A Dual-Coupled LCC-Compensated IPT System With a Compact Magnetic Coupler

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Abstract—This paper proposes a dual-coupled LCC-compensated inductive power transfer system with a compact magnetic coupler to improve misalignment performance. In the magnetic coupler, the main coils form the first coupling, and compensation inductors are integrated with the main coils to form a second coupling. In the design presented in this paper, the main coils are unipolar and the compensation inductors are in a Double D structure. The fundamental harmonics approximation method is used to analyze the circuit, and the couplings between the main coils and compensation inductors are considered to determine the net power flow. In misalignment cases, it is shown that the coupling between the compensation inductors, and the cross couplings between the compensation inductors and main coils, contribute to increasing the system power. A 3.5 kW prototype is designed and implemented to validate the proposed dual-coupled system.

I. INTRODUCTION

INDUCTIVE power transfer (IPT) technology is an effective method to charge electric vehicles [1], [2]. It usually consists of two planar coils, forming a loosely coupled transformer, and the compensation circuitry [3], [4]. The ac–dc efficiency of an IPT system from the power grid to the battery has reached 93% [5], which is comparable to a conductive charger.

The performance of an IPT system is determined by the compensation topologies, which can be clarified as series–series (SS) [6], [7], series–parallel [8], parallel–series [9], parallel–parallel [10], and LCC circuits [11], [12]. The SS compensation circuit has been widely used in electric vehicle charging applications because of its simplicity. However, its output power is inversely proportional to the coils’ coupling coefficient, and so the primary current increases rapidly when a receiver is not present. In comparison, the LCC compensation circuit provides power in proportion to the coupling coefficient, and achieves a constant-current operating mode for battery charging applications [13], [14]. However, the LCC circuit requires more components, which increases the system complexity.

In an LCC-compensated IPT system, there are three options when designing compensation inductors: air-core inductor [13], annular-core inductor [15], and integrated inductor [16]. In the air- and annular-core design, the inductors and main coils are separated, and the only coupling in the system is between the main coils, which can be denoted as a single-coupled IPT system. In an integrated design, the compensation inductors are integrated into the main coils, and there are both main coupling and compensation coupling, which is denoted as a dual-coupled IPT system. Air-core inductors can eliminate magnetic losses and increase efficiency [13], [17]. However, electromagnetic interference (EMI) is a problem. Annular-core inductors have the advantage of confining magnetic fields inside the ferrite core and alleviating the EMI. However, extra space is required for these external inductors. Therefore, integrated inductors can help reduce the system volume [18].

In previous attempts to integrate compensation inductors with main coils, the couplings with compensation inductors were not taken into account [19]–[21]. For example, the size of compensation inductors is usually much smaller than the main coils [19]–[21], and the couplings induced by the compensation inductors are relatively small or even negligible. In this work, the size of the compensation inductors is the same as those of the main coils. The couplings with the compensation inductors become comparable to the main coupling. It will be shown in this paper that this coupling can be used to increase power transfer and improve the misalignment performance.

In previous research, the misalignment problem in an IPT system has been studied, and two effective solutions have been proposed. The first solution is from the system design point of view, in which the structure of the inductive coupler is designed to achieve a good misalignment performance. For example, the unipolar structure [22], double D (DD) structure [23], [24], and DDQ structure [25], [26] have been proposed. However,
since the coupling coefficient is mainly determined by the size, the variation of structure does not significantly improve the misalignment performance. Also, an additional coupler can be used [27]. In the second solution, additional dc–dc converters are used at the primary and secondary sides to regulate power in misalignment cases. For example, Bosshard and Kolar [28] propose a method to use dc–dc converters to adjust its power and efficiency. Compared to the previous research, the contribution of this work is that misalignment performance is significantly improved without increasing coupler size or adding dc–dc converters.

II. INTEGRATED MAGNETIC COUPLER DESIGN

A. Coupler Structure

Fig. 1(a) shows the three-dimensional (3-D) view of the integrated magnetic coupler, in which \( L_1 \), \( L_2 \) are the main coils and \( L_{f1} \), \( L_{f2} \) are the compensation inductors. Mutual inductances are defined as

\[
M_{1-2} = k_{1-2} \cdot \sqrt{L_1 L_2}, \quad M_{f1-f2} = k_{f1-f2} \cdot \sqrt{L_{f1} L_{f2}}
\]

\[
M_{1-f1} = k_{1-f1} \cdot \sqrt{L_1 L_{f1}}, \quad M_{2-f2} = k_{2-f2} \cdot \sqrt{L_2 L_{f2}}
\]

\[
M_{1-f2} = k_{1-f2} \cdot \sqrt{L_1 L_{f2}}, \quad M_{f1-2} = k_{f1-2} \cdot \sqrt{L_{f1} L_2}
\]  

(1)

where \( k_{1-2}, k_{1-f1}, k_{1-f2}, k_{2-f1}, k_{2-f2}, \) and \( k_{f1-f2} \) are the coupling coefficient in the magnetic coupler.

It should be noted that only the different-side coupling coefficients, i.e., \( k_{1-2}, k_{1-f2}, k_{f1-f2}, \) and \( k_{f1-2} \), can contribute to power transfer. Therefore, the size of compensation inductors is designed to be the same as the main coils to maximize coupling.

Meanwhile, the same-side coupling coefficients, \( k_{1-f1} \) and \( k_{2-f2} \), do not contribute to transfer power. In this design, main coils are unipolar and the compensation inductors are in DD structure to minimize \( k_{1-f1} \) and \( k_{2-f2} \). It needs to be clarified that, as an alternative design, the main coils can also be in DD structure while the compensation inductors are unipolar.

Fig. 1(b) shows the front view of the integrated magnetic coupler. Ferrite plates are 25 mm larger than the coils. Also, aluminum sheets are 25 mm larger than the ferrite plates. The distance \( d_{Al} \) between the ferrite and aluminum plates is 15 mm in order to reduce induced eddy-current losses in the shielding.

The parameters describing the coupler dimensions are defined in Table I. Both the transmitter and receiver are square, and their lengths are defined as \( l_1 \) and \( l_2 \), respectively.

B. Dimension Design

The dimensions of the coils are chosen according to the recommendations in SAE J2954 standard [29]. The primary coil size is \( l_1 = 450 \) mm, and the secondary coil size is \( l_2 = 300 \) mm. The transfer distance is \( d_a = 120 \) mm. To simplify the design process, winding width ratios are defined

\[
r_{L1} = \frac{l_{w1}}{l_1}, \quad r_{L_{f1}} = \frac{2 \times l_{w1}}{l_1}, \quad r_{L2} = \frac{l_{w2}}{l_2}, \quad r_{L_{f2}} = \frac{2 \times l_{w2}}{l_2}.
\]  

(2)

It needs to be emphasized that, for a practical coil, the range of winding ratios is usually from 0.05 to 0.45. Finite element analysis by Maxwell is used in simulation.

Fig. 2 shows that, in the well-aligned case, the primary coil width ratio \( r_{L1} \) dominates the main coupling \( k_{1-2} \), and the influence of \( r_{L2} \) can be neglected. Therefore, the primary winding width ratio \( r_{L1} \) is chosen to be 0.45.

In \( x \)-direction misalignment, \( k_{1-2} \) is simulated in Fig. 3, in which \( r_{L1} \) is 0.45 and \( r_{L2} \) varies. For the main coils, the misalignment performances are the same in the \( x \)- and \( y \)-directions,
because they are unipolar and square. In this design, \( r_{L2} \) is therefore set to 0.45 to reduce conduction losses. Then, \( k_{1-2} \) is therefore 0.270 in the well-aligned case, and decreases to 0.110 at 150 mm misalignment.

For the compensation inductors, the simulated \( k_{f1-f2} \) is in Fig. 4. It indicates that \( k_{f1-f2} \) increases with the increasing \( r_{Lf1} \), and it is almost constant after \( r_{Lf1} \) is 0.30. Furthermore, \( k_{f1-f2} \) is largest when \( r_{Lf2} = 0.25 \). Therefore, the optimal range of \( r_{Lf1} \) is from 0.30 to 0.45, and \( r_{Lf2} \) is set to 0.25.

The \( x \)- and \( y \)-direction misalignment performance of \( k_{f1-f2} \) is shown in Fig. 5. It is set to 0.30 to reduce the usage of Litz wire. When \( r_{Lf1} = 0.30 \) and \( r_{Lf2} = 0.25 \), \( k_{f1-f2} = 0.136 \) in the well-aligned case, is 0.097 at 150 mm \( x \)-misalignment, and is -0.017 at 150 mm \( y \)-misalignment.

The couplings coefficient \( k_{1-f1} \), \( k_{1-f2} \), \( k_{f1-2} \), and \( k_{2-f2} \) need to be considered in \( y \)-misalignment cases due to the asymmetry of the coupler structure, as shown in Fig. 6. The maximum \( k_{1-f1} \) is 0.015 and the maximum \( k_{2-f2} \) is 0.005, which can be both neglected. However, the maximum cross couplings \( k_{1-f2} \) and \( k_{f1-2} \) are 0.115 and 0.139, and so should be considered.

### III. Working Principle of LCC-Compensated Dual-Coupled IPT System

#### A. Coupler Structure

The circuit topology of an LCC-compensated dual-coupled IPT system is shown in Fig. 7. Coils \( L_1 \) and \( L_{f1} \) are integrated together as a transmitter. Coils \( L_2 \) and \( L_{f2} \) are integrated as a receiver. There are four significant couplings, \( k_{1-f1} \), \( k_{1-f2} \), \( k_{f1-2} \), and \( k_{2-f2} \) in the system. The compensation inductors share the same ferrite and shielding plates with the main coils.

In the compensation circuit, capacitors \( C_1 \) and \( C_{f1} \) are used to resonate with \( L_1 \) and \( L_{f1} \), respectively, and \( C_2 \) and \( C_{f2} \) resonate with \( L_2 \) and \( L_{f2} \). At the primary side, a dc voltage source \( V_{in} \) is used as the power supply, followed by a full-bridge inverter used. Furthermore, an uncontrolled diode rectifier is adopted at the secondary side to provide dc current to a battery load \( V_{out} \).

#### B. Output Power Calculation

The fundamental harmonics approximation (FHA) method is used, as shown in Fig. 8. The square-wave voltages can be approximated as sinusoidal sources. The magnetic couplings
are represented by dependent sources. The power losses of the components are neglected to simplify the analysis.

The KCL equations of Fig. 8 are expressed as in (3), shown at the bottom of this page.

The resonant relationship is expressed as

\[
\omega^2 L_{f1} C_{f1} = \omega^2 L_{f2} C_{f2} = 1
\]

\[
\omega^2 (L_1 - L_{f1}) C_1 = \omega^2 (L_2 - L_{f2}) C_2 = 1.
\]

(4)

By substituting (4) into (3), it can be simplified as

\[
\begin{bmatrix}
0 & j\omega L_{f1} & j\omega M_{f1-f2} & j\omega M_{f1-f2} \\
-j\omega L_{f1} & 0 & j\omega M_{f2-f1} & j\omega M_{f2-f1} \\
-j\omega M_{f1-f2} & -j\omega M_{f2-f1} & 0 & j\omega L_{f2} \\
-j\omega M_{f1-f2} & -j\omega M_{f2-f1} & -j\omega L_{f2} & 0
\end{bmatrix}
\begin{bmatrix}
I_1 \\
I_{L1} \\
I_2 \\
I_{L2}
\end{bmatrix}
= \begin{bmatrix}
V_1 \\
0 \\
V_2 \\
0
\end{bmatrix}.
\]

(5)

Therefore, the input and output current can be calculated as

\[
\begin{bmatrix}
I_1 \\
I_2
\end{bmatrix}
= \begin{bmatrix}
-c \cdot \frac{M_{f1-f2}}{b - a \cdot c} & \frac{b \cdot M_{f1-f2}}{b - a \cdot c} \\
\frac{b \cdot M_{f1-f2}}{b - a \cdot c} & -a \cdot \frac{M_{f1-f2}}{b - a \cdot c}
\end{bmatrix}
\begin{bmatrix}
V_1 \\
V_2
\end{bmatrix}
\]

(6)

where, \(a, b,\) and \(c\) are defined as

\[
a = j\omega \cdot (-2M_{f1-f2}L_{f1})
\]

\[
b = j\omega \cdot (-L_{f1}L_{f2} + M_{f1-f2}M_{1-f2} - M_{f1-f2}M_{1-f2})
\]

\[
c = j\omega \cdot (-2M_{f1-f2}L_{f2}).
\]

(7)

If \(V_2\) is set as the reference phasor, and the phase difference with \(V_1\) is defined as \(\alpha\), the currents are

\[
I_1 = \frac{M_{f1-f2}}{b^2 - a \cdot c} \cdot \left[ -c \cdot \cos \alpha \cdot |V_1| + b \cdot |V_2| \right] - j \cdot c \cdot \sin \alpha \cdot |V_1|
\]

\[
I_2 = \frac{M_{f1-f2}}{b^2 - a \cdot c} \cdot \left[ b \cdot \cos \alpha \cdot |V_1| - a \cdot |V_2| \right] + j \cdot b \cdot \sin \alpha \cdot |V_1|.
\]

(8)

At the output side, the voltage \(V_2\) is in phase with current \((-I_2)\) [13], which means \((-I_2)\) is a positive real number, resulting in

\[
\cos \alpha = \frac{a}{b} \frac{|V_2|}{|V_1|}.
\]

(9)

Therefore, the currents are further simplified as

\[
I_1 = \frac{M_{f1-f2}}{b^2 - a \cdot c} \cdot \left( \frac{b^2 - a \cdot c}{b} \cdot |V_2| - j \cdot c \cdot \sin \alpha \cdot |V_1| \right)
\]

\[
I_2 = \frac{M_{f1-f2}}{b^2 - a \cdot c} \cdot b \cdot j \cdot \sin \alpha \cdot |V_1|.
\]

(10)

The output current \(I_2\) only depends on the input voltage \(V_1\), which means the proposed circuit behaves as a current source.

If the main coupling is designed to satisfy \(k_{f1-f2} > 0\), the second equation of (10) indicates \(\sin \alpha > 0\), therefore

\[
\sin \alpha = \sqrt{1 - \left( \frac{|a|^2}{|b|^2} \cdot \frac{|V_2|^2}{|V_1|^2} \right)}.
\]

(11)

The system output power is therefore expressed as

\[
P_{\text{out}} = |V_2| \cdot |I_2| = M_{f1-f2} \cdot \frac{|b|}{|b^2 - a \cdot c|} \sqrt{1 - \left( \frac{|a|^2}{|b|^2} \cdot \frac{|V_2|^2}{|V_1|^2} \right)} \cdot |V_1| \cdot |V_2|.
\]

(12)

If \(|V_1| = |V_2|\), the output power can be simplified as

\[
P_{\text{out}} = |V_2| \cdot |I_2| = M_{f1-f2} \cdot \sqrt{\left( \frac{|b|^2}{|b^2 - a \cdot c|} \right)^2} \cdot |V_1|^2.
\]

(13)

By substituting (7) into (13), it is expressed as (14), shown at the bottom of this page.

Using the coupling coefficients in (1), it is simplified as (15), shown at the bottom of next page. where \(\beta\) and \(\gamma\) are defined

\[
P_{\text{out}} = \frac{M_{f1-f2} \cdot \sqrt{\left( L_{f1}L_{f2} - M_{f1-f2}M_{f2-f1} + M_{f1-f2}M_{1-f2} \right)^2 - 4(M_{f1-f2}L_{f1})^2}}{\omega \left( L_{f1}L_{f2} - M_{f1-f2}M_{f2-f1} + M_{f1-f2}M_{1-f2} \right)^2 - 4(M_{f1-f2}L_{f1})(M_{1-f2}L_{f2})} \cdot |V_1|^2.
\]

(14)
Three parameters \(k_1, k_2, \) and \(K_3\) can be defined as
\[
K_1 = k_{1-2}k_{f1-2}\beta, \quad K_2 = k_{f1-2}k_{1-2}\beta, \quad K_3 = k_{f1-2}k_{1-2}\beta. \tag{17}
\]

It shows that \(K_1, K_2, \) and \(K_3\) relate to the coupling coefficient and inductance ratio. The output power is simplified as
\[
P_{out} = \frac{k_{1-2}\sqrt{L_1L_2}}{\omega L_1L_2} \sqrt{\frac{(1-K_1+K_2)^2-4K_3\gamma}{(1-K_1+K_2)^2-4K_2^2}} \cdot |V_1|^2. \tag{18}
\]

If the parameters satisfy \(|K_1K_2| << 1.0, |K_1K_3| << 1.0, \) and \(|K_2K_3| << 1.0, \) the output power can be approximated to be
\[
P_{out} \approx \frac{k_{1-2}\sqrt{L_1L_2}}{\omega L_1L_2} \cdot \frac{1}{1-2K_1-2K_2} \cdot |V_1|^2. \tag{19}
\]

Furthermore, it can be simplified as
\[
P_{out} \approx \frac{k_{1-2}\sqrt{L_1L_2}}{\omega L_1L_2} \cdot \frac{1}{1-3K_2+2K_3} \cdot |V_1|^2. \tag{20}
\]

According to the coupler design in Section II, there is \(k_{f1-2} \approx k_{1-2}, \) resulting in \(K_2 \approx K_3\) and the system power is
\[
P_{out} \approx \frac{k_{1-2}\sqrt{L_1L_2}}{\omega L_1L_2} \cdot \frac{1}{1-K_1-3K_2+2K_3} \cdot |V_1|^2. \tag{21}
\]

When well aligned, there are no cross couplings \(k_{f1-2}\) and \(k_{1-2}, \) which means \(K_2 = K_3 = 0. \) The output power is simplified as
\[
P_{out} = \frac{\sqrt{L_1L_2}}{\omega L_1L_2} \cdot \frac{k_{1-2}}{1-K_1} \cdot |V_1|^2. \tag{22}
\]

C. Power Flow Analysis

It is also necessary to analyze the power flow among the magnetic couplings, which can be expressed as
\[
S_{f1-f2} = P_{f1-f2} + jQ_{f1-f2} = j\omega M_{f1-f2} \cdot I_1 \cdot I_2^* \tag{23}
\]

\[
S_{1-f2} = P_{1-f2} + jQ_{1-f2} = j\omega M_{1-f2} \cdot I_1 \cdot I_2^*
\]

\[
S_{f1-1} = P_{f1-1} + jQ_{f1-1} = j\omega M_{f1-1} \cdot I_1 \cdot I_2^* \tag{24}
\]

\[
S_{1-1} = P_{1-1} + jQ_{1-1} = j\omega M_{1-1} \cdot I_1 \cdot I_2^*
\]

\[
S_{out} = P_{out} + jQ_{out} = \frac{j\omega M_{out}}{M_{out}} \cdot I_1 \cdot I_2^*, \tag{25}
\]

By substituting (25) into (23), the complex power received at the secondary side is expressed in (26).

Using the parameter definitions, the complex power received at the secondary side is simplified in Table II. There are both active and reactive power transfers among the couplings.

The active power flow across the couplings is shown in Fig. 9. If the power losses in the circuit components are neglected, the total power transferred from the primary side is equal to the total power received at the secondary side. This shows that active power is transferred from the primary side to the secondary side through four paths. The first path is from the primary main coil
Table II
POWER RECEIVED AT SECONDARY SIDE THROUGH MAGNETIC COUPLINGS

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Active power</th>
<th>Reactive power</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1 - L_2$</td>
<td>$P_{1-2} = \frac{K_1}{2} \cdot \frac{P_{out}}{K_{1+K_2}} \cdot f_{out}$</td>
<td>$Q_{1-2} = \frac{K_2}{2} \cdot \frac{P_{out}}{K_{1+K_2}} \cdot f_{out}$</td>
</tr>
<tr>
<td>$L_1 - L_2$</td>
<td>$P_{1-2} = \frac{K_1}{2} \cdot \frac{P_{out}}{K_{1+K_2}} \cdot f_{out}$</td>
<td>$Q_{1-2} = \frac{K_2}{2} \cdot \frac{P_{out}}{K_{1+K_2}} \cdot f_{out}$</td>
</tr>
</tbody>
</table>

IV. EXAMPLE OF LCC-COMPENSATED DUAL-COUPLED IPT SYSTEM

A. Misalignment Performance Analysis

The conventional LCC-compensated system [13], in which the coupler contains only the main coils, is defined as a single-coupled system. In this paper, the proposed system, in which the coupler contains the main coils and the compensation inductors, is defined as a dual-coupled system. Their output power are denoted as $P_{single}$ and $P_{dual}$, and expressed as

$$ P_{single} = \frac{1}{4} \frac{\sqrt{K_1}}{K_{1-2} \cdot |V_1|^2} \cdot |V_2|^2 $$

$$ P_{dual} = \frac{1}{4} \frac{\sqrt{K_1}}{K_{1-2}} \cdot \frac{1}{K_{1-2} - 3K_2 + 2K_3} \cdot \gamma \cdot |V_1|^2 \cdot |V_2|^2 $$

When there is misalignment, $k_{1-2}$ decreases, which leads to a decrease of system power. According to the definitions of $K_1$ and $K_2$, the structure of the proposed coupler can be designed to achieve increasing $K_1$ and $K_2$ with increasing misalignment. In this way, the misalignment performance is improved.

Considering the simulation in Section II, the polarity of $L_{f2}$ should be flipped to achieve $k_{f1-2} < 0$ and $k_{f1-2}k_{1-2} > 0$, which leads to the increasing of $K_1$ and $K_2$ with misalignment. Using (20) and (22), a coefficient $h$ can be defined as

$$ h = \frac{(1 - K_1)(|\text{well-aligned}| - |\text{mis-aligned}|)}{(1 - K_1 - 3K_2 + 2K_3 \gamma) |\text{mis-aligned}|} $$

According to (17) and the parameters in Section II, $h$ can be calculated in 150 mm x- and y-misalignment cases as

$$ h_{x=150} = \frac{1 + 0.0367 \beta}{1 + 0.0367 \beta} $$

$$ h_{y=150} = \frac{1 + 0.0367 \beta}{1 - 0.0386 \gamma} $$

It shows that increasing $\beta$ helps to increase $h$ in both x- and y-misalignment, which can improve the misalignment performance. Also, decreasing $\gamma$ improves the y-misalignment performance.

In x- and y-misalignment, the normalized output power relationship with the inductance ratios $\beta$ and $\gamma$ is shown in Fig. 10. It is compared to a single-coupled IPT system using only the main compensation inductor $k_{1-2}$. There are two comparisons in Fig. 10. First, a single-coupled system is compared to the proposed dual-coupled system. The proposed system improves misalignment performance. Second, different dual-coupled systems have different performances. It validates that increasing $\beta$ and decreasing $\gamma$ both improve the

Fig. 9. Active power flow across the couplings in a dual-coupled system.
misalignment performance. Fig. 10 and (29) provide guidelines to design the circuit parameters.

Fig. 10(a) shows the $x$-direction misalignment. Since cross couplings $k_{1-2}$ and $k_{1-2}$ are small, the $x$-direction misalignment performance is only determined by $\beta$ and is independent of $\gamma$. The $x$-direction misalignment is improved with increasing $\beta$.

Fig. 10(b) shows the $y$-direction misalignment, in which the output power increases with increasing $\beta$ and increasing $\gamma$. When $\beta$ becomes larger, there are two peaks in the output power, which can increase the component voltage stress.

### B. Circuit Parameter Design

In this section, a 3.5 kW system is designed. According to Fig. 10, the inductance ratios are selected to be $\beta = 8.5$ and $\gamma = 0.4$. Considering the size difference of main coils, the inductances satisfy $L_1 = 1.5 \times L_2$. Therefore, according to (4), (16), and (18), the specifications and circuit parameters are shown in Table III.

The parameters $K_1$, $K_2$, and $K_3$ can be calculated for different $x$- and $y$-direction misalignments, as shown in Fig. 11.

Fig. 11(a) shows $K_1$ increases with the $x$-direction misalignment. Since $k_{1-2}$ and $k_{1-2}$ are zero in the $x$-direction misalignment, $K_2$ and $K_3$ are also zero. According to (20), increasing $K_1$ helps to improve the $x$-direction misalignment performance.

Fig. 11(b) shows $K_1$ increases with the $y$-direction misalignment. According to (18) and (20), increasing $K_1$, $K_2$, and $K_3$ leads to an improvement of misalignment. Since there is a maximum value of $K_2$ and $K_3$, it indicates that there could be a maximum value of power, which is consistent with the two peaks in the waveform of system power in Fig. 10(b).

Using Table II and Fig. 11, the power distribution among the couplings is studied as shown in Fig. 12. Compare Figs. 10 and 12, it shows that the the curve of $P_{1-2}$ in Fig. 12 is much smoother than that in Fig. 10, either with $x$- or $y$-misalignment. It is because the integration of the compensation inductors changes the power flow. It is also consistent with the definition of $P_{1-2}$ in Table II, which shows that $K_1$ and $K_2$ can contribute to improve the misalignment performance.

Fig. 12(a) indicates that, in $x$-misalignment, $P_{1-2}$ and $P_{f1-f2}$ contribute to the system total power $P_{out}$. There are two power transfer paths: from $L_1$ to $L_2$ and from $L_{f1}$ to $L_{f2}$.

Fig. 12(b) indicates that, in $y$-misalignment, $P_{1-2}$, $P_{f1-f2}$, $P_{f1-2}$, and $P_{f1-f2}$ contribute to the system total power $P_{out}$. There are four power transfer paths: from $L_1$ to $L_2$, from $L_1$ to $L_{f2}$, from $L_{f1}$ to $L_2$, and from $L_{f1}$ to $L_{f2}$.

### C. System Simulation

LTspice is used in simulation. $C_2$ is increased by 10% to 19.8 nF to realize a soft-switching condition [13]. In the well-aligned case, the waveforms are shown in Fig. 13.
It can be seen that, at both the input and output, the voltage and current are almost in phase, which limits the reactive power circulating in the resonant circuit and reduces power losses.

The LTspice simulation provides the currents. According to \cite{13}, a 3.5 kW single-coupled system can be designed using the same voltages and dimensions. The number of turns of the coils can be acquired from the prototype design, as shown in Fig. 15 in the next section. The comparison of currents and number of turns is shown in Table IV, which shows that the dual-coupled system can reduce the currents in main coils $L_1$ and $L_2$.

Using the currents in Table IV as excitations, magnetic field emissions are simulated in Maxwell, as shown in Fig. 14. According to ICNIRP 2010 guidelines, the limit on magnetic field strength is 27 $\mu$T at 85 kHz for general public \cite{30}.

In Fig. 14(a), the coupler contains coils $L_1$, $L_2$ and inductors $L_{f1}$, $L_{f2}$. The safe area is about 200 mm from the side and 300 mm from the top. In Fig. 14(b), the coupler contains only $L_1$ and $L_2$, but the excitation currents are larger. The safe area is the same as Fig. 14(a). It can be concluded that the integration of $L_{f1}$ and $L_{f2}$ does not significantly increase field emissions.

V. EXPERIMENTS

A. Experimental Setup

According to Section II, a prototype of the dual-coupled magnetic coupler is constructed, as shown in Fig. 15.

The coils and inductors are wound by AWG38 Litz wire. To obtain the inductance in Table III, $L_1$ has 30 turns, $L_2$ has 31 turns, $L_{f1}$ has 4 turns, and $L_{f2}$ has 6 turns. Multiple litz wire bundles can be connected in parallel to reduce conduction loss. In future research, the IPT system will be studied to optimize the system cost, considering the hardware cost and the saved energy during its life cycle \cite{31}. Using this coupler, an experimental setup is shown in Fig. 16.

In this setup, the magnetic material PC40 is used to build the ferrite plates. They are placed close to the coils to increase the coupling. Aluminum sheets are placed on the top and bottom of the ferrite to provide a shielding effect. To reduce losses, film capacitors with a dissipation factor of 0.05% are chosen. SiC MOSFETs (C2M0025120D) are used in the inverter. A dc
source is used at the primary side, and the secondary side is connected to an electronic dc load to emulate a battery.

**B. Experimental Results**

When the transmitter and receiver are well aligned, and the input and output dc voltage are both 220 V, the system reaches full power. The experimental results are shown in Fig. 17.

The experimental waveforms agree with Fig. 13, and the soft-switching condition is achieved in the MOSFETs. Therefore, switching losses in the system are small. Fig. 17(b) shows that the system output power can reach 3.48 kW with a dc–dc efficiency of 94.8% from the dc input to the dc output.

In the well-aligned case, the power and efficiency are shown in Fig. 18. The dc–dc efficiency increases with system power. When the power is higher than 500 W, it can achieve a dc–dc efficiency higher than 94%. In future research, better ferrite material will be used to increase the system efficiency.
The system is tested in 150 mm x- and y-misalignment cases. The experimental waveforms are shown in Fig. 19. The experimental waveforms show that soft switching can still be maintained in the misaligned cases, so the system can realize a relatively high efficiency. Fig. 19 also shows that there is no apparent noise in the drive signal $V_{\text{drive}}$.

With x- and y-misalignment, the output power is compared with the calculation in (18), as shown in Fig. 20. With 150 mm x-misalignment, the output power decreases to 1980 W, which is 56.8% of the well-aligned value. With −150 mm y-misalignment, it decreases to 2880 W (82.6% of the well-aligned value). With +150 mm y-misalignment, it is 3130 W (89.8% of the well-aligned value). It validates that the proposed system has good misalignment performance.

Fig. 20 also shows that experimental results are consistent with the calculation. Since the calculation is based on the FHA method and only the fundamental harmonic current is considered, the power difference in Fig. 20 can be explained by the presence of third-order harmonics [13]. Also, in Fig. 20(b), the output power is asymmetric. This is due to asymmetry in the DD structure of the hand-made inductors $L_{f1}$ and $L_{f2}$.

The relationship between the normalized power and the main coupling coefficient $k_{1-2}$ are also measured in the single- and dual-coupled systems as shown in Fig. 21. In Fig. 21, the output power of the dual-coupled system are measured in both x- and y-misalignment cases. Compared to the single-coupled system, it indicates that the proposed system contributes to improve the misalignment performance, and the y-direction performance is improved even further.

VI. CONCLUSION AND FUTURE WORK

In this paper, a dual-coupled LCC-compensated IPT system is proposed to improve the misalignment performance. The compensation inductors are integrated into the main coils to transfer power to the secondary side. The circuit working principle of the dual-coupled IPT system is presented in detail, and it is shown that the magnetic couplings of the compensation inductors can improve the misalignment performance of an IPT system. Experimental results show that the proposed IPT system can retain at least 56.8% and 82.6% of the well-aligned power at 150 mm x- and y-direction misalignment, respectively.
In future research, a thorough economic analysis of the compensation inductors will be conducted to minimize the system cost, which includes short-term hardware cost and long-term energy cost during the life cycle. There is a tradeoff between the short- and long-term costs. For integrated inductors, since they share ferrite plates with the main coils, only the copper cost needs to be considered. If more copper is used, the short-term cost is increased but the long-term energy cost can be reduced due to higher efficiency.

REFERENCES


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