Basic study of cross coupling canceling in power transmission by two pairs of coils using magnetic resonance coupling

Keiichi Ikeda, Takehiro Imura
Graduate School of Technology and Science, Tokyo University of Science
Chiba 278-0022, Japan

***Abstract*—Regarding magnetic resonance coupling, which is highly useful for wireless power transfer that enables high efficiency, long transmission distance, and tolerance of misalignment, coils are used when considering power transmission by providing multiple coils on the power transmission side or power reception side. We generalized the effects of cross coupling on transmission efficiency and power, and verified the improvement of characteristics by cross coupling canceling. In power transmission with two power-receiving coils for two power-transmitting coils, cross coupling canceling, or elimination of canceling a particular magnetic coupling, is equivalent to manipulating the coupling elements in the theoretical equations for transmission efficiency and transmission power. It is shown by circuit simulation and experiment.**

Keywords—wireless power transfer, multiple feed, magnetic resonance coupling, cross coupling, cross coupling canceling

I. Introduction

Magnetic resonance coupling, which has recently emerged as an application for wireless power transfer (WPT), has advantages over conventional electromagnetic induction systems, such as relatively long transmission distances and less efficiency loss due to misalignment, etc. In the field of developing WPT, in-car power transmission for EVs has been developed, and these coils have It is required to generate a strong local magnetic flux with relatively high flux levels and to ensure efficient magnetic field coupling not only to generate horizontal flux but also to ensure efficient magnetic field coupling even when the gap between the charging coil and the EV coil in the ground or on the surface is large. It is necessary to allow for misalignment in the direction.

The coupling between closely adjacent coils in multiple feeds, which affects transmission efficiency and so on, occurs; in a WPT system, not only one-to-one, but also one-to-many [1][2][3][4][5] or multiple-to-many [6] coils are possible. In this case, cross coupling (CC) occurs between the relay coils and multiple transmission and receiving coils. It has been reported that the presence or absence of CC causes a change in the frequency response in power transmission [7], frequency tracking with CC [8] and impedance matching with CC [9] have been reported to maximize the efficiency of the transmission coils. For CC described in these reports, an efficiency formulation considering CC in the case of one-to-two transmitter/receiver coils and a method for improving efficiency by insertion of canceling coils and canceling capacitors [10] are also presented. However, most of the reports so far have discussed the efficiency subject, and the transmission power considering CC has not been considered. The effect of CC needs to be studied clearly by broadening the base to include transmission power as well as efficiency.

This paper proposes an efficiency and power formulation with an equivalent circuit that takes into account CC between the coils and evaluates the changes in efficiency and power characteristics by canceling the CC between the coils in a configuration with two transmission coils and two receiving coils with minimum units of CC. In Chapter 2 is the process of formulating the efficiency and transmission power of multiple power supplies, Chapter 3 examines the effects of cross coupling canceling (CCC) based on the parameters of the developed experimental equipment, and Chapter 4 presents a summary.

II. The Process of Formulation

A. System overview and equivalent circuit

Fig.1 shows the overall picture of the transmission system: the coupling between Tx and Rx is called the main coupling and the coupling between Tx and Tx or Rx and Rx is called CC. In the equivalent circuit shown below, the main coupling is shown as L_m and CC between Tx and Tx or Rx and Rx as L_c. This section deals with the phenomenon including the effect of CC in power transmission using two pairs of coils, which corresponds to the case where there are multiple coils on both the EV and ground sides and multiple coils on the ground side are in the power-on state at the same time. When the Tx and Rx coupling is minimal, in the above application CC can be ignored. However, if the Tx-Tx or Rx-Rx coupling is strong, the impact on efficiency and transmission power needs to be visualized.

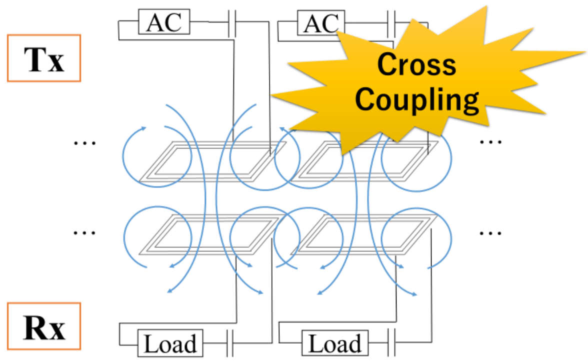


Fig.1. General view of the transmission system

B. Derivation of Multiple Power Supply Formula

In this section, we derive the equations for the efficiency of power transmission and input/output power at multiple loads... We note that CC can be positive or negative in some cases [10]. The formulation in this paper considers the case that CC has a negative value, i.e., when a coil is used for CCC. Fig.2 shows the equivalent circuit of the transmission system shown in Fig.1. The relationship between self-inductance and mutual inductance and the voltage and current of each device, taking into account CC at all points, is shown in equation (1). Here, the reactance due to the self-inductance L_n and the capacitance C_n cancels out theoretically when the operating frequency is ω_0(see the equation (2)), and the power supply voltage of Tx is set to be in opposite phase to each other to avoid complications of the general equation to be derived somewhat. The following conditions are applied (see equation (3)).

- The internal resistance and load resistance in the resonator are the same between the Tx and Rx coils.
- The coupling between each Tx coil and the Rx coil corresponding to each Tx coil and the Rx coil in the diagonal direction of each Tx coil is symmetrical.

Equation (4) is a relational equation applying the conditions in equations (2) and (3). The input power can be considered equivalent to the sum of the power consumed by the transmission and receiving devices, and the input power P_1 and the output power P_3 of the transmission and receiving devices in a pair are shown in equation (5). Although two pairs of coils are used in this study, here we look at the transmission efficiency in one pair (see equation (6)).

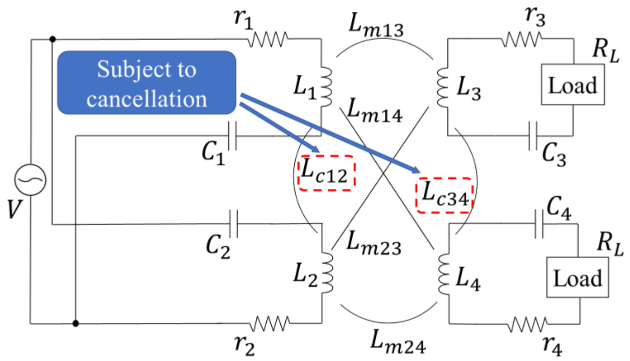


Fig.2. Equivalent circuit of the transmission system

$$\begin{bmatrix} V \\ V \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_1 & -j\omega Lc_{12} & j\omega L_{m13} & j\omega L_{m14} \\ -j\omega Lc_{12} & r_2 & j\omega L_{m23} & j\omega L_{m24} \\ j\omega L_{m13} & j\omega L_{m23} & r_3 + R_3 & -j\omega Lc_{34} \\ j\omega L_{m14} & j\omega L_{m24} & -j\omega Lc_{34} & r_4 + R_4 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{1}$$

$$j\omega L_n + \frac{1}{j\omega C_n} = 0 \tag{2}$$

$$\begin{cases} r_1 = r_2 \\ r_3 = r_4 \\ R_3 = R_4 = R_L \\ L_{m13} = L_{m24} = L_m \\ L_{m14} = L_{m23} = L_{dia} \end{cases} \tag{3}$$

$$\begin{bmatrix} V \\ V \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_1 & -j\omega Lc_{12} & j\omega L_m & j\omega L_{dia} \\ -j\omega Lc_{12} & r_1 & j\omega L_{dia} & j\omega L_m \\ j\omega L_m & j\omega L_{dia} & r_3 + R_L & -j\omega Lc_{34} \\ j\omega L_{dia} & j\omega L_m & -j\omega Lc_{34} & r_3 + R_L \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{4}$$

$$\begin{cases} P_1 = P_{r_1} + P_{r_3} + P_{R_L} = r_1|I_1|^2 + r_3|I_3|^2 + R_L|I_3|^2 \\ P_3 = P_{R_L} = R_L|I_3|^2 \end{cases} \tag{5}$$

$$\eta = \frac{P_3}{P_1} = \frac{R_L|I_3|^2}{r_1|I_1|^2 + r_3|I_3|^2 + R_L|I_3|^2} \tag{6}$$

Next, we derive the transmission characteristics formula for the case of CCC. When canceling coils with a reactance of self-inductance L_{Tcan} and L_{Rcan} are inserted in series in each of the circuits on the Tx and Rx side, the resonant condition before the insertion of the coils also applies. In this case, the equation of voltage and current is as shown in equation (7).

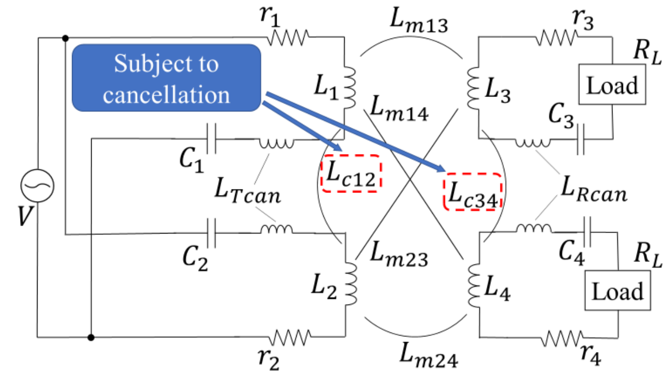


Fig.3 Equivalent circuit of the transmission system when inserting the canceling coil

C. Comparison of Efficiency and Power Theoretical Equations with and without CCC

The comparison of the results with and without CCC is shown in TABLE.1 and 2. It is possible to improve the efficiency up to the case where CC can be neglected by eliminating the term of coefficients on L_{c34}. On the other hand, TABLE.2 shows that the elements L_{Tcan} and L_{Rcan} due to the canceling coil are shown only in the terms of L_{c12} and L_{c34} in the power equation. As well as the efficiency, theoretically, the primary input power P_1 and the secondary output power P_3 can be improved to the power values where CC can be neglected by eliminating the coefficients of the terms L_{c12} and L_{c34}, depending on the values of L_{c12} and L_{c34}.

III. BASIC EVALUATION OF CROSS COUPLING CANCELING

A. Consistency between formulation and Experiment

In this section, CCC is evaluated by substituting the parameters of the fabricated coils into the theoretical equations of efficiency and power derived in Chapter 2. In the transmission circuit system, the input power supply V = 1 V, the Rx load R_L= 2 Ω is fixed, and the resonant frequency is 45 kHz for both the transmission and receiving sides. In this paper, we compare the parameters of the devices for which the resonance and CCC of each circuit can ideally be achieved (Ideal Param.) with those of the measured devices (Exp. Param.). The ideal device for both circuits is

$$\begin{bmatrix} V \\ V \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} r_1 + j\omega L_{Tcan} & -j\omega Lc_{12} & j\omega L_m & j\omega L_{dia} \\ -j\omega Lc_{12} & r_1 + j\omega L_{Tcan} & j\omega L_{dia} & j\omega L_m \\ j\omega L_m & j\omega L_{dia} & r_3 + R_L + j\omega L_{Rcan} & -j\omega Lc_{34} \\ j\omega L_{dia} & j\omega L_m & -j\omega Lc_{34} & r_3 + R_L + j\omega L_{Rcan} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} \tag{7}$$

TABLE.1 Comparison of Efficiency

	Efficiency：$\boldsymbol{\eta}$
Without CCC	$\dfrac{(L_m - L_{dia})^2 R_L \omega^2}{\{(L_m - L_{dia})^2 (r_3 + R_L) + r_1 \boldsymbol{Lc_{34}^2}\}\omega^2 + r_1 (r_3 + R_L)^2}$
With CCC	$\dfrac{(L_m - L_{dia})^2 R_L \omega^2}{\{(L_m - L_{dia})^2 (r_3 + R_L) + r_1 (\boldsymbol{L_{Rcan}} - \boldsymbol{Lc_{34}})^2\}\omega^2 + r_1 (r_3 + R_L)^2}$

TABLE.2 Comparison of Power

	Power (Primary side)：$\boldsymbol{P_1}$
Without CCC	$\dfrac{V_1^2\{(L_m - L_{dia}\}^2 (r_3 + R_L) + r_1 \boldsymbol{Lc_{34}^2}\}\omega^2 + r_1 (r_3 + R_L)^2}{(\{(L_m - L_{dia})^2 - \boldsymbol{Lc_{12}Lc_{34}}\}\omega^2 - \gamma)^2 + \{r_1 \boldsymbol{Lc_{34}} + \boldsymbol{Lc_{12}} (r_3 + R_L)\}^2 \omega^2}$
With CCC	$\dfrac{V_1^2\{(L_m - L_{dia})^2 (r_3 + R_L) + r_1 (\boldsymbol{L_{Rcan}} - \boldsymbol{Lc_{34}})^2\}\omega^2 + r_1 (r_3 + R_L)^2}{(\{(L_m - L_{dia})^2 + (\boldsymbol{Lc_{12}} - \boldsymbol{L_{Tcan}})(\boldsymbol{L_{Rcan}} - \boldsymbol{Lc_{34}})\}\omega^2 - \gamma)^2 - \{r_1 (\boldsymbol{L_{Rcan}} - \boldsymbol{Lc_{34}}) - (\boldsymbol{Lc_{12}} - \boldsymbol{L_{Tcan}})(r_3 + R_L)\}^2 \omega^2}$
	Power (Secondary side)：$\boldsymbol{P_3}$
Without CCC	$\dfrac{V_1^2 (L_m - L_{dia})^2 R_L \omega^2}{(\{(L_m - L_{dia})^2 - \boldsymbol{Lc_{12}Lc_{34}}\}\omega^2 - \gamma)^2 + \{r_1 \boldsymbol{Lc_{34}} + \boldsymbol{Lc_{12}} (r_3 + R_L)\}^2 \omega^2}$
With CCC	$\dfrac{V_1^2 (L_m - L_{dia})^2 R_L \omega^2}{(\{(L_m - L_{dia})^2 + (\boldsymbol{Lc_{12}} - \boldsymbol{L_{Tcan}})(\boldsymbol{L_{Rcan}} - \boldsymbol{Lc_{34}})\}\omega^2 - \gamma)^2 - \{r_1 (\boldsymbol{L_{Rcan}} - \boldsymbol{Lc_{34}}) - (\boldsymbol{Lc_{12}} - \boldsymbol{L_{Tcan}})(r_3 + R_L)\}^2 \omega^2}$

$\gamma = -r_1 (r_3 + R_3)$

TABLE.3 Parameters of fabricated devices

		Tx		Rx	
		$n = 1$	$n = 2$	$n = 3$	$n = 4$
Main Coils	L_n [μH]	47.4	48.8	48.6	46.4
	r_n [Ω]	0.093	0.089	0.074	0.075
	C_n [nH]	261.8	249.7	251.8	268.2
Cancel Coils	L_n [μH]	5.62	5.61	5.80	5.50
	r_n [Ω]	0.0089	0.019	0.0084	0.012

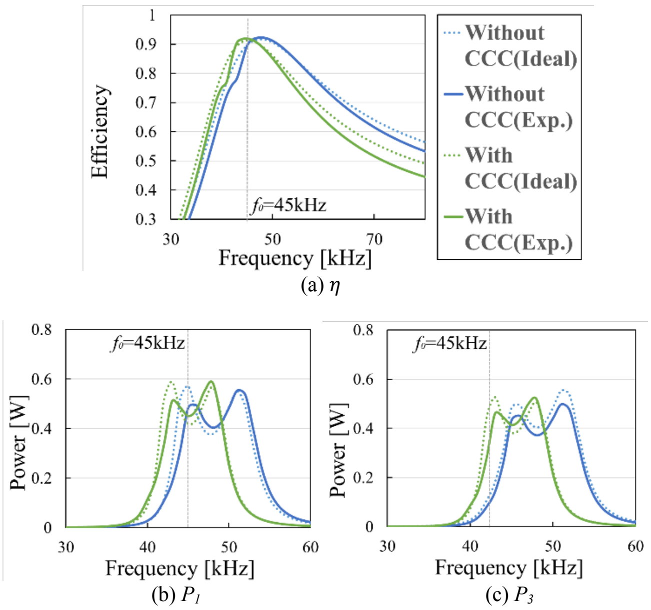


Fig.4 Consistency between formulation and circuit analysis

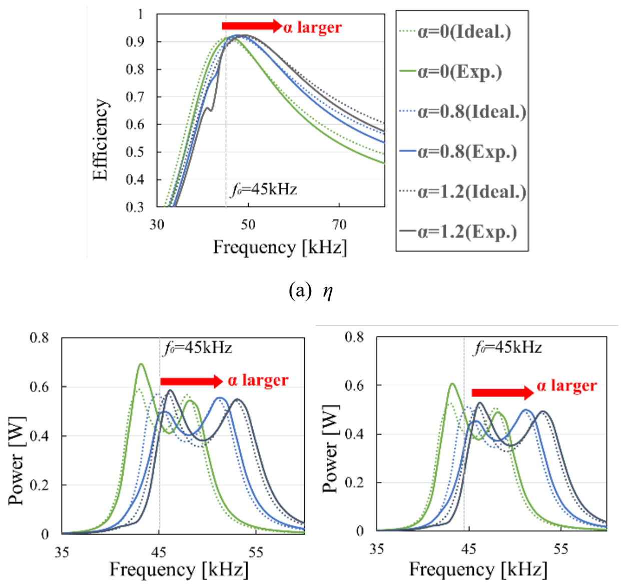
$L_n = 50\times10^{-6}$ μH, $r_n = 0.1\Omega$ and $C_n = 250\times10^{-9}$ nH. When the CCC is achieved, the terms for L_{c12} and L_{c34} in TABLE.1 and 2 are assumed to be zero. The parameters of the fabricated coils are shown in TABLE.3. They were measured with impedance analyzer (KEYSIGHT E4900A). The self-inductance, internal resistance and capacitance of the resonant capacitor of each coil are denoted as L_n, r_n and C_n, respectively. The parameters of the canceling coil inserted into each circuit for CCC are also shown. Fig.4 shows the comparison between the transmission characteristics of the ideal device (Ideal.) and the circuit analysis results using measured parameters (Exp.). It can be confirmed that the peak efficiency and the frequency point for the minimum power are almost the same for both devices. Although the values at arbitrary frequencies are different between the formulations and the experiment, the motion of the characteristics are almost the same.

B. Relative value change of CC

We have been shown up to the previous chapter that it is theoretically possible to increase efficiency and power by inserting a canceling coil. The relationship between the ratio of CC to the main coupling and the transmission characteristics is an important indicator when considering applications that take CC into account. When the absolute value of the ratio of the main coupling (L_m) to CC (L_c) is α (see equation (8)), the efficiency and the power shift are shown in Fig.5, respectively, where CC is set as $L_c = L_{c12} = L_{c34}$ and the ratio of the main coupling (L_m) to CC (L_c) is α ((8)). The transmission characteristics (Ideal.) obtained from the ideal device formulation and the experiment results using measured parameters (Exp.) are compared, and it can be confirmed that the peak efficiency and the frequency points for the minimum power are almost the same for different values of α in the formulations and the circuit analysis.

$$\alpha = |\frac{L_c}{L_m}| \quad (8)$$

We can see that the efficiency and power characteristic curve itself shifts to higher frequencies than 45 kHz as the value of α increases. Here, only the value of CC, i.e., the value of the molecule on the right side of equation (8), is changed. A larger value of CC relative to the main coupling shifts the efficiency curve more to the right. Due to the shift of the efficiency curve, the efficiency decreases at the 45 kHz resonance point and the efficiency improvement increases when CCC is achieved.



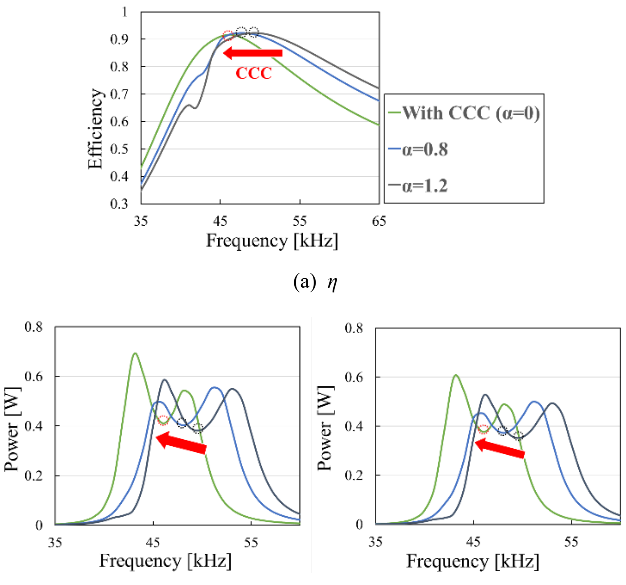
(a) η

(b) P_1 (c) P_3

Fig.5. Change in characteristics depending on α

C. *Impact of CCC on Power*

Fig.6 shows that the power value at the peak efficiency frequency decreases with the increase of α.



(a) η

(b) P_1 (c) P_3

Fig.6. Changes in efficiency and power values under actual resonance

In order to improve the power transmission characteristics considering CC, we consider a method of tracking from the defined resonant frequency to the frequency that is the central valley of the two peaks of power (higher than 45 kHz in this case; the direction of the arrow in Fig. 6) without changing the load connected to the Rx side. In this case, Fig.6(b) and (c) show that even if the efficiency is maintained as shown in Fig.6(a), the transmission power decreases. The case of α = 0 in Fig.5 and Fig.6 indicates the case where the exact CCC is achieved, which means that the power is improved in addition to the efficiency.

IV. CONCLUSION

In this paper, CCC is formulated and its credibility is confirmed through analysis verification. In the formulation, it has been confirmed that the efficiency and power can be improved by manipulating the elements involved in CC by inserting the canceling coil. In the future, we will determine the input conditions of the power supply and the target values of the transmission power, and expand the verification of the effect of CCC.

ACKNOWLEDGMENT

This work was partly supported by JSPS KAKENHI Grant Number 17H0491.

REFERENCES

[1] B. L. Cannon, J. F. Hoburg, D. D. Stancil, and S. Copen Goldstein: "Magnetic Resonant Coupling As a Potential Means for Wireless Power Transfer to Multiple Small Receivers", IEEE Transactions on Power Electronics, Vol.24, No.7, pp.1819-1825 (2009)

[2] T. Imura and Y. Hori: "Equivalent Circuit Theory of Multiple Antennas for Wireless Power Transfer via Magnetic Resonant Coupling", 2011 Annual Conference of the Institute of Electrical Engineers of Japan Industry Applications Society, 2-9, pp.II-399-II-402 (2011)

[3] T. Imura: "Simultaneous Wireless Power Transfer via Magnetic Resonant Coupling to Multiple Receiving Coils", 2014 the Institute of Electrical Engineers of Japan Industry Applications Society, Vol.134, No.6 pp.625-633

[4] S. Kim, G. A. Covic, and J. T. Boys: "Tripolar Pad for Inductive Power Transfer Systems for EV Charging", IEEE Transactions on Power Electronics, Vol.32, No.7, pp.5045-5057 (2017)

[5] H. Narita, T. Imura, H. Fujimoto, and Y. Hori: "Electromagnetic Field Suppression in Polyphase Wireless Power Transfer via Magnetic Resonance Coupling", The Institute of Electronics Information and Communication Engineers, June, 2014

[6] D. Cui, T. Imura, and Y. Hori: "Cross Coupling Cancellation for All Frequencies in Multiple-Receiver Wireless Power Transfer Systems", The Institute of Electronics Information and Communication Engineers, WPT2016-15, pp.29-32 (2016)

[7] T. Imura: "Equivalent Circuits of Repeater Antennas for Wireless Power Transfer via Magnetic Resonant Coupling", The Transactions of the Institute of Electrical Engineers of Japan, Vol.131, No.12, pp.1373-1382 (2011)

[8] C. K. Lee, W. X. Zhong, and S. Y. R. Hui: "Effects of Magnetic Coupling of Nonadjacent Resonators on Wireless Power Domino-Resonator Systems", IEEE Transactions on Power Electronics, Vol.27, No.4, pp.1905-1916 (2012)

[9] J. Kim, H. -C. Son, D. -H. Kim, and Y. -J. Park: "Impedance matching considering cross coupling for wireless power transfer to multiple receivers", Wireless Power Transfer (WPT), IEEE, pp.226-229 (2013)

[10] T. Imura: "Cross-Coupling Canceling Method for Wireless Power Transfer via Magnetic Resonance Coupling", The Transactions of the Institute of Electrical Engineers of Japan on Industry Applications, Vol.134, No.5, pp.564-574 (2014)