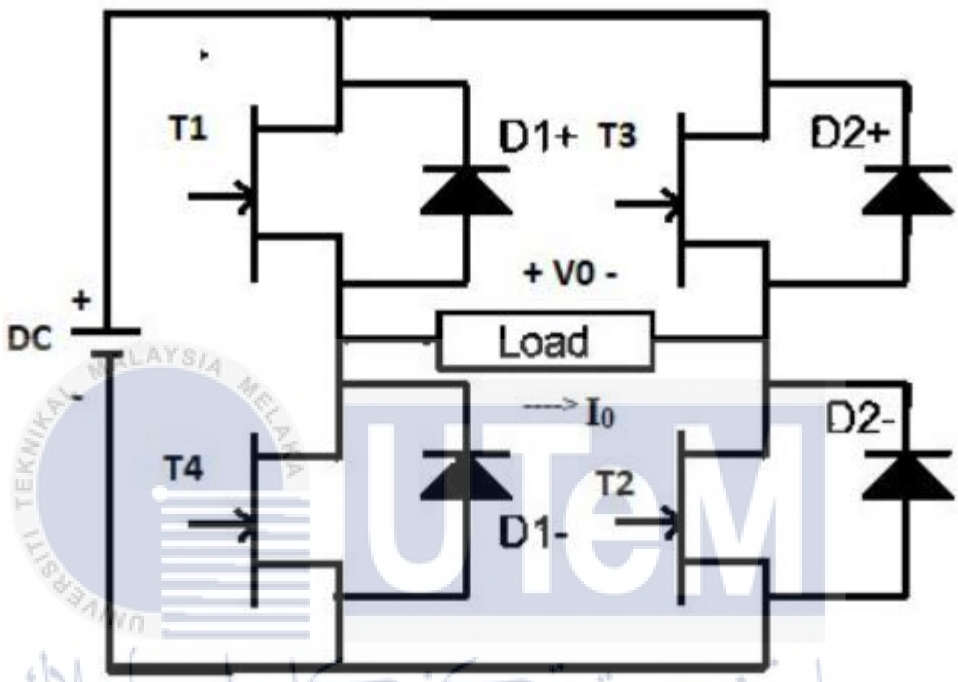

Figure 2.12: Full bridge inverter

A full bridge inverter circuit is shown in figure. Based on the figure 2.12 above, notice that there are 4 MOSFET in the circuit, each transistor and diode are connecter parallel. The positive side of load is connected to the T1 and T4 while negative side of the load is connected to the T3 and T2. The operation happened when the T1, T2 is ON while T3, T4 is OFF. During the first half cycle, the current will flow from positive DC source through T1, load, T2 and back to negative DC source which cause the waveform to become positive square wave. Then, when T1, T2 is turn OFF, T3, T4 will turn ON. During the remaining half cycle, the current will flow from positive DC source through T3, load, T4 and back to negative DC source which cause the waveform to become negative square wave. Because of this operation, a Direct Current is changed to an Alternating Current in square wave. The advantages of full bridge are more than half bridge. For instance, the energy is efficient and suitable for high input voltage by using full bridge inverter. Unfortunately, there are still some disadvantages occur which the noise and losses of full bridge quite high. But if compare to the half bridge, full bridge is more useful because the output voltage is twice of half bridge inverter by using the same parameters.

2.3 Related Research

Based on the study by Jie Li (2018), a Wireless Power System was design for the maximum efficiency. The method use by Jie Li was resonant WPT system because of the limitation of IPT which is short charging distance. The use of IPT doesn't fulfil his design. In other words, the resonant WPT use capacitors to compensate the coil for the purpose of reduction power and it can also charge at long distance.

Mohammad Shidujaman and Hooman Samani (2014) have mentioned the technologies used in wireless power transfer is Qi technology, Alliance for Wireless Power (A4WP) and Power Matters Alliance (PMA) technology. Based on the study, Qi technology is used small inductors to enable the power pass through high frequencies. The maximum charging distance is a few centimeters but the distance can be increase by using multiple resonator arrays. Other than that, A4WP is newer technology compare to Qi technology. It can charge multiple devices with differing power due to the use of electromagnetic field and the charging distance also can reach but not more than 10 centimeters. Besides, PMA technology used electromagnetic induction to transfer power. It is almost the same as Qi, just the different is both of them are operates with difference frequencies.

The research done by Oguzhan Dogan and Serhan Ozdemir (2020) proposed the used of IPT using Class D power amplifier. The study is slightly the same with this paper which are the used of IPT and class D amplifier but the resonant circuit is not same. The study suggested only two MOSFET and also the L-C resonant circuit. The study is only focus on the primary stage and it doesn't convert back to DC after transferring power to secondary stage. Figure 2.13 below shows the schematic diagram of class-D amplifier including the primary and secondary side which is done by the researcher. Since the research paper is also using class-D, so the formula proposed is also the same which are listed at Chapter 3.

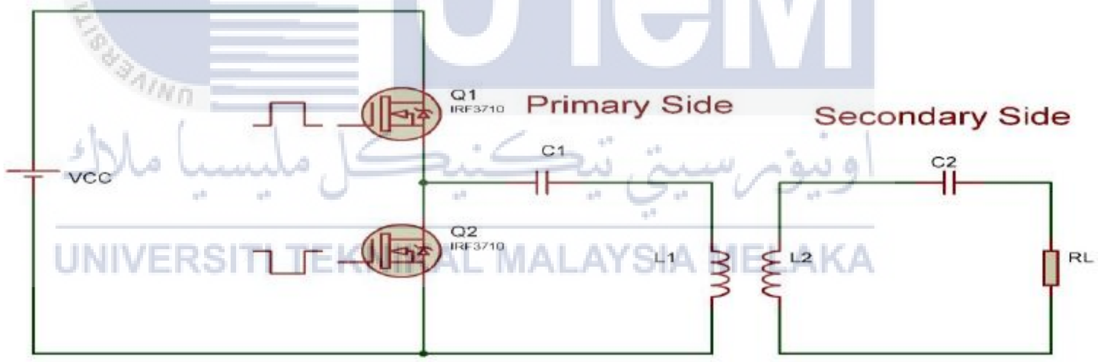

Figure 2.13: Schematic diagram of class-D amplifier

Besides, the paper done by Ong Kim Keat (2015) has added the magnetic field repeater in his project WPT with Class E Power Amplifier. The reason that he chooses class E was because of the class D is not suitable compared to class E in his application. Class E is not same as class D, which it only consists of 1 MOSFET which easier to control. Unlike class D, 4 MOSFET inside the circuit. The system proposed by Ong has successfully increased the efficiency to more than 80%. Not only that, he also added a magnetic field repeater in his system to increase the magnetic field. This is because the magnetic field will diffusion when there is no repeater. The magnetic field will affect the system efficiency, higher efficiency is depending on higher magnetic field received. That's why to overcome this problem, a relay coil can insert between device coil and excitation coil to improve the magnetic field received by the receiver. The relay coil helps to concentrate the magnetic flux. The only thing needs to be remembered is that the total number of repeaters need to be choose carefully to prevent frequency splitting effect which might reduce the efficiency of transmission.

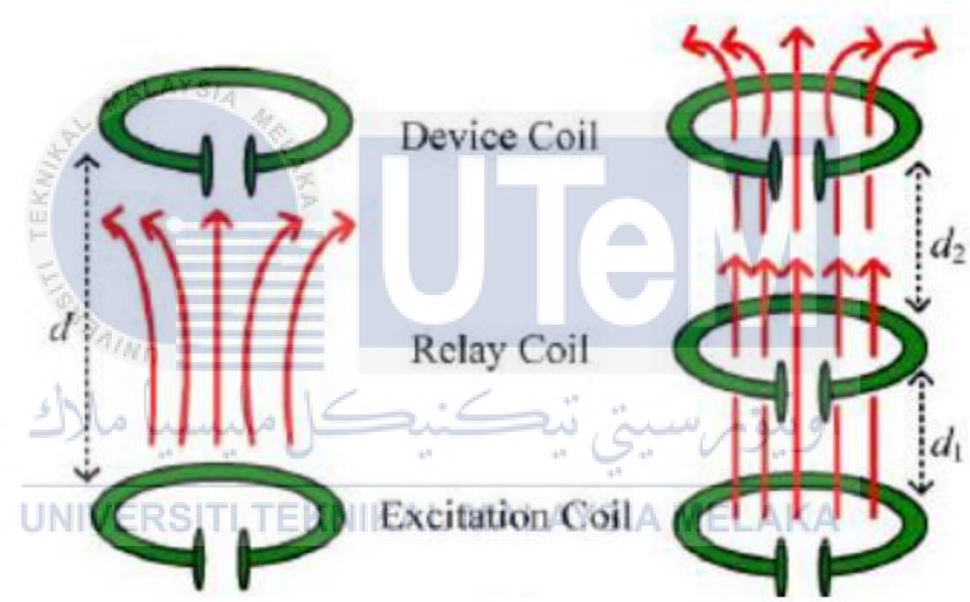

Figure 2.14: Magnetic field repeater

Next, the paper done by Wenxu Yan and Jingjing Chen (2017) has listed out the basic outline of Magnetic Resonant Coupled WPT. The figure below shows the basic structure of WPT draw by them.

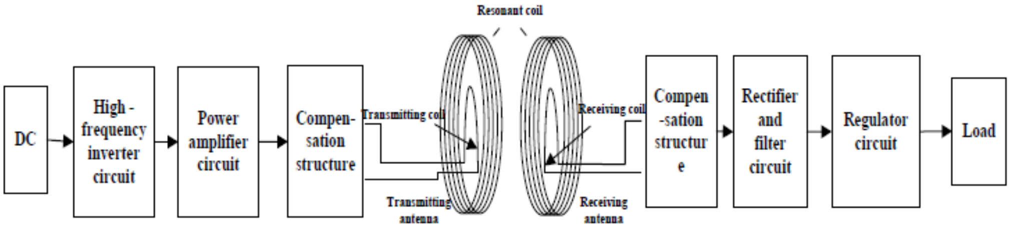

Figure 2.15: Basic structure of WPT

From the research, notice that they have separate the blocks into several parts. Each of the parts have include the details explanation and let's look at some examples. First of all, the high-frequency inverter circuit is selected as class E inverter because class E inverter has only one MOSFET and also simple to design. Figure 2.16 below shows the class E inverter circuit.

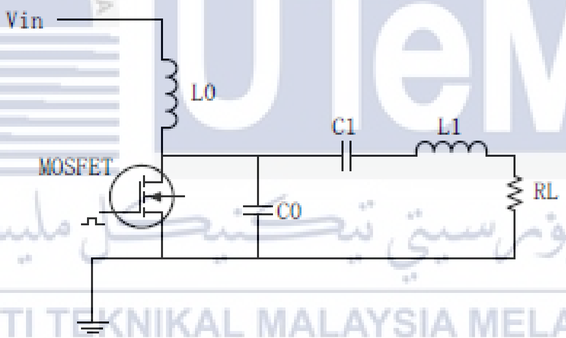

Figure 2.16: Class E inverter circuit

Furthermore, the compensation topology has also listed in order to see the difference. Figure 2.17 below shows the compensation topology and the number (C) is selected.

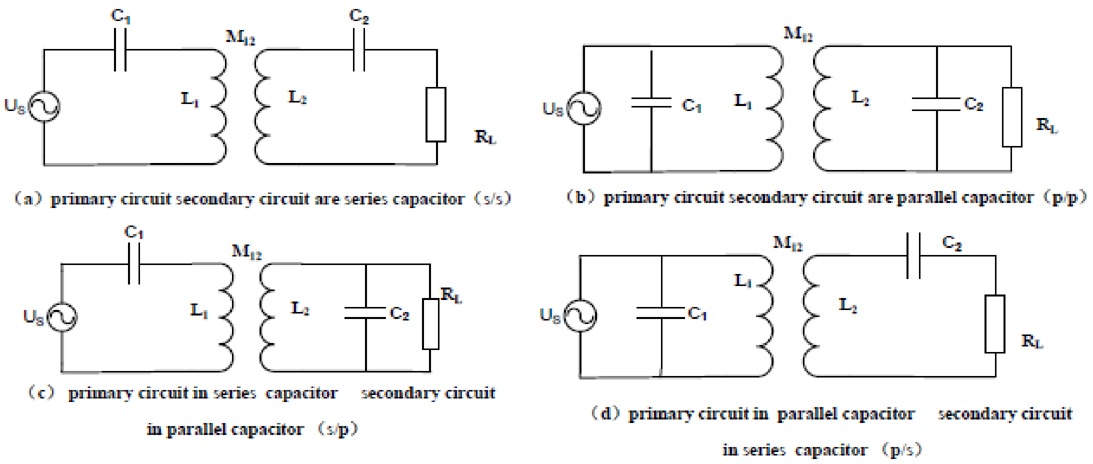

Figure 2.17: Type of compensation topology

Last, the selection of rectifier is also important because it allows the AC power convert back to DC power at the output. The researcher has mentioned that even though the half bridge rectifier is simple and less diodes required, but the circuit is only used half cycle of AC voltage, and thus the efficiency of output will be low. Whereas the used of full bridge rectifier used full cycle of AC voltage and cause it has a higher efficiency compare to half bridge. That's why the reason of full bridge is selected, figure 2.18 below shows the circuit of full bridge rectifier.

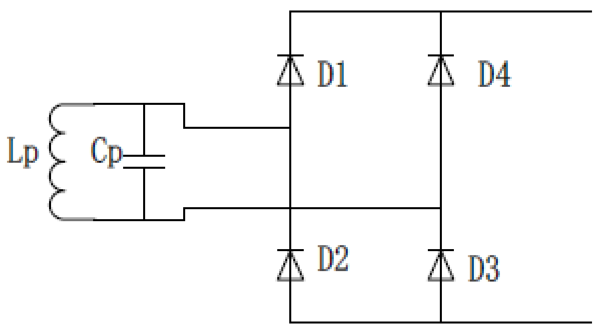

Figure 2.18: Full bridge rectifier

Table 2.1 shows the summary table of literature review. There are some of the references that are not mention in previous example but there are listed in the Table 2.1. The table below has highlighted the research gap for better understanding.

Table 2.1: Summary of Literature Review

References	Author	Title	Frequency, Hz	Air gap	Output Power, W	Efficiency, %
[5]	Jie Li (2018)	Wireless Power System Design for Maximum Efficiency.	6.78M	5cm	10	88.8
[6]	Oguzhan Dogan and Serhan Ozdemir (2020)	Development of Inductive Power Transfer System using Class-D Power Amplifier	200k	N.A.	1.8	70.58
[7]	Ong Kim Keat (2015)	Wireless Power Transfer with Class E Power amplifier and Magnetic Field Repeater	290k	25cm	3591.6m	47.89
[8]	Honhchang Li, Jingyang Fang, Kangping Wang, Yi Tang (2018)	Pulse Density Modulated ZVS Full-Bridge Converters for Wireless Power Transfer Systems	0.91M	20cm	10	89
[9]	Minfan Fu, He Yin, Ming Liu, Chengbin Ma (2016)	Loadingand Power Control for a High-Efficiency Class E PA-Driven Megahertz SPT System	6.78M	5cm	10	80
[10]	Ming Liu, Minfan Fu (2016)	Low-Harmonic-Contents and High-Efficiency Class E Full-Wave Current-Driven Rectifier for Megahertz Wireless Power Transfer Systems	6.78M	4cm	10	72

2.4 Chapter Summary

This chapter presented the type of wireless power transfer that are popular in the market. Among these methods, inductive power transfer (IPT) is selected due to the electromagnetic field and the inductive coupling which is not affected by dust. Next, some of the existing researches have also explained in this chapter. A class-D CLL topology and full-bridge rectifier has been decided after review the existing research. A summary table of literature review has been done for better observation in the system efficiency.

CHAPTER 3

METHODOLOGY

In this chapter, the technique used to design a wireless power transfer system is explained in detail. There are few categories of wireless power transfer which are inductive, capacitive, etc. The reason for using the technique and selected component will include as well. The two objectives have divided into two parts for detail explanation. Designing of IPT system is to achieved objective 1 while the performance analysis is to explain objective 2.

3.1 Methodology Flowchart

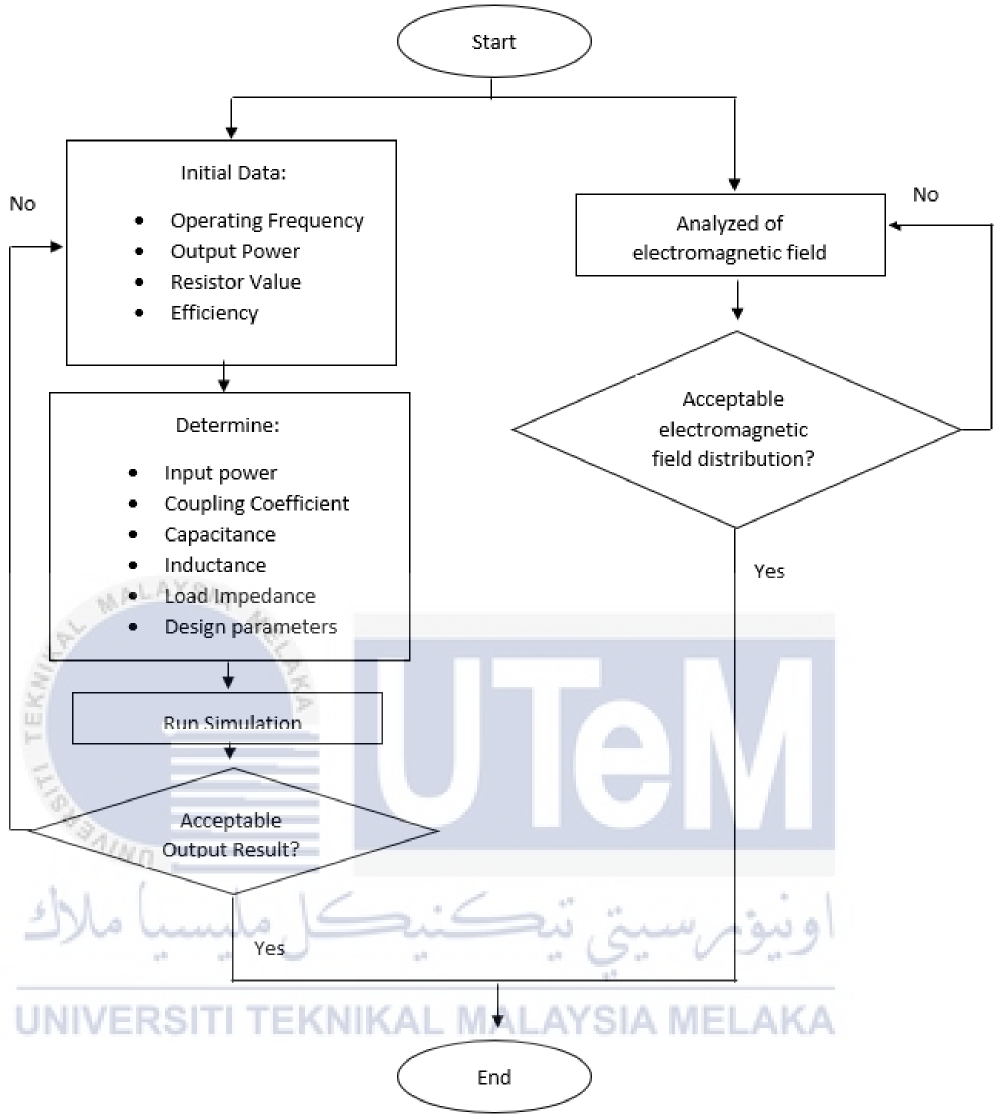

Figure 3.1: Methodology Flowchart of Wireless Power Transfer design

Figure 3.1 above shows the methodology flowchart of the project. The goal of the project is to design a wireless power transfer system. In order to achieve this goal, some research has to be done for a better understanding of the project title. This is also very useful in project design. Once getting enough information, proceed to the project proposal and prepare for the proposal defense. Other than that, the calculation for the required data such as the value of components can begin. After calculating the required data, proceed to circuit simulation. Check the circuit and make sure no error occurs. If any error occurs, recheck or recalculate the value of the components. Once the simulation circuit is successful, continue to simulation of electromagnetic field. Troubleshoot the problem if any error occurs. Observe the electromagnetic field distribution at transmitter and receiver coil. Observe the relationship between electromagnetic field and the distance between coils.

3.2 Block Diagram

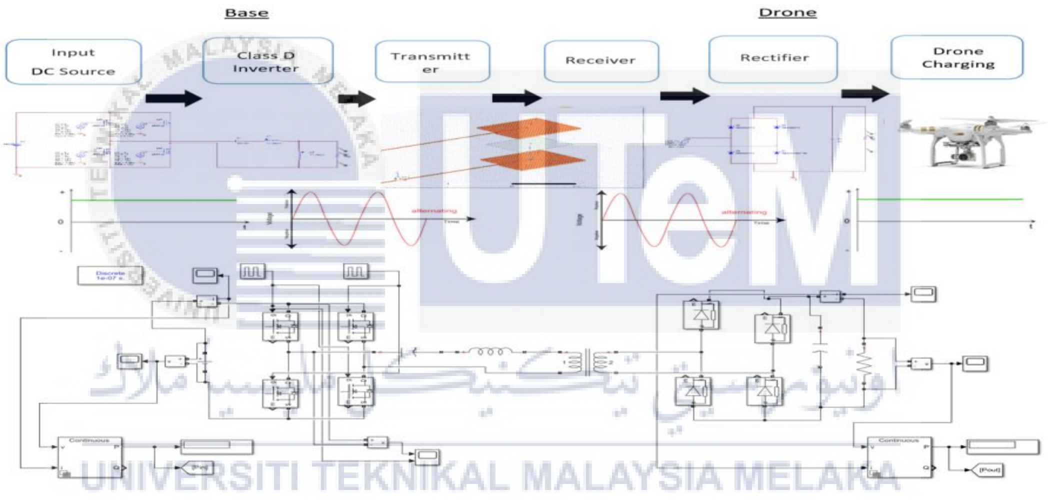

Figure 3.2: Block diagram of wireless power transfer

Figure 3.2 above shows the block diagram of an inductive power transfer system. Refer to figure 3.2, this WPT system requires a DC power source. If the power source is not a DC signal, it can also be converting from AC to DC signal by using the converter. Once the source has become a DC signal, the DC-to-DC converter is depending on the design. The DC-to-DC converter can be connected after the DC source to stabilize the Direct Current. The DC signal will then enter an inverter. The function of the inverter is converting DC to AC so that the energy can transfer through the transmitter coil. Next, the inverter will connect with the resonant circuit, which has a lot of examples. Each of the example have different functions. The resonant circuit will connect with the transmitter coil and transfer energy to the receiver coil. The energy will then be converted from AC back to DC by using a rectifier and the Direct Current after the rectifier will be used for charging. In this project, the source is selected to be a DC signal so it doesn't have to convert. The DC signal will enter the converter and become an AC signal. Then the AC signal will be transferred through the coils and be converted back to DC.

3.3 Design of the IPT system

3.3.1 Class D Inverter

To design the inverter, the specification needs to be determined for the use of calculation. In this project, half bridge inverter's calculation is used and some of the full bridge inverter's parameters is twice of the half bridge parameters. First of all, the output power is required to produce 10W of output. Other than the output power, the operating frequency is set to 100kHz and the DC input is set to 24V. Besides, the quality factor is also assumed as 10 and the load resister is 150 Ω. Due to the used of class D CLL topology, so the efficiency is theoretically 100% for the calculation. First, the maximum input power and maximum input current are calculated by using the formula. The efficiency has to convert to a decimal number which is 1.0.

$$\text{Efficiency}, \eta = \frac{P_o}{\mathrm{P_I}}$$

$$P_{Imax} = \frac{P_o}{\eta} = \frac{10W}{1} = 10W$$

$$I_{Imax} = \frac{P_{Imax}}{\mathrm{V}_1} = \frac{10W}{24V} = 0.42A$$

Since the Quality factor is assuming 10, the capacitor and inductors are then calculated by using the formula given. The w_O is calculate by using simple fundamental formula which is $w_O = 2\pi \mathrm{f_O}$.

$$C = \frac{Q_L}{w_O \mathrm{R_i}} = \frac{10}{2\pi(100kHz)(150\Omega)} = 106.1nF$$

$$L = \frac{R_i}{w_O Q_L} = \frac{150\Omega}{2\pi(100kHz)(10)} = 23.87uH$$

$$L_1 = L_2 = \frac{L}{1 + \frac{1}{A}} = \frac{23.87uH}{1 + \frac{1}{1}} = 11.94uH$$

where A is known as the ration of the inductances $A = \frac{L_1}{L_2}$. L_1 and L_2 is assuming the same. The output impedance can then be calculated by applying the formula,

$$Z_O = \frac{R_i}{Q_L} = \frac{150\Omega}{10} = 15\Omega$$

Next, the modulated current can be calculated by applying the formula.

$$I_m = \frac{2V_1|M_{Vr}|}{\pi Z_O Q_L}\sqrt{1 + \left[Q_L\left(\frac{w_O}{w}\right)(1 + A)\right]^2}$$

The $\frac{w_O}{w}$ is equal to 1 since the frequency f and $\mathrm{f_O}$ is same. Furthermore, the value of $|M_{Vr}|$ is equal to 1 after applying the formula. Hence,

$$I_m = \frac{2(24V)|1}{\pi(15\Omega)(10)}\sqrt{1 + [10(1)(1 + 1)]^2} = 2.04A$$

Not only that, by having the output power and the load resistor, the output voltage and output current can be calculated by applying the formula.

$$P_o = \frac{v_{Ri}^2}{\mathrm{R_i}}$$

$$v_{Ri}^2 = P_o \mathrm{R_i}$$

$$V_{Ri} = \sqrt{P_o \mathrm{R_i}}$$

$$V_{Ri} = \sqrt{10W(150\Omega)} = 38.73V$$

$$I_o = \frac{V_{Ri}}{\mathrm{R_i}} = \frac{38.73V}{150\Omega} = 0.258A$$

After getting the I_m, the voltage across capacitor and inductors can be calculated by follow the formula.

$$V_{L1m} = w\mathrm{L_1} I_m = 2\pi(100kHz)(11.94uH)(2.04A) = 15.3V$$

$$V_{L2m} = \sqrt{2} M_{VS} |M_{Vr}| V_1 = \sqrt{2}\left(\frac{\sqrt{2}}{\pi}\right)|1|(24V) = 15.28V$$

$$V_{Cm} = \frac{I_m}{wC} = \frac{2.04A}{2\pi(100kHz)(106.1nF)} = 30.6V$$

The calculated parameters are listed in the Table 3.1 and Table 3.2 below.

Table 3.1: Parameters of half bridge inverter

Parameter	Symbol	Value	Unit
Quality factor	Q	10	-
Frequency	f	100k	Hz
Input current	I_{Imax}	0.42	A
Input Voltage	V_1	24	V
Resistor	R_i	150	Ω
Capacitor	C	106.1n	F
Inductor 1	L_1	11.94u	H
Inductor 2	L_2	11.94u	H
Voltage Capacitor	V_{Cm}	30.6	V
Output Current	I_o	0.258	A
Output Voltage	V_{Ri}	38.73	V
Input Power	P_{Imax}	10	W
Output Power	P_O	10	W
Efficiency	η	100	%

Table 3.2: Parameters of full bridge inverter

Parameter	Symbol	Value	Unit
Quality factor	Q	10	-
Frequency	f	100k	Hz
Input current	I_{Imax}	0.84	A
Input Voltage	V_1	24	V
Resistor	R_i	150	Ω
Capacitor	C	106.1n	F
Inductor 1	L_1	11.94u	H
Inductor 2	L_2	11.94u	H
Voltage Capacitor	V_{Cm}	61.2	V
Output Current	I_o	0.516	A
Output Voltage	V_{Ri}	77.46	V
Input Power	P_{Imax}	10	W
Output Power	P_O	10	W
Efficiency	η	100	%

The reason of listing half bridge and full bridge is due to the calculation above is for half bridge inverter while the design of this project is full bridge inverter. For understanding, the calculation used for both half bridge and full bridge is same, the only different is some of the parameters for full bridge is twice of the half bridge parameters.

3.3.2 Full Bridge Rectifier

The circuit of rectifier is simple. Assume the voltage requirement for a drone is 40V. Consider the losses during wireless power transfer, the voltage requirement is set to higher voltage. By using simple Watt's law:

$$P = VI$$

$$I = \frac{P}{V}$$

$$I = \frac{10W}{40V}$$

$$I = 0.25A$$

3.3.3 Design Specification

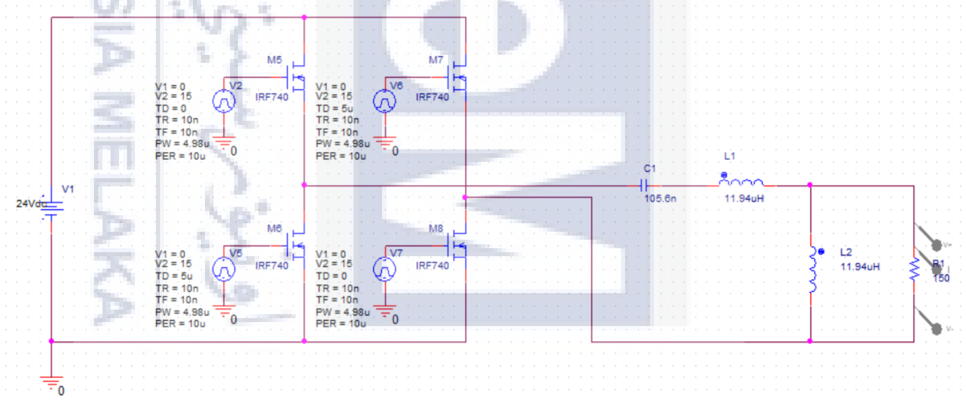

Figure 3.3: Schematic Circuit for Class D CLL Inverter

The project is then proceeded to the circuit simulation after the calculation is done. The simulation was construct by using ORCAD PSpice software. The schematic circuit is shown in figure 3.3. The DC voltage source is set as 24V and four MOSFET with pulse generator is used in this circuit. The MOSFET M5 and M8 is turn ON while M7 and M6 is turn OFF by using the pulse generator, vice versa. Besides, the pulse generator settings are depending on the design. For instance, PER stands for period which can get by $T = \frac{1}{f}$, thus 10us is get for period. Not only that, the PW pulse width can get by period (T) multiply by duty cycle (D), $PW = DT$. Other than that, pulse width can also get by using half of the period subtract TR and TF, $\left(\frac{PER}{2}\right) - TR - TF$ for more accurately. Next, the capacitor and inductor are set as the calculated parameters which is 105.6nF and 11.94uH. Last, the load resistor is set as 150 Ω. The DC voltage will enter the inverter and converted in to AC sinusoidal wave. The used of the resonant circuit is to smoother the sinusoidal wave.

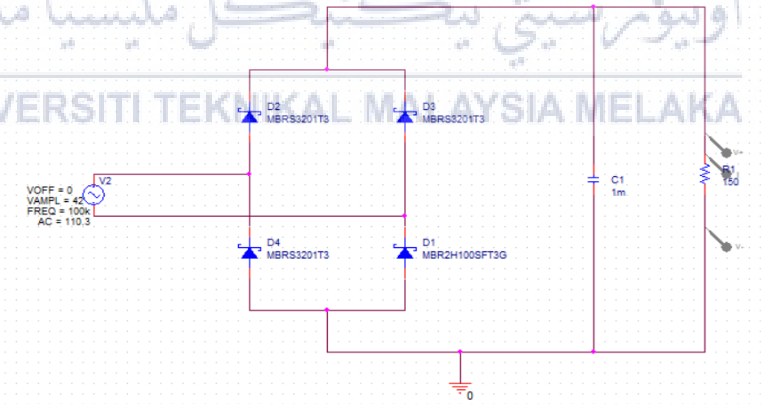

Figure 3.4: Schematic Circuit for Full Bridge Rectifier

Figure 3.4 shows the schematic circuit for full bridge rectifier. The circuit has used an AC source, four diode and a capacitor. The capacitor is used to reduce the ripple of DC output while the load resistor replaces the battery. The AC source has used back the output of inverter which is approximate to 110V. The AC will enter the rectifier and convert back to DC signal again.

3.4 Performance Analysis

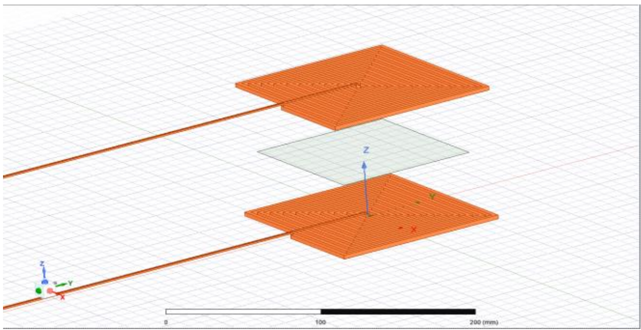

Figure 3.5: Maxwell 3D design of coupled coils

Figure 3.5 shows the transmitter and receiver coil which has drawn by using Ansys Maxwell 3D software. The plane between two coils is to observe the distribution of electromagnetic field. The 3D coils were supposed to connect to the complete circuit design by using Ansys simplorer software to observed the output of whole circuit in term of electromagnetic field. Somehow, the simplorer circuit is failed to obtain the same data as expected result that have been calculated due to the parameters setting. The expected result was supposedly come out with coupling coefficient or voltage and current versus the distance between two coils. However, the circuit was successfully constructed but the output was failed to get the expected graph. A coupling coefficient versus time's graph was successfully get but unfortunately it is not the expected graph. The reason of the selection of expected result is to observe how the distance between coils affect the coupling coefficient or the efficiency and electromagnetic distribution, but the time graph is not fulfilling the requirement. Thus, another simulation circuit using MATLAB has been done to observe efficiency of the system with load variation and distance variation to replace the Ansys analysis.

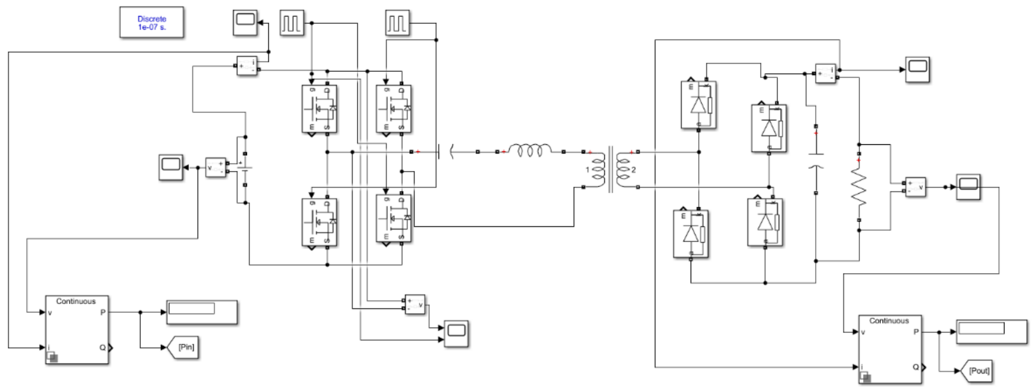

Figure 3.6: MATLAB Full circuit

A complete circuit is constructed by using MATLAB software is shown in figure 3.6. The circuit is basically based on the block diagram in figure 3.2 which has already separate part by part for easy understanding. The initial part with four MOSFET until the transformer is the class D CLL inverter circuit while after the transformer is a full bridge rectifier. The MATLAB simulation is used to determine the analysis of load variation and inductance variation which the inductance is used to replace with the distance between two coils. By using MATLAB Simulink, the analysis is conducted from 5uH to 50uH and 50Ω to 500Ω for the observation of system efficiency. Since the Simulink is to observe the electromagnetic field distribution, so the coupling distance is replaced with the inductance value. The higher the inductance value, the farthing the coupling distance. The power transfer is depending on the electromagnetic field in IPT. This means the electromagnetic field will affect the power transfer and affect the efficiency for sure. Thus, to observe the electromagnetic field distribution, the value of efficiency is very important. In theoretical, the higher the efficiency the stronger the electromagnetic field distribution.

3.5 Chapter Summary

This chapter explained the flowchart and block diagram of the project. The methodology is basically divided into two parts which related to two objectives. The design of IPT system is to achieved objective one. The design specification and simulation are included in this chapter. Besides, performance analysis is to explained objective two. The reason of using Ansys software and MATLAB is explained.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter will discuss about the output result of the project. The output waveform by using Pspice is shown in this chapter. A comparison table is listed in terms of simulation and calculation value. Other than that, the result for objective two is also explained.

4.1 Result for PSPICE Simulation

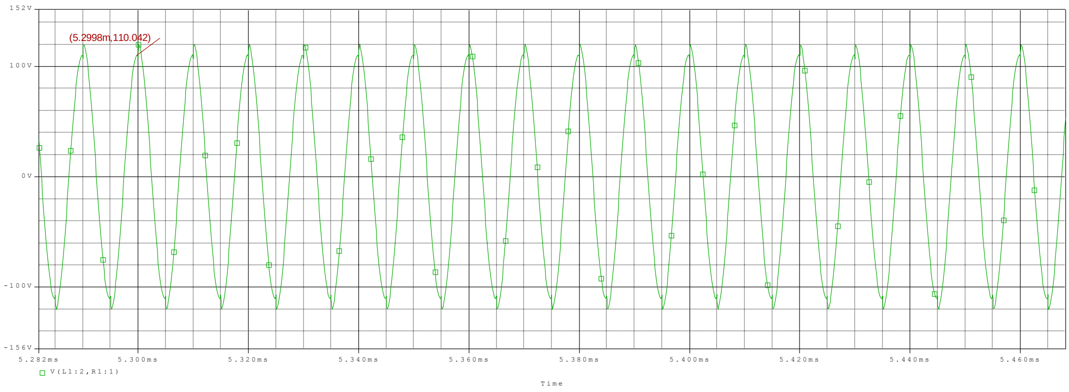

Figure 4.1: Output Waveform for Class D Inverter

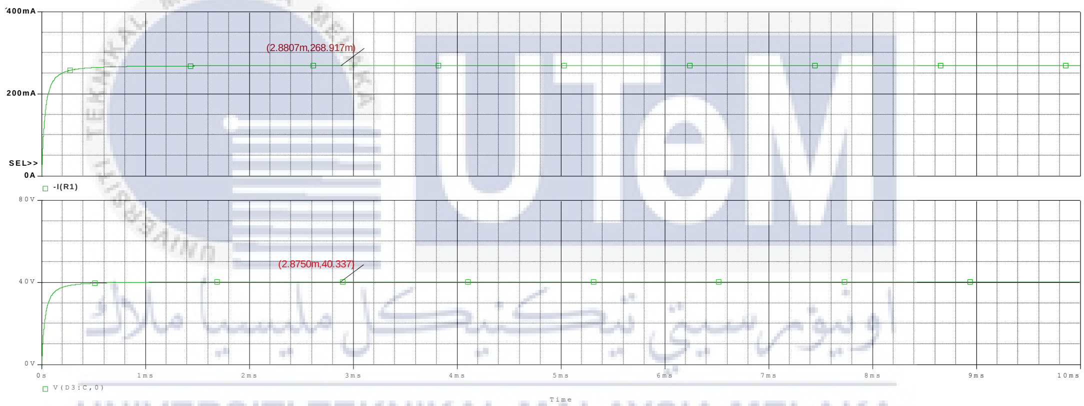

Figure 4.2: Output waveform for Full-Bridge Rectifier

In figure 4.1, observed that the output voltage is converted from DC to AC before transfer through coupled coils. While figure 4.2 shows the transferred voltage has been converted back to DC after passing through the rectifier. The simulation output power is calculated using Watt's Law which get $P = 40.35\ (269m)$. Thus, $P = 10.785W$. The simulation result is almost same as calculated result which is 10W.

Table 4.1: Comparison table for output result

Inverter				
Parameter	Unit	Calculation	Simulation	Difference (%)
Output current	Ω	730m	732m	0.27
Output voltage	V	109.87	109.54	0.3
Rectifier				
Output Current	A	250m	269m	7.6
Output Voltage	V	40	40.35	0.875
Output Power	W	10	10.785	7.85
Efficiency	%	100	92.72	7.24

Table 4.1 shows a comparison table of some important output for expected value and simulation value. For inverter part, the different of calculation and simulation value in terms of output current have 0.27% error while output voltage has 0.3% of error. As mention, the output voltage obtained in output inverter is used as the input voltage for rectifier. The output current has higher percentage error which is 7.6% while the output voltage is much better, only 0.875% of error. Due to the higher percentage error, the percentage error for output power is also increase. Thus, the efficiency of the system is 92.72% with 7.24% of error.

4.2 Result for Performance Analysis

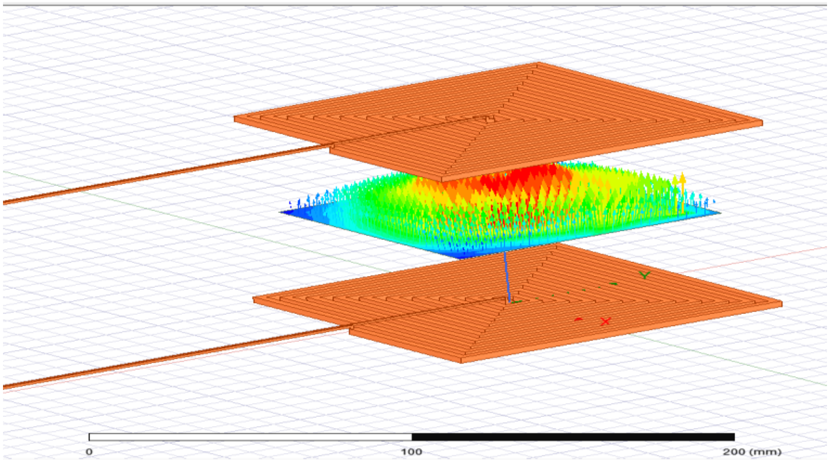

Figure 4.3: Sample view for two coupled coils

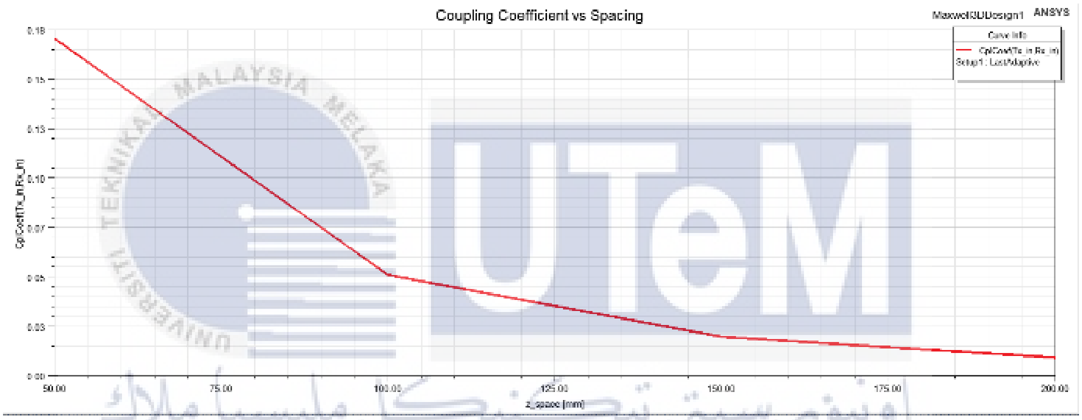

Figure 4.4: Graph Coupling Coefficient vs Spacing

Figure 4.3 is an example view which shows how the magnetic field flow between two coupled coils. Based on the diagram, the area near to the center of the plane, the stronger the electromagnetic field. Next, figure 4.4 shows the relationship between coupling coefficient and distance between two coupled coils. Based on the observation, the farther the distance between two coils, the lower the coupling coefficient. This means when one of the coils is moving apart from another coil, the coupling coefficient decrease and the efficiency of the system will also decrease. As mentioned, the complete output for connect Ansys Maxwell 3D and Simplorer is unsuccess due to the parameters setting. Hence, extra MATLAB Simulink analysis is done for the replacement of observation.

Table 4.2: Inductance variation table

Inductance, H	Pin, W	Pout, W	Vout, V	Iout, A	Efficiency, %
5u	16.74	10.72	40.15	267m	64.04
10u	17.77	11.03	40.70	271m	62.07
12u	17.616	10.86	40.37	269m	61.65
15u	16.57	10.21	39.11	261m	61.62
20u	14.54	8.94	36.62	244m	61.49
25u	12.61	7.72	34.02	227m	61.22
30u	10.86	6.6	31.42	210m	60.77
35u	9.32	5.6	28.97	193m	60.09
40u	8.01	4.76	26.74	178m	59.43
45u	6.93	4.08	24.73	165m	58.87
50u	6.02	3.51	22.93	153m	58.31

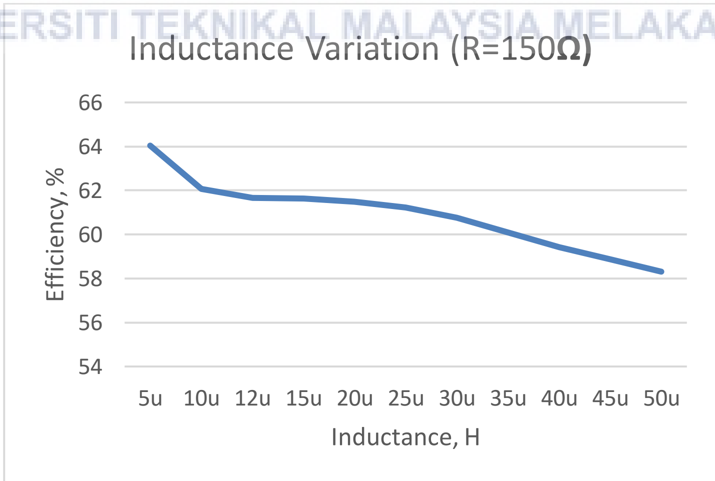

Figure 4.5: Graph Efficiency vs Inductance

Table 4.2 shows the analysis table of load constant and inductance variation. The analysis is chosen from 5uH to 50uH with 5uH of step size. Based on the table, notice that the output voltage and output current is decreasing when the inductance value increase. The increase of inductance value means that distance between two coils increased, thus the output voltage and output current is affected and decrease which caused the efficiency decrease also. Figure 4.5 shows the inductance variation graph which the efficiency versus the inductance.

Table 4.3: Resistor variation table

Resistor, Ω	Pin, W	Pout, W	Vout, V	Iout, A	Efficiency, %
50	38	29.71	38.54	771m	78
100	22.94	15.83	39.78	398m	69
150	17.616	10.86	40.37	269m	61.65
200	14.9	8.33	40.83	204m	55.9
250	13.26	6.8	41.24	165m	51.28
300	12.16	5.79	41.62	139m	47.62
350	11.37	5.04	41.97	120m	44.33
400	10.776	4.48	42.31	106m	41.57
450	10.31	4.04	42.62	94.7m	39.19
500	9.94	3.68	42.91	85.8m	37

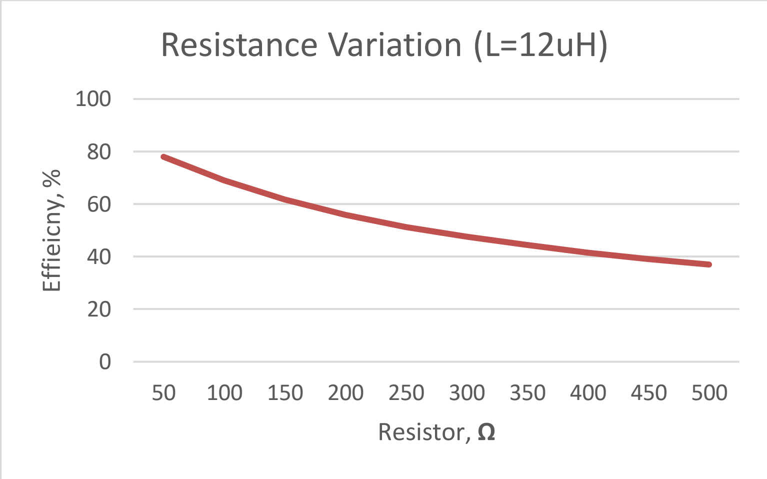

Figure 4.6: Graph Efficiency vs Resistor

Not only that, Table 4.3 shows the analysis table of inductance constant and load variation. The analysis is chosen from 50Ω to 500Ω with 50Ω of step size. Based on the table, notice that the higher the resistor value, the lower the output voltage and output current. This is because the higher resistor value will block the current pass through and once the current decrease, the voltage will also be affected. Since the output voltage and output current decrease, the efficiency will also decrease. Figure 4.6 shows the load resistance variation graph which the efficiency versus the inductance.

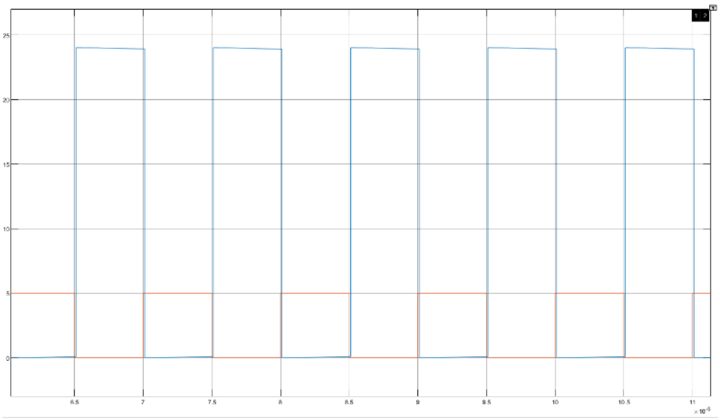

Figure 4.7: ZVS waveform

Figure 4.7 shows one of the examples of ZVS waveform. ZVS (Zero Voltage Switching) is a soft switching technique used to eliminate the transistor switching loss. This means that there are no overlapping current and voltage waveforms during the switching time intervals. This means in theory; it has zero power loss switching transition. Hence it can provide high efficiency with the high input voltage in the system. However, the design of this project is not perfect, there are some overlapping occur in the waveform which causes the output efficiency decrease and cannot achieved high efficiency same as theory. In this situation, this analysis is to observe how the inductance value and resistor value affect the electromagnetic field distribution and output efficiency. Based on the observation, changing the load resistance and inductance value doesn't affect the ZVS waveform. This means the ZVS waveform remain constant while changing the value of resistance and inductance.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

In conclusion, the design of wireless power transfer system based on class D CLL topology has simulated. The main objective has been achieved with 10.785W of DC output power and 100kHz operating frequency. The simulation results are closed to the expected results. The different of the results might due to the different in component selection. Nevertheless, the result shows that the class D CLL topology can be used for wireless power transfer system. Other than that, the rectangular spiral shaped of charging coil has drawn by using ANSYS Maxwell 3D software. The difference of distance between coil are clearly seen in the results. The farther the distance between two coils, the weaker the magnetic field. The circuit using ANSYS Simplorer has also been drawn but it failed to obtain the same data as the expected result due to the parameters setting. The result of distance between coils versus electromagnetic field distribution are unable to get as the expected output. The parameters setting for output display is not same with the expected result. However, another simulation circuit using MATLAB has been done to observe efficiency of the system with load variation and distance variation. Due to some issues which is covid-19, the distance variation is replaced with the inductance variation to observe the efficiency.

For sustainability, social and environmental impact, the wireless power transfer can be fully utilized to replace battery replacement reduced unnecessary waste such as cables. In addition, it also reduces battery disposal since only one set of batteries is needed and it can be charged without the need to replace many sets of batteries. Last, reduced battery usage can also reduce pollution. Hence the design of the WPT system is beneficial to many users.

For the future work, the completion of Ansys software simulation is suggested to observe the electromagnetic field distribution. Besides, the improvement of the efficiency of the system on practical design are strongly suggested. Other than that, it is strongly recommended someone can design the drone’s high battery capacity by using different methods.

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APPENDICES

The software used in this project is ORCAD PSPICE. OrCAD Systems Corporation was a software firm that created OrCAD, a proprietary software tool suite primarily used for electronic design automation (EDA). Electronic design engineers and electronic technicians primarily use the software to create electronic schematics, perform mixed-signal simulation, and generate electronic prints for the fabrication of printed circuit boards. Cadence Design Systems acquired OrCAD in 1999, and it has been integrated with Cadence Allegro since 2005.

Besides, OrCAD EE is an abbreviation for OrCAD Engineering Environment. PSpice is a SPICE circuit simulator application used for analogue and mixed-signal circuit simulation and verification. Formalized paraphrase Personal Simulation Program with Integrated Circuit Emphasis is an abbreviation for PSpice. Furthermore, OrCAD EE typically simulates circuits defined in OrCAD Capture, and it can optionally integrate with MATLAB/Simulink via the Simulink to PSpice Interface (SLPS). Formalized paraphrase with schematic entry, native analogue, mixed signal, and analysis engines, OrCAD Capture and PSpice Designer provide a complete circuit simulation and verification solution. A circuit to be analysed with PSpice is described by a circuit description file, which PSpice processes and runs as a simulation. PSpice generates an output file to store simulation results, which are also graphically displayed within the OrCAD EE interface. OrCAD EE is an enhanced version of the PSpice simulator that includes automatic circuit optimization as well as waveform recording, viewing, analysis, curve-fitting, and post-processing support. OrCAD EE includes a large library of physical component models, including approximately 33,000 analogue and mixed-signal devices and mathematical functions. OrCAD EE also includes a model editor, parameterized model support, auto-convergence and checkpoint restart, a magnetic part editor, and several internal solvers. In addition, OrCAD PSpice and Advanced Analysis technology bring together industry-leading native analogue, mixed-signal, and analysis engines to provide a complete circuit simulation and verification solution. OrCAD PSpice technology provides the best, high-performance circuit simulation to analyse and refine your circuits, components, and parameters before committing to layout and fabrication, whether you're prototyping simple circuits, designing complex systems, or validating component yield and reliability.

Ansys

Ansys, Inc. is an American corporation headquartered in Canonsburg, Pennsylvania. It creates and sells Multiphysics engineering simulation software for product design, testing, and operation, and it serves customers all over the world. John Swanson founded Ansys in 1970. In 1993, Swanson sold his stake in the company to venture capitalists. In 1996, Ansys went public on the NASDAQ. Ansys acquired a number of other engineering design firms in the 2000s, gaining additional technology for fluid dynamics, electronics design, and other physics analysis. On December 23, 2019, Ansys was added to the NASDAQ-100 index.

Other than that, Ansys creates market engineering simulation software that can be used throughout the product life cycle. Ansys Mechanical finite element analysis software is used to simulate computer models of structures, electronics, or machine components for the purposes of analysing strength, toughness, elasticity, temperature distribution, electromagnetism, fluid flow, and other properties. Besides, Ansys is used to determine how a product will perform under different conditions without the need for test products or crash tests. The majority of Ansys simulations are run on the Ansys Workbench system, which is one of the company's primary products. Typically, Ansys users break down bigger architectures into little components that are separately modelled and tested. A user can begin by specifying an object's dimensions, and then add weight, pressure, temperature, and other physical qualities. Finally, the Ansys programme models and evaluates over time movement, fatigue, fractures, fluid flow, temperature distribution, electromagnetic efficiency, and other impacts. Ansys also creates software for data management and backup, as well as academic research and education.

Formal paraphrase Ansys software is available as a yearly subscription. The software used in this project is Ansys Electromagnetic simulation known as Ansys Electronic Desktop.

ANSYS Electronics

Ansys HFSS is a 3D electromagnetic (EM) simulation software that is used to design and simulate high-frequency electronic products such as antennas, antenna arrays, RF or microwave components, high-speed interconnects, filters, connectors, IC packages, and printed circuit boards. Ansys HFSS software is used by engineers all over the world to design high-frequency, high-speed electronics used in communications systems, advanced driver assistance systems (ADAS), satellites, and internet-of-things (IoT) products.

MATLAB

MATLAB is known as Matrix Laboratory which is created by MathWorks. It was created to provide access to matrix software produced by the LINPACK and EISPACK projects, which together constitute the state-of-the-art in matrix calculation software. Other than that, it allows matrix manipulation, charting of functions and data, implementation of algorithms, construction of user interfaces, and connecting with programmes written in other languages. Besides, an additional programme called Simulink can provides graphical multi-domain simulation and model-based design for dynamic and embedded systems.

Next, MATLAB is a high-performance programming language used in technical computing. It combines computing, visualisation, and programming in a user-friendly environment in which problems and answers are stated in common mathematical notation. The application includes algorithm and application development, modelling, simulation, data analysis, visualization, etc. It is also an interactive system with an array as its basic data element that does not need dimensioning. This means user can solve many technical computing issues, particularly those using matrix and vector formulations.

Furthermore, MATLAB has grown through time with the help of numerous users. It is the typical educational tool in university settings for introductory and advanced courses in mathematics, engineering, and science. It is the industry standard for high-productivity research, development, and analysis. MATLAB has a collection of application-specific solutions known as toolboxes, which are very significant to most MATLAB users, allow them to understand and use specific technologies. Toolboxes are large sets of MATLAB functions (M-files) that expand the MATLAB environment to tackle specific types of issues. Toolboxes are offered in a variety of areas, including signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many more.