A Novel Driving Scheme for Inductive Power Transfer Systems Using Decoupled Transmitter Coils

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Abstract—This paper explores a novel and unsymmetrical driving scheme for an inductive power transfer system using decoupled transmitter (TX) coils. Instead of driving each TX in the same way, the proposed driving scheme would employ various compensations for different coils, and the power flow of each TX are closely coupled. Through circuit analysis, the proposed system would have multiple operation modes to avoid over load conditions. Meanwhile, it would maintain the benefits of a multiple-TX system like high misalignment tolerance, and enable the system design and control like a single-TX one, e.g., having load-independent output voltage. The experiment demonstrates the waveform of normal mode and protection mode, load-independent output voltage.

Keywords—Inductive power transfer, decoupled transmitter coils, various compensations, over-load protection

I. INTRODUCTION

The inductive power transfer (IPT) is widely used in mid-range high-efficiency wireless charging scenarios, including the implanted devices, household appliance, and movable robotics [1]–[4]. A typical IPT should at least include a transmitter (TX) and a receiver (RX) for power delivery. When the mutual inductance of the coupler are utilized to build the magnetic field, the leakage inductance would introduce large circulating energy if the coupler are driven directly by the ac source. In practice, the compensation networks (like series compensation or LCC compensation) are designed to reduce the circulating energy, and the high-order circuit with more design freedom also enable more desirable features, such as coupling-independent resonance, load-independent output, and zero phase angle (ZPA) operation [5], [6]. When the passive compensated coupler is terminated by high-efficiency active inverters and rectifiers, a complete resonant power converter is built and can be customized for various applications.

A simple one-TX one-RX coupler usually has limited spacial freedom in order to maintain sufficient coupling. With small coupling variation, a well-performed controller is able to regulate the power and maintain the overall system efficiency [7]–[9]. Once large misalignment happens, the original power transfer characteristics would be significantly affected or even destroyed. This limitation is determined by the nature of the coupler (i.e., the size, shape, position of coils), and cannot be avoided by controlling the active circuits [10], [11]. Usually the coupler with multiple coils is able to enlarge the spacial freedom [12]–[15]. However, complicated coupling among coils would dramatically affect the original reactance condition and power transfer characteristics. Currently, the most widely used multiple-coil techniques would employ decoupled TX coils or RX coils [16]–[18]. In such a system, the TX-RX coupling characteristics are improved under misalignment, the TX-TX or RX-RX coupling are avoided by specific coil design. The example efforts include the bipolar pad, tri-polar pad, double D-Quadrature (DDQ) pad, and bowl-shape transmitter [19]–[22]. These multiple-coils techniques can be applied at TX side, RX side, or both sides, and the elimination of the same-side cross coupling would significantly reduce the system complexity [23]–[25].

This paper would explore the potential benefits by using unsymmetrical driving scheme. An alternative driven scheme for a two-TX one-RX IPT system. The transmitter is a DDQ pad, where one TX coil is compensated by the LCC networks while the other use series compensation. The frond-end inverters are cascaded like a multiple-level converter, and the power flowing into each TX are strongly coupled. From the overall perspective, the proposed system can work exactly like a single-TX system using LCC compensation, i.e., enabling load-independent output voltage. Meanwhile, one more unique benefit is its multiple-modes operation and it can naturally provide the over-load protection without using additional circuits.

II. SYSTEM CONFIGURATION

Fig. 1. Traditional driving scheme for a two-TX system.

In a typical one-TX-one-RX system, the series or LCC compensation are usually used to drive the single
TX coil [26]–[29]. When the RX coil is series compensated, such a system is able to achieve either LI output current (using SS compensation) or LI output voltage (using LCC-S compensation). When more TX coils are included, the traditional driving scheme is to apply the same compensations and inverters to drive each TX independently as shown in Fig. (1). The sharing input dc source actually decouple the power flow of each TX, which is only determined by the coupling condition. The circuit symmetry would benefit the system design and analysis.

An unsymmetrical driving scheme is proposed as shown in Fig. (2), where different compensations are used for the decoupled TX coils, inverter 1 (formed with $S_1$ and $S_2$) and inverter 2 (formed with $S_3$ and $S_4$) are connected with dc source in series. In this system, power flow of each TX is actually coupled due to the cascaded connection of the two inverters. Unlike Fig. (1), TX1 and TX2 of the new system are actually in series from the dc point of view. Although the circuit analysis cannot decompose the whole system into different sub circuits, the derivation of this paper would show that the proposed system can work like the simple one-TX system and offer several unique benefits, such as overload protection and multiple operation modes.

$L_{tx1}$, $L_{tx2}$, and $L_{rx}$ represent the TX coils and RX coil respectively. $M_1$ and $M_2$ are the mutual inductance; $C_{tx1}$ is the series capacitor for TX 1; $C_{rx}$ is the series capacitor for RX; $C_{tx2}$, $L_t$, and $C_t$ forms the LCC compensation for TX 2. The resonance conditions are

$$\begin{align*}
\omega L_{tx1} - \frac{1}{\omega C_{tx1}} &= \omega L_{rx} - \frac{1}{\omega C_{rx}} = \omega L_t - \frac{1}{\omega C_t} = 0 \\
\omega L_{tx2} - \frac{1}{\omega C_{tx2}} - \omega L_t &= 0
\end{align*}$$

At the TX side, $v_1$ and $v_2$ are the inverter output voltage; $i_{tx1}$ and $i_{tx2}$ are the coil currents; $i_2$ is the inverter output current of TX2. At the RX side, $i_{rx}$, $v_{rec}$, and $V_o$ are the RX coil current, rectifier input voltage, and the final output load voltage respectively. $R_{rec}$ and $R_L$ is the equivalent load resistance of the rectifier and the final load. For a full-bridge rectifier, it has

$$R_{rec} = \frac{8R_L}{\pi^2}. \quad (2)$$

A. Inverter phase difference

Under resonance, the fundamental assumption is applied to simplify the circuit analysis, and then all the time-variant variables are represented in the phasor form. The phase difference (i.e., $\phi$) between the two inverters serve as a design variable and could be controlled by the gate signal. For convenience, the phase of $V_1 = V_{1} \angle 0$ is used as the reference, i.e., having zero phase, and then $V_2 = V_{2} \angle \phi$.

For the compensated coupler, the state equations are

$$\begin{align*}
V_1 &= j\omega M_1 I_{rx} \\
V_2 &= j\omega L_1 I_{tx2} \\
0 &= j\omega M_2 I_{rx} + j\omega L_1 I_2 \\
V_{rx} &= I_{rx} R_{rec} \\
V_{rx} &= j\omega M_1 I_{tx1} + j\omega M_2 I_{tx2}
\end{align*}$$

The TX coil currents are derived as

$$\begin{align*}
I_{tx1} &= \frac{V_o}{\omega M_1} \angle (\phi - 90^\circ) \\
I_{tx2} &= \frac{R_{rec}}{\omega M_2} V_1 \angle 0 - \frac{M_2}{\omega L_1 M_1} V_2 \angle (\phi - 90^\circ)
\end{align*}$$

According to (3), $V_{rx}$ is maximized when $I_{tx1}$ and $I_{tx2}$ is in phase. It means the flux from TX1 and TX2 work together to boost the output instead of canceling each other. Taking this phase requirement into (4) give

$$\phi = 90^\circ. \quad (5)$$
This phase requirement is used to maximize the induced voltage at the RX side.

B. Load boundary

The proposed system uses a single dc power supply to drive two TXs, and two split capacitors (i.e., C1 and C2) are used as the filters in Fig. 2. Since the loading circuits of these two capacitors are different, the overall input voltage \( V_{in} \) is no longer equally distributed. Define the voltage across C1 and C2 as \( V_{c1} \) and \( V_{c2} \), and it has \( V_{in} = V_{c1} + V_{c2} \). Since \( V_{c1} = \frac{\pi}{\sqrt{2}} V_1 \) and \( V_{c2} = \frac{\pi}{\sqrt{2}} V_2 \), it implies

\[
V_{in} = \frac{\pi}{\sqrt{2}} V_1 + \frac{\pi}{\sqrt{2}} V_2. \tag{6}
\]

Meanwhile, the two inverters are in series from the dc perspective, their average dc input current must be equal, which further means the amplitude of the inverter output currents are equal, i.e.,

\[
I_{tx1} = I_2. \tag{7}
\]

Combining (6) and (7), (3) can be rewritten as

\[
\begin{bmatrix}
\omega^2 \frac{M^2}{L_{rec}} + \omega \frac{M}{R_{rec}} & \frac{\sqrt{2} M}{L_{rec}} & 0 \\
1 & 0 & j \\
\omega^2 \frac{M^2}{L_{rec}} & -\frac{\sqrt{2} M}{L_{rec}} & j\omega L_t
\end{bmatrix}
\begin{bmatrix}
I_{tx1} \\
I_{tx2} \\
I_2
\end{bmatrix}
= \frac{\sqrt{2} V_{in}}{\pi}.
\tag{8}
\]

The currents are solved as

\[
\begin{bmatrix}
I_{tx1} \\
I_{tx2} \\
I_2
\end{bmatrix}
= \begin{bmatrix}
\frac{\omega^2 \frac{M^2}{L_{rec}} + \omega \frac{M}{R_{rec}}}{\omega^2 \frac{M^2}{L_{rec}} + \omega \frac{M}{R_{rec}} + j\omega L_t} \\
\frac{1}{\omega^2 \frac{M^2}{L_{rec}} + \omega \frac{M}{R_{rec}} + j\omega L_t} \\
\frac{j \frac{\omega^2 \frac{M^2}{L_{rec}}}{\omega^2 \frac{M^2}{L_{rec}} + \omega \frac{M}{R_{rec}} + j\omega L_t}}
\end{bmatrix}
\frac{\sqrt{2} V_{in}}{\pi}. \tag{9}
\]

It is clear the magnitude of \( I_{tx1} \) (i.e., \( I_{tx} \)) is larger than zero, but \( I_{tx2} \) is uncertain in (9). Since the induced voltage at RX side are contributed by both \( I_{tx1} \) and \( I_{tx2} \), a negative \( I_{tx2} \) actually means the phase is inverse. Therefore, (5) alone is not sufficient to ensure the in-phase operation of the TX coil currents. Taking \( I_{tx2} > 0 \) into (9) and considering \( R_{rec} = 8 R_L / \pi^2 \) would give

\[
R_L > R_{cri} = \frac{\pi^2 \omega M_1 M_2}{8}. \tag{10}
\]

The above discussions show the driving requirements and loading requirements (refer to (5) and (10)). They together ensure the induced voltage at the RX side is maximized instead of canceling each other.

### III. OPERATION MODE

#### A. Normal mode

The inverter phase difference and load boundary actually define the normal operation mode. Outside the load boundary, it does not mean a system failure. Instead, a unique protection mode would be activated without changing any driving signal.

When \( R_L \) meets the constrain of (10), the system works at the normal mode. Based on (3), the voltage matrix is derived as

\[
\begin{bmatrix}
V_1 \\
V_2 \\
V_{rec}
\end{bmatrix}
= \begin{bmatrix}
\omega^2 \frac{M^2}{L_{rec}} + \omega \frac{M}{R_{rec}} & \frac{\sqrt{2} M}{L_{rec}} & 0 \\
1 & 0 & j\omega L_t \\
\omega^2 \frac{M^2}{L_{rec}} & -\frac{\sqrt{2} M}{L_{rec}} & j\omega L_t
\end{bmatrix}
\begin{bmatrix}
I_{tx1} \\
I_{tx2} \\
I_2
\end{bmatrix}.
\tag{11}
\]

Combining (9) and (11) gives

\[
\begin{bmatrix}
V_1 \\
V_2 \\
V_{rec}
\end{bmatrix}
= \begin{bmatrix}
\omega \frac{M_1 M_2}{L_{rec}} \\
\frac{1}{\omega M} \\
\frac{j \omega L_t}{M}
\end{bmatrix} \frac{\sqrt{2} V_{in}}{\pi}.
\tag{12}
\]

Based on (12), the output voltage and power can be solved as

\[
\begin{bmatrix}
V_o \\
P_o
\end{bmatrix}
= \begin{bmatrix}
\frac{\pi}{\sqrt{2}} V_{rec} = \frac{\omega^2 M^2}{L_{rec}} V_{in} \\
\frac{\omega^2 M^2}{L_{rec}^2} V_{in}
\end{bmatrix}.
\tag{13}
\]

It is interesting to find that such a two-TX system with different compensations have the same output characteristics (i.e. (13)) as the one-TX system using LCC compensation. The overall system characteristics are totally determined by the LCC branch. For example, if the TX1 is disabled and the dc source directly drive TX2, the overall output power and voltage is exactly the same as (13). This feature really benefits the system design and control. It means all the control strategies for a one-TX one-RX system (using LCC-S compensation) can be applied to the proposed system. It will virtually work like a TX2-only system. However, it does not mean a two-TX system have the same performance as a TX2-only system. According to the analysis in previous, \( V_2 \) always leads \( V_1 \) by 90° for any conditions to ensure a maximum output. Under normal operation mode, the coil currents are in phase as show in Fig. (3) (a), and then together excite the RX.

#### B. Protection mode

The system under normal mode would work like a CV converter, and the final output voltage is load-independent like a TX2-only system using LCC-S compensation. However, it is also known that a CV-output converter needs to have over-load protection when the load resistance becomes small. This is usually achieved by software with the help of additional sensing circuits. The proposed system could naturally achieve over-load protection with the help of TX1.

When \( R_L \) is small, it shows \( I_{tx2} \) becomes negative, which also means the two coil currents are totally output of phase, i.e., 180° phase difference. Meanwhile, the voltage of TX2 inverter \( v_2 \) and the current \( i_{tx2} \) are also out of phase. This situation will
not happen in this practical system. Therefore, the voltage of TX2 inverter $v_2$ will drop to zero.

A typical waveform for protection mode is shown in Fig. (3) (b). The inverter of TX2 still leads that of TX1 by 90°. Once $R_L$ is smaller than its critical value, TX1 provides a large resistance. Almost all the input voltage is distributed on $C_1$, and there is no output at the inverter of TX2. With the decreasing $R_L$, $v_1$ is clamped by the dc input and $i_{tx1}$ gradually decreases.

Fig. 3. Typical waveform under different modes. (a) Normal mode. (b) Protection mode.

IV. EXPERIMENTAL VERIFICATION

For any IPT system, a well-designed driving circuit alone is impossible to ensure the efficient power transfer. In a multiple-TX system, the coupler is usually customized to ensure the RX is able to receive sufficient flux even under large misalignment. Therefore, it is the coupler structure that determine the overall coupling performance. In order to evaluate the benefits of unsymmetrical driving, a DDQ pad is implemented as the transmitter as shown in Fig.4(a). The RX coil is a simple rectangular one as shown in Fig.4(b). During the experiment, the RX coil is placed above the TX coils, and moves from the center position ($x = 0$ cm) to the edge position ($x = 10$ cm). The mutual inductance $M_1$ between $L_{tx1}$ and $L_{rx}$, $M_2$ between $L_{tx2}$ and $L_{rx}$ at different positions are shown in Fig. 4(d). Due to the special structure of DDQ, the mutual inductance $M_1$ will increase to a peak value and then decrease with moving receiver from center position to edge position. And the mutual inductance $M_2$ will drop to zero gradually with moving to edge position.

Fig. 4. Mutual inductance at different positions. (a) Moving RX from $x = 0$ cm to $x = 10$ cm. (b) Mutual inductance.

The proposed driving scheme is used to drive the decoupled DDQ pad as in shown in Fig.5. A dc supply is used to drive the cascaded converter, and the inverter phase difference are set by the signal generator. At the load side, an electronic load is used to swept the load resistance. All the system parameters are given in Table I.

At the edge position, the system waveforms are measured as shown in Fig. 6. At normal operation mode, the power is
transferred through both TX coils, and the phase difference of input voltage can ensure the in-phase coil current in Fig. 6 (a). When $R_{tx}$ (=1 Ω) is small in Fig. 6 (b), the protection mode is automatically activated. Small power is delivered through TX 1, and almost no power is delivered through the TX 2. These results are consistent with the simulation results from Fig. 3 (a) and Fig. 3 (b). In this IPT application, since the inverters are selectively used for power transfer and offer protection function, one of the inverter need to deal with all the input voltage. Therefore, Fig. 6 (b) shows the transistors of TX 1.

\[ \text{Fig. 6. Experiment waveform under different modes. (a) Normal CV TX IPT system. Different compensations are applied for the protection is needed (e.g., removing the driving signal).}
\]

For different load resistance, the input dc voltage is fixed at 80V, Fig. 7 shows the output voltage at different loads. At the normal region, the output voltage is stable like a single-TX system using LCC–S compensation. The overload protection will cause the quick voltage drop to limit the output power. A single-TX system cannot work in this way and a control-based solution will cause the quick voltage drop to limit the output power. A single-TX system using LCC–S compensation. The overload protection will cause the quick voltage drop to limit the output power. A single-TX system cannot work in this way and a control-based solution will cause the quick voltage drop to limit the output power.

\[ \text{TABLE I. SYSTEM SPECIFICATION AND PARAMETER VALUES.}
\]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{in}$</td>
<td>Input DC voltage</td>
<td>80</td>
<td>V</td>
</tr>
<tr>
<td>$V_o$</td>
<td>Output DC voltage</td>
<td>50</td>
<td>V</td>
</tr>
<tr>
<td>$f$</td>
<td>Switch frequency</td>
<td>500</td>
<td>kHz</td>
</tr>
<tr>
<td>$P_o$</td>
<td>Output power</td>
<td>100</td>
<td>W</td>
</tr>
<tr>
<td>$L_{tx1}$</td>
<td>Coil inductor of TX1</td>
<td>31.50</td>
<td>µH</td>
</tr>
<tr>
<td>$C_{tx1}$</td>
<td>TX1 compensation capacitor</td>
<td>3.14</td>
<td>nF</td>
</tr>
<tr>
<td>$L_{tx2}$</td>
<td>Coil inductor of TX2</td>
<td>27.24</td>
<td>µH</td>
</tr>
<tr>
<td>$C_{tx2}$</td>
<td>TX2 compensation capacitor</td>
<td>5.11</td>
<td>nF</td>
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<td>$L_t$</td>
<td>Compensation coil inductor of TX3</td>
<td>7.7</td>
<td>µH</td>
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<td>Compensation capacitor of TX2</td>
<td>13.16</td>
<td>nF</td>
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<tr>
<td>$L_{rx}$</td>
<td>Coil inductor of RX</td>
<td>27.24</td>
<td>µH</td>
</tr>
<tr>
<td>$C_{rx}$</td>
<td>RX compensation capacitor</td>
<td>3.8</td>
<td>nF</td>
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<td>$r_{tx1}$</td>
<td>Equivalent series resistance of TX1</td>
<td>0.30</td>
<td>Ω</td>
</tr>
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<td>$r_{tx2}$</td>
<td>Equivalent series resistance of TX2</td>
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<td>$r_x$</td>
<td>Equivalent series resistance of Compensation coil</td>
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<td>Ω</td>
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<tr>
<td>$r_{rx}$</td>
<td>Equivalent series resistance of RX</td>
<td>0.24</td>
<td>Ω</td>
</tr>
</tbody>
</table>

\[ \text{Fig. 7. Output characteristics under different load resistance.}
\]

V. CONCLUSION

This paper explores a novel driving scheme for a two-TX IPT system. Different compensations are applied for the decoupled TX coils, and the inverter for each TX are cascade connected to a dc source. Such a system can keep the benefits of multiple-TX (i.e., high misalignment tolerance) and LCC compensation (i.e., load-independent output voltage), while not suffers from over-load conditions.

REFERENCES

[9] K. Zhang, T. Ye, Z. Yan, B. Song, and A. P. Hu, “Obtain-


