Defining the mutual coupling of capacitive power transfer for wireless power transfer

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Capacitive power transfer (CPT) based on electric field coupling has been proposed recently as an alternative technology for wireless power transfer, and a good understanding of the capacitive coupling is of great importance in the design and evaluation of CPT systems. A new term named capacitive coupling coefficient k_E is introduced to provide a quantitative measure of the coupling condition between the coupling plates. The term is derived by modelling the capacitive coupling plates based on electric charge balance, and its physical meaning is explained clearly in relation to the equivalent primary/secondary and mutual capacitances, which is also experimentally demonstrated by comparing two CPT systems with different cross-coupling configurations.

Introduction: Capacitive power transfer (CPT), also termed as capacitively coupled power transfer, provides an alternative technology for wireless power transfer based on electric field coupling [1]. Unlike inductive power transfer (IPT), CPT offers some unique features such as the ability to transfer power through metal barriers [2, 3].

A typical CPT system is shown in Fig. 1. It consists of an AC power supply as a high-frequency (~MHz) alternating voltage source, a capacitive coupling interface formed by two pairs of conductive coupling plates, such as copper cladded boards and aluminium sheets, and a load. The capacitive coupling interface is the core element of a CPT system for achieving wireless/contactless power transfer. Normally, it is designed to form two main capacitances (C_{Aa} and C_{Bb} in Fig. 1) in series to constitute a power transfer loop. However, in practical systems, apart from the main coupling capacitance, two cross-coupling capacitances (C_{Ab} and C_{Ba}) between the plates on different sides, as well as two leakage capacitances (C_{AB} and C_{ab}) between the plates on the same side, may exist, as shown by the dotted lines in Fig. 2. These coupling capacitances can make the CPT tuning design and evaluation very difficult.

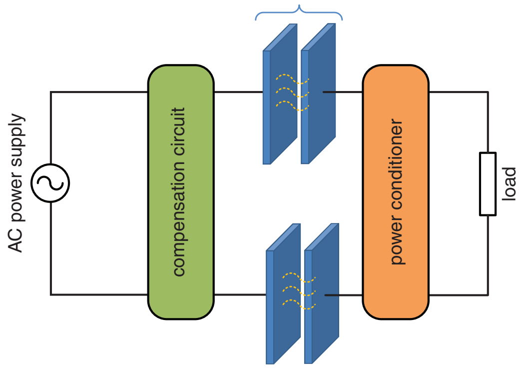

Fig. 1 *Typical CPT system*

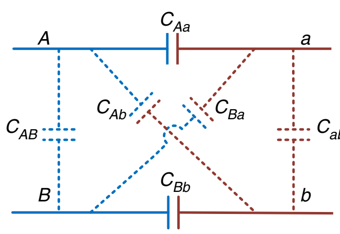

Fig. 2 *Cross-capacitances in capacitive coupling interface*

It is well known that the magnetic coupling coefficient has been used to define the mutual magnetic coupling between the coupled coils of an IPT system [4]. However, there is no appropriate term defined for the coupling plates of CPT systems, particularly when cross-coupling exists. Although a similar coupling coefficient has been defined based on the ratio between the mutual and storage energy of primary and secondary plates [5], it ranges from zero to infinity without giving a clear indication of the coupling degree. This Letter proposes a new capacitive coupling coefficient k_E with its magnitude ranging from 0 to 1 for quantifying the overall mutual electric coupling between the primary and secondary coupling plates by taking the cross-electric field coupling into consideration.

Modelling the capacitive coupling interface: A new model is established as shown in Fig. 3 to describe the cross-coupling between the primary and secondary coupling plates. Similar to leakage inductances in a transformer model, the two leakage capacitances (C_{AB} and C_{ab} in dotted lines) between the plates at the same side are not considered in the calculation of mutual coupling charges since neither of them contributes to the mutual coupling between the primary and secondary plates. They can be analysed separately at each side if needed.

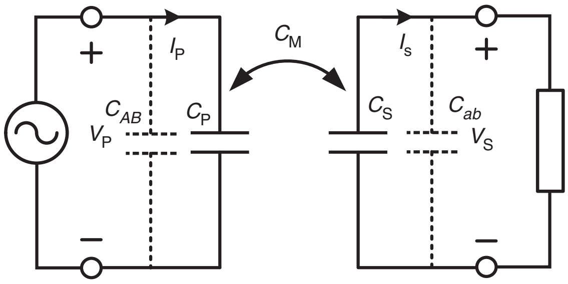

Fig. 3 *Proposed dual model of capacitive coupling interface*

In Fig. 3, the capacitive coupling interface is seen as two equivalent primary and secondary capacitances C_P and C_S coupled by a mutual capacitance C_M. If the voltages at the input and output of the coupling plates are V_P and V_S, respectively, the charges involved in the mutual coupling (without considering the leakage capacitances) will be

$$\begin{cases} Q_P = V_P C_P + V_S C_M \\ Q_S = V_S C_S + V_P C_M \end{cases} \tag{1}$$

C_P can be calculated by setting V_S to zero (secondary short circuited). From (1) and Fig. 2, C_P can be expressed as

$$C_P = \frac{Q_P}{V_P} = \frac{(C_{Aa} + C_{Ab})(C_{Ba} + C_{Bb})}{C_{Aa} + C_{Ab} + C_{Ba} + C_{Bb}} \tag{2}$$

Similarly, C_S can be obtained by setting V_P to zero

$$C_S = \frac{Q_S}{V_S} = \frac{(C_{Aa} + C_{Ba})(C_{Ab} + C_{Bb})}{C_{Aa} + C_{Ba} + C_{Ab} + C_{Bb}} \tag{3}$$

To obtain the mutual capacitance C_M, the secondary side is made an open circuit, and a current source can be modelled at the secondary side due to the capacitive coupling, as illustrated in Fig. 4. Under steady-state conditions, the open-circuit output voltage V_{SO} can be expressed as

$$V_{SO} = \mathrm{j}\omega C_M V_P \times \frac{1}{\mathrm{j}\omega(C_S + C_{ab})} = \frac{C_M V_P}{C_S + C_{ab}} \tag{4}$$

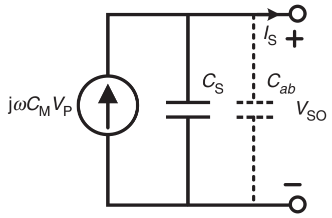

Fig. 4 *Equivalent model of secondary side*

Then C_M can be expressed as

$$C_M = \frac{V_{SO}}{V_P}(C_S + C_{ab}) \tag{5}$$

With a given V_P, V_{SO} can also be obtained by analysing the original circuit shown by Fig. 2

$$V_{SO} = V_P \frac{C_{Aa}C_{Bb} - C_{Ab}C_{Ba}}{C_{ab}(C_{Aa}+C_{Ab}+C_{Ba}+C_{Bb}) + (C_{Aa}+C_{Ba})(C_{Ab}+C_{Bb})} \quad (6)$$

Substituting (3) and (6) for C_S and V_{SO} into (5) gives

$$C_M = \frac{-C_{Ab}C_{Ba} + C_{Aa}C_{Bb}}{C_{Aa}+C_{Ab}+C_{Ba}+C_{Bb}} \quad (7)$$

which shows that C_M is only determined by the mutual capacitances, and is not affected by the leakage capacitances.

Now, similar to the magnetic coupling coefficient between two coils, a new term named capacitive coupling coefficient k_E can be defined as

$$k_E = \frac{C_M}{\sqrt{C_P C_S}} \quad (8)$$

From (2), (3) and (7), this coefficient can also been determined by the mutual capacitances

$$k_E = \frac{C_{Aa}C_{Bb} - C_{Ab}C_{Ba}}{\sqrt{(C_{Aa}+C_{Ab})(C_{Aa}+C_{Ba})(C_{Ab}+C_{Bb})(C_{Ba}+C_{Bb})}} \quad (9)$$

In a symmetrical coupling situation where $C_{Aa} = C_{Bb} = C_1$, and $C_{Ab} = C_{Ba} = C_2$, k_E can be further simplified as

$$k_E = \frac{C_1 - C_2}{C_1 + C_2} \quad (10)$$

According to (10), when C_2 is zero, i.e. there is no cross-coupling between the primary and secondary plates, k_E equals 1, indicating that only the main capacitances exist between the primary and secondary sides. In this case the equivalent primary and secondary C_P and C_S, as well as the mutual capacitance C_M are all equal to half of C_1 because the two coupling pairs are in series. When C_1 equals C_2, k_E becomes zero, indicating that cross-coupling cancels out the main coupling so the overall mutual coupling between the primary and secondary sides becomes zero. In this case, C_P and C_S both equal C_1 due to the contribution of cross-coupling, and the mutual capacitance C_M equals to zero due to the cross-coupling cancellation effect. When C_2 is larger than C_1, k_E will be negative, meaning that the coupling plates have changed to such an extent that the cross-coupling becomes larger than the main coupling. In such a case, the coupling pairs may be redefined to make k_E positive.

In fact, even for the general case defined in (9), it can be proven that k_E falls between −1 and 1, which provides a clear quantitative indication of the overall mutual capacitive coupling between the primary and secondary plates.

Experimental study: Two uncompensated CPT systems (referred to as CPT-1 and CPT-2) with different cross-coupling configurations were constructed to compare their capacitive coupling coefficients. The coupling plates of the systems were made of four 100 × 100 mm square aluminium sheets coated with polyethylene as dielectric materials. CPT-1 and CPT-2 have the same main coupling capacitances, but their cross and leakage capacitances are varied by making the distance between the coupled plate pairs of CPT-2 larger. All the coupling capacitances shown in Fig. 2 were measured using an accurate LCR meter and are shown in Table 1. Each parameter was measured independently by eliminating the effect of other plates. C_P and C_S (see Fig. 3) were obtained by measuring the total capacitances when the primary and secondary plates were shorted, respectively, after the leakage capacitances C_{AB} and C_{ab} were deducted. C_M can be determined by (5) after a sinusoidal voltage source (with a peak value of 20 V at an operating frequency of 1 MHz) is applied at the primary side while the peak value of the secondary side open-circuit voltage V_{SO} is measured. When C_P, C_S and C_M are known, k_E can be determined by (8). The theoretical values of C_P, C_S, C_M and k_E are also calculated from (2), (3) and (7) and are also shown in Table 1, and are in good agreement with the measured results.

The primary side is driven by a 1 MHz sinusoidal voltage source with a peak value of 20 V, and a pure resistive load of 2 kΩ is connected at the secondary output. Practical measurements showed that CPT-1 with a k_E of 0.60 produced an output voltage with a peak value of 9.2 V, while CPT-2 with a k_E of 0.75 produced an output voltage of 11.0 V. Clearly, the higher output voltage and thus the power of CPT-2 is contributed by a stronger overall mutual electric field coupling (reflected by a higher k_E) between the primary and secondary plates due to the reduced cross-coupling effect.

Table 1: Comparison of two CPT systems

	CPT-1		CPT-2	
C_{AB} (pF)	15		10	
C_{ab} (pF)	15		10	
C_{Aa} (pF)	201		200	
C_{Bb} (pF)	199		201	
C_{Ab} (pF)	43		23	
C_{Ba} (pF)	40		21	
	Measured	Theoretical	Measured	Theoretical
C_P (pF)	116	120	104	111
C_S (pF)	115	120	101	111
C_M (pF)	70	79	77	89
k_E	0.60	0.66	0.75	0.80

Conclusion: This Letter introduces a new term named capacitive coupling coefficient k_E to quantify the overall mutual capacitive coupling between the primary and secondary plates of a CPT system by taking the cross-electric field coupling into consideration. The term is derived from a new model based on charge balance, and its physical meaning is explained and demonstrated by experimentally comparing two CPT systems with different cross-coupling configurations.

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One or more of the Figures in this Letter are available in colour online.

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