



Article A Study on a Fully Integrated Coil Based on the LCCL-S Compensation Topology for Wireless EVs Charging Systems

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Abstract: This study proposes a full integration method for the double capacitances and inductanceseries (LCCL-S)-compensated inductive power transfer (IPT) of electric vehicles (EVs). The transmitter and receiver coils adopt the unipolar coil, and the compensation inductor is designed as an extended DD coil. Specifically, the use of an extended DD coil enhances the misalignment tolerance of the EVs. When the IPT system is in the misaligned state, a primary transfer path for magnetic flux is established between the transmitter and receiver coils, and a secondary transfer path is established between the extended DD coil and receiver coil. The distance between the two unipolar coils of the extended DD coil is optimized to maximize the magnetic flux on the secondary transfer path, thereby increasing the total power of the system misaligned state. Simultaneously, the most suitable turns and inner diameter of the extended DD coil are designed by using the finite element method (FEM) simulation tool. In order to verify the performance of the proposed integrated coil method, a 3.3 kW experimental prototype with a 100 mm air gap was constructed and compared with the conventional integration method under the same conditions. The experimental results show that the proposed magnetic coupling structure maintains at least a 63.6% well-aligned value at a door-to-door 150 mm misaligned state, and the output power of the system is 1.05 kW higher than that of the traditional integration method without extra control algorithms.

Keywords: electric vehicles (EVs); integration method; LCCL-S compensation; extended DD coil; misalignment tolerance

1. Introduction

In response to the mounting concerns regarding energy exhaustion and environmental contamination, there has been an increasing demand for environmentally friendly energy solutions in recent years. Consequently, Electric Vehicles (EVs) have emerged as an integral facet of the envisioned smart cities of the future [1,2]. At present, the prevailing lithium batteries employed in EVs are characterized by a low energy density, substantial weight, and elevated cost. Hence, organic photovoltaic devices, postured as an emergent battery technology, are perceived to hold considerable developmental potential and have been the subject of proactive research endeavors [3,4]. On the other hand, regarding the charging method for EVs, inductive power transfer (IPT) technology has the advantages of convenience, safety, reliability, etc.; therefore, it has also attracted considerable societal attention [5,6].

As shown in Figure 1, a typical IPT system includes a power supply, a power factor correction converter, an inverter, a compensation resonant network, a loosely coupled transformer (LCT), a rectifier, and a battery load. Because perfect alignment parking is a very difficult task for most drivers, several parking lots use parking limit blocks located at the rear of parking spaces to significantly reduce front-to-rear (*Y*-axis) misalignment.



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Figure 1. Typical stationary EV IPT system.

However, as mentioned in [7], the door-to-door (X-axis) misalignment between EVs is critical. Because it is rather inconvenient to adjust the X-axis misalignment when the EVs are parked, it is necessary to further improve the door-to-door misalignment performance.

Meanwhile, to improve the efficiency of the IPT system for EVs, the main research directions currently include coil design, the compensation resonant network, power converters, corresponding control methods, and environmental performance reference. Particularly, compensation topologies are the most crucial part that affects system performance. Interestingly, four traditional topologies have successively emerged: series–series (S-S) [8–10], parallel–parallel (P-P) [11], parallel–series (P-S) [12], and series–parallel (S-P) [13]. Additionally, many scholars have also developed high-order compensation topologies [14–17]. Among them, the double capacitances and inductance–series (LCCL-S) topology has been widely adopted. This is primarily because it can achieve good power stability and efficiency for a constant voltage (CV) output when charging EV batteries. The most attractive advantage of the LCCL-S topology is that it uses a small number of components, which can reduce the weight, size, and cost of the IPT system.

Furthermore, optimizing the magnetic coupling structure is one of the key techniques to improve the misalignment tolerance of the IPT system. Therefore, several magnetic structures have been studied, such as the solenoid structure coil [18], the magnetic structure of the unipolar coil [19], the double-D (DD) structure coil [20], and the double quadrature (DDQ) structure coil [21,22]. In [23], a new coil structure in which a large rectangular coil is connected in series with two small rectangular coils in a zigzag shape internally was studied. Small rectangular coils are connected back-to-back in series and are referred to as extended DD coils. More precisely, the advantage of an extended DD coil is that it maintains an almost uniform magnetic induction density when the EVs are charged in a misaligned state, which can greatly improve output power fluctuation. Meanwhile, to make the IPT system lighter and simpler, the compensation inductor is integrated with the transmitter coil [24–28]. Kan et al. proposed two different methods for the integrated coil using the LCCL-LCCL compensation topology; one method involves integrating the compensation inductors into the unipolar main coils (IU method) [29], and the compensation inductors are bipolar coils. In the other method, the compensation inductors are integrated into the bipolar main coils (IB method) [30], and the compensation inductors are unipolar coils. Comparing these two design methods, the IU method has a superior misalignment capability and greater load-carrying efficiency than the IB method. In [31], a dual-coupled integrated IPT system involving coupling between the compensation inductors and cross-coupling between the compensation inductors and main coils facilitated an increase in the total output power of a system in misalignment. However, compensation inductors are located in the upper and lower position of the transmitter and receiver coil, which will increase the package thickness. In [32,33], a fully integrated magnetic structure was proposed to

minimize system cost and increase power density. But, in the system misaligned state, the proposed method does not consider the effect of the cross-coupling generated between the compensation inductor and the main coil in the magnetic coupling structure.

In this study, a fully integrated IPT system based on the LCCL-S topology is proposed to reduce the magnetic pad volume and focus on solving the door-to-door misalignment problem. In the proposed system, the transmitter and receiver coils are used as unipolar coils, and the extended DD structure coil is integrated into the transmitter coil as a compensation inductor. The advantages of the proposed magnetic coupling structure are mainly demonstrated in two aspects: First, when the system is in the aligned state, the coupling effect of the extended DD coil to the transmitter and receiver coils is eliminated. Another advantage is, when in door-to-door misaligned state, the first magnetic coupling is generated between the transmitter and receiver coils, and a second magnetic coupling is generated between the receiver and the extended DD coils, which increases the total output power of the system. Specifically, this study utilized the finite element method (FEM) simulation tool to optimize the distance between the two unipolar small coils of the extended DD coil, as well as the number of turns and inner diameter of the extended DD coil. The main purpose of the optimization is to maximize the second magnetic coupling and improve the total output power of the misaligned system. Finally, to verify that the proposed magnetic coupling structure has high misalignment tolerance performance, two sets of magnetic coupling structures with the DD coil and the extended DD coil as the compensation inductors were established, and comparative experiments were performed.

This study is organized as follows: Section 2 provides an analysis of the fully integrated LCCL-S topology. In Section 3, an analysis of the proposed extended DD coil, as well as its design and optimization, is presented. Section 4 presents how our experiment was conducted along with a comparison of the volume and weight of different compensation inductor structures. Finally, conclusions are drawn in Section 5.

2. Analysis of the Proposed LCCL-S Topology

The proposed fully integrated LCCL-S topology is depicted in Figure 2. Where L_p and L_s adopt the unipolar coil as the transmitter and receiver coils, and L_{in} adopts the proposed extended DD coil as the compensation inductor, as shown in Figure 3. Specifically, the bipolar coil generates a magnetic field that travels from one side of the coil to the other, with the magnetic flux circulating between the two sides of the coil, forming a complete loop. Φ_{in-p} is the magnetic flux passing through L_{in} from L_p , then Φ_{p-in} is the magnetic flux excited by L_p passing through L_{in} . Φ_{in} and Φ_p represent their self-magnetic fluxes. As a result, the magnetic flux entering L_p is equal to the magnetic flux flowing out of it. Thus, the net magnetic flux Φ_{in-p} is zero, and K_{in-p} is also zero, according to (1). Similarly, the coupling effect between L_{in} and L_p , L_p and L_s , and L_{in} and L_s , respectively. Additionally, K_{p-s} is the coupling coefficient between L_p and L_s ; K_{in-p} and K_{in-s} are the coupling coefficients between L_{in} and L_p and L_s , respectively.

$$K_{in-p} = \sqrt{\frac{\Phi_{p-in}\Phi_{in-p}}{\Phi_p\Phi_{in}}} = 0.$$
⁽¹⁾

$$K_{in-p} = \frac{M_{in-p}}{\sqrt{L_{in}L_p}}, \ K_{in-s} = \frac{M_{in-s}}{\sqrt{L_{in}L_s}}, \ K_{p-s} = \frac{M_{p-s}}{\sqrt{L_pL_s}}.$$
 (2)



Figure 2. Circuit topology of a fully LCCL-S compensated IPT system.



Figure 3. (a) Transmitter coil with an extended DD coil and (b) receiver coil.

In the IPT system, the direct current (DC) to alternating current (AC) conversion is realized using a high-frequency full-bridge inverter, as shown in Figure 2, where U_{in} is the inverter AC output voltage, which can be expressed as follows:

$$U_{in} = \frac{2\sqrt{2}U_{DC}}{\pi}.$$
(3)

 R_{eq} is the equivalent AC load resistance of R_o , and the relationship can be represented as follows:

$$R_{eq} = \frac{8R_o}{\pi^2}.$$
(4)

The current and voltage in the circuit loop can be expressed by Kirchhoff's voltage law (KVL) as follows:

$$U_{in} = (R_i + j\omega L_{in})I_{in} + \frac{1}{j\omega C_p}(I_{in} - I_p) - j\omega M_{in-p}I_p + j\omega M_{in-s}I_s$$

$$0 = \frac{1}{j\omega C_p}(I_{in} - I_p) - (R_p + j\omega L_p + \frac{1}{j\omega C_f})I_p + j\omega M_{p-s}I_s + j\omega M_{in-p}I_{in}$$

$$0 = j\omega M_{in-s}I_{in} - j\omega M_{p-s}I_p + (R_s + R_{eq} + j\omega L_s + \frac{1}{j\omega C_s})I_s.$$
(5)

The nondiagonal components of the impedance matrix of the fully integrated LCCL-S circuit can be expressed as follows:

$$Z_a = R_i + j\omega L_{in} + \frac{1}{j\omega C_p}, Z_b = j\omega M_{in-p} + \frac{1}{j\omega C_p}, Z_c = j\omega M_{in-s},$$

$$Z_d = j\omega M_{p-s}, Z_e = R_p + j\omega L_p + \frac{1}{j\omega C_p} + \frac{1}{j\omega C_f}, Z_f = R_s + j\omega L_s + R_{eq} + \frac{1}{j\omega C_s}.$$
(6)

In addition, according to ZI = U, the impedance matrix can be written as follows:

$$\begin{bmatrix} Z_a & -Z_b & Z_c \\ Z_b & -Z_e & Z_d \\ Z_c & -Z_d & Z_f \end{bmatrix} \begin{bmatrix} I_{in} \\ I_p \\ I_s \end{bmatrix} = \begin{bmatrix} U_{in} \\ 0 \\ 0 \end{bmatrix}.$$
(7)

From the above analysis, the inverter output current I_{in} and the transmitter and receiver coil currents I_p and I_s can be expressed as follows:

$$I_{in} = \frac{U_{in}Z_eZ_g(Z_d^2(2-Z_d^2)-Z_eZ_g)}{Z_d^2(Z_eZ_g(Z_a-1)-Z_d^2-Z_b^2Z_g-Z_cZ_e^2)+Z_eZ_g(Z_e(Z_aZ_g+Z_c^2)-Z_b^2Z_g-2Z_bZ_cZ_d)'}$$

$$I_p = I_{in}\frac{Z_bZ_g-Z_cZ_d}{Z_eZ_g-Z_d^2}, \quad I_s = -I_p\frac{Z_bZ_d-Z_cZ_e}{Z_dZ_c-Z_bZ_g}.$$
(8)

At the resonant frequency (f_o), the compensation topology should satisfy the resonance conditions, and it can be expressed as follows:

$$C_p = \frac{1}{\omega^2 L_{in}}, C_s = \frac{1}{\omega^2 L_s}, C_f = \frac{1}{\omega^2 (L_p - L_{in})}.$$
(9)

The rectifier input voltage can be simplified to the following:

$$U_{out} = \frac{M_{p-s}}{L_{in}} U_{in} = \frac{2\sqrt{2}U_{dc}}{\pi}.$$
 (10)

Equation (10) clearly shows that the system maintains a constant output voltage independent of the load. Simultaneously, U_{out} can be adjusted by changing the size of L_{in} to satisfy the charging voltage requirements of the battery. The AC output power P_{out} can be expressed as follows:

$$P_{out} = U_{out}I_s = \frac{j\omega(M_{in-s}I_{in} + M_{p-s}I_p)2\sqrt{2U_{dc}}}{\pi R_o}.$$
 (11)

Combined with the designed magnetic coupling structure, the misalignment distance of the system increases. The K_{in-p} remains close to 0, but K_{in-s} increases; there are two couplings in the system. P_{out} can slowly decrease with the increase in M_{in-s} , so when the system is misaligned state, it is crucial to design the size of M_{in-s} .

3. Design and Optimization of the Proposed Extended DD Coil

3.1. Proposed Magnetic Pad Structure

A cross-sectional side view of the proposed fully integrated structure is shown in Figure 4. Specifically, the air gap of the magnetic coupler structure is designed to be 100 mm, which is acceptable for most EVs. Meanwhile, L_p and L_s are 9-turn and 10-turn rectangles with sizes of 440 mm × 340 mm × 5 mm and 250 mm × 250 mm × 5 mm, respectively. Further, the size of each unipolar coil-designed L_{in} is 160 mm × 100 mm × 5 mm, and ferrite is uses with dimensions of 440 mm × 340 mm × 5 mm. Additionally, aluminum plates are placed on the top and bottom of the ferrite to provide sufficient magnetic shielding.

3.2. Design of the Extended DD Coil

After the coil size has been determined, the extended DD coil can be optimally designed. The purpose of the optimized design is to minimize the cross-coupling of L_{in} to L_p and L_s when the system is in an aligned state. This results in a mutual decoupling effect and the achievement of a high-efficiency magnetic coupling structure. Furthermore, the optimized extended DD coil increases the system output power by maximizing the coupling between L_{in} and L_s when the system is in a misaligned state. Particularly, the extended DD coil comprises two oppositely electrically connected unipolar coils (D_1



and D_2), and the distance between them is used as a variable for the optimal design in this paper.

Figure 4. 3-D geometry and dimensions of the designed magnetic coupling structure.

The magnetic coupling structure designed was simulated by the FEM tool. Specifically, the door-to-door direction was set as the *X*-axis, and the front-to-rear direction was the *Y*-axis. First, the DD coil is adopted as the compensation inductor in the conventional integration method; the distance between D_1 and D_2 is 0 mm. Then, based on the DD coil, when the design variable is changed to shift the distance between D_1 and D_2 along the $\pm X$ -axis or $\pm Y$ -axis direction, the variation in the coupling coefficient between L_p and L_s is as shown in Figure 5a. It can be observed that D_1 and D_2 shift 0 to 80 mm on the $\pm X$ -axis or 0 to 15 mm on the $\pm Y$ -axis direction; K_{p-s} only changes by a small value of 0.0005 from 0.2160 to 0.2165 in the aligned state. Simultaneously, K_{in-p} and K_{in-s} are close to zero, which can be ignored; therefore, the changes are not shown here.



Figure 5. (a) K_{p-s} changes at different distances between D_1 and D_2 of the extended DD coil of the system in the aligned state and (b) K_{in-s} changes at different distances between D_1 and D_2 in the 150 mm *X*-axis misaligned state.

Since the transmitter coil is rectangular, the maximum misalignment distances for the *Y*-axis and *X*-axis are set to 100 mm and 150 mm, respectively. When the system is an *X*-axis direction misalignment of 150 mm, the K_{p-s} decreases due to changes in the magnetic field distribution. After the D_1 and D_2 move along the $\pm X$ -axis or $\pm Y$ -axis, K_{in-p} is still

close to 0, but the value of K_{in-s} changes, as shown in the simulation results in Figure 5b. As D_1 and D_2 move along the $\pm X$ -axis, the value of K_{in-s} increases. At this point, the second magnetic coupling of the system is generated, according to (11); hence, the designed magnetic coupling structure can slow down the decline in the P_{out} of the system in the misaligned state. If the distance moves along the $\pm X$ -axis and then the $\pm Y$ -axis, the second coupling will first increase and then decrease. For example, as the distance between D_1 and D_2 moves by 80 mm along the $\pm X$ -axis, K_{in-s} reaches its maximum of 0.0683. If the distance between D_1 and D_2 moves along the $\pm Y$ -axis by 15 mm, the value of K_{in-s} is reduced to 0.0562. As a result, D_1 and D_2 move 80 mm along the $\pm X$ -axis, with the $\pm Y$ -axis position remaining unchanged as it is the best position for D_1 and D_2 , as shown in Figure 3a.

Therefore, it can be seen from the above discussion that the proposed fully integrated LCCL-S topology has two coupling coefficients, and consequently, two magnetic flux transfer paths. Precisely, one path is from L_p to L_s , forming the first magnetic coupling, and the other path is from L_{in} to L_s , forming the second magnetic coupling. According to [31], combined with the topology proposed in this paper, the magnetic flux transmission path from L_{in} to L_s can increase the output power of the system in a misaligned state in the *X*-axis direction. Overall, this design is suitable for solving problems related to when EVs are in a misaligned state in the door-to-door direction.

Furthermore, this study utilized the FEM tool to simulate the LCT when the misalignment distance on the X-axis is increased to 150 mm. Particularly, the compensation inductors were designed to be a DD coil and extended DD coil, respectively, with an operating frequency of 85 kHz. The proposed fully integrated LCC-S compensation topology was incorporated, inputting the same circuit parameter values and resistance values as the calculated ones. Appropriate simulation step sizes were selected, and the magnetic coupler was partitioned along the Y-Z axis. Using contour plots, the magnetic flux distribution of the coupler can be clearly displayed, as shown in Figure 6.



Figure 6. Different compensation inductor FEM simulation diagrams: (**a**) DD coil and (**b**) extended DD coil.

Figure 6a shows the magnetic flux distribution of the LCT, in which the compensation inductor is adopted as the DD coil; specifically, the main transmission path of the magnetic flux is between L_p and L_s . Due to the small face-to-face area of D_1 or D_2 with L_s , the magnetic flux generated by L_{in} rarely passes through L_s . However, when the compensation inductor is adopted as the extended DD coil in Figure 6b, the magnetic flux can be transferred not only between L_p and L_s but also between L_{in} and L_s . Since D_1 or D_2 has a larger face-to-face area with L_s , more magnetic flux will be transmitted, thereby increasing the magnetic field strength, as shown in the red circled area in Figure 6. Therefore, with the proposed magnetic coupling structure, more energy will be transferred from the transmitter to the receiver sides, thereby improving the misalignment tolerance performance of the system.

3.3. Optimizing the Turns and Inner Diameter of the Extended DD Coil

To increase the second magnetic coupling coefficient between the compensation inductor and receiver coil, this study also optimizes the number of turns and inner diameter of the compensation inductor coil. The optimization process is shown in Figure 7, and the influence of different inner diameters and turns on the inductance value of the compensation inductor is analyzed in detail. Interestingly, the simulation results show that, for different inner diameters with the same number of turns, the larger the inner diameter, the higher the inductance value and the better the K_{in-s} value in the system in a misaligned state. Therefore, when the compensation inductor is a DD coil, the number of coil turns is meant to be eight. Then, D_1 and D_2 are moved by 80 mm along the $\pm X$ -axis direction to construct the proposed extended DD coil. The simulation results show that the inductance value gradually decreases with the increase in the distance between D_1 and D_2 , as shown in Figure 8. To fairly calculate the system output voltage when the compensation inductor is the DD coil or extended DD coil, it is necessary to ensure that the inductance values of the two types of coils are the same and that all parameters are the same. As a result, after several simulation optimizations, the extended DD coil is increased by 0.2 turns so that the simulated inductance value of the two compensation inductors is 19.2 μ H, and the inner diameter of the coil is set to 20 mm.



Figure 7. Design procedure of the proposed extended DD coil.





4. Experimental Verification of the Proposed Integration Method

To verify the above simulation analysis, a fully integrated LCCL-S structure prototype was developed, as shown in Figure 9. The design specifications and circuit parameters of the magnetic coupling structure are shown in Table 1. Among them, L_p , L_s , and L_{in} were wounded by EUW Litz wire. More precisely, the thickness of the ferrite bar used is 5 mm to prevent saturation and excessive core loss. Additionally, the dimensions of the coils, ferrites, aluminum plates, and air gap in the experiment are the same as the simulation conditions.



Figure 9. (a) Experimental prototype, (b) receiver coil, and (c) transmitter coil and two kinds of compensation inductor structures.

Table 1. Essential parameters of the proposed systemeters of the proposed systemeter

Variable	Selected Value	Variable	Selected Value
Lp	81.31 μH	fo	85 kHz
$\dot{L_s}$	43.83 μH	Air gap	100 mm
L_{in}	20.01 µH	Main coupling coefficient K_{p-s}	0.2018
C_s	80.28 nF	DC input voltage	380 V
C_p	167.22 nF	Output power	3.3 kW
$\dot{C_f}$	59.03 nF	Load resistance	14.62 Ω

First, when the compensation inductor is the DD coil and extended DD coil, the K_{p-s} , K_{in-s} , and K_{in-p} of the magnetic coupling structure are measured, respectively, and compared with the simulation results, as shown in Table 2. Since the simulated and measured values of K_{in-p} are close to 0 for the system in the aligned and misaligned state, they are not shown in Table 2. In particular, the measured results show that the K_{p-s} and K_{in-s} values are slightly different from the simulated values because any slight manipulation of the coil during the measurement process may affect the result, but the error is small and acceptable for the experiment.

Simulation Values Experiment Values DD Coil **Extended DD Coil** DD Coil **Extended DD Coil Coupling Coefficients** K_{in-s} K_{p-s} K_{in-s} K_{p-s} K_{in-s} K_{in-s} K_{p-s} K_{p-s} 0.2161 0.0001 0.0002 0.2011 0.0083 0.0075 0.2163 0.2018 Aligned X_{mis}-100 mm 0.18740.0012 0.1872 0.0855 0.1802 0.0076 0.1838 0.0833 X_{mis}-150 mm 0.1360 0.0026 0.1362 0.0683 0.1339 0.0010 0.1355 0.0622

 Table 2. Comparison of simulated and measured values.

Next, the proposed system is misaligned by 100 mm in the X-axis direction, adopting the DD coil as the compensation inductor, and the K_{in-s} of the magnetic coupling structure is 0.0125. However, when the extended DD coil is adopted as the compensation inductor, K_{in-s} is 0.0843 and still 0.0622 at a misalignment of 150 mm, resulting in relatively better second magnetic coupling, further verifying the simulation results. Moreover, comparing the inductance values of the DD coil and extended DD coil with the same number of turns, the DD coil inductance value is 0.56 µH higher than the extended DD coil because of the increased distance between the two small unipolar coils between the extended DD coil. Therefore, the extended DD coil has a slightly increased number of turns, which is the same as the inductance value of the DD coil.

Furthermore, two groups of comparative experiments are performed under the condition that the system is well-aligned. Precisely, the input voltage of the system is 380 V, and the DC power supply is connected to the full-bridge inverter and inverted into highfrequency AC power. Particularly, the inverter uses C3MOO30090K with a high withstand voltage as the SIC MOSFETs. Since the waveforms, input voltage, and output power of the two groups of experiments are similar, only the experimental results of the extended DD coil are shown. Figure 10 shows that the IPT system realized the zero-voltage switching (ZVS) between the inverter current and output voltage, which facilitates a reduction in the switching loss of the inverter and improves efficiency. In addition, it can be seen from Figure 11 that the system output power can reach 3.3 kW with a DC–DC efficiency reaching 94.359% when the system is in an aligned state.



Figure 10. Experimental input voltage and current waveforms.

U _{rms2}	380.073 V UDC Urms1	219.774 ∛ U _{dc}
I_{rms2}	9.2746 A Irms1	15.1017 A
P ₂	3.5173k₩ <i>P</i> _{in} P ₁	3.3189 k₩ <i>Pout</i>
I_{rms3}	17.4699 A Irms4	30.4102 A
7 1	94.359 % n Loss1	0.1984 k₩

Figure 11. Experimental power and efficiency in the system aligned state.

The proposed system was also verified with the system misaligned state; the results are shown in Figure 12. When the Y-axis direction is in misalignment by 100 mm, the system output power when the DD coil is used as the compensation inductor is reduced to 1.35 kW, which is 41% of the well-aligned value. Meanwhile, the output power of the system of the extended DD coil (as the compensation inductor) is reduced to 1.39 kW, which is 42.6% of the well-aligned value. Therefore, the results confirmed that the magnetic flux transfer path established between the extended DD coil and the receiver coil does not affect the output power of the system in the Y-axis misaligned state. However, when the X-axis direction is in misalignment by 100 mm, the system output power of the DD coil as the compensation inductor is reduced to 2.21 kW, which is 66.7% of the well-aligned value. Furthermore, the output power of the system power of the extended DD coil is 2.97 kW, which is 90% of the well-aligned value; when the misalignment distance is increased to 150 mm, the well-aligned value of 63.6% is still maintained, and the output power is 1.1 kW higher than that of the DD coil. Therefore, it can be confirmed that the proposed extended DD coil compensation inductor can improve the output power of the system in the X-axis misaligned state.



Figure 12. Comparison of the output power of the compensation inductor for the DD coil and extended DD coil in the system misaligned state: (a) *Y*-axis and (b) *X*-axis.

To demonstrate the convenience of the proposed fully integrated coil, an extra inductor with the same inductance extended DD coil was compared with respect to volume and weight as shown in Figure 13, and Table 3 presents the comparison results. Specifically, the proposed extended DD coil is superior to the extra inductor in terms of weight. Additionally, the extended DD coil is located inside the transmitter coil, eliminating the need for additional space and simplifying packaging. During the charging process of EVs, the ferrite core will generate heat and cause power loss, and the system also needs a cooling device; hence, this increases costs. Therefore, using the extended DD coil as the compensation inductor can save space and enhance misalignment tolerance.



Figure 13. Different types of compensation inductors: (**a**) extra inductor and (**b**) proposed extended DD coil.

Table 3. Comparing the weight and volume of different compensation inductors.

Туре	Occupied Space (cm ³)	Gross Weight (kg)	Size (cm) $X \times Y \times Z$
Extra inductor	75	0.39	$5 \text{ cm} \times 3 \text{ cm} \times 5 \text{ cm}$
Extended DD coil	0	0.12	$10~\text{cm}\times16~\text{cm}\times0.5~\text{cm}\times2$

5. Conclusions

In this study, a fully integrated LCCL-S-compensated IPT system was proposed. Specifically, the extended DD coil is integrated into the transmitter coil as a compensation inductor, and the optimization of the distance between the two unipolar coils of the extended DD coil is carried out using the FEM simulation tool. The purpose of the optimization is to eliminate the coupling effect of the extended DD coil to the transmitter and receiver coils when the system is in the aligned state. Moreover, in the door-to-door misaligned state, the optimized extended DD coil and receiver coil can establish a secondary magnetic flux transmission path, generating a second magnetic coupling, thereby increasing energy transfer performance. Two sets of comparative experiments are established in which the compensation inductors are the DD coil and extended DD coil; the aligned efficiency of both is 94.35% at 3.3 kW with a 100 mm air gap. However, when the extended DD coil is used as the compensation inductor and the system is in a door-to-door 150 mm misaligned state, the output power maintains 63.6% of the well-aligned value, which is 1.05 kW higher than that of the DD coil. Our experimental results show that the proposed fully integrated structure maintains good performance in an aligned state and improves the system output power in door-to-door misaligned state, exhibiting good misalignment performance. Finally, the weight and volume advantages of integrated coils have been demonstrated.

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References

- Ma, R.; Jiang, X.; Fu, J.; Zhu, T.; Yan, C.; Wu, K.; Müller-Buschbaum, P.; Li, G. Revealing the underlying solvent effect on film morphology in high-efficiency organic solar cells through combined ex situ and in situ observations. *Energy Environ. Sci.* 2023, 16, 2316–2326. [CrossRef]
- Mi, C.C.; Buja, G.; Choi, S.Y.; Rim, C.T. Modern advances in wireless power transfer systems for roadway powered electric vehicles. *IEEE Trans. Ind. Electron.* 2016, 63, 6533–6545. [CrossRef]
- 3. Ma, R.; Li, H.; Peña, T.A.D.; Xie, X.; Fong, P.W.-K.; Wei, Q.; Yan, C.; Wu, J.; Cheng, P.; Li, M.; et al. Tunable donor aggregation dominance in ternary matrix of all-polymer blends with improved efficiency and stability. *Adv. Mater.* **2023**, 2304632. [CrossRef]
- Ma, R.; Fan, Q.; Dela Peña, T.A.; Wu, B.; Liu, H.; Wu, Q.; Wei, W.; Wu, J.; Lu, X.; Li, M.; et al. Unveiling the morphological and physical mechanism of burn-in loss alleviation by ternary matrix toward stable and efficient all-polymer solar cells. *Adv. Mater.* 2023, *35*, 2212275. [CrossRef] [PubMed]
- 5. Bosshard, R.; Kolar, J.W. Inductive power transfer for electric vehicle charging: Technical challenges and tradeoffs. *IEEE Power Electron. Mag.* **2016**, *3*, 22–30. [CrossRef]
- Kurs, A.; Karalis, A.; Moffatt, R.; Joannopoulos, J.D.; Fisher, P.; Soljacic, M. Wireless power transfer via strongly coupled magnetic resonances. *Science* 2007, 317, 83–86. [CrossRef]
- Nguyen, T.D.; Li, S.Q.; Li, W.H.; Mi, C.C. Feasibility study on bipolar pads for effificient wireless power chargers. In Proceedings of the 2014 IEEE Applied Power Electronics Conference and Exposition-APEC 2014, Fort Worth, TX, USA, 16–20 March 2014; pp. 1676–1682.
- 8. Zahid, Z.U.; Dalala, Z.M.; Zheng, C.; Chen, R.; Faraci, W.E.; Lai, J.S.; Lisi, G.; Anderson, D. Modeling and control of series–series compensated inductive power transfer system. *IEEE J. Emerg. Sel. Top. Power Electron.* **2015**, *3*, 111–123. [CrossRef]
- 9. Zhang, W.; Wong, S.C.; Tse, C.K.; Chen, Q.H. Design for efficiency optimization and voltage controllability of series-series compensated inductive power transfer system. *IEEE Trans. Power Electron.* **2014**, *29*, 191–200. [CrossRef]
- Chen, Y.; Zhang, H.; Jin, N.; Guo, L.; Wu, J.; Park, S.-J.; Kim, D.-H. A unipolar-duty-cycle hybrid control strategy of seriesseries compensated IPT system for constant-current output and efficiency optimization. *IEEE Trans. Power Electron.* 2022, 37, 13884–13901. [CrossRef]
- 11. Fu, M.; Tang, Z.; Ma, C. Analysis and optimized design of compensation capacitors for a megahertz WPT system using full-bridge rectifier. *IEEE Trans. Ind. Informat.* 2019, *1*, 95–104. [CrossRef]
- Sohn, Y.H.; Choi, B.H.; Lee, E.S.; Lim, G.C.; Cho, G.H.; Rim, C.T. General unified analysis of two-capacitor inductive power transfer systems: Equivalence of current-source SS and SP compensations. *IEEE Trans. Power Electron.* 2015, 30, 6030–6045. [CrossRef]
- Zhang, W.; Wong, S.-C.; Tse, C.K.; Chen, Q.H. Analysis and comparison of secondary series- and parallel-compensated inductive power transfer systems operating for optimal efficiency and load-independent voltage transfer ratio. *IEEE Trans. Power Electron.* 2014, 29, 2979–2990. [CrossRef]
- 14. Feng, H.; Cai, T.; Duan, S.X.; Zhao, J.B.; Zhang, X.M.; Cheng, C.S. An LCC compensated resonant converter optimized for robust reaction to large coupling variation in dynamic wireless power transfer. *IEEE Trans. Ind. Electron.* **2016**, *63*, 6591–6601. [CrossRef]
- Chen, Y.F.; Zhang, H.L.; Park, S.J.; Kim, D.H. A switching hybrid LCC-S compensation topology for constant current/voltage EV wireless charging. *IEEE Access* 2019, 7, 133924–133935. [CrossRef]
- 16. Zhu, Y.; Wu, H.; Li, F.; Zhu, Y.; Pei, Y.; Liu, W. A comparative analysis of S-S and LCCL-S compensation for wireless power transfer with a wide range load variation. *Electronics* **2022**, *11*, 420. [CrossRef]
- 17. Li, G.Y.; Kim, D.-H. A wireless power transfer charger with hybrid compensation topology for constant current/voltage onboard charging. *Appl. Sci.* **2021**, *11*, 7569. [CrossRef]
- Takanashi, H.; Sato, Y.; Kaneko, Y.; Abe, S.; Yasuda, T. A large air gap 3 kW wireless power transfer system for electric vehicles. In Proceedings of the 2012 IEEE Energy Conversion Congress and Exposition (ECCE), Raleigh, NC, USA, 15–20 September 2012; pp. 269–274.
- 19. Budhia, M.; Covic, G.A.; Boys, J.T. Design and optimization of circular magnetic structures for lumped inductive power transfer systems. *IEEE Trans. Power Electron.* 2011, 26, 3096–3108. [CrossRef]
- 20. Budhia, M.; Boys, J.T.; Covic, G.A.; Huang, C.-Y. Development of a single-sided flux magnetic coupler for electric vehicle IPT charging systems. *IEEE Trans. Ind. Electron.* **2013**, *60*, 318–328. [CrossRef]
- 21. Covic, G.A.; Kissin, M.L.G.; Kacprzak, D.; Clausen, N.; Hao, H. A bipolar primary pad topology for EV stationary charging and highway power by inductive coupling. In Proceedings of the IEEE Energy Conversion Congress and Exposition (ECCE), Phoenix, AZ, USA, 17–22 September 2011.
- 22. Budhia, M.; Covic, G.A.; Boys, J.T.; Huang, C.-Y. Development and evaluation of single sided flux couplers for contactless electric vehicle charging. In Proceedings of the IEEE Energy Conversion Congress and Exposition, Phoenix, AZ, USA, 17–22 September 2011.
- 23. Alam, M.M.; Mekhilef, S.; Seyedmahmoudian, M.; Horan, B. Dynamic charging of electric vehicle with negligible power transfer fluctuation. *Energies* **2017**, *10*, 701. [CrossRef]
- 24. Li, W.H.; Zhao, H.; Li, S.Q.; Deng, J.J.; Kan, T.; Mi, C.C. Integrated LCC compensation topology for wireless charger in electric and plug-in electric vehicles. *IEEE Trans. Ind. Electron.* 2014, *62*, 4215–4225. [CrossRef]
- 25. Shi, K.; Tang, C.S.; Long, H.; Lv, X.C.; Wang, Z.H.; Li, X.F. Power fluctuation suppression method for EV dynamic wireless charging system based on integrated magnetic coupler. *IEEE Trans. Power Electron.* **2022**, *37*, 1118–1131. [CrossRef]

- Zhang, Y.M.; Wu, Y.M.; Shen, Z.W.; Pan, W.B.; Wang, H.; Dong, J.Q.; Mao, X.K.; Liu, X. Integration of onboard charger and wireless charging system for electric vehicles with shared coupler, compensation, and rectifier. *IEEE Trans. Ind. Electron.* 2023, 70, 7511–7514. [CrossRef]
- Shi, K.; Tang, C.S.; Wang, Z.H.; Li, X.F.; Zhou, Y.Z.; Fei, Y.J. A magnetic integrated method suppressing power fluctuation for EV dynamic wireless charging system. *IEEE Trans. Power Electron.* 2022, *37*, 7493–7503. [CrossRef]
- Zhang, Z.; Zheng, S.; Yao, Z.; Xu, D.M.; Krein, P.T.; Ma, H. Analysis, design, and implementation of a spatially nested magnetic integration method for inductive power transfer systems. *IEEE Trans. Power Electron.* 2021, 36, 7537–7549. [CrossRef]
- Kan, T.; Nguyen, T.D.; White, J.C.; Malhan, R.K.; Mi, C.C. Integrated coil design for EV wireless charging systems using LCC compensation. *IEEE Trans. Power Electron.* 2018, 32, 1112–1123. [CrossRef]
- 30. Kan, T.; Nguyen, T.D.; White, J.C.; Malhan, R.K.; Mi, C.C. A new integration method for an electric vehicle wireless charging system using LCC compensation topology: Analysis and design. *IEEE Trans. Power Electron.* 2017, 32, 1638–1650. [CrossRef]
- 31. Lu, F.; Zhang, H.; Hofmann, H.; Su, W.; Mi, C.C. A dual coupled LCC-compensated IPT system with a compact magnetic coupler. *IEEE Trans. Power Electron.* **2018**, *6*, 6391–6402. [CrossRef]
- Ramezani, A.; Narimani, M. A new wireless EV charging system with integrated DC–DC magnetic element. *IEEE Trans. Transp. Electrif.* 2019, 5, 1112–1123. [CrossRef]
- Ramezani, A.; Narimani, M. Optimal design of fully integrated magnetic structure for wireless charging of electric vehicles. *IEEE Trans. Transp. Electrif.* 2021, 12, 2114–2127. [CrossRef]

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