Cross Coupling Cancellation for All Frequencies in Multiple-Receiver Wireless Power Transfer Systems

Danyang Cui 1, Takehiro Imura 2, and Yoichi Hori 1,2
1 Graduate school of Engineering, The University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8561, Japan
2 Graduate school of Frontier Sciences, The University of Tokyo, 5-1-5, Kashiwanoha, Kashiwa, Chiba, 277-8561, Japan

***Abstract*—Nowadays Wireless Power Transfer (WPT) system using magnetic resonant coupling has become highly-anticipated. This paper investigates the negative effects of cross coupling in multi-receiver WPT systems, and proposes a Cross Coupling Cancellation (CCC) method to eliminate it at all frequencies. Simulations and experiments have been executed to verify the method.**

***Index Terms*—Wireless Power Transfer, magnetic resonant coupling, cross coupling cancellation, multiple receivers, power transfer efficiency.**

1. Introduction

Recently Wireless Power Transfer (WPT) using Magnetic Resonant Coupling (MRC) technique has become a research hotspot [1]-[2]. Fig. 1(a) shows one scenario of WPT application, where energy is transferred from a charging panel to multiple electrical appliances, constituting a multi-receiver WPT system.

In multi-receiver WPT systems, the coupling among receivers is called cross coupling. Paper [3] investigated the effect caused by cross coupling in a 1-Tx 2-Rx* WPT system and proposed a Cross Coupling Cancellation (CCC) method to eliminate the effect. However, this CCC method in [3] can only be applied to fully symmetric multi-Rx WPT systems, where all receivers are same and all the mutual inductance between Tx and each Rx are same. As a solution, [4] proposed an improved method to compensate cross coupling in general multi-Rx WPT systems. Yet these two methods in [3] and [4] can only function at the resonant frequency.

In this paper, a further-improved Cross Coupling Cancellation (CCC) method which can operate at all frequencies and suitable for generalized multi-Rx WPT systems is proposed.

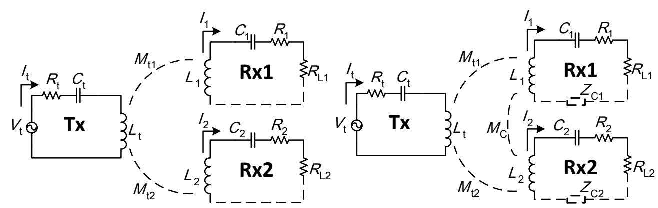
2. Methodology

To cancel the effect of cross coupling, two cancellation impedances are used. Fig. 2(a) shows the equivalent circuits without cross coupling while Fig. 2(b) shows that with cross coupling and cancellation impedances. Assume ω is a random frequency, according to Kirchhoff's voltage law, current expressions can be derived from (1) for Fig. 2(a) and from (2) for Fig.2 (b). The total power-transfer-efficiency can be calculated from the currents.

*Tx means transmitter, Rx means receiver.

(a) (b)

Fig. 1. (a) Wireless charging for mobile devices, (b) experiment scene.



(a) (b)

Fig. 2. Equivalent circuits of 1-Tx 2-Rx WPT systems (a) without Z_{C1} and Z_{C2}, (b) with M_{C} and Z_{C1} Z_{C2}.

$$
\begin{aligned}
0 &= j\omega M_{\mathrm{t1}} I_{\mathrm{t\_wo}} + (R_1 + R_{\mathrm{L1}} + \frac{1}{j\omega C_1} + j\omega L_1) I_{\mathrm{1\_wo}} \\
0 &= j\omega M_{\mathrm{t2}} I_{\mathrm{t\_wo}} + (R_2 + R_{\mathrm{L2}} + \frac{1}{j\omega C_2} + j\omega L_2) I_{\mathrm{2\_wo}}
\end{aligned} \tag{1}
$$

$$
\begin{aligned}
0 &= j\omega M_{\mathrm{t1}} I_{\mathrm{t\_wi}} + (R_1 + R_{\mathrm{L1}} + \frac{1}{j\omega C_1} + j\omega L_1) I_{\mathrm{1\_wi}} + j\omega M_{\mathrm{C}} I_{\mathrm{2\_wi}} + I_{\mathrm{1\_wi}} Z_{\mathrm{C1}} \\
0 &= j\omega M_{\mathrm{t2}} I_{\mathrm{t\_wi}} + (R_2 + R_{\mathrm{L2}} + \frac{1}{j\omega C_2} + j\omega L_2) I_{\mathrm{2\_wi}} + j\omega M_{\mathrm{C}} I_{\mathrm{1\_wi}} + I_{\mathrm{2\_wi}} Z_{\mathrm{C2}}{}^{\dagger}
\end{aligned} \tag{2}
$$

The two cancellation impedances Z_{C1} and Z_{C2} have both real part and imaginary part as in (3).

$$
Z_{\mathrm{C1}} = R_{\mathrm{C1}} + j\omega X_{\mathrm{C1}}, \quad Z_{\mathrm{C2}} = R_{\mathrm{C2}} + j\omega X_{\mathrm{C2}}. \tag{3}
$$

Consider the equivalent circuit in Fig. 2(a). Without Z_{C1} Z_{C2}, the efficiency formula is

$$
\eta_{\mathrm{wo}} = \frac{|I_1|^2 R_{\mathrm{L1}} + |I_2|^2 R_{\mathrm{L2}}}{|I_{\mathrm{t}}|^2 R_{\mathrm{t}} + |I_1|^2 (R_1 + R_{\mathrm{L1}}) + |I_2|^2 (R_2 + R_{\mathrm{L2}})}. \tag{4}
$$

† wo means without cross coupling and cancellation impedances, wi means with cross coupling and cancellation impedances.

Consider the equivalent circuit in Fig. 2(b). Because we can adjust the load resistance by DC-DC converter, the real parts of the cancellation impedances can be regarded as part of load resistances. Now with Z_{C1} Z_{C2}, the efficiency formula is

$$\eta_{\mathrm{wi}} = \frac{|I_1|^2(R_{\mathrm{L1}}+R_{\mathrm{C1}})+|I_2|^2(R_{\mathrm{L2}}+R_{\mathrm{C2}})}{|I_{\mathrm{t}}|^2R_{\mathrm{t}}+|I_1|^2(R_1+R_{\mathrm{L1}}+R_{\mathrm{C1}})+|I_2|^2(R_2+R_{\mathrm{L2}}+R_{\mathrm{C2}})}. \tag{5}$$

Comparing the two efficiency formulas (4) and (5), we can find that η_{wi} has one more term in its numerator and denominator than η_{wo}, which is $(|I_1|^2R_{\mathrm{C1}}+|I_2|^2R_{\mathrm{C2}})$. This term can be proved to be equal to zero all the time, so that η_{wi} always equals to η_{wo} if every parameter is the same. The proof will be shown at the end of this section. As the prerequisite of the identity of η_1 and η_2, all parameters in two efficiency formulas must be the same, currents particularly, shown in (6).

$$I_{\mathrm{t\_wi}} = I_{\mathrm{t\_wo}}, \quad I_{\mathrm{1\_wi}} = I_{\mathrm{1\_wo}}, \quad I_{\mathrm{2\_wi}} = I_{\mathrm{2\_wo}}. \tag{6}$$

With the assumptions above, from (1) and (2),

$$\begin{matrix} 0 = j\omega M_{\mathrm{C}}I_{\mathrm{2\_wo}} + I_{\mathrm{1\_wo}}Z_{\mathrm{C1}} \\ 0 = j\omega M_{\mathrm{C}}I_{\mathrm{1\_wo}} + I_{\mathrm{2\_wo}}Z_{\mathrm{C2}} \end{matrix} \Rightarrow \begin{matrix} Z_{\mathrm{C1}} = -j\omega M_C \dfrac{I_{\mathrm{2\_wo}}}{I_{\mathrm{1\_wo}}} \\ Z_{\mathrm{C2}} = -j\omega M_C \dfrac{I_{\mathrm{1\_wo}}}{I_{\mathrm{2\_wo}}}. \end{matrix} \tag{7}$$

From (1), the ratio of currents can be derived as

$$\frac{I_{\mathrm{1\_wo}}}{I_{\mathrm{2\_wo}}} = \frac{M_{\mathrm{t1}}}{M_{\mathrm{t2}}} \frac{R_2 + R_{\mathrm{L2}} + \frac{1}{j\omega C_2} + j\omega L_2}{R_1 + R_{\mathrm{L1}} + \frac{1}{j\omega C_1} + j\omega L_1}. \tag{8}$$

Substitute (8) into (7) leaves

$$\begin{aligned} Z_{\mathrm{C1}} &= -j\omega M_{\mathrm{C}} \frac{M_{\mathrm{t2}}}{M_{\mathrm{t1}}} \frac{R_1 + R_{\mathrm{L1}} + \frac{1}{j\omega C_1} + j\omega L_1}{R_2 + R_{\mathrm{L2}} + \frac{1}{j\omega C_2} + j\omega L_2} \\ Z_{\mathrm{C2}} &= -j\omega M_{\mathrm{C}} \frac{M_{\mathrm{t1}}}{M_{\mathrm{t2}}} \frac{R_2 + R_{\mathrm{L2}} + \frac{1}{j\omega C_2} + j\omega L_2}{R_1 + R_{\mathrm{L1}} + \frac{1}{j\omega C_1} + j\omega L_1}. \end{aligned} \tag{9}$$

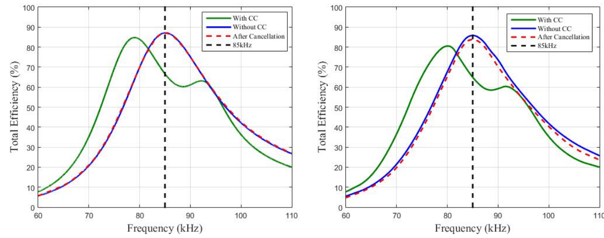
Equations (9) are the expressions for the cancellation impedances Z_{C1} and Z_{C2}. Now begins the proof of $|I_1|^2R_{\mathrm{C1}} + |I_2|^2R_{\mathrm{C2}} = 0$. At resonant frequency, $R_{\mathrm{C1}} = R_{\mathrm{C2}} = 0$, so $|I_1|^2R_{\mathrm{C1}} + |I_2|^2R_{\mathrm{C2}} = 0$. At off-resonant frequencies, after expanding Z_{C1} and Z_{C2}, the ratio of their real parts can be calculated as in (10).

$$\frac{R_{\mathrm{C1}}}{R_{\mathrm{C2}}} = -\frac{M_{\mathrm{t2}}^2}{M_{\mathrm{t1}}^2} \frac{(R_1 + R_{\mathrm{L1}})^2 + (\omega L_1 - \frac{1}{\omega C_1})^2}{(R_2 + R_{\mathrm{L2}})^2 + (\omega L_2 - \frac{1}{\omega C_2})^2} \tag{10}$$

From (8) and (10), the identity of η_{wo} and η_{wi} can be easily proved.

3. Simulation & Experiment

Using the method introduced above, simulations have been executed. The simulation result is shown in Fig. 3(a). The parameters used is shown in TABLE I. This system is set to be resonate at 85 kHz. The peak of the green line shifts to the left in frequency domain, and both the maximum efficiency and the efficiency at resonant frequency decrease. The red dashed line denotes the efficiency curve after cross coupling cancellation. This curve coincides with the blue curve at all frequencies.



(a) (b)

Fig. 3. (a) Simulation results, (b) experiment results.‡

TABLE I
PARAMETER VALUES USED IN SIMULATION AND EXPERIMENT

	V_{t}(V)	$R(\Omega)$	$L(\mu\mathrm{H})$	C(nF)	$R_{\mathrm{L}}(\Omega)$
Tx	2	0.36	129	27	-
Rx1	-	0.35	154	22.8	5
Rx2	-	0.23	75	47	3.3

k_{t1}	0.0626
k_{t2}	0.0320
k_{C}	0.1618

The experiment with same parameters has been executed, with results shown in Fig. 3(b). Fig. 1(b) shows one scene. The experimental outcomes in three circumstances (without cross coupling, with cross coupling, after cancellation) quite match the simulation results. However, the curve after cancellation did not coincide with the curve without cross coupling, while their waveforms match each other. This may be due to the equivalent series resistance (ESR) of the cancellation capacitors. To reduce the ESR of capacitors, we may simply install several capacitors in parallel, whose total capacitance equals to the desired one. We may also use more expansive capacitors with lower ESR.

4. Conclusion

This paper proposed a Cross Coupling Cancellation (CCC) method to eliminate the cross coupling at all range of frequencies in general multi-Rx WPT systems. Simulations and experiments were executed, proving the practicality and feasibility of the introduced CCC method.

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‡CC in the legends means cross coupling.