Live Coupling Coefficient Calculation Method for Capacitive Wireless Power Transfer with Multiple Receivers

Aris van Ieperen
Cosys-Lab
University of Antwerp
Antwerp, Belgium
aris.vanieperen@uantwerpen.be

Stijn Derammelaere
Cosys-Lab - AnSyMo/Cosys
University of Antwerp - Flanders Make
Antwerp, Belgium
stijn.derammelaere@uantwerpen.be

Ben Minnaert
Cosys-Lab
University of Antwerp
Antwerp, Belgium
ben.minnaert@uantwerpen.be

***Abstract*—Capacitive wireless power transfer shows promise for wireless energy delivery, utilizing capacitive coupling for transmission. Quantifying the coupling between individual transmitters and receivers is essential, as optimization techniques for optimal output impedance depend on accurate knowledge of the coupling coefficient. Methods to measure this coupling exist, but these are applied to a specific configuration of a capacitive power transfer system, requiring a new measurement each time the distance or alignment between transmitters and receivers change. Since practical capacitive power transfer systems often experience variations in distance or alignment, impacting the coupling coefficient and consequently, the optimal output impedance, it is desired to constantly measure the coupling coefficient. This paper proposes a concise, exact method for live coupling coefficient calculation, and looks into the application of this method for systems with one transmitter and one receiver, and one transmitter and multiple receivers.**

***Index Terms*—CPT, SISO, SIMO, Coupling**

I. INTRODUCTION

Capacitive wireless power transfer (CPT) is a promising technology for the wireless delivery of energy to electronic devices [1]. It employs a high-frequency electric field as a medium for transmitting electrical energy from one or more transmitters to one or more receivers. CPT systems have been applied in many areas, such as charging mobile devices, LED drivers, and vehicle charging [2]–[5].

The capacitive coupling interface is formed by conductive plates, and is well suited for system configurations with multiple receivers. The coupling between the plates in a capacitive coupling interface can be quantified using the capacitive coupling coefficient k [6]. Methods to measure this coupling coefficient are presented in [6] and [7], for single input single output (SISO) and multiple inputs multiple outputs (MIMO) systems respectively. However, these methods are applied to a specific configuration of a CPT system, and a change in distance or alignment would require a new measurement, which requires specific system states that do not occur during normal system operation, such as for instance a short circuit at the transmitter or receiver side. Therefore, these methods are not applicable for live coupling coefficient calculation.

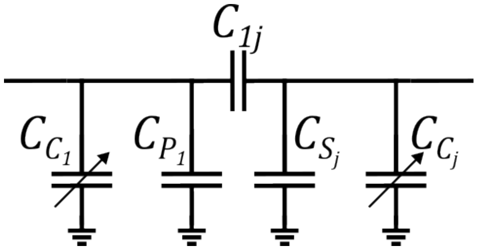

Fig. 1. Equivalent circuit representation of a SISO CPT coupling interface with controllable compensation capacitances C_{C_1} and C_{C_j}.

In practical CPT systems, change in distance or alignment between the transmitter and receivers is often inevitable. With such a change in distance or alignment, the coupling coefficient varies and as a result, the efficiency and power transfer changes. Optimization techniques exist for the optimal output impedance [8], [9], but these optimizations require knowledge of the coupling coefficient. Therefore, there is a need for live coupling calculation in CPT systems. In this paper we propose an exact method to calculate the coupling coefficient based on measured quantities during normal system operation. We apply the method analytically to SISO and single input multiple outputs (SIMO) CPT systems, and validate the method with a simulation of a SIMO CPT system.

II. METHODS

A CPT coupling interface can be represented by an equivalent circuit, given by a primary capacitance C_{P_1} at the transmitter side and a secondary capacitance C_{S_j} at the receiver side (with j the number of the receiver plus one), coupled by a mutual capacitance C_{1j} [6], as shown in Fig. 1. Controllable compensation capacitances C_{C_1} and C_{C_j} are added to maintain a constant sum of capacitances on one side (e.g. $C_{C_1} + C_{P_1} + C_{12}$ at the transmitter side for a SISO system),

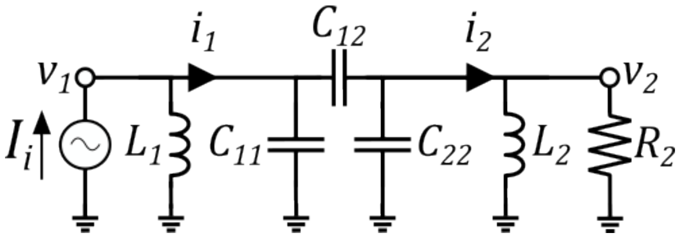

Fig. 2. Equivalent circuit representation of a SISO CPT system.

such that resonance frequency f stays constant under varying distance or alignment of the coupling plates. We introduce C_1 and C_j as this sum of the capacitances at the transmitter and receiver side respectively:

$$C_1 = C_{11} + \sum_{j=2}^{N} C_{1j}, \tag{1}$$

$$C_j = C_{jj} + C_{1j}, \tag{2}$$

with N the total number of receivers, C_{11} the sum of the compensation capacitance at the transmitter side C_{C_1} and the primary coupling interface capacitance C_{P_1}, and C_{jj} the sum of the compensation capacitance at the receiver side C_{P_j} and the secondary coupling interface capacitance C_{C_j}:

$$C_{11} = C_{C_1} + C_{P_1}, \tag{3}$$

$$C_{jj} = C_{C_j} + C_{S_j}. \tag{4}$$

The method we propose determines the primary capacitance C_{11} and secondary capacitances C_{jj}, based on current and voltage measurement at transmitter and receiver sides, from which the mutual capacitance C_{1j} can be deducted.

With the mutual capacitance C_{1j}, the coupling coefficient can be calculated according to [6]:

$$k_{ij} = \frac{C_{1j}}{\sqrt{C_1 C_j}}. \tag{5}$$

A. SISO

We consider an ideal resonant SISO CPT system as shown in Fig. 2, with L_1 and L_2 the inductances used to create a resonant system, C_{11} and C_{22} the primary and secondary capacitances, C_{12} the mutual capacitance and R_2 the resistive load. The transmitter is powered by a current source with peak value I_i and operating frequency f. We measure the currents i_1 and i_2, and voltages v_1 and v_2 as defined on the figure.

The measured currents at the primary i_1 and secondary side i_2 can be expressed as:

$$i_1 = i_{C_{11}} + i_{C_{12}}, \tag{6}$$

$$i_2 = i_{C_{12}} - i_{C_{22}}, \tag{7}$$

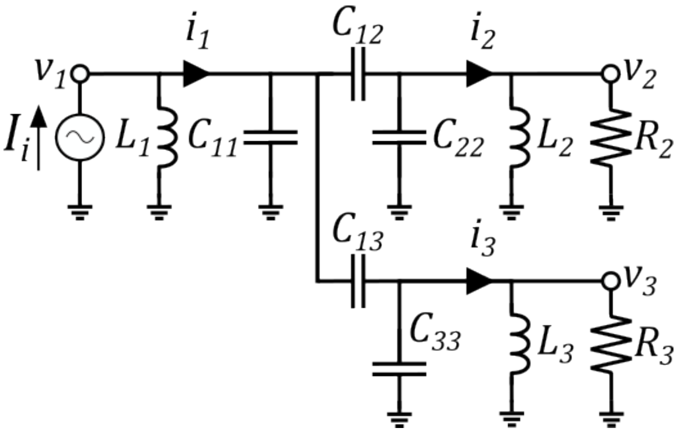

Fig. 3. Equivalent circuit representation of a SIMO CPT system with one transmitter and two receivers.

Combining these two equations gives:

$$i_1 - i_2 = i_{C_{11}} + i_{C_{22}}, \tag{8}$$

which we can write as:

$$i_1 - i_2 = C_{11}\frac{dv_1}{dt} + C_{22}\frac{dv_2}{dt}. \tag{9}$$

We can use (1) and (2) to express the primary C_{11} and secondary C_{22} capacitances as:

$$C_{11} = C_1 - C_{12}, \tag{10}$$

$$C_{22} = C_2 - C_{12}. \tag{11}$$

Substituting these two equations in (9) gives:

$$i_1 - i_2 = C_{11}\frac{dv_1}{dt} + \left(C_2 - C_1 + C_{11}\right)\frac{dv_2}{dt}, \tag{12}$$

which can be rearranged as an expression of C_{11}:

$$C_{11} = \frac{i_1 - i_2 - \left(C_2 - C_1\right)\frac{dv_2}{dt}}{\frac{dv_1}{dt} + \frac{dv_2}{dt}}. \tag{13}$$

Rearranging (10) results in an expression for the mutual capacitance C_{12}:

$$C_{12} = C_1 - C_{11}, \tag{14}$$

which can be used to calculate the coupling coefficient k_{12} according to (5). Note that we can calculate this coupling coefficient k_{12} using voltages and currents that can be measured during normal system operation. Therefore, the proposed method is suitable for live coupling calculation in SISO CPT systems.

B. SIMO

Our method is applicable for SIMO systems as well. We illustrate the methodology for a CPT system with one transmitter and two receivers, as shown in Fig. 3. For this system, (9) extends to:

$$i_1 - i_2 - i_3 = C_{11}\frac{dv_1}{dt} + C_{22}\frac{dv_2}{dt} + C_{33}\frac{dv_3}{dt}. \tag{15}$$

We can express the mutual coupling between the transmitter and the first receiver C_{12} as a function of C_{11}, measured values and known constants:

$$C_{12} = \frac{C_1 - C_{11}}{1 + \frac{v_3 R_2}{v_2 R_3}}, \tag{16}$$

and the mutual coupling between the transmitter and the second receiver C_{13} as a function of C_{12}:

$$C_{13} = \frac{v_3 R_2}{v_2 R_3} C_{12}. \tag{17}$$

To simplify the notation, the following definitions are introduced:

$$x_1 = \frac{v_3 R_2}{v_2 R_3}, \tag{18}$$

$$x_2 = \frac{1}{1 + x_1}. \tag{19}$$

We can express C_{22} and C_{33} in (15) as:

$$C_{22} = C_2 - (C_1 - C_{11})\, x_2, \tag{20}$$

$$C_{33} = C_3 - (C_1 - C_{11})\, x_1 x_2, \tag{21}$$

and after rearranging we get an expression of C_{11}, given by:

$$C_{11} = \frac{i_1 - i_2 - i_3 - (C_2 - C_1 x_2)\frac{dv_2}{dt} - (C_3 - C_1 x_1 x_2)\frac{dv_3}{dt}}{\frac{dv_1}{dt} + x_2\frac{dv_2}{dt} + x_1 x_2\frac{dv_3}{dt}}. \tag{22}$$

The mutual capacitances between the transmitter and the receivers can now be determined using (16) and (17), after which the coupling coefficients k_{12} and k_{13} can be calculated using (5). Note that we can calculate these coupling coefficients k_{12} and k_{13} using voltages and currents that can be measured during normal system operation. Therefore, the proposed method is suitable for live coupling calculation in SIMO CPT systems.

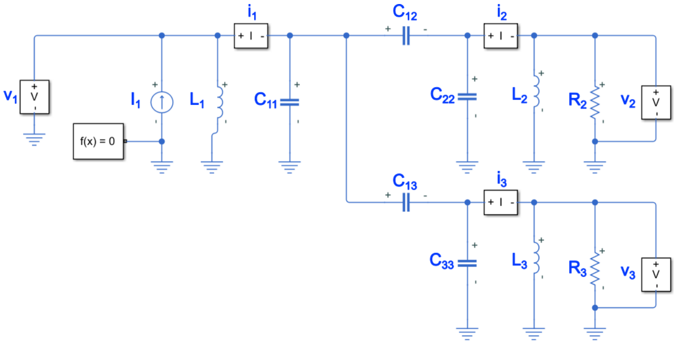

Fig. 4. Simscape model of SIMO CPT system.

TABLE I
VALUES OF SIMULATION COMPONENTS.

Parameter	System 1	Unit
C_1	250	pF
C_2	200	pF
C_3	350	pF
f	1	MHz
I	100	mA
L_1	101.32	µH
L_2	126.65	µH
L_3	72.37	µH
R_2	1000	Ω
R_3	500	Ω

III. RESULTS AND DISCUSSION

A. Circuit simulation

The analytical derivation is validated in the electric circuit simulation environment Simscape for Matlab Simulink using the equivalent circuit of a resonant CPT system with one transmitter and two receivers.

In Fig. 4, the Simscape model of the SIMO CPT system is shown. The supply at the transmitter side is represented by a current source with a frequency f and peak value I. The load of each receiver is modeled as a resistor with resistances R_2 and R_3. The capacitive link is represented by primary and secondary capacitances C_{11}, C_{22} and C_{33}, and their mutual capacitances C_{12} and C_{13}. The inductances L_1, L_2 and L_3 are used to create resonant circuits. The values of the parameters used in these simulations are listed in Tab. I.

In the simulation, the coupling coefficients are calculated for each simulation time-step, according to the following procedure: First, the primary capacitance C_{11} is calculated according to (22), using the indicated current and voltage measurements. Second, the secondary capacitances C_{22} and C_{33} are computed according to (20) and (21). Third, the mutual capacitances C_{12} and C_{13} are determined following (16) and (17). Fourth, the individual coupling coefficients k_{12} and k_{13} are calculated with (5).

The mutual capacitances C_{12} and C_{13} are linearly varied over time, with C_{12} decreasing from 100 pF to 50 pF, and C_{13} increasing from 50 pF to 100 µs. The calculated

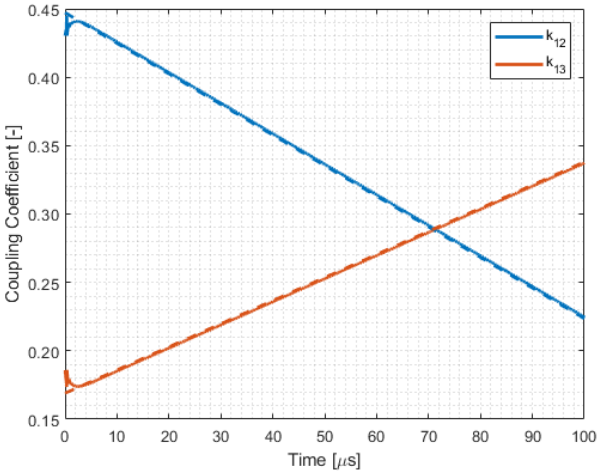

Fig. 5. Calculated (solid line) and theoretical (dashed line) coupling coefficients k_{12} and k_{13} of a SIMO CPT system with one transmitter and two receivers with varying mutual capacitances C_{12} and C_{13}.

coupling coefficients k_{12} and k_{13} are shown in Fig. 5. The live calculated values are in alignment with the theoretical values, validating the proposed method for live coupling estimation in CPT systems with multiple receivers.

IV. CONCLUSION

A method is proposed for live calculation of the coupling coefficients in CPT systems. The coupling coefficients are calculated based on voltages and currents that can be measured during normal system operation. Different system configurations (SISO and SIMO) are analytically analyzed to determine the feasibility of the proposed method. It is shown that the method is applicable to SISO and SIMO configurations, which is confirmed by simulation.

The proposed method can be further improved by taking non-idealities, such as equivalent series resistances into account. Further research include extending the method for MIMO CPT systems and experimental validation.

ACKNOWLEDGMENT

This work was supported by a grand from the Research Foundation Flanders (FWO) under Grant Number 1SH1224N.

REFERENCES

[1] M. Z. Erel, K. C. Bayindir, M. T. Aydemir, S. K. Chaudhary, and J. M. Guerrero, “A comprehensive review on wireless capacitive power transfer technology: Fundamentals and applications,” *IEEE Access*, vol. 10, pp. 3116–3143, 2022.

[2] G. G. da Silva and C. A. Petry, “Capacitive wireless power transfer system applied to low-power mobile device charging,” *International Journal of Electrical Energy*, vol. 3, 2015.

[3] D. Shmilovitz, S. Ozeri, and M. M. Ehsani, “A resonant LED driver with capacitive power transfer.” Institute of Electrical and Electronics Engineers Inc., 2014, pp. 1384–1387.

[4] J. Dai and D. C. Ludois, “Capacitive power transfer through a conformal bumper for electric vehicle charging,” *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. 4, pp. 1015–1025, 9 2016.

[5] S. Sinha, A. Kumar, B. Regensburger, and K. K. Afridi, “A new design approach to mitigating the effect of parasitics in capacitive wireless power transfer systems for electric vehicle charging,” *IEEE Transactions on Transportation Electrification*, vol. 5, pp. 1040–1059, 12 2019.

[6] L. Huang and A. P. Hu, “Defining the mutual coupling of capacitive power transfer for wireless power transfer,” *Electronics Letters*, vol. 51, pp. 1806–1807, 10 2015.

[7] W. Zhou, L. Huang, B. Luo, R. Mai, Z. He, and A. P. Hu, “A general mutual coupling model of MIMO capacitive coupling interface with arbitrary number of ports,” *IEEE Transactions on Power Electronics*, vol. 36, pp. 6163–6167, 6 2021.

[8] M. Dionigi, M. Mongiardo, G. Monti, and R. Perfetti, “Modelling of wireless power transfer links based on capacitive coupling,” *International Journal of Numerical Modelling: Electronic Networks, Devices and Fields*, vol. 30, May 2017.

[9] B. Minnaert, A. Costanzo, G. Monti, and M. Mongiardo, “Capacitive wireless power transfer with multiple transmitters: Efficiency optimization,” *Energies*, vol. 13, 7 2020.