Power Improvement of 5 kHz Wireless Power Transfer Using Multi-Magnetic Circular Planar Spiral Relay

by

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
B	Magnetic Field
C	Capacitor
F	Farad
H	Henry
V	Voltage
I	Current
W	Watt
M	Mutual Inductance
WPT	Wireless Power Transfer
CPT	Capacitive Power Transfer
IPT	Inductive Power Transfer
ICRWPT	Inductive Coupled Resonance Wireless Power Transfer
MCRWPT	Magnetically Coupled Resonance Wireless Power Transfer
PCB	Printed Circuit Board

LIST OF SYMBOLS

A_r	Average radius of coil
d_{tr}	Distance between transmitter and receiver coil
d_{in}	Inner diameter
d_{out}	Outer Diameter
d_w	Wire diameter
f	Frequency
I_t	Transmitter current
L	Inductance
I_r	Receiver current
N_t	Number of turns of transmitter coil
N_r	Number of turns of receiver coil
R	Resistance
s	Space between turns
V_{ac}	AC voltage
V_{dc}	DC voltage
V_t	Transmitter voltage
V_r	Receiver voltage
w_c	Width of coil
Φ_{tr}	Magnetic flux between transmitter and receiver coil
μ_o	Permeability of free space

Penambahbaikan Kuasa Pemindahan Kuasa Tanpa Dawai 5 kHz Menggunakan Geganti Bulatan Satah Pilin Berbilang-Magnet

ABSTRAK

Pemindahan kuasa tanpa dawai (WPT) ialah kaedah penghantaran kuasa tanpa menggunakan kabel atau dawai. Aplikasi WPT telah digunakan secara meluas dalam pelbagai sektor seperti bioperubatan, telekomunikasi, dan pengangkutan. Walau bagaimanapun, kecekapan sistem WPT sangat bergantung kepada jarak antara gegelung pemancar dan penerima. Semakin jauh jarak antara gegelung, kuasa yang lebih rendah boleh dipindahkan, dan sebaliknya. Oleh itu, objektif penyelidikan ini adalah untuk mendapatkan peningkatan kuasa sistem WPT 5 kHz dengan mereka bentuk gegelung lingkaran planar bulat untuk mendapatkan nilai kearuhan yang sesuai untuk frekuensi pemadanan 5 kHz. Tambahan pula, sistem ini dibina dan disimulasikan dengan menambah geganti bulatan satah pilin berbilang-magnet. Prestasi WPT kemudiannya dinilai dan disahkan berdasarkan simulasi dan eksperimen dengan peratusan ralat kurang daripada 10%. Sistem WPT dalam penyelidikan ini terdiri daripada tiga komponen utama. Tiga komponen tersebut ialah sumber voltan DC, litar pemancar, dan litar penerima. Litar pemancar dibina oleh pemacu nadi, penyongsang jambatan penuh dan gegelung, di mana sumber voltan DC utama ditukar oleh litar penyongsang kepada voltan AC dan kemudian disambungkan kepada gegelung pemancar berdasarkan prinsip gandingan induktif. Pembinaan gegelung telah dibina berdasarkan bentuk dan nilai kearuhan gegelung yang dikehendaki pada 337.4 µH dengan mengambil kira nilai N, d_{in}, d_{out}, d_w, dan s. Tambahan pula, gegelung yang dicadangkan juga digunakan sebagai geganti bulatan satah pilin berbilang-magnet untuk mengukuhkan kearuhan bersama antara gegelung pemancar dan penerima. Penyelidikan ini disimulasikan menggunakan perisian PSIM dan eksperimen menggunakan perkakasan yang telah dibangunkan menggunakan gegelung yang dicadangkan. Kedudukan gegelung pemancar, gegelung penerima dan geganti berbilang-magnet ditetapkan pada jarak tertentu untuk melihat penambahbaikan kuasa yang berlaku selepas geganti berbilang-magnet ditambah pada sistem. Hasilnya, kuasa yang diterima pada gegelung penerima dengan diberi V_{dc} = 30 V dan d_{tr} = 21 cm boleh ditingkatkan sehingga 67%. Penyelidikan yang dijalankan ke atas simulasi dan eksperimen telah dinilai dan disahkan dengan peratusan ralat yang diperoleh adalah kurang daripada 10%.

Power Improvement of 5 kHz Wireless Power Transfer Using Multi-Magnetic Circular Planar Spiral Relay

ABSTRACT

Wireless power transfer (WPT) is a method of transmitting power without using cables or wires. The application of WPT has been widely applied in various sectors such as biomedicals, telecommunications, and transportation. However, the efficiency of WPT system is very dependent on the distance between transmitter and receiver coils. The farther distance between the coils, the lower power can be transferred, and vice versa. Therefore, the objective of this research is to get an improvement in power of 5 kHz WPT system by designing circular planar spiral coils to obtain a suitable inductance value for the matching frequency of 5 kHz. Furthermore, the system is constructed and simulated by adding a multi-magnetic circular planar spiral relay. The WPT performance is then evaluated and validated based on simulations and experiments with an error percentage of less than 10%. The WPT system in this research consists of three main components. The three components are a DC voltage source, transmitter circuit, and receiver circuit. The transmitter circuit is constructed by pulse driver, full bridge inverter and coil, where the main DC voltage source is converted by the inverter circuit into AC voltage and then to be connected to the transmitter coil based on the principle of inductive coupling. The construction of the coils has been constructed based on the shape and value of the desired coil inductance at 337.4 µH by taking into account the values of N, d_{in}, d_{out}, d_w, and s. Furthermore, the proposed coil is also used as a multi-magnetic circular planar spiral relay to strengthen the mutual inductance between transmitter and receiver coils. This research is simulated using PSIM software and experiments using hardware that has been developed using the proposed coils. The positions of the transmitter coil, receiver coil, and multi-magnetic relay are set at certain distances to observe the power improvement that occurs after the multi-magnetic relay is added to the system. As the result, the power received at the receiver coil with given V_{dc} = 30 V and d_{tr} = 21 cm can be increased up to 67%. Research conducted on simulations and experiments has been evaluated and validated with the percentage errors obtained are less than 10%.

CHAPTER 1 : INTRODUCTION

1.1 Research Background

Wireless power transfer is a method of transmitting power without the use of cables or wire that was initially proposed by Nikola Tesla, a Serbian-American scientist around the turn of the twentieth century (Jhonson, 1982). His idea is based on his achievement in constructing the tesla coil, a set of electrical resonance transformers capable of producing high voltage and low current in form of high frequency AC. These findings prompted him to continue the experiment of wireless power transfer or wireless power transfer using electromagnetic waves with a wide range in order to induce electrical loads remotely. The project is a wireless power distribution system capable of delivering power directly to houses and factories.

Currently, the development and application of wireless power transfer in various aspects has been increasingly carried out. For example, wireless power transfer has been successfully implemented in several sectors such as electrical sectors, biomedicals (Ha-Van & Seo, 2019), telecommunications (Hong et al., 2017), battery chargers (Prawiro & Murti, 2018), and even in the transportation sector such as electric vehicles (Lee et al., 2020; Nama & Kumar Verma, 2020). This is done in order to simplify and optimize activities. Besides, it also can minimize costs on the use of wires as a medium for conducting power.

In general, wireless power transfer (WPT) system consists of three main components. The three components are DC voltage source, transmitter circuit, and receiver circuit (Leong & Irwanto, 2020). The transmitter circuit is constructed by an inverter circuit and coil, where the main DC voltage source is converted by the inverter circuit to be AC voltage and the to be connected to the transmitter coil. Based on the principle of inductive coupling, the AC power generated at the transmitter coil is then transferred to the receiver coil. The transmitted AC power depend on the amount of magnetic flux arriving the receiver coil and it is depending on the magnetic field generated by the transmitter coil, where it is also depends on the number of turn and length of coil, lastly it depends on the transmitter coil diameter (Gu & Choi, 2020; Park et al., 2015; Yang et al., 2017).

The AC power generated and transmitter on the wireless power transfer in this project research has a system frequency of 5 kHz, where it is depending on the inductance of transmitter and receiver coil to obtain the matching frequency. The type of coil shape affects the value of its inductance, thus a suitable type of coil and its inductance value is required to obtain the matching frequency of 5 kHz. Referring to Leong & Irwanto (2020), the AC power received by the receiver coil is always low, the higher distance between transmitter and receiver coil, the lower AC power on the receiver coil. Therefore, to improve the power of 5 kHz WPT, mutual inductance is required to strengthen the induction between the transmitter and receiver coils. In this case, multi-magnetic circular planar spiral relay is used to obtained the mutual inductance. For that reason, this project will be focused on the power improvement of 5 kHz wireless power transfer by using multi-magnetic circular planar spiral relay and also using mutual inductance to strengthen the magnetic field between the transmitter and receiver coil.

1.2 Problem Statement

The working principle of WPT is based on the concept of inductive coupling that occurs between the transmitter and receiver coils at the same frequency. However, the development of the WPT system used requires a frequency that is in accordance with the capacitance and the coil inductance that is adjusted to the system. The development of the WPT system in this research is set to operate at a frequency of 5 kHz considering to reduce the number of turns that can be formed as the transmitter and receiver coils. Because of the relationship between frequency and coil inductance is inversely proportional, the use of a higher frequency will cause a lower coil inductance. On the other hand, the inductance of the coil is directly proportional to the number of turns which means that each increase in the number of turns will cause a higher coil inductance.

Power transfer of inductive coupling happens by conducting an alternating magnetic field on the transmitter coil. Thus, the magnetic flux generated will be converted into an electric current in the receiver coil. The electric current generated in the receiver coil is always lower than the electric current delivered by the transmitter coil. The farther distance between the two coils, the lower current received on the receiver coil (Leong & Irwanto, 2020). Magnetic flux is a measurement of the total magnetic field which passes through transmitter and receiver coil. The flux is always focus in the centre of the coils. It affect to the AC power received by the receiver coil, the farther distance between transmitter and receiver coil, the lower AC power can be obtain on the receiver coil. However, the amount of flux can still be improved in order to make the magnetic field do not through out of the centre between the transmitter and receiver coils. Therefore, a multi-magnetic relay is required to be placed between the transmitter and receiver coil to optimize the flux and improve the AC power on the receiver coil.

1.3 Research Objectives

The objectives of this research are as follows:

1. To design a circular planar spiral coil for obtaining a suitable inductance value for the matching frequency of 5 kHz.

2. To simulate and construct WPT system with addition of a multi-magnetic circular planar spiral relay.

3. To evaluate and validate the simulation and measurement results of the performances of WPT system with and without the multi-magnetic circular planar spiral relay.

1.4 Research Scopes

The specific research scopes of this present research work are as below:

1. The technique used in this research is the electromagnetic field inductive resonance technique by making two copper coils in the form of a circular planar spiral which is used to produce mutual inductance.

2. The frequency of the WPT system developed in this research uses 5 kHz matching frequency.

3. The multi-magnetic circular planar spiral relay is placed between the transmitter and receiver coils to strengthen the mutual induction between coils

4. The circuit used to convert a DC source into an AC voltage is a single-phase full bridge inverter consisting of four power MOSFETs.

5. The WPT system is simulated by using PSIM software, and the data obtained is evaluated by using MATLAB.

6. The data collected from the experiment on the hardware that has been made is used as a comparison between the simulation and the experiment with an error percentage of ±10%.

1.5 Thesis Organization

Chapter 1 of this thesis presents an introduction to provide an overview for the reader about the WPT system discussed in this research. This chapter also describes the problems encountered in a WPT system. In addition, research objectives and research scope are presented in this chapter in order to providing an explanation of what is to be achieved in this research.

Chapter 2 presents some theories and reviews of various literatures related to WPT system. An explanation of the technology of WPT systems such as ICR – WPT, MCR – WPT, and CPT is also discussed in this section. Moreover, this chapter also discussed about transmitter and receiver coils, spiral inductors, mutual inductance between coils, and electronic devices such as full bridge inverters. Furthermore, the last part of this chapter presents a comparative analysis of existing work based on published methods and findings.

Chapter 3 presents and discusses the research methodology in which transmitter and receiver coils are proposed based on the concept of circular planar spiral coils. In addition, models and constructions for transmitter circuits and receiver circuits are discussed in this chapter. Furthermore, the modelling of the 5 kHz WPT system is presented in a simulation using PSIM software, while the hardware is developed using the construction of coils, transmitter circuits, and receiver circuits that have been made. Furthermore, the experimental setup describes the hardware testing process to examine the results of several parameters measured in this experiment so that they can be evaluated and validated based on simulation and hardware.

Chapter 4 discusses the results of the simulations and experiments that have been made. The first part of this chapter discusses the results of generating, rectifying, and filtering 5 kHz pulse signals in the transmitter circuit. The next section discusses the effect of DC voltage source and distance on the performance of a WPT system. In addition, the results of the performance of the WPT system when adding magnetic relays and multi-magnetic relays are discussed and compared. The final part of this chapter discusses the validation of simulation and experimental results on the performance of the WPT system.

Chapter 5 presents conclusions on the overall results obtained based on the objectives of this research. In addition, further work is also explained.

CHAPTER 2 : LITERATURE REVIEW

2.1 Wireless Power Transfer Technology

According to Jawad (2017) and Houran (2018), Wireless Power Transfer (WPT) can be separated into two classifications based on the mechanism of transferring power. Those classifications are near field and far field WPT system. However, this research is only focus on the near field WPT System. The near field WPT system is known as non-radiative wireless charging because it operates based on the magnetic field coupling between two coils inside the dimension of those coils for energy transfer (Lu et al., 2016). The power transfer over a distance is significantly limited because the magnetic field of an electromagnetic wave attenuates considerably quicker than the electric field. Due to its safety features, the near field WPT system has been used in daily household products ranging from hotplate to more complicated equipment such as electric autos. Furthermore, Houran (2018) also explained that near field WPT is divided into two categories: inductive power transfer (IPT) and capacitive power transfer (CPT). Then, the IPT is separated into two types: inductive coupled resonance wireless power transfer (ICR-WPT) and magnetically coupled resonance wireless power transfer (MCR-WPT).

2.1.1 Inductive Coupled Wireless Power Transfer (ICR-WPT)

Refers to the explanation by Arshad (2012), until now the inductive coupled WPT has been the most widely utilised technique for wireless charging low-power devices. It also has been used to power radio frequency identification (RFID) tags and medical implants by transferring power from one coil to another, sensors, wireless charging electrical gadgets, and the automobile manufacturing sectors are all areas where this technology is being used. According to Arai (2018), the common operation frequency of inductive coupling range in operation frequency of kilohertz and is generally utilised in several distance started from millimetres to centimetres of the desired load. The power output can be variated with power ranging from watt to kilowatt depending on the effectiveness of the transmission.

The WPT system with inductive coupling offers various advantages, including ease of construction and operation (Shevchenko et al., 2019). This is also reinforced by research that has been done by Jawad (2017), Arai (2018), and Zhu (2015). Because of its low transmission frequency, the inductive coupling is non-radiative and considered safe for people. Over short distances, this method of transmitting a power has a high efficiency up to 95%. In addition, this inductive coupling method does not cause sparks and electric short circuits so it is safe to operate in several fire-prone situations. Therefore, the working principle of this power transfer method is safe in its power transfer range because it adopts the principle of magnetic coupling. Nevertheless, one consequence of typical inductive coupled is that it works best over relatively limited transmission distances (short distance), expanding the transmission distance can be affected to the reduction of the performance significantly.

2.1.2 Magnetically Coupled Resonance Wireless Power Transfer (MCR-WPT)

Magnetically coupled resonance wireless power transfer (MCR-WPT) and inductive coupled resonance wireless power transfer (ICR-WPT) are both based on the same basic concept that transmits power without using any wires as a connection between source (transmitter) and load (receiver) (Luo et al., 2018). However, it operates on the basis of a magnetic resonance coils that resonates at the same frequency between the transmitter and the receiver. (Arai, 2018). Moreover, it is possible to attain up to 50% efficiency for power transmission over longer distances of transmitter and receiver by adopting MCR-WPT above standard ICR-WPT without reducing coil size or consumption of power (Shidujaman et al., 2014). MCR-WPT technology has attracted the attention of academics and industry to develop this concept because it has the potential to be used in many facets of human life such as electronic equipment in medical field, smart house, and as well as in the field of transportation such as the use of electric vehicles.

The operating frequency of MCR-WPT is in the hundreds of kHz to tens of MHz range. This WTP concept has advantages in terms of the distance of power transfer from the transmitter to the receiver where it can deliver power at a distance of several meters and it is not affected by weather conditions. MCR-WPT has the ability to transfer power with higher efficiency and over farther distances when compared to ICR-WPT. Therefore, MCR-WPT is one of the most effective WPT techniques used at medium distances to date (Chen & Gong, 2017). When compared to microwaves and WPT lasers, the magnetic resonance system between the transmitter coil combined with the magnetic resonance of the receiver coil does not pose a threat to the environment because it is non-radiative. However, the positioning of the transmitter coil and receiver coil needs to be considered because the frequency of the WPT developed based on the MCR-WPT concept can decrease with increasing distance due to the effect of axial mismatch (Jawad et al., 2017).

2.1.3 Capacitive Power Transfer (CPT).

In general, the power transfer mechanism by adopting the principle of Capacitive Power Transfer (CPT) using metal plates that used as an intermediary electrode for power transfer. By using electrodes as transmitter and receiver, it is possible to arrange a capacitor to hold a charge. Based on the working principle of electrostatic induction, the AC power generated from the electrode plate on the transmitter side can produce an AC power on the receiving plate on the load side (Bakolia et al., 2017).

Although capacitive power transfer is cheaper than other WPT principles, its implementation still relies heavily on close contact between the metal surfaces of the transmitter and receiver. As a result, it is severely constrained by range constraints. Yet, the electric fields do not have the same safety features as magnetic fields since their relative field intensity is significantly higher, posing a risk to both persons and electrical devices (Arai, 2018; Shidujaman et al., 2014). Furthermore, the quantity of coupling capacitance that may be achieved is limited by the device's accessible surface. When considering normal-sized portable electronic devices, however, it is difficult to achieve the necessary density of power for charging, which creates a design issue (Lu et al., 2016).

2.2 Transmitter and Receiver Coil

In WPT system, the form of coil is essential because different shapes create distinct patterns of magnetic field and flux. In some conditions, the form of coil may not produce a steady and appropriate magnetic flux, it will affect to the power efficiency of WPT system. Fernández (2002) conducted a study that analysed and demonstrated a spiral planar without a core had a higher efficiency of coupling and lower resistance if it compared to a rounded coil winding. Furthermore, Sallán (2009) and Villa (2009) agree with this assertion. Moreover, because of the many developments in battery charging of electric vehicles, the circular planar spiral coil has been widely applied and tested for its misalignment tolerance. In general, spiral coils are mostly used for phone charging (Choi et al., 2004; Fernández et al., 2002), whereas rectangular coils are primarily used for high power transmission, particularly in electric vehicles (Sallán et al., 2009).

In order to increase power efficiency, adding a core to the WPT system would provide a slew of functions and advantages. For example, to increase the coupling efficiency and higher power transmission, it can be done by adding a ferrite core (Aditya & Williamson, 2014; Chi et al., 2011). It can also be used for shielding, minimize interference to electronic devices and reducing exposure to human. However, another theory is that including an E-core into the windings can assist shape the magnetic field and minimise leakage inductance, therefore improving power transfer efficiency (Chi et al., 2011; Ryu et al., 2005). They explained that there is also another approach to minimize flux leakage, which is using ferromagnetic materials that had relatively low conductivity than paramagnetic materials which tend to had higher conductive properties as a technique in the formation of a magnetic field that occurs between the transmitter and receiver coils. In addition, an aluminium plate or a ferrite-aluminium plate under the coil is considered effective in increasing the coupling factor between the coils, which in turn has a good impact on minimizing flux leakage and eddy currents. In this case, the same applies to the use of ferrite polymer composite sheets. The same thing was also stated by Nagatsuka (2010) in his research entitled compact contactless power transfer system for electric vehicles. From these opinions, it can be concluded that the formation of a magnetic field can be increased by adding a core or sheet in order to improve efficiency in a WPT system.

Another way to make an improvement on the power efficiency of WPT system is by adding multiple coils between the main transmitter and receiver coil. This way will generate mutual inductions (M) and it will be required to strengthen the induction between the transmitter and receiver coils. According to (Dalal et al., 2015), there are several ways to compute mutual inductance, including Maxwell methods, Grover's techniques, FEA, and Neumann integrals formulation. Neumann formula has previously used in double integration to determine the mutual inductance that would optimise the efficiency of the inductive coupling power transfer in the author's prior publications. On the other hand, Grover's approach can offer useful and precise mutual inductance of the coils, but it becomes difficult and time-consuming when applied to different forms of coils, even when misalignment is present.

In Sonntag (2008), the mutual inductance that occurred in PCB planar coil was calculated using the Neumann formula in a very similar study. The magnetic vector potential and Faraday's law were derived to create the Neumann formula. Because of its complexity, it is recommended and limited for basic geometries with straight tracks, such as the hexagon form used in that study, rather than the circular shape. The misalignment in the x, y, and z-direction, which results in different mutual inductance, was also discussed in this research. In order to confirm the mutual inductance calculated analytically, an experiment was created utilising PCB planar windings in a hexagon form to test mutual inductance using secondary voltage and current. As a result, the percentage discrepancy between the experimental and analytical results is less than 5%.

2.3 Spiral Inductor

The appropriate construction of a passive inductor is critical for improving the efficiency of its system circuits. Self-inductance and mutual inductance are important factors in inductor design. The empirical formula yields an inductance value that is on the same scale as the real inductance (Gvozdenovic et al., 2015). Formulas derived mostly from the Maxwell and Grovier equations can be used to construct a planar inductor (Hurley & Duffy, 1997; Grover, 2004).

According to Pan (2004), spiral inductors have three significant figures of merit, including inductance, quality factor, and self-inductance (SRF). The quality factor is X_L/R_S ($X_L= \omega L$), and since the series resistance of a perfect inductor is almost zero, the quality factor is infinite. However, in actual circuits, the series resistance reduces the quality factor and raises the dissipation factor. The physical characteristics of the spiral inductors determine the series resistance. Figure 2.1 shows the physically specified characteristics such as diameter of wire (d_w), spacing between turns (s), number of turns (N), outer diameter (d_{out}), and inner diameter (d_{in}).

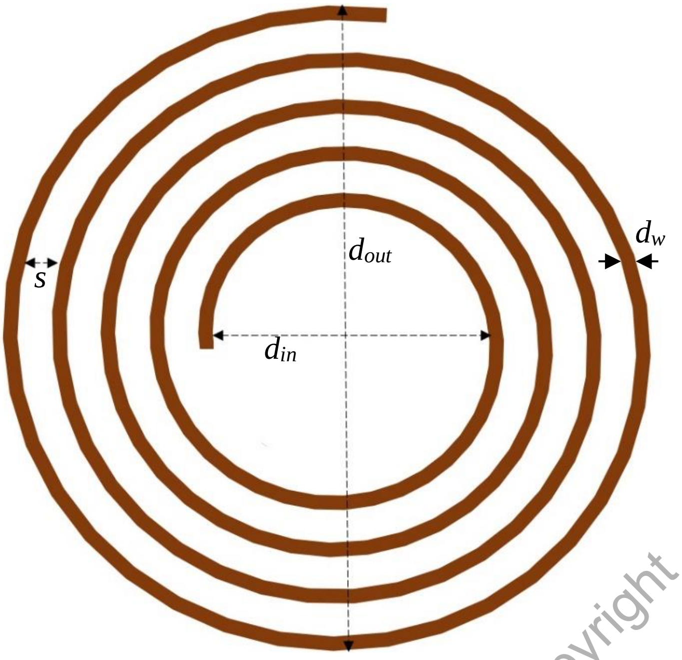

Figure 2.1: Geometry of the circular planar spiral coil

The physical parameters such as N, S, d_{in}, d_{out} and d_w are exactly proportional to the inductance of a spiral inductor. With a lower quality factor, the magnitude of the inductance rises. The spiral coil has a reactive inductance value that inversely proportional to the quality factor. The increase in reactance causes more energy to be dissipated rather than used. The passive spiral coil can be made in a variety of configurations, including single loop multiturn and straight narrow racks. Multi-turn inductors are utilised in the construction of larger inductance values, with circular and square configurations being the most common. Moreover, because of its tiny volumetric footprint and single-sided flux profile when utilised with a ferrite backplane, circular planar coil is now the preferred choice for a variety of applications.

According to Robertson & Lucyszyn (2001), they explain that the spiral inductor is a fundamental component that is used to construct RF matching networks, voltage controlled oscillators, filters, mixes, and a variety of other RF circuits. The passive devices are chosen based on the criteria for the area applications as well as the technology used to achieve greater efficiency. For constructing circular spiral inductors, Multilayer Integrated Circuits (MIC) is a moderate approach that is favoured for greater efficiency and reduced power consumption. Furthermore, Wu et al., (2010) explained for a wide range of RF/microwave applications, the MIC method gives diverse manufacturers with flexibility such as compactness, low cost, and high volume modules. This method allows the designer to create highly interconnected 3D modules with more flexibility.

2.4 Mutual Inductance on Circular Planar Coil

The mutual inductance can be defined as an ability of transmitter coil to cause an open circuit voltage in receiver coil that located in some distance away when the system powered by an alternating current (Esteban et al., 2015). In all magnetically coupled systems, mutual inductance is a critical figure of merit. Moreover, it is particularly important in the design of loosely coupled coils that used in inductive WPT systems. Esteban (2015) proposed a modification for the calculation of mutual inductance for circular planar spiral coils arranged in axial and non-axially aligned. Furthermore, Figure 2.2 shows an illustration of two circular planar coils arranged vertically. When the coil on the transmitter side is powered by AC voltage, the current flowing on the transmitter side will induce a mutual flux between the two coils which then causes an AC voltage to occur on the receiver coil. Φ_{21} is the magnetic flux that coupled the transmitter and receiver coils. For loosely coupled coils, this is normally just a fraction of the overall flux generated by the transmitter coil. N_2 refers to the number of turns in the receiver coil that actually receive Φ_{21}. I_1 is the transmitter coil excitation current, which energises it and generates the magnetic field. Considering Φ_{21} is depends on the number of turns of the transmitter coil, I_1, medium permeability, and surface areas that receive the mutual flux is essentially a geometrical quantity, including the sizes, shapes, and relative locations of the coils.

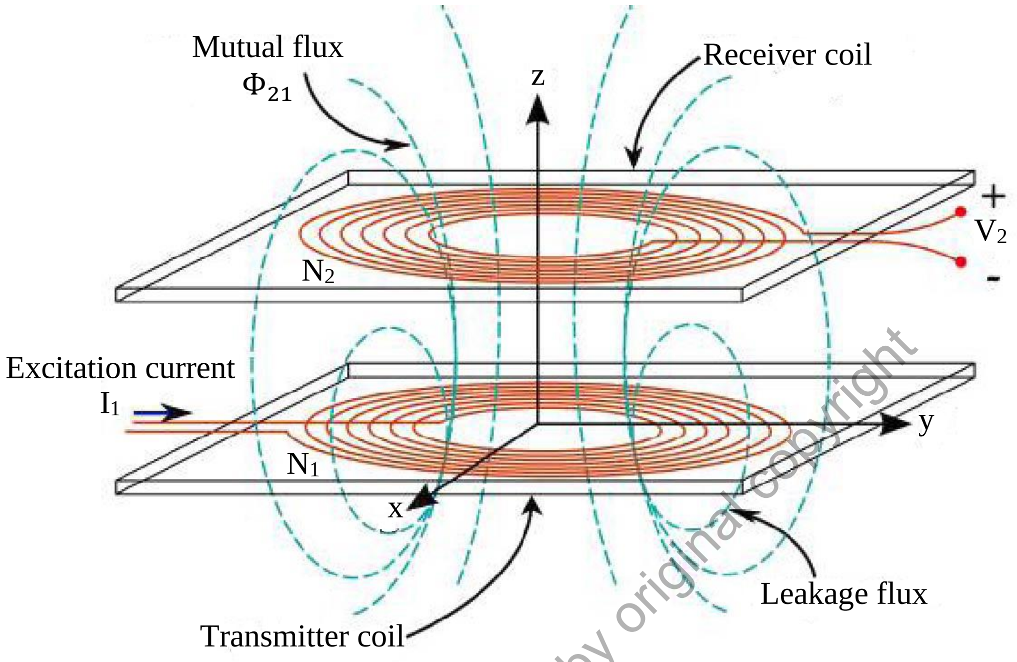

Figure 2.2: Inductively coupled circular planar spiral coils (Esteban et al., 2015)

The output of the induced open circuit voltage, V_2 and short circuit current, I_{sc} at the receiver coil can be used to obtain uncompensated power, S_u. When a load and receiver coil are connected each other, and the load is suited to the coil reactance, the maximum power that can be transferred to the load is only a half of the total S_u. This is insufficient for several requirements, needing further improvements to improve the this power transfer technique (Covic & Boys, 2013). They explained that to solve this problem it is necessary to have a capacitor that connected in series or parallel to the receiver coil. This method is known as capacitive compensation. When a compensated receiver coil cuts an AC magnetic field oscillating at or near to its resonant frequency, the total power may be delivered is raised by a value equivalent to the tuned circuit's loaded quality factor.

In the development of inductive power transfer, the power equation is important because of the squared nature of transmitter current and mutual inductance. They have the biggest impact on maximum power that can be obtained, but increasing value of mutual inductance is always recommended because it produces in a smaller transmitter current, which lowers the cost of the transmitter inverter and its compensation circuit (Covic & Boys, 2013). As a result, substantial research has been done in the literature to characterise and improve mutual inductance, notably in the case of circular planar spiral coils. Because of their tiny volumetric footprint and single-sided flux profile when utilised with a ferrite backplane, circular planar spiral coils are currently the favoured choice for a variety of applications.

A formulation to calculate mutual induction has also been developed by Amos (2013). The formulation he developed was used to find mutual induction between two circular filament coils that have different angles and parallels between the coils. Similar to the method used by Esteban (2015), the method used is the magnetic vector potential approach which is a model specifically formulated to calculate the mutual inductance between filament coils with lateral and angular misalignment. The results obtained were analysed using SCILAB software using angular and lateral misalignment data and different distances between coils. The results obtained from his research explain that the mutual inductance depends on the distance between the coils and the lateral and angular alignment of the coil placement. As the distance between the coils increases and the lateral and angular misalignment increases, the mutual inductance obtained will be smaller. In contrast, the smaller the lateral and angular misalignment and the closer the distance between the coils, the greater the mutual inductance obtained. Finally, this investigation shows that in order to calculate the mutual inductance of a magnetically coupled coil, misalignment of coils such as laterals and angles must be considered in the formula for calculating the mutual inductance between a circular planar coil with the air core.

Nguyen (2014) conducted a study about the effect of mutual inductance on WPT system efficiency that examined both in simulation and experiments. The total system efficiencies, as well as the efficiency gains of the driving class-E power amplifier, were investigated for various radius of coils and distances. In the WPT system, by adjusting the coils at a certain distance, it can produce different mutual inductances. The efficiency of the system may vary depending on the optimal level of mutual inductance. In other words, the efficiency of the WPT system can reach its maximum value when the distance between the coils is placed to produce the most optimal mutual inductance. This methodology can contribute in the optimization of coil characteristics and layout in order to achieve a high efficiency of WPT system. Furthermore, the research also explains that apart from the effect of mutual inductance, the efficiency of the WPT system can also be increased by considering other factors such as self-inductance. Self-inductance and mutual inductance can have an effect on the coupling distance and class-E amplifier used. The physical influence of field dispersion in distance was not studied since mutual inductance was simplified. However, the mutual inductance can vary in value when the transmitter and receiver coils are not aligned.

2.5 Full Bridge Inverter

An inverter can be defined as a device that converts direct current (DC) into alternating current (AC). Inverters are classified into three categories based on the output waveform: square wave, modified sine wave, and pure sine wave. In electrical circuit and signal processing, a square wave is a non-sinusoidal waveform that positive and negative phases of a square wave alternate on a regular basis. While a modified sine wave inverter has an output resembles of a square wave inverter, with the exception that it includes one extra level before turning positive or negative and going to zero volts. Whereas the output of pure sine wave inverter generated from DC supply into a near perfect sine wave. The sine wave inverter has very little harmonic distortion, providing very clean sine wave that can be used to power electronic devices like computers, microwave ovens, motors, and many other sensitive equipment without producing issues like noise or even ripple on the waveform. Pure sine wave inverter is also better for device like battery charger (Patil & Dighe, 2016).

Full bridge inverters are one of the most popular inverter types. This type of inverter circuit transforms DC to AC by toggling the switches on and off in the sequential cycles. It operates in four different states depending on which switches are opened or closed. Metal Oxide Semiconductor Field Effect Transistor (MOSFET) is one of the most often utilised switches. The advantage of using MOSFETs as switching component because its switches quickly and without causing a current interruption (Bernard, 2014).

Figure 2.3 illustrates a circuit for a full bridge inverter that uses power MOSFETs as switches. The circuit waveform can be positive, negative, or zero by adjusting which switches are on (closed) or off (opened) at any particular time. When switches S1 and S4 are closed and switches S2 and S3 are open, a positive voltage is provided across the load. In contrary reverse voltage is delivered to the load by closing S2 and S3 switches and opening S1 and S4 switches. Switches S1 and S3 should not be closed at the same time when using the notation above, since it could result in a short circuit and potentially destroying the devices or discharging the power supply. The same mechanism also can be occurred to switches S2 and S3.

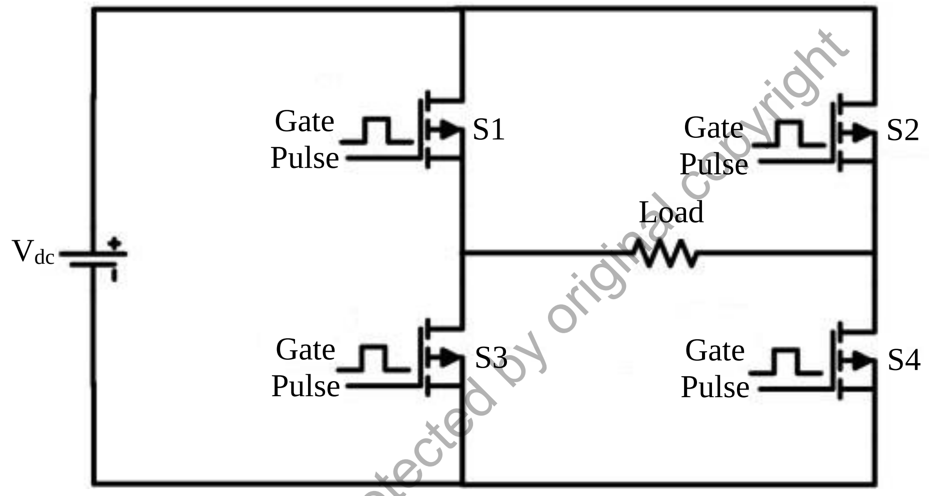

Figure 2.3: Full bridge inverter configuration circuit

A higher input voltage than the nominal gate threshold voltage (V_{th}) should be supplied to the gate to switch on a MOSFET. Almost no power is consumed by the gate drive of the MOSFET, this is common when the MOSFET is operating in the on or off state. The internal state of a MOSFET affects the gate-source capacitance observed by the driver output. MOSFET are widely applied as power electronic switches at frequencies in the range from a few kHz to hundreds of kHz. A MOSFET has an advantage as a switching device because of its low power consumption required to driving the gate. Those are some of the characteristics that make a MOSFET become an option to be applied to electronic devices such as inverters (Toshiba, 2018).

2.6 Comparative Analysis of Existing Work

Table 2.1: Comparative analysis of existing work

Authors	Method	Finding
(Irwanto & Leong, 2020)	Designed a 2.5 kHz WPT System which has the ability to transfer a DC voltage source using the concept of the electromagnetic principle that occured between transmitter and receiver coil in form of selenoid coils.	The AC current and magnetic field density on the transmitter coil rise as the DC voltage source increases, as does the capability of the incoming magnetic field on the receiver coil. As the results, the AC power on receiver coil is increased as the given DC source voltage increased.
(Gao et al., 2018)	With angular and lateral misalignment, a mathematical model for transmission efficiency was developed. In addition, analysing the changing regularity of the transmission efficiency as the angular and lateral misalignments changed. Moreover, simulation studies were used to investigate the impact of angular and lateral misalignment on transmission efficiency.	The results show that reducing the lateral misalignment between the coils can improve transmission efficiency when there is an angular misalignment between the transmitter and receiver coils. If there is a lateral misalignment between the coils, the angular misalignment between the coils can be adjusted to improve transmission efficiency.

Table 2.1: (Continue)

Authors	Method	Finding
(Yang et al., 2017)	A closed-loop wireless power transfer (WPT) system for deep brain stimulation-implanted biomedical applications is demonstrated in this research. As a second coil, a revolutionary two-layer PCB FR4 coil design is presented to increase the efficiency of WPT. An inner dual-layer printed spiral coil (PSC) and outside helical coil, as well as a T-type impedance-matching network, were used to obtain high-efficiency implanted WPT technology.	At a distance of 10 mm, the transmission efficiencies of FR4 and flexible printed circuit boards were 19.1% and 14.8% through the air, respectively, and 11.7% and 7.7% through the tissue, allowing milliwatts of power to be delivered to the stimulation circuits and successfully illustrating the stimulation tissue model with a V/I output current of up to 180 µA.
(Dalal et al., 2015)	This paper presents a generalised semi analytic of mutual inductance calculation approach that may be used with coils of different geometries and misalignments. The approach works by discretizing the secondary coil's area in terms of triangle elements, and then using the Biot-Savart law to compute the flux obtained on the secondary coil. For all studied geometries with vertical, lateral, planar, and angular misalignments in area, the mutual inductance of coils is determined.	To this day, the Grover filament approach is the most often used method for calculating direct mutual inductance. Grover's approach is fairly accurate, but the implementation is difficult by the employment of several formulations for the various filament layouts in a coil.

Table 2.1: (Continue)

Authors	Method	Finding
(Nguyen et al., 2014)	Simulations and experiments were developed to investigate the effect of mutual inductance on a two-coil WPT system. The WPT system developed works at a frequency of 1.3 MHz by adjusting the distance between the coils and the size of the coil with the aim of producing different mutual inductance in the equivalent circuit. Class-E amplifier is used to achieve the most optimal power transfer efficiency by examining the optimal mutual inductance at different coil sizes and distances.	The power transfer efficiency on the receiver coil side is 46% on a coil with a radius of 13 cm, 48% on a coil with a radius of 17 cm, and 44% on a coil with a radius of 21 cm. Meanwhile, the mutual inductance measured at each distance is 21.9 μH, 22.3 μH, and 21.4 μH. Basically, the value of mutual inductance to achieve the highest efficiency should be equal to the validity of the simulation model. However, the cross section of the receiver coil determines the efficiency of the transfer of power that can be sent as the coil increases with a larger one. By using a larger coil cross section, it is expected to connect more fields into the wire so that a longer distance is needed to achieve the most optimal mutual inductance.

Unlike the previous researches, this research has a modification using a transmitter and receiver coil in the form of circular planar spiral coils arranged vertically. In addition, this research also develops a multi-magnetic relay in the form of a circular planar spiral coil as a relay to strengthen the electromagnetic field between the coils. The inductance value (L) in each coil has the same inductance value for the transmitter coil, receiver coil, and multi-magnetic relay coil. The inductance value used is designed to operate at a frequency of 5 kHz. Furthermore, the comparison on performance improvements based on several parameters based on distance and DC voltage source when the WPT system does not use a magnetic relay is compared with the WPT system when one magnetic relay and multi-magnetic relay are added. In the end, the WPT system developed on the simulation and the hardware that has been made is then evaluated and validated with an error percentage of ±10% (Irwanto et al., 2020).