Non-uniform Spacing of Ferrite Bars for Optimizing a Solenoid-based Wireless Electric Vehicle Charger with Automatic Self-Alignment

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Acknowledgments

This research was supported by the Natural Sciences and Engineering Research Council of Canada.

Keywords
Contactless Energy Transfer, Wireless power transmission, Power converter for EV, Charging Infrastructure for EV’s, Electric Vehicle.

Abstract

This paper presents the design of a dual-coil charging pad for Wireless Power Transfer (WPT) in Electric Vehicles (EV). An electro-magnetic coil, denoted as the dc coil, generates a magnetic force that horizontally aligns a linear-slider-mounted transmitter pad to the receiver pad. A solenoid-based coil, denoted as the ac coil, is capable of 5kW WPT, which is performed only after the self-alignment of the pads. Two areas of optimization for the solenoid-based wireless charger are presented: optimum ferrite bar spacing and shield design. By using copper shields composed of a continuous sheet instead of multiple pieces connected with tape, the simulated eddy current loss is reduced by 29% while minimizing leakage flux from the ac coil. The optimum ferrite bar spacing is verified on a prototype of the dual-coil charging pad and allows the power capability to increase from 3.7 kW to 5 kW, without additional ferrite bars while achieving a peak dc-dc efficiency of 90.1%. The prototype of the dc coil generates a peak magnetic force of 3.51 N while also achieving a wide horizontal misalignment correction range of up to 240 mm.

Introduction

Wireless Power Transfer (WPT) is gaining attention in Electric Vehicles (EV) applications, as an enabling technology for autonomous vehicles. The demand for EVs is expected to reach 9 to 20 million vehicles by 2020 [1]. Inductive Power Transfer (IPT) is one of the most commonly used technologies to perform WPT [2–5]. A typical IPT system is composed of two coils, a transmitter, and a receiver, which enables power transfer by magnetic coupling in the coils. Hence, IPT systems can eliminate the need for driver intervention during the charging process. Limitations of IPT systems include high sensitivity to coil misalignment and weak magnetic coupling, which lead to inefficient power transfer. Even with autonomous vehicles, the misalignment error is inevitable due to limited parking accuracy. Furthermore, to achieve reasonable charging times, it is desirable to perform WPT at a reasonably high power level (Level 2), which requires significant magnetic flux density to overcome the weak coupling of the coils.

Several optimization techniques have been presented for the spiral coil structure. In [6, 7], systematic methods are presented to improve design parameters, such as the coupling coefficient and quality factor, by adjusting physical parameters, such as the number of turns and the inner radius of the coil. In [8], the coupling coefficient was improved by 21% when the pitch of the coil turns was optimized. In [9], a method was presented to optimize the receiver coil dimensions using the power transfer efficiency equation. Optimization of the solenoid coil structure was also investigated in [10, 11] where physical parameters, such as the spacing of the coil wiring, were varied to achieve the highest coupling coefficient.
This paper is focused on the optimization of a solenoid coil that is integrated into a dual-coil charging pad, as shown in Fig. 1. The charging pad is mounted on a linear slider and is capable of horizontal misalignment correction between the transmitter and receiver; eliminating the need for mechanical drive systems such as [12]. Furthermore, the dual-coil charging pad is primarily intended for fleet vehicles; enabling placement of the charging pad on the rear of the vehicle. By doing so, the separation gap between the pads is reduced, which improves the magnetic coupling whereas conventional underside-mounted WPT chargers achieve coupling coefficients ranging from 0.2 - 0.25 [13, 14]. The application of the solenoid coil within this dual-coil charging pad presents new areas of optimization, with this paper specifically focusing on two areas. First, the spacing distribution of the solenoid ferrite bars is investigated to increase power transfer. Secondly, shields composed of a continuous sheet or multiple isolated pieces of copper are investigated to minimize the leakage flux in the charging pad while mitigating eddy current losses in the shield. A system-level characterization of the dual-coil wireless charger is presented in [15], while the focus of this paper is the coil design and optimization of the dual-coil charging pad.

![Fig. 1. Target application of the dual-coil charging pad.](image)

**Architecture of Dual-Coil Charging Pad**

The charging pad is composed of two coils, as shown in Fig. 2. An electro-magnetic based coil, denoted as the dc coil, is activated by applying dc current, which creates a magnetic force, $F_{\text{mag}}$, as shown in Fig. 2(a), between the pads; resulting in horizontal alignment. The power transfer coil, denoted as the ac coil, is shown in Fig. 2(b). To maintain a high coupling coefficient, the ac coil performs WPT only after alignment.

![Fig. 2. WPT setup consisting of (a) the secondary electro-magnetic based coil and (b) the solenoid coil mounted inside the electro-magnetic based coil.](image)

The electrical architecture of the dual-coil charging pad is shown in Fig. 3. The Series-Series (SS) compensation [16] was chosen to achieve resonance with the ac coil, due to its size and simplicity. 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 architecture facilitates Vehicle-to-Grid (V2G) operation; allowing the EV battery to transfer energy to the grid during peak demand hours and provide grid-support functions.
Fig. 3. Electrical architecture of the WPT dual-coil charging pad.

The dimensions for both charging pads are given in Table I. To achieve a compact design, the dc coil serves as a structural case for the ac coil with both being integrated perpendicular to each other. The chosen orientation of the coils 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 which leads to lower dc core loss and improves the efficiency.

### Table I

<table>
<thead>
<tr>
<th>Dimensions of Dual-Coil Charging Pads</th>
<th>Transmitter pad</th>
<th>Receiver pad</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td>Thickness</td>
<td>36 mm</td>
</tr>
<tr>
<td></td>
<td>Height</td>
<td>210 mm</td>
</tr>
<tr>
<td></td>
<td>Width</td>
<td>200 mm</td>
</tr>
<tr>
<td><strong>Number of turns</strong></td>
<td>Ac coil</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>Dc coil</td>
<td>100</td>
</tr>
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</table>

### Design of Electro-magnetic 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 there is no need for Litz wire. As the pads align, the magnitude of $F_{mag}$ increases due to stronger magnetic coupling. However, the direction of the $F_{mag}$ vector shifts from along the linear slider towards the receiver, causing a decrease in $F_{mag,x}$, as shown in Fig. 2(a), that directly contributes to self-alignment. Thus, to achieve a wide misalignment correction range, $F_{mag,x}$ must be sufficiently large to overcome the linear-slider friction force for misalignments that are comparable to the pad width, which is 200 mm in this design.

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. 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 $\Delta d \geq 6$ 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 paper.

To increase $F_{mag}$ further, the dc steel core was extended by a height, $h_{ext}$, as shown in Fig. 2(b). 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. 4(b). By increasing $h_{ext}$ from 10 mm to 25 mm,
$F_{mag,x}$ increases from 3.99 N to 5.04 N; a 26.3% increase. In this way, $F_{mag,x}$ is increased independently of $\Delta d$, hence with a minimal impact on the dc core mass.

![Image](image.png)

Fig. 4. (a) Simulated $F_{mag,x}$ versus $\Delta d$ with $h_{ext} = 25$ mm and $I_{dc} = 30$ A. (b) Simulated $F_{mag,x}$ versus dc core extension, $h_{ext}$, with $\Delta d = 8$ mm and $I_{dc} = 30$ A.

**Design of Solenoid-based WPT Ac Coil**

The ac coil includes ferrite bars to improve the magnetic coupling, while Litz wire is used for the windings to minimize skin effect losses. A solenoid coil structure was selected due to its superior tolerance against vertical misalignment compared to other coil structures, as shown in [15]. 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 II. Due to the rear placement of the charger 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 [14].

<table>
<thead>
<tr>
<th>Designed parameters</th>
<th>Parameter Value</th>
<th>Unit</th>
</tr>
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<tbody>
<tr>
<td>Self-Inductance, $L_{ac}$</td>
<td>129</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Mutual Inductance, $M$</td>
<td>53.3</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Coupling Coefficient, $k$</td>
<td>0.41</td>
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<tr>
<td>Switching Frequency, $f_s$</td>
<td>85</td>
<td>kHz</td>
</tr>
<tr>
<td>Resonant Capacitor, $C_1$</td>
<td>27.17</td>
<td>nF</td>
</tr>
</tbody>
</table>

The simulated mutual inductance versus horizontal misalignment, $\Delta x$ is shown in Fig. 5(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.

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. 5(b). However, by leveraging the rear placement of the pads, the gap can be directly adjusted by the driver to maintain high mutual inductance.
Fig. 5. Simulated ac coil mutual inductance versus (a) misalignment in x-direction, $\Delta x$, and (b) separation gap, $\Delta y$.

**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.

Fig. 6. Magnetic flux density distribution of the solenoid coil. The increase of flux density at the edges of solenoid results in higher core loss.

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

$$B_{wire} = \frac{\mu_0 I}{2\pi r},$$  \hspace{1cm} (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 magnetic flux density distribution of the solenoid coil is shown in Fig. 6. 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 $2 \times B_{wire}$. 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 $3 \times B_{wire}$. 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 reduced 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 adopted in this work, 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 to determine its effect on the magnetic flux density distribution, as shown in Fig. 7. By increasing the concentration of ferrite bars near the edges of the ac coil as shown in Fig. 7(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.

![Simulated magnetic flux density distribution](image)

**Fig. 7.** 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%.

### 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

$$P_v = k \cdot f^a \cdot B^b,$$

(3)

where $P_v$ is the time average power per unit volume in mW/cm$^3$, $f$ 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(b). While a shield reduces losses in the steel core, eddy currents are generated in the shield which results 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

$$\delta = \sqrt{\frac{\rho}{\pi \cdot f \cdot \mu}},$$

(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. 8. 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 without increasing the total mass of the pad significantly.

![Graph showing eddy current loss versus shield thickness](image)

Fig. 8. Simulated eddy current loss versus shield thickness at 5kW WPT.

To optimize the copper shield design, the effect of implementing a shield with a continuous sheet versus multiple isolated pieces of copper was compared. Due to the U-shaped steel core, a continuous sheet of copper must be bent to properly shield the steel core from leakage flux. Due to manufacturing imperfections, air gaps between the shield and core exist when the copper sheet is bent to cover the corners of the steel core, which leads to dc core loss. Hence, an alternative solution is to create a shield from multiple isolated pieces of copper that have no gaps. Since eddy currents are induced in the shield, the distribution of eddy currents in shields composed of both a continuous sheet and multiple isolated pieces of copper are investigated.

A copper shield exposed to a time-varying magnetic flux density, $B_{\text{solenoid}}$, is shown in Fig. 9(a). By Faraday’s law of induction, an opposing electromotive force (EMF), $E$, is generated according to

$$E = -\frac{d\phi_{\text{solenoid}}}{dt}, \quad (5)$$

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 which generate an opposing magnetic flux density. 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. 9(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. In the case of the continuous sheet of copper, the eddy current is lower near the center since the current circulates along the edges of the sheet. Thus, a shield composed of multiple isolated pieces of copper incurs more eddy current losses than a shield composed of a continuous sheet.

![Diagram showing eddy current distribution](image)

Fig. 9. Eddy current distribution in (a) a continuous sheet of copper and (b) multiple isolated pieces of copper.
Electromagnetic simulations were performed to observe the current density distribution in the copper shield, as shown in Fig. 10. As expected, the current density increases significantly along the boundaries of copper pieces, as shown in Fig. 10(a), due to the eddy currents being constrained to each piece. To reduce the eddy currents, a copper tape of 88.9 µm thickness is used to electrically connect the multiple isolated pieces of copper which allow the eddy currents to 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. 10(b), with the peak current density decreasing from $1.08 \times 10^9$ A/m$^2$ to $8.13 \times 10^8$ A/m$^2$. This translates to a decrease in eddy current losses from $P_e = 238.4$ W to $P_e = 69.6$ W; a 71% reduction. While copper tape does reduce eddy current circulation, the main limitation of copper tape is its thickness 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. 10(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. 10(c). The current density is much smaller in the continuous sheet of copper, as shown in Fig. 10(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. 10(a) and (b), whereas it stays relatively uniform for the continuous sheet of copper, as shown in Fig. 10(c). This is primarily due to a thicker connection at each bend in the continuous sheet of copper which reduces the current density. 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; a 29% reduction.

![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.](image)

**Fig. 10.** 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.

**Experimental Results**

A prototype of the dual-coil charging pad was implemented, as shown in Fig. 2, to validate the simulation results of the dc and ac coil. The simulated and measured dc coil magnetic forces are shown in Fig. 11. The dc coil generates a peak $F_{mag,x}$ of 3.51 N; 70% of the simulated peak of 5.01 N. With a linear slider friction force of 0.76 N, the dc coil has a wide misalignment correction range of $20 \text{ mm} \leq \Delta x \leq 240 \text{ mm}$.

![Simulated $F_{mag,x}$ of dc coil versus $I_{dc}$. (b) Measured $F_{mag,x}$ of dc coil versus $I_{dc}$](image)

**Fig. 11.** (a) Simulated $F_{mag,x}$ of dc coil versus $I_{dc}$. (b) Measured $F_{mag,x}$ of dc coil versus $I_{dc}$. 
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(b). The uniformly spaced ferrite bars were first operated at a power level of 3.7 kW successfully, as shown in Fig. 12(a). However, the coil with uniformly spaced ferrite bars failed when 5kW WPT was attempted with the resulting ferrite damage shown in Fig. 12(b). As the bus voltage, $V_{bus}$, was gradually 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. 12(b). This validates the simulation results in Fig. 7(a), where the peak $B$ was observed directly below the ac coil windings in the top and bottom ferrite bars.

![Ferrite Bar Damage](image1)

Fig. 12. (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.

The non-uniformly spaced ferrite bars were then operated at a power level of 3.7 kW successfully, as shown in Fig. 13(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. 13(b), with a dc-dc efficiency of 90.1%.

![Ferrite Bar Waveform](image2)

Fig. 13. Measured waveforms of the non-uniformly spaced ferrite bars at (a) 3.7kW and (b) 5kW WPT.

**Conclusions**

A 5 kW solenoid-based dual-coil charging pad was implemented for EV wireless charging, where a secondary electro-magnetic based coil is capable of correcting a wide horizontal misalignment range of 20 mm to 240 mm. The concentration of ferrite bars near the solenoid edges was increased to alleviate the higher magnetic flux density. By doing so, the peak simulated magnetic flux density in the ferrite bars was reduced by 20%. The eddy current distribution in shields composed of a continuous sheet and multiple isolated pieces of copper was also analyzed. By using a continuous sheet, simulated eddy current losses were reduced by 29%. The more conventional design with uniform spacing failed beyond 3.7 kW, which validates the simulation approach. By using an optimized non-uniform spacing in the ferrite bars, the WPT prototype successfully transfers 5 kW with over 90% dc-dc efficiency.
References


