Management of Multiple-Transmitter Multiple-Receiver Wireless Power Transfer Systems Using Improved Current Distribution Control Strategy

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Abstract: For high-power single-transmitter single-receiver wireless power transfer (STSRWPT) systems, the coils suffer from high voltage and current stresses. With increased power requirements, the coils become bottlenecks for power flow. To increase the power level, multiple-transmitter multiple-receiver wireless power transfer (MTMRWPT) systems with parallel circuits are developed that reduce the voltage and current stresses on the coils and improve power-handling capability. Firstly, an improved current distribution (ICD) control strategy is developed to simultaneously achieve high transfer efficiency, balanced current distribution and constant output voltage. Secondly, it is further shown that the ICD control strategy has the advantage that the currents at the transmitter coils are balanced and it reduces the control complexity simultaneously. Thirdly, an asynchronous particle swarm optimization (APSO) algorithm is applied to the ICD control strategy to verify the feasibility of the proposed control strategy. Lastly, a two-transmitter two-receiver wireless power transfer (WPT) system based on the ICD control strategy is proved to obtain an efficiency of more than 89.1% and provides the target output voltage 20 V with balanced current distribution.

Keywords: power transmission; wireless power transfer system; impedance matching; current distribution

1. Introduction

High-power wireless power transfer (WPT) systems are being widely used due to growing demand for fast charging technology and high-power transfer technology. High-power WPT system are applied to electric vehicles (EVs) [1–3], electric buses [4,5], trains [6,7] and other transportation vehicles like online electric vehicles (OLEV) [8–10]. However, high-power WPT systems suffer from several drawbacks that include: having large voltage and current stresses at the coils, limited magnetic field space due to application-specific coil sizes and shapes. WPT systems with multiple coils are developed for several applications. one such example is having receiver coils under the front and the rear of the car respectively that can sufficiently utilize chassis space [11]. In addition, multiple-transmitter multiple-receiver wireless power transfer (MTMRWPT) systems are applied to roadway powered electric vehicles to provide large lateral tolerance between the rail and pick-up coils [12]. Multiple transmitters based on electromagnetic cavity resonance are applied to simultaneously power multiple small receivers in a three dimensional volume of space [13].
In recent years, many studies have been carried out using various approaches to increase system efficiency. Some research [14,15] has increased system efficiency by introducing new compensation networks. A mixed-resonant coupling model is developed [14,15] to either improve the transfer efficiency or extend the transfer range, which finally achieves 85% efficiency at a distance of 10 cm. Resonators [6,16] are added for a short distance to enhance magnetic field coupling. Whereas, intermediate coils [17,18] are introduced to optimize the magnetic coupling. However, it is difficult to place intermediate coils between transmitter coil and receiver coil in applications like EVs. Some research [19–21] has chosen optimizing the magnetic coupling with high-permeability materials such as ferrites. However, the extra weight and volume make this an inappropriate solution for compact applications. Some research increased efficiency by operating converters at high frequency in the MHz range [22,23]. However, it is not suitable for high-power applications. In WPT systems, maximum efficiency is obtained when load resistances correspond to the impedance-matching condition [24,25]. However, the impedance-matching method is difficult to apply to MTMRWPT systems due to the complex mutual coupling and electric connection between coils. In [12] load resistances are separated at two equal resistances in a two-transmitter two-receiver WPT system to simplify the system, but it is only suitable for two groups of coils of similar parameters. It is a complex exercise to derive the maximum efficiency conditions in conventional MTMRWPT circuit models, there is a need for further developing mathematical models to study the MTMRWPT systems in detail.

Various topologies and control strategies have been developed to improve system efficiency. A two-transmitter and two-receiver circuit is developed with uncontrolled rectifiers at the secondary side [26]. This reduces the complexity of control, but fails to manipulate the equivalent load resistances. A buck circuit [27] is introduced to the secondary side to control the equivalent resistances. However, this adds extra segments to the system and increases the overall power losses. WPT system introduces a buck-boost converter [28] to the secondary side to regulate the load resistances. When the system transfers 16 W to the load, the maximum efficiency is 78%. Moreover, a buck circuit is introduced at the primary side to manipulate the input voltage and a boost circuit to the secondary side [29] to manipulate the load. When the system supply 100 W, the obtained maximum system efficiency is 79%. Dual active bridges [30,31] are introduced to WPT system to manipulate the matching resistance so as to achieve high efficiency. The dual active bridges topology has the advantage of small conduction loss and the ability of manipulating the load resistances. Increased efficiency of 85.4% with a 468.6 W output power is obtained in [30], and 80.4% with a 18 W output power is obtained in [31]. However, it is a complicated exercise for the MTMRWPT system to simultaneously achieve high efficiency and voltage regulation by removing the mutual coupling between receiver coils and separating the electrical connections at the secondary side.

Some research on single-transmitter multiple-receiver WPT (STMRWPT) systems is presented in [24,32–36]. A STMRWPT system is developed in [32] for portable devices which are of low-complexity receiver design. Resonant coupling systems [33] with multiple receivers are modeled with a simplified circuit model and resonant frequency splitting issue is observed in multiple receivers system. To maximize the efficiency in STMRWPT system, impedance matching theory is introduced to the STMRWPT system [24]. To increase system efficiency, metamaterials [34] are introduced to multiple receiver WPT system, where the efficiency is increased by about 20%. To provide high efficiency and target output power in a two-receiver WPT system, a control strategy based on simplified math model is proposed [35]. To meet the constant source supply, a load independent output voltage method [36] is proposed to satisfy the demands of different load devices. However, STMRWPT systems are mostly applied for portable devices which do not need accurate tuning. This hardly meets the power level demands of each receiver, and the efficiencies of the systems have to be accurately optimized. Besides, single transmitter would suffer from high current stress for high-power applications.

Some research focused on MTMRWPT systems in [12,33,37–39]. Cross-coupling between multiple transmitters or receivers is investigated in [37]. It reveals that the effective resonant frequency is
changed because of cross-coupling and should be tuned accordingly. Moreover, the splitting frequency issues in multiple-coil WPT systems are observed in [33] and the chirp signals are used to spread and excited inductive multiple-transmitter multiple-receivers WPT system. To meet high-power demand, a new WPT topology based on LCL topology is presented to promote integration of multiple WPT applications [38]. However, it introduces extra intermediate circuits for the WPT system which cause inconvenience in field applications. MTMRWPT systems are developed in roadway-powered electric vehicles to provide higher power handling capacity and a large lateral tolerance [12]. However, the uncontrollable rectifiers are constructed at the secondary side and the receivers can not be controlled by the rectifier. The study in [39] develops a two-transmitter two-receiver WPT system to promote transmitter capacity and verifies that the same-side cross-coupling will lower system efficiency. However, the research only focuses on dual groups of coils with same parameters and multiple receivers with different parameters should be further studied. In addition, the approaches mentioned above have not solved the problems of maximum efficiency and balanced current distribution in multiple transmitters and receivers.

In this paper, an improved current distribution (ICD) control strategy is developed to address the challenges of delivering constant output voltage, improving current distribution, high-efficiency in power transfer through the MTMRWPT system. Besides, a detailed mathematical model of MTMRWPT systems is derived and analyzed, which is applicable for systems with multiple different receiver coils. An active bridge is introduced to the rectifiers to control the receivers. In this study, MTMRWPT systems are proposed to provide a higher power level and maximum utilization of space. The active bridges of transmitters are responsible for voltage regulation and current distribution, and the active bridges of receivers are responsible for resistance matching to provide high efficiency.

The organization of this paper is arranged as follows. Section 2 analyzes the mathematical model of the MTMRWPT system. Section 3 develops the ICD strategy to regulate output voltage, balance current distribution and operate under high efficiency. The asynchronous particle swarm optimization (APSO) method is introduced to the proposed control strategy to verify the proposed control strategy can reduce the control complexity in MTMRWPT systems. Simulation and experiment results are presented in Section 4. Finally, the conclusion is shown in Section 5.

2. Modeling of Multiple-Transmitter Multiple-Receiver Wireless Power Transfer (MTMRWPT) System and Best-Matching Resistances

This section describes a MTMRWPT system involving inductive coupling. For high-power single-transmitter single-receiver wireless power transfer (STSRWPT) systems, the coils suffer from high voltage and high current stresses. To solve the problem of improving the system power level, this research adopts the parallel circuits to improve the power level. Active bridge circuits are adopted to achieve both current distribution and maximum efficiency.

Figure 1a presents the schematic and equivalent circuits of the MTMRWPT system. Each coil group is composed of a transmitter coil and a receiver coil. For coil groups are placed far away from each other, the mutual inductances between each coil group are neglected. $R_i$, $L_i$, and $C_i$ represent the resistance, inductance, and compensation capacitance of the $i$th transmitter coil respectively; $R_j$, $L_j$, and $C_j$ represent the resistance, inductance, and compensation capacitance of the $j$th receiver coil respectively. $R_o$ denotes the load resistance, $C_o$ denotes the filter capacitance and $U_{in}$ denotes the input DC voltage. $Q_{1i} - Q_{8i} (i = 1, 2, \ldots, n)$ are the gate drive signals of the converters of the $i$th group. Figure 2 shows the square-wave voltages and resonant currents waveforms in the MTMRWPT system. $2\beta_1$ denote the conduction angle of the transmitter coils of, and $\phi_1$ denotes the phase difference between the fundamental component of the $U_{1i}$ square wave and resonant current $i_{1i}$. $2\beta_2$ denote the conduction angle of the receiver coils of the system, and $\phi_2$ denotes the phase difference between the fundamental component of the $U_{2i}$ square wave and resonant current $i_{2i}$.

Since it is complicated to derive the maximum efficiency by combining all the parameters mentioned above, this research analyzes the MTMRWPT system by splitting the electrical circuit into
various coil groups and derives the maximum efficiency of each split group. Figure 1b shows the equivalent circuit of the split group, and $Z_{eqi}$ denotes the equivalent load resistance of $i$th group.

![Figure 1](image1.png)

**Figure 1.** Schematic and equivalent circuits of multiple-receiver wireless power transfer (WPT) system: (a) schematic circuit of multiple-receiver WPT system; (b) equivalent circuit of multiple-receiver WPT system.

![Figure 2](image2.png)

**Figure 2.** Square-wave voltages and resonant currents waveforms in multiple-transmitter multiple-receiver wireless power transfer (MTMRWPT) system.
In Figure 1b, $U_{i1}$ denotes the fundamental component of inverter voltage. By performing the Fourier decomposition, $U_{i1}$ is derived as:

$$U_{i1} = \frac{2\sqrt{2}}{\pi} U_{in} \sin \beta_{i1} \times e^{j\phi_{i1}} \quad (1)$$

Using the Kirchhoff voltage laws (KVLs), the equivalent mathematical model of the $i$th group in the MTMRWPT system can be derived as:

$$\begin{bmatrix} R_i + j\omega L_i + \frac{1}{j\omega C_i} & -j\omega M_i \\ -j\omega M_i & R_{i2} + j\omega L_{i2} + \frac{1}{j\omega C_{i2}} + Z_{eq} \end{bmatrix} \begin{bmatrix} I_{i1} \\ I_{i2} \end{bmatrix} = \begin{bmatrix} U_{i1} \\ 0 \end{bmatrix} \quad (2)$$

Supposing that the filter capacitance is large enough, the output voltage will remain unchanged, once the system achieves its steady state. $U_{i2}$ denotes the fundamental component of the inverter voltage in receiver coils is derived as:

$$U_{i2} = \frac{2\sqrt{2}}{\pi} U_o \sin \beta_{i2} \times e^{j\phi_{i2}} \quad (3)$$

Solving (1) and (2), the output voltage and currents are derived as follows:

$$U_o = \frac{\pi U_{in} \sum_{i=1}^{n} \omega M_i \sin \beta_{i1} \sin \beta_{i2}}{\pi^2 + \frac{R_{i1} \sin^2 \beta_{i2}}{R_{i1} + \omega^2 M_i^2}} \quad (4)$$

$$I_{i1} = \frac{(\pi U_{i1} R_{i2} + 2 \sqrt{2} \omega M_i U_o \sin \beta_{i2})}{\pi (R_{i1} R_{i2} + M_i^2 \omega^2)} \quad (5)$$

$$I_{i2} = \frac{(M_i \pi U_{i1} \omega - 2 \sqrt{2} R_{i1} U_o \sin \beta_{i2})}{\pi (R_{i1} R_{i2} + M_i^2 \omega^2)} \quad (6)$$

The equivalent resistance of the matching resistance segment $R_{eq}$ is derived as:

$$R_{eq} = \frac{U_{i2}}{I_{i2}} \quad (7)$$

The input resistance $R_{ini}$ of $i$th group is:

$$R_{ini} = R_{i1} + \frac{\omega M_i^2}{R_{i2} + R_{eq}} \quad (8)$$

Resistance $R_{ri}$ ($i = 1, 2, \ldots, n$) is defined as follows to describe the resistance of receiver coils of the $i$th group:

$$R_{ri} = R_{i2} + R_{eq} \quad (9)$$

Supposing there is no efficiency loss in resistance matching segments, the output voltage $U_o$ satisfies:

$$\sum_{i=1}^{n} U_{i2} I_{i2} \cos \varphi_{i2} = \frac{U_o^2}{R_o} \quad (10)$$

The system efficiency $\eta$ satisfies:

$$\eta = \frac{\sum_{i=1}^{n} U_{i1} I_{i1} \cos \varphi_{i1}}{U_o^2 / R_o} \quad (11)$$
To solve the maximum efficiency of the systems, which is the best matching resistance control strategy, the $\beta_1$ and $\beta_2$ have to satisfy:

$$\frac{\partial \eta}{\partial \beta_1} = 0, \quad \frac{\partial \eta}{\partial \beta_2} = 0$$  \hspace{1cm} (12)

The solutions of (12) are difficult to derive by analytical calculation, it means that the best matching resistances are difficult to achieve. In this paper, a simplified solution is proposed to satisfy high-efficiency transfer demand.

3. Current Distribution and Improved Current Distribution (ICD) Control Strategy

3.1. Resistance-Matching Rules of ICD Control Strategy

Since, the system efficiency depends on the variables $\beta_1$ and $\beta_2$, it is difficult to directly derive the maximum efficiency by solving all the equations above. In this research, the matching resistance is adopted to achieve the maximum efficiency condition. If each group achieves its maximum efficiency, the maximum efficiency of overall system can be achieved. From [19], the matching resistance in STSRWPT system is obtained as follows:

$$R_{eq,\text{BEST}} = R_2 \sqrt{1 + \frac{\omega^2 M_i^2}{R_{i1} R_{i2}}}$$  \hspace{1cm} (13)

In addition, make $R_{eq} = R_{eq,\text{BEST}}$ in each group, the system will achieve its maximum efficiency. By solving (13), the $\beta_2$ can be derived as:

$$\beta_{2, \text{BEST}} = \arcsin \frac{R_{eq,\text{BEST}}M_i \prod_{j=1, j\neq i}^n \left(A_j + R_{eq,\text{BEST}}R_{j1}\right)}{2 \sqrt{2} \rho \sum_{i=1}^n \left(R_{eq,\text{BEST}}M_i^2 \prod_{j=1, j\neq i}^n \left(A_j + R_{eq,\text{BEST}}R_{j1}\right) \right)^2}$$  \hspace{1cm} (14)

where, $A_j = R_{j1} R_{j2} + \omega^2 M_j^2$.

Supposing $\beta_1$ are set the same value, the efficiency no longer depends on the variables $\beta_1$ and $U_{in}$ according to (11) and (13). Therefore, $\beta_1$ and $U_{in}$ can be tuned to control the output voltage under the constraint condition (4), to assure the constant output voltage. $\beta_2$ are tuned to assure the system operates under high efficiency. For a MTMRWPT system, a control strategy has to be developed to satisfy both minimum current distribution condition and maximum efficiency condition. However, when $\beta_1$ are set the same value, the current distribution in multiple coils are unbalanced, and some coils may suffer from high current stress. To solve this problem, the ICD control strategy trades-off with a little efficiency loss to balance the current distribution in different coils. From detailed simulation studies and experimental results, this proves that the strategy achieves balancing of the current stresses and operation at high efficiency. In this control strategy, the $\beta_2$ are tuned to assure system operate under high efficiency and $\beta_1$ are tuned to control the current distribution and output voltage. Therefore, the system can be simplified to an optimized problem.

3.2. Currents and Voltages Distribution

Under the proposed control condition based on (14), the voltage and the current distribution are analyzed as follows:

Based on the ICD control strategy, the $\beta_2$ at the receiver are set as $\beta_{2,\text{best}}$ and $\beta_1$ are swept from $0^\circ$ to $90^\circ$ to balance the current distribution. The variation of voltage and current at both transmitter and receiver coils are listed as follows:
(a) The voltages $U_{i1}$ at the transmitter coils change rapidly due to the variation of $\beta_{i1}$. It is because the input voltage $U_{in}$ remains unchanged and the $\beta_{i1}$ sweep from $0^\circ$ to $90^\circ$, and according to (1), the voltages $U_{i1}$ at the transmitter coils change rapidly due to the variation of $\beta_{i1}$.

(b) The voltages $U_{i2}$ at the receiver coils generally remain unchanged despite the variation of $\beta_{i1}$. It is because based on the constant output voltage condition the output voltage $U_o$ remains unchanged, and the $\beta_{i2}$ has to remain unchanged based on (14) to provide high efficiency. Therefore, according to (3), the voltages $U_{i2}$ at the receiver coils generally remain unchanged.

(c) The currents $I_{i1}$ at the transmitter coils remain unchanged generally despite the variation of $\beta_{i1}$. This is because, based on Figure 1b, the currents $I_{i2}(i = 1, 2, \ldots, n)$ follow (15).

$$I_{i2} = \frac{U_{i2} - I_{i2}(R_{i2} + jX_{i2})}{j\omega M_i}$$

Under full compensation condition, the $jX_{i2} = 0$ and $I_{i2}R_{i2}$ are comparatively too small compared to $U_{i2}$ so that equation (15) can be replaced by (16):

$$I_{i2} \approx \frac{U_{i2}}{j\omega M_i}$$

$U_{i2}$ remain generally unchanged based on previous description (b) and hence $I_{i2}$ are unchanged accordingly.

(d) The currents $I_{i2}$ at the receiver coils vary rapidly due to the variation of $\beta_{i1}$. It is because the output voltage $U_o$ and $\beta_{i2}$ remain unchanged, but the equivalent resistances $R_{eqi}$ of resistance matching segments vary when $\beta_{i1}$ vary. The current $I_{i2}$ is sensitive to the variation of equivalent resistances $R_{eqi}$, and the $I_{i2}$ vary rapidly accordingly.

For high-power level WPT systems, the unbalanced currents increase the current stress of coils. The currents $I_{i1}$ at the transmitter coils remain unchanged regardless of the variation of $\beta_{i1}$, the control distribution variables $I_{i1}$ and $I_{i2}$ reduce to $I_{i1}$.

3.3. ICD Control Strategy

For MTMRWPT systems, a control strategy has to be developed to satisfy the minimum current distribution condition and maximum efficiency condition. Such a problem can be simplified to an optimized question.

The target of the ICD control strategy is to assure minimum current distribution, that is

$$f_1 = \sum_{i=1}^{n} (I_{i1}^2 + I_{i2}^2)$$

For the proposed control strategy, the current distribution is generally balanced in transmitter coils of MTMRWPT system. The fitness function can be simplified to (18).

$$f_2 = \sum_{i=1}^{n} I_{i2}^2$$

The constraint condition under such a control strategy is to satisfy the constant output voltage $U_o$ according to (4).

The ICD control strategy can provide constant output voltage and balance the current distribution simultaneously. This is because in an $n$-transmitter $n$-receiver WPT system, the dimension of control variables $\beta_{i1}$ and $\beta_{i2}$ is $2n$, and the dimension of controlled variables $I_{i1}$, $I_{i2}$ and $U_o$ is $(2n+1)$ totally. However, based on ICD control strategy, the $\beta_{i2}$ are set as $\beta_{i2, \text{BEST}}$ to provide high efficiency, the
control variables $\beta_{12}$ and $\beta_{22}$ are reduced to $\beta_{11}$, the dimension of which is $n$. Moreover, according to Section 3.2 (c), since $l_{11}$ remain unchanged despite the variation of $\beta_{11}$ and are previously designed based on (16), the controlled variables $l_{11}$, $l_{22}$ and $U_o$ are reduced to $l_{22}$ and $U_o$, the dimension of which is $(n+1)$. Furthermore, the current distribution focuses on the balanced current distribution which can be represented as $\frac{l_{11}}{l_{12}} = k_i, \ (i = 1, 2, \ldots, n - 1)$. The dimension of current ratio $k_i$ is $(n-1)$. Therefore, the actual controlled variables $l_{11}$, $l_{22}$ and $U_o$ reduce to $k_i$ and $U_o$, the dimension of which is $n$ totally. This is equal to the dimension of actual control variables $\beta_{11}$ which is $n$ totally. Therefore, by controlling $\beta_{11}$, the ICD control strategy can control output voltage and current distribution simultaneously.

Otherwise, the efficiency of the system is controlled by $\beta_{22}$, and the output voltages and current distribution are cooperatively controlled by $\beta_{11}$.

For two transmitters and two receivers WPT systems, current index $l_{12}/l_{22}$ at the receiver coil changes more rapidly than $l_{11}/l_{21}$ at the transmitter coil with the change of $\beta_{11}$. Therefore, system control is simplified to control the current distribution in receivers, that is

$$f_{\text{min}} = l_{12}^2 + l_{22}^2$$  \hspace{1cm} (19)

Therefore, for two-transmitters two-receivers WPT systems, the ICD control strategy should satisfy the following conditions:

(a) The $\beta_{12}$ satisfy the optimal matching resistances based on (14);
(b) The current distribution satisfies $\frac{l_{12}}{l_{22}} = 1$;
(c) The output voltage equals $U_o$. In this study, the control variables are $\beta_{12}$ and $\beta_{22}$, the target variables are $\frac{l_{12}}{l_{22}}$ and $U_o$.

3.4. Asynchronous Particle Swarm Optimization (APSO)

As an evolutionary technique, particle swarm optimization (PSO) was proposed mainly for continuous optimization problems. In this paper, an APSO algorithm [40] is applied to search for a solution to the balanced current distribution problem. $\beta_{11}$ are the control variables to obtain a feasible solution of current distribution.

To illustrate the application of the APSO algorithm in tracking the optimized current distribution, first a solution vector of $x_i$ with $m$ particles and $n$ dimension is determined as follows:

$$\vec{x}_i = [\beta_{11}, \beta_{21}, \ldots, \beta_{n1}], \ (i = 1, 2, \ldots, m) \hspace{1cm} (20)$$

In this APSO algorithm, the solution vectors, which are also called particles, are scattered through the multi-dimensional search space. Generally speaking, the current distribution problem can be formulated as (17) or (18).

In multi-dimensional search space, during the $(t+1)^{th}$ transfer, the $i^{th}$ coordinate component of the transfer vector of the $i^{th}$ particle is manipulated according to the following equations:

$$v_{is}(t + 1) = v_{is}(t) + c_1r_{1s}(p_{is}(t) - x_{is}(t)) + c_2r_{2s}(p_{gs}(t) - x_{is}(t)) \hspace{1cm} (21)$$

$$x_{is}(t + 1) = x_{is}(t) + v_{is}(t + 1) \hspace{1cm} (22)$$

where, $i = 1, \ldots, m$, and $n$ is the size of the swarm; $d = 1, \ldots, n$, and $n$ is the size of the space of a given problem. Constant output voltage is the constriction factor. $c_1$ and $c_2$ are positive constants used to control the impact of the local and global component. $p_{is}$ is the best experience in each generation, and the $p_{gs}$ is the best particle in the swarm. $r_{1s}$ and $r_{2s}$ are random attenuation factors. $v_{is}(t)$ and $x_{is}(t)$ are the velocity and position of the $i^{th}$ particle in the $d^{th}$ dimension at $t^{th}$ generation. $r_{1s}$ and $r_{2s}$ are both the random numbers between 0 and 1.
The MTMRWPT system is constraint by the constant output voltage according to (4) and basic system constraints according to (23).

\[
\begin{align*}
0 \leq I_1 & \\
0 \leq I_2 & \\
0 \leq \beta_{i1} & \\
\beta_{i1} \leq 90^\circ
\end{align*}
\]  

(23)

In \(n\)-transmitter \(n\)-receiver WPT system, there are \(2n\) dimensions to the solution with \(\beta_{i1}\) and \(\beta_{i2}\) \((i = 1, 2, \ldots, n)\). The system should provide balanced current distribution and meanwhile provide constant output voltage. For \(\beta_{i2}\) are controlled to a set system manipulating in high-efficiency condition based on (14), the control dimensions are reduced to \(n\) dimensions. The output voltage is constraint by the equality constraint condition (4), the exact solution of current distribution is reduced to \((n-1)\) dimensions.

4. Results

To verify the validity of the proposed MTMRWPT system, the mathematical model is calculated and simulated using MATLAB and MATLAB/Simulink platform. An experimental prototype was implemented as shown in Figure 3. Table 1 presents parameters of a two-transmitter two-receiver WPT system.

In Figure 3, Tx1 and Tx2 denote the transmitter coils, Rx1 and Rx2 denote the receiver coils. \(C_{11}\) and \(C_{21}\) denote the compensation capacitances at the primary side, \(C_{22}\) and \(C_{22}\) denote the compensation capacitance at the secondary side. The active-bridge at each coil consist of two half-bridge circuit modules KIT8020CRD8FF1217P-1. The MOSFET used in half-bridge circuit modules is SCT3030KL, the turn on resistance of which is only 30 mΩ, approximately. Group 1 and group 2 are respectively controlled by a controller consist of a digital signal processor (DSP) TMS320F28335.

Figure 3. Experiment platform of the two-transmitter two-receiver WPT system.
which will reduce the complexity of system control. The constraint condition (17) is then reduced to (18), which will reduce the complexity of system control. 

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{11}, L_{12}, L_{21}, L_{22}$</td>
<td>Inductances of coils</td>
<td>$22.78 , \mu\text{H}, 22.97 , \mu\text{H}, 22.92 , \mu\text{H}, 22.30 , \mu\text{H}$</td>
</tr>
<tr>
<td>$C_{11}, C_{12}, C_{21}, C_{22}$</td>
<td>Compensation capacitor</td>
<td>$110 , \text{nF}, 110 , \text{nF}, 110 , \text{nF}, 110 , \text{nF}$</td>
</tr>
<tr>
<td>$R_{11}, R_{12}, R_{21}, R_{22}$</td>
<td>Parasitic resistances</td>
<td>$12.25 , \text{m}\Omega, 12.79 , \text{m}\Omega, 11.58 , \text{m}\Omega, 12.01 , \text{m}\Omega$</td>
</tr>
<tr>
<td>$f$</td>
<td>Operating frequency</td>
<td>$100 , \text{kHz}$</td>
</tr>
<tr>
<td>$M_1, M_2$</td>
<td>Mutual inductance</td>
<td>$5, \mu\text{H}, 5, \mu\text{H}$</td>
</tr>
<tr>
<td>$\psi_{11}, \psi_{12}, \psi_{21}, \psi_{22}$</td>
<td>Phase</td>
<td>$0, 0, 0, 0$</td>
</tr>
<tr>
<td>$U_{in}$</td>
<td>Input voltage</td>
<td>$30 , \text{V}$</td>
</tr>
</tbody>
</table>

Firstly, we compare output voltage and current distribution in different $\beta_{11}$. In this two-transmitter two-receiver WPT system, $R_o$ is set as $2 \, \Omega$. $\beta_{21}$ sweeps from $25^\circ$ to $75^\circ$ and $\beta_{11}$ is manipulated according to the constant output voltage condition (4) to provide constant output voltage. $\beta_{12}$ and $\beta_{22}$ are set according to (14) to assure system operate at high-efficiency condition. Figure 4 shows the experiment waveform of the transmitters and receivers.

According to the Section 3.3, the ICD control strategy can provide control output voltage $U_o$ and current distribution simultaneously. In Figure 5a, the output voltage is controlled by $\beta_{11}$ and $\beta_{21}$ based on (4) and remains unchanged in general. It indicates that by controlling $\beta_{11}$ and $\beta_{21}$, the ICD control strategy can control output voltage $U_o$. Figure 5b illustrates under the ICD control strategy in the two-transmitter two-receiver WPT system, when the $\beta_{21}$ changes and $\beta_{11}$ is set according to (4), the voltages $U_{11}$ and $U_{21}$ of active bridges in transmitters changes rapidly between 15 V and 27 V, and the variation range of the voltages $U_{12}$ and $U_{22}$ of active bridges in receivers is smaller between 17.5 V and 20 V compared to the voltages in transmitters. Figure 5c illustrates under the ICD control strategy in two-transmitter two-receiver WPT system, when the $\beta_{21}$ changes and $\beta_{11}$ is set according to (4), the currents $I_{12}$ and $I_{22}$ of active bridges in receivers changes rapidly between 3 A and 8 A, and the variation range of the currents $I_{11}$ and $I_{21}$ of active bridges in transmitters is smaller between 5.5 A and 6 A compared to the currents at receivers. For the ICD control strategy, as analyzed in Section 3.2 (c) and (d), the currents $I_{11}$ at the transmitter coils remain unchanged generally despite the variation of $\beta_{11}$, and the currents $I_{21}$ at the receiver coils change rapidly due to the variation of $\beta_{11}$. Therefore, the current distribution in the receivers has to be balanced while the current distribution in transmitter remained unchanged despite the variation of $\beta_{11}$. The constraint condition (17) is then reduced to (18), which will reduce the complexity of system control.
Figure 5. Cont.
A STSRWPT system can provide higher efficiency than MTMRWPT system because of fewer components and smaller power loss. However, the coils suffer from higher current and voltage stress and restrict the power level of the WPT system. To compare the efficiency of these two systems, the load resistance of a STSRWPT system is set at 4 Ω, while the load resistance of MTMRWPT system is set at 2 Ω. This ensures the optimal $\beta_{12}$ of two systems equal 85° and avoids the influence of conduction loss of inverters in receiver coils. The two systems transfer 200 W output power respectively and the input voltage of two systems is set the same value of 30 V. The coils of STSRWPT is composed of coil Tx1 and Rx1.

In experiment, the two systems provide 200 W power respectively, and the maximum efficiency of STSRWPT system is 89.8% which is a little higher than the 89.2% in the MTMRWPT system. The currents in the STSRWPT system are $I_{11} = 7.83$ A, $I_{12} = 7.34$ A, while the current in MTMRWPT are $I_{11} = 5.84$ A, $I_{12} = 5.85$ A, $I_{21} = 5.68$ A, $I_{22} = 5.29$ A when $\beta_{11} = 40^\circ$ and $\beta_{21} = 45^\circ$. This means that the MTMRWPT system reduces the current stress in the WPT system; the voltages in the STSRWPT system are $U_{11} = 25.05$ V, $U_{12} = 25.61$ V, while the voltages in the MTMRWPT are $U_{11} = 19.83$ V, $U_{12} = 20.68$ V, $U_{21} = 19.10$ V, $U_{22} = 19.10$ V. It can be inferred that the MTMRWPT system reduces the voltage stress in WPT system and it is valuable in high-power transfer system to balance the current distribution and control the output voltage.

Figure 5d illustrates efficiencies in two-transmitter two-receiver WPT system. Figure 6a,b show the input resistances $R_{in}$ at the transmitters vs. $\beta_{11}$ and $\beta_{22}$. Figure 6c,d show that the resistances $R_{r1}$ at the receiver coils vary more rapidly than input resistances $R_{in}$ at the transmitter coils in Figure 6a,b. In Figure 6a,b, the input resistances $R_{in1}$ vary.

**Figure 5.** Experimental results: (a) output voltage; (b) voltages of active bridges at different $\beta_{21}$; (c) currents of active bridges at different $\beta_{21}$; (d) efficiencies comparison for calculation, simulation and experiments.
between 0.937 Ω and 5.099 Ω and \( R_{\text{r2}} \) vary between 0.938 Ω and 5.099 Ω when the \( \beta_{11} \) and \( \beta_{21} \) vary from 10° to 90°. In Figure 6c,d, the resistances \( R_{\text{r1}} \) vary between 1.855 Ω and 11.988 Ω and \( R_{\text{r2}} \) varies between 1.850 Ω and 11.884 Ω when the \( \beta_{11} \) and \( \beta_{21} \) vary from 10° to 90°; it means the currents at the receiver coils vary more rapidly than the ones at the transmitter coils. \( \beta_{12} \) and \( \beta_{22} \) are set \( \beta_{12 \text{, BEST}} \) and \( \beta_{22 \text{, BEST}} \) at the receiver side, the reflected resistances of two receiver coils are similar and the currents at the transmitter coils are balanced, the fitness function in (17) can be simplified to (18).

In the Figure 6c,d, the equivalent resistances \( R_{\text{eq}} \) vary when \( \beta_{11} \) and \( \beta_{21} \) vary. It has the advantage that the equivalent resistances \( R_{\text{eq}} \) of receivers to match system requirement. The resistances \( R_{\text{r1}} \) at the receiver coils vary more rapidly than input resistances \( R_{\text{in}} \) at the transmitter coils. However, there is a wide-range stationary interval where \( R_{\text{r1}} \) vary slowly when \( \beta_{11} \) and \( \beta_{21} \) vary. The equivalent resistance \( R_{\text{r1}} \) varies between 2.823 Ω and 3.726 Ω, and \( R_{\text{r2}} \) varies between 2.815 Ω and 3.712 Ω when the \( \beta_{11} \) and \( \beta_{21} \) vary from 60° to 90°. Furthermore, when \( \beta_{11} \) and \( \beta_{21} \) get close to the optimal \( \beta_{11} \) and \( \beta_{21} \) at which the system achieves optimal efficiency, the efficiency changes slowly. As shown Figure 6c, when the \( \beta_{11} \) and \( \beta_{21} \) change between 60° to 90° and the efficiency changes between 92.52% and 92.56%. This means that the ICD control strategy has a wide control range of \( \beta_{11} \) and \( \beta_{21} \) at which system can provide high efficiency.

In Figure 6c when \( \beta_{11} \) is small the equivalent resistance \( R_{\text{r2}} \) increases rapidly. This is because when \( \beta_{11} \) is small the output voltage \( U_o \) becomes the low base on (4), but the current \( I_{22} \) remain unchanged based on (16). In the same way, Figure 6d reveals that when \( \beta_{21} \) is small the resistance \( R_{\text{r1}} \) increases rapidly. This indicates that the \( \beta_{11} \) and \( \beta_{21} \) should not be small to avoid rapid variation of resistances \( R_{\text{r1}} \). The equivalent resistances at the receiver coils is with wider control range and it is easier for the receiver coils to be manipulated to the resistance-matching condition (13).
The line trace in Figure 7 shows the efficiencies solutions based on best resistance matching control strategy and the solutions based on the ICD control strategy, and the histograms show the current distribution. In Figure 7, the efficiencies of best resistance matching control strategy, which are 92.788%, 92.792%, and 92.790%, respectively, are higher than the efficiencies based on the ICD control strategy which are 92.804%, 92.860%, and 92.858%, respectively. However, the current distribution is not well balanced in the best resistance-matching control strategy. This is because the input resistances are unbalanced in the best resistance-matching control strategy. Focusing on solutions based on the ICD control strategy, the current distribution is decently balanced and the efficiency is still high enough to satisfy system demands. Figure 7 shows that the efficiency based on the APSO method with fitness function $f_1$ and $f_2$ are higher than the efficiency based on the calculation method. This is because the calculation method is based on the conditions that satisfy $\beta_{11} = \beta_{21} = \beta_{31}$ while the $\beta_{11}, \beta_{21}$ and $\beta_{31}$ in APSO method are optimized for balanced current distribution.

**Table 2.** Key parameters of the three-transmitter three-receiver WPT system.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{11}, L_{12}, L_{21}, L_{22}, L_{31}, L_{32}$</td>
<td>Inductances of coils</td>
<td>22.78 $\mu$H, 22.97 $\mu$H, 22.92 $\mu$H, 22.30 $\mu$H, 22.93 $\mu$H, 22.28 $\mu$H</td>
</tr>
<tr>
<td>$C_{11}, C_{12}, C_{21}, C_{22}, C_{31}, C_{32}$</td>
<td>Compensation capacitor</td>
<td>110 nF, 110 nF, 110 nF, 110 nF, 110 nF, 110 nF</td>
</tr>
<tr>
<td>$R_{11}, R_{12}, R_{21}, R_{22}, R_{31}, R_{32}$</td>
<td>Parasitic resistances</td>
<td>12.25 m$\Omega$, 12.79 m$\Omega$, 11.58 m$\Omega$, 12.01 m$\Omega$, 12.26 m$\Omega$, 12.78 m$\Omega$</td>
</tr>
<tr>
<td>$f$</td>
<td>Operating frequency</td>
<td>100 kHz</td>
</tr>
<tr>
<td>$M_1, M_2, M_3$</td>
<td>Mutual inductance</td>
<td>5 $\mu$H, 5 $\mu$H, 5 $\mu$H</td>
</tr>
<tr>
<td>$\phi_{11}, \phi_{12}, \phi_{21}, \phi_{22}, \phi_{31}, \phi_{32}$</td>
<td>Phase</td>
<td>0, 0, 0, 0, 0, 0</td>
</tr>
<tr>
<td>$U_{in}$</td>
<td>Input voltage</td>
<td>30 V</td>
</tr>
</tbody>
</table>
Figure 7. Simulation results of current distribution and efficiency in three-transmitter three-receiver WPT system. ‘ICD’ represents the improved current distribution (ICD) control strategy, ‘Best’ represents the best resistance matching method, ‘Cal’ represents the model based on the calculation method to get the $p_1$.

Figure 8 shows the generation simulation results of three-transmitter three-receiver WPT system based on APSO with different fitness functions. The parameters of three-transmitter three-receiver WPT system are listed in Table 2. Figure 8a shows the simulation results of APSO with fitness function $f_1$ and Figure 8b shows the simulation results of APSO with fitness function $f_2$. The output probability versus generations based on APSO is calculated on account of (17-18). As shown in Figure 8, it is found that both the output probability based on fitness function $f_1$ and $f_2$ decreases quickly and good convergences are achieved within 15 generations. It also reveals that the current distribution in both the APSO based on the ICD control strategy with both fitness function $f_1$ and $f_2$ are balanced in Figure 7. This means the fitness function $f_2$ can replace the fitness function $f_1$ in practical applications to reduce the control complexity of balancing current distribution.

Figure 8. Tracking fitness versus generations by two different fitness: (a) asynchronous particle swarm optimization (APSO) with fitness $f_1$; (b) APSO with fitness $f_2$. 
5. Conclusions

In this article, an ICD control strategy for the MTMRWPT system has been developed to provide high system efficiency, constant output voltage, and balanced current distribution. Firstly, a detailed mathematical model has been derived and analyzed, and a two-transmitter two-receiver WPT system has been implemented to verify the practicability of the ICD control strategy. Secondly, a STSRWPT system and two-transmitter two-receiver WPT system have been compared through experimental results to verify that the proposed system can reduce the voltage and current stresses with small power loss, which improves system power capacity. Thirdly, a three-transmitter three-receiver WPT system has been further simulated to prove that the ICD control strategy can applied to MTMRWPT system. And an APSO methods with different fitness functions has been simulated to verify that the ICD strategy has the advantage that the currents at the transmitter coils are balanced and it reduces the control complexity simultaneously. Lastly, it has achieved an 89.2% efficiency, 20 V target output voltage, 200 W output power and balanced current distribution at 100 kHz in a two-transmitter two-receiver WPT system.

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References


