New Receiver Coil for Enhanced Misalignment Tolerance in Wireless Charging of Hybrid/Electric Vehicles

Nikola Stojakovic
University of Windsor

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New Receiver Coil for Enhanced Misalignment Tolerance in Wireless Charging of Hybrid/Electric Vehicles

By

Nikola Stojakovic

A Thesis
Submitted to the Faculty of Graduate Studies through the Department of Electrical and Computer Engineering in Partial Fulfillment of the Requirements for the Degree of Master of Applied Science at the University of Windsor

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New Receiver Coil for Enhanced Misalignment Tolerance in Wireless Charging of Hybrid/Electric Vehicles

By

Nikola Stojakovic

APPROVED BY:

______________________________________________
Dr. A. Sobiesiak, External Reader,
Department of Mechanical, Automotive & Materials Engineering

______________________________________________
Dr. R. Rashidzadeh, Internal Reader
Department of Electrical & Computer Engineering

______________________________________________
Dr. M. Sid-Ahmed, Co-Advisor
Department of Electrical & Computer Engineering

______________________________________________
Dr. N. Kar, Co-Advisor
Department of Electrical & Computer Engineering

May 26, 2016
Declaration of Originality

I hereby certify that I am the sole author of this thesis and that no part of this thesis has been published or submitted for publication.

I certify that, to the best of my knowledge, my thesis does not infringe upon anyone’s copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owner(s) to include such material(s) in my thesis and have included copies of such copyright clearances to my appendix.

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Abstract

With the emergence and development of hybrid and electric vehicles in recent years, the technology known as wireless charging has caught the attention of many Original Equipment Manufacturers (OEM). Convenience, safety and cost reduction are just some of the many benefits of this emerging technology. However, one of the current challenges associated with the development and implementation of wireless charging is the misalignment tolerance between the emitter and receiver coil. Values of magnetic coupling between these two can help improve the efficiency of the entire system, but the rate of variation of the same when coils get misaligned determines the available charging zone. If the coupling variation is large, the charging zone gets smaller.

In order to address and resolve the above mentioned challenges this thesis will propose two new receiver coil structures that can reduce the coupling variation in XY and XYZ direction respectively and expand the charging area by more than two times. Both solutions were designed and compared against the traditional circular planar coil of the same area using MAXWELL simulator in order to address all of its advantages and disadvantages. An experimental model for the misalignment extension in the XYZ direction was built and tested in order to verify the new concept. Experimental results are in good agreement with the conceptual theory used in this work.
Dedication

To my loving family
Acknowledgements

I would like to express my sincerest gratitude to my supervisors, Dr. Maher Sid-Ahmed and Dr. Narayan Kar for giving me the opportunity to explore this beautiful technology and for their guidance and support throughout this journey. I would like to thank my committee members, Dr. Rashid Rashidzadeh and Dr. Andrzej Sobiesiak for taking the time out of their busy schedule to be part of my committee and for their valuable suggestions. I am very grateful to my friend Bryan Esteban for all of his help that he provided me with throughout this work and for sharing his knowledge of wireless power transfer with me.

Most importantly I would like to thank from the bottom of my heart my parents Damir and Marijana, my brother Ognjen and especially my beloved wife and daughter Jessie and Sofia for all of your endless love, support, and sacrifice and for being a true inspiration in my life.
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Chapter 1

1. Introduction

1.1 Overview

Wireless inductive power transfer or wireless charging is a technology that allows transfer of electromagnetic energy over an air gap, from the power source to the electric load using a time-varying magnetic field [1] [2] [3].

In today's world humans have become increasingly dependent on the use of technology. All around us there are electrically powered devices that are used for a variety of purposes. It is almost impossible to imagine a household without a television or a computer, a life without a smartphone or iPad and many other devices that serve different purposes in our daily lives. One thing in common for all of these devices is that they are all powered by electrical energy. Most of these products use batteries for energy storage while others need to be plugged into the power grid. Often this creates a jumble of wires behind the unit such as a television, DVD player, computer etc. Battery driven devices can run out of battery power at an inconvenient time. In today’s world, where majority of the jobs demand our availability at all times and where most of the business is being done with the use of electronic devices, running out of battery-power is not an option. For these reasons, and many others it is easy to see why the technology known as Wireless Power Transfer will become prevalent. Two industries where application of this technology will make a significant impact are Consumer Electronics and Electric Vehicles.
1.2 Electronic Devices

One of the earliest fields of application of wireless electricity and a field where most of the Wireless Power Transfer research is focused is consumer electronics.

With this new technology, the cost of production of electronic devices would drop because the batteries would be smaller and less expensive, while consumer’s interest would rise due to the ability and ease of charging products on the go. Research done by [4] indicates that "Wireless Power Transfer technology not only helps reduce the cost of the devices but also significantly enable the portability and flexibility properties"(p.327). With wireless electricity, recharging our batteries and using cables will be as obsolete as using a candle instead of light bulb.

1.3 Electric Vehicles

When it comes to Electric Vehicles (EV), one of the main drawbacks today is the limited range they can travel before the battery pack needs to be recharged. In the case of TESLA motors super charger [5][6]this can require up to 30 minutes to charge the batteries by 80% capacity, or up to four hours for Chevy VOLT [7]. Furthermore, the majority of the weight in EV’s comes from the huge battery packs. This weight essentially increases the load, which in return reduces the range of the vehicle. However, with a wireless charging system in place, inductive pads can be placed into the roads where EV’s can be charged dynamically (while driving) which could virtually make the range of these vehicles unlimited. A potential benefit that is driving the development of this technology is the reduction of harmful CO₂ emission coming from Internal Combustion Engine (ICE) vehicles. Electric vehicles in combination with other renewable power sources have the potential to drastically reduce the amount of Carbon Dioxide emissions. For this to happen, consumers need to feel comfortable with switching to Electric Vehicles, and that is possible with the implementation of wireless power transfer systems. According to [8] "It is expected that wireless charging will vastly improve the charging experience for EV owners, making such vehicles more attractive to consumers"(p.4).
1.4 Market potential

Inductive Power Transfer (IPT) is emerging as a technology that is gaining global interest. Convenience and added safety aspect of delivering power wirelessly has gained the attention of many researchers and industry in the last 20 years. Broad spectra of applications that are ranging from consumer electronics to medical implants and electric vehicles attracted industries attention, but even more so the attention of potential consumers. Numerous studies are suggesting an exponential market growth for wireless charging. According to [9] the market revenue for wireless charging that was $216 million in 2013 is projected to rise to as much $8.5 billion by 2018, and this is only estimated for consumer electronics. If EV’s are included in that projection, that estimate will grow dramatically to reflect the growing interest in EV’s and public transportation (busses, light rail, etc.)

1.5 History

The concept of wireless transmission of energy has been proposed more than a hundred years ago [10] by Nikola Tesla. During his time at Colorado spring 1891-1899 [11], Mr. Tesla performed numerous experiments in the attempt to transfer large amounts of energy over large distances. Although his approach and methods were somewhat different, the principles of resonance that he based his technology on represent the cornerstone of today’s Wireless Power Transfer.

For a long time after Nikola Tesla concluded his research on WPT, no one had attempted to recreate and further investigate this technology. Finally in the late 70’s the research team from UC Berkley attempted to transfer large amounts of power over 7.6 cm air gap in order to charge bus battery. The system had poor efficiency and high expenses [12]. It has to be pointed out that main reason for the poor system performance was that the semiconductor technology available at that time that could not provide the power and high frequency needed for near field power transmission.

In the last 20 years this technology once again sparked the interest of researches around the world. At the University of Hong Kong, Dr. Ron Hui and his team performed
research on planar low power inductive battery chargers based on a low power printed circuit board technology [13] [14].

Almost at the same time, in Auckland New Zealand, Dr. Covic and Dr. Boys started looking into high power WPT applications for mostly static charging. They have published numerous patents and journal papers, in order to describe and to highlight multiple aspects of this technology, ranging anywhere from power electronics to various circuit topologies and coil designs and optimizations [15] [16] [17] [18] [19].

Another significant breakthrough in the development of this technology was made at the Korea Advanced Institute of Science and Technology (KAIST), where focused was placed on the on-road or in motion charging of Electric Vehicles. During the course of their project called On-Line Electric Vehicle (OLEV), research team from KAIST have managed to transfer 60 kW of power to the busses, and 20 kW to the SUV’s with efficiencies of 70% and 83% respectively. What is most interesting conclusion that came out of this project is that the price of infrastructure necessary for implementation of on-road charging technology was less than $400,000 per kilometer [20] [21].

Although multiple researching teams, have invested significant time and effort into investigating WPT, it wasn’t that until 2007 when the public attention was drawn toward this technology. A team of researchers from Massachusetts Institute of Technology (MIT) led by Dr. Marin Soljacic, investigated near field power transfer at distances higher than the coil radius [22]. They successfully demonstrated a 60 W power transmission over 2 m distance with coils radius of 25 cm and proved that the power transfer distance can be boosted by using highly resonant system [23].

1.5.1 Dynamic Vehicle Charging

The idea behind dynamic charging is, as the name suggests, the charging of electric vehicles while in motion. Ideally, there would be a charging lane on a highway that would serve as a charging station. There are several proposed system that could satisfy the charging requirements, where receiver coil would be mounted at the bottom of the vehicle. In this case the transmitter would be imbedded in the road in the form of either, charging track or a series of circular coils.
Dynamic charging is still some years away from practical and industrial implementation. This is largely due to the overall system complexity as well as necessary infrastructure needed for its practical implementation. Although dynamic charging is significantly more complex than static charging, some serious contributions to the development of this technology have been made in recent years. Through the OLEV project, KAIST University have made some serious contributions in the field of dynamic charging. From the time that project OLEV was launched in 2009 until 2013, KAIST has developed dynamic wireless chargers ranging from 3 kW for consumer vehicles to as much as 180 kW for trains and busses, operating with an average efficiency of 75%. This essentially helped reducing battery pack to one fifth of its original size [20] [24] [25].

1.5.2 Static Vehicle Charging

Wireless charging type that is of particular interest for this thesis and that is most likely to hit the automotive market soon, is static charging. As is the case with dynamic charging, the receiver coil is to be mounted at the bottom of the vehicle, while transmitter coil is to be embedded either on the ground or in the ground. Ideally there would be parking spots for EV’s that would serve as charging stations, where each spot would have these coils embedded in the ground. In addition, this type of charging is of particular interest for city bus transportation, since the transmitting coils could be placed on every bus station where vehicle could be recharged more often. This idea has already been tested and implemented successfully in Turin, Italy [26].

Although static wireless charging is not yet as efficient as the plug-in approach, this form of charging possess certain characteristics that are more favorable with respect to the plug-in technique, mainly in the terms of convenience and safety.

In terms of convenience, wireless charging requires from the driver only to park at his parking spot. From that point on the communication between vehicle and charging station (embedded coil) takes care of the battery charging requirements, so the action required from a driver is virtually eliminated in terms of worrying about plugging and unplugging the charger.
In terms of safety, the elimination of the cables and fact that coils are embedded in the ground significantly decreases the potential threat of vandalizing the system. Furthermore, the risk of cable deterioration and electric sparks is completely removed.

### 1.6 Current problems and motivation for this thesis

As explained in the previous section, the stationary wireless charging will likely see the market in the next year or so. Some of the current main drawbacks for implementation of this technology are industrial standardization and increased challenge in misalignment tolerance [16] [27] [28].

In 2010, Society of Automotive Engineers (SAE) formed a task force known as J2954 in order to establish an industry standards guideline that will help in defining acceptable radiation levels, interoperability, minimum performance, safety and testing for wireless charging of electric vehicles. To date many of the issues have been resolved and many of the terms have been established, however one of the main issues that are still holding this technology back is interoperability. Under that category falls the design of emitter and receiver coils. There are multiple proposed coil designs that will be further explained in chapter III, but the one that most likely will be accepted is going to be the circular planar coil because of its low leakage flux in comparison to the other proposed structures (more on this in chapter III).

When it comes to misalignment tolerance, it was proven numerous times [15] [29] [30] [31] [32], that efficiency of the overall system drops as the vehicle offsets from the center axis of the emitter coil. This can pose a problem in the practical world, since it would require additional guiding systems to be installed in order to properly align the vehicle during parking, or it would require a driver to re-park multiple times until the vehicle is in the charging zone. Both of these problems may defeat the purpose of wireless charging since its main argument for implementation (convenience) would no longer be an advantage.

With the aforementioned issues in mind the motivation of this thesis is to explore the alternative design of charging pads in order to enhance misalignment tolerance.
Namely, this thesis will present a novel secondary receiver pad design optimized through ANSYS MAXWELL software and finally tested experimentally.

The following chapters are laid out as follows: **Chapter 2** will describe the fundamental principles of operation of Wireless (Inductive) Power transfer (better known as IPT), modern day IPT system layout with complete mathematical derivation of power equation and importance of resonance and mutual inductance; **Chapter 3** will describe the three most popular coil designs researched to date along with all of theirs advantages and disadvantages; **Chapter 4** will propose a novel secondary 3 coil array for the enhanced misalignment tolerance in XY direction, accompanied with the guiding principles and optimization done in MAXWELL; **Chapter 5** will present a novel secondary 5 coil array that will control the variation in coupling in XY and Z direction, along with experimental procedure and proof of the concept; **Chapter 6** will conclude the work done on this thesis and make future recommendations.
Abstract

In this chapter fundamental laws and principles of IPT will be explained in order to better understand today’s wireless charging technology. An IPT system diagram will be presented and explained along with the mathematical modeling of the same. Finally, the importance of coupling and mutual inductance for the IPT performance will be described in details.

2.1 Introduction

Development and a design of inductive power transfer technology are based on two basic principles: electromagnetic induction and resonance. Electromagnetic induction has been discovered roughly some two hundred years ago and is based on two fundamental laws of electromagnetics, namely Ampere’s law and Faraday’s law. Resonant induction was pioneered by Nikola Tesla at the end of the nineteenth century for application of wireless power transfer at a relatively larger distance.
2.2 Ampere’s and Faraday’s Law

Amperes law was derived out of Biot-Savart law and it represents its simplified version. Namely it is derived in order to evaluate magnetic field distribution around highly symmetric current configurations, whereas with Biot-Savart law these evaluations would be more complex. Ampere’s law states that a current flowing through a wire will generate a magnetic field around that wire as shown in Fig. 2-1. Mathematically Ampere’s law is described by the following equation:

\[ \oint_C \mathbf{B} \cdot d\mathbf{l} = \mu I_0 \]  

(2.1)

What equation (2.1) basically states is that the strength of magnetic flux density field, \( \mathbf{B} \), is directly proportional to the strength of the current, \( I_0 \), and/or permeability, \( \mu \), of the space in which the field propagation is occurring. On the other hand the strength of the magnetic flux density field is inversely proportional to the distance of the field point from the current conductor. In other words, the further away you move from the current conductor, the magnetic field will weaken. Furthermore, it is important to state that this field, described by ampere’s law, stores potential energy and it changes at the same rate as the current that generates it.
In inductive power transfer this law is used on a primary side where high frequency time varying magnetic field is generated by pushing high frequency current through the primary coil or emitter.

Seven years after Biot-Savart and Amperes law was described, that states that a steady current produces magnetism, Michael Faraday went on to experiment and to see whether magnetic field can produce current flow. What he found was that static magnetic field produces no current flow but the time varying magnetic field produces an induced voltages or electromotive force (emf). Therefore, Faraday's law states the following: “the induced emf in any closed circuit is equal to the time rate of change of the magnetic flux linkage by the circuit.”

\[ V_{emf} = -N \frac{d\psi}{dt} \]  \hspace{1cm} (2.2)

Where N is the number of turns in the coil or circuit, and \( \Psi \) represents the flux through each of the turn. Negative sign means that induced voltage acts in such a way so as to oppose the flux that produces it.

The following expression links Faraday’s law to Ampere’s law:

\[ V_{emf} = -\frac{d}{dt} \int_S \mathbf{B} \cdot d\mathbf{S} \]  \hspace{1cm} (2.3)

Electromotive force can be induced in three different ways. One way to induce emf would be if you have a time varying magnetic field. The other way would be if you have time varying loop area, and the third way would be if both magnetic field and loop area are time varying. Since for the application of static wireless charging, loop area, or receiving coil, is stationary and the magnetic field is time varying the equation (one above) will become

\[ V_{emf} = -\int_S \frac{\partial \mathbf{B}}{\partial t} \cdot d\mathbf{S} \]  \hspace{1cm} (2.4)
To further expand upon this expression, if on the secondary side there is a load, in this case in the form of resistor $R$, then a power can be deliver to the secondary side by,

$$P = \frac{V_{emf}^2}{R}$$ (2.5)

When speaking of Inductive Power Transfer, we can conclude from equations (2.4 & 2.5) that the power delivered to the secondary side depends heavily on the strength of the magnetic field and its rate of change.

### 2.2.1 Nikola Tesla Concept

During his time in Colorado Springs, Nikola Tesla noticed that if two separate systems operate at the same resonant frequency an exchange of energy between them will occur. In his patent [33], Tesla describes wireless transmission of energy between two resonant coils placed at a distance apart.

This system acts as an open capacitor where transmission of electrical energy is done via resonant electric field established between two capacitive spheres $D$ and $D'$. Transmitter $D$ in connected thorough wire $B$ with coil $A$, and receiver $D'$ connected through wire $B'$ to coil $A'$, figure 2-2, are both scaled so as to have identical natural resonance. For the better understanding of today’s wireless charging technology, it is important to describe operational principles on the transmitter side of patent # US649621A, or what is known today simply as *Tesla’s Coil*. 
In order to deliver extremely high voltages at a very high frequency without significant losses to the transmitting sphere Tesla used what is known today as a resonant air core transformer, which in figure 2-2 is constituted out of coil C and coil A. On the driving side figure 2-3, he used a spark gap G that would act as a high frequency pulse switch, sending square wave pulses through an $L_1C_1$ filter. In addition, spark gap is adjusted in such way as to make and break circuit or send pulses at the same frequency as the $L_1C_1$ filters natural frequency was, so as to filter first harmonic wave out of the injected pulse. Furthermore, the inductor $L_2$ and a capacitive globe $C_2$ are tuned at the
same frequency as $L_1C_1$. Due to the low coupling between coil $L_1$ and coil $L_2$ (no core), it was important to match resonant frequencies of all subsystems in order to deliver high voltages at very high frequencies to the transmitting globe, with minimal losses.

![Circuit Diagram](image)

**Fig. 2-3. Primary Side of Tesla Patent #US649621A**

Studying the primary side of Tesla’s entire system, figure 2-3, explains how Amperes and Faraday’s law in combination with principles of electrical resonance, are representing fundamental principles of operation for today’s WPT.

This first side or transmitter side of Tesla’s patent #US649621A is what constitutes a base for today’s inductive power transfer. In today’s WPT systems we use inverters with electronic switches instead of spark gaps and the energy transfer is scaled down to smaller distances.

### 2.3 Modern Day IPT System

In the design of every IPT system it is important to start with basic parameter such as: desired power transfer, primary and secondary current and voltage limitations etc. In order to be able to appropriately determine these values and to scale the system accordingly, one has to start with the power equation. In this section the full derivation of the power equation will be shown along with full system diagram so as to better
WIRELESS (INDUCTIVE) EV CHARGING SYSTEM

Fig. 2-4. Circuit diagram of Modern day IPT system [34]
understand the overall system performance and most importantly, the importance of the initial coil design.

The overall system can be broken down into the following subsystem, figure 2-4: utility input, AC-DC, DC-AC, Resonant/matching network, primary transmitter coil, secondary pick up coil, resonant/matching network, load and wireless feedback system to adjust the primary current according to the load on the secondary side.

1) The utility input can be either one phase or three phase
2) AC-DC stage serves not only to convert the input voltage into DC but to carry out power factor correction PFC. In addition, in this stage a DC-DC converter is usually installed to serve as control mechanism that would regulate the overall power requirements of the system
3) DC-AC stage serves to transform DC voltage into high frequency AC, usually around 85 kHz for the EV application that will in turn generate a high frequency oscillating magnetic field in the primary coil, necessary for the power transfer.
4) Resonant capacitor is placed either in a series or in a parallel topology. The addition of a capacitor has a purpose to filter out harmonics and to keep the fundamental frequency from a square wave AC output of the inverter, and to ensure that the system is operating at the desired resonant frequency.
5) Primary transmitter coil in combination with a capacitor constitutes a resonant network on the primary side. On top of that and what is most important, this coil emits the high frequency oscillating magnetic field and is loosely coupled with the secondary receiving coil.
6) Secondary receiving coil, due to the high frequency oscillating magnetic field in its proximity, induces voltages.
7) Matching capacitor on the secondary side serves the same purpose as the one on the primary side, and due to the fact that both sides are tuned to the same resonant frequency the power transferred to the secondary side is boosted by a factor Q, which will be further explained in section 2.3.2
8) Wireless communication system is necessary in IPT in order to close the loop. The emitter side of the system needs to know the position of the receiver and the load in order to accordingly adjust the supply current in the primary coil.

2.3.1 Mathematical modeling of IPT system

When looking at figure 2-5 in order to express $V_{oc}$ induced across the $L_2$, in terms of mutual inductance $M$ and primary current $I_1$ the following expression holds true:

$$V_{oc} = j \omega MI_1$$

(2.6)

Since both $V_{oc}$ and $I_1$ can be measured experimentally with an oscilloscope and $\omega$ is predetermined, then by rearranging equation (2.6) we can calculate $M$ using:

$$M = \frac{V_{oc}}{\omega I_1}$$

(2.7)

The coupling coefficient, $k$, which defines the strength of coupling between the two coils, can be calculated using the following expression:

$$k = \frac{M}{\sqrt{L_1L_2}}$$

(2.8)

If k=1 the two coils are perfectly coupled. The coupling coefficient is limited between 0 (no coupling) and 1. If k>0.5 the two coils are said to be tightly coupled and if k<0.5 the two coils are said to be loosely coupled.
Relating back to the figure 2-5, in order to express the $I_{sc}$ in the terms $M$ and $I_1$, which, once again, could be easily obtained with oscilloscope and the use of the above equations, we can find $I_{sc}$ to be:

$$I_{sc} = \frac{V_{oc}}{j\omega L_2} = \frac{MI_1}{L_2}$$

(2.9)

By multiplying these two products that were previously derived, $V_{oc}$ and $I_{sc}$, we get the uncompensated VA of the pickup:

$$S_u = \omega I_1^2 \frac{M^2}{L_2}$$

(2.10)

It is important to say that without compensation the maximum power that can be extracted from the pickup is equal to $S_u/2$ [35], which in most cases, and especially for high power application, is not enough. In order to boost available power the capacitor is added in either series or parallel with the coil $L_2$ in such way as to resonate at the same or near the resonant frequency of primary side. This addition of capacitor and tuning of the secondary $L_2C_2$ network, allows the overall power output to be boosted by a factor $Q$ resulting in:

$$P = S_uQ = \omega I_1^2 \frac{M^2}{L_2}Q$$

(2.11)

If the compensating capacitor $C_2$ is added in series then the output current will be boosted by $Q$, whilst if $C_2$ is added in parallel then the output voltage will be increased by the circuits resonant $Q$ as presented in table 2-1.

**Table 2-1 Circuit quality factor**

<table>
<thead>
<tr>
<th></th>
<th>Series compensation</th>
<th>Parallel compensation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quality factor $Q$</td>
<td>$Q_s = \frac{\omega L}{R}$</td>
<td>$Q_p = \frac{R}{\omega L}$</td>
</tr>
</tbody>
</table>
2.3.2 Derivation of Power Equation

In order to mathematically explain the importance of resonance, the following derivation of the power equation will be explained on the example of parallel secondary topology as outlined in [34] [36].

Using simple circuit analysis tools we can see, figure 2-6, that when the secondary side is reflected back onto primary it is represented in the form of reflected impedance \( Z_r \) and is given by:

\[
Z_r = R_r(M, R_{eq}) - j \frac{1}{\omega C_r(M, R_{eq})}
\]  
(2.12)

From the equation (2.12) we can see that \( Z_r \) is constituted out of two parts, real and imaginary. The real part is a function of a variable mutual inductance, \( M \), that changes with misalignment of the coils, and equivalent resistance \( R_{eq} \), equation (2.13), that changes depending on the battery voltage and current requirements during charging process.

\[
R_{eq} = \frac{\pi^2 R_L}{8}
\]  
(2.12)

On the other hand the imaginary part is purely capacitive in nature [35] [37] and is a function of mutual inductance and equivalent resistance. \( R_r \) and \( C_r \) are provided by the following equations:
\[ R_r(M, R_{eq}) = \frac{R_{eq}(\omega M)^2[\omega^2 C_2 L_{2eq} - (\omega^2 C_2 L_{2eq} - 1)]}{R_{eq}^2(\omega^2 C_2 L_{2eq} - 1)^2 + (\omega L_{2eq})^2} \quad (2.14) \]

\[ C_r(M, R_{eq}) = \left[ -\frac{\omega^4 M^2[C_2 R_{eq}^2(\omega^2 C_2 L_{2eq} - 1) + L_{2eq}]}{R_{eq}^2(\omega^2 C_2 L_{2eq} - 1)^2 + (\omega L_{2eq})^2} \right]^{-1} \quad (2.15) \]

\( L_{2eq} \) from (2.14 & 2.15) represents a virtual secondary coil inductance after partial series compensation is applied and it is described as:

\[ L_{2eq} = L_2 - \frac{1}{\omega^2 C_{S2}} \quad (2.16) \]

Therefore the power that can be delivered to the secondary side is expressed as follows:

\[ P = R_e \{I_1^2 Z_r\} = \frac{R_{eq}(\omega I_1 M)^2[\omega^2 C_2 L_{2eq} - (\omega^2 C_2 L_{2eq} - 1)]}{R_{eq}^2(\omega^2 C_2 L_{2eq} - 1)^2 + (\omega L_{2eq})^2} \quad (2.17) \]

The term that is of particular interest from this equation for the resonant wireless power transfer, and where resonance plays a key role is the term \( \omega^2 C_2 L_{2eq} \). Namely if the system is operated at, or very close to the resonant frequency of the secondary side:

\[ \omega_0 = \frac{1}{\sqrt{L_{2eq} C_2}} \quad (2.18) \]

Then the term \( \omega^2 C_2 L_{2eq} \) will be equal or very close to one, and an equation (2.17) can be simplified as follows:

\[ P = \frac{R_{eq}(\omega I_1 M)^2}{(\omega L_{2eq})^2} = \frac{\omega_0 M^2 I_1^2 Q_{2v}}{L_{2eq}} \quad (2.19) \]

Where for the case of parallel connection with partial series compensation \( Q_{2v} \) is:

\[ Q_{2v} = \frac{R_{eq}}{\omega L_{2eq}} \quad (2.20) \]
The power equation represents the first step in the design of every resonant IPT system [35] [36]. A couple of factors are important to note from this expression and that are of value to the research work done for this thesis. From equation (2.19) the biggest contributors to the power delivered to the load are $I_1$ and $M$ since they are both squared. During the operation of the system, depending of the value of $M$ (M varies depending on distance) the primary current $I_1$ can be controlled in order deliver rated power. In the same manner the frequency $\omega$ can be adjusted accordingly on the primary side, but only to protect the power electronics and not to boost the power.

Since $M$ is one of the two biggest contributors to the power transfer, but cannot be controlled electronically; it is desirable to design the coils in such way so as to boost the value of $M$ as much as possible. It is also important to note that one of the biggest loss contributors in the overall system are losses associated with coil design (copper losses, eddy current losses, core losses, etc.) [28] [38] which only further explains why initial coil development represents one of the key factors in the overall efficiency of the system.

### 2.4 Mutual Inductance and Coupling Coefficient in IPT System

As pointed in the equation (2.19) and described in the previous section, making the value of $M$ or $k$ as large as possible can help reduce the value of supply current and consequently reduce losses associated with it. However, in the practical application very high levels of coupling are neither practically achievable nor advisable [28] [39].

In the conventional transformers and other tightly coupled systems it is desirable to achieve levels of coupling ranging between 0.92-0.98. In the IPT system, suggested coupling range is anywhere between 0.1-0.4, making it loosely coupled system. Although coupling ranges for IPT systems is relatively small when compared to the tightly coupled transformers, achieving values that are close to 0.4 with large air gap (10cm - 40cm) is hard. Biggest obstacle in designing pads with higher coupling is their practical limitation in size of the coil that can be mounted on the vehicle.

Another important feature of the magnetic pads is the variation in $M$ and $k$ over the range of misalignment or over a height variation. More specifically, the value of $M$ and consequently $k$, decreases as the secondary pad moves away from the center of the
primary pad. On the other hand if the air gap between the pads decreases the parameters M and k will increase.

Majority of the study done to date had concentrated on maximizing the value of k, without taking in consideration practical issues associated with misalignment. In practice, it is highly unlikely that the EV user will be able to park so as to axially align both primary and secondary pad in order to achieve the highest possible coupling. Furthermore, due to the weight load that is being packed in the car or due to the tire deflation, the air gap between the pads can vary a couple of centimeters up or down, which can significantly change the magnetic profile of the pads.

The variation in mutual inductance and coupling affects the performance of the IPT system in two ways; larger supply current is required to deliver rated power when coupling decreases, and big variation in coupling can affect inverter performance. Larger supply current increases copper losses on the primary side, while on the other hand change in inductance detunes the circuit, decreases the transferred power and puts a significant amount of stress on the power electronics. Although some tuning adjustments are possible with dynamic control of frequency, recent guidelines limit the allowable frequency variation [28].

Another problem associated with coupling variation is leakage flux. Three most influential factors that are affecting the amount of a leakage flux are: operating frequency, primary VA rating and the coupling. According to International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines, [40], the proposed magnetic field exposure limit for humans is limited to 27 $\mu T$ (microtesla - a unit used to measure the strength of magnetic field) at frequencies ranging between 10-100 kHz. Operating frequency for EV charging that was suggested by Society of Automotive Engineers (SAE) and International Electro-technical Commission (IEC), ranges between 81.38-90 kHz, where nominal frequency is set at 85 kHz [28].
2.5 Conclusion

The coupling coefficient is the measure of a ratio of the flux captured by the secondary pad over total flux emitted by the primary pad:

\[
k = \frac{\Psi_{21}}{\Psi_{1L}}
\]  

(2.21)

The leakage flux is the amount of emitted flux \(\Psi_{1L}\) that is not being captured by the secondary pad and is proportional to \((1 - k)\), which suggests that \(\downarrow k \propto \Psi_{\text{leakage}} \uparrow\). In addition, from (2.1) we can conclude that larger supply current (that is demanded by the secondary side in order to deliver rated power when \(k\) is decreasing) will result in a larger magnetic field radiation.

Taking in consideration the mentioned physical constraints of the system, as well as guidelines that were imposed by the ICNIRP, SAE and IEC, we can see why the large variation in coupling is not a desirable feature in the IPT application and can impose a significant problems in the overall performance.
3. Popular Coil Structures

Abstract

In this chapter the most popular coil designs, Circular Planar pads, Solenoidal Pads and Double D Pads will be described in terms of their self-inductance, mutual inductance, coupling profile and natural quality factor Q so the reader can get a better understanding of design principles behind them.

3.1 Introduction

One of the first steps in the development of every IPT system is coil design and characterization. Magnetic profile of the pads will determine the values of all of the other components. Therefore it is of great importance to build pads that will help maximizing power transfer over the desired range of air gap and misalignment, while at the same time complying to all of the safety standards and regulations.

Up to date there have been numerous proposals for different coil structures. Biggest diversity in pads design has been shown in the field of low power wireless charging [41], since the air gap, position and angle of the device that needs to be charged can vary significantly.

For the EV charging application, coil structures that have been proposed to date can be divided into three groups based on their magnetic field distribution patterns: non polarized or unipolar pads [15], polarized pads [42], and a combination of the two which are called Double D pads [16].
3.2 Circular Planar coil

Circular planar coils (CP) are most popular representative of non-polarized pads. One of the most attractive features of this geometry is their uniform field distribution as shown in figure 3-1(a)

![3D view of flux distribution](image)

a) 3D view of flux distribution

![2D view of flux height](image)

b) 2D view of flux height
In terms of wireless power transfer, uniform field distribution allows for coupling profile curve to be the exact same in every direction. This is particularly convenient when designing IPT system since it eases overall control scheme. In order to explain the variation of $k$, $M$ and $Q$ that were explained in [15] [38] [43], the terms from figure 3-1(c) will be defined as follows;

- $R_o$- outer radius of the coil
- $R_i$- inner radius of the coil
- $p$- (space between the windings)
- $d_w$- wire diameter
- $S_a$- back plate shielding usually made out of copper or aluminum
- $f$- ferrite spokes

If the outer radius $R_o$ is being increased and all other parameters are kept the same then both coupling and mutual inductance will increase. Coupling will increase since the height of flux path shown in figure (3-1,b) will be longer, which will result in higher amount of flux captured by the receiving pad. At the same time, since more windings need to be added in order to expand $R_o$ the pad inductances will increase.
accordingly. Since mutual inductance is a function of both coupling and primary and secondary inductance, $M$ will increase as well.

If the $R_i$ is increased and all other parameters are kept the same, the opposite scenario from $Ro\uparrow$ will happened. This is to be expected since the flux path and both inductances are being decreased. Therefore, the increase in $R_i$ will result in decrease in $k$ and $M$.

If the pitch between the windings is being increased, the coupling will remain relatively the same since $Ro$ and $R_i$ have not changed which will allow the flux path to remain unchanged. However, higher pitch will result in the reduction of number of windings which in turn will reduce the inductance of the coil. This reduction of the inductance value comes as a result of a flux collapse between the windings. Naturally with smaller coil inductance and constant $k$ the value of $M$ will decrease as well.

If the $dw$ increases and $Ro$ and $R_i$ remain the same (pitch has to decrease since in order for $Ro$ and $R_i$ to remain unchanged) then mutual inductance will increase while coupling once again will remain relatively the same. Coupling will remain unchanged for the same reason explained in the previous example. On the other hand smaller gap between the windings will allow for a smaller amount of flux collapse between the windings which will directly affect the increase of coil inductance. Naturally with higher inductance the mutual inductance will rise as well.

For the circular pads, native quality factor is equivalent to $Q = \omega_0 L/R$. This shows that $Q$ can be increased either by frequency, which in the case of wireless charging it is assumed to be fixed, or by increase or decrease of $L$ and $R$ respectively. In terms of $L$ and $R$, when $Ro$ and $R_i$ are being kept constant and the decrease in $p$ results in additional windings added, then Inductance $L$ will increase at a higher rate than resistance $R$. This will effectively increase the native quality factor $Q$.

Ferrite spokes, $f$, have a significant impact on the aforementioned parameters. Addition of ferrite spokes reduces the reluctance path of magnetic field which helps increase of the coil $L$, $Q$ and naturally $M$. In addition, ferrite is used to compress the magnetic field inside the charging zone which additionally helps in a reduction of leakage fields.
Shielding, $Sa$, that is usually made out of aluminium or copper is added to almost all of the coil structures to date. It is usually mounted behind the coil with area larger than winding area. Shielding acts opposite of ferrite, in a way that it reduces the inductance and with that mutual inductance as well. Although shielding plates induce eddy currents that are increasing losses associated with the system, these plates are best solution to date that protects electronics and reduces leakage fields.

When it comes to varying the size of the coils, it is important to mention that circular pads achieve highest coupling when both pads are of the same or similar size [15] [28]. In addition, if the air gap is being kept constant then in order to achieve higher coupling the pad size needs to be increased.

### 3.3 Solenoidal Pad

Solenoidal pad (SP) is the most popular and one of the first researched coil structures with polarized field distribution.

![Polarized flux distribution](image)

a) 3D-View with coil dimensions,
Behaviour of solenoidal pads in terms of varying pitch, wire diameter and coil area is very similar to circular pads when the coils are perfectly aligned [42]. In addition, SP’s can achieve higher coupling with the coils of the same area when compared to CP’s. This is due to the fact that a flux path from figure 3-2 (b), is significantly higher when compared to CP’s.

One of the biggest problems with SP’s is the fact that they have a large leakage flux associated with them. Because these coils are flattened out, they have two sided flux distribution. The entire bottom half from figure 3-2 (b) constitutes leakage flux. Highest leakage fields occur with the primary coil since they have a higher Volt-Ampere (VA, apparent power) rating and therefore it is not recommended to use SP’s on the emitter side.

Another problem associated with the SP’s is a large coupling variation when the coils are misaligned in the direction orthogonal to the direction of winding. This can add complexity in the control scheme and reduce the charging zone in one of the axis direction. In addition, in order to develop an SP of the same area as CP almost twice more Litz wire needs to be used. Litz wire is a type of cable designed to reduce skin effect and proximity effect (current crowding) losses.
3.4 Double D Pads

Double D coils are essentially two circular planar coils connected electrically in parallel and placed next to each other. They have one sided flux distribution just like the circular planar coils. However, due to the nature of their positioning, in the middle section they form a polarized flux distribution path or “Flux Pipe”, figure (3-3). In this way, these coils are able to achieve higher flux path and consequently higher coupling (such is the case with solenoidal coils) while keeping one sided flux distribution and reducing the leakage problems associated with solenoidal pads.

This structure can achieve 1.4 times higher coupling than a Circular planar pad of the same area and can transfer twice as much uncompensated power. In addition, these coils have a highest quality factor when compared against the two aforementioned structures.

On the other hand, due to the added coil and larger area coverage that these coils occupy, almost twice the amount of Litz wire needs to be used for the construction which increases the cost of production. In addition, the same coupling variation problem that is associated with solenoidal pads is present in the case of DD pads due to their polarized flux distribution.
3.5 Conclusion

Between the three mentioned structures, it was shown in [28] that CP coil has smallest coupling when coils are axially aligned, but at the same time it has smallest coupling variation when coils get misaligned. In addition, CP has smallest leakage flux associated with them. Best operational results (coupling, mutual inductance, magnetic efficiency) are achieved when primary and secondary are of the same type. However, when tried to test interoperability, it was shown that CP-SP can operate only when the coils are misaligned. On the other hand DDP can operate in pair with any of the three structures.

In conclusion, although CP structure has smaller coupling than other two coil types, its small leakage field, even coupling profile in every direction and small amount of material necessary for its production makes them a most likely candidate for the application of EV charging.
Chapter 4

4. New Secondary 3 Coil Array for Enhanced Misalignment Tolerance in XY plane

Abstract

In this chapter a new secondary 3 coil array will be presented, with the intention to improve upon issue of misalignment. First the coupling curve of CP’s will be presented and its limited tolerance to misalignment will be discussed. Then the operational principles of a novel 3 coil secondary structures will be explained. Finally, two different sets of simulations will be done using the MAXWELL simulator:

1) To compare the new coil performance to the circular planar coil of the same area.
2) To optimize the new coil structure

4.1 Introduction

Previously we explained different popular coil structures along with their advantages and disadvantages. Since it was clearly stated that circular planar coils are most likely to be adopted as a standardized structure, it is therefore desirable to try to improve on some of their aspects, namely to reduce the variation of coupling for a set range of misalignments.
4.2 Coupling Variation

The figure 4-1 represents experimentally extracted coupling curve of CP’s that were readily available in the CHARGE Labs. Even though the CP’s have a lowest coupling variation when compared to SP’s and DDP’s, one can still notice that coupling drop can vary quite a bit. This feature is not desirable, as mentioned in chapter 2, because it affects the primary side inverter and overall system performance.

4.2.1 Zero Voltage Switching (ZVS) in IPT System

Every inverter is built and IPT components are scaled so as to achieve resonance between primary and secondary side and to ensure a ZVS on the inverter [35] in order to protect the switches and to reduce switching losses.
The idea is to ensure that source current reaches zero before voltage wave kicks in, figure 4-2 (a). Ideal case is not possible in practice, but the designer needs to ensure that the overlap between the two is as small as possible since that area represents the power losses associated with switching \( P_{\text{loss}} = I_s V_{DS} \) as shown in figure 4-2 (b).

ZVS is affected by the phase change of reflected impedance from equation (2.13), where in turn the phase changes in impedance are directly proportional to the change in mutual inductance/coupling. What this means is following: if the components are scaled at certain coupling level (usually everything is scaled at the coupling level of the desired distance), then large increase in coupling will change the phase angle of impedance, that in turn will increase the source current. This will in turn increase the losses associated
with switching, but more importantly it can exceed current and power ratings of the switches, in which case the failure of the switches and system in general is inevitable [44]. Therefore the misalignment range depends on the variation in coupling that can be tolerated by inverter. For example, if the inverter is built so it can handle maximum coupling range from 0.15-0.25, then maximum misalignment that IPT system can handle based on a coupling profile presented in figure 4-1 would be as presented in table 4-1.

<table>
<thead>
<tr>
<th>Height (cm)</th>
<th>Range (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>13-17</td>
</tr>
<tr>
<td>16</td>
<td>0-15</td>
</tr>
<tr>
<td>20</td>
<td>0-7</td>
</tr>
</tbody>
</table>

4.3 Novel Secondary 3 Coil Structure

In order to extend the misalignment range, but at the same time to stay in the coupling range, the additional solenoidal coils are added in a cross like formation, figure 4-3, on the secondary side in series combination with the secondary CP.

Fig. 4-3. Novel 3 Coil Concept

Since the coupling of CP’s decreases as they get axially misaligned, the addition of SP’s serves to compensate for that drop.
4.3.1 Theory

We know from equation (2.6) that the induced voltage on the secondary side will be equal to,

\[ V_{oc} = j\omega MI_1 \]  

(4.1)

Using the relation between \( k \) and \( M \) from chapter 2 and rewriting equation 4.1 we get

\[ V_{oc} = j\omega I_1 k\sqrt{L_1L_2} \]  

(4.2)

Isolating for \( k \)

\[ k = \frac{V_{oc}}{j\omega I_1 \sqrt{L_1L_2}} \]  

(4.3)

Since there are three coils in this arrangement then \( V_{oc} \) will represent the summation of induced voltages in each of the three coils.

\[ V_{oc} = V_{cp} + V_{sx} + V_{sy} \]  

(4.4)

In the same instance the terms \( L_2 \) will equal to the summation of all three coils self-inductances along with their respective mutual inductances.

\[ L_2 = L_{cp} + L_{sx} + L_{sy} \pm 2L_{cpsx} \pm 2L_{cpsy} \pm 2L_{sxy} \]  

(4.5)

Subsequently these three coils are wound in such way so as to be orthogonal to each other where mutual inductance between them will equal to zero. Then \( L_2 \) and \( k \) can be rewritten as,

\[ L_2 = L_{cp} + L_{sx} + L_{sy} \]  

(4.6)

\[ k = \frac{V_{cp} + V_{sx} + V_{sy}}{j\omega I_1 \sqrt{L_1(L_{cp} + L_{sx} + L_{sy})}} \]  

(4.7)
4.3.2 Need for Switching

When coils are axially aligned, then only $V_{cp}$ will induce voltage while $V_{sx}$ & $V_{sy}$ will have zero induced voltage since they lay in the XZ and YZ plane respectively where the resultant B field will be in the same plane where these coils lay. On the other hand overall inductance will be larger due to the summation of the three coils. Naturally this will reduce the coupling at this location in comparison to the regular CP to CP combination.

$$k = \frac{V_{cp} + 0 + 0}{j\omega I_1\sqrt{L_1(L_{cp} + L_{sx} + L_{sy})}} \quad (4.8)$$

It is worth nothing that although coupling will drop when coils are axially aligned, the mutual inductance should remain the same since from equation (4.1)

$$M = j\omega I_1 V_{oc} \quad (4.9)$$

And since $V_{oc}$ at zero offset position in both cases will be the same, then mutual inductance of both CP and 3 Coil Array will be same

$$M_{cp@0} = M_{3coil@0} \quad (4.10)$$

However, as soon as the coils get misaligned and $V_{cp}$ starts dropping, both $V_{sx}$ and $V_{sy}$ will enter the polarized region of flux distribution and will start inducing voltage that will in turn start compensating for the drop in $V_{cp}$. Using this relation one can extend the range of misalignment while staying in the range of coupling. On the other hand, this can be counterproductive in terms of coupling, because if three coils are wound using single length of wire, then SP will induce voltages that are in phase with CP in one direction and $180^0$ out of phase in the opposite, figure 4-4.
Figure 4-4 indicates two different scenarios with respect to SP misalignment. Although voltages induced will be of the same magnitude, because of the “right hand rule” and a direction of magnetic field they will be of the opposite polarity. Therefore for the SP in the positive x plane the induced voltage will be,

\[ V_{+x} = -V_{emf} \]  \hspace{1cm} (4.11)

While for the SP in the negative x plane

\[ V_{-x} = +V_{emf} \]  \hspace{1cm} (4.12)

Since CP coupling curve is dropping at the same rate in every direction, this means that in case where voltages of opposite phase are induced in SP’s the equation (4.7) will become,

\[ k = \frac{V_{cp} - V_{sx} - V_{sy}}{j\omega I_1 \sqrt{L_1 (L_{cp} + L_{sx} + L_{sy})}} \]  \hspace{1cm} (4.13)
This will result in a significant coupling drop and consequently reduce the range of operation. It is therefore necessary to introduce a switching scheme, figure 4-5, that will insure that these three coils are connected in such way so that induced voltages in them are always in phase with each other so the coupling level can be maintained.

![Diagram](image1.png)

a) IPT circuit with new 3 coil secondary

![Diagram](image2.png)

b) switching circuit
c) switching regions

**Fig. 4-5. Switching system for new secondary 3 coil array**

Using position sensors to find out in which region the center of the primary coil is in we can make sure that appropriate switching scheme is turned on. The table 4-2 represents a possible switching scheme for the case when all the coils are wound in a clockwise direction.

**Table 4-2. Switching scheme for 3 coil array**

<table>
<thead>
<tr>
<th>Region</th>
<th>CP</th>
<th>Terminal 2</th>
<th>Terminal 1</th>
<th>Terminal 2</th>
<th>Terminal 1</th>
<th>Terminal 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sx2</td>
<td>Sy2</td>
<td>CP2</td>
<td>T</td>
<td>Sx1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Sx2</td>
<td>Sy1</td>
<td>CP2</td>
<td>Sx1</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sx1</td>
<td>CP2</td>
<td>Sy1</td>
<td>Sx2</td>
<td>T</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Sx1</td>
<td>CP2</td>
<td>Sy2</td>
<td>T</td>
<td>Sx2</td>
<td></td>
</tr>
</tbody>
</table>
4.4 Verification of the concept

a) secondary and secondary structural parameters

b) secondary top (left) and bottom (right) view

c) side view with structural parameters of the secondary

Fig. 4-6 Structural parameters for the simulation
In order to verify this concept, the simulation was built using MAXWELL software, where new secondary three coil array was compared against the regular secondary CP coil of the same area. The following table highlights the structural parameters of the coils that were used in the simulation along with the primary side, which was same in both cases.

<table>
<thead>
<tr>
<th>Primary CP</th>
<th>Secondary CP</th>
<th>3 coil array</th>
</tr>
</thead>
<tbody>
<tr>
<td># of turns</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>r1</td>
<td>70 mm</td>
<td>60 mm</td>
</tr>
<tr>
<td>r2</td>
<td>294 mm</td>
<td>184 mm</td>
</tr>
<tr>
<td>Conductor diameter</td>
<td>5.8 mm</td>
<td>5.8 mm</td>
</tr>
<tr>
<td>pitch</td>
<td>3 mm</td>
<td>3 mm</td>
</tr>
</tbody>
</table>

In addition, the area of the primary and a secondary side was scaled according to proposed industrial standards for passenger vehicles as it was suggested in [28], where primary was of 0.36 $m^2$ and secondary of 0.1225 $m^2$.

a) coupling coefficient comparison
b) mutual inductance comparison

Fig. 4-7 CP vs. New 3 coil array comparison

Figure 4-7(a) represents three different cases of coupling variations at 16 cm air gap. Blue line represents the coupling curve when regular CP is used on the secondary side while red and green are coupling curves when 3 coil array is used on the secondary side. Reason for difference between red and green curve is because in one case ( red ) the coil is misaligned along the X axis, which means that only SPy will induce voltage while SPx will remain neutral. In case of the green curve, secondary side is misaligned diagonally with respect to XY axis, which means that both SP’s will induce voltages and consequently will increase the coupling. Furthermore, 3 coil array has smaller coupling then CP and same mutual inductance when coils are axially aligned, which goes to confirm the equation (4.8 & 4.10).

From the presented curves one can easily see that 3 coil array has smaller coupling variation in comparison to CP and therefore allows for a longer range of operation. If we refer back to the example where we assumed that inverter can handle coupling variation in the range of 0.15-0.25, then the following table 4-4 and figure 4-8 summarizes the range and operational area of the secondary coils:
### Table 4-4. Range comparison of CP vs. 3 Coil Array

<table>
<thead>
<tr>
<th></th>
<th>CP</th>
<th>3 coil Array</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X or Y axis offset</td>
<td>Diagonal offset</td>
</tr>
<tr>
<td>Range (cm)</td>
<td>11.5</td>
<td>16</td>
</tr>
<tr>
<td>Operational area (cm$^2$)</td>
<td>415.47</td>
<td>940.6</td>
</tr>
</tbody>
</table>

![Diagram of range comparison](image)

**Fig. 4-8.** Charging area of New 3 Coil array (green) vs. Charging Area of CP (orange)

### 4.5 Optimization of the new coil structure

To observe the behaviour of the new coil under different structural conditions, three different variations of SP’s were tested while the CP part of it remained unchanged. Figure 4-9 Case I: SP’s were consisted of five turns with winding separation of 2 mm. Case II: SP’s were consisted of 10 turns with winding separation of 2 mm. Case III: SP’s were consisted of five turns with winding separation of 8 mm. All of the other structural parameters are same as in table 4-2. Simulations were done at 16 cm vertical gap at 85 kHz in order to go in accordance with the proposed operating frequency. Horizontal sweeps were done over 40 cm of axial misalignment along X axis and along diagonal offset with respect to XY axis.
a) Primary and secondary in simulation setup

b) Case I

c) Case II

d) Case III

Fig. 4-9. MAXWELL Simulation setup for three cases used for optimization
Magnetic parameters that were of interest for this optimization and that are needed for the design of IPT systems, are as follows; coupling coefficient, mutual inductance, primary and secondary inductance $L_1$ & $L_2$, primary and secondary quality factors $Q_{L1}$ & $Q_{L2}$, and magnetic efficiency $\eta$. $Q_{L1}$ & $Q_{L2}$ represent intrinsic pad quality factors for the primary and secondary pads respectively while magnetic efficiency was calculated using following expression highlighted in [28]

$$\eta = \frac{1}{1 + \frac{2}{k\sqrt{Q_{L1}Q_{L2}}}}$$

(4.14)

![Diagram a) Coupling Coefficient vs Misalignment](image1)

![Diagram b) Mutual inductance vs Misalignment](image2)
c) Primary inductance vs Misalignment

d) Secondary inductance vs Misalignment

e) Q1 vs Misalignment
Coupling—When it comes to coupling coefficient we can see from figure 4-10(a) that in Cases I & III curve is almost identical and it reaches its peak at ~ 5 cm, which means that increase in pitch will not affect the coupling significantly. In case II, at zero offset value is smaller than I & III. However, case II reaches its peak value at ~10 cm which can potentially increase the operational area due to the smaller variation in coupling. On the other hand, case II indicates that if we put too many turns on SP it can result in very small central coupling and a big variation of the same when it is offset in one of the diagonal directions.
**Mutual inductance** follows the same curves as in the case of coupling with the difference that mutual inductances of all three cases are of the same value at central position, which was discussed in equation (4.10). This only goes to say that case II will have a highest mutual inductance over the operational region.

Primary inductance remains relatively unchanged in all three cases, while secondary inductance shows some variations as expected. Since case II has a highest number of turns and small pitch, naturally it will have a highest value. In cases where pitch is varying, we can see that with the increased pitch (case III) the inductance goes down, as it was explained in chapter 3.

**Quality factor** of the primary side shows the influence of the three cases. We can notice from graphs 4-10(d)(f) that as \( L_2 \uparrow \) then \( Q_1 \downarrow \). This is because higher \( L_2 \) results in higher impedance reflected onto primary which consequently reduces its native quality factor. On the secondary side, once again Case III shows the smallest quality factor while cases I & III show small variations with respect to each other. It is interesting to note that in Case II evidently \( R_{ac} \) will be higher than in other two cases since more wire is used for the assembly, but its inductance is increasing at a smaller rate than \( R_{ac} \) which is in opposition to suggested optimization in [38].

Although magnetic efficiency remains relatively high and unchanged in all three cases, slight differences can be noticed. Since \( \eta \) is a function k, Q1 and Q2, naturally from previously analyzed results case II will result in smallest efficiency.

### 4.6 Conclusion

One of the desirable features for the secondary charging pad, aside from keeping the surface area well within the proposed limits, is to reduce the thickness of the pad. With the new coils, as is the case with any coil in IPT structures that is, it is highly desirable to maintain similar operational characteristics in the 360 degrees radius of misalignment. Therefore, aside from the leading circular planar coil, it is necessary to have a minimum of two more solenoidal type coils that would be placed orthogonal to each and wound around CP so as to have zero mutual inductance between each other. Throughout the simulation process it was shown that the rise in coupling as we move
diagonally with respect to the SP’s, is higher in comparison to the axial offset. This leads to the conclusion that if we use four, six or more (it has to be even number of coils to ensure same coupling curve in any direction) SP coils in the star like formation the rise in coupling would be significantly higher in any direction whilst the coupling at zero misalignment would be lower with each new addition of SP pairs, equation (4.8). This is not desirable feature since it defeats the purpose of maintaining relatively low coupling variation in the given operational region. Furthermore, the addition of more than 3 coils would significantly increase the overall thickness of the coil which would pose a problem in the vehicle instalment and ground clearance. Practically, this means that with the addition of each new pair of SP’s the overall thickness secondary pad would increase by 2 cm, taking in consideration that litz wire radius is around 5mm.

Another point to be made when it comes to addition of more coils is the pad quality factor. It is known that with the addition of more wire the AC resistance would increase. Naturally the solenoidal pads don’t have a high Q when compared to Circular pads or DDQP pads, so it is desirable in this coil array to design these SP’s so as to have a highest possible Q, and the addition of more SP pairs would result in higher number of coils with overall smaller Q which would reduce overall efficiency.

In conclusion, the new coil structure has showed lower quality factor and consequently lower magnetic efficiency when compared to CP coil of the same size. On the other hand, three coil array has shown to have more than twice the operational area coverage. Although new coil structure has smaller magnetic efficiency, its extended coupling range can help in overall system efficiency over the entire range of operation due to the smaller supply current that would be required for the operation.
Chapter 5

5. New Secondary 5 Coil Array for Enhanced Misalignment Tolerance in XYZ Direction

Abstract

In this chapter, new secondary coil structure will be presented, with the intention of reducing coupling variation in all three axis of misalignment. First the theory and guiding principles will be explained followed by comparative simulation of 5 coil array, 3 coil array and CP. Finally, a detailed experimental procedure will be explained and experimental results will be analyzed.

5.1 Introduction

In chapter 4 we learned that with the addition of SP’s in series with the CP on the secondary side we can expand the charging area of IPT system. However, a problem still remains when the Z distance is varied as it was presented in figure 4-1. Air gap can be caused by multiple things: deflated tires, suspension, weight loaded vehicle etc. Table 4-1 describes how different operational range can be, at three different height levels.

In case of the coil designs, and IPT systems for that matter, it is desirable to design them in such way so as to fit a range of different vehicles. In [28] it was suggested that for different type of vehicles (passenger, trucks, busses) a different coil sizes are to be used to ensure that they meet standardization guidelines. However, even if we focus only on passenger vehicles group, where ground clearance can vary few centimeters up or down depending on the manufacturer, one standardized set of coils (CP-CP in this case)
would mean that some vehicles would have a smaller operating charging area or that different vehicles would have to have a differently scaled system. It is therefore desirable to build coils that will ensure small coupling variation in all three axis.

Using experience and knowledge acquired from chapter 4 and building upon it, a new secondary coil structure, figure 5-1, has been proposed to ensure control of coupling variation in all three axis.

![Figure 5-1](image)

*Fig. 5-1 Top (left) and bottom (right) view of new 5 coil secondary structure*

### 5.2 Theory

It was explained in chapter 4 that when 3 coil arrays is in axially aligned position, then only \( Vcp \) will induce voltage, and since overall secondary inductance is larger than when only CP is used, than consequently from equation(4.8) coupling will be smaller at this position.
However, if solenoidal coils are split in two per axial direction, figure 5-2, and spaced apart so that they are both in bipolar flux distribution path when CP’s are axially aligned, then secondary induced voltage will be

\[ V_{oc} = V_{cp} \pm V_{sx1} \pm V_{sx2} \pm V_{sy1} \pm V_{sy2} \]  

(5.1)

And overall secondary inductance will be

\[ L_2 = L_{cp} + L_{sx1} + L_{sx2} + L_{sy1} + L_{sy2} \pm 2L_{cpsx1} \pm 2L_{cpsx1} \]

\[ \pm 2L_{cpsy1} \pm 2L_{cpsy2} \pm 2L_{sx1sy1} \pm 2L_{sx1sy2} \]  

(5.2)

Unlike 3 coil array where all three coils were orthogonal to each other and their respective mutual inductances are zero, for five coil array that is not the case. From figure 5-1 we see that since SX pair, SY pair and CP are orthogonal to each other their respective mutual inductances will be zero. On the other hand, Sx1&Sx2 and Sy1&Sy2 coils will have mutual inductances between them. Then (5.2) can be rewritten as

\[ L_2 = L_{cp} + L_{sx1} + L_{sx2} + L_{sy1} + L_{sy2} \pm 2L_{sx1sx2} \pm 2L_{sy1sy2} \]  

(5.3)
Now coupling of IPT system with five coil array on the secondary side can be expressed as

\[
k = \frac{V_{cp} \pm V_{sx1} \pm V_{sx2} \pm V_{sy1} \pm V_{sy2}}{j\omega I_1\sqrt{L_1 (L_{cp} + L_{sx1} + L_{sx2} + L_{sy1} + L_{sy2} + L_{var})}} \tag{5.4}
\]

Where \( L_{var} \) can be anywhere in between

\[
-2(L_{sx1sx2} + L_{sy1sy2}) \leq L_{var} \leq 2(L_{sx1sx2} + L_{sy1sy2}) \tag{5.5}
\]

Although, we are using addition and subtraction of induced voltages to control coupling levels, one can easily see from equation (5.4) that depending on the connections (voltages adding or subtracting) between Sx1 & Sx2 and Sy1 & Sy2, overall secondary Inductance L2 can vary by the amount of \( L_{var} \)

In IPT system if \( L_{var} \) range is large, then in certain connection arrangements L2 value can change to the point where secondary resonant frequency will be beyond the value that can be tolerated by the system. It is therefore desirable to space axial coils apart enough so that their mutual inductance is as small as possible. This will ensure that variation in L2 is within the range that can be tolerated by the system.

Using the above mentioned principles and coil arrangement from figure 5-1, coupling reduction that was present in the case of three coil array axial alignment can be neutralized and coupling variation can be reduced even more. Furthermore, in case where height level decreases and coupling curve increases, one can easily reduce the coupling levels by simply switching coil connection.

5.3 MAXWELL verification and comparison to 3 coil array and CP

In order to verify equation (5.4) and suggested principles a simulation was built in Maxwell and compared against the 3 coil array (Case I) and CP from chapter 4. Table 5-1 and figure 5-3 highlights structural parameters used in the simulation.
a) CP structural parameters

b) Secondary structural parameters

Fig. 5-3 Structural parameters considered for building simulation

| Table 5-1. Structural parameters used in simulation of 5 coil array |
|------------------|------------------|------------------|------------------|------------------|
|                  | Primary CP       | 5 coil array     |                  |                  |
|                  | CP               | Sx1              | Sx2              | Sy1              | Sy2              |
| # of turns       | 35               | 20               | 5                | 5                | 5                |
| r1               | 70 mm            | 60 mm            | 40 mm            | 40 mm            | 40 mm            |
| r2               | 294 mm           | 184 mm           | 368 mm           | 368 mm           | 368 mm           |
| Wire diameter    | 5.8 mm           | 5.8 mm           | 5.8 mm           | 5.8 mm           | 5.8 mm           |
| pitch            | 3 mm             | 3 mm             | 2 mm             | 2 mm             | 2 mm             |
| s                | na               | na               | 100 mm           | 100 mm           |

All of the simulations were done at 16 cm air gap and sweep was done along +X axis direction in the range of 35 cm. Three coil array was switched so that when misaligned $V_{oc} = V_{cp} + V_{sy}$, while five coil array was tested in three different cases:

**Case I** - $V_{oc} = V_{cp} + V_{sy1} + V_{sy2} + V_{sx1} + V_{sx2}$

**Case II** - $V_{oc} = V_{cp} + V_{sy1} - V_{sy2} + V_{sx1} + V_{sx2}$

**Case III** - $V_{oc} = V_{cp} + V_{sy1} - V_{sy2} + V_{sx1} - V_{sx2}$
Note that expressions from Cases I, II & III apply only for axially aligned position, since as coils get misaligned and SP’s pass central axis they will change polarity of induced voltage in which occasion the aforementioned Voc expressions will change.

(a) Coupling coefficient comparison

(b) Inductance Comparison
c) Quality factor comparison

**Fig. 5-4. Comparison of 5 coil array vs. 3 coil array vs. CP**

**Coupling:** From figure 5-4 (a) we see that in case of 5 coil array we can achieve three different coupling profiles for three different coil interconnections. At zero offset, we can have almost same k as that of CP. In addition, due to the spacing between the coils we can achieve extended coupling profile in XY plane when compared to 3 coil array. If we use same example from chapter 4, where inverter can handle coupling variation between 0.15-0.25, then with the five coil array we can offset as much as 20 cm in planar axial direction. What is more important for coupling control in XYZ is the fact that we showed in this simulation that coupling can be reduced by simply switching interconnections, which in case when Z gap gets reduced it can help keeping coupling in the operational range. Experimental testing on a different height levels will be presented in the section 5.4 where the Z gap coupling control will be further explained and proved.

**Inductance:** Naturally due to added coils overall inductance will be higher when compared to CP or 3 coil array. However, what is more important for the application in IPT system is the variation in L2 and possible system detuning that was discussed in section 5.2. We can see small variations in L2 between three cases which was expected and explained with \( L_{\text{var}} \). Although this variation in L2 is small (\( \pm 1.4 \% \) variation for 5 coil arrays, whereas for CP L2 varies by \( \pm 0.8 \% \)) and would not pose a problem for the application in IPT, it is worth noting that it can be even further reduced by either
increasing S distance, figure 5-3(b), reducing number of turns of SP coils or increasing the pitch on the SP coils.

**Quality factor**- When compared to 3 coil and/or CP, five coil array has the smallest quality factor in case II, whilst cases I&III show higher Q than 3 coil array. This variation of Q comes as a result of inductance change ($L_{var}$) when switching is applied.

### 5.4 Experimental procedure and concept verification

In order to extract magnetic parameters of inductive coils ($k$, $M$, $L_{1oc-sc}$, $L_{2oc-sc}$, Q1&Q2, magnetic efficiency), a different methods have been proposed in different literature [34] [45]. Measurement of $R$ and $L$ are being done with the use of LCR meter ($L$- inductance, $C$-capacitance, $R$-resistance), where both of the parameters are being measured over the operational range. Furthermore, depending on which topology is being used in IPT system (parallel or series), a coupled self-inductances have to been measured for two different cases; when secondary is open, and when secondary is shorted (same test needs to be done for the primary side). For measurements of $k$, an equation (2.7) and (2.8) from chapter 2 can be used. In this case, an accurate measurements of primary current and secondary open circuit voltage needs to be made, and along with the values obtained from LCR meter one can easily extract coupling coefficient curve.

However, a different method proposed in can be used to extract coupling profile by using only measurements that were previously obtained by LCR meter. This method was chosen for this thesis because by obtaining only one set of measurements, one can potentially reduce experimental error. The following mathematical derivation [46] will serve to explain the concept behind this testing method.

We know that primary and secondary voltages are:

$$V_1 = j \omega L_{11} i_1 + j \omega M i_2$$  \hspace{1cm} (5.6) \\
$$V_2 = j \omega M i_1 + j \omega L_{22} i_2$$  \hspace{1cm} (5.7)

When secondary is shorted then equation (5.6)(5.7) become,
\[ V_1 = j\omega L_{sc}i_1 \quad (5.8) \]
\[ V_2 = 0 = j\omega M i_1 + j\omega L_{22}i_2 = Mi_1 + L_{22}i_2 \quad (5.9) \]

Then \( i_2 \) from (5.9) is

\[ i_2 = -i_1 \frac{M}{L_{22}} \quad (5.10) \]

Combining (5.6) and (5.8) and simplifying

\[ L_{sc}i_1 = L_{11}i_2 + Mi_2 \quad (5.11) \]

Substituting (5.10) in (5.11)

\[ L_{sc} = L_{11} - \frac{M^2}{L_{22}} \quad (5.12) \]

Rearranging (5.12)

\[ 1 - \frac{L_{sc}}{L_{11}} = \frac{M^2}{L_{11}L_{22}} \quad (5.13) \]
\[ \sqrt{1 - \frac{L_{sc}}{L_{11}}} = \frac{M}{\sqrt{L_{11}L_{22}}} \quad (5.14) \]

Comparing (5.14) to (2.8) we get

\[ k = \sqrt{1 - \frac{L_{sc}}{L_{11}}} \quad (5.15) \]

Where \( L_{sc} \) is primary inductance when secondary is shorted and \( L_{11} \) is primary inductance when secondary is open.
5.4.1 Physical construction

Fig. 5- 5. Design and look of the coils used in experiment
Coil former structure was designed using Catia V5, figure 5-5 (a), to ensure a precise finish for the CP part of the coil and to make the overall structure rigid enough to withstand the movements during the experiment. This was later milled with a CNC machine on a 2.5 cm thick acrylic sheet and formed into 5 coil array as in figure 5-5 (b).

Since the focus of this study is a new design of the secondary side, CP coil from figure 5-5(c) that was readily available in the CHARGE Labs was used in this experiment as the primary. Table 5-2 highlights the structural parameters of both primary and secondary coil.

**Table 5-2. Structural parameters of experimental coils**

<table>
<thead>
<tr>
<th></th>
<th>Primary CP</th>
<th>5 coil array</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>CP</td>
</tr>
<tr>
<td># of turns</td>
<td>22</td>
<td>13</td>
</tr>
<tr>
<td>Inner r/thickness (for SP) (mm)</td>
<td>50.5</td>
<td>40</td>
</tr>
<tr>
<td>Outer r/length(for SP) (mm)</td>
<td>241.3</td>
<td>160</td>
</tr>
<tr>
<td>Wire diameter (mm)</td>
<td>5.84</td>
<td>6.5</td>
</tr>
<tr>
<td>Pitch (mm)</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Spacing between SP (mm)</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>

Test bench from figure 5-6 was used to ensure that the precise horizontal and vertical measurements are made.

![Fig. 5-6 Experimental test bench](WWW.CHARGELABS.CA)
Finally the switching circuit, figure 5-7, was built to ensure that all possible coil connections are being tested. For the experimental purpose, the author used mechanical toggle switches with three positions (on-off-on).

Note that in practical application, it is intended to use electronic switches in combination with position detecting system in place so as to ensure that the best switching combination for the system is used at all times.

![Diagram of switching circuit](image)

a) Switching circuit for 5 coil array

![Practical implementation image](image)

b) Practical implementation of (a)

Fig. 5-7 Switching circuit
5.4.2 Experimental results

Experimental measurements were done on three different height levels (12 cm, 14 cm, 16 cm) across 28 cm of horizontal offset (on every 2 cm). Three different cases (same as in section 5.3) were tested on every height level where their connections were presented with respect to addition or subtraction of induced voltages when the coils are axially aligned. Chosen frequency for testing was 100 kHz (LCR meter KETHLEY3330 has options for 1, 10, 100 kHz) which represents the closest available option to 85 kHz (standardized operating frequency).

![Graph a) Coupling @ 12cm air gap](image1)

![Graph b) Coupling @ 14cm air gap](image2)
c) Coupling @ 16 cm air gap

d) Mutual Inductance @ 12 cm air gap

e) Mutual Inductance @ 14 cm air gap
f) Mutual Inductance @ 16 cm air gap

g) L1 @ 12 cm air gap

h) L1 @ 14 cm air gap
i) \( L_1 \) @ 16 cm air gap

j) \( L_2 \) @ 12 cm air gap

k) \( L_2 \) @ 14 cm air gap
l) L2 @ 16 cm air gap

m) Q1 @ 12 cm air gap

n) Q1 @ 14 cm air gap
o) Q1 @ 16 cm air gap

p) Q2 @ 12 cm air gap

q) Q2 @ 14 cm air gap
r) $Q_2$ @ 16 cm air gap

s) Efficiency @ 12 cm air gap

t) Efficiency @ 14 cm air gap
Coupling – As expected from equation (5.4), experiment has shown that for three different height levels figure 5-8 (a, b, c) it is possible to maintain the coupling levels relatively unchanged. For example, at zero offset position, the coupling value of Case III figure 5-8(a), Case II figure 5-8(b), and Case I figure 5-8(c) is 0.15. Similarly, as coils get misaligned the system can switch to the arrangement that is closest to the ideal coupling value. Profile of the coupling curve naturally corresponds to the curve of **mutual inductance**, figure 5-8(d, e, f), however with slight variation due to the variations in profile of L1&L2.

Inductance- Experiment has shown that primary inductance, figure 5-8(g, h, i) remains relatively unchanged in case I and II, whereas in case III there is a slight decrease in the curve profile. This decrease can be explained by larger secondary inductance and its reflectance onto primary. On the secondary side, figure 5-8(j, k, l), larger oscillations in the curve profile are noticeable, as predicted in the equation (5.5). Depending on the connection of the coils, overall secondary inductance will vary by the amount of $L_{var}$.

Quality factor- On the primary side, Q remains relatively unchanged over entire range of testing and measured $R_{ac}$ for L1 was 0.29 $\Omega$. On the secondary side, Q2 shows variation corresponding to the L2-oc curve, where measured $R_{ac2}$ was 0.44 $\Omega$. Smaller
Q2 comes as expected and explained in chapter 3.3, because of addition and spacing of SP’s.

**Efficiency**- Case I shows biggest drop in efficiency over the entire range of testing. This comes naturally as a result of biggest coupling drop over the testing range. Case II showed biggest efficiency over the entire range, namely because of its extended and high coupling profile.

### 5.5 Conclusion

Novel secondary 5 coil array structure represents an upgraded version of 3 coil array from chapter 4. In this chapter it was proven both through simulation and experimentally that by using conceptual theory from section 5.2 and suggested placement of compensating SP coils, it is possible to maintain relatively unchanged coupling coefficient in all three axis of misalignment. Furthermore, when simulation of new coils was compared to the 3 coil array, it showed additional extension in coupling in XY plane. This extension comes as a result of coil separation. However, addition of extra coils requires additional wire and additional set of switches required for the operation of a new secondary structure, which represents added cost to the manufacturing.
6. Conclusion and Future Work

6.1 Conclusion

Wireless charging of EV’s has gained a global attention over the course of the last decade, with many companies investing significant research funds in the development of this technology well before its official approval and standardization. Many features of wireless charging such as convenience, safety and extended range of EV’s, appear very appealing for the consumers.

However, in the case of static charging the problem of pads misalignment (which is almost inevitable to happen during the parking process) and height variation still remains to be largely unsolved. Proposed solutions usually involve vehicle guidance or increasing the coil size. The first solution requires extra set of electronics, and it would still require a user to readjust vehicle position in order to achieve optimal alignment which contradicts the aspect of convenience. As far as the increasing coil size goes, with the newly proposed coil sizes this option seems to be limited.

This thesis has proposed two different secondary coil structures that could help solve the aforementioned issues.

The first solution, 3 coil array, has focused on reduction of coupling variation in XY plane in order to extend the range of operation. It was shown, in chapter 4 that with the addition of two orthogonally wound solenoidal coils connected in series to the existing secondary circular pad, operational area can be extended by more than 2 times while keeping the secondary size same.

The second solution, 5 coil array, presents an improved version of the aforementioned coil where coupling variation can be reduced in all three axis. It was
shown in chapter 5 that with suggested coil arrangement coupling variation can not only be controlled in Z axis, but in XY plane it can surpass the range of 3 coil array.

In conclusion, both of the proposed structures showed a significant improvement in reduction of coupling variation and consequently range extension, when compared to the circular pad of the same size.

6.2 Future work and recommendations

Considering progress and advancements that were made over the last few years at the University of Windsor in the field of wireless EV charging, it would be beneficial to continue upgrading the existing IPT system and building upon the work that was done thus far. In order to complete and upgrade the existing system the following list highlights the necessary components and upgrades to make the system fully operational and autonomous according to the existing standards:

1) Upgrade the system to 85 kHz (current operational frequency-30 kHz)
2) Build the Power Factor Correction (PFC) on the primary side
3) Optimize the new 5 coil array
4) Add position detection system.
5) Establish communication between receiver and emitter
6) Close the loop
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Vita Auctoris

NAME: Nikola Stojakovic
PLACE OF BIRTH: Belgrade, Serbia
YEAR OF BIRTH: 1984
EDUCATION: University of Windsor, M.A.Sc. in Electrical Engineering, Windsor, Ontario, Canada, 2016
University of Windsor, B.A.Sc. in Electrical Engineering, Windsor, Ontario, Canada, 2015