Wireless Charger for Electric Vehicles with Electromagnetic Coil Based Position Correction

by

Nameer Ahmed Khan

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Electrical and Computer Engineering
University of Toronto

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Abstract

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Wireless Power Transfer (WPT) is an enabling technology for the mass deployment of Electric Vehicles (EVs) as it minimizes driver intervention during the charging process. Major challenges of WPT systems include coil misalignment and large air-gap, as both degrade efficiency. To address these issues, a vertically-mounted compact dual-coil charging pad for reduced air-gap is presented in this thesis. A linear-slider-mounted transmitter pad allows for lateral self-alignment using two integrated electromagnetic coils. Due to parking accuracy, the vertically-mounted charging pads increase variation in the air-gap, which degrades the electromagnetic coil operation. A position-correcting control algorithm that detects the system impedance and resonant frequency is proposed for improved pad alignment. An experimental prototype achieves a peak DC-DC efficiency of 90.1%. The charging pads laterally align in 1.75 s and correct misalignments as large as 240 mm. The control algorithm is successfully demonstrated with the pads being corrected to within 10 mm of perfect alignment.
Acknowledgements

First and foremost, I thank God, the gracious, the merciful whose countless blessings have provided me with success in my life thus far. I would like to express my deepest gratitude to my supervisor, Professor Olivier Trescases, whose constant encouragement, motivation, and guidance have helped me develop my skills and flourish throughout my master’s. His experience and dedication to high quality inspired me to always work at the highest level. I look forward to continuing my Ph.D. studies under his supervision.

I would also like to express my sincerest thanks to Professor Hirokazu Matsumoto of Aoyama Gakuin University who was a visiting researcher at the University of Toronto during my master’s studies. His immense knowledge in magnetics was a critical aspect in the design of the dual-coil charging pad. His assistance in conducting ANSYS simulations and obtaining preliminary efficiency and position measurements of the wireless charger cannot be emphasized enough. I wish him all the best in his future endeavors and hope we have the opportunity to work together in the future.

I am grateful to Amir Assadi for his assistance in measuring the system-level efficiency of the dual-coil charging pad. His feedback and critiquing of ideas assisted in further developing the core aspects of this thesis. I would also like to thank Dr. Shuze Zhao, whose patience and advice helped me adjust to graduate school. I wish him all the best. I am also thankful to my fellow graduate associates, Miad Nasr, Sam Murray, Zhe Gong, Carl Lamoureux, Mojtaba Ashourloo, Venkata Raghuram Namburi, Violet Jiang, and Mohammad Shawkat Zaman for all their help and advice through discussions. I would also like to acknowledge the National Science and Engineering Research Council of Canada (NSERC) for funding this work presented in this thesis.

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Chapter 1

Introduction

1.1 Background and Motivation

With worldwide energy demand increasing by 2.3% in 2018 [1], one of the major global challenges is the increasing emissions of greenhouse gases and their associated impact on climate change. One significant contributor to greenhouse gas emissions is the use of gasoline-powered vehicles. In the U.S. alone, the transportation sector contributed to 29% of their overall greenhouse gas emissions in 2017, as shown in Fig. 1.1 [2].

![Figure 1.1: Total U.S. Greenhouse Gas Emissions by Economic Sector, 2017 [2].](image)

One way of reducing greenhouse gas emissions is the adoption of Electric Vehicles (EVs), which do not consume gasoline. Many car manufacturers are already offering EVs such as the Nissan Leaf, Chevrolet Bolt, and Tesla Model S with increasing demand. The
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The global market for EV sales has already expanded to $17.23 billion in 2018 and is expected to further grow with a Compound Annual Growth Rate (CAGR) of 8.26% from 2019 to 2025 [3]. In 2018, 1.2 million EVs were sold in China alone, which accounts for more than half of global EV sales [4]. Governments are also aggressively encouraging the mass adoptions of EVs, with several countries such as UK and France planning on banning Internal Combustion Engines (ICE) by 2040 [5].

A key enabling technology for the mass deployment of EVs is Wireless Power Transfer (WPT), which minimizes driver intervention during the EV charging process. Thus, WPT systems act as an enabling technology for autonomous vehicles. With over 85 million autonomous vehicles expected to be deployed by 2035 [5], WPT systems will be a critical aspect of the EV charging infrastructure. Furthermore, WPT systems eliminate the need for charging cables, which presents a safety hazard given the increasing power ratings of on-board EV chargers. According to SAE J1772, on-board chargers are categorized into two categories, Level 1 and 2 AC, which are summarized in Table 1.1. DC fast charging is colloquially referred to as Level 3, although it is currently being standardized. While Level 1 and 2 AC chargers have an AC-DC converter, DC fast chargers connect directly to the battery to charge at high power levels, as shown in Table 1.1.

<table>
<thead>
<tr>
<th>Type</th>
<th>Charge Time</th>
<th>Supply Voltage</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1 AC</td>
<td>Up to 17 hours</td>
<td>120 V_{AC}</td>
<td>0 - 1.9 kW</td>
</tr>
<tr>
<td>Level 2 AC</td>
<td>Up to 1.2 hours</td>
<td>240 V_{AC}</td>
<td>1.9 - 19.2 kW</td>
</tr>
<tr>
<td>DC Fast Charging</td>
<td>Up to 30 minutes</td>
<td>500 V_{DC}</td>
<td>40 kW - 62.5 kW</td>
</tr>
</tbody>
</table>

Based on Table 1.1, Level 2 AC charging is approaching voltage levels that are dangerous if the charging cable is exposed. With WPT systems, the chance for an electrical shock is reduced due to their contactless nature. Due to their numerous benefits, the wireless EV charging market is expected to grow from 8 million USD in 2020 to 407 million USD by 2025 [7]. Various WPT technologies are being developed due to the projected demand for WPT chargers, which are described in the following section.

1.2 Wireless Charging Technologies

WPT technologies can be categorized into two broad categories based on the power transfer distance: near-field and far-field, both of which are described as follows.
1.2.1 Far-field Wireless Power Transfer

Far-field WPT encompasses technologies, such as laser and microwaves, that transmit power wirelessly from several meters to kilometers. These technologies transfer power using radiated electromagnetic waves, which require stringent line-of-sight conditions.

1. Laser Power Transmission (LPT) utilizes high-intensity laser beams to send power to Photovoltaic (PV) panels, which convert the optical energy to electricity, as shown in Fig. 1.2(a). LPT is being developed for applications such as Unmanned Aerial Vehicles (UAV) and satellites. The efficiency of both the laser and PV panel are limiting factors in the adoption of LPT systems with several groups attempting to improve their efficiency, as shown in Table 1.2.

<table>
<thead>
<tr>
<th>Output Power</th>
<th>System Efficiency</th>
<th>Transfer Distance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>[8], 2010</td>
<td>100 W</td>
<td>1.25%</td>
<td>1.1 km</td>
</tr>
<tr>
<td>[9], 2014</td>
<td>9.7 W</td>
<td>11.6%</td>
<td>100 m</td>
</tr>
<tr>
<td>[10], 2006</td>
<td>18.96 W</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2. Microwave Power Transmission (MPT) is similar to LPT, is being developed for UAV and Space Solar Power (SSP) applications. In SSP, multiple satellites are placed in geosynchronous orbit to capture solar energy using PV panels. The solar energy is larger in space given the higher light intensity. The PV panels convert solar energy to electrical energy. Magnetrons receive the electrical energy and convert it to microwaves. A phased array beams these microwaves to the surface of the earth, where it is converted back to electrical energy using rectifying antennas (rectenna) arrays [11]. With efficiency being the bottleneck, several groups have further developed MPT systems, which are summarized in Table 1.3.

<table>
<thead>
<tr>
<th>Output Power</th>
<th>System Efficiency</th>
<th>Transfer Distance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>[12], 2018</td>
<td>8.25 W</td>
<td>16.5%</td>
<td>11 m</td>
</tr>
<tr>
<td>[13], 2004</td>
<td>25.6 mW</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>[14], 2012</td>
<td>8.56 mW</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Based on the examples presented above, it is evident that the fundamental limit on WPT efficiency and physical size of LPT and MPT systems are not sufficient for high-power applications such as EV charging.

1.2.2 Near-field Wireless Power Transfer

Near-field WPT has a transfer distance range from a few millimeters to meters and operates at a higher efficiency than far-field WPT, achieving higher peak power transfer for the same generated heat. Near-field WPT technologies can be broadly divided into two categories:

1. **Inductive Power Transfer (IPT):** Wireless charging is achieved by magnetically coupling two coils. The transmitter coil is excited with high-frequency AC power, which generates time-varying magnetic flux in the surrounding space. Due to faraday's law of induction, a voltage is induced in the receiver coil when placed within proximity of the transmitter coil. By connecting a load to the receiver coil, wireless charging is achieved. A compensation capacitor is connected to each coil to achieve resonance when high-frequency AC power is applied to the resonant tank, as shown in Fig. 1.3. Compensation is necessary to reduce the reactance of the inductive coil, which creates a phase shift between the voltage and current and increases the reactive power drawn. With minimal phase difference between voltage and current, the VA-rating of the power electronics and thus, semiconductor loss is also reduced. IPT systems are easy to implement, safe, and highly efficient at short transfer distances. The efficiency does degrade rapidly with increasing transfer distance due to the increase in leakage flux.

For larger transfer distances, IPT systems typically employ multiple resonator coils to increase the coupling between the transmitter and receiver, as shown in Fig. 1.4.
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This set of IPT systems are typically referred to as **magnetic resonance systems**. The resonator coils are connected in parallel to a capacitor and, by exciting the transmitter coil at their resonating frequency, high efficiency is maintained at a larger transfer distance. The cost of IPT systems increases due to the addition of these multiple coils. Furthermore, the efficiency of IPT systems degrades rapidly when the coils are misaligned. Thus, IPT systems use large coils to maintain the coupling during coil misalignment for a given power level, which increases both the size and cost of the system.

The efficiency and transfer distance improvements introduced by multiple resonator coils increases the operating power of IPT systems to a practical EV charging range and enables its application in several areas, as shown in Table 1.4.
Table 1.4: Survey of Inductive Power Transfer

<table>
<thead>
<tr>
<th>Output Power</th>
<th>System Efficiency</th>
<th>Transfer Distance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>[15], 2014</td>
<td>5.6 kW</td>
<td>95.4%</td>
<td>150 mm</td>
</tr>
<tr>
<td>[16], 2016</td>
<td>3.3 kW</td>
<td>96.6%</td>
<td>200 mm</td>
</tr>
<tr>
<td>[17], 2014</td>
<td>3.3 kW</td>
<td>92%</td>
<td>210 mm</td>
</tr>
<tr>
<td>[18], 2014</td>
<td>6.6 kW</td>
<td>95.6%</td>
<td>200 mm</td>
</tr>
<tr>
<td>[19], 2018</td>
<td>6.6 kW</td>
<td>96.5%</td>
<td>200 mm</td>
</tr>
</tbody>
</table>

2. Capacitive Power Transfer (CPT): While inductive and magnetic resonance coupling transmit power via magnetic fields, capacitive coupling transfers power wirelessly through electric fields, as shown in Fig. 1.5. In capacitively coupled systems, the transmitter and receiver are metal plates that are coupled with an electric field. Inductors are used for compensation and reactive power minimization in CPT systems. Similar to IPT systems, the resonant tank is excited with high-frequency AC power with an AC-DC rectifier connecting the receiver to the load.

Since the capacitance is inversely proportional to the transfer distance, CPT systems operate at high frequencies, typically 6.78 or 13.56 MHz, to maintain the same impedance and power level at distances that are common for IPT systems.
Capacitively coupled systems have low losses, negligible electromagnetic emission, and no eddy current losses [20]. The limiting factor in CPT systems is the energy density of electric fields, which is roughly $10^4$ smaller than magnetic fields [21]. As a result, CPT systems cannot achieve the same power levels as IPT systems for a given coupling area.

<table>
<thead>
<tr>
<th>Output Power</th>
<th>System Efficiency</th>
<th>Transfer Distance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>[22], 2018</td>
<td>1.2 kW</td>
<td>89.8%</td>
<td>120 mm</td>
</tr>
<tr>
<td>[23], 2019</td>
<td>2.25 kW</td>
<td>90%</td>
<td>120 mm</td>
</tr>
<tr>
<td>[24], 2018</td>
<td>884 W</td>
<td>91.3%</td>
<td>120 mm</td>
</tr>
<tr>
<td>[25], 2016</td>
<td>2.2 kW</td>
<td>85.9%</td>
<td>150 mm</td>
</tr>
<tr>
<td>[26], 2016</td>
<td>&gt; 1 kW</td>
<td>≈ 90%</td>
<td>≈ 0 mm</td>
</tr>
</tbody>
</table>

Based on Table 1.4 and 1.5, IPT is the best choice for EV charging applications as it provides higher efficiency, for a given power level and separation gap, than CPT systems. Furthermore, due to the lower electric field density of CPT systems, IPT systems achieve much higher power levels, comparable to Level 2 AC on-board chargers. Thus, IPT is selected as the WPT technology for this thesis. An important aspect of IPT systems is its compensation topology and given its impact on efficiency, several different topologies are discussed in the following section.

### 1.3 Compensation Topologies for IPT systems

IPT systems rely on a capacitive impedance to resonate with the self-inductance of the coil to minimize the reactance of the resonant tank, which reduces the VA rating of the power electronics and, consequently, increases efficiency. By using a capacitor as a compensation device, four topologies are possible: **Series-Series (SS), Series-Parallel (SP), Parallel-Series (PS), Parallel-Parallel (PP)**, as shown in Fig. 1.6. Advanced topologies, such as the **double-sided LCC topology** shown in Fig. 1.6(e), have been developed for additional benefits, albeit at increased system cost.
For EV charging applications, voltage-fed inverters are typically used to generate fast-switching waveforms for power transfer. In the case of the PS and PP topologies, the parallel capacitor, $C_1$ on the transmitter side represents a challenge. Applying a fast switching voltage waveform across $C_1$ would inject large current into $C_1$ according to

$$i_{C_1} = C_1 \frac{dv_{C_1}}{dt}$$  \hspace{1cm} (1.1)

Due to this phenomenon, these topologies are used in current-fed inverter applications and, thus, are not commonly used in IPT systems. A detailed analysis of these topologies is presented in [27]. Due to the high currents in PS and PP topologies, only the SS, SP and double-sided LCC topologies are described in detail.

1. **Series-Series**: Two compensation capacitors, $C_1$ and $C_2$ are connected in series to the transmitter and receiver coils, as shown in Fig. 1.6(a). Each capacitor value is
Chapter 1. Introduction

Determined according to

\[ C_1 = \frac{1}{L_1 \cdot \omega_s^2} \]  

(1.2)

where \( \omega_s \) is the angular operating frequency. From the receiver side, the total impedance, \( Z_2 \), is determined according to

\[ Z_2 = j\omega_s L_2 + \frac{1}{j\omega_s C_2} + R_L, \]  

(1.3)

where \( R_L \) is the load resistance and \( L_2 \) is the self-inductance of the receiver coil. Based on (1.2) and (1.3), the receiver-side impedance, \( Z_2 \), is purely resistive. To determine the impact of compensation on system performance, \( Z_2 \) is reflected to the transmitter according to [28]

\[ Z_r = \frac{\omega_s^2 M^2}{Z_2} = \frac{\omega_s^2 M^2}{R_L} \]  

(1.4)

The resulting impedance has no imaginary component, which allows for high tolerance against system parameter variations. Furthermore, the resonant frequency, \( f_r \), does not heavily depend on mutual inductance and load variations, which enables load regulation by controlling the switching frequency, \( f_s \). By setting \( f_s \) slightly higher than \( f_r \), Zero Voltage Switching (ZVS) is achieved, which reduces switching losses in the power electronics.

The compensation capacitors also act as a blocking capacitor; ensuring no DC offset in the coils to prevent magnetic material saturation. A series-compensated primary coil reduces the voltage seen by the transmitter coil, which potentially relaxes the isolation requirements of the coil design. Due to its ease of implementation and size, several inductive chargers use this topology [29–31].

2. Series-Parallel: Similar to the SS topology, two compensation capacitors are used however, \( C_1 \) is connected in series while \( C_2 \) is connected in parallel, as shown in Fig. 1.6(b). Thus, the receiver-side impedance, \( Z_2 \), changes and is given by

\[ Z_2 = j\omega_s L_2 + \frac{1}{j\omega_s C_2 + \frac{1}{R_L}}. \]  

(1.5)

When \( Z_2 \) is reflected to the transmitter, the reflected impedance, \( Z_r \), is simplified
Based on (1.6), the reflected reactance in this topology is non-zero and depends on the switching frequency, which impacts the controllability of the charger. Similar to SS topology, the primary side capacitor also acts as a blocking capacitor to prevent saturation of the coils. Due to the non-zero reflected reactance, the SP topology is not as popular as the SS topology, however, several works are further developing this topology [32–34]

3. LCC-compensation: A compensation inductor, $L_{f1}$, is connected to a compensation capacitor network on the primary side. On the secondary side, the same compensation network exists. This topology provides both Constant-Voltage (CV) and Constant-Current (CC) operation at all loads conditions if $L_{f1}$ and $C_{f1}$ resonate at the operating frequency. As EV charging requires both CV and CC charging, a compensation network that provides both features is extremely desirable. By using this compensation topology, multiple loads can be charged wirelessly concurrently [28]. The topology is sensitive to variations in the capacitors and inductors, whose addition also increases system cost. Due to its multiple benefits, several groups are developing this topology for IPT systems [35–38]

1.4 Power Electronics for IPT Systems

Wireless charging, specifically inductive power transfer, relies on the principle of Faraday’s law of induction,

$$\mathcal{E} = -\frac{d\phi(t)}{dt}.$$  \hspace{1cm} (1.7)

(1.7) states that time-varying magnetic flux, $\phi(t)$, is required to induce a time-varying potential difference, $\mathcal{E}$, on the secondary loop. However, in EV charging, the battery requires DC power. Thus, power electronics is necessary to interface the charging coils with the battery and AC grid.

On the transmitter side, a high-frequency AC-DC inverter connects the grid voltage to a bus voltage, $V_{bus}$, as shown in Fig. 1.7. The AC-DC inverter is required for Power Factor Correction (PFC) and regulates $V_{bus}$. A full-bridge connects the bus voltage to the transmitter resonant tank, and by operating the inverter near the resonant frequency,
$f_r$, the reactive power drawn by the coils is reduced. Similar to resonant converters, operating the transmitter full-bridge slightly above $f_r$ allows for Zero-Voltage Switching (ZVS) operation for higher efficiency and lower switch stress.

On the receiver side, an AC-DC rectifier composed of diodes interfaces the receiver resonant tank and the EV battery. By tuning the compensation capacitor, $C_2$, to resonate with the self-inductance of the receiver coil, $L_2$, the reflected impedance becomes purely resistive. To control the flow of power, the receiver wirelessly communicates the output power to the transmitter, which then adjusts the input power by controlling $V_{bus}$ or $f_s$.

![Figure 1.7: Conventional power electronics architecture for IPT systems.](image)

### 1.5 Cost of IPT Systems

The cost of IPT systems is dominated by the charging pads, which are composed of expensive ferromagnetic material and Litz wire to minimize high-frequency AC losses. However, only the receiver pad and the AC-DC rectifier are placed in the EV, which reduces the onboard area requirements. Since the transmitter pad and its associated power electronics are off-board and shared amongst multiple EVs, its cost is consequently distributed amongst these EVs and thus, the cost per vehicle of the charger is significantly reduced. In addition, WPT chargers eliminate the need for charging cables, which are quite costly in charging stations due to the amount of copper required in these cables. According to Bosch Automotive Service Solutions, the cable and connector are a third of the entire cost of the charging station due to the amount of copper [39]. However, with high volume production, the cost of these components is expected to decrease.

Inductive chargers for EVs are being manufactured commercially by the U.S. company Plugless. Their plug-in IPT chargers have been designed for the Tesla Model S, BMW i3, and Chevrolet Volt. The price of these IPT chargers ranges from $1260 - $3000 USD depending on the EV [40]. Typical Level 2 charging stations for fleet vehicles cost
approximately $500 - $1000 USD [41]. Based on the cost of both wireless and wired chargers, IPT charger costs approximately 2-3× the cost of traditional wired chargers. The major difference in cost can be attributed to the use of ferrites and Litz wire in the charging pads which are necessary for high coupling.

1.6 WPT Systems and Associated Challenges

Several challenges with WPT systems limit their deployment on a commercial level. Some of the major issues are described below:

**Coil Misalignment:** The inevitable misalignment between the transmitter and receiver, which degrades charger efficiency, is a major impediment to the adoption of WPT systems. Several different coil structures are proposed in literature to improve misalignment tolerance. The spiral coil, shown in Fig. 1.8(a), is the most commonly used due to its simple structure [42–45]. Other coil structures such as DD type [46, 47] and solenoid type [48, 49], shown in Fig. 1.8(b) and (c) respectively, allow for larger misalignment along a particular axis.

![Figure 1.8: Model of (a) spiral, (b) DD, and (c) solenoid coil structures.](image_url)

More advanced coil structures have been proposed to improve the efficiency under large misalignment, some of which are listed below.

- In [50], an asymmetric multi-coil wireless EV charger is presented for a 20 kW Inductive Power Transfer (IPT) system. The charger incorporates a second counter-current coil into the transmitter pad to increase the misalignment tolerance of the charger. By doing so, the charger observes a 1.15 kW increase in output power at rated load. Furthermore, there was a 4.76kWh (6.3%) increase in energy transfer over a standard charging profile.
• A new coil structure, the Quad D Quadrature (QDQ) coil, is proposed in [51]. A 700W prototype of the QDQ coil structure achieved an efficiency of 93.8% near-perfect alignment, while maintaining an efficiency of 78.5% when subjected to 150 mm misalignment.

• An adjustable coupler composed of multiple coils is proposed for IPT systems in [52]. The coupler can be energized into three separate areas using semiconductor switches. By enabling the least misaligned area, the system increases the efficiency from 8.3% to 28.6%.

When the misaligned distance approaches the width of the coil, these structures cannot mitigate the drop in efficiency. Hence, transmitter coils much larger than the receiver pads are used in WPT systems to improve their misalignment tolerance.

Advanced compensation topologies also impact the misalignment tolerance of the charger. In [53], a four-coil compensation topology was presented in [53]. The proposed topology maintains a coil efficiency of 95% with 20 cm of misalignment. While the passive mitigation of the coil misalignment is desirable, the addition of multiple coils and capacitors increases the system size and cost.

Alternatively, the transfer efficiency can be improved by reducing the coil misalignment before commencing WPT. In [54], a WPT charger was demonstrated with a mechanical drive system consisting of conveyors and servo motors that align the transmitter to the receiver. This system provides a wide correction area within the range and resolution of the conveyor and sensors, respectively. The additional mechanical components, however, result in high system cost.

To avoid such complicated mechanical drive systems, the coil position can be sensed and sent as feedback for improved alignment. Such sensing techniques can be categorized into two categories:

• Radio position-sensing
• Magnetic position-sensing

Radio position-sensing techniques use RFID tags placed on the charging pads to accurately determine the pad positions [55]. The additional RF hardware, however, increases the system cost and complexity significantly.

Magnetic-positioning sensing schemes estimate the coupling coefficient of the coil structure, which depends on misalignment, to provide feedback for improved alignment. While less accurate than radio, magnetic position-sensing utilizes most of
the existing hardware, which reduces system cost. Several examples of magnetic-position sensing schemes are listed below:

- In [56], four auxiliary coils are mounted on the secondary coil to sense the coil position in three dimensions.
- In [57], an optimized pick-up coil array is used to minimize the position detection error in a magnetic motion-sensing system [57].
- In [58], a wireless LC-based scheme with three small sensing coils is proposed to estimate the coupling coefficient and provide feedback on coil position.
- In [59], a set of non-overlapping coils are presented for wireless EV chargers, which are used for metal object and vehicle position detection.

**Efficiency degradation over large gap:** The separation gap is limited to 120 mm due to the EV ground clearance, which degrades the coupling coefficient and transfer efficiency. Consequently, the larger gap results in higher transmitter current consumption for a given power level; leading to more stringent switch requirements. Several works have attempted to increase the separation gap while maintaining high efficiency, with some of them being summarized in Table 1.6.

<table>
<thead>
<tr>
<th>Output Power</th>
<th>System Efficiency</th>
<th>Transfer Distance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>[60], 2014</td>
<td>1 kW</td>
<td>80%</td>
<td>250 mm removes additional communication hardware by transferring information via amplitude modulation of the coil current</td>
</tr>
<tr>
<td>[61], 2013</td>
<td>6.6 kW</td>
<td>88%</td>
<td>200 mm</td>
</tr>
<tr>
<td>[62], 2018</td>
<td>2.75 kW</td>
<td>&gt;90%</td>
<td>185 mm</td>
</tr>
<tr>
<td>[63], 2014</td>
<td>3.7 kW</td>
<td>95.12%</td>
<td>≈ 0 mm Introduced mechanical structure to guarantee zero air-gap and misalignment</td>
</tr>
<tr>
<td>[64], 2018</td>
<td>15.6 kW</td>
<td>75%</td>
<td>150 mm</td>
</tr>
</tbody>
</table>

### 1.7 Placement of WPT Charging Pads in EVs

For WPT chargers, the placement of the charging coils is particularly important as the coils are typically much larger than the associated power electronics. Furthermore, the challenges associated with WPT systems such as coil misalignment and large separation gap are directly related to the placement of the charging pads.
Conventionally, the charging pads are placed on the underside of the EV [65–67], as shown in Fig. 1.9, which allows the transmitter pad ease of access to the receiver pad. Furthermore, underside-mounted WPT chargers enable the application of quasi-static and dynamic wireless charging. Quasi-static wireless charging [68] refers to a hybrid of static and dynamic charging. For instance, in EV buses, receiver coils can be installed at bus stations, maximizing the charge time for the EV bus and reducing battery requirements.

![Figure 1.9: Conventional WPT systems are mounted on the EV underside [69, 70].](image)

Dynamic charging refers to the continuous wireless charging of EVs while the vehicle is in motion [71–75]. Multiple receiver coils are installed within the road so that energy is transferred once the EV is within proximity of a particular coil. Doing so reduces the battery requirements significantly and expedites the commercialization of EVs.

The safe emission of magnetic fields created by the underside placement of the charging pads is a major challenge. With the increasing requirements of reduced charging times, manufacturers are trending towards EV charging at high power. However, in WPT systems, high power transfer results in larger magnetic field emission. The large separation gap results in low magnetic coupling which, consequently, leads to higher leakage flux. While certain coil structures channel magnetic flux in a single direction such as the spiral and DD type, several coil structures, such as the solenoid coil, generate flux in both directions. Thus, there are safety concerns regarding the emission of magnetic field given the proximity of the coils to the EV passengers.

Standards have been placed on wireless EV chargers to ensure safe emission of magnetic field. ICNIRP 2010 sets the maximum magnetic flux density for general exposure, $B_{RL} = 27 \, \mu T$ [76], at 85 kHz. Under all operating conditions, human exposure to magnetic flux density cannot exceed this value during wireless power transfer. Ferromagnetic material is used to reduce the reluctance between the transmitter and receiver coil. The
resulting magnetic flux is well-contained and allows for a higher coupling coefficient. However, the primary method of reducing leakage flux is by placing a shield between the vehicle underside and receiver coil. Shielding reduces the emission of magnetic field by inducing eddy currents, which create their own magnetic field. These induced magnetic fields cancel the leakage flux and reduce the overall magnetic field emission. Shields are typically composed of aluminum and occupy a significant area of the vehicle underside.

Many of the challenges associated with underside-mounted WPT chargers can be resolved by vertically-mounting the charging pads. In underside-mounted WPT chargers, the separation gap is limited by the EV ground clearance, typically to 120 mm. However, by vertically-mounting the charging pads, the separation gap is no longer constrained by the EV ground clearance. The smaller separation gap results in a higher coupling coefficient and thus, higher efficiency. The target application for the wireless charger in this thesis is fleet vehicles, shown in Fig. 1.10, as their flat rear is an ideal location for vertically mounted WPT chargers. The charger is placed further from humans when vertically mounted, which potentially reduces human exposure to magnetic field.

![Figure 1.10: The target application of the proposed wireless charger is fleet vehicles.](image)

1.8 Thesis Motivation and Objectives

To address the issue of coil misalignment, mechanical alignment is an attractive solution due to its small size pads, for a given power level, and high-efficiency over a wide misalignment range, however, the maintenance cost of mechanical components such as motors is a limitation. Hence, the goal is to achieve self-correction mechanically, but with the simplest possible mechanical design.
Based on this goal, the focus of this thesis is the design and optimization of a dual-coil charging pad capable of lateral self-alignment for reduced coil misalignment. Aside from better coupling, the self-alignment capability of the pad reduces the size of the large transmitter coils necessary in existing solutions. The charging pad is vertically mounted on the EV for a reduced separation gap and, consequently, high efficiency. However, the separation gap varies based on parking accuracy. Thus, a position-correcting control algorithm is required to systematically correct the pad position for improved pad alignment. The objectives of this thesis are:

1. Achieve a peak DC-DC efficiency above 90% with a nominal separation gap of 50 mm at 5kW WPT to achieve charging times comparable to Level 2 AC charging.

2. Reduce lateral misalignment to less than 20 mm with the dual-coil charging pad.

3. Optimize the charging pad structure for increased power transfer and lower losses.

4. Design a control algorithm for systematically position-correcting the charging pads to perfect alignment.

To validate the proposed dual-coil charging pad, simulation and experimental data are used to verify the feasibility of the design. This leads us to the following methodology:

- Design a simulation model to verify the performance of the charging pads
- Build a prototype of the dual-coil charging pad with the target specifications
- Evaluate the performance of the prototype system under real-world scenarios and
- Characterize the performance of the position-correcting control algorithm with various parking scenarios

The experimental results along with the simulation results demonstrate the effectiveness of the dual-coil charging pad for EV wireless charging. Moreover, the proposed position-correcting control algorithm enables the proposed WPT system to operate under ideal parking condition and, consequently, high efficiency.

This thesis is organized as follows. The system-level architecture of the dual-coil charging pads along with the simulation results is presented in Chapter 2. The proposed position-correcting control algorithm is presented and analyzed in Chapter 3. The experimental verification of the dual-coil charging pads and position-correcting control algorithm under real-world scenarios is presented in Chapter 4. The conclusions drawn from this work and potential future developments are outlined in Chapter 5.
References


REFERENCES


REFERENCES


REFERENCES


[70] A. Coquet, “Battery Icon,” From the Noun Project.


Chapter 2

Dual-Coil Charging Pad Architecture

2.1 Design of Dual-Coil Charging Pad

The proposed WPT system is comprised of a rear-side receiver pad and a vertically-mounted transmitter pad, as shown in Fig. 2.1. Compared to a conventional WPT system with an underside-mounted charging pad, the proposed placement results in a smaller gap, leading to better magnetic coupling and higher efficiency. The transmitter pad is mounted on a linear slider that allows for lateral movement.

Each charging pad is composed of two coils, as shown in Fig. 2.1. An electro-magnetic-based coil, denoted as the DC coil, is activated by applying a fixed-duration pulse of DC current, which creates a magnetic force, $F_{mag}$, between the pads. The resulting magnetic force laterally aligns the linear-slider mounted transmitter pad to the receiver pad. The
power transfer coil, denoted as the AC coil, is integrated with the DC coil, as shown in Fig. 2.1. To maintain high coupling, the AC coil performs WPT only after alignment.

Throughout this thesis, the misalignment along the x-direction and z-direction are defined as $\Delta x$ and $\Delta z$, as shown in Fig. 2.2(a) and (b). Likewise, the separation gap between the charging pads is defined as $\Delta y$, as shown in Fig. 2.2(c).

![Simulation model of the dual-coil charging pad defining (a) lateral misalignment, $\Delta x$, (b) vertical misalignment, $\Delta z$, and (c) separation gap, $\Delta y$.](image)

To achieve a compact design, the DC coil serves as a structural case for the AC coil with both being perpendicularly integrated with each other. This orientation reduces the circulation of the AC coil magnetic flux density in the DC core. Nevertheless, there is still leakage flux from the AC coil during WPT that induces eddy currents in the DC core, causing shielding to become critical for this charging pad as it leads to lower losses in the DC core and improves the efficiency.

### 2.1.1 Power Electronics Architecture

The power electronics architecture, shown in Fig. 2.3, consists of full-bridge converters, $M_1 - M_4$ and $M_7 - M_{10}$, being used to drive the AC coils for WPT and half-bridge converters, $M_{5,6}$ and $M_{11,12}$, driving the DC coils during self-alignment. The DC coil current, $I_{DC}$, is regulated to a constant value using the half-bridges, which maintains a constant $F_{mag}$ for the duration of self-alignment.

On the transmitter side, the full-bridge inverter converts the bus voltage, $V_{bus}$, to an 85 kHz square waveform with 50% duty cycle. The Series-Series (SS) capacitor compensation [1], shown in Fig. 2.3, is chosen for resonance at 85 kHz due to its ease of implementation and size. The values of $C_1$ and $C_2$ were selected for resonance at 85 kHz with the AC coil self-inductances, $L_1$ and $L_2$, at $\Delta x = 0$ mm.
On the receiver side, the full-bridge converter, as shown in Fig. 2.3, acts as a synchronous rectifier to supply current to the EV battery. To achieve a charging time comparable to traditional on-board wired chargers, the WPT system was designed for Level-2 AC charging ports with a power rating of 5 kW. The symmetric nature of the system architecture allows for bi-directional power transfer; enabling Vehicle-to-Grid (V2G) operation of the proposed WPT system. An increasing number of bi-directional EV chargers are adopting V2G operation [2–4]. By enabling V2G operation, the EV battery can transfer energy to the grid during peak demand hours and provide grid-support functions.

![Power electronics architecture of the proposed WPT system.](image)

**Figure 2.3:** Power electronics architecture of the proposed WPT system.

### 2.1.2 Design of Electromagnetic-Based DC Coil

The core of the DC coil is constructed with low-cost carbon steel. The DC coil is implemented with standard copper windings, as Litz wire is not required to reduce skin effect losses. The transmitter DC coil has 100 turns while the receiver DC coil has 70 turns. As the pads are aligned, $|F_{mag}|$ increases due to stronger magnetic coupling. However, the direction of $F_{mag}$ changes from along the x-axis to the y-axis, causing a decrease in its x-component, $F_{mag,x}$, which directly contributes to self-alignment. Thus, to achieve a wide misalignment correction range, $F_{mag,x}$ must be sufficiently large to overcome the friction force of the linear slider for misalignments that are comparable to the pad width.

The thickness of the steel core, $\Delta d$, which impacts the cost and weight of the charger system, was selected to generate sufficient $F_{mag,x}$, as shown in Fig. 2.4(a). For $\Delta d \leq 4$ mm, $F_{mag,x}$ diminishes significantly while only a marginal increase in $F_{mag,x}$ is observed for
\[ \Delta d \geq 6 \text{ mm.} \] Hence, \( \Delta d \) was chosen to be 8 mm to overcome the slider friction force over a wide range of \( \Delta x \). While a lighter core results in lower friction force and core loss during WPT, \( F_{mag} \) also diminishes with smaller \( \Delta d \); presenting an interesting optimization problem beyond the scope of this thesis.

To further increase \( F_{mag} \), the DC steel core was extended by a height, \( h_{ext} \). By increasing the surface area of the steel core, the magnetic flux linkage between the two coils increases; allowing for larger \( F_{mag} \) for a given \( I_{DC} \), as shown in Fig. 2.4(b). By increasing \( h_{ext} \) from 10 mm to 25 mm, \( F_{mag,x} \) increases from 4 N to 5 N. In this way, \( F_{mag,x} \) is increased independently of \( \Delta d \) and hence, with minimal impact on the DC core mass.

![Figure 2.4: (a) Simulated \( F_{mag,x} \) versus \( \Delta d \) with \( h_{ext} = 25 \text{ mm} \) and \( I_{DC} = 30 \text{ A.} \) (b) Simulated \( F_{mag,x} \) versus DC core extension, \( h_{ext} \), with \( \Delta d = 8 \text{ mm} \) and \( I_{DC} = 30 \text{ A.} \)]
2.1.3 Design of Solenoid-based AC Coil

The AC coil is comprised of ferrite bars to improve the magnetic coupling. To minimize skin effect losses, Litz wire is used for the AC coil windings. The ferrite bars are designed to optimize the inductance and coupling of the coils for WPT. A shield is placed around the DC coil, as shown in Fig. 2.1, to prevent the magnetic field of the AC coil from flowing through the DC steel core during WPT. The shield reduces the losses in the steel core and increases the AC coil magnetic flux linkage.

![Normalized vertical misalignment vs. normalized mutual inductance](image)

Figure 2.5: Simulated mutual inductance versus Δz for various coil structures.

Since the target application of the proposed charger is fleet vehicles, the payload of the vehicle would create compression variations in the shock absorbers; resulting in vertical misalignment, Δz, between the charging pads. Given that the DC coil self-corrects for Δx, the AC coil structure was selected for its inherent tolerance against Δz. Three coil structures shown in Fig. 1.8, Spiral, DD, and solenoid, were simulated to compare their mutual inductance versus Δz, as shown in Fig. 2.5. The vertical misalignment was normalized to the charging pad width for a fair comparison. Based on Fig. 2.5, the solenoid coil structure was selected since it maintains 18% of its nominal mutual inductance despite a 150% increase in Δz.

The height of the AC coil, \(h_{sol}\), is determined by

\[
h_{sol} = h_{pad} - 2h_{ext},
\]

where \(h_{pad} = 210\) mm and \(h_{ext} = 25\) mm. The ferrite bars are spatially distributed across the AC coil. The nominal AC coil design parameters are provided in Table 2.1. Due to the vertical mounting of the charging pad, the separation gap is not limited by the vehicle suspension, where 120 mm is typically needed. A nominal separation gap of 50 mm is feasible; resulting in a coupling coefficient, \(k\), of 0.41; an 87.9% increase as compared to
conventional coil designs such as [5].

The simulated mutual inductance versus lateral misalignment, $\Delta x$ is shown in Fig. 2.6(a). The mutual inductance begins to decrease rapidly for $\Delta x \geq 20$ mm. At $\Delta x = 100$ mm, there is zero coupling between the pads due to the symmetric positioning of the coils canceling the magnetic field. However, the self-alignment of the pads ensures a small $\Delta x$; resulting in high mutual inductance during WPT.

![Figure 2.6: Simulated AC coil mutual inductance versus (a) misalignment in x-direction, $\Delta x$, and (b) separation gap, $\Delta y$.](image)
The impact of the separation gap, $\Delta y$, is much more significant for the charger operation as the dual-coil charging pad cannot correct for any $\Delta y$. The mutual inductance varies almost linearly with the separation gap, as shown in Fig. 2.6(b). However, by leveraging the vertical mounting of the pads, the gap can be directly adjusted by the driver to maintain high mutual inductance.

### 2.2 Optimization of Ferrite Bar Spacing

At relatively high power transfer, it becomes necessary to increase the magnetic coupling of the coils to reduce leakage flux. To accomplish this, separate ferrite bars are used in solenoid coils as their low reluctance channels the magnetic flux through the bars from transmitter to receiver. Due to the high cost of ferromagnetic material, the minimum amount of ferrite volume is used. The custom-fabricated bars are distributed across the solenoid coil to distribute the magnetic flux. The spacing is necessary, otherwise, the temperature of the ferrite bars increases due to the high core loss associated with high magnetic flux density. To understand the effect of ferrite bar spacing on power transfer, an analysis of the magnetic flux density, $B$, in the solenoid coil is required.

![Magnetic flux density distribution of the solenoid coil. The increase of flux density at the edges of solenoid results in higher core loss.](image)

Assuming steady-state sinusoidal current flow in an infinitely long straight wire, a
steady-state sinusoidal flux density, $B_{\text{wire}}$, is generated around the wire according to

$$B_{\text{wire}} = \frac{\mu_0 I}{2\pi r},$$  \hspace{1cm} (2.2)$$

where $\mu_0$ is the magnetic permeability, $I$ is the current through the wire, and $r$ is the distance away from the wire.

The simulated magnetic flux density distribution of the solenoid coil is shown in Fig. 2.7. Ferrite bars placed near the center of the coil are exposed to the Litz wire on the front and back sides; causing them to experience a magnetic flux density of $2 \times B_{\text{wire}}$. Approximating the Litz wire at the top of the solenoid as a straight wire, the ferrite bars placed at the solenoid edges are exposed to the Litz wire on three sides; resulting in a magnetic flux density of $3 \times B_{\text{wire}}$. The higher $B$ results in a higher core loss in the ferrite bars near the edges as compared to the ferrite bars near the center. The high core loss limits the maximum power transfer since the resulting increase in core temperature cannot be stabilized by convection cooling.

A potential solution is to use a uniform block of ferrite as opposed to multiple bars, which results in a lower reluctance. This distributes the magnetic flux such that lower $B$ is experienced at the solenoid edges at the expense of increased ferrite volume and cost. Another approach, as demonstrated in this thesis, is to use ferrite bars with non-uniform spacing near the solenoid edges, where higher $B$ is expected. Electromagnetic simulations of the AC coil were performed at 5kW WPT as the spacing of the ferrite bars was varied.

![Figure 2.8: Simulated magnetic flux density distribution at 5kW WPT with (a) 10 mm spacing, and (b) optimally spaced ferrite bars. Note that in the case of non-uniformly spaced ferrite bars, the flux density is more uniform and the peak is reduced by 20%.](image-url)
to determine its effect on the magnetic flux density distribution, as shown in Fig. 2.8. By increasing the concentration of ferrite bars near the edges of the AC coil as shown in Fig. 2.8(b), the peak magnetic flux density decreases from 260 mT to 208.2 mT; a 20% reduction without increasing the total volume of ferrite material.

### 2.3 Optimization of Copper Shield

Although ferrite bars increase the magnetic coupling, the solenoid coil structure still suffers from significant leakage flux that induces eddy currents in the DC core, causing core loss according to core loss according to

$$P_v = k \cdot f^a \cdot B^b,$$  \hspace{1cm} (2.3)

where $P_v$ is the time average power per unit volume in mW/cm³, $f$ is the frequency in kHz, and $k$, $b$, and $a$ are empirically determined coefficients based on the B-H curve of the material. To mitigate this effect, a copper shield is placed between the AC coil and DC coil, as shown in Fig. 2.1. While shielding reduces losses in the steel core, eddy currents generated in the shield result in ohmic losses as well. Due to the skin effect, the high-frequency eddy currents circulate primarily within a penetration depth of 0.224 mm, which is calculated according to

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}},$$ \hspace{1cm} (2.4)

where $\delta$ is the penetration depth, $\rho$ is the resistivity of copper, $f$ is the frequency, and $\mu$ is the magnetic permeability of copper. To account for the skin effect, the shield thickness was varied in simulation to reduce the eddy current losses, as shown in Fig. 2.9. As expected, the eddy current loss, $P_e$, increases significantly below a shield thickness of 0.3 mm as the thickness approaches the penetration depth. A shield thickness of 0.5 mm was selected to achieve a low eddy current loss of 49.3 W at 5kW WPT without increasing the total mass of the pad significantly.

Due to the U-shape of the DC steel core, the copper shield must be bent to mitigate the leakage flux circulation in the steel core. Due to manufacturing imperfections, gaps and crevices between the shield are created when the copper sheet is bent to cover the corners of the steel core. This phenomenon allows leakage flux to directly circulate within the DC core, which leads to significant losses. Hence, an alternative solution is to create a shield from multiple isolated pieces of copper that have no gaps or crevices. Since eddy
currents are induced in the shield, the current distribution in the shields composed of both a continuous sheet and multiple isolated pieces of copper is analyzed.

A continuous sheet of copper covering a corner of the DC core is exposed to a time-varying magnetic flux density, $B_{\text{solenoid}}$, as shown in Fig. 2.10(a). By Faraday’s law of induction, an opposing electromotive force (EMF), $\mathcal{E}$, is generated according to

$$\mathcal{E} = -\frac{d\phi_{\text{solenoid}}}{dt},$$

(2.5)

where $\phi_{\text{solenoid}}$ is the magnetic flux due to $B_{\text{solenoid}}$ over a certain area, $A$. The EMF results in circulating eddy currents that generate an opposing magnetic flux density. The eddy currents are lower near the center since the currents circulate along the edges of the sheet. Since the circulation path is the entire sheet, the resulting ohmic loss is low. To understand the current distribution of the shield composed of multiple isolated copper pieces, the continuous sheet is split into three pieces, as shown in Fig. 2.10(b). By doing so, the eddy currents are constrained to each individual piece of copper, which causes the current density around the boundary to increase and resulting in high ohmic losses. Thus, a shield composed of multiple isolated pieces of copper incurs more eddy current losses than a shield composed of a continuous sheet at the expense of lower DC core loss caused by shield manufacturing imperfection.

To verify this analysis, electromagnetic simulations were performed to observe the current density distribution in the copper shield, as shown in Fig. 2.11. The hypothetical worst-case scenario was first considered, where a shield is composed of multiple copper pieces that are electrically isolated. As expected in this scenario, the current density is
Figure 2.10: Eddy current distribution in (a) a continuous sheet of copper and (b) multiple isolated pieces of copper.

significantly high along the boundaries of copper pieces, as shown in Fig. 2.11(a), due to the eddy currents being constrained to each piece. To reduce eddy current loss, a realistic option is to use a conductive copper tape of 88.9 µm thickness to electrically connect the multiple isolated pieces of copper. By doing so, the eddy currents circulate around the entire shield.

To account for the resistance of the copper tape in the simulation, each piece of the shield is connected with an 88.9 µm strip of copper. The copper tape reduces eddy currents significantly, as shown in Fig. 2.11(b), with a 71% reduction in eddy current losses from $P_e = 238.4$ W to $P_e = 69.6$ W. While copper tape does reduce eddy current circulation, the limiting factor is the thickness of the copper tape, which is much smaller than the penetration depth of copper at 85 kHz. Thus, due to the skin effect, the current density is still relatively higher along the boundaries, as shown in Fig. 2.11(b).

To mitigate this effect, a shield composed of a continuous sheet of copper was simulated to observe the eddy current density, as shown in Fig. 2.11(c). The current density is much smaller in the continuous sheet of copper, as shown in Fig. 2.11(c), with a peak of $5.74 \times 10^7$ A/m$^2$ as compared to $8.13 \times 10^8$ A/m$^2$ in the shield with copper tape. The current density peaks around the boundaries of each copper piece in Fig. 2.11(a) and (b), whereas it stays relatively uniform for the continuous sheet of copper, as shown in Fig. 2.11(c). This is primarily due to a thicker connection at each bend in the continuous sheet of copper. In terms of eddy current loss, the continuous sheet of copper performs much better with $P_e = 49.3$ W as compared to $P_e = 69.6$ W for the copper tape shield.
Current density increases at boundaries due to eddy current path constraint

\[ J \left[ \text{A/m}^2 \right] \]

Current density larger near boundaries due to thin copper tape

\[ J \left[ \text{A/m}^2 \right] \]

Eddy current circulation around entire shield leads to lower current density

\[ J \left[ \text{A/m}^2 \right] \]

\[ P_e = 238.4 \text{ W} \]

\( \text{(a)} \)

\[ P_e = 69.6 \text{ W} \]

\( \text{(b)} \)

\[ P_e = 49.3 \text{ W} \]

\( \text{(c)} \)

Figure 2.11: Simulated current density distribution at 5kW WPT of the shield when composed of (a) multiple isolated pieces of copper, (b) multiple isolated pieces connected with thin copper tape and, (b) a continuous sheet of copper

2.4 Simulation Results of Dual-Coil Charging Pad Operation

The simulated magnetic field distribution of the coil system during self-alignment and WPT are shown in Fig. 2.12. To prevent interference of magnetic fields, the DC and AC coils are physically integrated perpendicular to each other. Doing so minimizes the losses in the steel core of the DC coil incurred due to the magnetic field. During WPT, the magnetic field in the DC coil is nearly zero due to the copper shield.
Figure 2.12: Simulated magnetic field distribution during (a) self-alignment and (b) 5kW WPT.

The simulated efficiency versus lateral misaligned distance, $\Delta x$, at 5 kW WPT is shown in Fig. 2.13. The efficiency was determined by extracting the lumped element model of the coil structure using Finite Element Analysis (FEA) simulation tools and then running a circuit-level simulation including non-ideal switches in PLECs. Losses due to magnetic fields such as core and eddy current loss are also included by using FEA tools. A peak efficiency of 96.5% is achieved at $\Delta x = 0$ mm and high efficiency is maintained up to $\Delta x = 20$ mm. The shield entirely covers the DC coil and so the loss in the DC coil are not accounted for the simulated efficiency. Furthermore, carbon steel is not commonly used as a core in high-frequency applications and thus, there is no core loss data for carbon steel at 85 kHz. In the experimental results, it is expected that due to imperfections in the shielding, the leakage flux circulation in the DC steel core would further degrade the system efficiency. Given that there is a 6.5% difference between the simulation and target efficiency of 90%, there is sufficient margin to achieve the target efficiency despite the additional losses in the DC core.
The loss breakdown of the dual-coil charging pad is shown in Fig. 2.14 at $V_{bat} = 400$ V and 5kW WPT. The eddy current loss in the shield is approximately equal to the loss in the ferrite cores. The large loss in the shield is due to the solenoid coil structure, as it inherently generates magnetic flux bidirectionally. Thus, the resulting leakage flux contributes to the eddy current loss in the shield. Due to EV payload variations, the inherent vertical misalignment of the solenoid coil structure is necessary, as shown in Fig. 2.5. For simplicity and verification of functionality, the full-bridge rectifier was composed of diodes instead of MOSFETs, which results in the rectifier losses being twice as large as the inverter losses. By doing so, the safety margin between the simulated and target efficiencies is increased.
The simulated magnetic field distribution of the coil system under 5kW WPT is shown in Fig. 2.15 under two conditions; Δx = 0 and 80 mm. The magnetic field is well contained within the coil system with an offset, Δx, of 0 mm, as shown in Fig. 2.15(a). At Δx = 80 mm, the magnetic field dramatically increases to 15 mT and the transmitter current increases from 13.5 A\text{rms} to 59.1 A\text{rms} due to the reduction in the AC magnetic field linkage. This corresponds to the steep efficiency drop in Fig. 2.14 around Δx = 80 mm. Note that the efficiency at Δx = 100 mm is not presented since WPT is not feasible due to the excessive transmitter current required. The operation of the proposed charger is not affected by low-efficiency operating conditions caused by Δx as WPT only occurs after the self-alignment process is performed.

![Transmitter Receiver](image)

Figure 2.15: Magnetic field simulation of 5kW WPT with (a) Δx = 0 mm, and (b) Δx = 80 mm, before self-alignment.

Fig. 2.16(a) shows the simulated magnetic force in the x-direction, $F_{mag,x}$, with respect to lateral misalignment, Δx. With Δz = 0 mm, $F_{mag,x}$ peaks at 5 N and is able to
overcome the friction force from $\Delta x = 20 \text{ mm}$ to $\Delta x > 200 \text{ mm}$, which is the coil width in this design. Similarly, even at $\Delta z = 60 \text{ mm}$, $F_{\text{mag,x}}$ is able to overcome the friction force over a large range of $\Delta x$. The vertical magnetic force, $F_{\text{mag,z}}$, versus vertical misalignment, $\Delta z$ is shown in Fig. 2.16(b). If $\Delta z$ is significantly large, the vertical misalignment in the $z$-direction can be resolved by the DC coils as well by using an additional linear slider and installing counterweights.

Figure 2.16: (a) Simulated $F_x$ versus $\Delta x$ with $I_{\text{DC}} = 30 \text{ A}$. (b) Simulated $F_{\text{mag,z}}$ versus $\Delta z$ with $I_{\text{DC}} = 30 \text{ A}$.

### 2.5 Chapter Summary and Conclusions

In this chapter, the architecture of the dual-coil charging pads was presented along with simulation results to determine the feasibility of the proposed charger. A simulation model of the dual-coil charging pad was created using ANSYS 3D Maxwell to determine the charging pad design parameters. For the AC coil, the solenoid coil structure was
selected due to its superior tolerance to vertical misalignment. The peak simulated efficiency was 96.5% with a steep drop in efficiency as $\Delta x$ increases. The impact of the thickness of the DC core was determined on the generated magnetic force and its trade-offs were considered. The electrical architecture of the charger was presented, which highlighted the symmetric nature of the power electronics facilitates bi-directional power transfer. The ferrite bar spacing was varied to determine its impact on the charger operation. The AC coil magnetic flux is reduced by 20% when a non-uniform ferrite bar spacing is used, which increases the power transfer capability of the charger. Details of the copper shield required for leakage flux minimization were also investigated. The eddy current loss in the shield is reduced by 29% when using a single copper piece as opposed to multiple pieces.
References


Chapter 3

Position-Correcting Control Algorithm

3.1 Introduction

While the DC coils correct for lateral misalignment, $\Delta x$, the vertical mounting of the charger can lead to larger variations in the separation gap, $\Delta y$, due to inaccurate parking. Thus, feedback on the coil position must be provided, which enables efficient WPT under ideal parking conditions. Several papers that address the issues of coil position sensing are mentioned in Section 1.6, however, each has its own unique challenges:

- In [1], four auxiliary coils are mounted on the secondary coil to sense the coil position in three dimensions. The primary coil generates a magnetic field, which induces a voltage on the auxiliary coils used for position sensing. For safety reasons, the magnetic field must be weak which can otherwise damage hardware if the coil is operated with large misalignment at high power.

- An optimized pick-up coil array is used to minimize the position detection error in a magnetic motion-sensing system [2]. The detection error is reduced to sub-millimeter order, twenty-five LC resonant tanks are used which increases cost and size significantly.

- A wireless LC-based scheme with three small sensing coils is proposed to estimate the coupling coefficient and provide feedback on coil position [3]. A wireless LC-based scheme with three small sensing coils is proposed to estimate the coupling coefficient and provide feedback on coil position, however, the additional coils and capacitors increases system cost and size.
In [4], a set of non-overlapping coils are presented for wireless EV chargers, which are used for metal object and vehicle position detection. The detection scheme depends on the ferrite core dimensions which constrains the charger design.

All of these works require additional sensing components to estimate the coupling coefficient, which depends on lateral misalignment and sends it as feedback for improved vehicle alignment. This work proposes a position-correction control algorithm for the dual-coil charging pad which is presented in this chapter. The algorithm utilizes solely the existing coil structure and hence, does not require any additional sensing components. The control algorithm, shown in Fig. 3.1, corrects $\Delta x$ using the DC coils and provides feedback on $\Delta y$ for gap adjustment. Once the vehicle is parked, the receiver communicates wirelessly to the transmitter to begin the position-correcting process. The initial parking conditions may result in both large $\Delta x$ and $\Delta y$, which necessitates a systematic method for position correction. The control algorithm operates in three phases iteratively:

1. **DC coil self-alignment** is performed by energizing the DC coil to correct $\Delta x$. The DC coils are enabled for a sufficiently large duration to correct $\Delta x$ in the presence of weaker $F_{mag}$. However, if $\Delta y >> 50$ mm, a significant $\Delta x$ persists irrespective of the self-alignment duration. Thus, $\Delta y$ must be first reduced before self-alignment can be performed to correct $\Delta x$. Finally, before proceeding to WPT, self-alignment is performed to remove any residual $\Delta x$.

2. **AC coil impedance detection** measures the impedance of the resonant tank to estimate magnetic coupling, as described in Section 3.2. If the coupling is sufficient, the charger proceeds to WPT. However, if the coupling remains weak despite DC coil self-alignment, the controller attributes the weak coupling to a large $\Delta y$ which requires adjustment.

3. **AC coil resonant frequency detection** provides feedback on $\Delta y$ with a detailed description in Section 3.3. On the initial gap adjustment attempt, the vehicle is adjusted until the resonant frequency, $f_r$, reaches a threshold, $f_{r,1}$. This is necessary as it provides sufficient $F_{mag}$ for self-alignment to correct any remaining $\Delta x$ despite $\Delta y > 50$ mm. Otherwise, the $f_r$ detector would compensate for remaining $\Delta x$ with $\Delta y < 50$ mm. Self-alignment is repeated, which further reduces $\Delta x$ due to the larger $F_{mag}$. AC coil impedance detection checks for alignment again, however, it fails as $\Delta y$ is too large. Thus, the AC coil $f_r$ detector is enabled however, this time, the vehicle is adjusted until $f_r < f_{r,2}$ which results in $\Delta y = 50$ mm.
Once alignment is achieved, the charger commences WPT. Aside from rectifying the AC current from the charging pad, the receiver communicates with a Battery Man-

---

Figure 3.1: Proposed position-correcting control scheme.
agement System (BMS) which sends commands to the charger to control the charging process. The output power data is sent to the transmitter, which regulates power by adjusting \( V_{bus} \). Once the battery is charged, the receiver signals the transmitter to terminate the power transfer.

### 3.2 Impedance-Based Detection for Improved Self-Alignment

To determine when alignment is achieved, this technique measures the transmitter tank impedance, \( Z_{tank,tx} \), as the self-inductance of the transmitter coil, \( L_1 \), a component of \( Z_{tank,tx} \), varies with \( \Delta x \), as shown in Fig. 3.2. The variation in \( L_1 \) occurs due to the position of the receiver pad ferrite bars altering the magnitude of \( L_1 \). The receiver pad is disconnected from the battery during this phase and thus, \( i_{tank,rx} = 0 \).

![Figure 3.2: Simulated \( L_1 \) versus \( \Delta x \). \( \Delta y = 50 \) mm.](image)

\( Z_{tank,tx} \) can be approximated by applying a small perturbation voltage, \( v_{tank,tx} \), as shown in Fig. 3.3(a), to the resonant tank. By setting the perturbation frequency, \( f_s \), near the resonant frequency, \( f_r \), the tank current, \( i_{tank,tx} \), is sinusoidal with the higher-order harmonics being attenuated due to the high-quality factor of the resonant tank. As the pads align, the magnitude of \( i_{tank,tx} \), \( i_{perturb} \), increases and reaches a maximum value when the capacitor, \( C_1 \), resonates with the nominal value of \( L_1 \). By setting a threshold, \( i_{th} \), the pads are considered aligned once \( i_{perturb} > i_{th} \) and then proceed to WPT. However, by applying \( v_{tank,tx} \) with a fixed duty-cycle, \( D \), \( i_{perturb} \) increases significantly near alignment due to the high-quality factor of \( Z_{tank,tx} \). Thus, it is necessary to regulate \( i_{perturb} \) to a low value, to prevent over-current.
Figure 3.3: Typical waveforms of $v_{\text{tank, tx}}$, $i_{\text{tank, tx}}$, and $|Z_{\text{tank, tx}}|$ with (a) constant and (b) variable $D$. 
To determine how to regulate $i_{perturb}$, the RMS value of $v_{tank,tx}$ is calculated according to,

$$ v_{tank,tx,rms} = \sqrt{\frac{1}{T_s} \cdot \int_{t_0}^{t_1} v_{tank,tx}^2(t) \, dt}. \tag{3.1} $$

After integrating and averaging $v_{tank,tx}$ over the perturbation period, $T_s$, the rms value of $v_{tank,tx}$ is given by,

$$ v_{tank,tx,rms} = \sqrt{2D \cdot V_{bus}}. \tag{3.2} $$

From (3.2), $v_{tank,tx,rms}$ is controlled with the duty cycle, $D$. By extension, $|Z_{tank,tx}|$ is estimated according to the following equation

$$ |Z_{tank,tx}| = \frac{\sqrt{2D \cdot V_{bus}}}{i_{perturb,rms}} \tag{3.3} $$

As the pads align, $i_{perturb}$ increases for constant $D$ due to the increase in $L_1$. Therefore, the duty cycle, $D$, of $v_{tank,tx}$ is controlled to regulate $i_{perturb}$ as shown in Fig. 3.3(b). Once $|Z_{tank,tx}|$ drops below a threshold, $|Z_{min}|$, the technique determines that alignment is achieved.

After DC coil self-alignment is performed, it is possible $Z_{tank,tx}$ changes from capacitive to inductive depending on $f_s$. If $f_s \approx f_r$, the duty cycle, $D$, could reach a local minimum earlier than alignment due to variation in $L_1$ impacting $f_r$ which results in a significant $\Delta x$. To prevent this scenario, $f_s$ is selected to be significantly lower than $f_r$; causing $|Z_{tank,tx}|$ to monotonically decrease versus $\Delta x$ as $Z_{tank}$ is capacitive, as shown in Fig. 3.3(b). By doing so, alignment is determined based on the following condition: $D < D_{min}$, where if true, alignment has been achieved.

Due to the symmetric power electronics architecture, this technique can also be performed on the receiver side, which eliminates communication between the transmitter and receiver pad during this stage. By using the receiver pad, the technique does consume energy from the battery and thus, there is a trade-off between communication overhead and discharging the battery. In addition to the impedance detection technique, the position-correcting control algorithm uses a resonant frequency detector to provide feedback on $\Delta y$. 


3.3 Resonant Frequency Tracking for Gap Adjustment

For self-alignment to correct large $\Delta x$, it is necessary for $\Delta y$ to be approximately 50 mm. By vertically mounting the pads on the EV, variations in $\Delta y$ occur due to vehicle parking accuracy. If the resulting weaker $F_{mag}$ cannot overcome the linear guide friction force, $F_{friction}$, the impedance detection technique does not achieve the alignment condition, $D < D_{min}$. Therefore, the vehicle must be adjusted to correct the gap and improve efficiency. Similar to $F_{mag}$, $L_1$ diminishes with $\Delta y$, as shown in Fig. 3.4, and since $f_r$ depends on $L_1$, feedback on $\Delta y$ can provided by measuring $f_r$. Similar to the impedance detection technique, this technique is performed on the transmitter pad, with the receiver pad being disconnected from the battery.

Figure 3.4: Simulated $L_1$ versus $\Delta y$. $\Delta x = 0$ mm.

By estimating $f_r$ in real time, the vehicle can adjust $\Delta y$ accurately. One method is to sweep the perturbation frequency, $f_s$, while maintaining constant $D$ and measure $i_{perturb}$. Once $i_{perturb} > i_{th}$, $L_1$ resonates with $C_1$ at $f_s \approx f_r$. The issue is $i_{perturb}$ varies depending on $L_1$. This dependence leads to scenarios where $i_{th}$ is never met. Thus, a more robust method is required to estimate $f_r$.

While $i_{perturb}$ varies depending on $L_1$, $i_{perturb}$ always peaks at $f_r$ as $|Z_{tank,xz}|$ is minimized. By tracking $i_{perturb}$ during the frequency sweep, as shown in Fig. 3.5(a), $f_r$ can be determined regardless of the variation in $L_1$. Using this approach, the system is capable of estimating $f_r$ to adjust $\Delta y$. If significant $\Delta x$ remains due to weak $F_{mag}$, then $L_1 < L_{1,nom}$ which results in a resonant frequency higher than its nominal value, as shown in Fig. 3.5(a). As the vehicle is adjusted to correct the gap, $L_1$ increases due to stronger coupling and $f_r$ approaches its nominal value, as shown in Fig. 3.5(b). By setting a threshold, $f_{th}$, for $f_r$, an accurate measure of $\Delta y$ is provided. Once $f_r = f_{th}$,
self-alignment can be applied again to reduce $\Delta x$ as $F_{mag}$ increases due to a smaller $\Delta y$.

Figure 3.5: Typical waveforms of $v_{tank,tx}$, $i_{tank,tx}$, $i_{perturb}$, and $|Z_{tank,tx}|$ during $f_r$ detection with (a) large and (b) small $\Delta y$. 
3.4 Operation of Position-Correcting Control Algorithm

For a better understanding of the position-correcting algorithm, a parking scenario is presented along with the timing sequence of the position-correcting control, which is shown in Fig. 3.6. The correction sequence begins when the vehicle is parked with an arbitrary \( \Delta x \) and \( \Delta y \). Due to the linear-guide mounted transmitter pad, the algorithm can decouple the lateral misalignment, \( \Delta x \), from the separation gap, \( \Delta y \). To determine whether to correct \( \Delta x \) or \( \Delta y \) first, the self-inductance of the AC coil, \( L_1 \), and its dependence on \( \Delta x \) and \( \Delta y \) must be considered. If \( \Delta y \) is adjusted first, a significant change in \( f_r \) must be detected, which indicates the dependence of \( L_1 \) on \( \Delta y \) must be strong, as shown in Fig. 3.4. Otherwise, the vehicle would adjust the gap until it collides with the transmitter since there is no significant change in \( L_1 \) and, consequently, \( f_r \).

Figure 3.6: Timing diagram of proposed position-correcting control algorithm.
This occurs when $\Delta x$ is large, as shown in Fig. 3.2, where $L_1$ is relatively constant. Hence, it is only possible to adjust $\Delta y$ first if $\Delta x$ is small, which limits the correction range of the algorithm. Alternatively, if $\Delta x$ is corrected first, there is no issue since the self-alignment process is an open-loop operation and requires no dependence on $L_1$. Once DC coil self-alignment is performed first, as shown in Fig. 3.6, $\Delta x$ is reduced, however, there is no guarantee that $\Delta x \approx 0$ mm. Since $\Delta y$ could be greater than 50 mm, $F_{mag}$ can diminish which is what results in the remaining $\Delta x$.

The DC coil self-alignment operates in open-loop and therefore, the impedance detection technique described in section 3.2 is used to determine alignment. Once enabled, it is determined $D > D_{min}$ which indicates to the algorithm that either $\Delta x$ or $\Delta y$ is not sufficiently small. Having performed self-alignment, the algorithm proceeds to adjust the separation gap, $\Delta y$, described in section 3.3. While $\Delta x$ is reduced by self-alignment, there is no guarantee it is sufficiently small for the resonant frequency detector to adjust $\Delta y$ to 50 mm. Hence, the gap adjustment process is decomposed into the two stages. On the initial adjustment attempt, where $N = 0$, the resonant frequency threshold, $f_{th}$, is set to $f_{r,1}$ which reduces $\Delta y$ but not to 50 mm, as shown in Fig. 3.6. This step is necessary as it increases $F_{mag}$ to further reduce $\Delta x$ before $\Delta y$ is adjusted to 50 mm. To ensure $f_{r,1}$ is not used again, $N$ is incremented.

Now that $F_{mag}$ has increased, self-alignment is performed again which further reduces $\Delta x$. However, when the impedance detection technique is enabled again, it determines that $D > D_{min}$ indicating alignment is not achieved, as shown in Fig. 3.6. With the smaller $\Delta x$, the resonant frequency detection technique is enabled with $f_{th} = f_{r,2}$ since a significant change in $f_r$ can be detected. By doing so, the vehicle is adjusted such that $\Delta y = 50$ mm. Due to the high torque generated by EVs at low speeds, it is possible for EVs to accurately adjust $\Delta y$ to within a few centimeters. In the case of autonomous vehicles, the accuracy is further improved since the onboard computer can detect the change in resonant frequency faster than human drivers. With $\Delta y$ adjusted to its nominal value, only the residual $\Delta x$ remains from when self-alignment was performed with a larger $\Delta y$. Hence, self-alignment is performed a final time which reduces $\Delta x \approx 0$ mm, as shown in Fig. 3.6. The algorithm proceeds to the impedance detection technique, which determines $D < D_{min}$ indicating alignment is achieved, as shown in Fig. 3.6. The charger then commences WPT, with the aid of the position-correcting algorithm, under ideal parking conditions.

It is important to note that if $\Delta y >> 50$ mm due to vehicle parking, $\Delta x$ will remain significantly large despite self-alignment. Hence, during gap adjustment, a change in $f_r$ will not be detectable, even when $f_{th} = f_{r,1}$. In this scenario, the vehicle will collide with
the transmitter pad. To prevent this, emergency proximity sensors can be used to detect when the vehicle is going to collide with the transmitter pad; to prevent damage.

### 3.5 Chapter Summary

In this chapter, a control algorithm for position-correcting the charging pads is described in detail. A detailed flow chart of the algorithm presents the system-level coordination between the multiple stages. The impedance-based detection technique to determine alignment is discussed along with its design considerations. In particular, the technique requires the perturbation frequency to be much lower than the switching frequency, which provides a monotonically decreasing impedance tank. A resonant frequency detection technique for gap adjustment is also presented, where the benefits of detecting the resonant frequency instead of the tank current are mentioned. Finally, a hypothetical parking scenario is present with the timing diagram of the position-correction algorithm operating. The scenario is used to justify certain design choices that were made such as correcting $\Delta x$ before $\Delta y$ and why the gap adjustment stage uses two different frequency thresholds.
References


Chapter 4

Experimental Results

4.1 Prototype of Dual-Coil WPT Charger

The fabricated prototype of the proposed charger composed of the coil system and power electronics is shown in Fig. 4.1.

A close-up view of the DC coil is shown in Fig. 4.2(a). To accommodate the linear slide on the transmitter side, the DC coil windings were partitioned in two sections. To reduce the cost, the DC coil is comprised of carbon steel and copper windings since DC
current is applied to them. The prototype of the dual-coil charging pad is presented in Fig. 4.2(b). By integrating the AC and DC coil, the charging pad achieves a compact volume of 1428 cm$^3$ with the physical dimension being shown in Fig. 4.2(b). The ferrite cores are housed within a lightweight custom 3D printed case. The copper shield is placed directly on the DC steel core to minimize the induced eddy current. All Litz and copper wires were covered in electrical isolation tape to reduce the chance of short circuit.

![Figure 4.2: WPT setup consisting of (a) the DC coil and (b) the AC coil mounted inside the DC coil.](image)

The converter parameters are specified in Table 4.1. For WPT, all switches in the converter are implemented with Silicon Carbide (SiC) MOSFETs with forced air cooling, as shown in Fig. 4.3.

<table>
<thead>
<tr>
<th>Designed parameters/components</th>
<th>Parameter Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated Power, $P_{bat}$</td>
<td>5</td>
<td>kW</td>
</tr>
<tr>
<td>Battery Voltage, $V_{bat}$</td>
<td>320 - 440</td>
<td>V</td>
</tr>
<tr>
<td>Switching Frequency, $f_s$</td>
<td>85</td>
<td>kHz</td>
</tr>
<tr>
<td>Bus Capacitance, $C_{bus}$</td>
<td>960</td>
<td>$\mu$F</td>
</tr>
<tr>
<td>Filter Inductor, $L_f$</td>
<td>1</td>
<td>mH</td>
</tr>
<tr>
<td>Fan Speed</td>
<td>31.3</td>
<td>CFM</td>
</tr>
<tr>
<td>SiC MOSFET On-Resistance, $R_{ds,on}$</td>
<td>78</td>
<td>$\Omega$</td>
</tr>
</tbody>
</table>

To achieve synchronous rectification and V2G capability, $i_{tank_{rx}}$ is sensed using a high-bandwidth hall-effect current sensor whose output is sampled using a parallel 10-bit Analog-to-Digital Converter (ADC). The digital controller, which is implemented on a Field Programmable Gate Array (FPGA), commutates the MOSFETs whenever $i_{tank_{rx}}$
changes polarity using a Zero Cross Detection (ZCD) circuit. The battery voltage, \( V_{bat} \), is also sensed to prevent overcharging. A Zigbee module is also included to allow for coordinated power flow between the charging pads.

Figure 4.3: Power electronics PCB for driving the dual-coil charging pad.

For self-alignment, \( M_6 - M_7 \) and \( M_{11} - M_{12} \) are passively cooled as their brief operation prevents the junction temperature, \( T_j \), of the MOSFETs from exceeding the maximum of 150°C. A current pulse is applied to both pads with the current, \( I_{DC} \), being regulated using Average Current Mode Control, as shown in Fig. 4.4. The efficiency and alignment time of the charger are measured against different parameters such as \( \Delta y, \Delta z, \) and \( V_{bat} \) to characterize its performance in real-world charging scenarios.

Figure 4.4: Measured current waveforms of the DC coils during self-alignment.
4.1.1 Design of Compensation Capacitor

An important aspect of the AC coil is the design of the SS compensation capacitors, $C_1$ and $C_2$, as shown in Fig. 4.5(a). Due to their series connection, the capacitors process large current during WPT. Since, the capacitor voltage depends on current according to,

$$v_c = \frac{1}{C} \int i_c \cdot dt,$$

the voltage rating of the capacitors must be considered when implementing the compensation capacitor. Due to the high quality of the resonant tank, the tank current, $i_{tank,tx}$ is sinusoidal and based on (4.1), $V_{C_1}$ is sinusoidal as well. Assuming no losses at $V_{bat} = 400$ V and $P_{bat} = 5$ kW, $i_{tank,tx} = 12.5$ A$_{rms}$ which is equal to a peak current of 17.67 A. Knowing $i_{tank,tx}$ and $C_1$, which is 27.17 nF theoretically, the maximum $V_{C_{1, rms}}$ is 861.4 V$_{rms}$. However, due to non-idealities, $V_{C_1}$ is expected to be larger than this value. With a safety margin of 1.5×, the selected capacitor must have a voltage rating of at least 1300 V$_{rms}$. The best choice would be ceramic capacitors as they provide lowest Equivalent Series Resistance (ESR) and Inductance (ESL), however, for the specified voltage rating and capacitance value, the cost of a ceramic capacitor would be extremely high. Electrolytic capacitors can provide the high capacitance and voltage rating at a relatively low cost, however, their ESR and ESL are higher, which is undesirable due to the large high-frequency current the capacitors must process.

Hence, film capacitors were selected for compensation, however, the voltage rating of film capacitors derates with frequency, which must be considered. Due to this limitation, the EPCOS 2.2 nF film capacitor, which has a nominal voltage rating of 1000 V$_{rms}$, was used as a building block of the capacitor array whose value is 27.17 nF. At $f_s = 85$ kHz, its voltage rating decreases to $\approx 950$ V$_{rms}$, which means placing two capacitors in series should provide a sufficient margin for the voltage rating, as shown in Fig. 4.5(b). However, the overall compensation capacitance is halved due to the two series capacitors. Hence, each capacitor array must be sized such that it is twice the desired capacitance of 27.17 nF. This is accomplished by 25 2.2nF capacitors in parallel, which achieves a capacitance of 55 nF, as shown in Fig. 4.5(c). Due to the discrete nature of the capacitor array, having two 55 nF film capacitors allows us to achieve 27.5 nF of capacitance which is close to the desired 27.17 nF. The slightly higher capacitance indicates that at 85 kHz, the resonant tank impedance becomes slightly inductive, which is necessary for Zero Voltage Switching (ZVS).
Figure 4.5: (a) Ideal SS compensation topology. (b) SS topology to reduce voltage across capacitor. (c) SS topology to achieve desired capacitance while accounting for film capacitor voltage rating.

4.2 Self-Alignment Operation with DC Coil

The simulated and experimental DC coil magnetic force, $F_{mag}$, versus $\Delta x$ for varying $I_{dc}$ is shown in Fig. 4.6. The DC coil generates a peak $F_{mag,x}$ of 3.5 N; 70% of the simulated peak of 5 N. The friction force of the linear guide was measured to be 0.76 N. Based on this, $F_{mag}$ can overcome $F_{friction}$ when $20 \text{ mm} < \Delta x < 240 \text{ mm}$ at $I_{dc} = 30$ A. The prototype is capable of correcting $\Delta x$ ranging from 20 mm to 240 mm which is 20% larger than the charging pad width.

The position of the WPT pads during self-alignment was measured for varying $I_{dc}$, as shown in Fig. 4.7, using a 240 frames per second (FPS) video camera. When $I_{dc}$ increases from 20 A to 30 A, the alignment time is reduced from 6.2 s to 2 s. Position overshoot occurs during self-alignment when $I_{dc} = 30$ A with the pad settling to $\Delta x = -11.5$ mm. Based on Fig. 2.14, this should not degrade the efficiency, which remains relatively constant for $\Delta x < 20$ mm.
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Figure 4.6: (a) Simulated $F_{\text{mag},x}$ of DC coil versus $I_{dc}$. (b) Measured $F_{\text{mag},x}$ of DC coil versus $I_{dc}$.

Figure 4.7: Position measurement of DC coils for varying $I_{dc}$.

The self-alignment process was repeated for varying $\Delta y$ as shown in Fig. 4.8. The system aligns well for small $\Delta y$ with the coil position overshooting and settling to $\Delta x = -11.5$ mm due to the large $F_{\text{mag}}$ at $\Delta y = 50$ mm. Due to this overshoot, the alignment
time decreases from 2 s to 1.75 s when \( \Delta y \) is increased to 60 mm. However, as \( \Delta y \) is increased from 50 mm to 80 mm, \( F_{mag} \) diminishes significantly resulting in the alignment time increasing from 2 s to 2.5 s while \( \Delta x \) increases from -11.5 mm to 45 mm.

![Figure 4.8: Position measurement of DC coils for varying separation gap, \( \Delta y \) (diagram)](image)

The position of the DC coil during self-alignment for varying \( \Delta z \) was also measured, as shown in Fig. 4.9. The alignment time varies by 6.3\% for \( \Delta z < 25 \) mm, which is approximately 12.5\% of the coil width. Slight overshoot occurs due to the large magnetic force at \( \Delta z = 0 \) mm which results in a slightly larger alignment time under perfect conditions. The system is capable of mitigating \( \Delta x = 200 \) mm for \( \Delta z \leq 43 \) mm with the charging pad settling to within 15 mm of perfect alignment. Beyond this, an increase of 25\% was observed in the alignment time when \( \Delta z = 68 \) mm was applied. The charging pads settle to a large \( \Delta x \) with an increase from 5 mm to 78 mm at \( \Delta z = 68 \) mm.

![Figure 4.9: Position measurement of DC coils for varying vertical misalignment, \( \Delta z \) (diagram)](image)
4.3 Wireless Power Transfer Operation with AC Coil

The measured waveforms of the converters at 5kW WPT are shown in Fig. 4.10. \( V_{bus} \) was adjusted to achieve the desired \( P_{bat} \). The total efficiency, \( \eta \), from \( V_{bus} \) to \( V_{bat} \), was 90.1% at 5kW WPT. The voltages, \( v_{tank,tx} \) and \( v_{tank,rx} \) were applied to the transmitter and receiver AC coils, respectively. The resulting sinusoidal currents, \( i_{tank,tx} \) and \( i_{tank,rx} \), verify that the capacitors, \( C_1 \) and \( C_2 \), resonate with \( L_1 \) and \( L_2 \).

Figure 4.10: Measured current and voltage waveforms of the WPT charger at 5 kW.

The proposed WPT charger was operated at 5 kW to determine its preliminary thermal performance, as shown in Fig. 4.11. The peak temperature is 87.7° C, as shown in Fig. 4.11(a), which occurs in the copper shield. In order to limit the risk of thermal damage to the expensive prototype, the system was only operated continuously for 3 minutes. The custom 3D printed cases for the ferrite bars also have limited tempera-

Figure 4.11: Thermal images of (a) WPT coil system at 5kW WPT, (b) transmitter and (c) receiver MOSFETs.
ture tolerance which can potentially cause deformation at high temperatures. The PCBs utilize fan-mounted heatsinks with forced-air cooling for the full-bridge converter. This results in the transmitter and receiver MOSFETs reaching a peak packaging temperature of 47.6°C and 49.7°C, respectively, as shown in Fig. 4.11(b) and (c).

The efficiency is measured for varying $V_{\text{bat}}$, as shown in Fig. 4.12. For $P_{\text{bat}} \geq 3.5$ kW, the efficiency remains relatively flat with only variations of 2%. The efficiency degrades significantly at low $P_{\text{bat}}$ due to the large $i_{\text{ac,tx}}$ required for the AC magnetic flux linkage.

![Efficiency vs. $P_{\text{bat}}$ for varying $V_{\text{bat}}$. $V_{\text{bus}}$ is manually adjusted for desired $P_{\text{bat}}$.](image1)

Figure 4.12: Measured DC-DC efficiency versus $P_{\text{bat}}$ for varying $V_{\text{bat}}$. $V_{\text{bus}}$ is manually adjusted for desired $P_{\text{bat}}$.

With modern parking sensors and on-board cameras, it is reasonable to expect that the EV should be capable of parking within 50 mm of the transmitter pad. However, to account for variations in the parking sensors, the efficiency was measured for varying $\Delta y$, as shown in Fig. 4.13. The efficiency degrades linearly with $\Delta y$; justifying the importance of minimizing the gap by vertically mounting the charger on the EV. The charger is less susceptible to large $\Delta y$ at rated $P_{\text{bat}}$ with only a 5.6% drop at 5 kW as compared to a 10.25% drop at 2 kW; incentivizing charging at high $P_{\text{bat}}$.

![Efficiency vs. $\Delta y$. $V_{\text{bus}}$ is manually adjusted for desired $P_{\text{bat}}$.](image2)

Figure 4.13: Measured efficiency versus $\Delta y$. $V_{\text{bus}}$ is manually adjusted for desired $P_{\text{bat}}$. 

Given that the target application of this charger is fleet vehicles, the charger pads will inevitably be subjected to vertical misalignment depending on the EV payload. The efficiency was measured against $\Delta z$ for varying $P_{bat}$, as shown in Fig. 4.14. The efficiency varies by only 1.8% for $\Delta z \leq 36$ mm, which indicates good tolerance against small $\Delta z$. This correlates to the performance of the DC self-alignment which also tolerated $\Delta z$ up to 25% of the coil width. The efficiency significantly degrades as $\Delta z$ approaches 90 mm, approximately 45% of the pad width. Also, the overall degradation in efficiency is much smaller at 5 kW, 7.34%, as compared to 13.1% at 2 kW.

![Figure 4.14: Measured efficiency versus $\Delta z$. $V_{bus}$ is manually adjusted for desired $P_{bat}$.](image)

Two custom-made 3D-printed cases were manufactured to vary the spacing of the ferrite bars of the AC coils; one with uniform 10 mm spacing and another with non-uniform spacing as shown in Fig. 2.2(b). The uniformly spaced ferrite bars were first operated at a power level of 3.7 kW successfully, as shown in Fig. 4.15(a). However, the coil with uniformly spaced ferrite bars failed when 5kW WPT was attempted with the resulting ferrite damage shown in Fig. 4.15(b). As the bus voltage, $V_{bus}$, was gradually

![Figure 4.15: (a) Measured waveforms of the uniformly spaced ferrite bars at 3.7kW WPT and (b) image of damaged uniformly spaced ferrite bars after attempted operation at 5kW WPT.](image)
increased to achieve higher power transfer, the uniformly spaced ferrite bars were unable to operate beyond 4kW WPT. It is interesting to note that the visible damage to the ferrite is done in the area directly below the Litz wire, as shown in Fig. 4.15(b). This validates the simulation results in Fig. 2.8(a), where the peak $B$ was observed directly below the AC coil windings in the top and bottom ferrite bars. The non-uniformly spaced ferrite bars were then operated at a power level of 3.7 kW successfully, as shown in Fig. 4.16(a). WPT was then increased to 5 kW and the coil with non-uniformly spaced ferrite bars achieved successful steady-state operation, as shown in Fig. 4.16(b).

Figure 4.16: Measured waveforms of the non-uniformly spaced ferrite bars at (a) 3.7kW and (b) 5kW WPT.

### 4.4 Real-time Impedance Detection with AC Coil

A Proportional-Integral (PI) controller was implemented to regulate the RMS value of the transmitter AC coil current, $i_{perturb,rms}$, by controlling the duty cycle, $D$, of $v_{tank,tx}$ such that $i_{perturb,rms} = 4 \, A_{rms}$ to reduce losses. The startup response of the PI controller is shown in Fig. 4.17 demonstrating the controller regulates $i_{perturb}$ to the reference.

Figure 4.17: Startup response of the PI-controller.
The PI controller regulating $i_{\text{perturb}}$ at $\Delta x = 0$ mm and 200 mm is shown in Fig. 4.18(a) and (b) respectively. $i_{\text{perturb},rms}$ is maintained at 4 $A_{\text{rms}}$ as $D$ increases from 2.2% to 4.0% to compensate for the increase in $\Delta x$. Furthermore, $f_s = 79.3$ kHz was selected such that $f_s << f_r$, resulting in $i_{\text{tank},tx}$ leading $v_{\text{tank},tx}$. This ensures $D$ increases monotonically for all operating conditions. If $Z_{\text{tank},tx}$ changes from capacitance to inductive, a resulting local minimum for $D$ prevents self-alignment.

$Z_{\text{tank},tx}$ was measured versus position, as shown in Fig. 4.19, to verify it has no local minima. $V_{\text{bus}}$, $i_{\text{tank},tx}$ and duty cycle of $v_{\text{tank},tx}$, $D$, were measured and then (3.3) is used to calculate $Z_{\text{tank},tx}$. It is clear that irrespective of the initial coil position, $|Z_{\text{tank},tx}|$ monotonically decreases as the vehicle approaches perfect alignment. Thus, by simply having a threshold limit, $D_{\text{min}}$, the charging system can determine when alignment is achieved for efficient WPT.

Figure 4.18: $i_{\text{perturb}}$ regulated to 4 $A_{\text{rms}}$ at (a) $\Delta x = 0$ mm and (b) $\Delta x = 200$ mm.

Figure 4.19: Measured $|Z_{\text{tank},tx}|$ versus position.
4.5 Real-time Resonant Frequency Detection with AC Coil

The measured waveforms of the transmitter coil during the resonant frequency detection technique are shown in Fig. 4.20. The perturbation frequency, $f_s$, is repetitively swept from 78 kHz to 90 kHz to ensure the peak current is detectable for various coil positions. The charging system at $\Delta y = 120$ mm is shown in Fig. 4.20(a). $i_{\text{perturb}}$ peaks at a high $f_s$ since $L_1 < L_{1,\text{nom}}$ which results in a high $f_r$. Once $\Delta y = 50$ mm, $L_1$ approaches $L_{1,\text{nom}}$ which causes a decrease in $f_r$. Thus, the peak current occurs at a lower $f_s$, as shown in Fig. 4.20(b).

![Figure 4.20: AC coil resonant frequency detection at (a) $\Delta y = 120$ mm and (b) $\Delta y = 50$ mm.](image)

To adjust $\Delta y$, $f_r$ should be smaller than $f_{th}$. For $\Delta x \geq 100$ mm, $|Z_{\text{tank},tx}|$ does not change significantly versus $\Delta y$ as shown in Fig. 4.19, which is why it is necessary to reduce $\Delta x$ before adjusting $\Delta y$. The change in $|Z_{\text{tank},tx}|$ becomes significant for $\Delta x \leq 80$ mm which is the area where $\Delta y$ is detected accurately.

The final receiver pad positions, after gap adjustment, are shown in Fig. 4.21 versus $\Delta x$ for different $f_{th}$. The technique is unable to detect a change in $f_r$ for $\Delta x \geq 100$ mm since there is no significant change in $|Z_{\text{tank},tx}|$, as shown in Fig. 4.19, and by extension $f_r$. In this scenario, the vehicle must be reparked to reduce either $\Delta x$ or $\Delta y$ before restarting the control sequence. It is important to note $F_{\text{mag}}$ must be sufficiently large to minimize $\Delta x$. Hence, the gap adjustment technique is decomposed into two stages, as shown in Fig. 3.1. On the initial attempt, the gap adjustment technique is enabled with a threshold set to a much higher value, $f_{r,1}$. The vehicle is adjusted until $f_r$ is less than $f_{r,1}$. By doing so, the vehicle can achieve a separation gap of approximately 80 mm for $\Delta x \leq 60$ mm, as shown in Fig. 4.21. Self-alignment is performed again to further reduce
Δx. With a smaller Δx, a second threshold, \( f_{r,2} \), can be set for the gap adjustment which results in Δy = 50 mm for \( \Delta x \leq 40 \) mm, as shown in Fig. 4.21.

![Diagram showing experimental results](image)

Figure 4.21: Resulting receiver pad position after application of gap adjustment technique with various \( f_r \) threshold.

### 4.6 Position-Correction Scenarios

The receiver pad is placed at arbitrary starting positions to evaluate the position-correcting control. The step-by-step position of the pads is shown on an XY plot during the position-correcting process. The four scenarios represent different combinations of Δx and Δy to determine the robustness of the control scheme.

**Scenario 1:** If the vehicle is precisely parked, both Δx and Δy are small, as shown in Fig. 4.22. First, the DC coil self-alignment corrects Δx from 80 mm to 10 mm. Since the vehicle is parked near the transmitter pad, there is sufficient \( F_{mag} \) to correct Δx in one attempt. However, the impedance detection technique determines alignment is not achieved since Δy = 70 mm. The vehicle is parked such that the initial gap adjustment requires no correction since \( f_r \) is already less than \( f_{r,1} \). Once \( f_{th} = f_{r,2} \), gap adjustment is performed with Δy being corrected from 70 mm to 51 mm. With Δy ≈ 50 mm, the impedance technique determines alignment is achieved. Due to the close proximity of the pads when the vehicle is initially parked, the position-correcting control only requires two correction steps to improve vehicle alignment.
Scenario 2: If the vehicle is not precisely parked, a realistic scenario is a small $\Delta x$ but $\Delta y$ is large. A parking scenario with $\Delta x = 100$ mm and $\Delta y = 90$ mm, shown in Fig. 4.23, is used to test the position-correcting control. Once DC coil self-alignment is performed, $\Delta x$ is corrected from 100 mm to 38 mm. Due to weaker $F_{mag}$, $\Delta x$ is not completely corrected. The impedance detection technique determines alignment is not achieved which indicates $\Delta y$ is too large. Since $D > D_{min}$, the gap adjustment technique is enabled with $f_{th} = f_{r,1}$. The vehicle adjusts $\Delta y$ until $f_r \leq f_{th}$ which reduces $\Delta y$ from 90 mm to 70 mm. The DC coil self-alignment is performed again which reduces $\Delta x$ from

Figure 4.22: Bird’s eye view of charging pads during the position-correcting control scheme for scenario 1.

Figure 4.23: Bird’s eye view of charging pads during the position-correcting control scheme for scenario 2.
42 mm to 20 mm. The impedance detection technique determines that alignment is still not achieved as $\Delta y = 71$ mm. With $f_{th} = f_{r,2}$, the gap adjustment technique is enabled which reduces $\Delta y$ from 71 mm to 49 mm. Finally, self-alignment removes any remaining $\Delta x$ after which the impedance detection technique determines alignment is achieved.

**Scenario 3:** Another scenario is the vehicle is parked such that $\Delta y$ is small but $\Delta x$ is very large. This is possible since the transmitter pad will be encased and thus, is not directly visible. A parking scenario with $\Delta x = 160$ mm and $\Delta y = 60$ mm was created, as shown in Fig. 4.23, to determine whether it can be corrected by the control scheme. Due to the small $\Delta y$, the DC coil self-alignment corrects $\Delta x$ from 160 mm to -6 mm. The impedance detection technique determines that alignment is not achieved. By enabling the gap adjustment, $\Delta y$ is reduced from 60 mm to 51 mm. Due to the small $\Delta x$, DC coil self-alignment has no effect since $F_{mag}$ is too weak. However, since the impedance technique indicates alignment is achieved, the small $\Delta x$ is insignificant. Based on this scenario, the gap adjustment technique has a high resolution as it can distinguish between 60 mm and 50 mm. Once again, due to the small $\Delta y$, the position-correcting control can align the two pads within two correction steps. It is important to note that the trivial one-step correction process is not shown which occurs when $\Delta y \approx 50$ mm. In this case, self-alignment completely corrects $\Delta x$ which allows the charger to proceed to WPT.

![Scenario 3: Large $\Delta x$ & Small $\Delta y$ (2 step correction)](image)

Figure 4.24: Bird’s eye view of charging pads during the position-correcting control scheme for scenario 3.

**Scenario 4:** Finally, the worst-case scenario is a parked vehicle with both large $\Delta x$ and $\Delta y$, as shown in Fig. 4.25. First, DC coil self-alignment corrects $\Delta x$ which is reduced from 200 mm to 42 mm since there is sufficient $F_{mag}$ at $\Delta y = 80$ mm as shown in Fig. 4.7(b). The impedance detection technique then determines alignment is not
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achieved. Thus, the gap adjustment technique is enabled with $f_{th} = f_{r,1}$. The vehicle adjusts $\Delta y$ until $f_r \leq f_{th}$ which reduces $\Delta y$ from 80 mm to 71 mm. The DC coil self-alignment is applied again which reduces $\Delta x$ from 42 mm to 20 mm. The impedance detection technique determines that alignment is still not achieved as $\Delta y > 50$ mm. With $f_{th} = f_{r,2}$, the gap adjustment technique is enabled, which reduces $\Delta y$ from 71 mm to 49 mm. Finally, self-alignment removes any remaining $\Delta x$ after which the impedance detection technique determines alignment is achieved.

![Scenario 4: Large $\Delta x$ & Large $\Delta y$ (5 step correction)](image)

Figure 4.25: Bird’s eye view of charging pads during the position-correcting control scheme for scenario 4.

4.7 Chapter Summary and Conclusions

In this chapter, the efficiency and self-alignment capabilities of the dual-coil charging pads are measured under real-world charging scenarios such as varying separation gap, vertical misalignment, and battery voltage. The charger achieves a peak DC-DC efficiency of 90.1% at 5kW WPT. The charger performance heavily depends on the separation gap, with a 5.6% efficiency drop being observed for a 20mm increase in the separation gap. The charger performs much better under vertical misalignment with the efficiency only varying by 1.8% for $\Delta z \leq 36$ mm.

The performance of the DC coils was characterized by position and magnetic force measurements under varying DC current, separation gap, and vertical misalignment. The prototypes of the DC coils generate a peak magnetic force of 3.5 N at 30 A, approximately 70% of the simulated peak of 5 N, which allows the pad to easily overcome the friction
force of the linear slider. The DC coil can correct $\Delta x \leq 50$ mm for $\Delta y$ up to 80 mm and $\Delta z$ up to 50 mm.

Details of the power electronics necessary to drive the dual-coil charging pad were presented, including the implementation of the compensation capacitor array. The ferrite bar spacing was varied to increase the power transfer capabilities of the charger from 3.7 kW to 5 kW. Finally, the position-correcting control algorithm was tested successfully with four parking scenarios with the receiver pad corrected to 10 mm radius of perfect alignment.
Chapter 5

Conclusion and Future Works

5.1 Thesis Summary and Contributions

The goal of this work is to investigate the application of the proposed dual-coil charging pad for fleet vehicles to achieve high efficiency with charging times comparable to Level 2 AC on-board chargers. To accomplish this, a position-correcting control algorithm was proposed to systematically correct the transmitter pad position.

In Chapter 2, a simulation model of the dual-coil charging pad was constructed to select certain design parameters such as resonant capacitance, coil structure, and physical dimensions of the pads. The simulation model was designed in ANSYS 3D Maxwell, accounting for eddy current and core losses and intricate details such as flux distribution of the charging pads. Furthermore, the model provides an estimate of the generated magnetic force of the electromagnetic coil which is used for sizing the coils. The novel contributions of Chapter 2 include:

- Development of an ANSYS simulation model of the dual-coil charging pad to design an experimental prototype of the charging pad while accounting for non-idealities;
- Description of the design choices of the AC and DC coils and the reasoning behind those design choices;
- Simulation results of the dual-coil charging pad operating in both WPT and self-alignment;
- Simulated efficiency and magnetic force results demonstrating the feasibility of the proposed WPT charger;
- Simulation results demonstrating a reduction in the peak AC coil magnetic flux density due to variation of ferrite bar spacing; and
• Comparison of different shield manufacturing techniques and their subsequent impact on the eddy current losses of the shield.

The analysis in Chapter 2 demonstrates a 20% decrease in the peak magnetic flux density when a non-uniform ferrite bar spacing is used. In terms of eddy current loss, a reduction of 29% is achieved when using a uniform piece of copper as a shield instead of multiple pieces. A peak simulated efficiency of 96.5% was achieved when taking into the non-idealities such core and semiconductor losses. Furthermore, with magnetostatic simulations, the DC coils generate a peak magnetic force of 5 N, which is sufficient to overcome the friction force of the linear slider and self-align the charging pads.

Chapter 3 is devoted to the analysis and explanation of the position-correcting control algorithm. The novel contributions of Chapter 3 include:

• A system-level control algorithm to position-correct the charging pads to their perfect alignment

• An impedance detection technique for alignment detection is presented; a critical aspect of the algorithm. Certain design choices such as the selection of perturbation frequency are highlighted

• A resonant frequency detection technique is proposed to accurately detect the gap, which is then used by the algorithm to position-correct the pads

The chapter concludes with a parking scenario being used to describe the detailed operation of the algorithm. Necessary design choices such as the need to correct $\Delta x$ before $\Delta y$ are explained with the use of a timing diagram.

Finally, the experimental results of the dual-coil charging pad along with the position-correcting algorithm are presented in Chapter 4. The prototype of the proposed WPT charger along with implementation details of power electronics and compensation capacitors is presented. The self-alignment capabilities of the DC coils are tested against various parameters such as $\Delta y$, $\Delta z$, and $I_{dc}$. The DC coils are capable of correcting $\Delta x$ as large 240 mm. With large parameter variation, the DC coil performance degrades as large $\Delta x$ can be observed when $\Delta y \geq 80$ mm. Similarly, for $\Delta z$, self-alignment is performed well until $\Delta z \geq 50$ mm.

The system achieves a peak DC-DC efficiency of 90.1% at 5kW WPT. The efficiency does degrade quite rapidly with respect to $\Delta y$, however, against $\Delta z$ it has a much better tolerance due to the solenoid coil structure. The ferrite bar spacing was experimentally varied and with non-uniform spacing, the power transfer capability of the system was
increased from 3.7 kW to 5 kW. Finally, the experimental validation of the position-correcting control algorithm was presented. The algorithm was tested with four different parking scenario with various combinations of $\Delta x$ and $\Delta y$. For all four scenarios, the algorithm was able to correct the receiver pad to within a 10mm radius of perfect alignment.

The system-level architecture and experimental characterization of the dual-coil charging pad presented in Chapters 2 and 4, respectively, has been published in [1]. The optimization of ferrite bar spacing and copper shield presented in Chapters 2 and 4 has been published in [2]. The position-correcting algorithm and its experimental results presented in Chapters 3 and 4 have been submitted to [3].

## 5.2 Future Work

Based on the research presented in this thesis, the following avenues are suggested for further exploration.

- Implementation of adaptive impedance and resonant frequency thresholds to account for variations in parameters such as vertical misalignment, $\Delta z$.

- Implementation of wireless Vehicle-to-Vehicle (V2V) charging which is feasible due to the vertical mounting of the charging pads and symmetric nature of power electronics architecture.

- Improved thermal design of DC steel core for increased power transfer and steady-state thermal performance.

- Optimization study on the dimensions of the DC steel core to minimize weight and losses of the DC coil.
References

