A Multi-load Capacitive Power Relay System with Load-independent Constant Current Outputs

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Abstract—This paper proposes a power relay system to wirelessly power multiple loads via capacitive coupling. The intermediate capacitive relay unit is designed to power the load as well as enhance the power transfer capability, which contains two receiving plates and two transmitting plates. It is proven in this paper that the capacitive coupling between the receiving and transmitting plates in the same relay unit can be eliminated by being placed perpendicularly with the help of the proposed split-inductor-based compensation network. A general mathematical model of the multi-load capacitive power relay system is established. The L compensation circuits are employed to compensate the first and the last relays, while the LCL compensation circuits are designed to compensate the intermediate relays. Thus, the constant current output (CC) can be obtained for each load without affecting each other when neglecting the parasitic resistances. Additionally, the load current and efficiency variations versus the load resistance, coupling coefficient, and quality factor are thoroughly analyzed. Finally, a three-load experimental prototype is constructed to verify the feasibility of the proposed multi-load capacitive power transfer (CPT) relay system. The maximum efficiency can reach 86.1% at a power level of 37W.

Index Terms—Capacitive power transfer (CPT), constant current (CC) outputs, multiple loads, power relay.

I. INTRODUCTION

Capacitive power transfer (CPT) utilizes an electric field to transfer energy from the transmitter to the receiver. Recently, CPT has received extensive attention from researchers because of its desirable characteristics of no sensitivity to surrounding metal objects and no thermal effects generated by the eddy current [1, 2]. To enhance the power transfer capability and achieve output stability, various compensation topologies such as LCL-L [3], LC-LC [4, 5], LCL-LCL [6], LCLC-LCLC [7, 8], etc. have been proposed.

Most of the published CPT technology can only power one load [9, 10]. In some cases, however, multiple loads need to be powered simultaneously with a constant current (CC) such as charging batteries in series [11] and powering multiple light-emitting diodes (LEDs) [12]. Ref. [13] adopted a mixed high-order resonant topology consisting of a Π-LCL resonant network in the transmitter and multiple T-CLC resonant networks in the receivers. In this study, large transmitting plates are required to provide enough capacitive coupling to all receiving plates. However, the capacitive coupling model in [13] was not accurate since each transmitter-receiver pair was simply modeled as two capacitances and some parasitic capacitances were neglected. In [14], two shunt inductors are connected in parallel with the capacitive coupler at the primary side and the secondary side respectively to achieve maximum power transfer. Nevertheless, the receivers are then coupled with each other, which induces mutual interference between loads and increases system control complexity. In [15], the LCLC primary compensation circuit is adopted to ensure a load-independent voltage across two transmitting plates of the capacitive coupler, while multiple parallel-series LC secondary compensation circuits are employed for all the receivers to achieve CC outputs. Although the capacitive coupler in each transmitter-receiver pair is modeled as an equivalent Π-type model when considering all six coupling capacitances, the receivers are required to be placed very far from each other in order to neglect the cross-coupling among them. In addition to the aforementioned single-input and multi-output CPT system, Ref. [16] and [17] proposed a multi-input and multi-output CPT system which was deployed by multiple single-input and single-output CPT systems in parallel. Nevertheless, cross-coupling capacitances between two arbitrary plates in the transmitter and receiver respectively were not taken into account in [16]. Although [17] adopted tuning inductors to compensate the capacitive cross-coupling capacitance between two adjacent transmitters and receivers respectively, it is difficult to obtain the compensation inductances accurately because the high-frequency CPT system is sensitive to parameter deviations. In the aforementioned structures, a large separation space between adjacent transmitters or receivers is essential to minimize the cross-coupling among them. Furthermore, the transfer distance between the coupled transmitter and receiver is limited to ensure a large mutual capacitance.
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Recently, a novel power relay structure was proposed for the inductive power transfer (IPT) system in [18, 19] where two relay coils were grouped into one relay unit and the receiving relay coil was placed perpendicularly to the transmitting relay coil to achieve magnetic decoupling. With the CLC compensation network in [18] and the LCC compensation network in [19], constant current outputs can be obtained. This power relay structure provides a different solution for the multiple wireless power transfer system. Ref. [20] proposed a CPT power relay system where a relay is placed between the transmitter and the receiver to extend the power transfer distance, and LC compensation networks are adopted to compensate the capacitive coupling interface. However, only one load can be powered in [20]. Up until now, no paper has investigated the CPT power relay system for powering multiple loads simultaneously.

As a counterpart of the multi-load IPT power relay system in [18], this paper proposes a novel multi-load CPT relay system, where each intermediate power relay consists of two receiving plates and two transmitting plates placed perpendicularly to each other. With the help of the split-inductor-based compensation network, each relay can achieve load power decoupling. Moreover, a general mathematical model of the multiple capacitive coupling interface considering all coupling capacitances is presented. Compared with the modeling method in [21], no complicated matrix operations are required and the compensation network is taken into account during the modeling process. In addition, the L compensation network is designed in the first and last relay, and the LCL compensation network is designed in the intermediate relay to achieve load-independent constant current outputs. The effect of parasitic resistances on the load output currents and system efficiency are also elaborated. An experimental prototype with three loads is established to demonstrate the validity of the proposed multi-load CPT relay system.

The contributions of this paper are summarized as follows:

i) A multi-load CPT system using a capacitive power relay to transfer energy is proposed.

ii) A novel capacitive power relay structure is designed where the two receiving plates are perpendicular to the transmitting plates. Together with the proposed split-inductor compensation network, the coupling between the receiving and transmitting pads can be neglected, which greatly simplifies the systems design and analysis.

iii) A general mathematical model of the capacitive coupling interface with L and LCL compensation network is established so that multiple load-independent constant current outputs can be achieved.

Fig. 1 The topology of the proposed multi-load CPT relay system.

II. SCHEMATIC OF THE PROPOSED MULTI-LOAD CPT RELAY SYSTEM

A. System Description

The proposed multi-load CPT relay system with multiple constant current outputs is shown in Fig. 1, which consists of an inverter and (N+1) capacitive power relays. The dc-link voltage of the inverter is $V_d$ and the inverter operates in a complementary manner. The fundamental component of the inverter output voltage $v_{inl}$ can be calculated as,

$$v_{inl} = V_{inl} \sin(\omega_0 t) = \frac{2\sqrt{2}V_d}{\pi}\sin(\omega_0 t) \quad (1)$$

where $V_{inl}$ is the RMS value of the fundamental component of the inverter output voltage and $\omega_0$ is the operational angular frequency of the system. Relay #0 contains two plates $P_1$ and $P_2$, which transfers power to Relay #1. Relay #m ($m=1, 2, \ldots, N$) contains four plates, where plates $P_{4(m-1)+1}$ and $P_{4(m-1)+2}$ are used to receive power from the previous relay, while plates $P_{4m+1}$ and $P_{4m+2}$ are used to transfer power to the next one. Relay #N contains two plates $P_{4(N-1)+3}$ and $P_{4(N-1)+4}$, and receives power from Relay #N-1. At each receiving end, usually the load circuit should contain a full-bridge rectifier to transform the AC power to a DC source for the real load. The full-bridge rectifier with a real load can be modeled as a load impedance $Z_{L,m}$ ($m=1, 2, \ldots, N$), $L_{m, 1}$ and $L_{m, 2}$ are the compensation inductances in Relay #0. $L_{N, 1}$ and $L_{N, 2}$ are the compensation inductances in Relay #N. $L_{m, 1}$, $L_{m, 2}$, $L_{f, m+1, 1}$, $L_{f, m+1, 2}$ and $C_{3, m}$ are the compensation inductances and compensation capacitance in Relay #m ($m=1, 2, \ldots, N$). $P_{4(m-1)+1}$ and $P_{4(m-1)+2}$ form Port 2m-1, while $P_{4m+1}$ and $P_{4m+2}$ form Port 2m ($m=1, 2, \ldots, N$). External capacitors $C_{ex, 2m-1}$ ($m=1, 2, \ldots, N$) and $C_{ex, 2m}$ ($m=1, 2, \ldots, N$) are connected in parallel with Port 2m-1 and Port 2m, respectively.

Fig. 2 shows the capacitive coupling interface of the proposed CPT power relay system. In Relay #m ($m=1, 2, \ldots, N$-1), the receiving plates are designed to be perpendicular to the transmitting plates. The aluminum oxide ceramic is embedded between every two adjacent relays to enhance the capacitive coupling. The dimensions of the copper plates and the ceramic plates are $l_1^*l_2^*d_2$ and $l_1^*(d_1+2l_2)^*d_3$ respectively.
where \( l_1 \) and \( l_2 \) are the length and width of all copper plates and ceramic plates; \( d_1 \) is the separation distance between two adjacent copper plates; \( d_2 \) is the height of all copper plates; \( d_3 \) and \( d_4 \) are the heights of the ceramic and air-gap. In addition, \( l_1 = d_1 + 2l_2 \).

\[ Z_{\text{load}} = \frac{Z_{\text{impedance}}}{2} \]

**B. Decoupling Method and Modeling**

The decoupling capacitance between any two plates \( P_i \) and \( P_j \) is defined as \( C_{ij} (i, j = 1, 2, \ldots, 4, \ i \neq \ j) \), totaling to \( C_{24} \) coupling capacitances. The complicated electric coupling inevitably increases difficulties in the systems design and analysis. In order to achieve decoupling in each relay unit in Fig. 1, as well as the elimination of undesired mutual capacitance, the split-inductor-based compensation networks are employed. This connotes that the above inductances in the forward path should be equal to the inductances in the return path, i.e., \( L_{1,1} = L_{1,2}, L_{N,1} = L_{N,2}, L_{m,1} = L_{m,2} \) (\( m = 1, 2, \ldots, N-1 \)), and \( L_{d,m} = L_{d,m} \) (\( m = 2, 3, \ldots, N \)). The reasons are analyzed in detail as follows.

First, it is assumed \( Z_{L_1} = Z_{L_2} = \cdots = Z_{L_N} \neq 0 \). The influence of load impedances will be discussed in Section II D. As shown in Fig. 1, the proposed relay structure has \( 2N \) ports. Without losing the general characteristics, the following analysis will take the simplest 2-load CPT system with one intermediate power relay as an example to facilitate the analysis. The coupling capacitance mode is shown in Fig. 3. The inverter’s output voltage can be modeled as two sinusoidal voltage sources \( v_{1,l} = 0.5V_m\sin(\omega_l t) \) and \( v_{2,l} = 0.5V_m\sin(\omega_l t + \pi) \) applied at nodes \( A \) and \( B \), respectively, which has the same magnitude but \( 180^\circ \) phase difference. Similarly, the second load voltage \( v_{L_2,j} \) can be modeled as two sinusoidal voltage sources \( v_{3,l} = 0.5V_{L_2}\sin(\omega_l t + \phi) \) and \( v_{4,l} = 0.5V_{L_2}\sin(\omega_l t + \phi + \pi) \) applied at nodes \( C \) and \( D \), where \( V_{L_2} \) is the RMS value of the second load voltage and \( \phi \) is the initial phase angle of \( V_{L_2} \). When \( v_{1,l}, v_{2,l}, v_{3,l} \) and \( v_{4,l} \) work together, the current flowing through \( C_{ij} (i, j = 1, 2, \ldots, 8, \ i \neq \ j) \) is defined as \( i_{C_{ij}} \) and the direction is marked in Fig. 3(a). When

\[ v_{ij} (l = 1, 2, 3, 4) \text{ is applied while others are short-circuited, the current flowing through } C_{ij} (i, j = 1, 2, \ldots, 8, \ i \neq \ j) \text{ is defined as } i_{C_{ij}}. \]

The coupling capacitances at the symmetrical position have the same values because the facing area between two copper plates are the same as shown in Fig. 2. On the inverter side, as shown in Fig. 3(b) and (c), \( v_{1,l} \) and \( v_{2,l} \) are applied respectively while other voltage sources are short-circuited. It can be derived that the corresponding currents flowing through coupling capacitances located at the symmetrical position have the same magnitude but opposite directions because the circuit is symmetrical when split-inductors are used, i.e., \( i_{C_{1,1}} = -i_{C_{2,2}}, \ i_{C_{1,2}} = -i_{C_{2,1}}, \ i_{C_{1,3}} = -i_{C_{2,4}}, \ i_{C_{1,4}} = -i_{C_{2,3}} \).

Thus, it can be identified from \( P_1 \) to \( P_4 \) works while others are short-circuited, as shown in Fig. 3(d) and (e), the above conclusion is still tenable. Similarly, when \( v_{3,l} \) or \( v_{4,l} \) works, the currents flowing through all coupling capacitances in Fig. 3(a) are equal to the sum of currents when four independent sources work separately. Then applying Kirchhoff’s Current Law at nodes \( P_1, P_2, P_3, P_4, P_5, P_6, P_7, \) and \( P_8 \) respectively, the following equation can be obtained.

\[ \begin{align*}
    i_{C_{1,1}} + i_{C_{1,2}} &= -(i_{C_{2,1}} + i_{C_{2,2}}), \\
    i_{C_{1,2}} + i_{C_{1,3}} &= -(i_{C_{2,3}} + i_{C_{2,4}}), \\
    i_{C_{1,3}} + i_{C_{1,4}} &= -(i_{C_{2,4}} + i_{C_{2,3}}), \\
    i_{C_{1,4}} + i_{C_{1,2}} &= -(i_{C_{2,2}} + i_{C_{2,1}}) \\
    i_{C_{2,1}} + i_{C_{2,3}} &= -(i_{C_{1,3}} + i_{C_{1,1}}), \\
    i_{C_{2,2}} + i_{C_{2,4}} &= -(i_{C_{1,4}} + i_{C_{1,2}}), \\
    i_{C_{2,4}} + i_{C_{2,3}} &= -(i_{C_{1,2}} + i_{C_{1,1}})
\end{align*} \]

where \( i_{a1}, i_{a2}, i_{b1}, i_{b2}, i_{c1}, i_{c2}, i_{d1}, \) and \( i_{d2} \) are defined in Fig. 3(a). Thus, it can be identified from (2) that all coupling capacitances in the power relay structure consisting of one intermediate relay can be regarded as six two-port networks, i.e. Part I, Part II, Part III, Part IV, Part V and Part VI, as shown in Fig. 3(a). The above analysis process and conclusion can be extended to the system with \( N \) loads which is a \( 2N \)-port network. The currents flowing through the coupling capacitances located at the symmetrical position are still equal to that of the proposed relay structure and split-inductors. Thus, all coupling capacitances in the proposed \( 2N \)-port relay structure can be divided into \( C_{2N} \) two-port networks. Then, the two-port network analysis method in [6] can be used to calculate the self-capacitances and mutual capacitances. The self-capacitance of port \( a \) is defined as \( C_{\text{port}, a} (a = 1, 2, \ldots, 2N) \) and is the sum of the self-capacitance of all two-port networks containing port \( a \), which can be calculated as (3).
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\[
C_{\text{port},a} = \begin{cases} 
C_{1,1} + \sum_{j=3,5,\ldots,4(N-1)+3}^{j=4,6,8,\ldots,4(N-1)+4} \frac{(C_{i,j} + C_{j,i}) \cdot (C_{2,i} + C_{2,j})}{C_{i,j} + C_{j,i} + C_{2,i} + C_{2,j}} & a = 1 \\
C_{1,1} + \sum_{j=3,5,\ldots,-2}^{j=2,4,6,\ldots,-2} \frac{(C_{i,j} + C_{j,i}) \cdot (C_{3,4} + C_{4,3})}{C_{i,j} + C_{j,i} + C_{3,4} + C_{4,3}} + \sum_{j=2,4,6,\ldots,-2}^{j=3,5,\ldots,-2} \frac{(C_{i,j} + C_{j,i}) \cdot (C_{3,4} + C_{4,3})}{C_{i,j} + C_{j,i} + C_{3,4} + C_{4,3}} & a = 2,3,\ldots,2N-1 \\
\end{cases}
\]

\[
i \neq j; i = 3,5,7,\ldots,4(N-1)+1; j = 4,6,8,10,\ldots,4(N-1)+2; a = j / 2 \\
C_{4(N-1)+3,4(N-1)+4} + \sum_{j=2,4,6,\ldots,-2}^{j=3,5,\ldots,-2} \frac{(C_{i,j} + C_{j,i}) \cdot (C_{x,y})}{C_{i,j} + C_{j,i} + C_{x,y}} + C_{y,x} + C_{y,x} & a = 2N
\]

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**Coupling capacitances and compensation network**

- Part I
  - **Part V**
  - **Part VI**

- Part II
  - **Part V**
  - **Part VI**

- Part III
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  - **Part VI**

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  - **Part VI**

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  - **Part V**
  - **Part VI**
Fig. 3 Coupling capacitance model of the simplest multi-load CPT system with one intermediate power relay. (a) $V_{d1}$, $V_{d2}$, $V_{d3}$ and $V_{d4}$ works together. (b) only $V_{d1}$ works and other power supplies are short-circuited. (c) only $V_{d2}$ works and other power supplies are short-circuited. (d) only $V_{d3}$ works and other power supplies are short-circuited. (e) only $V_{d4}$ works and other power supplies are short-circuited.

The mutual capacitance $C_{Mab}$ ($a, b = 1, 2, \ldots, 2N, a \neq b$) between port $a$ and port $b$, which were formed by plates $P_{2a-1}$, $P_{2a}$, $P_{2b-1}$, and $P_{2b}$, can be derived as,

$$C_{Mab} = \frac{C_{2a,2b} - C_{2a,1,2b-1} - C_{2a,1,2b} \cdot C_{2a,2b-1}}{2C_{2a,2b} + C_{2a,1,2b-1} + C_{2a,1,2b} + C_{2a,2b-1}}$$

(4)

The sum of mutual capacitances between port $a$ and the other ports are defined as $C_{Mport,a}$ ($a = 1, 2, \ldots, 2N$), which can be calculated as,

$$C_{Mport,a} = \sum_{b=2}^{2N} C_{Mab} \ (b \neq a)$$

(5)

Thus, the equivalent $\Pi$ model of the proposed relay structure is shown in Fig. 4. $V_1, I_1, V_2, I_2, \ldots, V_{2N}, I_{2N}$ are the terminal voltages and currents of the $2N$ ports.

![Fig. 4 Equivalent $\Pi$ model of the capacitive coupling interface in the proposed CPT power relay system.](image)

It should be noted that in Relay #m ($m = 1, 2, \ldots, N-1$) that is formed by port $2m$ and port $2m+1$, $C_{4(m-1)+3}$, $4m+1 = C_{4(m-1)+3}$, $4m+2 = C_{4(m-1)+4}$, $4m+1 = C_{4(m-1)+4}$, $4m+2$ can be derived because of the symmetrical capacitive coupling structure in Fig. 2. Substituting this equation into (4), it can be derived that the mutual capacitance $C_{M2m,2m+1}$ in relay #m ($m = 1, 2, \ldots, N-1$) is zero. Thus, the transmitting plates and receiving plates in each intermediate relay are decoupled.

C. Design Example

<table>
<thead>
<tr>
<th>Table I</th>
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<tbody>
<tr>
<td>Dimensions of the Proposed Relay System</td>
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<tr>
<td>Parameter</td>
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<tr>
<td>$l_1$</td>
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<tr>
<td>$l_2$</td>
</tr>
<tr>
<td>$d_1$</td>
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<tr>
<td>$d_2$</td>
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</tbody>
</table>

The dimensions of the capacitive coupling interface are listed in Table I. The permittivity of the ceramic is 7.1. A four-relay, three-load capacitive coupler structure is built in the Ansys/Maxwell environment to present the relationship of the coupling capacitances concerning the ceramic-gap $d_3$ and air-gap $d_4$. The relay structure consists of 12 copper plates and 3 aluminum oxide ceramic plates. Each aluminum oxide ceramic plate is embedded between every two adjacent relay units. In Relay #1 and Relay #2, the mutual capacitance $C_{M2,3}$, and $C_{M4,5}$ are around zero because of the perpendicular arrangement. The mutual capacitance $C_{M1,2}$, $C_{M3,4}$ and $C_{M5,6}$ in each transmitter-receiver pair are only related with the ceramic-gap $d_3$. The mutual capacitance $C_{M1,3}$, $C_{M1,4}$, $C_{M1,5}$, $C_{M1,6}$, $C_{M2,4}$, $C_{M2,5}$, $C_{M2,6}$, $C_{M3,5}$, $C_{M3,6}$, and $C_{M4,6}$ are not only related to the ceramic-gap $d_3$ but also with the air-gap $d_4$. In this paper, $d_3$ is designed to be equal to $d_4$. Fig. 5 shows the variations of mutual capacitances with different $d_3$ and $d_4$. It can be observed that the mutual capacitance $C_{M1,2}$, $C_{M3,4}$, and $C_{M5,6}$ in each transmitter-receiver pair will decrease with the increase of $d_3$ and $d_4$. The other mutual capacitances between two non-adjacent ports are much smaller than $C_{M1,2}$, $C_{M3,4}$, and $C_{M5,6}$. Thus, in this paper, only the mutual capacitances between port $2m$-1 and port $2m$ ($m=1, 2, \ldots, N$) need to be considered and other mutual capacitances can be neglected. In this case, the equivalent $\Pi$ model in Fig. 4 can be simplified as in Fig. 6. Then the calculation of the compensation network in Section III can be obtained with constant current outputs. Otherwise, the crossing mutual capacitance between two nonadjacent ports will make it difficult to design the compensation network.

![Fig. 5 Mutual capacitance with the same variations of the ceramic-gap $d_3$ and air-gap $d_4$.](image)

D. Discussion

A four-relay, three-load system is built in LTspice to show the influence of the split-inductor-based compensation network and the load impedances on the system outputs. The coupler specifications are obtained from Section II C. The capacitive coupler is modeled as the simplified equivalent $\Pi$ model as in Fig. 6. The compensation circuit parameters are the same as...
TABLE II in the experiment section according to the design process in Section III A.

1) The influence of the split-inductor based compensation network on system outputs

As stated in Section II B, when all load impedances are zero, the proposed system is decoupled by employing the split-inductor-based compensation network. It is evident from Fig. 7(a) that without split-inductors, the amplitude of the load currents varies noticeably. Instead, when the split-inductors are employed as shown in Fig. 7(b), the amplitudes of output currents are nearly the same. The simulation results prove that the split-inductor-based compensation network is vital to achieving system decoupling.

![Simulation results](image)

Fig. 7 Simulation results (a) without split inductors. (b) with split inductors. (Zt = 0).

2) The influence of load impedances on system outputs

Nevertheless, in a practical system, the load impedances are not zero. The symmetry of the proposed system no longer exists. However, when the load impedances vary in a wide range from 20 – j150 to 500 – j600 with the split-inductor-based compensation network, as in Fig 8, the load currents are nearly constant. It proves that the load resistances have a negligible effect on the system decoupling performance and outputs.

III. SYSTEM ANALYSIS

A. Constant Current Output

In order to facilitate the analysis, the parasitic resistances of the compensation circuit are not considered first because their values are usually small. The influence of the parasitic resistances on the system outputs and efficiency will be analyzed in the next section. Based on the above modeling of the capacitive coupler interface and the band-pass filter characteristic of the resonant circuits, the equivalent II model of the proposed multi-load power relay system in Fig. 1 using the fundamental harmonic approximation (FHA) method can be redrawn as in Fig. 9. Since the currents flowing through the split inductors in the forward path and the return path are identical, the two split inductors can be combined as one inductor during the analysis, i.e., L1 = L1,1 + L1,2, LN = LN,1 + LN,2, Lf,m = Lf,m,1 + Lf,m,2 (m = 1, 2, ..., N), and Ls,m = Ls,m,1 + Ls,m,2 (m = 2, 3, ..., N). Cs,2m-1 and Cm,2m are the self-capacitances in the mth transmitter and receiver, respectively, which can be calculated as,

$$C_{s,2m-1} = C_{port,2m-1} + C_{cr,2m-1}, C_{s,2m} = C_{port,2m} + C_{cr,2m}$$ (6)

where Cport,2m-1 and Cport,2m are the internal self-capacitances of Port 2m-1 and Port 2m in the mth transmitter-receiver pair, respectively, which can be obtained from (3). The mutual capacitances between Port 2m-1 and Port 2m can be obtained from (4) and are redefined as CM,m (m = 1, 2, ..., N). Accordingly, the coupling coefficient km,m (m = 1, 2, ..., N) among them can be derived as,

$$k_{m,m} = \frac{1}{\sqrt{C_{s,2m-1}C_{s,2m}}}$$ (7)

![Relay diagram](image)

Fig. 9 The equivalent II model of the proposed multi-load CPT relay system using the FHA method.

In order to facilitate the derivation of resonant conditions to obtain constant current outputs and realization of zero phase angle (ZPA) of the input impedance, inductance Ls,m can be regarded as two inductances Ls,x,m and Ls,y,m connected in series. Inductance Lf,m can also be regarded as two inductances Lf,x,m and Lf,y,m connected in series. As can be seen from Fig. 1 and Fig. 9, the proposed multi-load CPT power relay system can be regarded as N transmitter-receiver pair in cascade. The mth (m = 1, 2, ..., N) transmitter-receiver pair consisting of Ls,x,m, Ls,y,m, Lf,x,m and Lf,y,m is redrawn in Fig. 10. It should be noted that Cs,s and Ls,s do not exist in the 1st transmitter-receiver pair, and Ls,y,N does not exist in the Nth transmitter-receiver pair.
In this case, once the capacitive coupler in the multi-load CPT relay system is determined beforehand, $C_{M,m}$, $C_{1,m}$, and $C_{2,m}$ are known. Then $L_{L,m}$, $L_{N,m}$, $L_{m}^{(m=1, 2, \ldots, N-1)}$ and $L_{f,m}$ ($m=2, 3, \ldots, N$) can be obtained from (10), (13) and (14).

Since the capacitive coupling interface of each relay has the same structure, the mutual capacitances between each transmitter-receiver pair are identical, which satisfies $C_{M,1} = C_{M,2} = \cdots = C_{M,N} = C_{M}$. When the self-capacities of each transmitter-receiver are identical, i.e., $C_{1,1} = C_{1,3} = \cdots = C_{1,2N-1} = C_{1}$, and $C_{2,1} = C_{2,4} = \cdots = C_{2N-3} = C_{2}$, the coupling coefficients of each transmitter-receiver are identical, which means $k_{c,1} = k_{c,2} = \cdots = k_{c,N} = k$. Substituting the above equations into (10), (13) and (14), the compensation inductances and compensation capacitance at the same position in each transmitter-receiver are also identical, i.e., $L_{L,N} = L_{L,1} = \cdots = L_{L,N}$, $L_{f,3} = L_{f,1} = \cdots = L_{f,N}$, $L_{f,1} = L_{f,2} = \cdots = L_{f,N}$. Moreover, if all load impedances are the same, i.e., $Z_{L,N} = Z_{L,1} = \cdots = Z_{L,L}$, all loads can acquire identical load power.

**B. Power Transfer Capability**

In a practical system, parasitic resistance is inherent and will affect the load current output characteristic and system efficiency. In Fig. 9, the quality factor of $L_{1}$, $L_{2}$, $L_{f}$, $L_{N}$, $C_{1}$, $C_{2}$, $C_{M}$, $C_{1}C_{M}$, and $C_{2}C_{M}$ is defined as $Q_{L1}$, $Q_{L2}$, $Q_{Lf}$, $Q_{LN}$, $Q_{C1}$, $Q_{C2}$, $Q_{CM}$, $Q_{CP}$ and $Q_{C2}$, respectively. The parasitic resistances and admittances of all components can be expressed as,

$$
\begin{align*}
\alpha_{L1} &= \alpha_{L2}/Q_{L1}, \alpha_{Lf}/Q_{Lf}, \alpha_{LN}/Q_{LN}, \\
\alpha_{C1} &= \alpha_{C2}/Q_{C1}, \alpha_{CM}/Q_{CM}, \\
\alpha_{CP} &= \alpha_{C2}/Q_{CP},
\end{align*}
$$

(15)

where $\alpha_{L1}$, $\alpha_{L2}$, $\alpha_{Lf}$, $\alpha_{LN}$, $\alpha_{C1}$, $\alpha_{CM}$, $\alpha_{CP}$ and $\alpha_{C2}$ are the parasitic resistances of $L_{1}$, $\ell_{1}$, $L_{f}$, $L_{N}$, $C_{1}$, $C_{M}$, $C_{1}C_{M}$, $C_{2}C_{M}$, respectively. $Y_{L1}$, $Y_{L2}$, $Y_{Lf}$, $Y_{LN}$, $Y_{C1}$, $Y_{C2}$, $Y_{CM}$ are the admittance of $L_{1}$, $\ell_{1}$, $L_{f}$, $C_{1}$, $C_{M}$, $C_{1}C_{M}$, $C_{2}C_{M}$, respectively. $Y_{CP}$ is the admittance of the last load branch. $Y_{C2}$ is the admittance of the rest of the load branches. Applying the node voltage method to Fig. 9, the following equation can be obtained:

$$
\begin{bmatrix}
G_1 & B_1 & O_{2,3} & O_{2,3} & \cdots & O_{2,3} & O_{2,3} \\
C_1 & G_2 & B_2 & O_{3,3} & \cdots & O_{3,3} & O_{3,3} \\
O_{3,3} & C_2 & G_3 & B_3 & \cdots & O_{3,3} & O_{3,3} \\
& & & & \cdots & & \\
& & & & \cdots & & \\
& & & & \cdots & & \\
O_{p+1} & O_{p+3} & O_{p+3} & O_{p+3} & \cdots & G_{N-1} & B_{N-1} \\
O_{p+2} & O_{p+3} & O_{p+3} & O_{p+3} & \cdots & G_{N-1} & G_{N}
\end{bmatrix}
\begin{bmatrix}
V_{p1} \\
V_{p2} \\
V_{p3} \\
\vdots \\
V_{pN-1} \\
V_{pN}
\end{bmatrix} =
\begin{bmatrix}
I \\
O_{p,1} \\
O_{p,2} \\
\vdots \\
O_{p,N-1} \\
O_{p,N}
\end{bmatrix}
$$

(16)

where $G_{mn}, B_{mn}, C_{mn}, V_{mn}$, and $I$ are as expressed as (17) ~ (21), respectively. $O_{p,q}$ represents the zero matrices with $p$ rows and $q$ columns.
The load impedance $Z_{L,m}$ is regarded as resistive when analyzing the influence of parasitic resistances on load currents and system efficiency. Usually, the quality factors of all components in Fig. 9 are different. However, to simplify the analysis of the load currents and efficiency, the quality factors of all components are assumed the same as $Q$. Such assumptions will not affect the generality of conclusions, because only the specific values are different. Furthermore, all load resistances are identical and change simultaneously in the following analysis of load current and system efficiency. Fig. 11(a) shows the normalized load current variations versus the normalized load power, which indicates the load currents decrease gradually as the load power increases. The further the distance between the load and Relay #0, the faster the load current drops. Thus, the last load current can be regarded as an evaluation criterion for the constant load currents characteristic. The load output power $P_{o,m}$ $(m=1,2,…,N)$ in each transmitter-receiver pair can be calculated as,

$$P_{o,m} = I_{L,m}^2 Z_{L,m}$$  \hspace{1cm} (25)$$

The input power $P_{in,m}$ $(m=1,2,…,N)$ in each transmitter-receiver pair is,

$$P_{in,m} = \begin{cases} I_{L,m}^2 + I_{C,m}^2 C_{L,m} + I_{C,m}^2 C_{L,m} + I_{L,m}^2 f_{C}^2 + I_{L,m}^2 f_{L}^2 + P_{o,m} & m=1 \\ I_{C,m}^2 + I_{L,m}^2 f_{L}^2 + I_{C,m}^2 C_{L,m} + I_{C,m}^2 f_{C}^2 + I_{L,m}^2 f_{C}^2 + P_{o,m} & m=2,3,…,N-1 \\ I_{C,m}^2 + I_{L,m}^2 f_{L}^2 + I_{C,m}^2 C_{L,m} + I_{C,m}^2 f_{C}^2 + I_{L,m}^2 f_{C}^2 + P_{o,m} & m=N \end{cases}$$  \hspace{1cm} (26)$$

Then, the efficiency $\eta_f$ for $N$ multiple loads can be derived as,
Fig. 12 System efficiency analysis (b) The system efficiency variation against the normalized load resistance. (N= 3, k= 0.15, Q= 500). (b) Maximum achievable efficiency variations with different coupling coefficients and quality factors (N= 3, ZL/Zb = 0.6).

Fig. 12 (a) shows the system efficiency variation versus the normalized load power. It can be observed that as the number of loads increase, the system efficiency will decrease. As opposed to the one-load CPT system with only four plates where the maximum efficiency is achieved at ZL/Zb=1, the optimal normalized load power for the multi-load CPT relay system to achieve the maximum efficiency will decrease as the number of the load increases. This is because more power is consumed in the parasitic resistances of the compensation network and the capacitive coupling interface. Fig. 12(b) shows variations of the maximum achievable efficiency versus the coupling coefficient and quality factor in a three-load capacitive power relay system concluding that higher efficiency can be achieved with a higher coupling coefficient or a higher quality factor.

IV. EXPERIMENTS

A. Prototype Setup and Experiment Results

An experimental prototype consisting of one inverter and three loads is constructed, as shown in Fig. 13(a). Since the load currents are constant and the load power is nearly decoupled in the proposed system, the constant current output characteristics will not be changed by the type of load. In this case, resistive loads are used to simplify the experimental verification. The SiC MOSFETs are adopted in the inverter to generate a source of 1.5MHz AC for the compensation circuits. The input voltage \( V_{DC} \) of the inverter is 50V. The dimensions of the multi-load CPT relay system are consistent with the Maxwell simulation parameters as shown in Section II C. The coupling coefficient \( k \) of each transmitter-receiver pair is selected as 1.5. Adopting the derivation of compensation component parameters in Section III, the system specifications are listed in TABLE II. \( L_{s1,1} \) and \( L_{s1,2} \) are slightly reduced by the same value to achieve zero-voltage switching (ZVS) for the MOSFETs. The compensation inductors are made of 660-strand Litz wire and are wound on the PVC tube to eliminate the skin effect and magnetic losses. When the normalized load power is 0.186, the experiment waveforms are presented in Fig. 13(b) and (c). Referring Fig. 13(b), the inverter output current lags the inverter output voltage, which indicates ZVS is achieved in this system. The first load output current lags the inverter output voltage by about 90°, and the adjacent load output currents are around 180° out of phase, which is consistent with the analysis in Section III.

Fig. 14(a) shows the load current variation versus the increasing load power. Normalized load current decreases gradually with the increase of the normalized load power, which is consistent with the analysis in Section III. It is worth noting that the system can still be regarded as multiple constant current outputs although the slight load output current attenuation. The current decay can be decreased with a large \( k \) or \( Q \) as analyzed above. For some occasions with the requirement with different output currents, the DC/DC converter can be employed before each real load to regulate the output currents. This will not affect the validity of the proposed scheme because multiple loads are decoupled in this system. Therewithal, the proposed system can be easily modified to feed the loads with different currents by redesigning the compensation topology parameters according to (12) and (14). Even when the three load resistances are different, the load current variations are still within 3% as shown in Fig. 14(b), which indicates that the proposed multi-load CPT relay system can retain the constant current output characteristic with different load resistances.

The system efficiency variation versus the increasing load power is shown in Fig. 14(c). The optimal normalized load power is 0.403 to achieve the maximum efficiency of 86.1%. This efficiency is reasonable because of the inverter loss and the parasitic resistances in compensation topologies. Higher efficiency can be obtained with a large \( k \) or \( Q \) as analyzed in Section III. It is noticed that the efficiency can vary in a wide range from around 70% to 86.1% and the optimized system efficiency is related to the equivalent AC load impedance. In practical applications, DC-DC converter can be employed before each real load to dynamically change the equivalent AC load impedance so that the maximum efficiency tracking can be achieved. In this case, the system can work in a wide dynamic range.

Fig. 15 shows the transient behavior when the normalized load power \( Z_{L1}/Z_b, Z_{L2}/Z_b \) and \( Z_{L3}/Z_b \) changes from 0.495 to 0.135, respectively. As can be seen from Fig. 15 (a), when \( Z_{L1} \) changes while the other two loads remain unchanged, \( I_{L2,1} \) immediately changes and the other two load currents \( I_{L2,2} \) and \( I_{L2,3} \) also change accordingly, but the starting instants that \( I_{L2,2} \) and \( I_{L2,3} \) change are slightly later than \( I_{L2,1} \) and the degree of change is also less than \( I_{L2,1} \). Then after around 8\( \mu s \), the three load currents will stabilize again. In Fig. 15 (b), only \( Z_{L1}/Z_b \)
changes to 0.135 while the other two loads remain unchanged. In Fig. 15 (c), only $Z_{L,1}/Z_b$ changes to 0.135 while the other two loads remain unchanged. It can be observed from Fig. 15 (b) and Fig. 15 (c) that the transient behavior is similar to that in Fig. 15 (a). The above experiment waveforms indicate that when one load changes, the current flowing through the other two loads will also change subsequently. Then after a while, the output currents will stabilize at around the original value. Hence, the phenomena shown above prove that the proposed system renders good decoupling performance when the load changes.

Due to the parameter tolerance of devices, temperature rise and aging of the circuit components in practical applications, the system performance will inevitably deviate from the nominal value. To maintain the normal operation of the system, the compensation capacitors and inductors can be replaced with variable switch-controlled capacitors or variable inductors [23, 24]. In the future, a control algorithm and tuning methods of LC components will be studied to obtain resonance conditions. The power density of the system can be further increased by increasing the switching frequency or DC input voltage of the inverter. In the future, compensation topology optimization will be studied to increase the power density. The power level of the proposed scheme can be improved by increasing the input voltage and the capacitive coupler area or decreasing the external capacitances according to (12) and (25).

**B. Electromagnetic Interference (EMI)**

In the capacitive power transfer system, the energy is transferred with the assistance of an electric field, which has the property of starting on the positive plate and ending on the negative plate [25]. Hence, the electric field contained in the capacitive coupler is the main cause of the EMI. The electric field intensity in the capacitive coupler is not only related to the
size but also related to the voltage applied to the plate [8]. The parasitic resistances in the compensation network have a very small effect on the voltage stress on the plate, as shown in Fig. 16. When the proposed system operates at maximum efficiency, the electric field intensity around the plates is simulated by the Ansys/Maxwell software, as shown in Fig. 17. It can be seen that there is no electric field if the distance is 13mm away from the system.

![Fig. 16 The voltage stress across the capacitive coupler with different quality factors of the compensation components.](image1)

![Fig. 17 Electric field intensity around the capacitive coupler. (a) frontal plane. (b) profile plane. (c) top view.](image2)

### C. Comparison to Other Works

<table>
<thead>
<tr>
<th>Proposed in</th>
<th>[13]</th>
<th>[15]</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of loads</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Efficiency</td>
<td>79% (DC-DC)</td>
<td>83.6% (DC-DC)</td>
<td>86.1% (DC-AC)</td>
</tr>
<tr>
<td>Power level</td>
<td>260W</td>
<td>15W</td>
<td>37W</td>
</tr>
<tr>
<td>Frequency</td>
<td>50kHz</td>
<td>10MHz</td>
<td>1.5MHz</td>
</tr>
<tr>
<td>Dielectric material</td>
<td>antistatic plastics</td>
<td>glass</td>
<td>Aluminum ceramic</td>
</tr>
<tr>
<td>Dielectric gap</td>
<td>0.2mm</td>
<td>1mm</td>
<td>8mm</td>
</tr>
<tr>
<td>Mutual capacitance C_M</td>
<td>15.6nF</td>
<td>370pF</td>
<td>39pF</td>
</tr>
<tr>
<td>Analysis of the coupling between receivers</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The comparison of the multi-load CPT system in [13], [15] and the work in this paper is given in Table III. The selection criteria for the above works is that they all power multiple loads simultaneously and a dielectric material is inserted between each transmitter-receiver pair. Furthermore, they all are experimentally verified. It can be seen that this work can achieve a high efficiency at a power level of 37W with a lower mutual capacitance. Neither of the compared works has discussed how to eliminate the coupling between different receivers, however, in this work the coupling between receivers is nearly zero by placing capacitive plates perpendicularly.

### V. CONCLUSION

A novel multi-load CPT system with multiple relays has been proposed in this paper, which can be used to charge batteries in series and powering multiple light emitting diodes. The relay is designed to power each load, where transmitting plates are placed perpendicularly to receiving plates with the assistance of the split-based compensation circuit to eliminate electric coupling. A general mathematic model of the capacitive coupler structure is provided when considering all coupling capacitances. The L and LCL compensation network with the corresponding resonant condition is utilized to obtain multiple load-independent constant current outputs when neglecting parasitic resistances. The influence of the parasitic resistances on load currents and system efficiency are also presented, which indicates that a higher coupling coefficient or a higher quality factor is beneficial for the minimum load current drop and maximum efficiency. Finally, a three-load experimental prototype is constructed and the experimental results show that the system can achieve the maximum efficiency of 86.1%. Future research will focus on compensation topology optimization and the control algorithm for efficiency optimization.

### REFERENCES


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