HOMOGENEOUS COIL DESIGN FOR WIRELESS CHARGING ELECTRIC VEHICLES

BY

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A dissertation submitted in fulfillment of the requirement for the degree of Master of Science in Communication Engineering.

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ABSTRACT

Electric vehicles are slowly becoming the first option for consumers. As time passes, the challenges limiting the chances of its existence are being reduced by the efforts of the researchers; they have the idea of having a green world and aim to achieve it by eliminating any source of pollution that found a green replacement. However, how well the performance of electric vehicles is not enough to make an industrial change. While there are challenges yet to be solved additionally, the main problem is the time to fully charge the battery in static and dynamic charging. However, time is rapidly being enhanced for static charging due to the fast charging cable improvements. Still, for dynamic charging, it is all about the efficiency of the connection during the power transmission. In this project, a homogenous coil has been designed, and the main focus is the radius of the coil. The design is tested under different conditions, and the optimal case is when the radius of the transmission coil is bigger than the radius of the receiver coil. The design has recorded an efficiency of up to 95%. Lastly, an enhanced method has been produced to wirelessly charge the electric vehicle with the help of homogeneous pads.

ملخص البحث

أصبحت السيارات الكهربائية ببطء الخيار الأول للمستهلكين ، مع مرور الوقت ، تقل التحديات التي تحد من فرص وجودها بسبب جهود جميع الباحثين حول فكرة وجود عالم محافظ للبيئة قدر الإمكان من خلال القضاء على أي مصدر للتلوث او وجد بديلاً محافظ للبيئة. ومع ذلك ، فإن مدى جودة أداء السيارات الكهربائية لا يكفي لإجراء تغيير صناعي في حين أن هناك تحديات لم يتم حلها بعد ، بالإضافة إلى أن المشكلة الرئيسية هي الوقت المستغرق لشحن البطارية بالكامل في كلا الاتجاهين الشحن الثابت والديناميكي ومع ذلك ، بالنسبة للشحن الثابت ، يتم تحسين الوقت بسرعة بسبب التحسينات في كابل الشحن السريع ، ولكن بالنسبة للشحن الديناميكي ، فإن الأمر كله يتعلق بكفاءة الاتصال أثناء نقل الطاقة. في هذا المشروع ، تم تصميم ملف متجانس والتركيز الرئيسي هو نصف قطر الملف ، ويتم اختبار التصميم في ظل ظروف مختلفة وكان الأمثل عندما يكون نصف قطر ملف النقل أكبر من نصف قطر ملف جهاز الاستقبال ، سجل التصميم كفاءة تصل إلى 95٪ أخيرًا ، تم إنتاج طريقة محسنة لشحن السيارة الكهربائية لاسلكيًا بمساعدة الوسادات المتجانسة.

APPROVAL PAGE

I certify that I have supervised and read this study and that, in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Science in Communication Engineering.

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

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LIST OF ABBREVIATIONS

BP	Bipolar Pad
CRP	Circular Pad
DDP	Double-D Pad
DDQP	Double-D quadrature Pad
HP	Homogeneous Pad
Rx	Receiver Coil
Tx	Transmission Coil
WPT	Wireless Power Transfer

CHAPTER ONE

INTRODUCTION

1.1 INTRODUCTION

The beginning of everything related to wireless power transfer was in the 1890s when Nikola Tesla started experimenting with wireless power transfer using radio frequency and a coil named after him. The Tesla coil has produced high voltage and high switching since the researchers started working on this technology (Brown, 1996). In recent years, wireless charging has been involved in almost all electrical devices we use, such as cell phones that we use daily. Since the beginning, the limitations faced by this technology have not been improved. A big improvement has been made to make this technology the target for all companies to switch all their devices to wireless. Indeed, many have switched, but not all are convinced by the technology performances.

Figure 1.1 How Big is the Involvement of Wireless Technology in Our Daily Lives (Janjua et al., 2020)

Wireless charging, on the other hand, is one of the main focuses of this project and is more concerned about how the technology is implemented depending on its application. In addition, the most famous coupling used for this purpose is the Near-field or Far-field wireless power transmission for Electric vehicles.

Table 1.1 Categories of Wireless Power Transfer for Electric Vehicle Charging Systems (Qiu et al., 2014)

Energy carrying medium	Technology		Power	Range	Efficiency	Comments
Electromagnetic field	Near field	Traditional Inductive power transfer	High	Low	High	
		Coupled Magnetic Resonance	High	Medium	High	Good for ELECTRIC VEHICLE charging
	Far field	Laser, Microwaves	High	High	High	Must have a direct line of sight for transmission. Difficult tracking system
		Radio wave	High	High	Low	Limitation of Efficiency
Electric field	Capacitive power transfer		low	Low	High	Distance and power are very small
Mechanical force	Magnetic gear		High	Medium	High	Good for ELECTRIC VEHICLE charging

Electric cars are taking over as time goes by. However, the challenges faced in implementing wireless charging technology differ from one country to another, as some countries have better infrastructure than others. How strong the country is economically is also another key factor to being able to install such huge technology in all its streets. Additionally, traditional fuel-based vehicles are still predominantly favored by consumers as their primary choice. However, this could change if they understand the greater good in changing to electric vehicles, which comes to having a green life and lowering the usage of any product that harms the environment.

On the other hand, the challenge that is making the technology of wireless charging not being considered as a solution is the period for the electric vehicle to be fully charged using WPT, compared to 10 to 15 seconds for fuel-supported cars to have a full tank; that is considered as the biggest challenge that has yet to be fully solved. In addition, WPT for electric vehicles has categories that are being tested. The most common one is the near field and far field from the electromagnetic field, were both come with pros and cons in terms of the power being transferred, the range, and the efficiency of the transmission. The coil design is an important rule in the power transmission process as it greatly affects the transmission range and efficiency. For that, there are many coil designs with different properties. For charging electric vehicles, there are four major charging schemes available. They are categorized depending on the charging voltage, current, power, and charging time (Popovic, 2017).

1.2 MOTIVATIONS

Wireless charging is becoming an important technology as we are changing to electric vehicles to help save the environment. However, it comes with many challenges; dynamic wireless charging is an important step to reduce them as much as possible. Furthermore, dynamic WPT has been and is still tested, but it still cannot produce a comparable result in the time taken to be fully charged compared to the fuel-supported vehicles.

1.3 PROBLEM STATEMENT AND ITS SIGNIFICANCE

Electric vehicles have proved their worthiness compared to fuel-supported vehicles. However, the performance is insufficient to make an industrial change as challenges are yet to be solved. The main problem is the time for the battery to be fully charged in static and dynamic charging. Even so, for static charging, the time is rapidly being enhanced due to the enhancement in the fast charging cables. But for dynamic charging, the process is all about the efficiency of the connection during the power transmission. Improving it requires some time as it has many factors taking part in that. For example, the coil design connects the Tx and Rx circuits. Furthermore, based on current research, wireless charging is emerging as the primary method to rapidly reduce electricity consumption by providing public access to charging infrastructure for all vehicles. For that to be applied, an issue to be addressed and solved is choosing which cable to be used for the design with the higher transmission efficiency.

1.4 Objectives

The main objective of this project is to design a wireless charging system for a vehicle. The sub-objectives are as follows:

i. To identify the weakness of current systems for wireless charging for a vehicle.
ii. To propose a method for vehicle charging wirelessly.
iii. To evaluate the performance of the proposed method.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

In this section, the discussion will focus on the design of the wireless transfer systems with a closer look at the coil design in terms of advantages, disadvantages, and all the challenges faced while designing and implementing the design in the real world.

2.2 OVERVIEW AND HISTORY OF WIRELESS POWER TRANSFER

Wireless Power Transfer is simply data transfer without using any physical medium. It was invented by Nikola Tesla in the nineteenth century to transmit messages wirelessly, which was extremely difficult at that time. He studied the subject extensively, and his partner Heinrich Hertz helped him. The primary idea behind Tesla's concept is to use planet Earth as a medium to transfer data to anyone on the planet. Finally, Tesla could transmit electricity by lighting a lamp 25 miles from the transmission station in 1988, after which he built the Wardenclyffe Tower in 1901. After many trials by Tesla and his team to transmit a message with no positive result, the financer of the project stopped sponsoring him. After the ideas were ignored as no objective was met until later, William C. Brown introduced the Microwave theory. After that, he invented the rectenna in 1960 to convert Microwave power to DC power after the revolution of Wireless Power Transfer took place. Today, all the companies specializing in the matter are investing a lot of time and money to get the best result in implementing this technology on their products (Qiu et al., 2014).

Figure 2.1 Wardenclyffe Tower Reference (Qiu et al., 2014)

2.3 MAIN CONCEPT OF WIRELESS POWER TRANSFER

Wireless power transmission is the transmission of electrical energy without using any conductor or wire. It is useful to transfer electrical energy to those places where it is hard to transmit energy using conventional wires.

Wireless power transfer is taking a big step in our daily life as it is used for wirelessly charging cell phones. Although the efficiency of the power transferred is not like the wired one, it is good enough to charge a phone. On the other hand, we had the concept implemented in the TV remote control and air conditioning remote control, which carried the same concept; transferring the signal wirelessly. Lastly, the most recent and biggest implementation of the concept of Wireless Power Transfer is in electric vehicles' charging system, which takes place through wireless charging in many different ways. We will discuss most of them later on. Wireless Power Transfer for electric vehicles can be implemented with many different theories. In all the research, the major problem was the rate of the received signal efficiency.

2.4 OIL DESIGNS FOR WIRELESS CHARGING

The electric vehicle market has been trending in the past years since the studies of the effect of petrol cars on the environment. Thus, the whole production leans toward green approaches. The technology is becoming more favorable since it is considered supported by wireless charging. The coil design is the key factor for having the best performance.

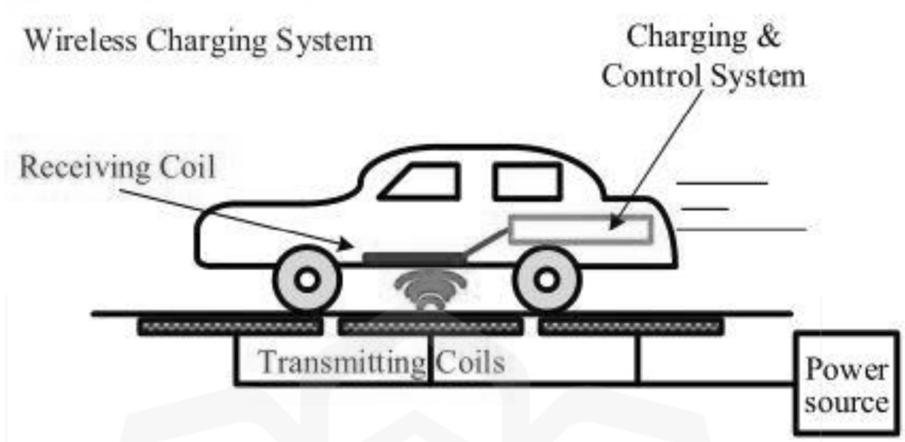


Figure 2.2 Components of the WPT (Popovic, 2017)

The coil designs that have been used and showed promising results were the Circular Rectangular Pad (CRP), Circular Pad (CP), Homogeneous Pad (HP), Double-D Pad (DDP), Double-D Quadrature Pad (DDQP), and Bipolar Pad (BP). The figure below shows the CRP (Brown, 1996).

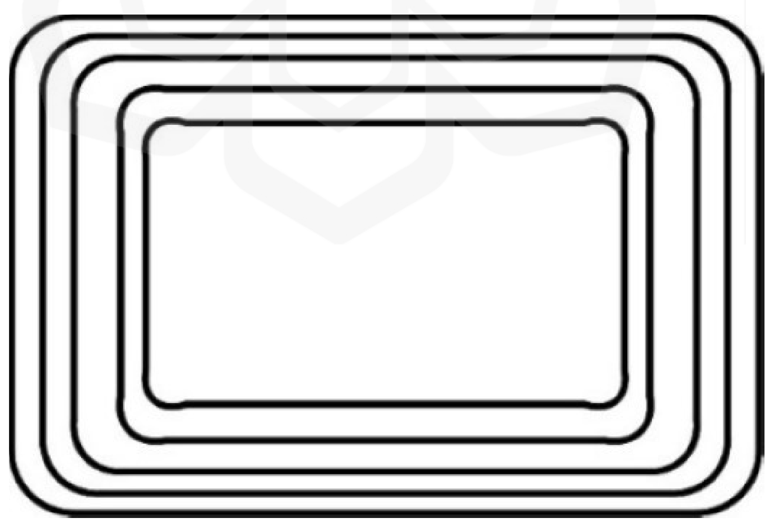


Figure 2.3 The Circular Rectangular Pad (Popovic, 2017)

- **Circular/Rectangular Pad (CRP/CP)**

In the early development of WPT, the Circular Rectangular Pad was proposed for many years, which consists of four fillets, as shown in Figure 2.4. This topology mainly improves the flux area, where the flux leakage in the edge can be reduced. However, the low efficiency resulting from poor coupling and the large total flux leakage are indispensable. Therefore, it is generally acknowledged that the design of the transmitting coil should be tailored to meet specific requirements. With all these issues, the researchers produced the CP to overcome all these drawbacks with almost identical specifications regarding the transferable power as in the pads' design, their weights, the cost of material, and the applicable distance for the transmission. The figure below shows the CP (Liu et al., 2017).

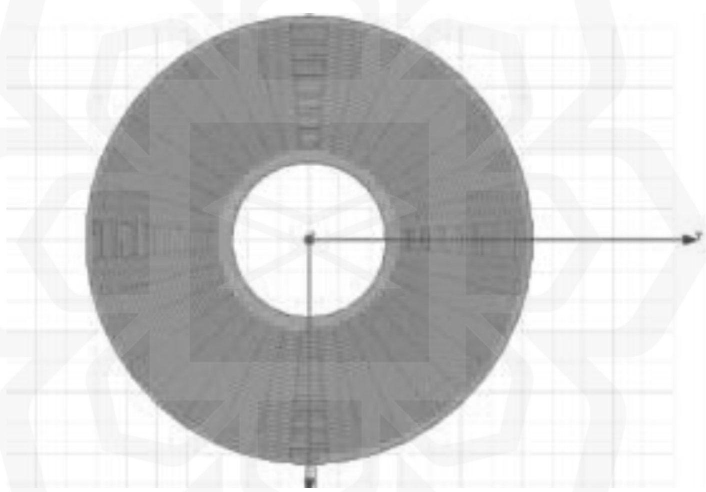


Figure 2.4 The Circular Pad CP (Brown, 1996)

In De Marco et al. (2019), the coil design had a symmetric double-sided flux path height. The below figure shows the proposed design.

$$\Delta P_z \alpha_4^1 P_d \qquad (2.1)$$

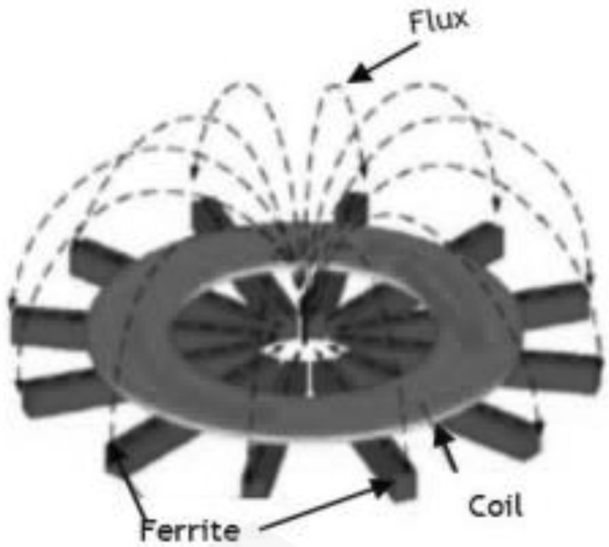


Figure 2.5 Symmetric Double-Sided Flux (Liu et al., 2017)

In this design, the path of the fundamental flux with a height proportional to around 0.25 of the pad diameter cannot be used for dynamic wireless charging. In Al-Saadi et al. (2018), the proposed design was carried out in 3 different ways by various coil diameter sizes for the primary and secondary coils and recording the readings of the power transfer with a comparison with the Misalignment and Magnetic flux. An important observation with the best-recorded results was that the outer diameter of the secondary and primary coils was the same as for the other two cases. It has recorded lower values of magnetic flux between the coils, which determines low power transfer.

In Zaini et al. (2021), the design used rectangular coil and spiral windings intending to have an organized magnetic field and a better result regarding the misalignment. However, the designed coil has a low distance range for the transmission system and poor interoperability characteristics. Furthermore, the results of Zaini et al. (2021) regarding the testing on the dynamically charging using CRP and CP coil designs gave the same concluded results in a study by (Qiu et al., 2015).

- **Homogeneous Pad (HP)**

One of the primary challenges faced when introducing homogeneous pads in the field was the limitation of inductive power transmission, which is restricted to the surface in order to achieve high efficiency. The ability to have a lateral displacement between the receiver and transmitter coils is most likely going to cause an effect on the coupling factor. For that, the author describes an approach for determining the turn distribution to ensure homogenous coupling between coils of different diameters. However, an array of transmitter coils can also create lateral displacement across a broader region. The receiver coil is chosen so that it always covers the whole transmitter coil. The power transmission area can be arbitrarily big with homogeneous magnetic coupling if only a proper sensing circuit triggers the covered transmitter coil (Khalid et al., 2022; Zhang et al., 2015).

This coil design is one of the keys to having the ability to charge the electric vehicle while moving, as its circuit design contains multiple primary coils. However, this design has some challenges, like its low power transfer and high material cost, while its transmission distance is medium. The HP circuit is shown below in Figure 2.6.

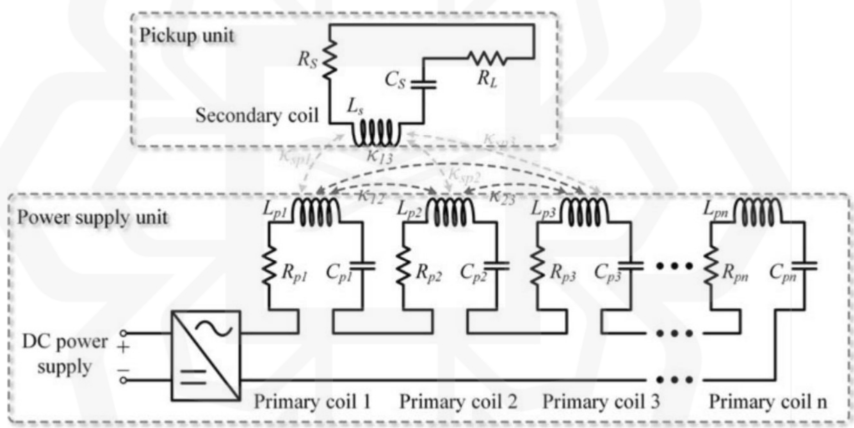


Figure 2.6 Basic Circuit for Dynamic Charging Circuit (Zhang et al., 2015)

The fundamental structure of a wireless charging mechanism for move-and-charge systems is depicted in the diagram, in which the power supply unit uses several series of linked primary coils arranged along the charging target's moving trace.

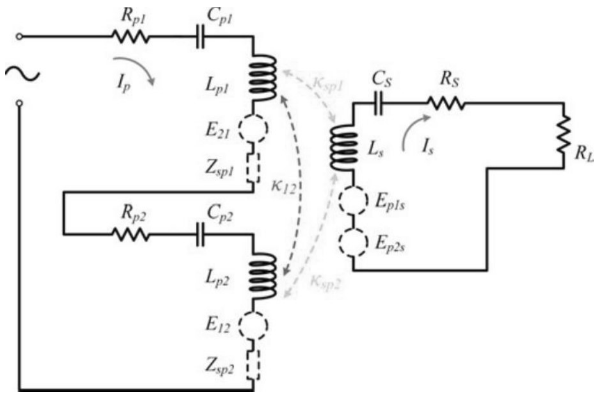


Figure 2.7 The Equivalent Circuit Modal (Zhang et al., 2015)

In Figure 2.7, the equivalent circuit shows how the mechanism of the dynamic charging is processed when the transmission is happening from the first primary coil to when it is between the two primary coils and so on. The mutual inductance can be calculated from the following:

$$L_{12} = K_{12}\sqrt{L_{p1}L_{p2}} \tag{2.2}$$

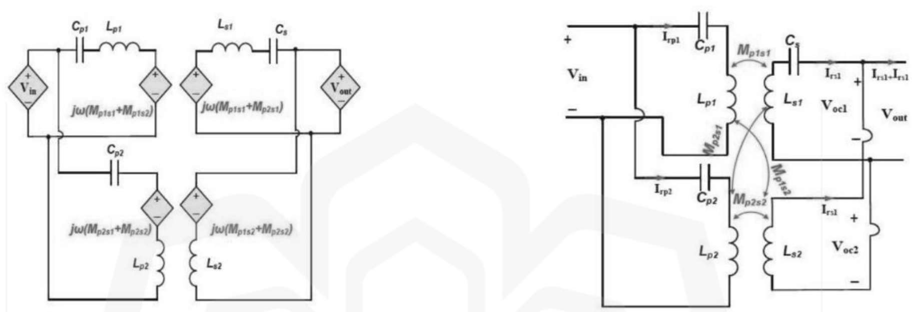
$$L_{sp1} = K_{sp1}\sqrt{L_{p1}L_{p2}} \tag{2.3}$$

$$L_{sp2} = K_{sp2}\sqrt{L_{p2}L_{s}} \tag{2.4}$$

In a study by Zhang et al. (2015), HP was designed to attempt to have the system continuously energized while enhancing the magnetic flux. However, misalignment is a major issue when it comes to HP, though the main course was to have the transmission between the main and secondary coil continuously. Moreover, in Zhang and Chau (2015), the issues and the drawbacks of this coil design were raised again in such the power transfer was low and transmission distance was fairly acceptable with an affected transmission efficiency.

- **Bipolar And Double-D Pads (BP and DDP)**

A few topologies have two couplers in the WPT design, designed specifically with the BPP and DD circuit design. Furthermore, this kind comes with a topology of Parallel-Parallel compensation. The BP and DDP coil designs are mostly used together as the BP for the receiver and the DDP for the transmitter sides. Below is the circuit for the primary and secondary sides (Zhang et al., 2014).



(a) (b)

Figure 2.8 (a) Simplified IPT Circuit for Double Couplers Configuration, (b) IPT Systems Consists of Two Primary Couplers and Two Secondary Couplers (Zhang & Chau, 2015)

The following formula can be used to calculate the output power of an inductive power transfer system (Zhang et al., 2014)

$$P_{out} = w_r \frac{M^2}{L_2} I_{rp}^2 Q_2 \tag{2.5}$$

- **Double-D Quadrature Pad (DDQP)**

Double-D Quadrature topology was designed to overcome the lack of experience with the DDP and CP regarding poor interoperability characteristics. Thus, the DDQ-pad is solving this drawback with a design that has a parallel and perpendicular magnetic field. Moreover, this topology can produce polarized and non-polarized filed by organizing the current flowing in the coil, with its flexibility being the highest compared to the other topologies. However, the disadvantage of this design is the cost, as it requires a greater number of coils.

In Jafari et al. (2021), the design of the DDP allows current to flow in opposite directions in the double coils. The flux path is being created with the ferrite bars; however, it has a poor interoperability characteristic issue. Therefore, the design was changed in the study by Zaheer et al. (2015), in which the DDQ pad design solved the issue. However, that comes with a higher cost of more material and the cost of the rectifier. Furthermore, the DDQ and BP coil designs can achieve almost identical power transmissions as the design can be adjusted to fit the given sized structure. In contrast, the primary side has no effect, whether polarized or non-polarized. Below is the figure showing the DDQ.

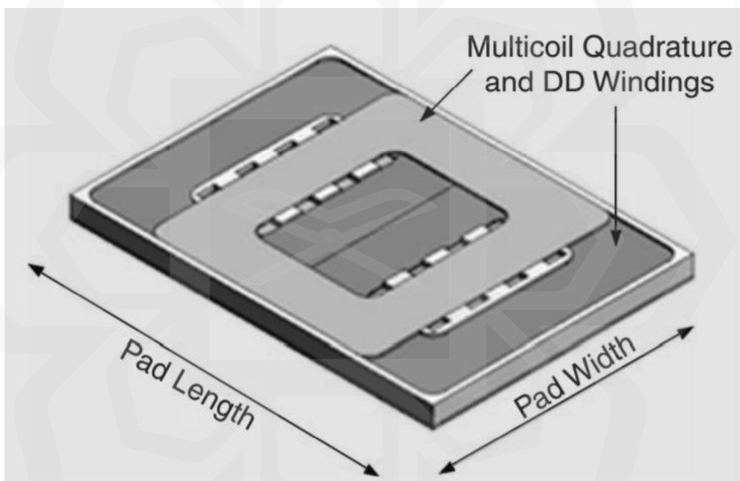


Figure 2.9 The DDQ (Zaheer et al., 2015)

Table 2.1 A Comparison Between the Coil Pads Features (Liu et al., 2017)

Type	CRP/CP	HP	DDP	DDQP	BPP
Factors	• Cost and size constraints • System weight • Electric Vehicle Types • Power Level • Distance Between Primary and Secondary Batteries • Chassis Structure	• High misalignment needed • Size design of each cell coil • Secondary size and direction design • Small system cost and size • System weight	• Ferrite bar length and thickness • Unwanted flux leakage • Low system cost and size • System weight • Power level • Coupled flux direction need	• Ferrite bar length and thickness • Control methods • System cost and size limitations • System weight • Electric vehicle types • Power level • Chassis structure	• Ferrite bar length and thickness • System costs and size are kept to a minimum. • The central area is overlapping • Amount of power • The distance between primary and secondary coils • Structure of the chassis

Type	CRP/CP	HP	DDP	DDQP	BPP
Features	• Flux is symmetric around the center of the CP • A pattern of the non-polarized perpendicular field by CP • It is most commonly utilized in primary and secondary coils • Inadequate interoperability characteristics • Create perpendicular flux and couple it • Adaptable applications	• Inadequate interoperability characteristics • Create and link polarised parallel flux along the length of the pads. • It's a term that's commonly used in primary coils • Cost-effective • Magnetic field distribution that is homogeneous • High misalignment potential	• Generation of a single-sided flux • Improve performance and interoperability with a variety of secondary topologies • A term commonly used in primary coils • At high power rates, ferrite bars are easily saturated • There is no reverse flux to remove the undesirable back flux	• As a secondary, giving three times the z charge zone of DDP • Improved performance with various secondary topologies • A term commonly used in secondary coils • Excitation modes with variable excitation • Inefficient material utilisation • Flexible central coil design to accommodate the airgap	• Partially overlapping coil structure that is mutually disconnected • DDQP utilized as a secondary has about the same performance as DDQP used as a primary • DDQP uses less copper than this • Improved performance with various secondary topologies • It's a term that's commonly used in secondary coils

2.5 WPT TOPOLOGIES

In wireless power transfer, there are four topologies that can be employed to connect the primary and secondary coils, namely parallel, series, or a combination of both. The below figure shows the topologies. SS has a series connection, SP has a series-parallel connection, PS has a parallel series connection, and PP has a parallel series connection.

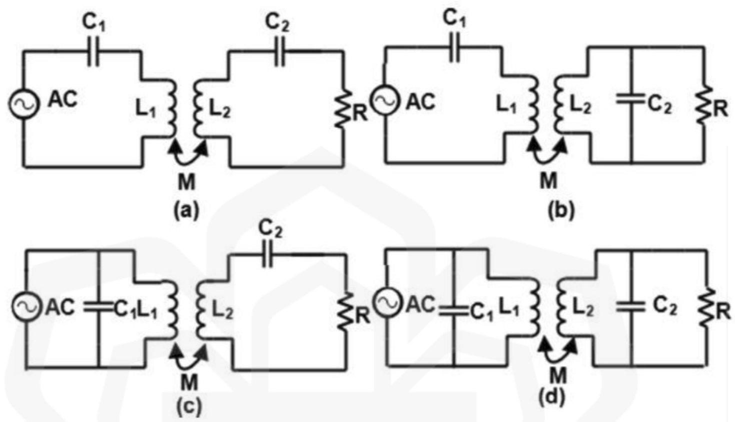


Figure 2.10 WPT Topologies; (a) SS, (b) SP, (c) PS, and (d) PP (Boys & Covic, 2015; Chopra & Bauer, 2011; Davis, 2018; García et al., 2015)

Table 2.2 The Advantages and Disadvantages of these Topologies (Boys & Covic, 2015; Chopra & Bauer, 2011; Davis, 2018; García et al., 2015)

Specifications	SS	SP	PS	PP
Sensitivity with relation over distance	low	low	medium	medium
The value of the impedance at resonant	low	low	high	high
Compatibility with EV	High	High	Medium	Medium
PT capability	High	High	Low	Low
Tolerance of the alignment	High	High	Medium	Low
Tolerance of frequency in relation to the efficiency	Low	High	Low	High

2.6 RELATED WORK

This project focuses on the dynamic wireless charging field, as all the researchers are all eyeing the ability to have continuous charging while moving, which is often possible when considering a homogenous design.

Table 2.3 Related Work

Author/Year	Method	Advantages	Limitations
Nikola Tesla (1882)	Electromagnetic induction	The founder of the wireless power transfer	The project collapsed due to no funding
Kalwar et al. (2016)	Series-series and series-parallel topology for dynamic wireless charging	Series-series is best capable of delivering power to the load with similar parameters when the electric load is higher, whereas, Series-Parallel is found to be more appropriate for lower load	The series-parallel configuration is found to have a lower value of power efficiency than the Series-series under the same conditions
Biswal et al. (2021)	Direct field-circuit coupling multi-physical.	This paper reflects the influence of different parameters on the system during the dynamic coupling process.	The coupling coefficient decreases significantly in one of the testing conditions.
Liu et al. (2018)	Estimate the output Current/voltage in the primary side of a two-transmitter inductive wireless power transfer system.	Continuity and stability of charging in dynamic wireless power transfer system.	Theoretical analysis with ideal results without any considerations of loss. Ideal results

Author/Year	Method	Advantages	Limitations
Wang et al. (2017)	Coil design for high coupling performance.	High coupling coefficient and small output fluctuation.	The limitations are defined by the author in compassion between two different coils used in terms of the efficiency of the systems.
Z. Wang et al. (2019)	Inductive coupling under Static and Dynamic wireless charging.	Charging system with an efficiency of 89.54%.	Coupling limitations, enhancement on the transmission connection.
Moon et al. (2021)	Maximization of the efficiency and a controller to maintain the impedance in the receiver side at its optimal state.	An improvement in the transfer efficiency under a state of misalignment with a certain percentage.	An excellent analysis, but it comes with a loss of ignorance.
Diep et al. (2019)	Dynamic wireless charging near-field coupling.	Induction values and coupled system obtained values under the dynamic state.	In-complete result analysis, how efficient is the system in charging
Shuguang et al., 2018)	Narrow-width three-phase magnetic coupling mechanism.	Reduced fluctuations in the output power	The proposed Series-series topology cannot support a higher distance than 30 mm
Cui et al. (2018)	Experimenting and evaluating on the Coupling effect.	The testing was done in both simulation and practical, with the results being compared.	The configuration used is the basic one, and it could have been enhanced at least a little bit to avoid any power loss.

In Kalwar et al. (2016), a system with a higher tolerance for misalignment was produced with a DQD coil design, ensuring a high coupling and a high power transfer under a reasonable misalignment between the secondary and primary coils. In Biswal et al. (2021), the produced system had topologies (SS, SP), most commonly used for dynamic wireless charging designs. The evaluation was produced in comparison between the 2 topologies in PTE and PDE because of the change of position. In Wang et al. (2017), a method was proposed to control and estimate the output current, voltage. This ensures the continuity of the power flowing on the receiver side and continuous charging. In Wang et al. (2019), a receiver coil was designed and proposed with its high coupling coefficient and output stability. The design of the coil was a DDQ plus OQO type.

CHAPTER THREE

METHODOLOGY AND IMPLEMENTATION

3.1 INTRODUCTION

This section briefly discusses what to do for the work section and how the testing will occur. To enable wireless power transfer, a suitable medium is necessary. Various methods are employed for this purpose, each with its advantages and disadvantages. The selection of a specific method is based on careful consideration of these factors. In the project, inductive power transfer was chosen based on the power level, range, efficiency, availability, and cost, which is very important for any project to meet the objectives at the lowest possible cost. It is near a field with high power to be delivered in a short range, which is ideal for the proposed project, and the efficiency is great. Traveling long distances requires a fully charged battery, and thus, charging several times along the way is needed. For example, the latest BMW that is supported by the aforementioned technology, as the company reported (Zhao et al., 2016), takes 3.5 hours to be fully charged, which is a very long time compared to vehicles powered by gas, which takes no longer than 5 minutes, and even trying to improve the time to less than 3.5h. However, the number of cars will not be satisfied because the number of stations can never meet the number of cars. Additionally, the dynamic wireless charging system will eliminate the problem by more than 50%. The rest is for the users to have at least a 40% charge or more, allowing them to leave their homes and travel to any road supporting the technology.

3.2 IMPLEMENTATION

- **Primary and Secondary Circuit Design**
- **Primary side**

The circuit configuration topology followed in this project is the parallel-parallel configuration. The design of the transmission and receiving circuits is similar to the one in Ahmed and Khalifa (2020), with few optimizations has been done.

In this project, the oscillator was based on the Royer Oscillator design, as shown in Figure 3.1. The Royer oscillator is one of the easiest designs to transform from Dc to Ac voltage and smoothly switch the rectangular wave to a sin wave. In this project, the MOSFET switching RO is used, which comes in the project's Tx circuit. Fig 3.1 shows the initial Tx circuit with the RO switching.

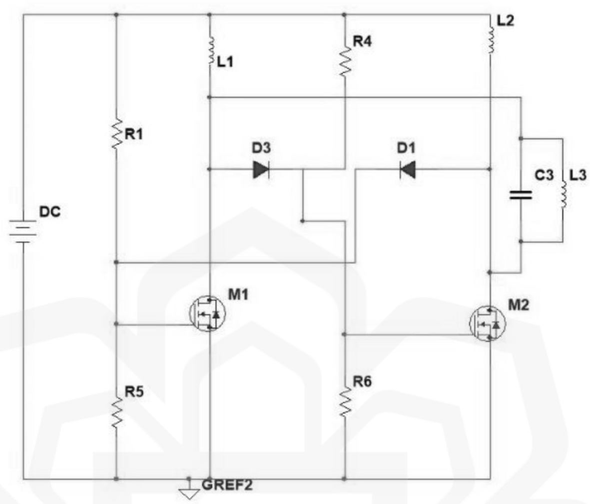


Figure 3.1 Tx Circuit

However, the issue with this design was that the generated Ac voltage in a sin wave form was having the effect of ringing. The signal was also dissipated, caused by the leakage of the induced magnetic field. To solve this issue, an RC snubber was added in parallel with the Diodes, as shown in Figure 3.2.

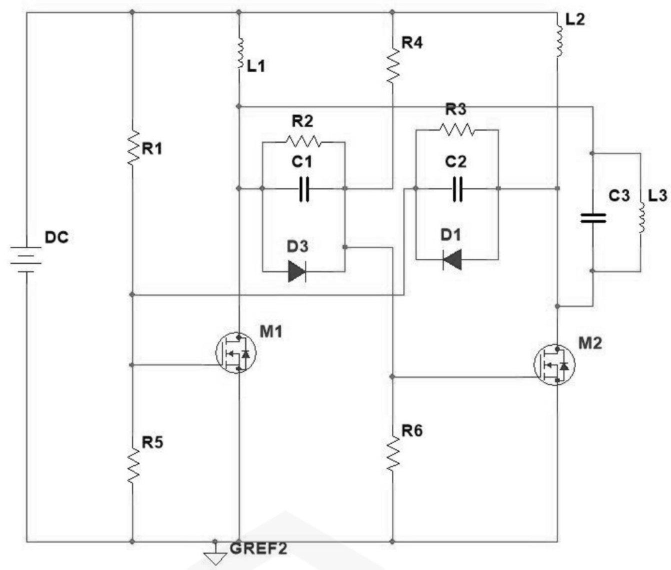
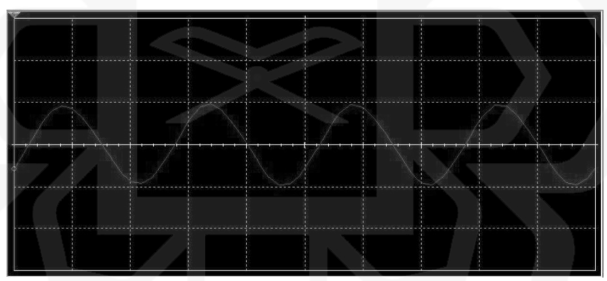
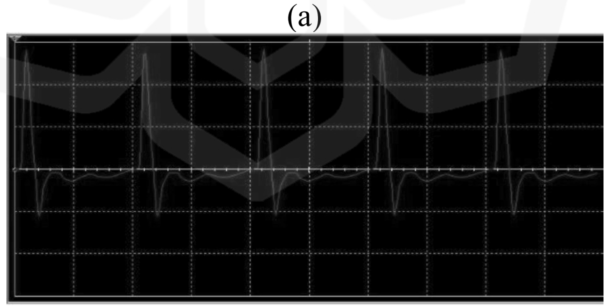


Figure 3.2 Tx Circuit with the Snubber RC

The following Figure 3.3 shows the effect of with or without the snubber.



(a)



(b)

Figure 3.3 (a) With, (b) Without

Figure 3.3 shows the reading recorded in Multisim using Oscilloscope, the X-axis represents the time in (ms), and the Y-axis represents the voltage in (V) received.

Table 3.1 Parameters

	Parameter	Value
Primary Side	DC	15 volts
	R1	1k ohms
	R2	1k ohms
	R3	1k ohms
	R4	100 ohms
	R5	10k ohms
	R6	10k ohms
	C1	10u F
	C2	10u F
	C3	0.4u F
	D1	1N1401G
	D3	1N1401G
	L1	91u H
	L2	91u H
	L3	Calculated Through Ansys
	M1	IRF530N
	M2	IRF530N
	Ground	
Secondary Side	L4	Calculated Through Ansys
	C4	0.33u F
	C5	470u F
	C6	0.33u F
	C7	0.33u F
	D2	1N4148
	D4	1N4148
	D5	1N4148
	D6	1N4148
	LM	Voltage Regulator
	Ground	

- **Snubber circuit**

The RC snubber circuit comes in handy when the circuit has an inductor and is controlled through a switch or multiple switches. This current design is connected with the diodes that enhance the switching effect, transforming the current from Dc to Ac. The snubber circuit is mainly used to absorb the energy stored in the inductor and limit the voltage rise through the values calculated for the design to have the best performance in canceling and stabilizing the flow.

- **Receiver circuit**

The receiving circuit is initially a full-wave rectifier to receive the AC from the Tx and then transform it to a Dc voltage to charge the load; in this case, a battery. Figure 3.4 shows the Receiver circuit.

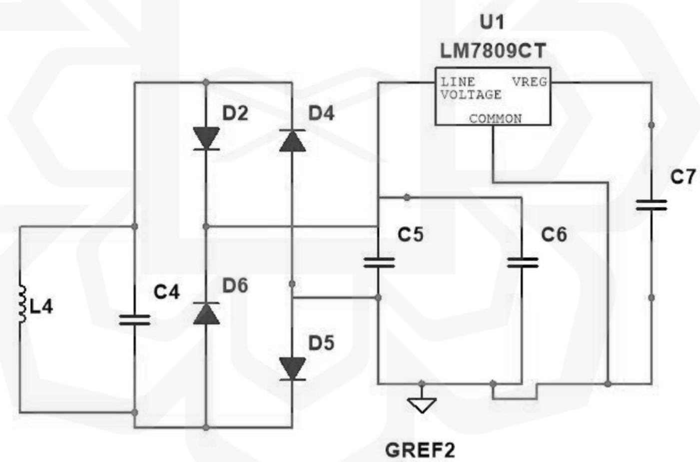


Figure 3.4 Rx Circuit

3.2.1 Coil Design

With the rapid growth of the electric vehicle (EV) market, the new wireless EV charging technology has gotten a lot of attention in recent years. The coil design is critical for increasing the performance of a wireless charging system for electric vehicles.

The main parts should be considered when designing the coil after determining which type will be used for the parameter calculations, which will affect the maximum efficiency of the coil. In this project, a copper coli has been chosen. The parameters are: Outer radius ($R_{Tx,Rx}$), Wire radius (r_o) and the number of turns ($N_{Tx,Rx}$). Power transfer efficiency (PTE), transfer distance, transferred power, and misalignment tolerance is some of the most important WPT performance parameters. PTE is calculated using the following formula:

$$PTE_{max} = \frac{k^2\, Q_{Tx}\, Q_{Rx}}{(\,1+\sqrt{1+k^2 Q_{Tx}\, Q_{Rx}}\,)^2} \tag{3.1}$$

- **Coil radius effect**

The radius of the coil can control the amount of power that will be received. For that, the following testing has been conducted to double-check and ensure the radius of the homogenous coil used in this project will have the best results. The testing coil was created with n = 17, as shown in Figure 3.5.

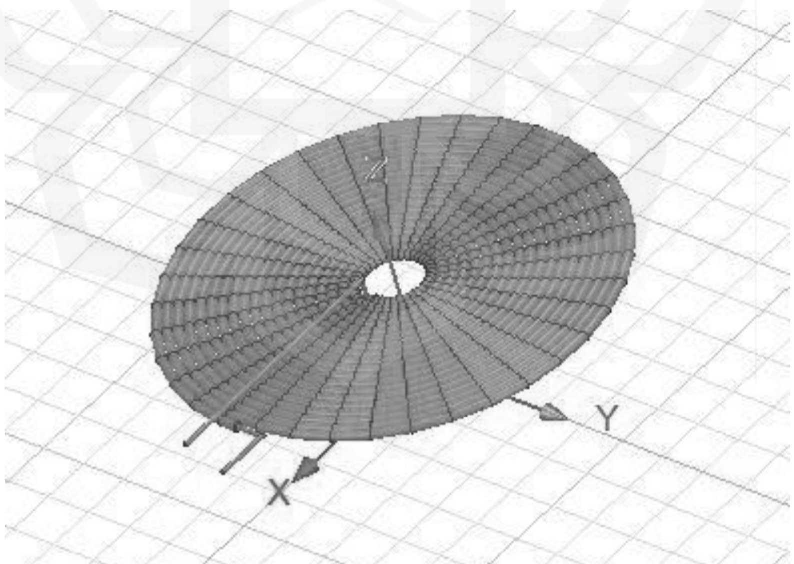


Figure 3.5 Testing Coil

The design has been tested on the Ansys Maxwell software with a value of 15A for the current and 6.87 Hz as the resonance frequency. The coil radius was examined with different values and compared on both coils. The comparison between all the test results is carried out based on the plotted efficiency.

The first coil was constructed with starting radius of 3mm for the transmission side and 3mm for the receiver side. The way Ansys software works is that the coils must be connected to terminals, and the terminals must be in contact with the region. Then, the region must be created to simulate the surroundings as if the process is in a room, as it has been assigned air material, while the coils are assigned copper material.

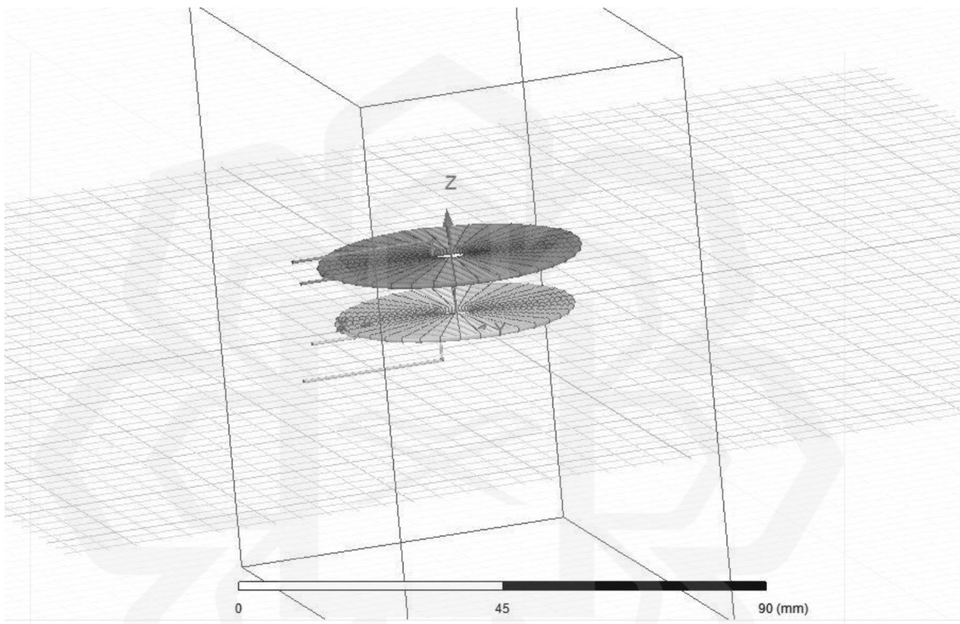


Figure 3.6 Primary and Secondary Coil for the Radius Testing

The process started by assigning excitations to the terminals connected to the primary coil with 15A current and 0A for the receiver coil, as it will be excited later by the magnetic field generated from the primary coil. This step is important as it tells the software exactly where the current will flow in the created structure. Secondly, a mesh is assigned to both the coils and the region. Mesh analysis is a crucial technique employed to enhance the accuracy of simulations. However, increasing the mesh values can significantly extend the computation time. Nevertheless, this trade-off is justified as higher mesh values lead to more realistic and precise results. In addition to mesh analysis, another important aspect of the project involves assigning the testing parameters. Specifically, the focus was on offset variations in the X-axis and the Y-axis.

To ensure comprehensive coverage, this assignment was carried out in four different variations, allowing for a comprehensive exploration of the parameter space:

Table 3.2 Radius Testing Variations

Primary coil radius (mm)	Secondary coil radius (mm)
3	3
3	5
5	3
5	5

Steps of coil design on Ansys

Step 1: The creation of the coil.

Creating the coil and assigning the copper material to it, as shown in Figure 3.7.

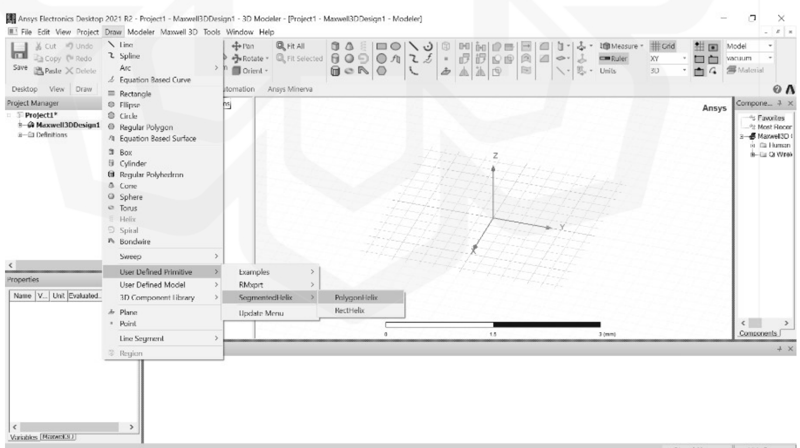
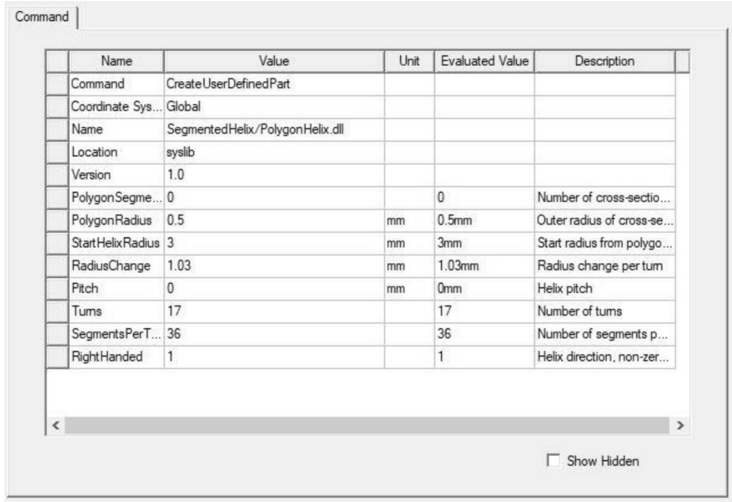


Figure 3.7 Steps in Creating the Coil

Step 2: Command coil configurations.

The assigning of the coil design parameters.



	Name	Value	Unit	Evaluated Value	Description
	Command	CreateUserDefinedPart			
	Coordinate Sys...	Global			
	Name	SegmentedHelix/PolygonHelix.dll			
	Location	syslib			
	Version	1.0			
	PolygonSegme...	0		0	Number of cross-sectio...
	PolygonRadius	0.5	mm	0.5mm	Outer radius of cross-se...
	StartHelixRadius	3	mm	3mm	Start radius from polygo...
	RadiusChange	1.03	mm	1.03mm	Radius change per turn
	Pitch	0	mm	0mm	Helix pitch
	Turns	17		17	Number of turns
	SegmentsPerT...	36		36	Number of segments p...
	RightHanded	1		1	Helix direction, non-zer...

Figure 3.8 Configurations for the 3mm Coils

The configurations are listed in the table in Figure 3.8. Some details are standard, which relates to how the file is saved and where it is saved in the machine. But the important parameters are the key factors of how the coil will be and what is the voltage induction that will be in the coil are further discussed:

- **Polygon segment** = 0, as it does not add anything to the design and does not affect how the process proceeds.
- **Polygon radius** = 0.5 mm, the coil radius. The thicker the radius, the better the results when compared with real-world results. However, since this project's scale is chosen small, the value does the work.
- **Start helix radius** = 3, which is the inner radius of the coil.
- **The pitch** value will determine whether the coil's radius will change every turn with a certain height value increase. The pitch is assigned to zero because the coil design is circular, so the change is applied with the radius change parameter.
- **Radius change** = 1.03mm, setting it to a bit more than double the amount of the Polygon radius, adding a very small distance between each turn.
- **Self-Inductance:**

  The amount of voltage inducted in the coils is measured by the Ansys Maxwell using the following formula:

$$L = \frac{\mu_o N^2 A}{l} \tag{3.2}$$

With $\mu_o = 4\pi \times 10^{-7}$, N= number of turns, A is the area of the coil, and l is the length of the coil.

Step 3: Boundary

For Ansys to simulate, the coils must be within a space created and assigned with the material of the user's choice. In this case, the boundary is a box created and assigned with air material.

Step 4: Excitation

In this step, 2 terminals are created for both ends in both cables, and both are connected to the box surface and assigned with the flow of current, with one being the input and the other being the output.

Step 5: Validate

Before validating the coils, the coils must be assigned with a matrix to generate solutions and validate the whole creation in the space of Ansys. This tests if all the parameters are correctly assigned and prepared for simulation.

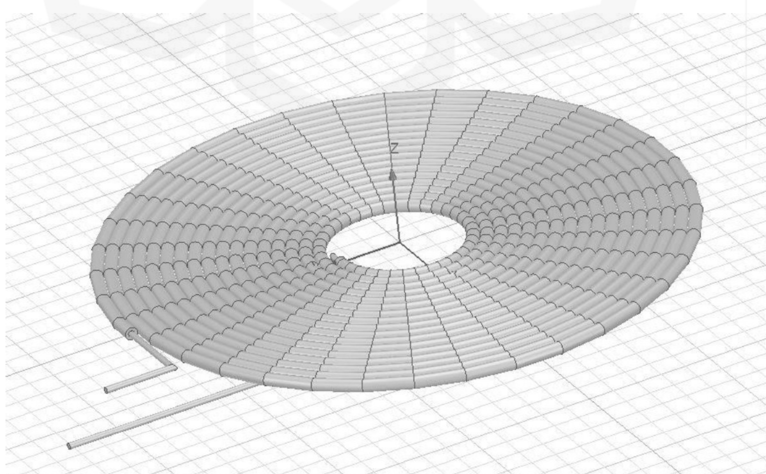


Figure 3.9 The Transmission Coil with a Radius of 5mm

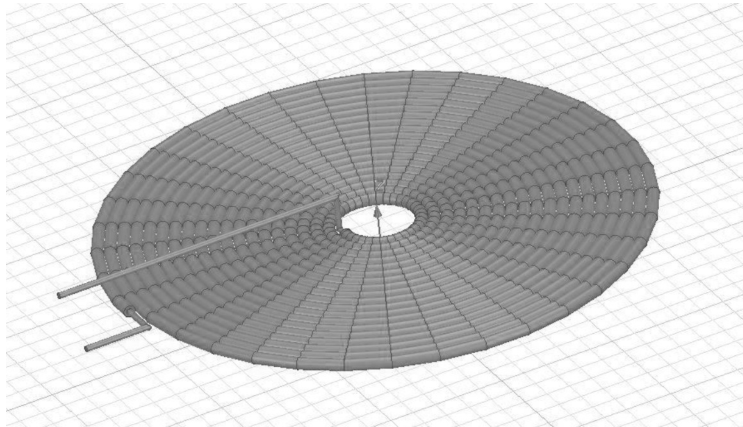


Figure 3.10 The Receiver Coil with a Radius of 3mm

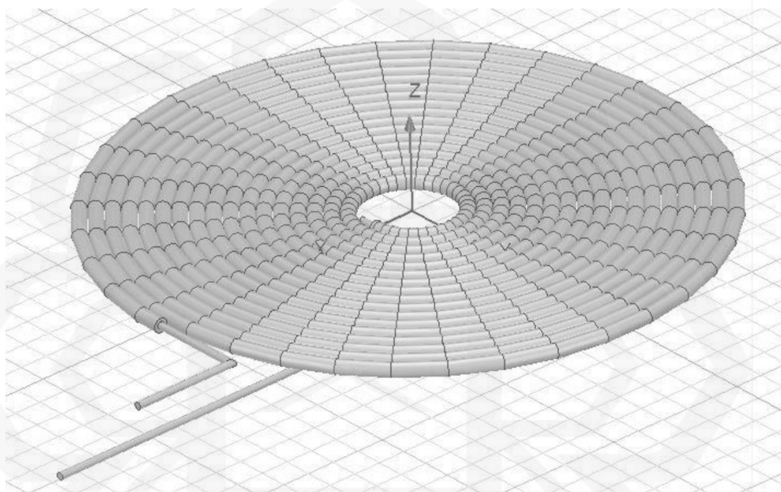


Figure 3.11 The Transmission Coil with a Radius of 3mm

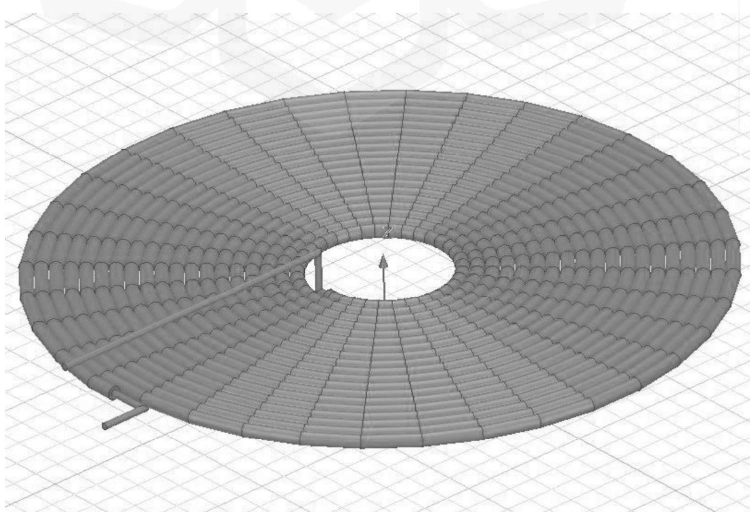
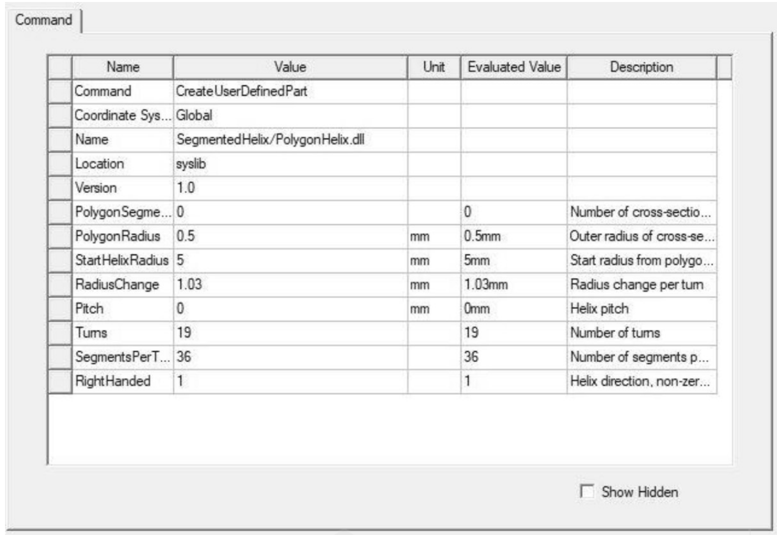


Figure 3.12 The Receiver Coil with a radius of 5mm



Command

Name	Value	Unit	Evaluated Value	Description
Command	CreateUserDefinedPart			
Coordinate Sys...	Global			
Name	SegmentedHelix/PolygonHelix.dll			
Location	syslib			
Version	1.0			
PolygonSegme...	0		0	Number of cross-sectio...
PolygonRadius	0.5	mm	0.5mm	Outer radius of cross-se...
StartHelixRadius	5	mm	5mm	Start radius from polygo...
RadiusChange	1.03	mm	1.03mm	Radius change per turn
Pitch	0	mm	0mm	Helix pitch
Turns	19		19	Number of turns
SegmentsPerT...	36		36	Number of segments p...
RightHanded	1		1	Helix direction, non-zer...

Show Hidden

Figure 3.13 Configurations for the 5mm Coils

3.2.2 Homogeneous Coil Structure (Rx)

From the previously obtained results, it has been observed that the radius of the primary circuit has a greater effect of better transmission efficiency under bigger displacements between the primary and secondary coils, which will be discussed in detail in the results and analysis chapter. On the other hand, having a bigger radius in the receiver coil influences the efficiency, which does not produce an efficient WPT as it does not support a wider gap between the primary and the secondary.

Based on that, the homogeneous coil has been created on Ansys software with a Tx homogeneous coil radius of 5mm and Rx coil radius of 3mm. Figure 3.10 shows the homogeneous coil that has been created.

Important considerations:

- The homogeneous coil design is mainly introduced to better results for the dynamic wireless charging for electric vehicles.
- Installing such a big installation on a country's roads will be costly, so only a few countries have started implementing it in a few areas with the present infrastructure.
- Many countries that support electric vehicles have issues with being unable to cover every area of the country to have a station for charging. The owner of the EV must

search and make sure that there is a station in the way of travel; otherwise, the owner needs to change the route or, in other cases, have different transportation.

Design Idea

The problem that this project is looking to solve is ensuring the connecting roads are dynamic charging supported to a certain extent so that the owner of an electric car will be less concerned with whether their car can reach the destination. So far, it has been included in many pieces of research that there will be a speed limit for the vehicle to charge while moving. Only one side of the road will have a vehicle charging facility to ensure that the other drivers with full battery or gas support can drive at a higher speed. The consideration in terms of the coupling coefficient in the design was to have more than one transmitter coil. A single coil structure design tested there wears a large leakage flux. For that reason, the segmented or multiple transmitters are better as they provide a better coupling which affects the transmission efficiency and reduces the leakage.

Figure 3.10 shows the homogeneous coil structure that has been created for testing. The figure shows every transmitter having two terminals; however, the inner structure of the circuit has all the coils being connected in the twin builder. This specific step is to obtain the values of inductance and coupling coefficients and other results that are coil based.

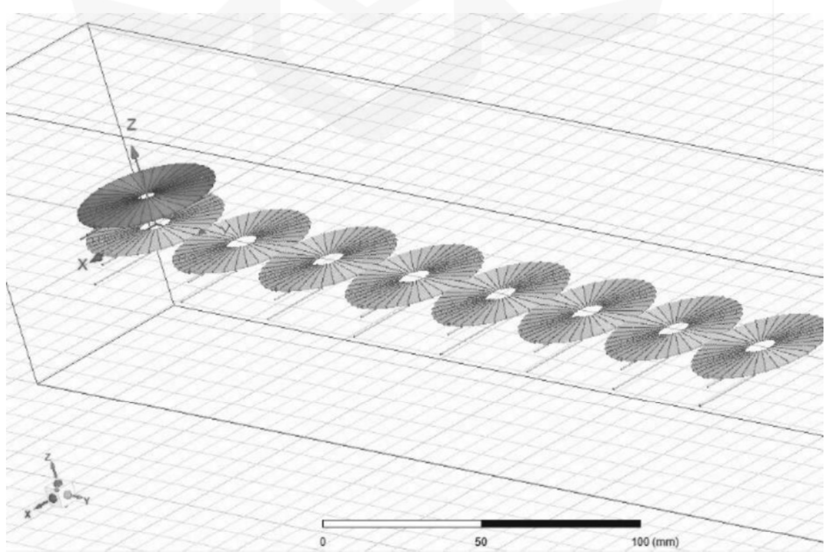


Figure 3.14 Homogeneous Coil Structure

CHAPTER FOUR

RESULT ANALYSIS

4.1 INTRODUCTION

The testing that has been carried through this project first started with recording the behavior of the coil. The focus was on the coil's radius and how efficient the transmission and receiving of the power are.

4.2 RESULT ANALYSIS

4.2.1 The Behaviour of the Coil

The coil radius was examined with different values and compared on both coils. The comparison between all the test results is carried out based on the plotted efficiency. The radius of the primary side is 3mm; for the secondary side is 3mm. The results are as follows:

Table 4.1 Efficiency

Distance (mm)	Efficiency (%)
5	92.66
10	78.35
15	66.2

Meanwhile, the coupling coefficient is given as follows:

Table 4.2 Coupling Coefficient

Distance (mm)	Coupling coefficient
5	0.5
10	0.3
15	0.18

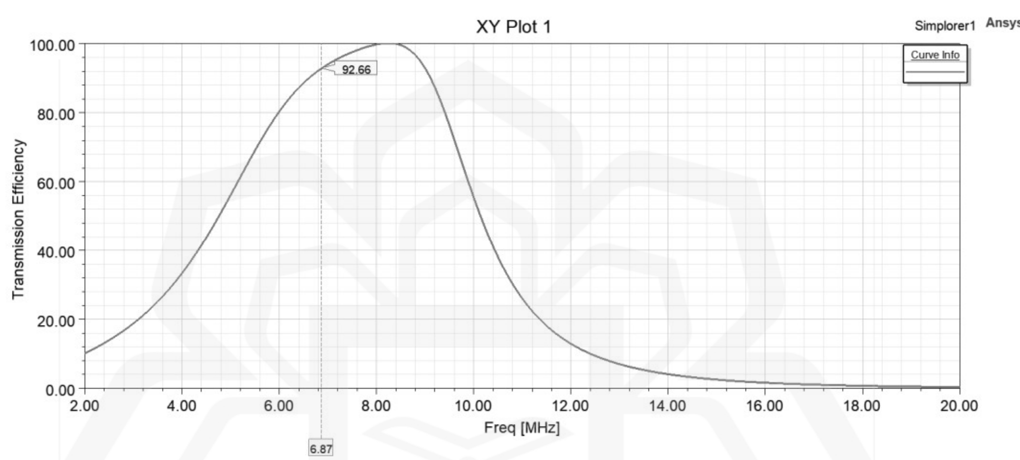


Figure 4.1 The Transmission Efficiency in a 5mm Distance Gab

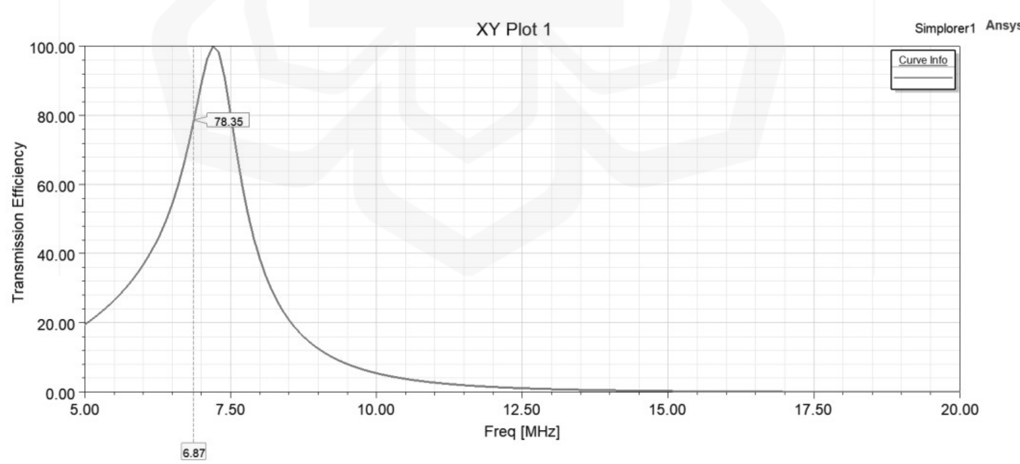


Figure 4.2 The Transmission Efficiency in a 10mm Distance Gab

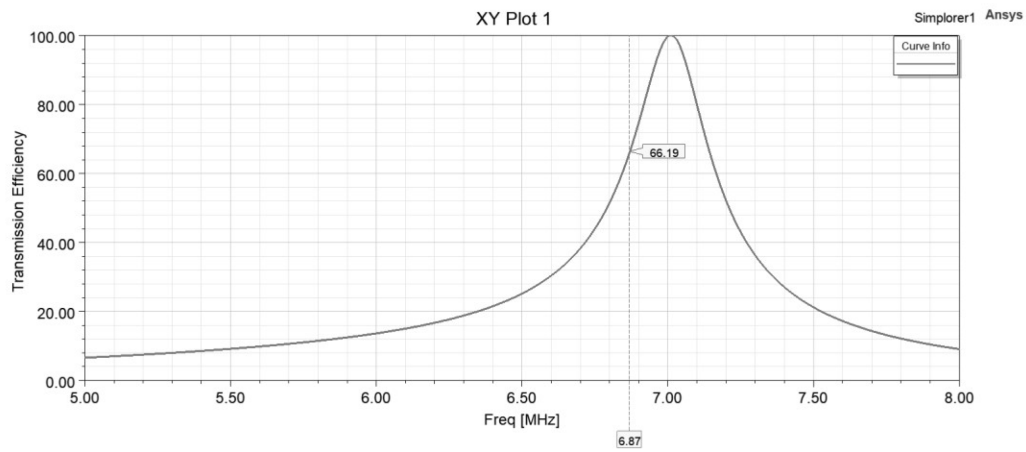


Figure 4.3 The Transmission Efficiency in a 15mm Distance Gab

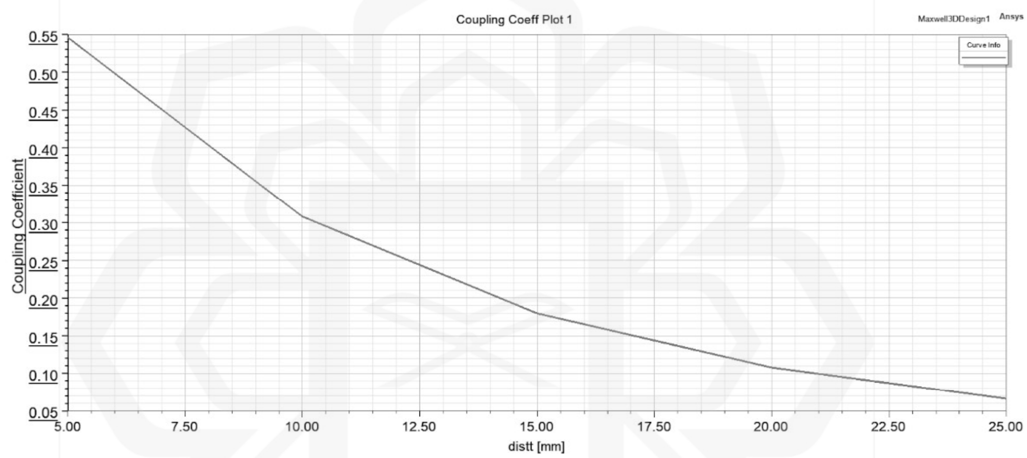


Figure 4.4 Coupling Coefficient

In Figure 4.1, the graph shows an efficiency of 92%, and that's due to the small gap between the primary and secondary. The coils match, so the magnetic flux leakage is low. On the other hand, in Figure 4.2, the design recorded around 78% efficiency of transmission, and that's due to the higher distance between the coils and higher leakage because of the smaller radiuses used for both coils. The same applies to Figure 4.3, as it has lower efficiency. The radius of the primary side is 3mm, and the secondary side is 5mm. The results are as follows:

Table 4.3 Efficiency

Distance (mm)	Efficiency (%)
5	84.8
10	70.28
15	67.9

Meanwhile, the coupling coefficient is given as follows:

Table 4.4 Coupling Coefficient

Distance (mm)	Coupling coefficient
5	0.54
10	0.31
15	0.18

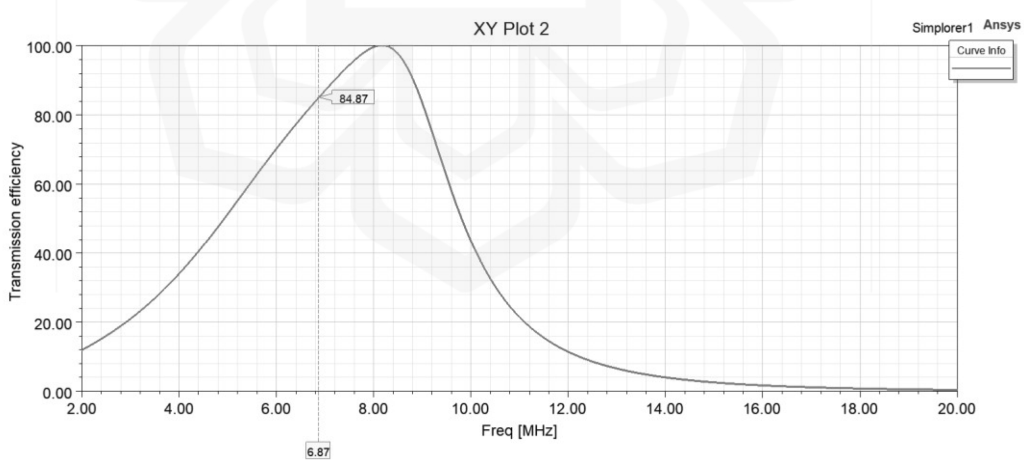


Figure 4.5 The Transmission Efficiency in a 5mm Distance Gap

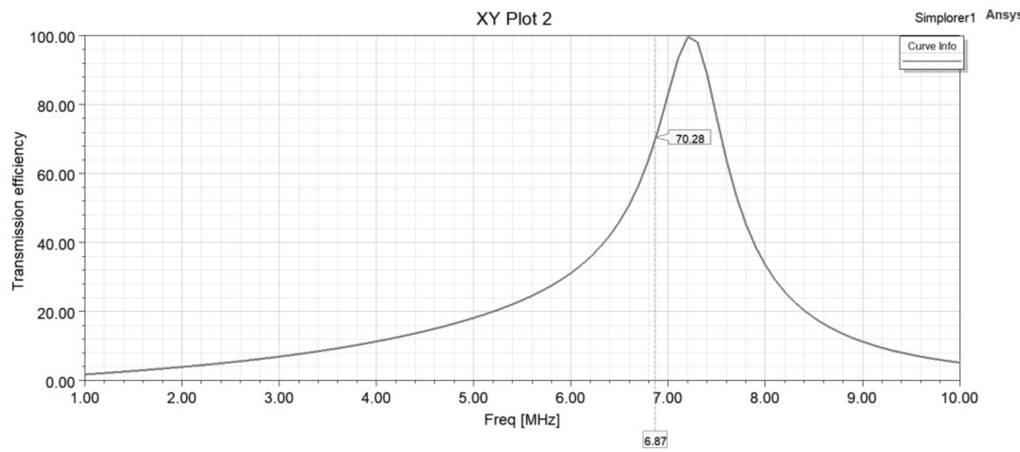


Figure 4.6 The Transmission Efficiency in a 10mm Distance

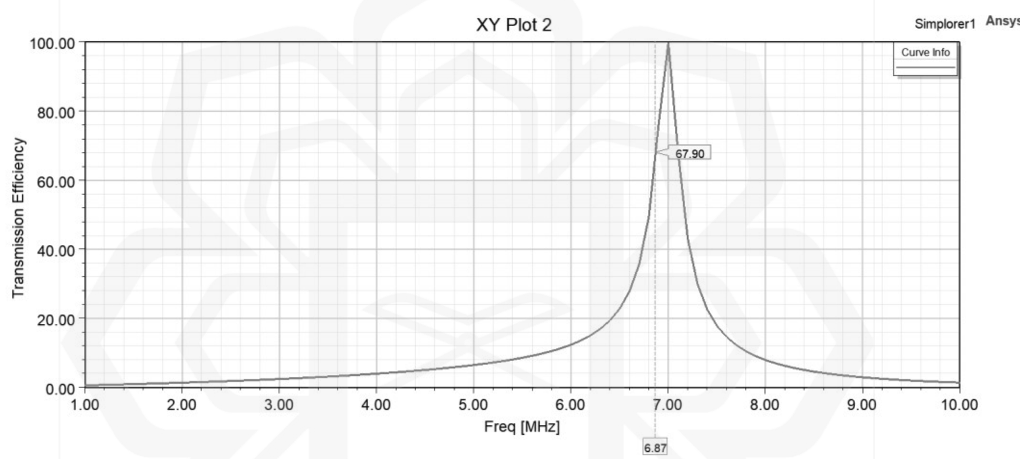


Figure 4.7 The Transmission Efficiency in a 15mm Distance Gap

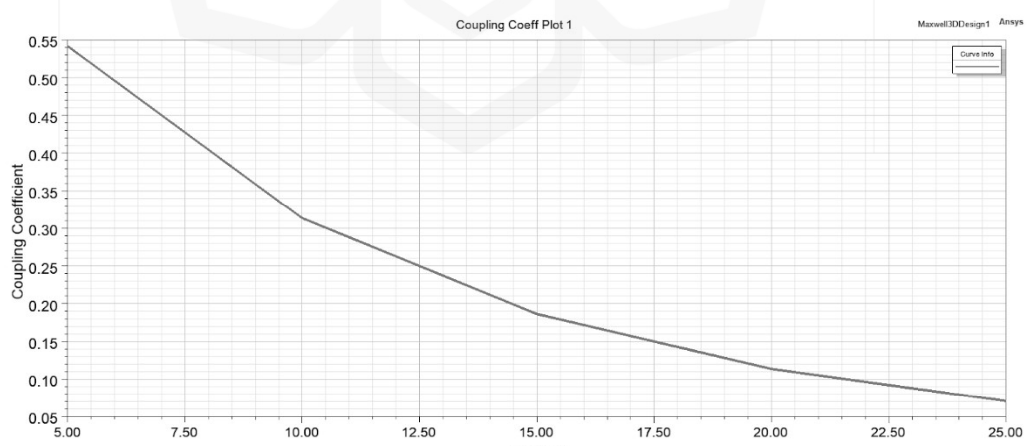


Figure 4.8 Coupling Coefficient

In Figure 4.5, the graph shows an efficiency of 84%, and that's due to the leakage in the magnetic field caused by the higher difference between the receiver and transmitter coils. On the other hand, in Figure 4.6, the design recorded around 70% transmission efficiency. The higher the gap, the more effective the distance. But because the difference in the coil radius is high when the transmission coil has a closer radius to the receiver radius, the 70% might become 80%. The same applies to Figure 4.7, as it has lower efficiency.

The radius of the primary side is 5mm, and the secondary side is 3mm. The results are as follows:

Table 4.5 Efficiency

Distance (mm)	Efficiency (%)
5	95 || R = 300ohm
10	77.8
15	71.5

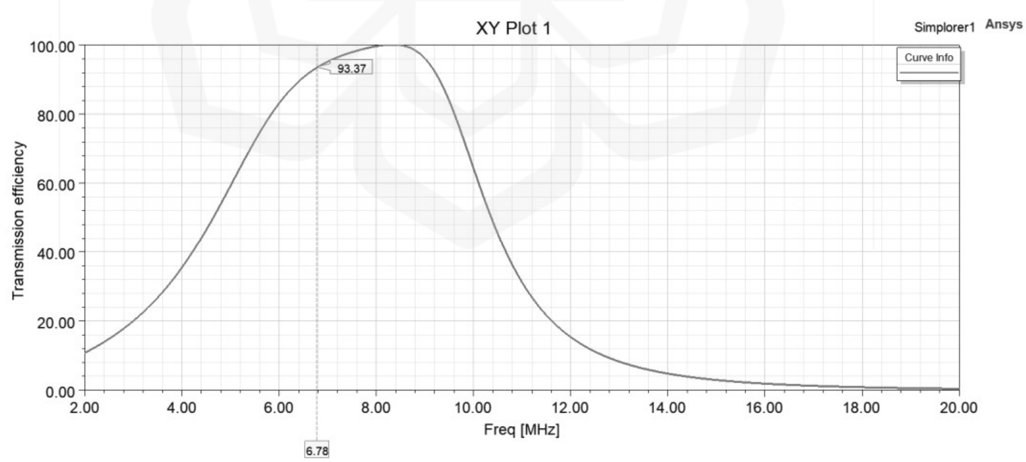


Figure 4.9 The Transmission Efficiency in a 5mm Distance Gap

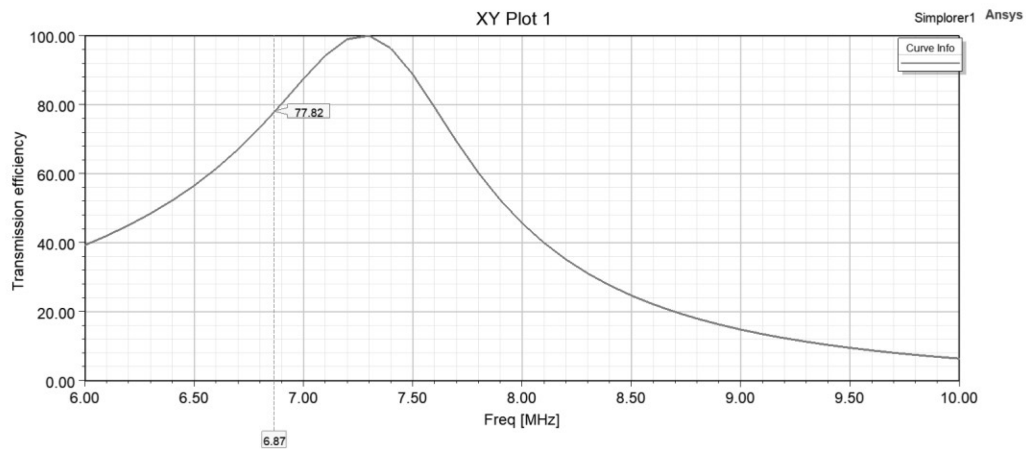


Figure 4.10 The Transmission Efficiency in a 10mm Distance Gap

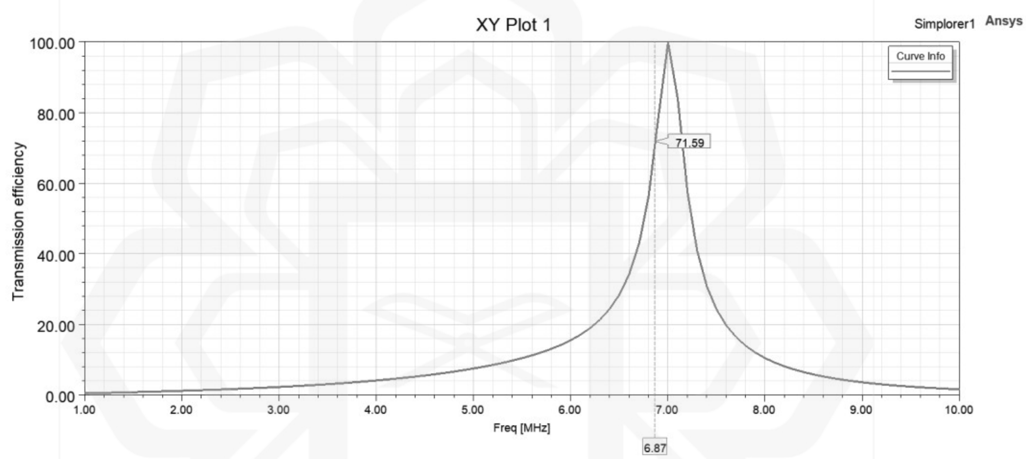


Figure 4.11 The Transmission Efficiency in a 15mm Distance Gap

And the coupling coefficient is as follows:

Table 4.6 Coupling Coefficient

Distance (mm)	Coupling coefficient
5	0.56
10	0.32
15	0.19

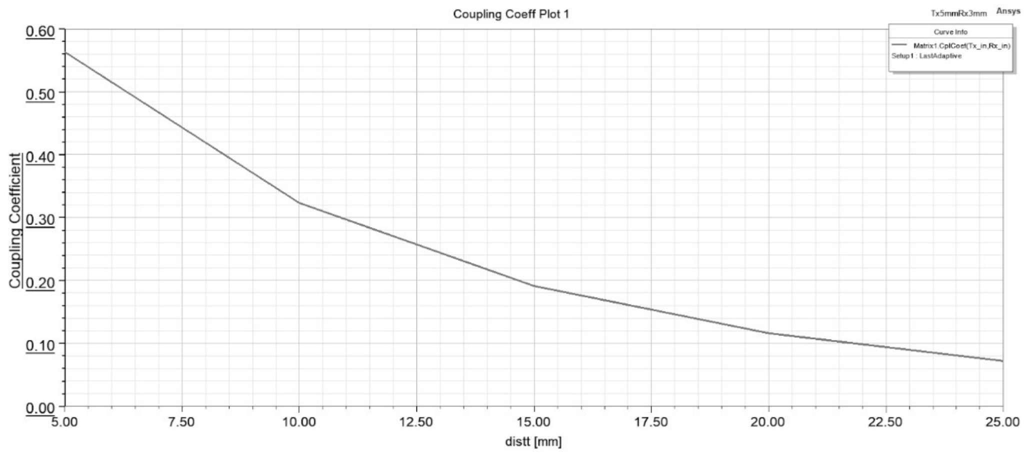


Figure 4.12 Coupling Coefficient of 5mm and 3mm

In Figure 4.9, the graph shows an efficiency of 93% up to 95% due to the higher transmission radius than the receiver circuit. On the other hand, in Figure 4.10, the design recorded around 77% transmission efficiency decreased due to the gap increase between the coils. The same applies to Figure 4.11, as it has lower efficiency.

The radius of the Primary side is 5mm, and the secondary side is 5mm. The results are as follows:

Table 4.7 Efficiency

Distance (mm)	Efficiency (%)
5	87.99
10	80.27
15	74

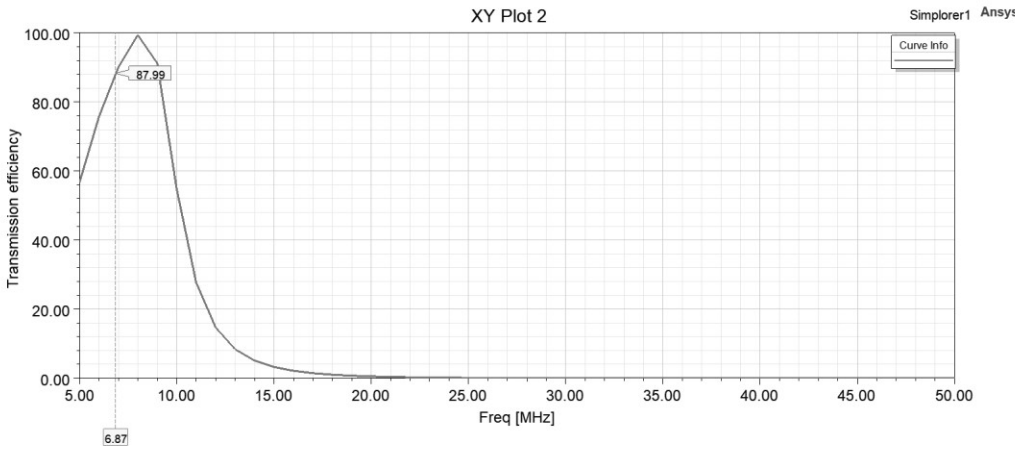


Figure 4.13 The Transmission Efficiency in a 5mm Distance Gap

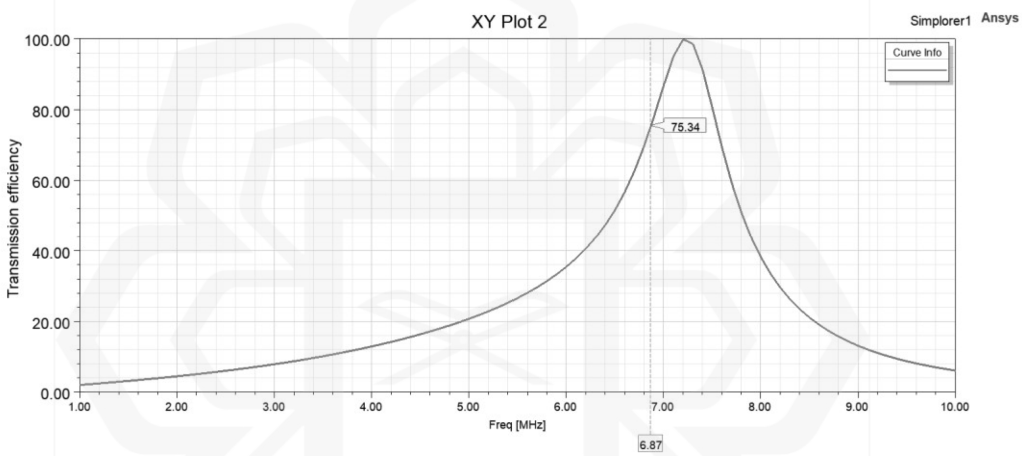


Figure 4.14 The Transmission Efficiency in a 10mm Distance Gap

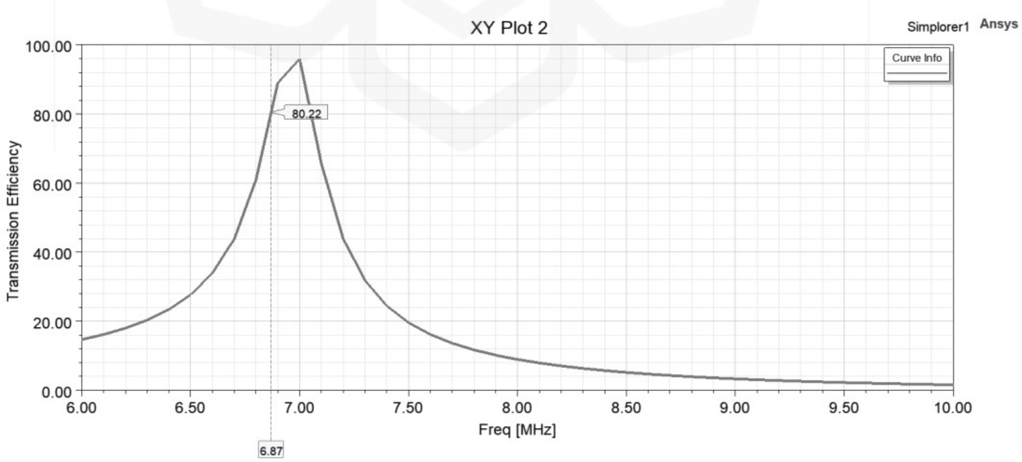


Figure 4.15 The Transmission Efficiency in a 15mm Distance Gap

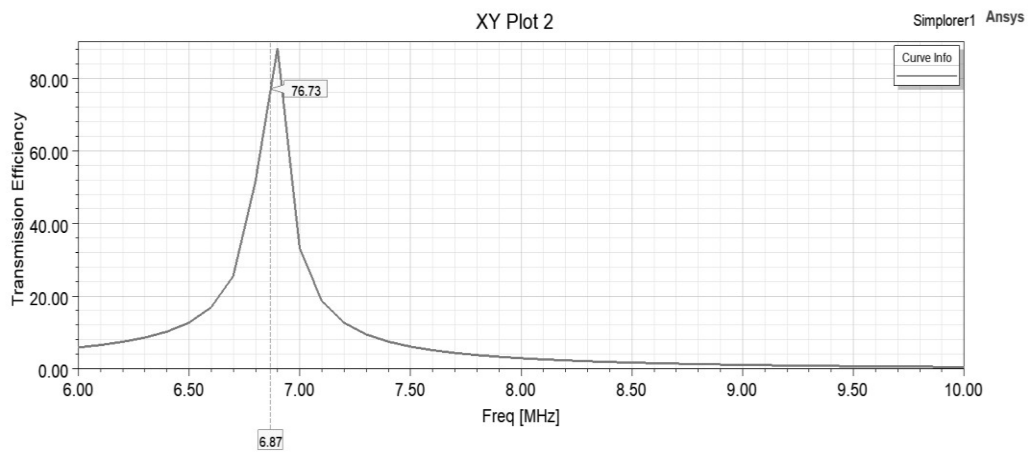


Figure 4.16 The Transmission Efficiency in a 20mm Distance Gap

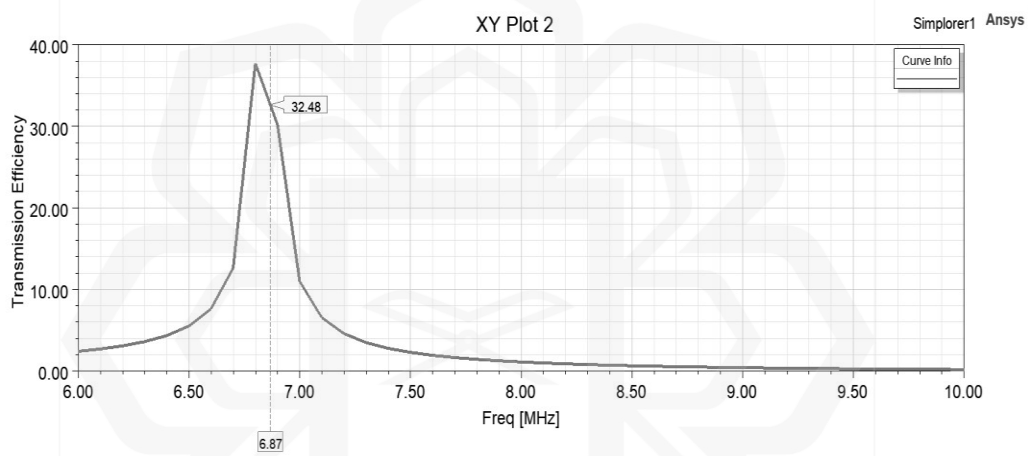


Figure 4.17 Transmission Efficiency in a 25mm Distance Gap

Meanwhile, the coupling coefficient is given as follows:

Table 4.8 Coupling Coefficient

Distance (mm)	Coupling coefficient
5	0.56
10	0.33
15	0.20

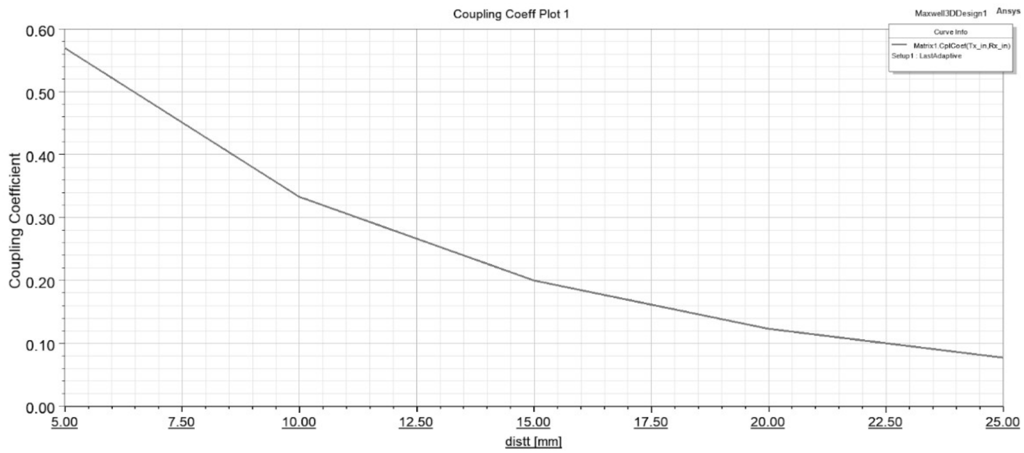


Figure 4.18 Coupling Coefficient of 5mm and 5mm

In Figure 4.13, the graph shows an efficiency of 87%, and that is due to having both coils possessing the same radius. On the other hand, in Figure 4.14, the design recorded around 75% of transmission efficiency due to the higher radius of both coils. The rest of the cases recorded higher efficiency as the effective distance increased.

Homogeneous testing

The testing was carried out for the homogeneous design, and the results for the coupling coefficient are as follows. The distances ranging from 0-100mm along the X-axis were examined in various positions, taking into account perfect alignment with the transmission coil as well as different misalignment conditions.

Table 4.9 Coupling Coefficient Values with Respect to Distance

Distance(mm)	Coupling coefficient	Coil
0 perfectly matched	0.33	Primary coil 1
10	0.24 and -0.04	Primary coils 1 and 2
20	0.07 and 0.01	Primary coils 1 and 2
30	-0.02 and 0.15	Primary coils 1 and 2
45	0.33	Primary coil 2
90	0.33	Primary coil 3

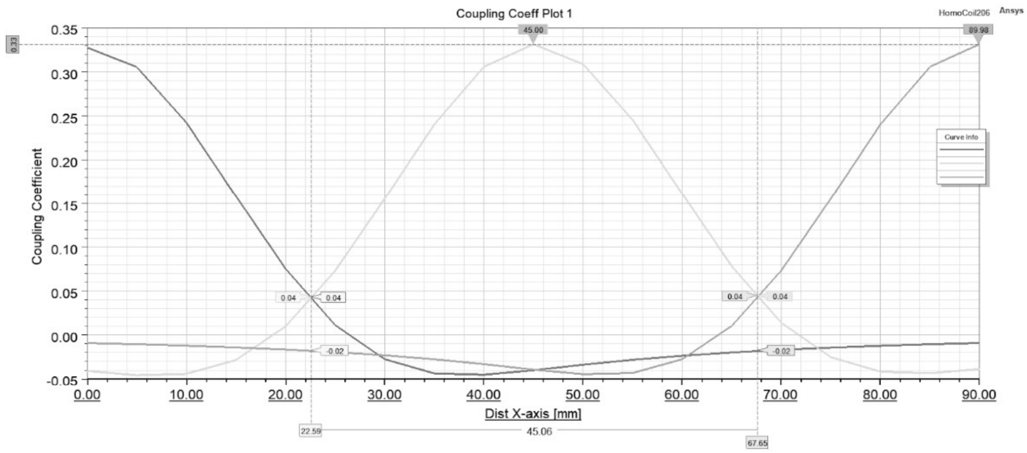


Figure 4.19 Coupling Coefficient

Induction values obtained have varied based on the distance with which the transmitter coil is occurring. The power transfer process has 2.22 uH, perfectly matched with 0 misalignments, which recorded various values based on its percentage from 0.5 to 2.2 uH. However, the self-inductance recorded was 6.68 uH for the transmitter coils and 6.9 uH for the receiver coil. The results obtained after gaining the parameters from the simulation carried out on Ansys are in Figures 4.13 to 4.17.

The switching on the primary side has produced an Ac voltage of approx. 26v, and the secondary side was able to receive approx. 24v. This is because the Ac values are in the form of a sine wave, so the value varies in a very small change. In this condition, the coupling coefficient had a value of 0.3.

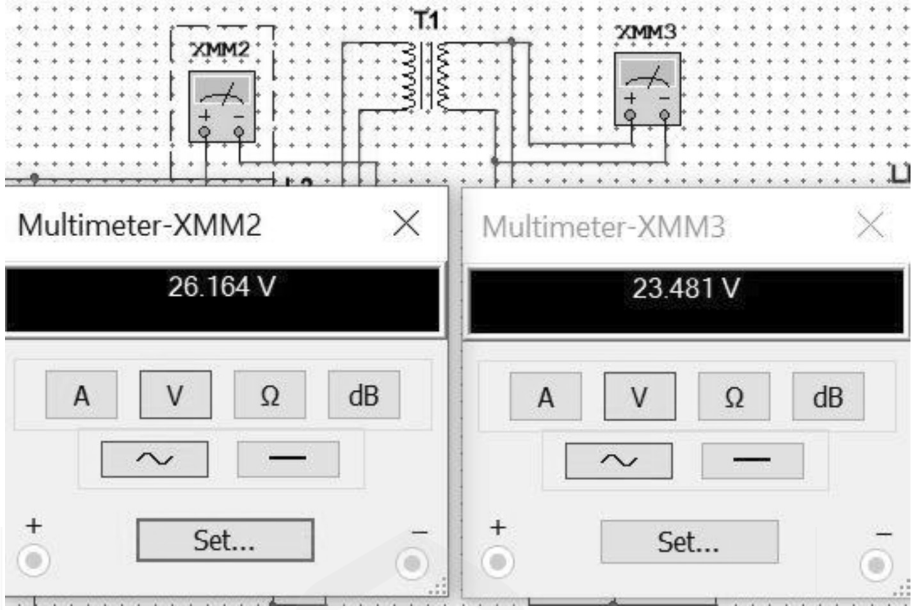


Figure 4.19 Ac Voltage in the Transmitter Side and the Receiver Side

The following table shows the values of the received voltage with respect to the distance and coupling coefficient.

Table 4.10 Received voltage with respect to the distance and coupling coefficient.

Coupling coefficient / L	T: 6.68uH	R: 6.9uH
0.3 primary coil 1	26v	23v
0.24 primary coil 1	26v	22v
0.15 primary coil 1	26v	19v
0.07 primary coil 1 & 0.01 primary coil 2	26v	14v
0.01 primary coil 1 & 0.07 primary coil 2	26v	14v
Negative primary coil 1 & 0.15 primary coil 2	26v	19v

The following figure shows the field of the simulated coils. The number of transmitters was reduced for this testing as it takes much time to be simulated.

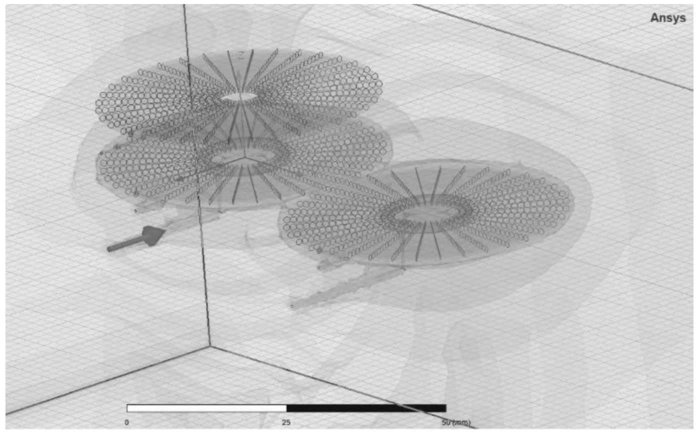


Figure 4.20 The magnetic field

The mutual inductance values are as follows in the table below.

Table 4.11 Mutual Inductance

Distance in the X-axis (mm)	Mutual inductance (uH)
0	2.22 Primary coil 1
5	2.07 Primary coil 1
10	1.64 Primary coil 1
15	1.07 Primary coil 1
20	0.51 Primary coil 1 & 0.07 Primary coil 2
25	0.08 Primary coil 1 & 0.5 Primary coil 2
30	-0.1 Primary coil 1 & 1.06 Primary coil 2
45	2.22 Primary coil 2
90	2.22 Primary coil 3

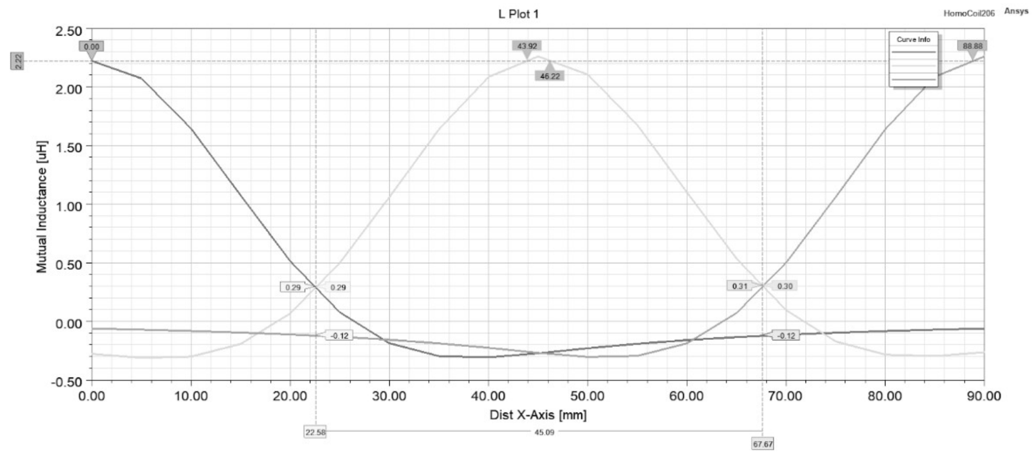


Figure 4.21 Mutual Inductance Graph

The following results are for the Inductance values obtained in testing for the homogenous coil with respect to the distance along the X-axis and the Y-axis' fixed values.

Table 4.12 Self-Inductance Tx Coils

Distance	Self-inductance Tx coils (uH)
0	6.648992522
5	6.648995608
10	6.649422879
15	6.649358028
20	6.649226916
25	6.649561609
30	6.648989952
35	6.648867963
40	6.649051348
45	6.648677466
50	6.649046427
55	6.64878576
60	6.649214882
65	6.649147052
70	6.649195714
75	6.648923394
80	6.649408136
85	6.648873999
90	6.649501976

Table 4.13 Mutual Inductance

Distance	Rx and Tx_1 (uH)
0	2.22185397
5	2.072788607
10	1.646988248
15	1.077705938
20	0.51662636
25	0.080933484

30	-0.182542068
35	-0.292347963
40	-0.302492939
45	-0.268156808
50	-0.225202798
55	-0.18707582
60	-0.155870679
65	-0.130593308
70	-0.10995944
75	-0.092958131
80	-0.078829626
85	-0.067000511
90	-0.057040219

Table 4.14 Mutual Inductance

Distance	Rx and Tx_2 (uH)
0	-0.273420214
5	-0.306778574
10	-0.29668364
15	-0.188934757
20	0.0708558
25	0.501566706
30	1.061609691
35	1.639614622
40	2.085182267
45	2.25972698
50	2.105149944
55	1.674768776
60	1.101018822
65	0.536798998
70	0.098207579

75	-0.167853878
80	-0.279844933
85	-0.291838333
90	-0.259115197

Table 4.15 Mutual Inductance

Distance	Rx and Tx_3 (uH)
0	-0.057560043
5	-0.06690415
10	-0.078140817
15	-0.091672735
20	-0.10810093
25	-0128156025
30	-0.152901252
35	-0.183661334
40	-0.22138611
45	-0.264392305
50	-0.299013161
55	-0.290278037
60	-0.183309519
65	0.075479345
70	0.505524085
75	1.064849966
80	1.642271623
85	2.087365004
90	2.26092919

Table 4.16 Self-Inductance Rx Coil

Distance	Self-inductance Rx coil (uH)
0	6.918974533
5	6.925523587
10	6.93610304
15	6.947153141
20	6.94627244
25	6.947456995
30	6.951130314
35	6.950858987
40	6.955011238
45	6.953529373
50	6.952932831
55	6.956501861
60	6.957020907
65	6.955205501
70	6.955740232
75	6.957258955
80	6.95563089
85	6.959538975
90	6.954162154

4.3 BENCHMARKING

In Li et al. (2019), the research was conducted on a wider range which first covered the symmetrical system to test the effect of the radius change for both coils, with the primary and the secondary together. The main purpose of benchmarking is the efficiency of the power that has been received. The figure below shows the system's effectiveness, which recorded a high efficiency of 90%. Whereas in this project, the efficiency was recorded and was found to be 95%, as shown in Figure 4.9.

The design in the study by Li et al. (2019) used series-series topology. This project was done using parallel-parallel topology.

- **Influence of the Transmission coil**

Li et al. (2019) found the effective distance in this project to increase when the transmission coil radius increases, so the distance will be smaller between the two coils if the difference in the radius is great. However, the efficiency of the design proposed by Li et al. (2019) was good in this project. The efficiency was higher due to the change in the resistance value to try to enhance the effectiveness of the proposed design.

The efficiency recorded by Li et al. (2019) and in this project is as follows:

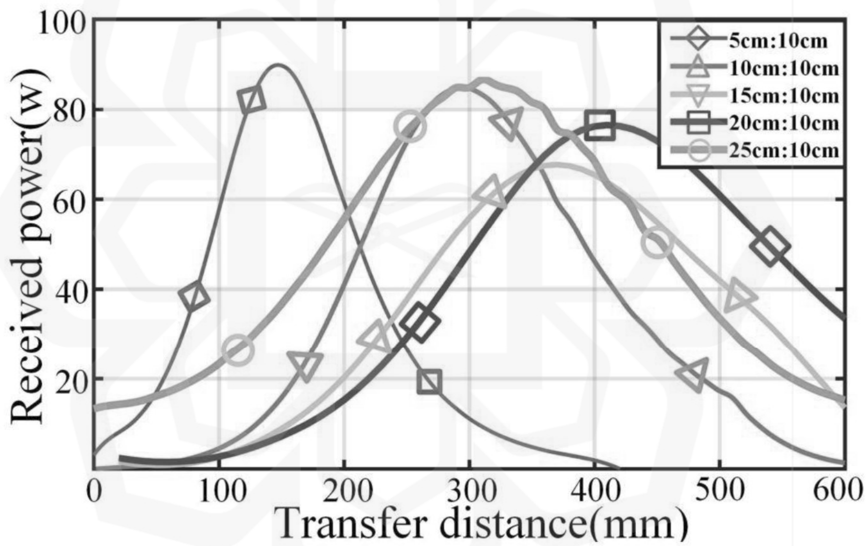


Figure 4.22 Received power vs Transfer distance Li et al. (2019)

Figure 4.22 shows the results from Li et al. (2019). The testing was conducted by fixing the Tx coil radius to 10 cm and varying the Rx coil. The results show that the cases with the higher power received are with the Tx coil having a bigger radius than the Rx coil radius. However, the efficiency was around 90% at its best. In this project, the highest obtained efficiency was around 95%, an enhancement of about 5%. The result is shown in Figure 4.9.

- **Influence of the Receiver Coil**

The results in this project were not different from those obtained by Li et al. (2019), which confirms that having a bigger inner radius for the receiver side coil will not be beneficial and will cause a leakage in the magnetic field.

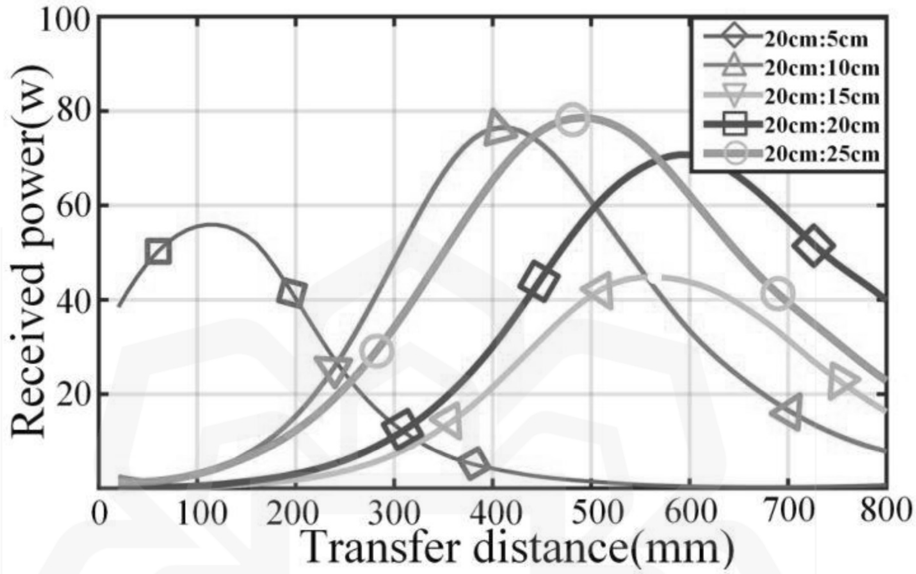


Figure 4.23 Received power vs Transfer distance Li et al. (2019)

In Figure 4.23, the power received is plotted against the effective distance. The highest power was observed when the coils had the same radius. The increased distance is attributed to the coupling process and the matching distance relative to the coil radius. The magnetic field leakage was less than when the distance was too close. The coupling was not obtained due to the high leakage. The highest efficiency recorded was the Tx radius; the Rx radius is the same, around 79%. In this project, the findings matched, but the design recorded an efficiency of around 88%, as shown in Figure 4.13.

4.4 RESEARCH CONTRIBUTIONS

In this project, the main concern and focus were placed on producing a system that can wirelessly transfer power in the best possible way by configuring the design in terms of the coil design, specifically with the inner radius of the coil, which in turn affected the values obtained for the mutual inductance and the coupling coefficient. From this project, the main concluded segment was that the best power transfer would be obtained whenever the system has been designed to have the primary coil with an inner radius larger than the secondary coil's inner radius.

CHAPTER FIVE

CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

In this project, a homogenous coil design was proposed. It was found that the radius of the transmitter coil can have a greater impact on the efficiency of the process. It happens when the radius of the transmitter is bigger than the radius of the receiver coil and is supported by the obtained results of 95% transmission efficiency, which is a 5% enhancement. In addition, the change in radius was also found to have an effect that might take this topic to other paths to help fulfill other objectives. When the receiver coil's radius had a bigger and equal radius to the transmission coil, the further the coils were separated. The better the connection and the efficiency means, the more effective distance is directly related to the radius of the coils in some cases.

Furthermore, dynamic wireless charging was obtained and approved as an effective design for this project. It was done with different distances to trace all applicable changes. However, there is still room for more improvements.

5.2 FUTURE RECOMMENDATIONS

The work done throughout this project was only focused on one way of testing: using coils of copper material and with a varying design to observe the factors causing a bad or good power transfer. Still, the work doesn't stop at this point. There are many more materials to be tested and many conditions to be considered to obtain real and close to the none ideal results. This project has obtained the ideal results only and has not added any noise effect.

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