Automatic Active Compensation Method of Cross-Coupling in Multiple-receiver Resonant Inductive Coupling Wireless Power Transfer Systems

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Automatic Active Compensation Method of Cross-Coupling in Multiple-receiver Resonant Inductive Coupling Wireless Power Transfer Systems

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***Abstract*—The ability to charge to multiple receivers simultaneously with a single transmitter is one of the advantages of resonant inductive coupling wireless power transfer (RIC-WPT) technologies. However, in multiple-receiver RIC-WPT systems, each receiver often suffers from the magnetic coupling among receivers, i.e., cross-coupling. The cross-coupling not only complicates the control of the receivers but also significantly decreases the output power of each receiver. Hence, the purpose of this paper is to propose a compensation method of the influence due to the cross-coupling. To achieve this purpose, we first analyze the requirement to compensate for the influence of the cross-coupling. As a result, we reveal that it is necessary to control the phase of the current in all the receiver to be orthogonal to the phase of the transmitter current. Then, we propose the method to adjust the current phase of each receiver automatically to the desired phase by using only the phase information of the transmitter current, which results in the full compensation of the influence due to the cross-coupling. Furthermore, the proposed method also compensates for the influence of a detuning of the resonant frequency of each receiver due to the natural tolerance. Experiments of a two-receiver RIC-WPT system successfully verify the effectiveness of the proposed method.**

Keywords*—*wireless power transfer, resonant inductive coupling, multiple-receiver, cross-coupling, automatic active compensation

I. Introduction

Recently, wireless power transfer (WPT) technologies have been attracting significant public attention because the WPT technologies remove physical cable connections, which results in convenient, reliable, and safe power supplies. Among the WPT technologies, resonant inductive coupling WPT (RIC-WPT) technologies, which transfer the power via the magnetic coupling between coils, are widely studied owing to their comparatively high efficiency and high output power. Because of the advantage, the RIC-WPT technologies are expected to be applied to various application fields ranging from a few milliwatts up to several kilowatts of output power.

One of the attractive advantages of the RIC-WPT is that a single transmitter can transfer the power to multiple receivers simultaneously. Recently, owing to this attractive advantage, multiple-receiver RIC-WPT systems have been widely studied for low power applications such as mobile devices, wearable devices, and biomedical devices [1–7]. Usually, the multiple-receiver RIC-WPT system requires that the output power of each receiver does not depend on the position and output power of other receivers [1, 4]. In this study, we refer

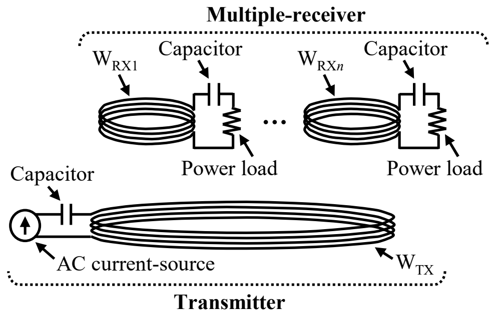


Fig. 1. Multiple-receiver resonant inductive coupling wireless power transfer (RIC-WPT) system.

to a receiver whose output power is not affected by the state of other receivers as a decoupled receiver.

The influence which a certain receiver receives from other receivers is divided into the following two types by its mechanism, and we must deal with two influences simultaneously to realize the decoupled receiver.

1) The first is the influence caused by the change in the amplitude of the transmitter current according to the output power of the receivers. The output power changes if the amplitude of the transmitter current changes because the induced voltage on the receiver from the transmitter is proportional to the amplitude of the transmitter current. Usually, in a common transmitter composed of a series LC resonant circuit, the resonance in the transmitter is excited by the AC voltage source consisting of a DC voltage source and a voltage-fed inverter [8, 9]. Hence, the amplitude of the transmitter current depends on the input impedance of the transmitter. The input impedance of the transmitter depends on not only parasitic resistance of the transmitter but also the output power of each receiver. Therefore, the amplitude of the transmitter current depends on the output power of each receiver.

2) The second is the influence caused by the induced voltage due to the magnetic coupling among receivers (i.e., cross-coupling). In this paper, we mainly focus on this influence. The influence of the cross-coupling occurs remarkably when the receivers are disposed of close to each other. Certainly, we can avoid the influence of the cross-coupling when the separation among the receivers is sufficiently larger than the size of receiver coils [6]. However, as pointed in [7], when there is the multiple-receiver in a limited space, we cannot probably avoid the influence of the cross-coupling. In the multiple-receiver RIC-WPT systems, the output power of each receiver may be significantly reduced when the cross-coupling occurs [1–3]. Furthermore, the control of the

receiver may become quite complicated because the output power depends on the output power of the other receivers and the relative positions of receiver coils [4].

Between two influences, it is known that the first influence can be solved relatively easily [1, 4]. To solve this problem, we have only to use the AC current source to excite the transmitter as shown in Fig. 1, where W_{TX} is the transmitter coil and W_{RXi} (i=1, …, n) are the receiver coils. As a result, we can obtain the transmitter current with the constant amplitude independent of the output power of each receiver, which eliminates the first influence. The AC current source can be implemented by feedback control of the voltage-fed inverter [10]. Alternatively, we may adopt an LCC topology [11] or a K-inverter [1] to the transmitter to obtain the load-independent transmitter current.

Then, the second influence due to the cross-coupling can be also solved theoretically by inserting an appropriate reactance to each receiver. Based on the previous studies [3, 4], the essence of the influence due to the cross-coupling is a detuning of the resonant frequency of each receiver. Therefore, the influence of the cross-coupling can be fully compensated by inserting an appropriate reactance to each receiver to retune the resonant frequencies [3, 4].

However, inserting the appropriate reactance to each receiver according to various situations is practically difficult. The appropriate reactance depends on the relative positions of coils and the output power of other receivers [3, 4]. Hence, we must accurately dynamically adjust the resonant frequency of each receiver by using a variable reactance element such as a variable capacitor and a variable inductor after estimation of the relative positions of coils and the output power of other receivers. Usually, this procedure is quite complicated.

Therefore, the purpose of this paper is to propose a compensation method of cross-coupling, which does not need the estimation of the relative positions of coils and the output power of other receivers. To achieve this purpose, we first investigate the phase of the transmitter current and receiver currents when the appropriate reactance is inserted into each receiver. The result shows that it is necessary to control the phase of the current in all the receiver to be orthogonal to the phase of the transmitter current. This insight is promising to compensate for the influence of the cross-coupling because adjusting the phase of each receiver current may be easier than inserting the appropriate reactance to each receiver. Then, we propose the receiver with a simple switching circuit, which adjusts the phase of the receiver current to the desired phase. The proposed method can adjust the phase of each receiver current automatically dynamically to the desired phase by using only the phase information of the transmitter current. As a result, we can fully compensate for the influence due to the cross-coupling without the estimation of the relative positions of coils and the output power of other receivers.

The remainder of this paper is structured into four sections. Section II shows the requirement of the phase of each receiver current to compensate for the influence of the cross-coupling. Section III shows the multiple-receiver RIC-WPT system with the proposed compensation method. Section IV carries out experiments to verify the effectiveness of the proposed compensation method. Finally, section V describes the conclusions.

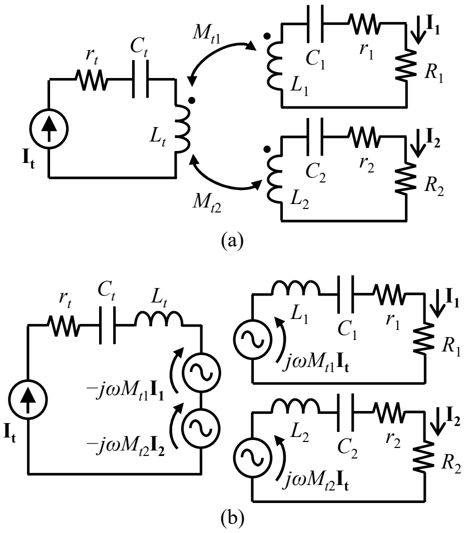


Fig. 2. Equivalent circuit of two-receiver RIC-WPT system without cross coupling. (a) Model based on coupling circuit. (b) Model based on induced voltage

II. Requirement for Compensation of Cross-Coupling

In this section, we first derive the output power of the decoupled receiver by analyzing the equivalent circuit ignoring the cross-coupling. The derived output power is used as a criterion to determine whether the decoupled receiver has been achieved. Then, we review the appropriate reactance for compensation of the influence due to the cross-coupling. In this paper, we specifically focus on the phase of the current in the transmitter and receivers when the appropriate reactance is inserted into each receiver. As a result, we show that the phase of the current in all the receiver must be orthogonal to the phase of the transmitter current to compensate for the influence of the cross-coupling.

In this study, a two-receiver RIC-WPT system is discussed as a representative example for simplicity. Furthermore, we assume that the quality factors of the resonators are high enough to adopt the first harmonic approximation analysis.

A. Output Power of Decoupled Receiver

Fig. 2 shows the equivalent circuit of Fig. 1 ignoring the cross-coupling. In Fig. 2, $\mathbf{I_t}$, $\mathbf{I_1}$, and $\mathbf{I_2}$ are the transmitter current and the receiver currents, respectively; L_t, L_1, and L_2 are the self-inductances of W_{TX}, W_{RX1}, and W_{RX2}, respectively; r_t, r_1, and r_2 are the parasitic resistances of W_{TX}, W_{RX1}, and W_{RX2}, respectively; R_1 and R_2 are the equivalent values of load resistances; C_t, C_1, and C_2 are the capacitances of the resonant capacitors; M_{t1} is the mutual inductance between W_{TX} and W_{RX1}; M_{t2} is the mutual inductance between W_{TX} and W_{RX2}. The magnetic couplings of Fig. 2 (a) can be replaced with the induced voltage as shown in Fig. 2 (b).

Usually, in the RIC-WPT systems, the receiver is required to obtain the output power as high as possible from a given induced voltage generated by the transmitter. Therefore, the total reactance of the self-inductance of the coil and the capacitance of the resonant capacitor is designed to be zero at the operating frequency, i.e., $\omega L_1-1/\omega C_1=0$ and $\omega L_2-1/\omega C_2=0$. In this case, because the receivers are resistive circuits, the induced voltages from the transmitter, i.e., $j\omega M_{t1}\mathbf{I_t}$ and $j\omega M_{t2}\mathbf{I_t}$, achieve a unity power factor. The output power of each receiver, i.e. P_1 and P_2, can be expressed as

$$P_1 = R_1 \left| \frac{j\omega M_{t1}\mathbf{I_t}}{r_1 + R_1} \right|^2, \quad P_2 = R_2 \left| \frac{j\omega M_{t2}\mathbf{I_t}}{r_2 + R_2} \right|^2. \tag{1}$$

The equations of (1) show the output powers of the decoupled receiver because Fig. 2 does not consider the cross-coupling.

B. Phase Condition of Resonator Currents for Compensation of Cross-Coupling

Then, we discuss the appropriate reactance for compensation of the influence due to the cross-coupling. Fig. 3 shows the equivalent circuit of Fig. 1 considering the cross-coupling, where M_{12} is the mutual inductance due to the cross-coupling, X_{opt1} and X_{opt2} are the reactances to compensate for the influence of the cross-coupling. As in Fig. 2, the magnetic coupling of Fig. 3 (a) can be replaced with the induced voltage as shown in Fig. 3 (b). Note that $j\omega M_{12}\mathbf{I_2}$ and $j\omega M_{12}\mathbf{I_1}$ are the induced voltages due to the cross coupling.

Even if the cross-coupling occurs, we can compensate for the influence of the cross-coupling by adjusting the reactances of X_{opt1} and X_{opt2} so that the phase of each receiver current is orthogonal to the phase of the transmitter current. Fig. 3 (c) shows the phasor diagrams at the adjustment, where, the phase angle of $\mathbf{I_t}$ is defined as $-\pi/2$. Furthermore, in Fig. 3 (c), I_t, I_1, and I_2 denote the effective values of $\mathbf{I_t}$, $\mathbf{I_1}$, and $\mathbf{I_2}$, respectively. As shown in Fig. 3 (c), in each receiver, the phase of the induced voltage due to the cross-coupling is orthogonal to the phase of the receiver current, which means that the induced voltage of the cross-coupling behaves as the reactance of the receiver. The voltages of X_{opt1} and X_{opt2} operate to cancel the induced voltages of the cross-coupling. At this condition, each receiver receives only the effective power from the transmitter and does not receive the effective power from another receiver. Therefore, the receivers only exchange reactive power. As a result, the output power of each receiver is identical to (1). Furthermore, from Fig. 3 (c), the appropriate reactances to compensate for the influence of the cross-coupling can be derived as

$$\begin{cases} X_{opt1} = -\omega M_{12} M_{t2}\left(r_1 + R_1\right) / M_{t1}\left(r_2 + R_2\right), \\ X_{opt2} = -\omega M_{12} M_{t1}\left(r_2 + R_2\right) / M_{t2}\left(r_1 + R_1\right). \end{cases} \tag{2}$$

Equation (2) is identical to optimal load reactances to compensate for the influence of the cross-coupling revealed in [4] (See (22) of [4]). The appropriate reactances depend on the load resistances (i.e., the output powers), the parasitic resistances, and the mutual inductances (i.e., the relative positions of coils). Therefore, as pointed in [4], inserting the appropriate reactance may require the estimation of the load resistances, the parasitic resistances, and the mutual inductances. However, as shown in this paper, we can compensate for the influence of the cross-coupling by detecting the phases of the transmitter current and receiver currents and adjusting the phase of each receiver current instead of inserting the appropriate reactances after estimating the output powers, the parasitic resistances, and the mutual inductances.

III. Proposed Method

In this section, we propose the method to adjust the phase of each receiver current and compensate for the influence of the cross-coupling. First, we show the circuit configuration of the multi-receiver RIC-WPT system with the proposed compensation method. Then, we describe its operating principle.

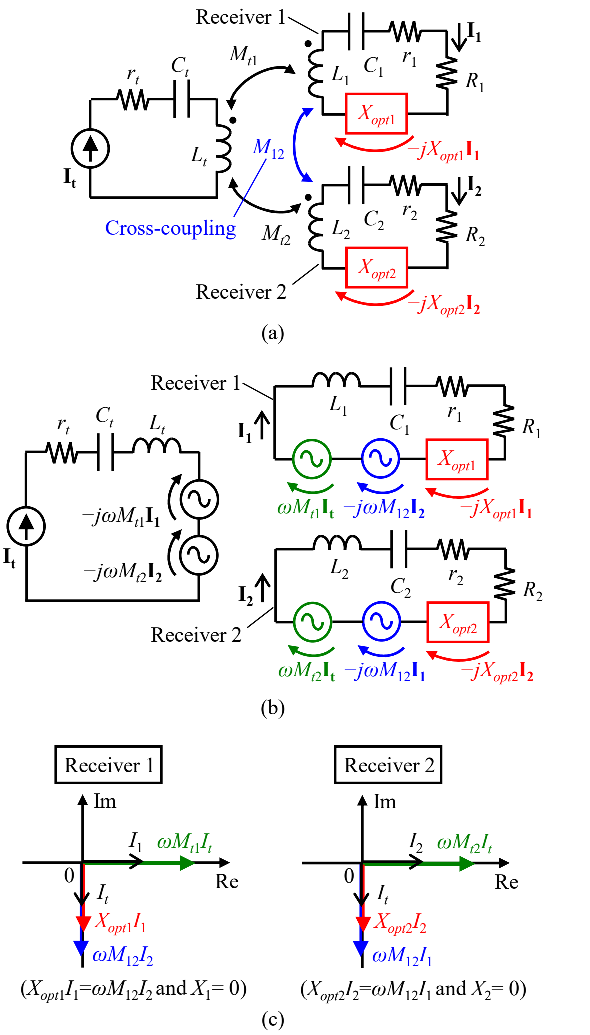


Fig. 3. Equivalent circuit with appropriate reactance for compensating cross coupling. (a) Model based on coupling circuit. (b) Model based on induced voltage. (c) Phasor diagram of two receivers.

A. Circuit Configuration

As a method to adjust the phase of the receiver currents, we apply the variable reactance element to each receiver. Recently several techniques have been proposed to configure the variable reactance element, such as a capacitor matrix [12–14], DC-voltage-controlled variable capacitor [15], gate-controlled series capacitor [16], mechanical variable capacitor controlled by the stepping motor [17], variable inductor [18, 19], and simple switching circuit named automatic tuning assist circuit (ATAC) [20–22]. Among these techniques, the ATAC is more attractive than other variable reactance elements for the compensation of the influence due to the cross-coupling. The ATAC can automatically adjust the phase of the receiver current to the desired phase without detecting the receiver current. Hence, in this paper, we propose an application of the ATAC to each receiver to compensates for the influence of the cross-coupling.

The ATAC is originally proposed by [20] for a single receiver SS topology of the RIC-WPT. The previous study [20] approached a problem where the resonant frequency of the transmitter has the natural tolerance due to the manufacturing tolerance by proposing the ATAC. Usually, the variation in the resonant frequency of the transmitter is a critical issue for the RIC-WPT system because it decreases the power factor of the power source, which results in lowering the output power and efficiency. The previous study [20] revealed that the transmitter with ATAC automatically achieves a unity power factor of the power source without detecting the transmitter current even if there is the variation in the resonant frequency of the transmitter. On the other hand, in this paper, we reveal that the receiver with the ATAC can automatically compensate for the influence of the cross-coupling.

Fig. 4 shows the multiple-receiver RIC-WPT system with the ATACs. As shown in Fig. 4, the ATAC comprises the half-bridge circuit. The DC bus of the half-bridge circuit has only the smoothing capacitor. Note that the DC bus of the half-bridge circuit does not have any additional voltage supply. The smoothing capacitor does not contribute to the resonant frequency of the receiver because the smoothing capacitor has a sufficiently large capacitance than the resonant capacitor. The half-bridge circuit of the ATAC operates at the same operating frequency as the transmitter current. Therefore, in the equivalent circuit, the ATAC can be described as the AC voltage source, where V_{A1_dc} and V_{A2_dc} are the DC voltages of the smoothing capacitors, $\mathbf{V_{A1}}$ and $\mathbf{V_{A2}}$ are the output voltages of the ATACs.

B. Operating Principle

To compensate for the influence of the cross-coupling, the half-bridge circuit of each ATAC has only to operate with the fixed phase difference shifted by π against the transmitter current. Hence, the ATAC does not require to detect the phase of the receiver currents to adjust the phase of the receiver current to the desired phase. Fig. 5 shows the phasor diagrams at this operation, where, the phase angle of $\mathbf{I_t}$ is defined as $-\pi/2$ as a reference. Furthermore, in Fig. 5, V_{A1} and V_{A2} denote the effective values of $\mathbf{V_{A1}}$ and $\mathbf{V_{A2}}$, respectively. Fig. 6 shows the key waveforms of Fig. 4 in the steady state. Ideally, the ATAC does not have any resistive components because the ATAC consists of only the half-bridge circuit and the smoothing capacitor, which means that the ATAC does not receive the effective power in the steady state. Therefore, in the steady state, the phase of the receiver current must be orthogonal to the phase of the output voltage of the ATAC. Hence, if we set the phase of the output voltage of the ATAC in advance, the phase of the receiver current is automatically determined so that the phase of the receiver current is orthogonal to the phase of the output voltage of the ATAC. This means that the ATAC inserts the reactance to the receiver and adjust the phase of the receiver current to the target phase. Therefore, the amplitude of the output voltage of the ATAC is automatically determined according to the value of the reactance required for the phase of the receiver current to adjust to the target phase.

Then, based on the operating principle of the ATAC, we derive the output powers and the output voltages of the ATACs. According to Kirchhoff's voltage law, based on Fig. 5, the operation of the receivers can be described as

$$\begin{cases} jV_{A1} + \omega M_{t1} I_t - j\omega M_{12} I_2 = \left[\left(r_1 + R_1 \right) + jX_1 \right] I_1, \\ jV_{A2} + \omega M_{t2} I_t - j\omega M_{12} I_1 = \left[\left(r_2 + R_2 \right) + jX_2 \right] I_2. \end{cases} \quad (3)$$

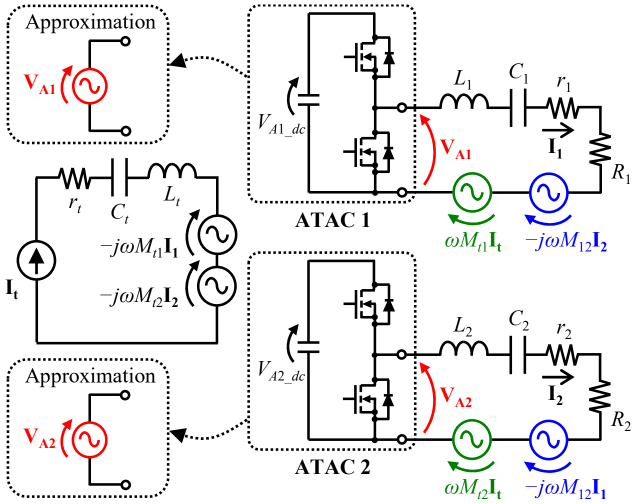


Fig. 4. Two-receiver RIC-WPT system with proposed compensation method of cross coupling.

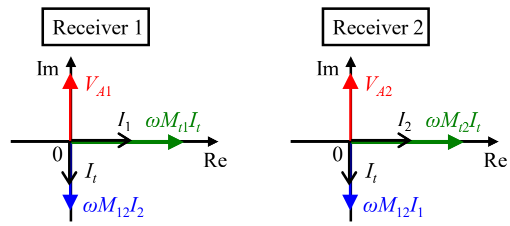


Fig. 5. Phasor diagram of receivers in Fig. 4.

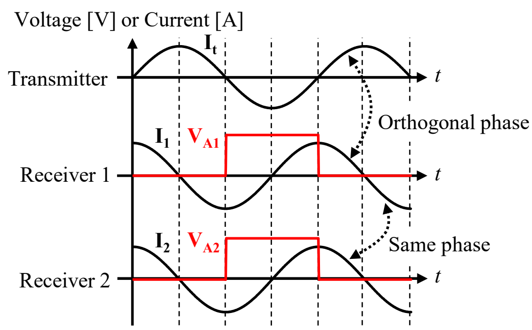


Fig. 6. Key waveforms of Fig. 4 in zero-voltage-switching (ZVS) operation.

From (3), the output power of each receiver can be obtained respectively as

$$P_1 = R_1 \left(\frac{\omega M_{t1} I_t}{r_1 + R_1} \right)^2, \quad P_2 = R_2 \left(\frac{\omega M_{t2} I_t}{r_2 + R_2} \right)^2. \quad (4)$$

The results of (4) and (1) are identical, which indicates that the proposed compensation method achieves the decoupled receiver. Then, the output voltages of the ATACs can be obtained respectively as

$$\begin{cases} V_{A1} = \omega^2 M_{t2} M_{12} I_t / \left(r_2 + R_2 \right) + \omega M_{t1} X_1 I_t / \left(r_1 + R_1 \right), \\ V_{A2} = \omega^2 M_{t1} M_{12} I_t / \left(r_1 + R_1 \right) + \omega M_{t2} X_2 I_t / \left(r_2 + R_2 \right). \end{cases} \quad (5)$$

The first terms on the right-hand side of (5) are the voltages to compensate for the influence of the cross-coupling. On the

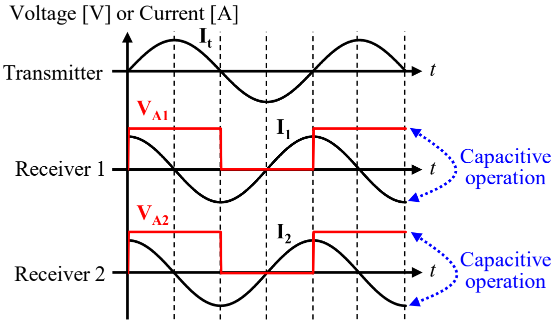


Fig. 7. Waveforms of Fig. 4 in hard switching operation.

other hand, the second terms on the right-hand side of (5) are the voltages to compensate for the influence due to the natural tolerance of the resonant frequency in the receiver. Usually, the self-inductance and the capacitance of the receiver have the natural tolerance due to the manufacturing tolerance, the temperature characteristic, and the aging deterioration (i.e., $X_1 \neq 0$, $X_2 \neq 0$). Therefore, to make consistent the resonant frequency of each receiver with the operating frequency is practically difficult. The natural tolerance of the resonant frequency in the receiver decreases the output power as well as the efficiency. The proposed compensation method can automatically compensate not only the influence of the cross-coupling but also the influence of the natural tolerance in the receivers.

The loss of the ATACs should be suppressed as much as possible for the high efficiency. Therefore, the half-bridge circuit of the ATAC must avoid the hard-switching operation. In other words, the half-bridge circuit of the ATAC must maintain the zero-voltage-switching (ZVS) operation. To achieve the ZVS operation, V_{A1} and V_{A2} must be positive when the phase angle of $\mathbf{I_t}$ is defined as $-\pi/2$. In this case, the ZVS operation is achieved because the relations between $\mathbf{V_{A1}}$ and $\mathbf{I_1}$ as well as $\mathbf{V_{A2}}$ and $\mathbf{I_2}$ are inductive, respectively. However, based on (5), V_{A1} and V_{A2} may be negative depending on the polarities of M_{t1}, M_{t2}, and M_{12}. The smoothing capacitor of the ATAC cannot charge negative voltage owing to the body diodes of the half-bridge circuit. Therefore, when V_{A1} and V_{A2} of (5) fall below the zero, the ATAC operate as the shorted circuit because the output power of the ATAC is zero. Even if V_{A1} and V_{A2} of (5) fall below the zero, to obtain the positive voltage in the smoothing capacitor of the ATAC, the ATAC must operate so that the phase of the output voltage of the ATAC is identical to the phase of the transmitter current as shown in Fig. 7. However, in this case, the relations between $\mathbf{V_{A1}}$ and $\mathbf{I_1}$ as well as $\mathbf{V_{A2}}$ and $\mathbf{I_2}$ are capacitive. In the operation of Fig. 7, although the influence of the cross-coupling can be compensated, the half-bridge circuit of the ATAC cannot avoid the hard-switching operation. Therefore, in some cases, we must design X_1 and X_2 in advance so that V_{A1} and V_{A2} of (5) are positive under all values of the supposed mutual inductances.

IV. Experiment

In this section, we experiment to verify that the proposed method is effective to compensate for the following two influences:

1) Influence of the cross-coupling
2) Influence of the variation in the resonant frequency of the receiver

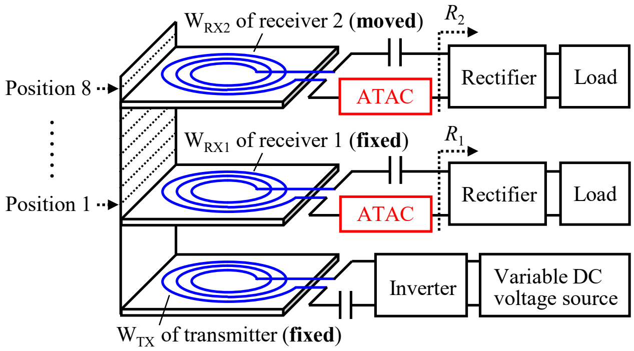


Fig. 8. Schematic of experimental setup.

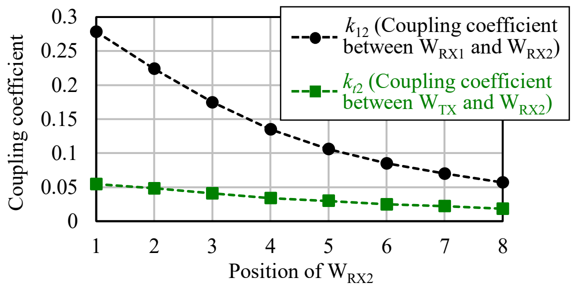


Fig. 9. Coupling coefficient.

TABLE I. Circuit Parameters for Verification of Effectiveness Against Cross-Coupling

Symbols / Parameters		Values
L_t	Self-inductance of W_{TX}	140.95 μH
L_1	Self-inductance of W_{RX1}	55.15 μH
L_2	Self-inductance of W_{RX2}	55.24 μH
r_t	Parasitic resistance of transmitter	0.24 Ω
r_1	Parasitic resistance of receiver 1	0.13 Ω
r_2	Parasitic resistance of receiver 2	0.13 Ω
C_t	Capacitance of transmitter	7.12 nF
C_1	Capacitance of receiver 1	17.92 nF
C_2	Capacitance of receiver 2	17.97 nF
k_{t1}	Coupling coefficient between W_{TX} and W_{RX2}	0.11
I_t	Transmitter current	1.0 A
f_s	Operating frequency	160.10 kHz
R_1	Equivalent load resistance of receiver 1	4.56 Ω
R_2	Equivalent load resistance of receiver 2	2.02 Ω

A. *Verification of Effectiveness Against Cross-Coupling*

Fig. 8 shows the schematic of the experimental setup of the proposed system. In this paper, we refer to the system with the proposed method as the proposed system. The AC current-source of the transmitter is implemented by the voltage-fed inverter and the variable DC voltage source. The positions of W_{TX} and W_{RX1} of the receiver 1 are fixed. Hence, M_{t1} is a constant value. On the other hand, to evaluate characteristics dependence on the cross-coupling, W_{RX2} of the receiver 2 is moved through eight different vertical positions. Hence, M_{t2} and M_{12} are different depending on the position of W_{RX2}, respectively. In this subsection, we evaluate the output power, the efficiency, and the voltages of the ATACs on the receivers at each position of W_{RX2}. Fig. 9 shows the coupling coefficients according to the position of W_{RX2}, where, $k_{t2}=M_{t2}/(L_tL_2)^{1/2}$ and $k_{12}=M_{12}/(L_1L_2)^{1/2}$. Other circuit

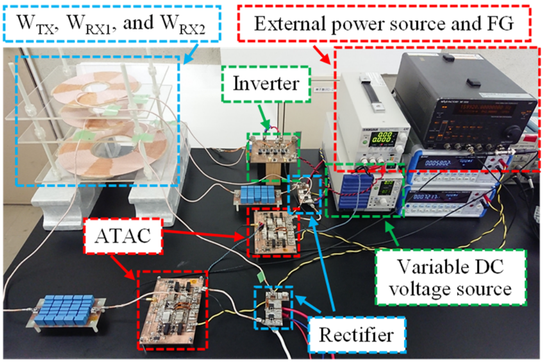
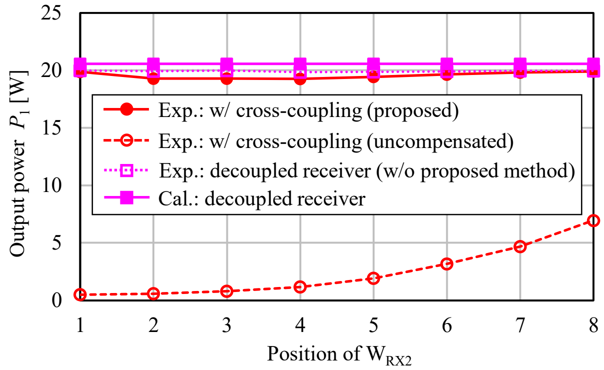


Fig. 10. Photograph of experimental setup.

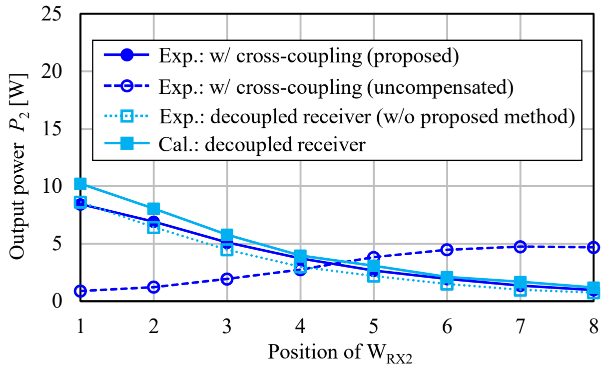
parameters are summarized in Table I, where $k_{t1}=M_{t1}/(L_tL_1)^{1/2}$. In the experiments of this subsection, the inductance and the capacitance of the receivers are well-tuned to satisfy $X_1\approx0$ and $X_2\approx0$ at the operating frequency. Furthermore, the coils are arranged so that the polarities of all mutual inductances are positive.

Fig. 10 shows the photograph of the experimental setup of the proposed system. In this paper, we generate the gating signals for the ATACs and the inverter of the transmitter by using a synchronized function generator (FG). Furthermore, we use a common external power source as a power source for the gate drive circuits for the ATACs and the inverter of the transmitter. Certainly, the proposed method requires an additional synchronization technique to drive the ATACs with the phase difference of π from the transmitter current if we apply the proposed method to practical multi-receiver RIC-WPT systems. However, the purpose of this paper is to show the feasibility of the proposed method to compensate for the influence of the cross-coupling. Therefore, the synchronization technique is out of the scope of this paper. The synchronization technique may be studied in future papers.

Fig. 11 shows the output power of each receiver according to the position of W_{RX2}. In this paper, we refer to the system which does not compensate for the influence of the cross-coupling as an uncompensated system. Hence, the uncompensated system does not have the proposed method. When we measure the output power of the decoupled receiver, we measure the output powers separately for each receiver, and the unmeasured side of the receiver is opened. As shown in Fig. 11 (a), in the proposed system, the output power of the receiver 1 is almost constant regardless of the position of W_{RX2}. This result well corresponds to the experimental result of the decoupled receiver. Furthermore, in the proposed system, the output power of the receiver 2 can obtain almost the same power of the decoupled receiver. Fig. 12 shows the experimental waveforms of the proposed system at position 4. As shown in Fig. 12, the phase of each receiver current is orthogonal to the phase of the transmitter current. Hence, we can compensate for the influence of the cross-coupling. Meanwhile, in the uncompensated system, the output power of receiver 1 significantly decreases as W_{RX2} is close to W_{RX1}. Furthermore, in the uncompensated system, the transition of the output power in receiver 2 largely deviates from the transition of the output power in the decoupled receiver. Fig. 13 shows the experimental waveforms of the uncompensated system at position 4. As shown in Fig. 13, the phase of each receiver current is not orthogonal to the phase of the transmitter current. Therefore, the output power of each



(a)



(b)

Fig. 11. Experimental results of output power at each position of W_{RX2}. (a) Receiver 1. (b) Receiver 2.

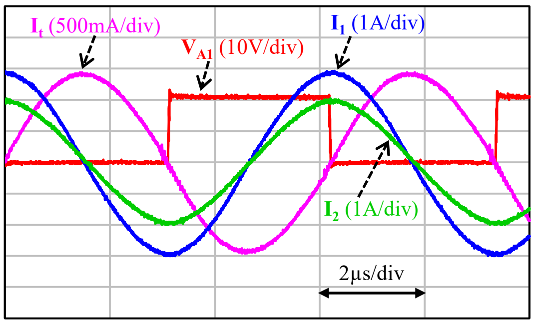


Fig. 12. Experimental waveforms of proposed system at position 4.

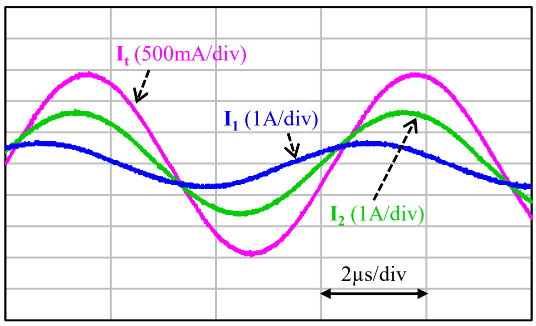


Fig. 13. Experimental waveforms of uncompensated system at position 4.

receiver suffers from the influence of the cross-coupling. Certainly, in positions 5–8, the output power of receivers 2 of the uncompensated system are more significant than the output powers of the decoupled receiver because the receiver 1 operates as a repeater [21] to relay the magnetic field to W_{RX2} from W_{TX} [2]. However, this is not practical for the

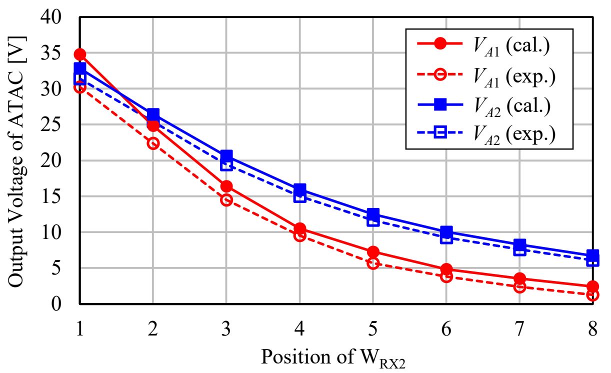


Fig. 14. Experimental results of output voltages of ATACs at each position of W_{RX2}.

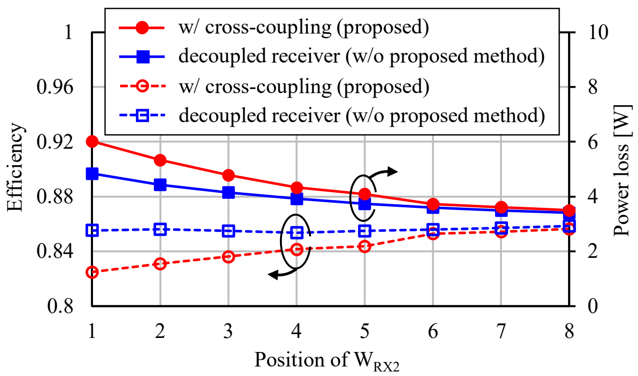


Fig. 15. Experimental results of Efficiency and power loss at each position of W_{RX2}.

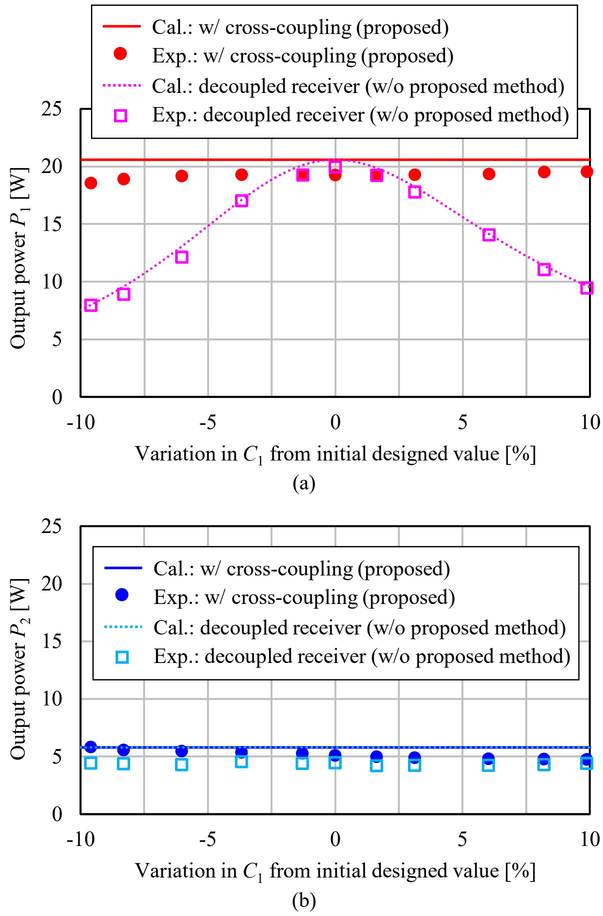


Fig. 16. Experimental results of output power against variation in C_1 from initial value of Table I. (a) Receiver 1. (b) Receiver 2.

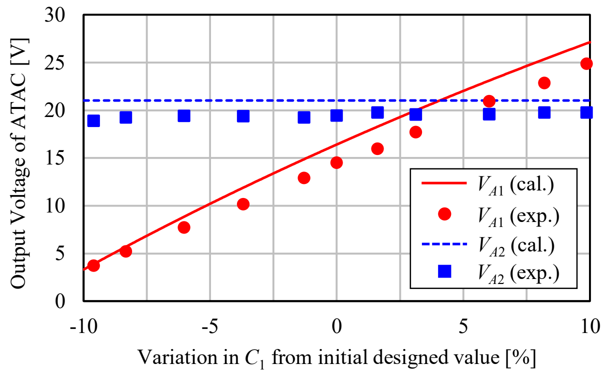


Fig. 17. Experimental results of output voltages of ATACs against variation in C_1 from initial value of Table I.

multiple-receiver RIC-WPT system because the decoupled receiver is not achieved.

Then, Fig. 14 shows the output voltages of the ATACs according to the position of W_{RX2}. The ATACs automatically adjust the output voltage by itself so that the phase of each receiver current is orthogonal to the phase of the transmitter current. The voltages of the ATACs increase as W_{RX2} is close to W_{RX1} because the induced voltage due to the cross-coupling to be compensated by the ATAC increases. The experimental results are in relatively good agreement with the theoretical calculation results.

Next, we evaluate the power loss from inserting the ATACs. Fig. 15 shows the comparison results of the efficiency and power loss. The efficiency and the power loss consider the power loss of the transmitter. In Fig. 15, we define the input/output power of the decoupled receiver system as the sum of the powers measured separately for each receiver. From Fig. 15 and Fig. 14, the additional power loss from inserting the ATACs tends to be large as the output voltages of the ATACs increase. Hence, the additional power loss from inserting the ATACs is assumed to be mainly caused by the switching loss of the ATACs. However, owing to the ZVS operations of the ATACs, the additional power loss from inserting the ATACs is at most a few watts. Therefore, the proposed system can compensate for the influence of the cross-coupling with only a slight loss. From the above results, the effectiveness of the proposed method against the influence of the cross-coupling can be verified.

B. Verification of Effectiveness Against Variation in Resonant Frequency of Receiver

Finally, we show that the proposed method can suppress the lowering the output power due to the variation in the resonant frequency of the receiver. In the experiments for this subsection, the receiver 2 is fixed to the position 3. The other circuit parameters are the same as the values of Table I. In this subsection, we evaluate the characteristics when the resonant frequency of the receiver 1 changes. The variation in the resonant frequency of the receiver 1 is achieved by changing C_1 from the initial designed value of Table I by ±10%.

Fig. 16 and Fig. 17 show the results of the output power and the output voltages of the ATACs against the variation in

C_1 from initial designed value, respectively. In the decoupled receiver system, the output power of receiver 1 decreases as C_1 deviates from the initial designed value because residual reactance of X_1 restricts the current flow in the receiver 1. On the other hand, in the proposed method, the output power of the receiver 1 is almost constant regardless of the variation in C_1. As shown in Fig. 17, the ATAC on the receiver 1 automatically adjust the output voltage to compensate for the voltage of the residual reactance due to the variation in C_1. The output voltage of the ATAC on the receiver 2 does not depend on the variation in C_1 because the current in the receiver 1 is constant owing to the operation of the ATAC on the receiver 1. From the above results, it is verified that the proposed method can also compensate for the influence of the variation in the resonant frequency of the receiver.

V. Conclusion

The decoupled receiver is usually required to realize the practical multiple-receiver RIC-WPT systems. However, to realize the decoupled receiver is practically difficult due to the cross-coupling. Hence, in this paper, we first showed that the influence of the cross-coupling can be compensated fully when the phase of the current in each receiver is orthogonal to the phase of the transmitter current. Then, we proposed the receiver with the ATAC to adjust the phase of the current in each receiver to the desired phase. The proposed method can fully compensate for the influence of the cross-coupling by only driving the ATAC with the fixed phase difference of π to the transmitter current. Furthermore, the proposed method also can compensate for the influence of the detuning of the resonant frequency of the receiver due to the natural tolerance. Certainly, when we apply the proposed method to the practical multi-receiver RIC-WPT systems, the ATACs require an additional synchronization technique to synchronize the phase of each receiver current to the transmitter current. However, the proposed method does not need the complicated estimations of the disposition of the receivers and the output power of other receivers. Furthermore, the proposed method does not need to detect the phase of the receiver currents to compensate for the influence of the cross-coupling. The effectiveness of the proposed method is successfully verified by the experiments of the two-receiver RIC-WPT system. The experimental results suggest that the proposed method is promising to realize the decoupled receiver for the practical multi-receiver RIC-WPT systems.

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