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.

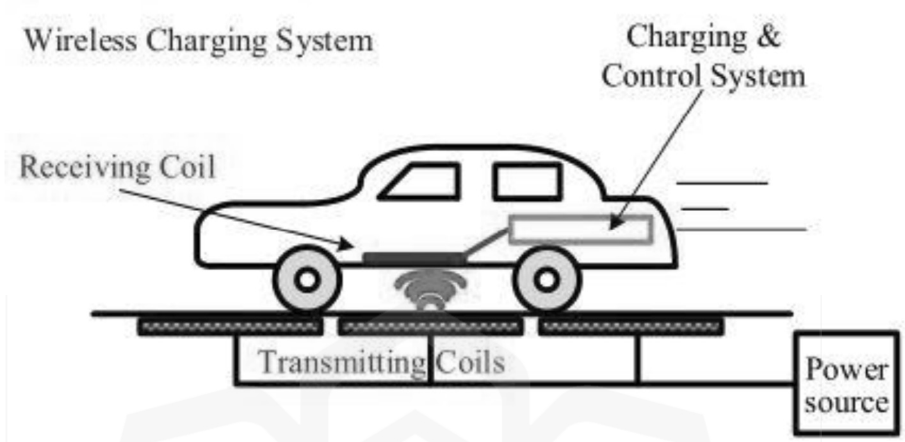

Figure 2.2 Components of the WPT (Popovic, 2017)

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).

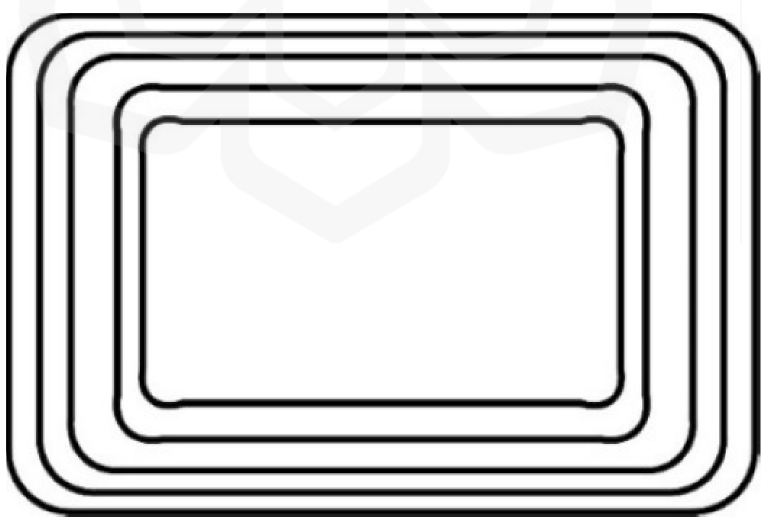

Figure 2.3 The Circular Rectangular Pad (Popovic, 2017)

- **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).

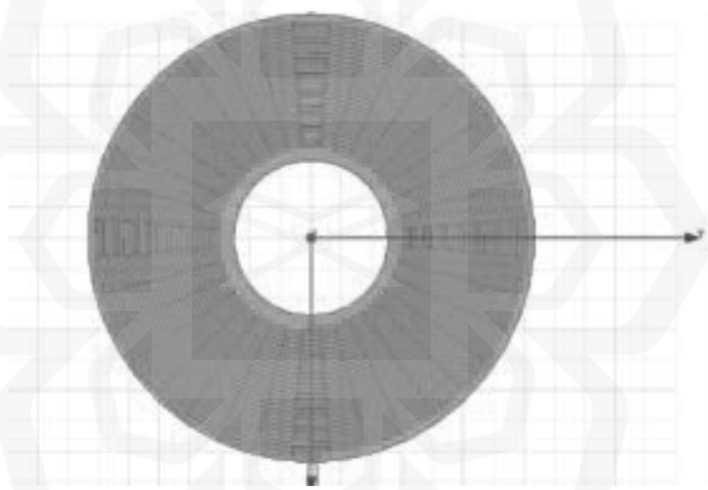

Figure 2.4 The Circular Pad CP (Brown, 1996)

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

$$\Delta\ P_z \alpha_4^1\ P_d \tag{2.1}$$

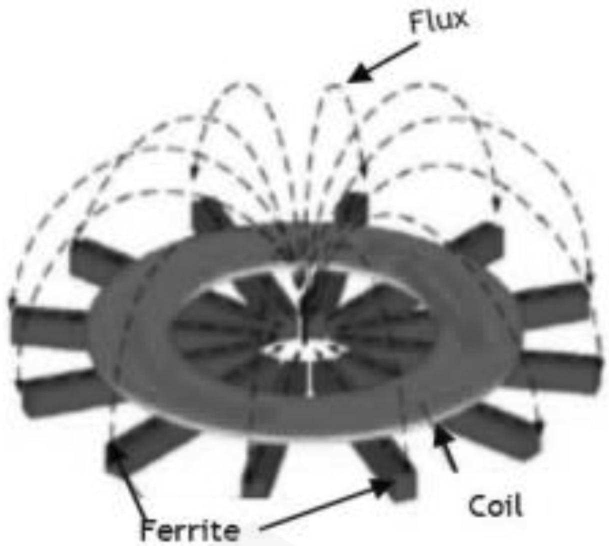

Figure 2.5 Symmetric Double-Sided Flux (Liu et al., 2017)

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.

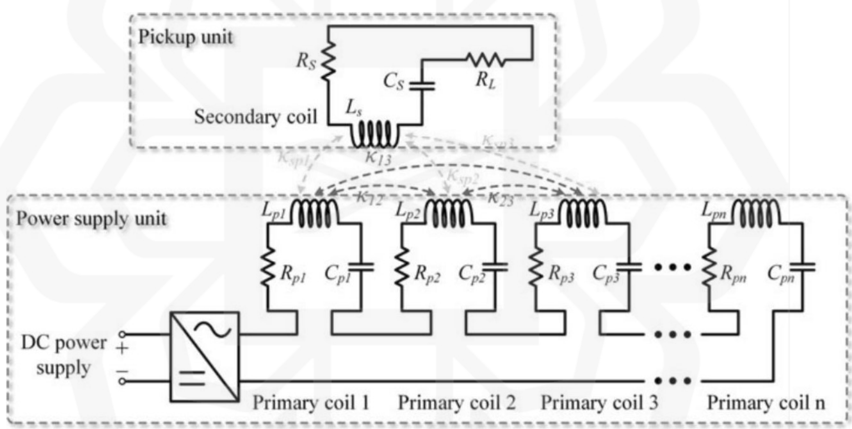

Figure 2.6 Basic Circuit for Dynamic Charging Circuit (Zhang et al., 2015)

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.

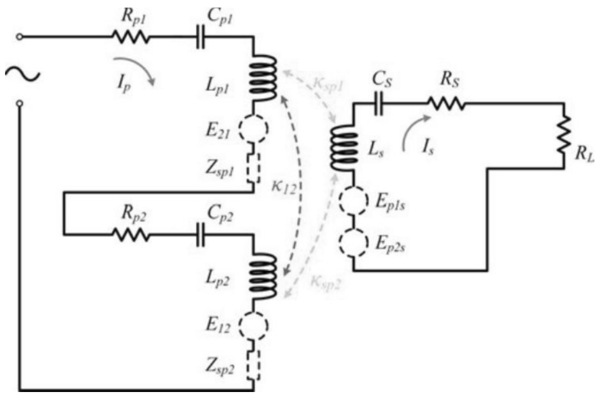

Figure 2.7 The Equivalent Circuit Modal (Zhang et al., 2015)

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).

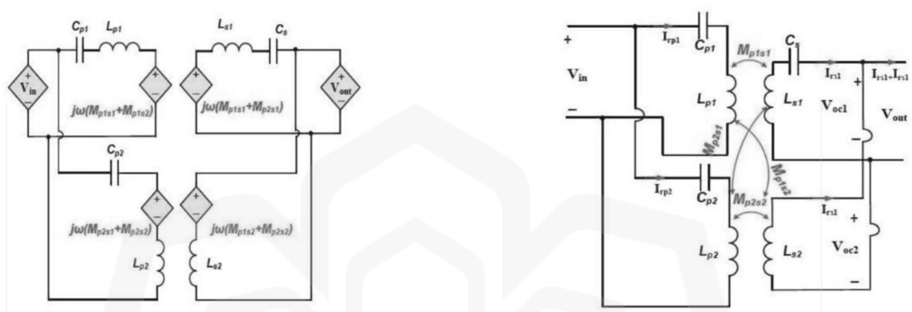

Figure 2.8 (a) Simplified IPT Circuit for Double Couplers Configuration, (b) IPT Systems Consists of Two Primary Couplers and Two Secondary Couplers (Zhang & Chau, 2015)

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

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

- **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