

# Six-Plate Capacitive Coupler to Reduce Electric Field Emission in Large Air-Gap Capacitive Power Transfer

Hua Zhang<sup>1b</sup>, Student Member, IEEE, Fei Lu<sup>2b</sup>, Student Member, IEEE, Heath Hofmann, Senior Member, IEEE, Weiguo Liu, Senior Member, IEEE, and Chunting Chris Mi<sup>3b</sup>, Fellow, IEEE

**Abstract**—This paper proposes a six-plate capacitive coupler for large air-gap capacitive power transfer to reduce electric field emissions to the surrounding environment. Compared to the conventional four-plate horizontal structure, the six-plate coupler contains two additional plates above and below the inner four-plate coupler to provide a shielding effect. Since there is a capacitive coupling between every two plates, the six-plate coupler results in a circuit model consisting of 15 coupling capacitors. This complex model is first simplified to an equivalent three-port circuit model, and then to a two-port circuit model which is used in circuit analysis and parameter design. This six-plate coupler can eliminate the external parallel capacitor in the previous LCLC topology, which results in the LCL compensation and reduces the system cost. Due to the symmetry of the coupler structure, the voltage between shielding plates is limited, which reduces electric field emissions. Finite element analysis by Maxwell is used to simulate the coupling capacitors and electric field distribution. Compared to the four-plate horizontal and vertical structures, the six-plate coupler can significantly reduce electric field emissions and expand the safety area from 0.9 to 0.1 m away from the coupler in the well-aligned case. A 1.97 kW prototype is implemented to validate the six-plate coupler, which achieves a power density of 1.95 kW/m<sup>2</sup> and a dc–dc efficiency of 91.6% at an air-gap of 150 mm. Experiments also show that the output power maintains 65% of the well-aligned value at 300 mm *X* misalignment, and 49% at 300 mm *Y* misalignment.

**Index Terms**—Capacitive power transfer (CPT), electric field emission, equivalent circuit model, six-plate coupler.

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H. Zhang is with the School of Automation, Northwestern Polytechnical University, Xi'an 710072, China, and also with the Department of Electrical and Computer Engineering, San Diego State University, San Diego, CA 92182 USA (e-mail: hzhang@mail.sdsu.edu).

F. Lu is with the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109 USA, and also with the Department of Electrical and Computer Engineering, San Diego State University, San Diego, CA 92182 USA (e-mail: feilu@umich.edu).

H. Hofmann is with the Department of Electrical Engineering and Computer Science, University of Michigan, Ann Arbor, MI 48109 USA (e-mail: hofmann@umich.edu).

W. Liu is with the School of Automation, Northwestern Polytechnical University, Xi'an 710072, China (e-mail: lwgll@nwpu.edu.cn).

C. C. Mi is with the Department of Electrical and Computer Engineering, San Diego State University, San Diego, CA 92182 USA (e-mail: mi@ieee.org).

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## I. INTRODUCTION

CAPACITIVE power transfer (CPT) utilizes electric fields, instead of magnetic fields, to transfer power without galvanic contact [1], [2]. Despite parasitic displacement currents, electric fields do not generate significant eddy current loss in nearby metals, so the CPT system can be an attractive alternative to the traditional inductive power transfer (IPT) system [3], [4]. Furthermore, the CPT system uses metal plates as the capacitive coupler and eliminates ferrites, which reduces the system cost and weight.

However, application of CPT systems is currently limited by transfer distance and electric field emissions [5]. The coupling capacitance is determined by the plate area and distance. Since the power storage in a capacitor is calculated as  $P = 0.5 f_{sw} C V^2$ , when the coupling capacitance is in the pF range, it requires either a high switching frequency or a high voltage to achieve high power transfer, which is difficult to realize in practice. Therefore, the short-distance CPT technology is mostly studied in previous research works [6]–[9].

One solution to increasing the transfer power and distance is to increase the voltage between the metal plates to establish a stronger electric field. Therefore, various compensation circuit topologies have been proposed to resonate with the capacitive coupler and produce high voltage. The double-sided LCLC [10], [11] compensation topology can increase the plate voltage to several kV, which resulted in a transfer power of 2.4 kW across a 150 mm air-gap for electric vehicle charging applications. It also has some variations, such as CLLC [12], LCL [13], [14], and LC [15] compensation. Moreover, Z-impedance compensation [16] and class-E amplifiers [17]–[20] can also help increase the plate voltage and achieve a high-efficiency CPT system. However, increasing the voltage may exceed the breakdown field of air between the plates, which can result in arcing. Also, the electric field emissions in the surrounding environment can exceed the safety requirements of the human body [21], which limits the maximum voltage for given gap distances.

One solution to reducing electric field emissions without reducing the plate voltage is to optimize the structure of the capacitive coupler. The external field cancellation method, which drives the adjacent metal plates with 180° phase difference to limit field emissions, is a good candidate, but it has special requirements on the control algorithm [22], [23]. Another can-

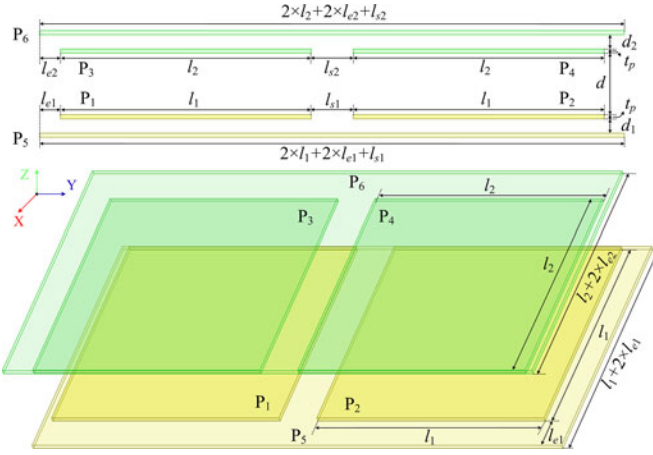


Fig. 1. Structure and dimensions of a six-plate coupler.

didate is the combination of a four-plate horizontal [10] and vertical [13] structure, which results in a six-plate capacitive coupler topology [24]. The two extra plates are large enough to cover the internal four plates. The external plates can provide coupling capacitors to simplify the compensation circuit. More importantly, they can also be used as electric field shields to reduce field emissions.

This paper will provide an equivalent circuit model of the six-plate coupler topology, which is then used to analyze the CPT system working principle and provide design circuit parameters. Similar to the four-plate vertical structure, the double-sided LCL compensation circuit is used to resonate with the six-plate coupler. Finite element analysis (FEA) by Maxwell compares the electric field emissions of the six-plate coupler to the four-plate horizontal and vertical couplers, and shows that the six-plate coupler achieves electric field shielding and therefore expands the safety area. Finally, a 1.97 kW CPT prototype is designed and implemented to validate the proposed six-plate coupler.

## II. SIX-PLATE CAPACITIVE COUPLER AND ITS CIRCUIT MODEL

### A. Plate Structure

The six-plate capacitive coupler structure is shown in Fig. 1. Plates  $P_1$ ,  $P_2$ , and  $P_5$  are placed at the primary (transmitter) side, and  $P_3$ ,  $P_4$ , and  $P_6$  are at the secondary (receiver) side.  $P_1$ ,  $P_2$ ,  $P_3$ , and  $P_4$  work as the power transfer plates.  $P_5$  and  $P_6$  work as the shielding plates, and they are larger than the other plates to provide better shielding of the electric fields. The dimensions of the six-plate coupler are also shown in Fig. 1. The definitions of the dimensions are described in Table I.

### B. Full-Capacitor Model of Six-Plate Coupler

In the six-plate coupler, every two plates are capacitively coupled, which results in 15 coupling capacitors in total. Fig. 2 shows all the coupling capacitances between plates.

The capacitors  $C_{15}$  and  $C_{25}$  dominate the self-capacitance of the primary side, and the capacitors  $C_{36}$  and  $C_{46}$  dominate the self-capacitance of the secondary side. Since the two

TABLE I  
PARAMETERS DESCRIBING SIX-PLATE STRUCTURE

| Parameter | Description              | Parameter | Description                |
|-----------|--------------------------|-----------|----------------------------|
| $l_1$     | Primary plate length     | $l_2$     | Secondary plate length     |
| $l_{s1}$  | Primary plate separation | $l_{s2}$  | Secondary plate separation |
| $l_{e1}$  | Primary shielding edge   | $l_{e2}$  | Secondary shielding edge   |
| $d_1$     | Primary gap distance     | $d_2$     | Secondary gap distance     |
| $d$       | Primary–secondary gap    | $t_p$     | Plate thickness            |

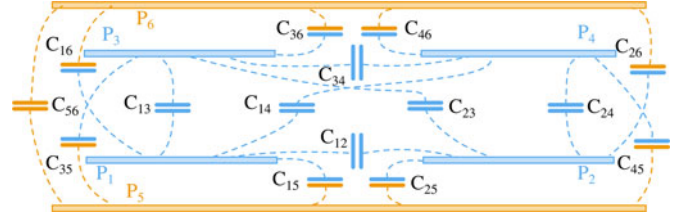


Fig. 2. Coupling capacitors between plates.

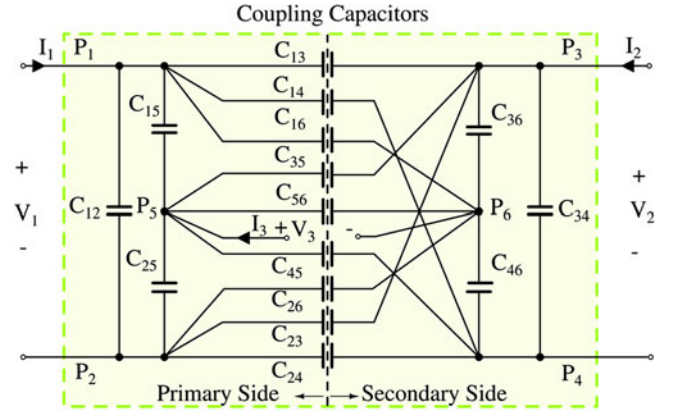


Fig. 3. Full-capacitor model of a six-plate coupler.

pairs of plates,  $P_1 - P_3$  and  $P_2 - P_4$ , are the main power transfer plates, the capacitors  $C_{13}$  and  $C_{24}$  dominate the mutual capacitance between the primary and secondary sides. Other capacitors, such as  $C_{14}$ ,  $C_{23}$ , etc., also affect the self and mutual capacitances.

Considering the all the couplings, the full-capacitor model of the coupler is shown in Fig. 3, in which  $V_1$  and  $V_2$  are the voltages at the primary and secondary sides, respectively. The voltage  $V_3$  and current  $I_3$  are imaginary external excitations between plates  $P_5$  and  $P_6$ , which are used to simplify the circuit analysis. In real application  $I_3 = 0$ . Compared to the 4-plate model in [13], the 6-plate model is very complex. It is, therefore, useful to acquire an equivalent but simplified circuit model to help design the corresponding resonant circuit. In this paper, the full-capacitor model is first simplified as a three-port equivalent model and then a two-port model.

### C. Three-Port Model of Six-Plate Coupler

A three-port network can be used to represent the equivalent circuit model of the six-plate coupler as shown in Fig. 4. Plates  $P_1$  and  $P_2$  are connected to the primary side circuit, and form

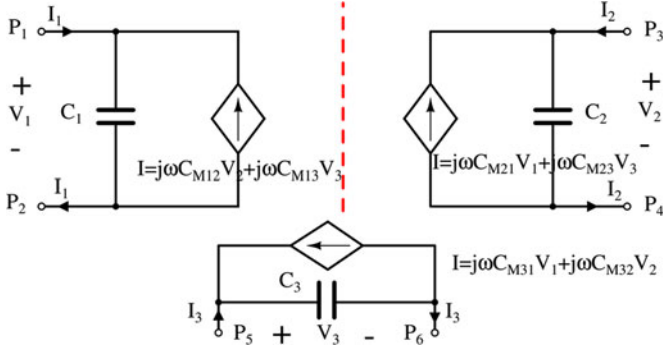


Fig. 4. Three-port behavior source model of a six-plate coupler.

the first port. Plates  $P_3$  and  $P_4$  are connected to the secondary side circuit and form the second port. Plates  $P_5$  and  $P_6$  form the third port, which is used to simplify analysis. The terminal voltages and currents of the three ports are represented as  $V_1$ ,  $I_1$ ,  $V_2$ ,  $I_2$ ,  $V_3$ , and  $I_3$ . The relationships between the variables are expressed as follows:

$$\begin{cases} I_1 = j\omega C_1 V_1 - j\omega C_{M12} V_2 - j\omega C_{M13} V_3 \\ I_2 = -j\omega C_{M21} V_1 + j\omega C_2 V_2 - j\omega C_{M23} V_3 \\ I_3 = -j\omega C_{M31} V_1 - j\omega C_{M32} V_2 + j\omega C_3 V_3 \end{cases} \quad (1)$$

where  $C_1$ ,  $C_2$ , and  $C_3$  are the self-capacitances at each of the three ports,  $C_{M12}$ ,  $C_{M13}$ ,  $C_{M21}$ ,  $C_{M23}$ ,  $C_{M31}$ , and  $C_{M32}$  are the mutual capacitances, and  $\omega = 2\pi f_{sw}$ , where  $f_{sw}$  is the switching frequency. Using energy arguments, it can be shown that  $C_{M12} = C_{M21}$ ,  $C_{M13} = C_{M31}$ , and  $C_{M23} = C_{M32}$ .

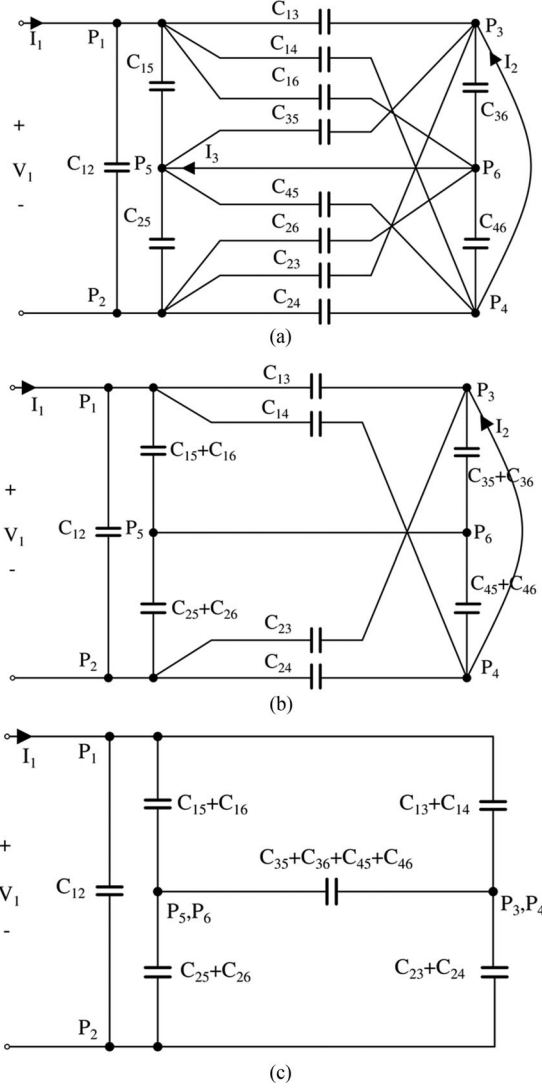
It is necessary to determine the relationships between the parameters in the full-capacitor model and the three-port model. The self-capacitances are calculated first, followed by the mutual capacitances. The self-capacitance  $C_1$  is used as an example. According to (1),  $C_1$  is determined as follows:

$$C_1 = \left. \frac{I_1}{j\omega V_1} \right|_{V_2=V_3=0}. \quad (2)$$

Fig. 5 shows the process to simplify the circuit to get the equivalent model. When  $V_2$  and  $V_3$  are short-circuited, the full-capacitor model is shown in Fig. 5(a).  $I_1$ ,  $I_2$ , and  $I_3$  represent the currents induced by  $V_1$  at the three ports. Since  $P_5$  and  $P_6$  are short-circuited, the capacitors can be combined together as shown in Fig. 5(b). It needs to be emphasized that the simplification from Fig. 5(a) to (b) does not affect the current  $I_2$ . To calculate the self-capacitance, the circuit is further simplified, as shown in Fig. 5(c). All the capacitors related to  $P_3$ ,  $P_4$ ,  $P_5$ , and  $P_6$  are then combined together, as follows:

$$\begin{cases} C_{a1} = C_{13} + C_{14} \\ C_{b1} = C_{23} + C_{24} \\ C_{c1} = C_{15} + C_{16} \\ C_{d1} = C_{25} + C_{26} \\ C_{e1} = C_{35} + C_{36} + C_{45} + C_{46} \end{cases} \quad (3)$$

The plate nodal voltages are defined as  $V_{P1}$ ,  $V_{P2}$ ,  $V_{P3}$ , and  $V_{P5}$ .  $P_2$  is defined as the reference node, which means  $V_{P2} = 0$ . The Kirchhoff's current equations of the four nodes in Fig. 5(c)


 Fig. 5. Simplification process of capacitor model when  $V_2 = V_3 = 0$ . (a) Full-capacitor model, (b) combine parallel capacitors, and (c) further combine capacitors.

are expressed as

$$\begin{cases} (C_{12} + C_{a1} + C_{c1}) \cdot V_{P1} - C_{a1} V_{P3} - C_{c1} V_{P5} = I_1 / (j\omega) \\ C_{12} V_{P1} + C_{b1} V_{P3} + C_{d1} V_{P5} = I_1 / (j\omega) \\ (C_{a1} + C_{b1} + C_{e1}) \cdot V_{P3} - C_{a1} V_{P1} - C_{e1} V_{P5} = 0 \\ (C_{c1} + C_{d1} + C_{e1}) \cdot V_{P5} - C_{c1} V_{P1} - C_{e1} V_{P3} = 0 \end{cases} \quad (4)$$

According to (4),  $V_{P3}$  and  $V_{P5}$  are expressed as

$$\begin{aligned} V_{P3} &= V_{P4} = \frac{[C_{e1}(C_{a1} + C_{c1}) + C_{a1}(C_{c1} + C_{d1})] \cdot V_1}{C_{e1}(C_{a1} + C_{b1} + C_{c1} + C_{d1}) + (C_{a1} + C_{b1})(C_{c1} + C_{d1})} \\ V_{P5} &= V_{P6} = \frac{[C_{e1}(C_{a1} + C_{c1}) + C_{c1}(C_{a1} + C_{b1})] \cdot V_1}{C_{e1}(C_{a1} + C_{b1} + C_{c1} + C_{d1}) + (C_{a1} + C_{b1})(C_{c1} + C_{d1})} \end{aligned} \quad (5)$$

To simplify analysis, capacitors  $C_{01}$  and  $C_T$  are defined as

$$C_{01} = \frac{C_{e1}(C_{a1} + C_{c1})(C_{b1} + C_{d1})}{C_{T1}} + \frac{C_{a1}C_{b1}(C_{c1} + C_{d1}) + C_{c1}C_{d1}(C_{a1} + C_{b1})}{C_{T1}}$$

$$C_{T1} = C_{e1}(C_{a1} + C_{b1} + C_{c1} + C_{d1}) + (C_{a1} + C_{b1}) \cdot (C_{c1} + C_{d1}). \quad (6)$$

The self-capacitance  $C_1$  is then determined to be

$$C_1 = C_{12} + C_{01}. \quad (7)$$

After the self-capacitance  $C_1$  is determined, the mutual capacitance  $C_{M12}$  can also be acquired with  $V_2 = V_3 = 0$ . From the second equation of (1),  $C_{M12}$  can be calculated as

$$C_{M12} = \frac{I_2}{-j\omega V_1} \Big|_{V_2=V_3=0}. \quad (8)$$

Fig. 5(b) can be used to calculate  $C_{M12}$ . At node  $P_4$ , the current  $I_2$  can be expressed as

$$\frac{I_2}{j\omega} = -(C_{14} + C_{24} + C_{45} + C_{46})V_{P4} + C_{14}V_{P1} + (C_{45} + C_{46})V_{P6}. \quad (9)$$

By substituting (5) into (9), the mutual capacitance is expressed as

$$C_{M12} = \frac{C_{e1}(C_{24}C_{c1} - C_{14}C_{d1}) + (C_{45} + C_{46})(C_{a1}C_{d1} - C_{b1}C_{c1})}{C_{T1}} + \frac{(C_{13}C_{24} - C_{14}C_{23})(C_{c1} + C_{d1} + C_{e1})}{C_{T1}}. \quad (10)$$

Therefore, when  $V_2$  and  $V_3$  are short-circuited, the self-capacitance  $C_1$  is expressed in (7), and the mutual capacitance  $C_{M12}$  is expressed in (10). The parameters  $C_1$  and  $C_{M12}$  are shown in the first column in Table II.

Following similar procedures, the parameters  $C_2$  and  $C_{M23}$  are determined with  $V_1$  and  $V_3$  short-circuited, and shown in the second column in Table II. The parameters  $C_3$  and  $C_{M13}$  are acquired with  $V_1$  and  $V_2$  short-circuited, and shown in the third column in Table II. In conclusion, all the equivalent self- and mutual-capacitances of the six-plate coupler are summarized in Table II. It can be further proved that  $C_{T1} = C_{T2} = C_{T3}$ , so they can be represented by  $C_T$ . It shows that equivalent capacitances depend on the couplings between plates.

#### D. Two-Port Model of Six-Plate Coupler

When the six-plate coupler is connected into a circuit, only  $P_1$ ,  $P_2$ ,  $P_3$ , and  $P_4$  are directly connected and  $P_5$  and  $P_6$  are floating. This means there is no external voltage or current source connected to  $P_5$  and  $P_6$ , and hence  $I_3 = 0$ . The three-port circuit model is then further simplified into an equivalent two-port model shown in Fig. 6.

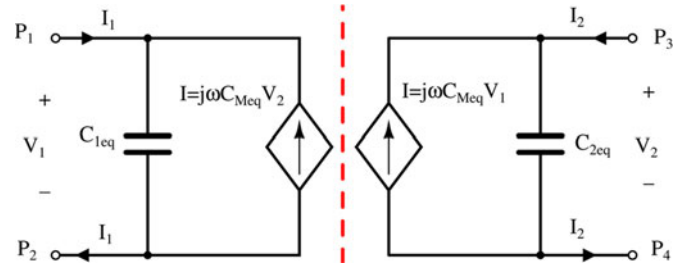


Fig. 6. Two-port equivalent model of six-plate coupler.

The equivalent 2-port parameters are calculated from (1) with  $I_3 = 0$ , which results in

$$\begin{cases} I_1 = j\omega \left( C_1 - \frac{C_{M13}^2}{C_3} \right) \cdot V_1 \\ \quad - j\omega \left( C_{M12} + \frac{C_{M13}C_{M23}}{C_3} \right) \cdot V_2 \\ I_2 = -j\omega \left( C_{M12} + \frac{C_{M13}C_{M23}}{C_3} \right) \cdot V_1 \\ \quad + j\omega \left( C_2 - \frac{C_{M23}^2}{C_3} \right) \cdot V_2 \end{cases} \quad (11)$$

Therefore, the equivalent 2-port parameters are expressed as

$$\begin{cases} C_{1eq} = C_1 - \frac{C_{M13}^2}{C_3} \\ C_{2eq} = C_2 - \frac{C_{M23}^2}{C_3} \\ C_{Meq} = C_{M12} + \frac{C_{M13}C_{M23}}{C_3} \end{cases} \quad (12)$$

### III. EXAMPLE OF LARGE AIR-GAP CPT SYSTEM WITH SIX-PLATE COUPLER

#### A. Coupler Dimension Design

To simplify the design process, the transmitter and receiver plates are symmetric in this case. The primary and secondary plate lengths are therefore  $l_1 = l_2 = 610$  mm, the plate separations are  $l_{s1} = l_{s2} = 100$  mm, and the shielding plate edge lengths are  $l_{e1} = l_{e2} = 50$  mm. The primary-secondary gap is 150 mm, aiming at electric vehicle charging applications. The influence of plate thickness ( $t_p = 2$  mm) on the couplings can be neglected. The primary and secondary plate distances are also the same, which means  $d_1 = d_2$ . Therefore,  $d_1$  is the only parameter that needs to be designed.

ANSYS Maxwell is used to perform FEA of the six-plate coupler. It provides the 15 coupling capacitances between every two plates. Table II is then used to calculate the equivalent capacitances. Due to the symmetry of the coupler,  $C_1 = C_2$ . When the transmitter and receiver are well-aligned and  $d_1$  varies,  $C_1$ ,  $C_3$ , and  $C_{M12}$  are shown in Fig. 7. Since  $C_{M13}$  and  $C_{M23}$  are smaller than 0.1 pF, they are neglected.

The self-capacitances  $C_1$  and  $C_3$  decrease with increasing  $d_1$ , and the mutual capacitance  $C_{M12}$  increases slightly with  $d_1$ . A larger  $C_{M12}$  means higher transfer power; however, a



TABLE II  
EQUIVALENT SELF- AND MUTUAL CAPACITANCES OF SIX-PLATE COUPLER

| $V_2=V_3=0$   | $V_1=V_3=0$  | $V_1=V_2=0$  |
|---|--|--|
|   |  |  |
| $\begin{cases} C_{a1} = C_{13} + C_{14} \\ C_{b1} = C_{23} + C_{24} \\ C_{c1} = C_{15} + C_{16} \\ C_{d1} = C_{25} + C_{26} \\ C_{e1} = C_{35} + C_{36} + C_{45} + C_{46} \end{cases}$  | $\begin{cases} C_{a2} = C_{35} + C_{36} \\ C_{b2} = C_{45} + C_{46} \\ C_{c2} = C_{13} + C_{23} \\ C_{d2} = C_{14} + C_{24} \\ C_{e2} = C_{15} + C_{16} + C_{25} + C_{26} \end{cases}$         | $\begin{cases} C_{a3} = C_{15} + C_{25} \\ C_{b3} = C_{16} + C_{26} \\ C_{c3} = C_{35} + C_{45} \\ C_{d3} = C_{36} + C_{46} \\ C_{e3} = C_{13} + C_{14} + C_{23} + C_{24} \end{cases}$         |
| $C_1 = C_{12} + C_{01}$   | $C_2 = C_{34} + C_{02}$  | $C_3 = C_{56} + C_{03}$  |
| $C_{M12} = \frac{C_{e1}(C_{24}C_{c1} - C_{14}C_{d1})}{C_T} + \frac{(C_{45} + C_{46})(C_{a1}C_{d1} - C_{b1}C_{c1})}{C_T} + \frac{(C_{13}C_{24} - C_{14}C_{23})(C_{c1} + C_{d1} + C_{e1})}{C_T}$  | $C_{M23} = \frac{C_{e2}(C_{46}C_{c2} - C_{36}C_{d2})}{C_T} + \frac{(C_{16} + C_{26})(C_{a2}C_{d2} - C_{b2}C_{c2})}{C_T} + \frac{(C_{35}C_{46} - C_{36}C_{45})(C_{c2} + C_{d2} + C_{e2})}{C_T}$ | $C_{M13} = \frac{C_{e3}(C_{26}C_{c3} - C_{25}C_{d3})}{C_T} + \frac{(C_{24} + C_{23})(C_{a3}C_{d3} - C_{b3}C_{c3})}{C_T} + \frac{(C_{15}C_{26} - C_{16}C_{25})(C_{c3} + C_{d3} + C_{e3})}{C_T}$ |
| $\begin{cases} C_T = C_{ei}(C_{ai} + C_{bi} + C_{ci} + C_{di}) + (C_{ai} + C_{bi}) \cdot (C_{ci} + C_{di}) \\ C_{0i} = \frac{C_{ei}(C_{ai} + C_{ci})(C_{bi} + C_{di}) + C_{ai}C_{bi}(C_{ci} + C_{di}) + C_{ci}C_{di}(C_{ai} + C_{bi})}{C_T}, i=1, 2, 3 \end{cases}$ |  |  |

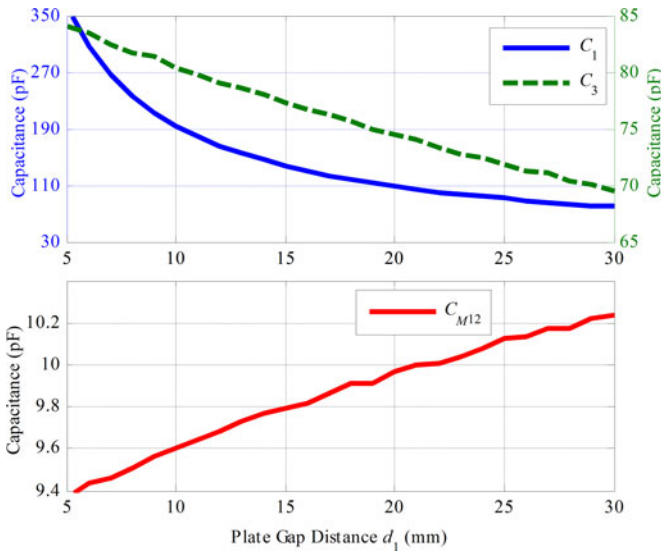


Fig. 7. Maxwell-simulated equivalent capacitances at different  $d_1$ .

low self-capacitance requires a large resonant inductor, which is difficult to realize. Therefore,  $d_1$  is set to be 19 mm in this case, which results in the Maxwell-simulated original and equivalent capacitances as shown in Table III. The differences between  $C_{15}$ ,  $C_{25}$ ,  $C_{36}$ , and  $C_{46}$  are due to the calculation tolerance of the Maxwell solver.

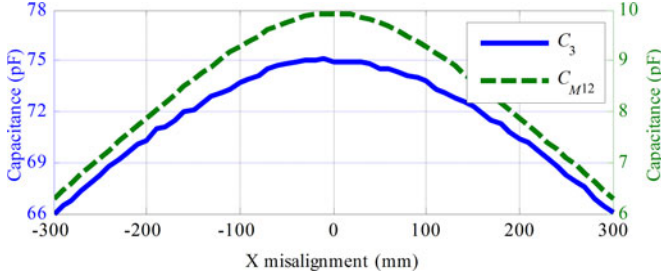
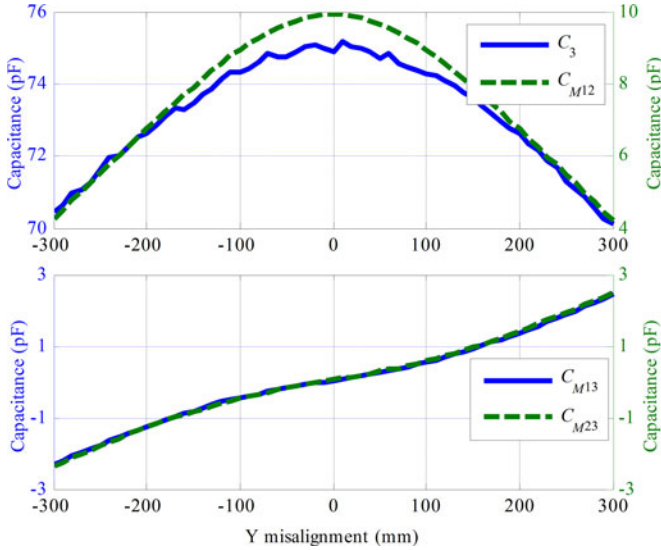
TABLE III  
MAXWELL-SIMULATED AND EQUIVALENT CAPACITANCES WHEN WELL-ALIGNED AND  $d_1 = 19$  MM

|                | P <sub>1</sub>      | P <sub>2</sub> | P <sub>3</sub>      | P <sub>4</sub> | P <sub>5</sub>      | P <sub>6</sub> |
|----------------|---------------------|----------------|---------------------|----------------|---------------------|----------------|
| P <sub>1</sub> |                     | 0.77pF         | 20.38pF             | 0.56pF         | 200.48pF            | 4.42pF         |
| P <sub>2</sub> | 0.77pF              |                | 0.52pF              | 20.35pF        | 197.75pF            | 4.26pF         |
| P <sub>3</sub> | 20.38pF             | 0.52pF         |                     | 0.77pF         | 4.27pF              | 198.35pF       |
| P <sub>4</sub> | 0.56pF              | 20.35pF        | 0.77pF              |                | 4.41pF              | 200.64pF       |
| P <sub>5</sub> | 200.48pF            | 197.75pF       | 4.27pF              | 4.41pF         |                     | 26.11pF        |
| P <sub>6</sub> | 4.42pF              | 4.26pF         | 198.35pF            | 200.64pF       | 26.11pF             |                |
|                | $C_1 = 112.94$ pF   |                | $C_{M12} = 9.91$ pF |                | $C_{M13} = 0.04$ pF |                |
|                | $C_{M21} = 9.91$ pF |                | $C_2 = 112.94$ pF   |                | $C_{M23} = 0.05$ pF |                |
|                | $C_{M31} = 0.04$ pF |                | $C_{M32} = 0.05$ pF |                | $C_3 = 74.90$ pF    |                |

With the designed dimensions, the misalignment ability of the coupler is analyzed in Maxwell, and the simulated capacitances are shown in Figs. 8 and 9. The X and Y directions are defined in Fig. 1.

Fig. 8 shows the equivalent capacitances  $C_3$  and  $C_{M12}$  with X-direction misalignment. Compared to the well-aligned case, the variations of the other capacitances are too small to be neglected. This indicates that  $C_3$  decreases by 12.2% and  $C_{M12}$  decreases by 36.7% when the X misalignment is 300 mm.

Fig. 9 shows the equivalent capacitances  $C_3$ ,  $C_{M12}$ ,  $C_{M13}$ , and  $C_{M23}$  with Y-direction misalignment. The variations of the other capacitances are also neglected. It indicates that  $C_3$  decreases by 6.7% and  $C_{M12}$  decreases by 54.4% when the Y

Fig. 8. Maxwell-simulated capacitances at  $X$  misalignment conditions.Fig. 9. Maxwell-simulated capacitances at  $Y$  misalignment conditions.

misalignment is 300 mm. It also shows that the mutual capacitances  $C_{M13} = C_{M23}$  in the  $Y$  misalignment case, and their absolute value is 2.4 pF at 300 mm  $Y$  misalignment. The negative value of capacitance indicates that the direction of induced current is opposite the predefined positive direction.

### B. LCL Compensation Topology

The six-plate coupler can eliminate an external parallel capacitor in the previous LCLC topology [10], which results in an LCL compensation and reduces system cost. The circuit topology is shown in Fig. 10. A full-bridge inverter is used to inject ac excitation, and a full-bridge rectifier provides dc current to the load. When the coupler is represented by the 2-port model, the equivalent circuit of the CPT system is shown in Fig. 11.

The output power of the CPT system [13] is expressed as

$$P_{\text{out}} = \frac{\omega \cdot C_{M\text{eq}} \cdot C_{f1} C_{f2}}{(1 - k_C^2) \cdot C_{1\text{eq}} C_{2\text{eq}}} \cdot |V_{\text{in}}| \cdot |V_{\text{out}}| \quad (13)$$

where  $C_{f1}$  and  $C_{f2}$  are the compensation capacitors,  $V_{\text{in}}$  and  $V_{\text{out}}$  are rms values of the ac input and output voltages to the resonant tank, and  $k_C$  is the capacitive coupling coefficient,

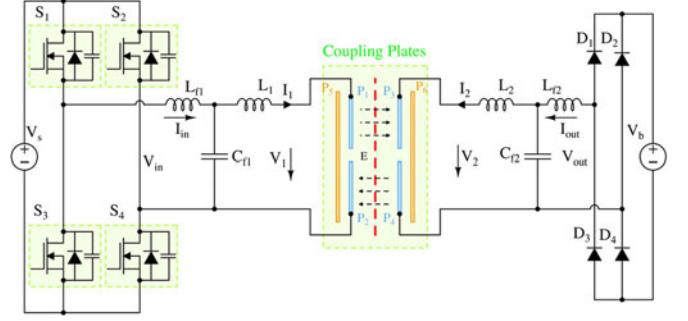


Fig. 10. Circuit topology of an LCL-compensated six-plate CPT system.

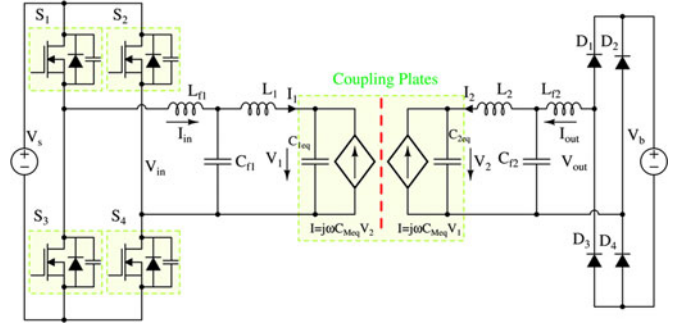


Fig. 11. Equivalent circuit of an LCL compensated six-plate CPT system.

TABLE IV  
SYSTEM SPECIFICATIONS AND CIRCUIT PARAMETERS

| Parameter             | Design Value        | Parameter             | Design Value        |
|-----------------------|---------------------|-----------------------|---------------------|
| $V_s$                 | 270 V               | $V_b$                 | 270 V               |
| $l_1$ ( $l_2$ )       | 610 mm              | $l_{s1}$ ( $l_{s2}$ ) | 50 mm               |
| $l_{e1}$ ( $l_{e2}$ ) | 50 mm               | $d_1$ ( $d_2$ )       | 19 mm               |
| $t_p$                 | 2 mm                | $d$                   | 150 mm              |
| $f_{\text{sw}}$       | 1 MHz               | $C_{M\text{eq}}$      | 9.91 pF             |
| $L_{f1}$              | 9.21 $\mu\text{H}$  | $L_{f2}$              | 9.21 $\mu\text{H}$  |
| $C_{f1}$              | 2.75 nF             | $C_{f2}$              | 2.75 nF             |
| $L_1$                 | 235.3 $\mu\text{H}$ | $L_2$                 | 244.7 $\mu\text{H}$ |
| $C_{1\text{eq}}$      | 112.9 pF            | $C_{2\text{eq}}$      | 112.9 pF            |

which is defined as follows:

$$k_C = \frac{C_{M\text{eq}}}{\sqrt{C_{1\text{eq}} \cdot C_{2\text{eq}}}}. \quad (14)$$

The parameters should satisfy the following resonant relationships:

$$\begin{aligned} \omega &= 2\pi f_{\text{sw}} = 1/\sqrt{L_{f1} C_{f1}} = 1/\sqrt{L_{f2} C_{f2}}, \\ L_1 &= 1/(\omega^2 C_{f1}) + 1/(\omega^2 C_{1\text{eq}}), L_2 \\ &= 1/(\omega^2 C_{f2}) + 1/(\omega^2 C_{2\text{eq}}). \end{aligned} \quad (15)$$

### C. 2.0 kW CPT System Parameter Design

According to (13)–(15), a 2.0 kW CPT system is designed with the six-plate coupler. The system specifications and circuit parameters are shown in Table IV.

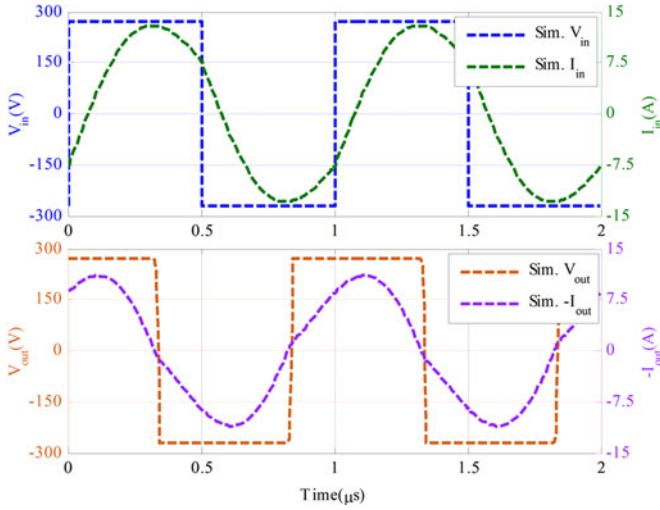


Fig. 12. LTspice-simulated input and output waveforms of the designed system.

The input and output dc voltages are both set at 270 V to achieve a 2.0 kW output. The switching frequency is 1 MHz. Most of the parameters are symmetric from the primary to secondary side, except that  $L_2$  is slightly larger than  $L_1$  to provide a soft-switching condition to the MOSFETs of the input inverter.

The circuit performance is simulated in LTspice, and the waveforms are shown in Fig. 12. It is seen that the input voltage and current are almost in phase, which limits the reactive power circulating in the circuit and therefore increases the system efficiency. The output voltage and current are also in phase on the rectifier side.

#### IV. ELECTRIC FIELD SHIELDING OF SIX-PLATE COUPLER

##### A. Voltage Between Plates

The voltages between the plates determine the electric field emissions to the surrounding environment. The voltages  $V_1$  and  $V_2$  are the external inputs to the six-plate coupler, and are also the voltage between plates  $P_1$  and  $P_2$ , and plates  $P_3$  and  $P_4$  [13]. In Fig. 11, the voltages can be calculated as

$$\begin{aligned} V_1 &= \frac{C_{f1} \cdot V_{in}}{(1 - k_C^2) \cdot C_{1eq}} + \frac{C_{Meq} C_{f2} \cdot V_{out}}{(1 - k_C^2) \cdot C_{1eq} C_{2eq}} \\ V_2 &= \frac{C_{Meq} C_{f1} \cdot V_{in}}{(1 - k_C^2) \cdot C_{1eq} C_{2eq}} + \frac{C_{f2} \cdot V_{out}}{(1 - k_C^2) \cdot C_{2eq}}. \end{aligned} \quad (16)$$

According to (1) and  $I_3 = 0$ , the voltage stress between  $P_5$  and  $P_6$  is expressed as

$$V_3 = \frac{C_{M13}}{C_3} V_1 + \frac{C_{M23}}{C_3} V_2. \quad (17)$$

The coupler dimension design in Section III-A shows that  $C_{M13}$  and  $C_{M23}$  are zero in the well-aligned case, which means the voltage between  $P_5$  and  $P_6$  is zero. When there is 300 mm X or Y misalignment, there exist  $C_{M13} \ll C_3$  and  $C_{M23} \ll C_3$ . Therefore,  $V_3$  is limited, and the electric field emissions are reduced.

TABLE V  
RMS VALUE OF THE VOLTAGE STRESSES BETWEEN PLATES

| Parameters    | Well-aligned | 300 mm X misalignment | 300 mm Y misalignment |
|---------------|--------------|-----------------------|-----------------------|
| $ V_{P1-P2} $ | 6.51 kV      | 6.47 kV               | 6.44 kV               |
| $ V_{P1-P3} $ | 4.18 kV      | 4.32 kV               | 4.40 kV               |
| $ V_{P1-P5} $ | 3.25 kV      | 3.26 kV               | 3.28 kV               |
| $ V_{P5-P6} $ | 0            | 0                     | 0.34 kV               |

The voltage between plates on the same side should be limited to avoid potential arcing problems. Using (5) and similar analysis process in Section II-C, the voltage between plates  $P_1$  and  $P_5$  is calculated as

$$\begin{aligned} V_{P1-P5} &= \frac{C_{e1}(C_{b1} + C_{d1}) + C_{d1}(C_{a1} + C_{b1})}{C_T} \cdot V_1 \\ &+ \frac{C_{a2}C_{d2} - C_{b2}C_{c2}}{C_T} \cdot V_2 \\ &- \frac{C_{e3}(C_{b3} + C_{d3}) + C_{b3}(C_{c3} + C_{d3})}{C_T} \cdot V_3. \end{aligned} \quad (18)$$

Similarly, the voltage between the other plates, such as  $V_{P2-P5}$ ,  $V_{P3-P6}$ ,  $V_{P4-P6}$ ,  $V_{P1-P3}$ , etc., can also be calculated [13]. Due to the symmetry of the coupler and circuit parameters,  $|V_{P1-P2}| = |V_{P3-P4}|$ ,  $|V_{P1-P3}| = |V_{P2-P4}|$ , and  $|V_{P1-P5}| = |V_{P2-P5}| = |V_{P3-P6}| = |V_{P4-P6}|$ . By substituting the values in Table IV, the voltages between plates are shown in Table V.

This shows that the voltage between plates  $P_5$  and  $P_6$  is limited to 0.34 kV in the misalignment case. Therefore, the electric field emissions are reduced. The voltage between  $P_1$  and  $P_5$  is 3.25 kV, and the distance between them is 19 mm. Since the breakdown voltage of dry air is about 3 kV/mm, there is no significant concern about arcing between plates.

##### B. Electric Field Shielding

The electric field emissions to the surrounding environment relate to the safety of the CPT technology in practical applications. In this design, a 2.0 kW six-plate CPT system has a power density of 1.95 kW/m<sup>2</sup>. The electric field should be smaller than 614 V/mm at 1 MHz [21]. Maxwell is used to simulate the shielding effect of the six-plate coupler, as shown in Fig. 13.

In Fig. 13, there are charge excitations on  $P_1$ ,  $P_2$ ,  $P_3$ , and  $P_4$ . The two shielding plates  $P_5$  and  $P_6$  are floating, and there is no charge excitation on them. The primary shielding plate  $P_5$  is set as the voltage reference, and the voltages of the other plates achieve the values listed in Table V. The region that has an electric field strength higher than 614 V/m is illustrated in red. The maximum field strength between the transmitter and receiver plates is 27 kV/m, and the maximum field strength between the same side power and shielding plates can reach 170 kV/m. Due to the shielding effect of  $P_5$  and  $P_6$ , the electric field is dramatically reduced above and below the coupler. There is only a small field from the air-gap leaking out to the surroundings, and it decreases quickly with distance. The safety range is about 0.1 m away from this coupler.



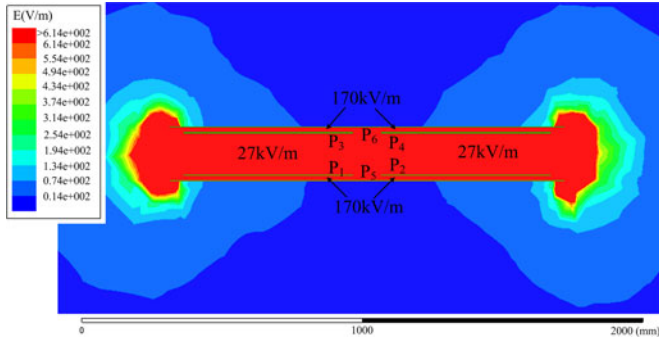


Fig. 13. Maxwell-simulated shielding effect of a six-plate coupler under well-aligned condition.

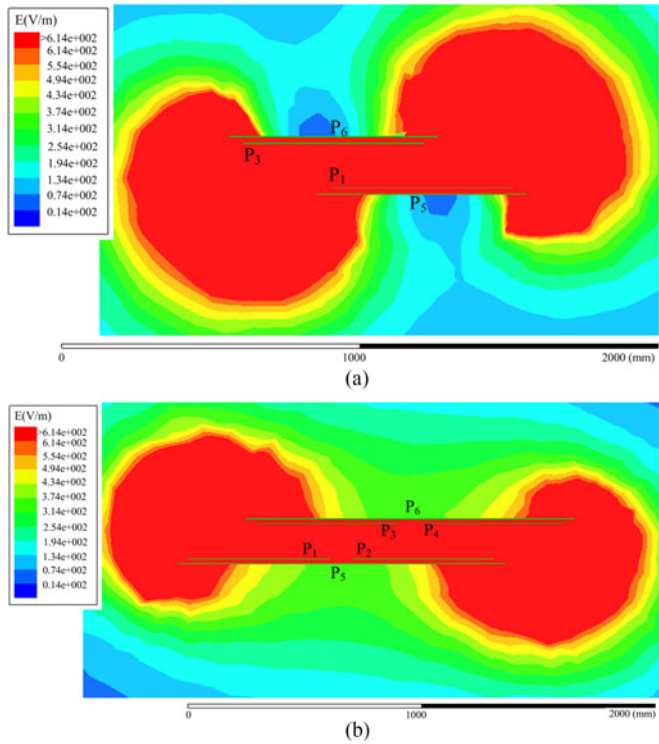


Fig. 14. Maxwell-simulated electric field emission of six-plate coupler at 300 mm misalignment condition (a) X misalignment and (b) Y misalignment.

Fig. 14 shows the electric field emission when there is 300 mm X- and Y-direction misalignment. Since the plates  $P_5$  and  $P_6$  cannot provide as good of a shielding effect with misalignment, the leakage field is increased. The safety range is 0.4 m from the coupler when there is misalignment.

### C. Comparison With Four-Plate Coupler

According to [10] and [13], four plates are sufficient to form a capacitive coupler, and can be horizontally or vertically arranged. The four-plate horizontal coupler is very basic. It can resonate with an LCLC compensation circuit. In a 2.4 kW CPT system with a power density of  $2.29 \text{ kW/m}^2$ , the safety range is about 0.6 m away from the right and left of the coupler, and 0.9 m away from the top and bottom of the coupler [10].

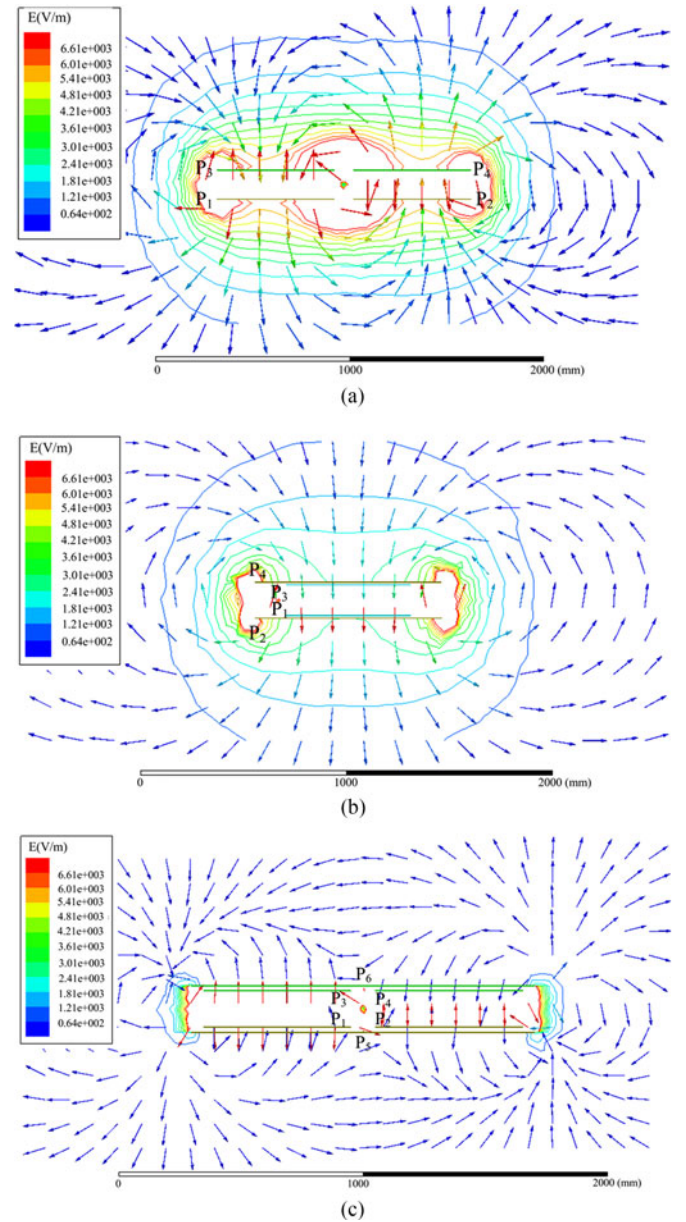


Fig. 15. Maxwell-simulated electric vector distribution of different couplers. (a) Four-plate horizontal coupler, (b) four-plate vertical coupler, and (c) six-plate coupler.

The four-plate vertical structure is more compact, where two of the plates are smaller and vertically arranged with the other two plates. It resonates with an LCL compensation circuit. In a 1.9 kW CPT system with a power density of  $2.25 \text{ kW/m}^2$ , the safety range is about 1.0 m away from the coupler [13].

Compared to the four-plate structure, the six-plate coupler can significantly reduce the electric field emissions to the surroundings. At similar power levels, the safety range of the six-plate coupler is increased. This phenomenon can be explained by the electric field vector ( $E$  vector) distribution. The vector direction is determined by the voltage difference between plates. The  $E$  vectors of the four-plate horizontal, four-plate vertical, and six-plate systems are shown in Fig. 15(a), (b), and (c), respectively.



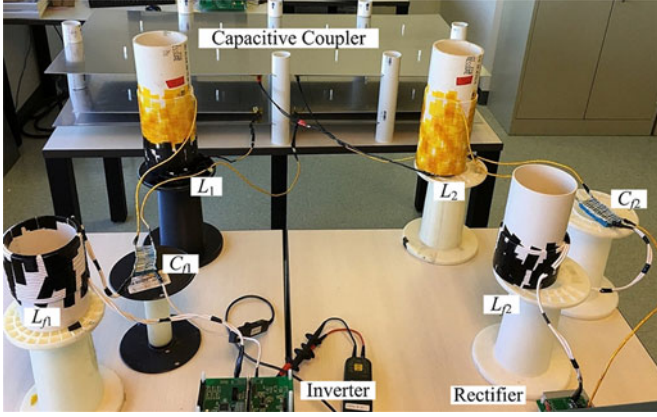


Fig. 16. Experiment prototype of a 2.0 kW CPT system with a six-plate coupler.

In Fig. 15(a), there is a large voltage difference between every pair of plates [10]. Therefore, the E vector indicates that the electric flux goes from one plate to the other. Since the air-gap between the plates is large, the leakage flux causes significant electric field emissions. In Fig. 15(b), there is a voltage difference between  $P_2$  and  $P_4$  [13], so the electric flux goes from  $P_2$  to  $P_4$ , which generates electric field emissions. In Fig. 15(c), there is no voltage difference between  $P_5$  and  $P_6$ , so there is no electric flux going directly between them. Because  $P_6$  is floating and covers  $P_3$  and  $P_4$ , it limits the electric flux between  $P_3$  and  $P_4$  to below  $P_6$ . Symmetrically, the leakage flux to the bottom of  $P_5$  is also limited. Therefore, the plates  $P_5$  and  $P_6$  can act as electric field shielding.

## V. EXPERIMENTAL RESULTS

### A. Experimental Setup

Using the designed six-plate coupler and compensation parameters in Table IV, a 2.0 kW CPT system is implemented as shown in Fig. 16. The coupler is made with 2 mm thickness aluminum plates, and PVC tubes are used to hold the coupler plates in place. Ceramic spacers are used between the same side plates to provide insulation. The distance between the transmitter and receiver is 150 mm.

Since the switching frequency is 1 MHz, silicon carbide (SiC) MOSFETs (C2M0080120D) are used in the inverter, and SiC diodes (IDW30G65C) are used in the rectifier. To reduce the power losses induced by the skin effect, 3000-strands AWG 46 Litz-wire is used in the windings of the compensation inductors. The inductors have air cores to further eliminate magnetic losses. Furthermore, high-frequency and low-loss thin-film capacitors are used for the compensation capacitors.

### B. Well-Aligned Experiment

When the transmitter and receiver are well-aligned, the experimental results of six-plate CPT system are shown in Fig. 17. In Fig. 17(a), when the input and output dc voltages are both 270 V, the system output power is 1.97 kW, and the dc-dc efficiency from the dc source to electronic dc load is 91.6%. In Fig. 17(b), the input voltage and current are almost in phase

|             |              |           |              |
|-------------|--------------|-----------|--------------|
| Udc2        | 270.26 V     | Udc3      | 270.24 V     |
| Idc2        | 7.961 A      | Idc3      | 7.294 A      |
| $P_{in}$    | 2.1513 kW    | $P_{out}$ | 1.9717 kW    |
| S2          | 2.6543 kVA   | S3        | 2.4318 kVA   |
| Q2          | -1.5547 kvar | Q3        | -1.4234 kvar |
| $\eta$      | 91.650 %     | Ploss     | 179.63 W     |
| $\lambda_2$ | 0.8105       | Utpk2     | 275.51 V     |
| Req2        | 33.899 ohm   | Req3      | 37.000 ohm   |

(a)

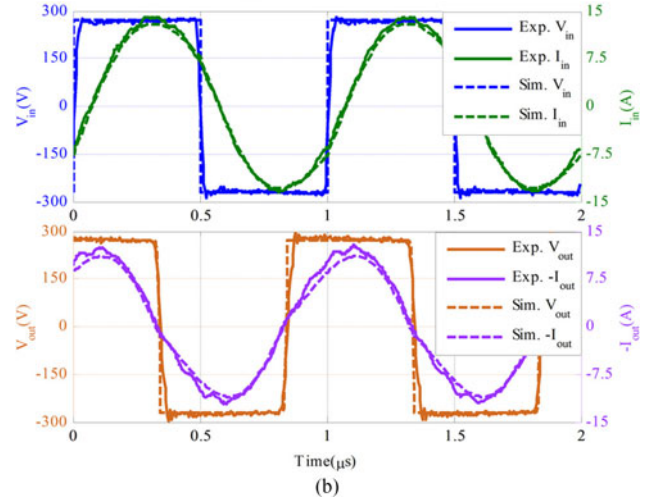


Fig. 17. Experimental results of six-plate CPT system at well-aligned case. (a) System power and (b) input and output waveforms.

with each other, which limits the reactive power circulating in the resonant circuit. The cut-off current at the switching transient is about 6 A, which helps the soft-switching of MOSFETs in the inverter. The experimental waveforms are extracted from the oscilloscope, which agree well with the LTspice simulation in Fig. 12, which validate the proposed CPT system.

In full-power condition, Fig. 17(a) shows that the total power loss is 179.6 W. Using a power loss model for each component [25], the power losses can be estimated in inductors, capacitors, MOSFETs, and diodes. This suggests that the remaining losses are in the metal plates. Therefore, the loss distribution among the circuit components is estimated as shown in Fig. 18. It indicates that the six-plate coupler dissipates 34% of the total loss. Since the plate area is large, there is not any significant temperature rise on the plates.

The relationship between output power and dc-dc efficiency is shown in Fig. 19. The system dc-dc efficiency increases with the output power. After the output power reaches 400 W, the dc-dc efficiency is maintained higher than 91%.

### C. Misalignment Experiment

The misalignment experiment is performed in the X and Y directions, and the results are shown in Fig. 20. When the X misalignment is 300 mm, the output power decreases to 65% of the well-aligned value, and the dc-dc efficiency drops from

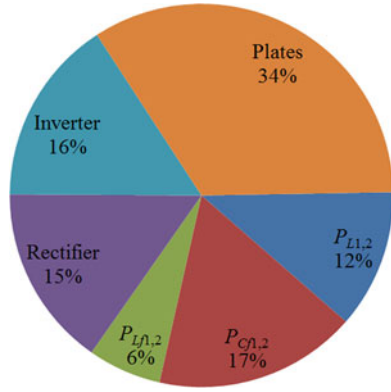


Fig. 18. Estimated power loss distribution in a six-plate CPT system.

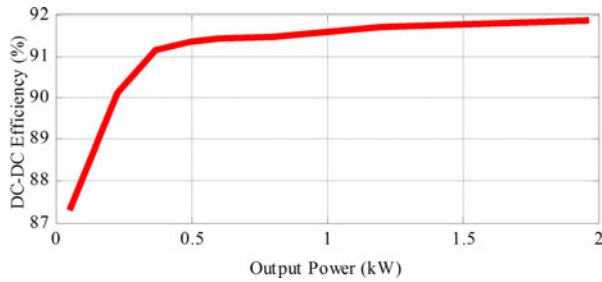


Fig. 19. Experimental output power and dc-dc efficiency in well-aligned case.

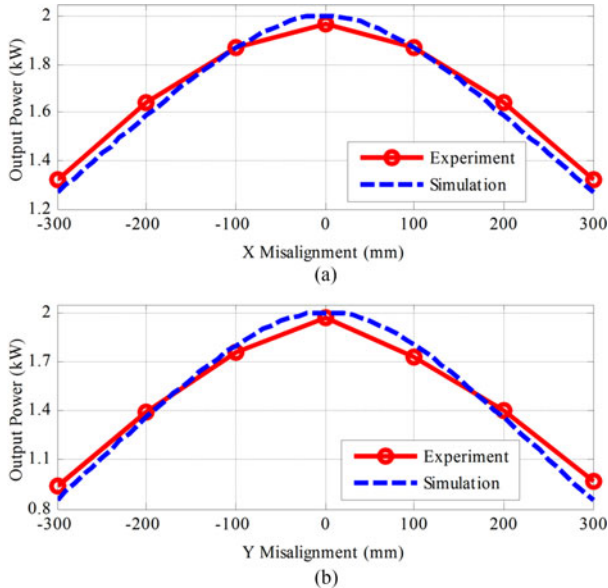


Fig. 20. Experimental and simulated misalignments of six-plate CPT system. (a) X misalignment and (b) Y misalignment.

91.6% to 91.0%. When the  $Y$  misalignment is 300 mm, the output power decreases to 49% of the well-aligned value and the dc-dc efficiency drops to 89.2%. Therefore, the six-plate coupler has better misalignment ability in the  $X$  direction than the  $Y$  direction.

The misalignment ability is also simulated in LTspice, using the parameters in Figs. 8 and 9. The experiment results agree well with the simulations, which also proves the effectiveness of the six-plate coupler and validates the proposed circuit model

of the previous analysis. In future research, the misalignment performance will be improved by the coupler structure design.

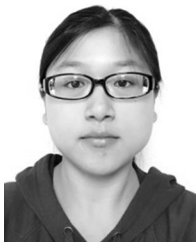
## VI. CONCLUSION

This paper proposes a six-plate coupler structure for a large-air-gap CPT system to reduce electric field emissions to the surroundings. Two large metal plates cover a four-plate horizontal coupler on top and bottom to provide shielding. Equivalent three-port and two-port behavior source models of the coupler are derived. The six-plate coupler can eliminate the external parallel capacitor in the previous LCLC topology, which results in the LCLC compensation and reduces the system cost. A 2.0 kW CPT system is design and implemented with the six-plate coupler. It shows that the voltage between the shielding plates is limited, which contributes to the reduction of electric field emissions. FEA analysis by Maxwell shows that the safety range of the six-plate coupler is 0.1 m in the well-aligned case, and 0.4 m in the 300 mm  $X$  or  $Y$  misalignment case. Compared to the four-plate horizontal and vertical coupler, the safety area is significantly increased. A 2.0 kW CPT prototype with six-plate coupler is implemented, and experiment results show that the six-plate coupler achieves 1.97 kW power transfer with a dc-dc efficiency of 91.6% across an air-gap of 150 mm. In future research, the six-plate coupler structure will be studied in dynamic charging applications.

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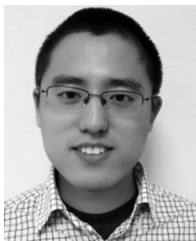
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**Hua Zhang** (S'14) received the B.S. and M.S. degrees in electrical engineering, in 2011 and 2014, respectively, from the Northwestern Polytechnical University, Xi'an, China, where she is currently working toward the Ph.D. degree in electrical engineering.

From September 2014 to August 2015, she was a joint Ph.D. student founded by the China Scholarship Council with the University of Michigan, Dearborn. From September 2015, she started to work in San Diego State University, San Diego, CA, USA. Her research interest focuses on the coupler design of high power IPT and CPT system.



**Fei Lu** (S'12) received the B.S. and M.S. degrees in electrical engineering from the Harbin Institute of Technology, Harbin, China, in 2010 and 2012, respectively. He is currently working toward the Ph.D. degree in electrical engineering from the University of Michigan, Ann Arbor, MI, USA.

He is working on the high power and high efficiency capacitive power transfer through an air-gap distance up to 100s of millimeters. He is also working on the application of wide band-gap devices on wireless power transfer (WPT) system to increase the

system frequency. His research interest focuses on WPT for the application of electric vehicle charging.



**Heath Hofmann** (M'98–SM'15) received the B.S. degree in electrical engineering from the University of Texas at Austin, Austin, TX, USA, in 1992, and the M.S. and Ph.D. degrees in electrical engineering and computer science from the University of California, Berkeley, CA, USA, in 1997 and 1998, respectively.

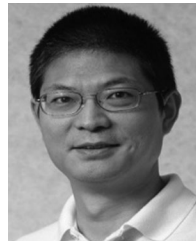
He is currently an Associate Professor with the University of Michigan, Ann Arbor, MI, USA. His research interests include the design, analysis, and control of electromechanical systems, and power electronics.



**Weiguang Liu** (SM'07) received the B.S. degree in electrical machines engineering from the Huazhong University of Science and Technology, Wuhan, China, and the M.S. degree in electrical engineering and the Ph.D. degree in control theory and control engineering from the Northwestern Polytechnical University, Xi'an, China, in 1982, 1988, and 1999, respectively.

He is a Professor in the Department of Electrical Engineering, Northwestern Polytechnical University, and a Guest Professor with the University of Federal Defense, Munich, Germany. He is the Director of the Institute of Rare Earth Permanent Magnet Electrical Machines & Control Technology, Northwestern Polytechnical University. His research interests include brushless dc machines, PM synchronous machines, dc machines, and induction machines.

Dr. Liu was the Chairman of Organizing Committee of the 32nd Chinese Control Conference, July 2013, Xi'an, China.



**Chunting Chris Mi** (S'00–A'01–M'01–SM'03–F'12) received the B.S.E.E. and M.S.E.E. degrees in electrical engineering from the Northwestern Polytechnical University, Xi'an, China, and the Ph.D. degree in electrical engineering from the University of Toronto, Toronto, ON, Canada, in 1985, 1988, and 2001, respectively.

He is a Professor and the Chair of electrical and computer engineering and the Director of the Department of Energy-funded Graduate Automotive Technology Education Center for Electric Drive Transportation, San Diego State University (SDSU), San Diego, CA, USA. Prior to joining SDSU, he was with the University of Michigan, Dearborn, MI, USA, from 2001 to 2015. He was the President and the Chief Technical Officer of IPower Solutions, Inc., from 2008 to 2011. He is the Co-Founder of Gannon Motors and Controls LLC and Mia Motors, Inc. He has conducted extensive research and has published more than 100 journal papers. He has taught tutorials and seminars on the subject of HEVs/PHEVs for the Society of Automotive Engineers (SAE), the IEEE, workshops sponsored by the National Science Foundation, and the National Society of Professional Engineers. He has delivered courses to major automotive OEMs and suppliers, including GM, Ford, Chrysler, Honda, Hyundai, Tyco Electronics, A&D Technology, Johnson Controls, Quantum Technology, Delphi, and the European Ph.D. School. He has offered tutorials in many countries, including USA, China, Korea, Singapore, Italy, France, and Mexico. He has published more than 100 articles and delivered 30 invited talks and keynote speeches. His research interests include electric drives, power electronics, electric machines, renewable-energy systems, and electrical and hybrid vehicles.

Dr. Mi received the "Distinguished Teaching Award," the "Distinguished Research Award" of University of Michigan, Dearborn, the 2007 IEEE Region 4 "Outstanding Engineer Award," the "IEEE Southeastern Michigan Section Outstanding Professional Award," and the "SAE Environmental Excellence in Transportation (E2T)." He has also served as a Panelist in major IEEE and SAE conferences.