A Hybrid Inductive Power Transfer System with High Misalignment Tolerance Using Double-DD Quadrature Pads

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Abstract: Inductive power transfer (IPT) has been widely adopted as an efficient and convenient charging manner for both static and in-motion EVs. In this paper, a new hybrid topology is presented to improve the coupling tolerance under pad misalignment. The double inductor–capacitor–capacitor (LCC-LCC) network and series hybrid network combining the LCC-LCC topology and series-series (SS) topology are connected in parallel to provide better tolerance against self- and mutual inductance changes, particularly with a large Z-axis transmission distance. A double-DD quadrature pad (DD2Q) consists of a Q pad, and double orthogonal DD pads are analyzed in detail, which are employed to decouple the cross-mutual inductance. Moreover, a parametric design method based on the misalignment characteristics of the DD2Q pads is also proposed to maintain relatively constant power output. A 650-W hybrid topology with a fixed operating frequency of 85 kHz was built to verify the system’s feasibility. The size of the DD2Q pads was 280 mm × 280 mm, and the air gap was 100 mm. The results clearly show that the proposed hybrid topology can achieve a fluctuation within 5% in the output current with load varying from 100% full load to 25% light load conditions when the Z-axis transmission distance varies from 80 mm to 150 mm, and the maximum efficiency can reach 91% when the Z-axis transmission distance is 80 mm.

Keywords: inductive power transfer; DD2Q pads; hybrid topology; misalignment tolerance

1. Introduction

An IPT system can deliver power over relatively large air gaps via magnetic couplings, including a high-frequency inverter, compensation topology, coupling coils, and charging circuits. An IPT system has the excellent advantages of safety with galvanic isolation [1], high reliability [2], and being environmentally friendly [3] compared with traditional conductive charging technology. Nowadays, the IPT system has been widely employed in powering electronic applications, such as low-power portable electronic devices, implantable medical instruments [4], electric vehicle (EV) charging [5], and autonomous underwater power supplies [6]. Much research has been conducted by numerous organizations, such as the Massachusetts Institute of Technology (MIT), Auckland University, Korea Advanced Institute of Science and Technology (KAIST), and Oak Ridge National Laboratory (ORNL).

The misalignments between the primary and secondary magnetic couplers can cause the variation of self-inductances and mutual inductances, which may in practice lead to a reduction in power transfer, instability of the system, and increased power losses. Aside from that, the equivalent load varies during the battery charging process [7]. Therefore, the goal of this paper is to design an IPT system with high misalignment tolerance and load-independent current output.
In order to improve the misalignment tolerance of the IPT system, some control schemes, such as increasing DC-DC conversion [8,9], phase shift control, and variable frequency control [10–15], have been proposed to modulate the output current or voltage. The additional DC-DC converter combines with MOSFET, the filter inductor and capacitor, and the driver circuit, which results in extra volume and cost and decreasing the system efficiency. The phase shift control and variable frequency control usually need a wireless communication device to collect the voltage and current signals of the secondary side to realize closed-loop control. However, wireless communications can be interrupted in highly magnetic conditions, which may result in instability of the IPT system. Moreover, phase shift control may not achieve ZVS under a wide range of loads, which increases the switching loss, and variable frequency control may result in bifurcation phenomena and decreasing the output power. Hence, in order to solve the above-mentioned defects, considerable efforts focus on proper magnetic coupler design [16–21], such as bipolar and double-D pads, tripolar pads, quadruple-D pads, and unsymmetrical pads, which can offer a relatively uniform magnetic distribution. For example, the quadruple-D pads are proposed in [16] to be tolerant to lateral misalignment, which consists double quadrature coils at the primary and secondary sides. Tripolar pads are proposed in [18] to improve the omnidirectional misalignment tolerance. However, these tripolar pads need to consist of three inverters at the primary side. That aside, unsymmetrical pads are presented in [19] to minimize the cost of copper and the size of the coil structure, adopting the method of concentrated magnetic flux to achieve misalignment tolerance. As an alternative method, hybrid topologies combining two different topologies with opposite output trends are implemented to maintain a stable output under misalignment conditions. A hybrid topology combines with LCC-LCC and SS topologies [20,21] to realize relatively constant power output within 50% Y-axis misalignment. In [22], LCC-S and S-LCC topologies are employed to tolerate 50% X-axis pad misalignment, where the primary sides are connected in parallel and the secondary sides are connected in series. Although the previous hybrid topologies are able to tolerate a pad’s special misalignment, as shown in Figure 1, the working range of misalignment tolerance is still narrow. Therefore, better misalignment tolerance, particularly with Z-axis tolerance for different EV class heights with a wider coupling variation range, is desired, which is identified as the research gap for this research.

![Figure 1. Comparison of the different topologies.](image)

This paper presents a new hybrid topology using DD2Q pads to achieve stable output power at a large vertical misalignment, and the main contributions of this article are summarized as follows:

1. This article proposes a new hybrid IPT system with high misalignment tolerance. The hybrid system consists of a series hybrid topology and LCC-LCC topology. The series hybrid topology and LCC-LCC topology are connected in parallel at the primary side and secondary side. The proposed approach can improve the output power...
compared with the single compensation topology and reduce the switch voltage stress. Moreover, the proposed hybrid IPT system can achieve a near load-independent current output.

(2) DD2Q pads are used in the hybrid IPT system, which consist of a single-Q coil and double-DD coils. The size of the DD2Q pads is 280 mm × 280 mm, and the air gap is 100 mm. The double-DD coils are orthogonally placed, and the Q coil is placed in a centrally symmetric position, which can realize decoupling of the DD and Q coils on the same side of the primary and secondary sides. Therefore, the independent current output of the series hybrid topology and LCC-LCC topology can be achieved.

(3) A parameter optimization method based on DD2Q mutual inductances is proposed to realize a relatively constant output current with high misalignment tolerance, which is able to simplify the control complexity. By using the monotonic decreasing characteristic of the series hybrid topology and monotonic increasing characteristic of the LCC-LCC topology to realize the complementary output of the two topologies, the output current is ensured to be relatively stable.

Specifically, the mathematical model of the proposed hybrid topology is systematically analyzed in Section 2. In Section 3, the mutual inductance characteristics of the DD2Q pads and the parameter optimization are presented. The experimental results are provided in Section 4 to verify the theoretical analysis. Finally, the conclusion is drawn in Section 5.

2. Theoretical Analysis

The circuit of the proposed hybrid IPT system is shown in Figure 2, which consists of a series hybrid topology and LCC-LCC topology. The high-frequency inverter combines with four MOSFETs (Q1–Q4). Inductor $L_0$ and capacitors $C_0$, $C_1$, and $C_3$ ($L_7$, $C_2$, $C_4$, and $C_7$) constitute the series hybrid topology, while inductor $L_8$ and capacitors $C_5$ and $C_6$ ($L_9$, $C_6$, and $C_9$) constitute the LCC-LCC compensation topology. The primary and secondary sides of the series hybrid topology and LCC-LCC topology are both connected in parallel, together forming the proposed hybrid topology. The main magnetic coupling between the coils is $M_{12}$, $M_{34}$, and $M_{56}$. The full-bridge rectifier comprises four diodes (D1–D4). Because the inductor $L_0$ ($L_7$) and capacitor $C_3$ ($C_4$) are connected in series in the proposed hybrid topology, and therefore they can be treated as a passive component, such as inductor $L_e$ or capacitor $C_e$, which can be expressed as [16]

$$
\begin{align*}
    j\omega L_0 &= j\omega L_0 + 1/ j\omega C_1, & \text{if } \omega L_0 - 1/ \omega C_1 > 0 \\
    1/ j\omega C_1 &= j\omega L_0 + 1/ j\omega C_3, & \text{if } \omega L_0 - 1/ \omega C_3 < 0
\end{align*}
$$

(1)

The full-bridge rectifier is adopted in the secondary side, and thus the input voltage $U_{AB}$, the input current $I_{AB}$, and the equivalent resistance $R_{AB}$ of the rectifier can be expressed as [8]

$$
\begin{align*}
    U_{AB} &= \frac{2\sqrt{2}}{\pi} U_L \\
    I_{AB} &= \frac{\pi \sqrt{2}}{4} I_L \\
    R_{AB} &= \frac{8}{\pi^2} R_L
\end{align*}
$$

(2)
2.1. Analysis of the Series Hybrid Topology

The circuit of the series hybrid topology is shown in Figure 3, where $U_{\text{out}}$ is a high-frequency inverter output voltage. In order to minimize the VA rating of the power inverter, the compensation networks are tuned to the same resonant angular frequency $\omega$. Thus, the resonant parameters should satisfy the following equations:

$$
\begin{align*}
\omega^2 L_0 C_0 &= \omega^2 L_c \frac{C_1 C_6}{C_5 + C_1} = 1, \\
\omega^2 L_1 C_7 &= \omega^2 L_c \frac{C_1 C_7}{C_5 + C_7} = 1, \\
\omega^2 L_3 C_3 &= \omega^2 L_c C_4 = 1.
\end{align*}
$$

(3)

According to Kirchhoff’s voltage law, we can find

$$
\begin{bmatrix}
Z_{10} & Z_{01} & Z_{02} & Z_{03} & 0 \\
Z_{10} & Z_{11} & Z_{12} & Z_{13} & 0 \\
Z_{20} & Z_{21} & Z_{22} & Z_{23} & 0 \\
Z_{30} & Z_{31} & Z_{32} & Z_{33} & 0
\end{bmatrix}
\begin{bmatrix}
\hat{i}_0 \\
\hat{i}_1 \\
\hat{i}_2 \\
\hat{i}_3
\end{bmatrix}
= \begin{bmatrix}
\hat{U}_{\text{out}} \\
0 \\
0 \\
0
\end{bmatrix}
$$

(4)

where

$$
\begin{align*}
Z_{20} &= j\omega M_{23}, & Z_{00} &= j\omega L_0 + (j\omega C_0)^{-1} + j\omega L_3 + (j\omega C_3)^{-1}, & Z_{01} &= -(j\omega C_0)^{-1} + j\omega M_{13}, \\
Z_{02} &= -j\omega M_{23}, & Z_{03} &= j\omega M_{34}, & Z_{10} &= j\omega M_{13} - (j\omega C_0)^{-1}, & Z_{11} &= j\omega L_0 + (j\omega C_0)^{-1} + (j\omega C_3)^{-1}, \\
Z_{12} &= -j\omega M_{12}, & Z_{13} &= j\omega M_{14}, & Z_{21} &= j\omega M_{12}, & Z_{22} &= j\omega L_2 + (j\omega C_2)^{-1} + (j\omega C_7)^{-1}, \\
Z_{23} &= (j\omega C_7)^{-1} + j\omega M_{24}, & Z_{30} &= j\omega M_{34}, & Z_{31} &= j\omega M_{14}, & Z_{32} &= -(j\omega C_7)^{-1} - j\omega M_{24}, \\
Z_{33} &= j\omega L_3 + (j\omega C_3)^{-1} + j\omega L_3 + (j\omega C_3)^{-1} + R_{AB}.
\end{align*}
$$
By designing proper coupling structures, which will be discussed in Section 3, the effects of the cross couplings \((M_{13}, M_{14}, M_{23},\) and \(M_{24})\) on the output can be ignored. Hence, by solving Equation (4), the currents are expressed by

\[
\begin{align*}
    i_0 &= \frac{U_{\text{in}}}{\omega^2 (L_0 L_7 + M_{12} M_{34})^2} \left( M_{12} R_{\text{AB}} \right) \\
    i_3 &= \frac{U_{\text{in}}}{\omega^2} \left( M_{12} \frac{L_7}{M_{12} + M_{34}} \right)
\end{align*}
\]

According to Equation (5), the input equivalent impedance \(Z_{\text{in-series}}\) of the series hybrid system can be deduced to be

\[
Z_{\text{in-series}} = \frac{\omega^2 (L_0 L_7 + M_{12} M_{34})^2}{M_{12}^2 R_{\text{AB}}}
\]

According to Equations (5) and (6), the series hybrid topology can achieve zero phase angle (ZPA). Aside from that, the output current \(I_3\) is related to the inverter output voltage \(U_{\text{out}}\), resonant angular frequency \(\omega\), inductors \(L_0\) and \(L_7\), and mutual inductances \(M_{12}\) and \(M_{34}\). In order to achieve symmetry between the primary and secondary circuits, inductors \(L_0\) and \(L_7\) are usually assumed to be the same. The main mutual inductances \(M_{12}\) and \(M_{34}\) are assumed to have the linear trend with the air gap, which will be discussed in Section 3. Therefore, the output current of the series hybrid topology is shown in Figure 4, where all the related parameter values will be listed in Table 1. It is obvious that the output current \(I_3\) shows a downward concave parabolic trend with the decrease in the mutual inductance. Although the series hybrid topology has a certain misalignment tolerance, the operating range is still narrow.
2.2. Analysis of the LCC-LCC Topology

Figure 5 shows the LCC-LCC equivalent circuit, where $U_{\text{out}}$ is also a high-frequency inverter output voltage. The compensation topology is tuned to the same resonant angular frequency $\omega$. Therefore, the resonant tanks should satisfy the following equations:

\[
\begin{align*}
\omega^2 L_2 C_2 &= \omega^2 L_5 C_5 + C_6 = 1 \\
\omega^2 L_3 C_5 &= \omega^2 L_6 C_6 + C_7 = 1
\end{align*}
\tag{7}
\]

According to Kirchhoff’s voltage law, we find

\[
\begin{bmatrix}
Z_{00} & Z_{01} & 0 & 0 & I_4 & U_{\text{out}} \\
Z_{01} & Z_{11} & Z_{12} & 0 & I_5 & 0 \\
0 & Z_{21} & Z_{22} & Z_{23} & I_6 & 0 \\
0 & 0 & Z_{32} & Z_{33} & I_7 & 0
\end{bmatrix} = 0
\tag{8}
\]

where

\[
Z_{00} = j\omega L_2 + (j\omega C_2)^{-1}, \quad Z_{01} = Z_{10} = -(j\omega C_5)^{-1}, \quad Z_{11} = (j\omega C_5)^{-1} + (j\omega C_6)^{-1} + j\omega L_5, \\
Z_{12} = Z_{21} = -j\omega M_{56}, \quad Z_{22} = j\omega L_5 + (j\omega C_6)^{-1} + (j\omega C_7)^{-1}, \quad Z_{23} = Z_{32} = -(j\omega C_7)^{-1}, \\
Z_{33} = j\omega L_6 + (j\omega C_7)^{-1} + R_{AB}.
\]

By solving Equation (8), the currents are yielded as

\[
\begin{align*}
I_4 &= \frac{M_{56} \cdot U_{\text{out}}}{\omega^2 L_2 L_5} R_{AB} \\
I_5 &= \frac{M_{56} \cdot U_{\text{out}}}{j\omega L_5 L_6} I_7
\end{align*}
\tag{9}
\]

According to Equation (9), the output voltage of the inverter is also in the same phase with the current, which aids in maintaining ZVS across the entire operating region and improving the output efficiency of the system. The output current $I_7$ is related to the inverter output voltage $U_{\text{out}}$, resonant angular frequency $\omega$, inductors $L_5$ and $L_6$, and mutual inductance $M_{56}$. In this paper, inductors $L_5$ and $L_6$ are also assumed to be the same. Therefore, the output current $I_7$ is shown in Figure 6, where all the related parameter values will be listed in Table 1. It is clear that the output current $I_7$ shows a monotonous downward trend with the decrease in the mutual inductance.

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<table>
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<th>$C$</th>
<th>Value 2</th>
</tr>
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<td>$C_2$</td>
<td>25.7 nF</td>
</tr>
<tr>
<td>$L_3$</td>
<td>149.8 uH</td>
<td>$C_5$</td>
<td>27.8 nF</td>
</tr>
<tr>
<td>$L_4$</td>
<td>156.1 uH</td>
<td>$C_6$</td>
<td>27.7 nF</td>
</tr>
<tr>
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<td>156.0 uH</td>
<td>$C_7$</td>
<td>232.2 nF</td>
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<tr>
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<td>160.1 uH</td>
<td>$C_8$</td>
<td>110.2 nF</td>
</tr>
<tr>
<td>$L_7$</td>
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<td>$C_9$</td>
<td>110.3 nF</td>
</tr>
<tr>
<td>$L_8$</td>
<td>32.1 uH</td>
<td>$E$</td>
<td>70 V</td>
</tr>
</tbody>
</table>

---

**Figure 5.** LCC-LCC topology circuit.
2.3. Analysis of the Proposed Hybrid Topology

According to Equations (5) and (9), the total output current of the inverter is expressed by

\[ i_{\text{out}} = i_3 + i_4 = \frac{U_{\text{out}} R_{AB}}{\omega^2} (\frac{M_{12}^2}{(L_9 L_7 + M_{12} M_{34})^2} + \frac{M_{56}^2}{(L_9 L_7)^2}) \] \tag{10}

Then, the total input equivalent impedance of the proposed hybrid topology can be given by

\[ Z_{\text{in}} = \frac{U_{\text{out}}}{i_{\text{out}}} = \frac{\omega^2}{R_{AB}} \frac{1}{(L_9 L_7 + M_{12} M_{34})^2} + \frac{M_{56}^2}{(L_9 L_7)^2} \] \tag{11}

From Equations (10) and (11), the total input impedance of the proposed hybrid topology is purely resistant, which aids to improving the overall transmission efficiency.

According to the characteristics of the parallel circuit, the total output current of the proposed hybrid topology can be expressed as

\[ i_{\text{out}} = i_3 + i_4 = \frac{U_{\text{out}}}{j\omega} \left( \frac{M_{12}}{L_9 L_7 + M_{12} M_{34}} + \frac{M_{56}}{L_9 L_7} \right) \] \tag{12}

From Equation (12), the system can realize a load-independent current output. When misalignment occurs, the main mutual inductance \( M_{12}, M_{34}, \) and \( M_{56} \) will drop at the same time. By designing appropriate compensating inductors \( L_0, L_7, L_8, \) and \( L_9, \) the constant current output can be realized in a certain range of misalignment.

3. Parametric Design of the Proposed Hybrid Topology

3.1. Misalignment Analysis of DD2Q Pads

As analyzed in Section 2, the expected coupling pad should have the following characteristics:

1. The expected coupling pad should consist of three transmitters and three receivers.
2. The cross mutual inductances are designed to be zero or small enough when misalignment occurs, and thus the proposed hybrid topology can realize a load-independent output.

Recently, the DDQ and DD coils have had anti-misalignment characteristics, which can realize decoupling in the X- and Z-axis to eliminate the influence of cross-coupling. However, these two coupling coil structures can only be applied to four-coil structures.
Based on the DD coil and DDQ coil, the DD2Q coil structure is proposed in this paper, as shown in Figure 7. The DD2Q coils consist of a single-Q coil and double-DD coils, and there are three coils at both the transmitter and receiver sides. The size of the Q coil is 280 mm × 280 mm, the size of the DD coil is 280 mm × 280 mm, and the Z-axis transmission distance is 100 mm.

Figure 7. Structure of the proposed DD2Q pads.

The misalignment between the primary and pick-up pads is unavoidable in the charging system, including the X-axis, Y-axis, Z-axis, and XY-axis. Therefore, Figure 8 shows the measured mutual inductances of the DD2Q pads with misalignment along the X-, Y-, Z-, and XY-axes separately.

Obviously, the main mutual inductances $M_{12}$, $M_{34}$, and $M_{56}$ and the cross-coupling mutual inductances vary significantly when X-axis, Y-axis, and XY-axis diagonal misalignments occur in Figure 8a,b,d. The reason for this is that non-orthogonal magnetic flux is coupled in the X-axis, Y-axis and XY-axis diagonal misalignments. The main mutual inductances $M_{12}$, $M_{34}$, and $M_{56}$ show a linear decreasing trend with the Z-axis transmission distance, and the cross-couplings are too small to be ignored, as shown in Figure 8c. Moreover, the main mutual inductances ($M_{34}$ and $M_{56}$) of the double orthogonal DD pads have the same change trend at the Z-axis transmission distance. Therefore, the proposed hybrid topology cannot provide a constant current output in the X-axis and Y-axis misalignments, as analyzed in Section 2. In many applications, such as cars, SUVs, and trucks, the X-axis and Y-axis misalignments can be adjusted by auxiliary devices for cars, such as a reversing camera and reversing radar, but the vertical air gap is hard to adjust. Hence, the DD2Q coils are fit for the proposed hybrid topology with a relatively constant current output, where the vertical direction changes dramatically.
3.2. Parametric Design Method

The design of compensation parameters is of great importance to realize a relatively constant output within the maximal misalignment. A parametric design method based on inductances $L_0$, $L_7$, $L_8$, and $L_9$ is presented to maintain the output current in a certain range of misalignment.

From Figure 8c, the relationship between $M_{12}$, $M_{34}$, and $M_{56}$ can be expressed by

$$
\begin{align*}
M_{56} = M_{34} + aM_{12} + b \\
M_{34} = aM_{12} + b
\end{align*}
$$

where $a$ and $b$ are coefficients and the calculated parameters $a$ and $b$ are $0.86$ and $-6.75 \times 10^{-6}$, respectively, when the secondary pads move between $80$ mm and $150$ mm along the Z-axis transmission distance.

Thus, the total output current of the proposed hybrid topology is rewritten as

$$
I_{AB} = \left( \frac{U_{in}M_{12}}{\omega(L_0L_7 + M_{12}(0.86M_{12} - 6.75 \times 10^{-6}))} \right) + \left( \frac{U_{in}(0.86M_{12} - 6.75 \times 10^{-6})}{\omega L_8 L_9} \right)
$$

(14)

According to Equation (14), we can obtain the current $I_L$ of the load $R_{AB}$:

$$
I_L = \left( \frac{4U_{in}M_{12}}{\pi \sqrt{2} \omega(L_0L_7 + M_{12}(0.86M_{12} - 6.75 \times 10^{-6}))} \right) + \left( \frac{4U_{in}(0.86M_{12} - 6.75 \times 10^{-6})}{\pi \sqrt{2} \omega L_8 L_9} \right)
$$

(15)

To simplify the complexity of multi-objective parameter design, inductances $L_0$ and $L_7$ are assumed to be equal, and inductance $L_8$ is also assumed to be equal with inductance $L_9$. Figure 8 shows that the output current $I_L$ varies with different inductors $L_0$ and $L_8$. It can be found that the output current of the series hybrid topology shows a downward concave parabolic trend, while the output current of the LCC-LCC topology shows a monotonous downward trend with the decrease in $M_{12}$. Therefore, we used the monotonous decreasing characteristic of the LCC-S topology and monotonous increasing characteristic of the LCC-LCC topology to realize the complementary output of the two topologies and ensured the output current was relatively stable. In this article, an acceptable output current fluctuation ratio was limited within 5%, and the rated output current of the load $R_{AB}$ was set to be $6$ A. It is clear that the dashed line region in Figure 9 can satisfy the set requirement within an $80$–$150$-mm Z-axis transmission distance. Thus, the values of $L_0$ and $L_7$ were both designed to be $15$ uH, while $L_8$ and $L_9$ were both designed to be $32$ uH.
Finally, the resonant parameter value of the proposed hybrid topology could be obtained from Equations (1), (3), and (7).

![Figure 9](image)

**Figure 9.** The function of \( L_L \) and \( M_{12} \) in Z-axis transmission distance.

4. Experimental Verifications

In order to verify the analysis of the proposed method, a 650-W hybrid IPT system was designed and implemented as illustrated Figure 10. The detailed parameters of the system are listed in Table 1. The inverter of the system operated with a fixed frequency and duty cycle control to demonstrate the performance of a constant current output with high misalignment tolerance.

![Figure 10](image)

**Figure 10.** Experimental set-up of the proposed hybrid IPT system.

The output current of the load is drawn in Figure 11, varying with a full load, half load, and quarter load under different Z-axis transmission distances. Within a 80–150-mm Z-axis transmission distance, the output current of the load was between 5.7 A and 6.3 A, which indicates that the output current variation was within 5% when the system worked in the full load and half load conditions. Aside from that, the output current of 4 \( \Omega \) under the condition of a transmission distance between 110 mm and 130 mm was larger than 6.3 A, which was slightly over the limitation of 5%. Moreover, the output current climbed to the maximum at a 120-mm Z-axis transmission distance. This clearly demonstrates that the proposed hybrid topology with the parameter optimization process had high misalignment tolerance.
Figure 11. Output current of the proposed hybrid system.

The experimental waveforms of $U_{\text{out}}$, $I_{\text{out}}$, $U_{\text{L}}$, and $I_{\text{L}}$ with $R_L = 17 \, \Omega$, $8.5 \, \Omega$, and $4 \, \Omega$ are shown in Figures 12–14 when the Z-axis transmission distance was 80 mm, 120 mm, and 150 mm, respectively. $U_{\text{out}}$ and $I_{\text{out}}$ are the inverter output voltage and current when the input DC power is 70 V, respectively.

Figure 12 illustrates the system operating at full load with $R_L = 17 \, \Omega$. It is clear that ZVS could be achieved between an 80-mm and 150-mm Z-axis transmission distance, which could reduce the switching loss and improve the efficiency. Moreover, the output current was 5.84 A, 6.21 A, and 6.16 A, and the load output voltage was 99.30 V, 105.61 V, and 104.75 V, respectively. Hence, the fluctuation of the load current was within 5% when the variation of the Z-axis transmission distance was within 70%.

Figure 13 shows the system works at half load with $R_L = 8.5 \, \Omega$. The load output current was 5.92 A, 6.25 A, and 6.18 A, and the load output voltage was 50.30 V, 53.38 V, and 52.35 V, which illustrated the current fluctuation to be 1.33%, 4.17%, and 3.0%, respectively, meeting the design requirements. That aside, the output voltage and current of the inverter were almost in phase, which indicates that soft switching could be achieved and decrease the switching losses.

Figure 14 shows the system operating in a light load conditions when the load was 25% against the fill load with $R_L = 4 \, \Omega$. The load output current was 5.96 A, 6.42 A, and 6.23 A, and the load output voltage was 23.84 V, 25.68 V, and 24.92 V, which illustrated the current fluctuation to be 0.66%, 7%, and 3.8%, respectively. It is clear that the output current may slightly exceed the limitation of 5% under light load conditions.
Figure 12. Experimental waveforms of $U_{out}$, $I_{out}$, $U_I$, and $I_I$ for full load with $R_L = 17\ \Omega$. 

(a) the 80-mm Z-axis transmission distance

(b) the 120-mm Z-axis transmission distance

(c) the 150-mm Z-axis transmission distance
Figure 13. Experimental waveforms of $U_{out}$, $I_{out}$, $U_{L}$, and $I_{L}$ for half load with $R_{L} = 8.5 \, \Omega$.

(a) the 80-mm Z-axis transmission distance

(b) the 120-mm Z-axis transmission distance

(c) the 150-mm Z-axis transmission distance
Figure 14. Experimental waveforms of $U_{out}$, $I_{out}$, $U_i$, and $I_i$ for one-quarter load with $R_l = 4 \Omega$.

Figure 15 clearly illustrates that there is an opposite trend of the output current $I_3$ of series hybrid topology and the output current $I_7$ of the LCC-LCC topology when the Z-axis transmission distance varied, and the RMS values of the output currents $I_3$ and $I_7$ had a slight deviation from the theoretical analysis in Section 2 due to the influence of parasitic resistance and parameter drift on the resonant parameters. Aside from that, the total output current $I_{AB}$ of the proposed hybrid topology could almost remain stable. Moreover, there was a small phase angle between the output current of the series hybrid topology and LCC-LCC topology because the resonant parameters in the series hybrid topology and LCC-LCC topology operated in a weak inductive state.
Figure 15. Experimental waveforms of $I_3$ and $I_7$ with $R_L = 17 \, \Omega$.

Figure 16 shows the output power and efficiency along the $Z$-axis transmission distance. Figure 16a illustrates that the output power was relatively gentle and consistent with the variation curve of the load output current. The maximum output power was 650 W when the $Z$-axis transmission distance was 120 mm at full load with $R_L = 17 \, \Omega$. Figure
16b shows that the efficiency varied with the load and misalignment, and the maximum efficiency could reach 91% with a full load at an 80-mm Z-axis transmission distance.

![Graph](image)

(a) output power (b) efficiency

**Figure 16.** Measured output power and efficiency versus transmission distance.

Some comparisons with traditional control schemes and existing hybrid topologies are listed in Table 2, which are made in terms of control, number of inductors and capacitors, coupling pads, misalignment tolerance, cost, output characteristic, etc. Compared with the traditional control schemes in [9,11], the proposed IPT system can realize a constant current output and misalignment tolerance without additional DC-DC converters and phase shift control, which can simplify the complicated controls. The topologies in [18,21,22] are named the “series hybrid topology”, while the topologies in [20] are named the “parallel hybrid topology”. These mentioned hybrid topologies all use four coils to transfer power. Aside from that, the number of inductors, capacitors and coupling pads and the cost of the hybrid topologies are higher than the traditional topologies with closed-loop controls. Moreover, the proposed hybrid topology has a wider misalignment tolerance compared with the four-coil hybrid topologies in [18] and [20–22], even though this topology has slightly more components than the other topologies. Thus, the proposed hybrid topology is superior to the traditional control schemes and other hybrid topologies in terms of misalignment tolerance.

**Table 2.** Comparison of traditional control schemes and existing hybrid topologies.

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<thead>
<tr>
<th>Control</th>
<th>[9]</th>
<th>[11]</th>
<th>[18]</th>
<th>[20]</th>
<th>[21]</th>
<th>R22]</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of inductors</td>
<td>1</td>
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<td>2</td>
<td>2</td>
<td>0</td>
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<td>6</td>
<td>6</td>
<td>6</td>
<td>10</td>
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<tr>
<td>Coupling coils</td>
<td>DD + BP</td>
<td>Q</td>
<td>QDQP</td>
<td>DD</td>
<td>DD</td>
<td>DDQ</td>
<td>DD2Q</td>
</tr>
<tr>
<td>Number of coils</td>
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<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Cost</td>
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<td>Low</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Size of coupling pad X * Y * Z (mm)</td>
<td>738 * 391 * 200</td>
<td>360 * 360 * 400</td>
<td>400 * 400 * 391 * 738 * 775 * 391 * 400 * 400 * 280 * 280 * 150</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Misalignment tolerance (mm)</td>
<td>X:200 (27.5%)</td>
<td>X:140 (38.8%)</td>
<td>X:150 (37.5%)</td>
<td>X:160 (40.9%)</td>
<td>Y:160 (40.9%)</td>
<td>X: Z:</td>
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**Table 2.** Comparison of traditional control schemes and existing hybrid topologies.
5. Conclusions

A hybrid wireless charging system using DD2Q pads has been presented to improve the misalignment tolerance. The new proposed system, combined with the series hybrid topology and LCC-LCC topology, was studied based on the full mathematical model in the context, where the DD2Q pads consisted of a single-Q coil and orthogonal DD coils. The new pad geometry is able to decouple the cross-mutual inductances so as to realize the independent output of the two topologies. Moreover, a parameter optimization design method on the basis of the characteristics of the DD2Q pads is presented to maintain a stable output current and provide high misalignment tolerance in the Z-axis direction. A 650-W hybrid IPT system has been designed and implemented to verify the analysis of the proposed method. The experimental results validate that the proposed hybrid topology can maintain a relatively constant output current at 6 A when the Z-axis misalignment varies from −20 to +50 mm, and the output current fluctuation is within 5% when the load varies from 100% full load to 25% light load. In comparison with the conventional hybrid topology, the new proposed system showed a significant improvement in Z-axis misalignment tolerance, even though this topology has slightly more components. Moreover, the maximum efficiency can reach 91% when the Z-axis transmission distance is 80 mm.

In future research, a thorough economic analysis of the proposed method will be adopted to minimize the system cost, which consists of the number of inductors, capacitors, and coupling coils. That aside, the coupling coil structure should be improved to have better X-, Y-, and Z-axis misalignment tolerance.

Author Contributions: Conceptualization, Z.G. and J.L.; methodology, Z.G.; software, Z.G. and Y.F.; validation, Z.G., J.L., and X.T.; formal analysis, Z.G.; investigation, Z.G.; resources, Z.G. and J.L.; data curation, Z.G.; writing—original draft preparation, Z.G.; writing—review and editing, Z.G.; visualization, Z.G. and Y.F.; supervision, J.L. and X.T.; project administration, Z.G.; funding acquisition, Z.G. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

References

