A 2m Quasi-Wireless Capacitive Power Transfer System Using Earth Ground as the Current-Returning Path

ABSTRACT

This digest proposes a quasi-wireless capacitive power transfer system to achieve long-distance power transfer. Compared to the conventional four-plate CPT system, the proposed quasi-wireless system only requires two metal plates, and the other two plates are replaced by the earth ground, which provides a current-returning path. In long-distance power transfer applications, the coupling capacitances between plates are affected by the appearance of the earth ground, which are analyzed by the method of mirror images. Based on the circuit model of the coupler, a double-sided LC compensation circuit is used to realize a long-distance and loosely-coupled CPT system. Its output properties, including output power and efficiency, are presented in detail. Two 0.91m×0.91m aluminum plates are used to implement the proposed two-plate system. Experimental results show that the prototype can realize 216.5W power transfer with 52.2% dc-dc efficiency at an air-gap distance of 2.0m. When the distance is 1.5m, the efficiency can reach 67%, and when the distance increases to 2.5m, the system can still maintain an efficiency of 20%.

I. INTRODUCTION

Capacitive power transfer (CPT) technology [1, 2] is an important alternative to the traditional inductive power transfer (IPT) system. High-frequency electric field is used to transfer power, which does not generate extra heat in the nearby metals [3, 4]. However, a CPT system usually requires four metal plates [5, 6] in a capacitive coupler, forming two coupling capacitances for the current to flow back and forth. Compared to an IPT system, this coupler structure needs more space and reduces the system power density.

This digest proposes to use two metal plates to transfer power, which can help to simplify the structure of a CPT system. Two metal plates are adopted to generate electric fields and transfer power from the primary side to the secondary side. The transmitter and receiver share the same earth ground, which acts as the current-returning path, resulting in a quasi-wireless CPT system. Since the earth ground contributes to transfer power, it is similar to the Single Wire Earth Retuning (SWER) system in high-power electricity transmission application [7], the electric fence protection system [8], or the single-contact power transmission system [9]. In this digest, using the proposed two-plate coupler structure, a CPT system can transfer hundreds Watts of power through a distance of 2.0m with an efficiency of 52.2%, which validates that the CPT technology is also suitable to achieve long-distance power transfer with a considerable efficiency.

II. System Structure

The structure of a two-plate long-distance quasi-wireless CPT system is shown in Fig. 1. At the primary side, an inverter is used to provide an ac excitation voltage to the system, followed by a compensation circuit to form a resonance with the capacitive coupler. The resonance can generate high voltages in the circuit for high power transfer. The capacitive coupler contains two metal plates, with P_1 at the primary side as a transmitter and P_2 at the secondary side as a receiver. The capacitance between P_1 and P_2 allows the current flowing forward to the receiver, and the earth ground provides the current-returning path back to the transmitter. At the secondary side, a compensation circuit is also used to build up a resonance to serve power to the load. The advantage of this structure is that the ground helps to carry current and eliminates two plates in the conventional four-plate system. However, it needs to be pointed out the ground-side resistance and power loss is an important concern. In a practical application, the conductivity of earth ground and the connection from the circuit to the ground should be paid attention. For example, in the indoor environment, the protection earth ground on the wall can be used as the returning path to reduce loss.

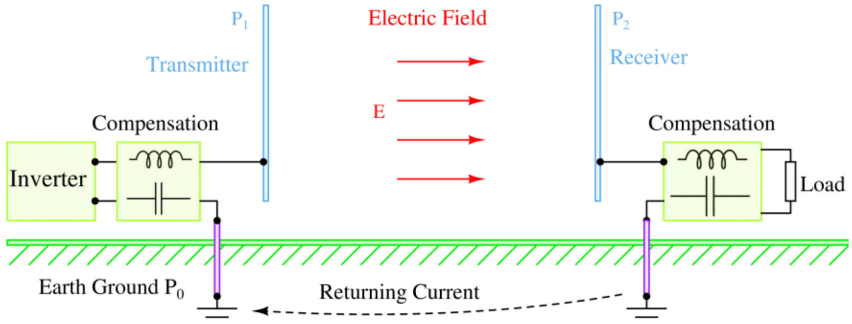

Fig. 1. Structure of a two-plate long-distance quasi-wireless CPT system

III. Compensation Circuit Design

The double-sided LC compensation [10] circuit is used to realize a two-plate quasi-wireless CPT system, which is shown in Fig. 2. In the capacitive coupler, the capacitance between P_1 and P_2 is defined as C_M. There are also capacitances between the plates P_1 and P_2 to the earth ground, which are defined as C_{in1} and C_{in2}, respectively. In a long-distance application, since the coupling capacitances are usually small, external capacitances C_{ex1} and C_{ex2} are required to increase the equivalent capacitances. To resonate with the capacitances, inductors L_1 and L_2 are used at the primary and secondary side. The equivalent load resistance is defined as R_L. Using the behavior-source model of the coupler, the equivalent circuit topology is shown in Fig. 3.

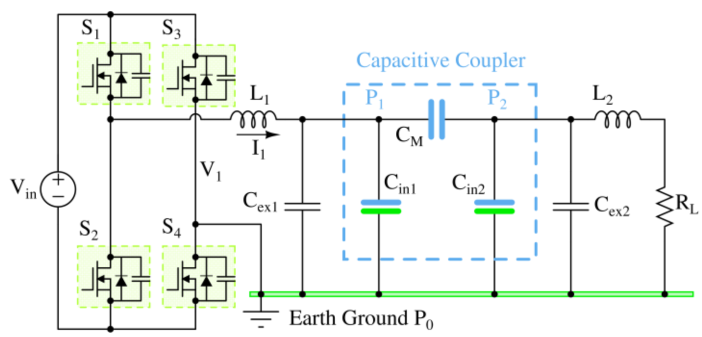

Fig. 2. Double-sided LC-compensated two-plate quasi-wireless CPT system

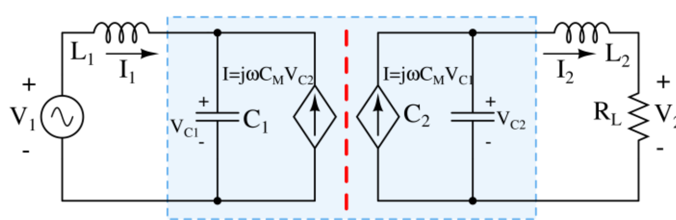

Fig. 3. Equivalent circuit topology of a two-plate quasi-wireless CPT system

Considering the circuit working principle in [10], the parameters can be designed to achieve a constant current working mode, which is expressed in (1). The capacitive coupling coefficient is defined as k_C. The parasitic resistances of the circuit components are defined as R_{L1}, R_{C1}, R_{L2}, and R_{C2}, which are used to calculate the system output power and efficiency as shown in (2). The quality factor Q_1, Q_2 and the resistance ratio α are defined in (3). According to (2), several interesting conclusions can be drawn.

$$\begin{cases} k_C = C_M / \sqrt{C_1 C_2} \\ \omega = 2\pi f_{sw} = \dfrac{1}{\sqrt{\left(1-k_C^2\right) L_1 C_1}} = \dfrac{1}{\sqrt{\left(1-k_C^2\right) L_2 C_2}} \end{cases} \quad (1)$$

$$\begin{cases} P_{out} = \dfrac{V_1^2}{R_1} \cdot \dfrac{k_C^2 Q_1 Q_2}{\left(1 + k_C^2 Q_1 Q_2 \dfrac{\alpha}{1+\alpha}\right)^2} \cdot \dfrac{1}{\alpha + \dfrac{1}{\alpha} + 2} \\ \eta = \dfrac{1}{1 + \alpha + \dfrac{1}{k_C^2 Q_1 Q_2} \cdot \left(\alpha + \dfrac{1}{\alpha} + 2\right)} \end{cases} \quad (2)$$

$$\begin{cases} R_1 = R_{L1} + R_{C1}, R_2 = R_{L2} + R_{C2} \\ Q_1 = 1/(\omega C_1 R_1), Q_2 = 1/(\omega C_2 R_2) \\ \alpha = R_2 / R_L \end{cases} \quad (3)$$

$$\eta_{\max} = \frac{k_C^2 Q_1 Q_2}{\left(1 + \sqrt{1 + k_C^2 Q_1 Q_2}\right)^2} \quad (4)$$

First, if the parasitic and load resistances are pre-determined, there exists an optimal k_C that can maximize the system output power. In this case, the system efficiency is calculated as η_1=0.5/(1+α). Since α is usually much smaller than 1, η_1 is therefore close to 50%. In a real application, the variation of k_C can be achieved by changing the distance, which means there is an optimal distance that can maximize the system power. According to (2), the maximum output power is $P_{out}=0.25V_1^2/R_1$. Then, The relationship between the normalized output power with k_C, Q, and α is shown in Fig. 4. It indicates that, for a given α, there exist an optimal product k_CQ that can achieve maximum power.

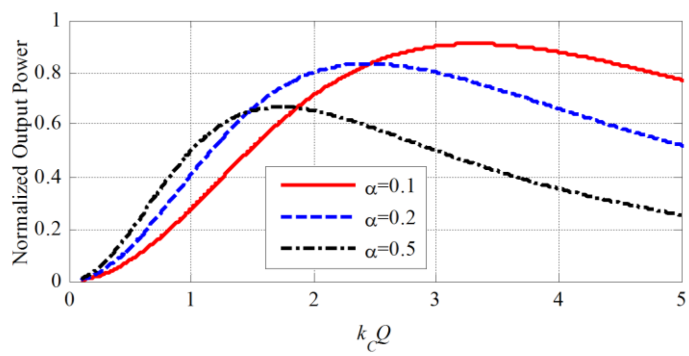

Fig. 4. Normalized output power at different α and k_CQ

Second, if the parasitic resistances and coupling coefficient k_C are pre-determined, there exist an optimal load resistance R_L that can maximize the system efficiency, which is expressed as in (4). Then, if Q_1 and Q_2 are equal (Q=Q_1=Q_2), the relationship between the maximum efficiency $\eta_{\max}$, the system quality factor Q, and the coupling coefficient k_C is shown in Fig. 5. It indicates that increasing k_C and Q can both improve the system efficiency.

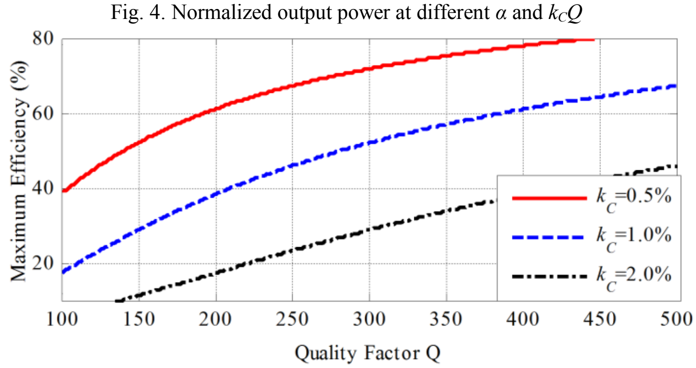

Fig. 5. Maximum achievable efficiency at different k_C and Q

IV. Capacitive Coupler Design

The method of mirror image is used to analyze the coupling capacitance between plates in a grounded system [11]. Since the earth ground can be treated as an infinite conducting plane, the electric field decrease to zero in the ground plane. Using this boundary condition, the electric field in this two-plate CPT system is equivalent to that in a four-plate CPT system with opposite charges at symmetric positions with respect the ground plane, as shown in Fig. 6. At an arbitrary position P, the electric field is the add-on of the field generated by the four plates P_1, P_2, P_3 and P_4. Considering the capacitance model in [10], the equivalent mutual capacitance C_M between P_1 and P_2 is therefore calculated as shown in (5), where C_{12}, C_{34}, C_{14} and C_{23} are the capacitances between each two plates. In long-distance applications, the cross-coupling capacitance C_{14} and C_{23} are usually comparable to the main-coupling capacitances C_{12} and C_{34}. Therefore, the mutual capacitance C_M in a grounded system is usually very small.

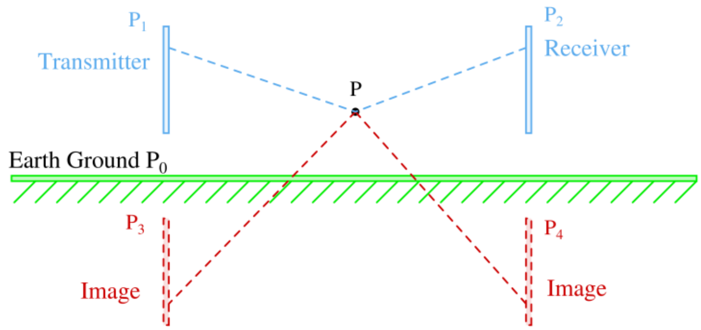

Fig. 6. Equivalent coupling plates with mirror images

$$C_M = \frac{2\cdot\left(C_{12}C_{34} - C_{14}C_{23}\right)}{C_{12} + C_{34} + C_{14} + C_{23}} \qquad (5)$$

Two 0.91m×0.91m metal plates are used to design a capacitive coupler. The distance from the plates to ground is 1m. The plate distance is defined as d. Maxwell is used to simulate the coupling capacitances in Fig. 2, which shows $C_{in1}=C_{in2}=50$pF. In a long-distance application, when d varies from 1.5m to 2.0m, the Maxwell-simulated C_M is shown in Fig. 7. It indicates that C_M decreases with increasing distance d. When d is 2.0m, C_M is about 2.0pF.

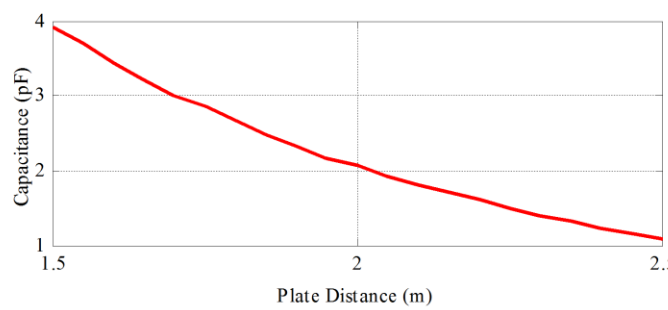

Fig. 7. Maxwell-simulated mutual capacitance C_M between two metal plates

V. Prototype Design and Experiments

A prototype of two-plate long-distance CPT system is implemented as shown in Fig. 8. Two aluminum plates are used as the capacitive coupler. Since the conductivity of the floor is not good enough, the earth ground on the wall can help to reduce conductive loss in the indoor environment.

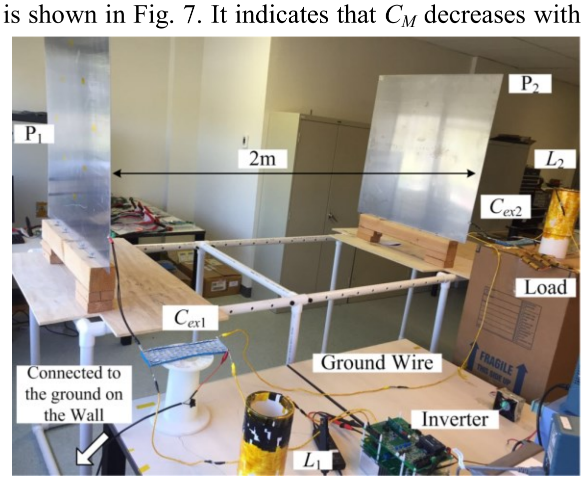

Fig. 8. Prototype of a long-distance two-plate CPT system

Therefore, a wire is used to connect one terminal of C_{ex1} and C_{ex2} to the earth ground on the wall as the ground wire shown in Fig. 8, which is also consistent with the circuit topology in Fig. 2. Because of this connection wire to the ground, this system is a quasi-wireless CPT system. The circuit parameters and system specifications are shown in Table I.

Table I. System specifications and circuit parameter values

Parameter	Design Value	Parameter	Design Value
V_{in}	100 V	R_L	5-50 Ω
f_{sw}	1 MHz	C_M	1.0-4.0 pF
C_{in1} (C_{in2})	50 pF	k_C	0.76%-2.98%
C_{ex1} (C_{ex2})	80 pF	L_1 (L_2)	195 μH

When the input voltage increases to 100V and the load resistance is 20Ω, the experimental waveforms are shown in Fig. 9. It shows that soft-switching is achieved for the MOSFETs.

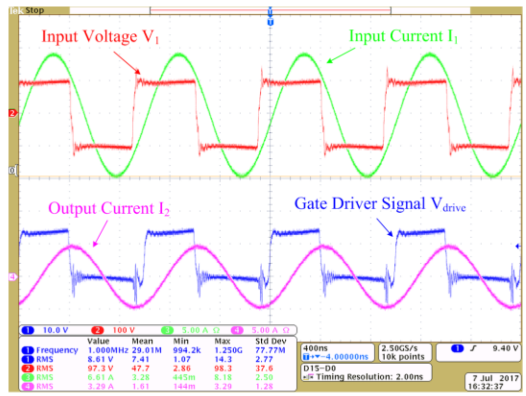

Fig. 9. Experimental waveforms at 2.0m distance

In Fig. 10, when the plate distance *d* is 2.0m, the system can achieve maximum output power (216.5W) with an efficiency of 52.2%, which is consistent with the first conclusion in Section III. When *d* is 1.5m, the efficiency increases to 67%, and when *d* is 2.5m, it can still maintain an efficiency of 20%.

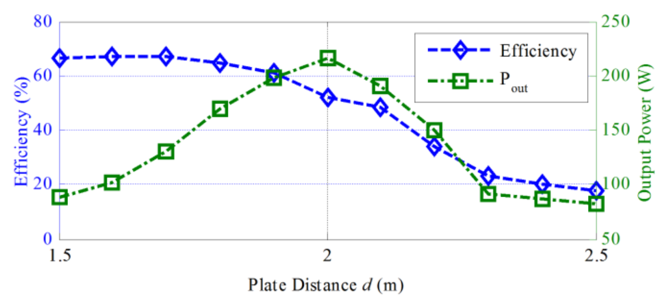

Fig. 10. Output power and efficiency at different *d* when R_L=20Ω

In Fig. 11, when the load resistance R_L is 15Ω, the system can achieve maximum efficiency, which is consistent with the second conclusion in Section III. In Fig. 12, it shows that the system can maintain 110W output power with 27% efficiency at 1m misalignment case.

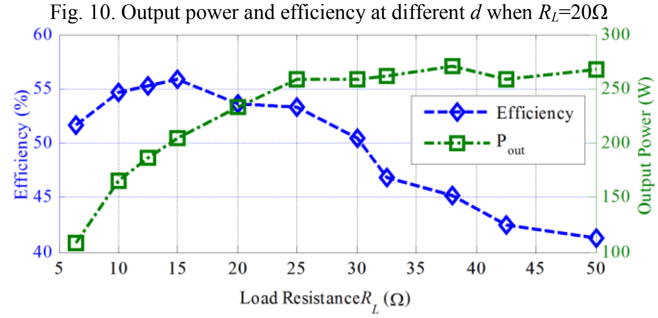

Fig. 11. Output power and efficiency at different R_L when *d*=2m

VI. Conclusion and Future Work

A two-plate quasi-wireless capacitive power transfer system is proposed and implemented. The earth ground is used to as the current returning path, which helps to reduce two metal plates. It can be used in both indoor and outdoor applications. The prototype can transfer 216.5W with an efficiency of 52.2% across a distance of 2m. In future work, the system power and efficiency will be improved.

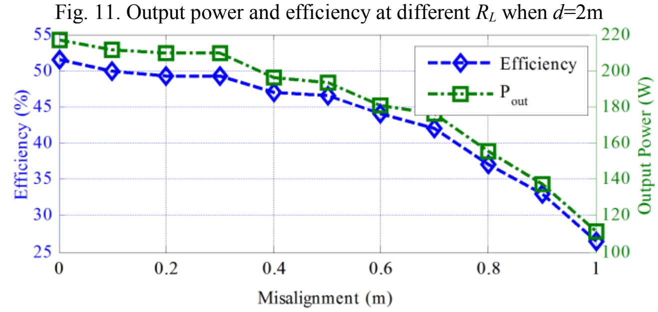

Fig. 12. Output power and efficiency with misalignment when R_L=20Ω, *d*=2m

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