Efficiency Maximization of Wireless Power Transfer Systems with Two Modes of Half Active Rectifier Based on Primary Current Measurement

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Abstract Applying wireless power transfer (WPT) to transportation applications is one of the best solutions to overcome drawbacks of electric vehicles (EVs). Although dynamic charging of EVs can extend their driving distance, control techniques have to be further developed to maintain maximum transmitting efficiency and to ensure a stable supply of energy because a dynamic WPT system has to deal with parameter variation such as distance change, load change, and so on. This paper proposes an efficiency maximization method based on the primary current change with power control on the secondary side using Half Active Rectifier. The reference value of the primary voltage is calculated based on the primary current measurement without signal communication. Simulations and experiments demonstrated that the reference voltage can be obtained with satisfactory accuracy and the transmitting efficiency can be maximized by primary-side voltage control regardless of secondary-side voltage variations.
Key words Wireless power transfer, Magnetic resonance coupling, Primary-side control, Efficiency maximization

1. Introduction

Wireless power transfer (WPT) has received much attention in transportation applications because eliminating the use of wiring improves convenience and safety [1]–[3]. In addition, dynamic charging of electric vehicles (EVs) is expected to extend the cruising distance of EVs and to reduce the size of the high-cost energy storage devices of EVs [4]. WPT via magnetic resonance coupling [5] is an excellent method for these applications because of its capability for a highly efficient mid-rage transmission. However, to maintain its maximum transmitting efficiency and a stable supply of energy, control techniques have to be further developed for a dynamic WPT system, which has to overcome parameter variation such as distance change, load change, and so on.

This paper aims to achieve power control and efficiency maximization simultaneously without signal communication and proposes a primary-side efficiency maximization method with power control on the secondary side. Simulations and experiments demonstrate the effectiveness of the proposed method.

2. Wireless Power Transfer System

2.1 System structure

The circuit diagram of the WPT system is shown in Fig. 1. The full-bridge inverter supplies the transmitter with a square voltage wave. Since this paper employs a series-series compensated circuit topology of WPT via magnetic resonance coupling, the transmitter and the receiver are designed as follows:

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{1}$$

where ω_0 is the angular frequency of the primary-side inverter.

Half Active Rectifier (HAR) is used for power control on the secondary side. The load is assumed to be a battery charging system, a motor drive system, and so on. In this paper, it was demonstrated by an electronic load (PLZ1004W, KIKUSUI).

Fig. 2 shows the experimental equipment. The specifications of the coils are indicated in Tab. 1. The power converters were controlled by a DSP (PE-PRO/F28335A, Myway).

2.2 Operation modes of HAR [3]

HAR consists of the upper arm diodes and the lower arm MOSFETs. The charging power is controlled by the two operation modes of HAR, which are illustrated in Fig. 3.

During the rectification mode, the charing power P is rectified by turning off the lower arm MOSFETs and flows into the DC link capacitor and the load. If P is larger than the load power P_L, the surplus power increases the DC link voltage V_{dc}.

On the other hand, the receiver is shorted by turning on the lower arm MOSFETs during the short mode. Although P is cut-off, P_L is supplied from the DC link capacitor. As a result, V_{dc} is decreased during the short mode.

By repeating these operation modes, V_{dc} can be controlled by HAR and the average charging power $\bar{P}$ accords with P_L

2.3 Efficiency maximization on the primary side

Since the charging power can be controlled by HAR on the secondary side, the primary voltage is optimized for maximizing the transmitting efficiency of the WPT system.

In this paper, an efficiency maximization method based on the measured primary current is proposed. In order to eliminate the need for signal communication between the primary side and the secondary side, the reference value of the primary voltage is derived based on primary-side information.

Especially, this paper focuses on the primary current during the each operation modes on HAR and the reference voltage is calculated based on the primary current measurement.

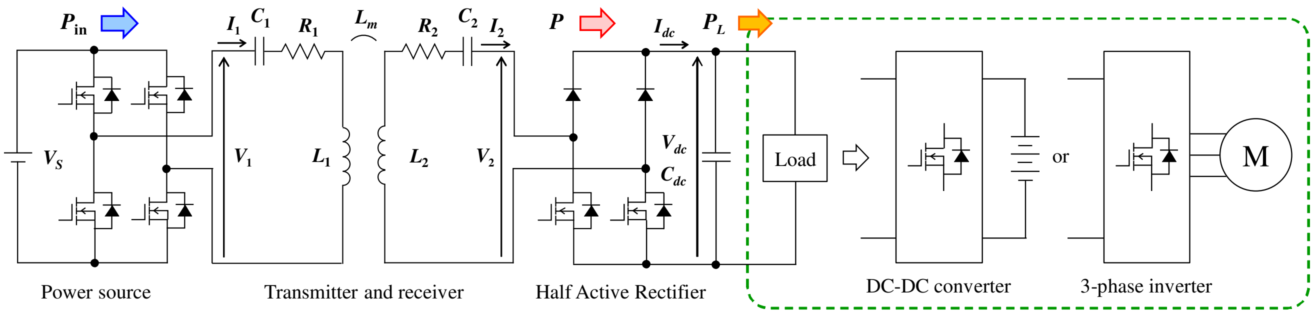
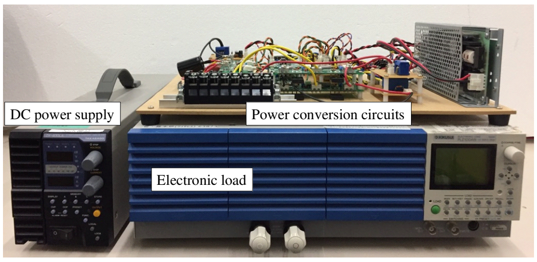
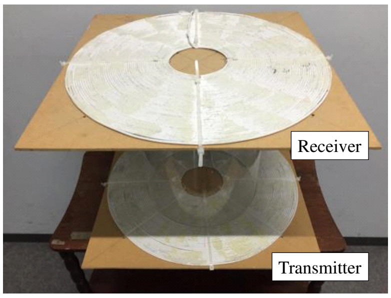


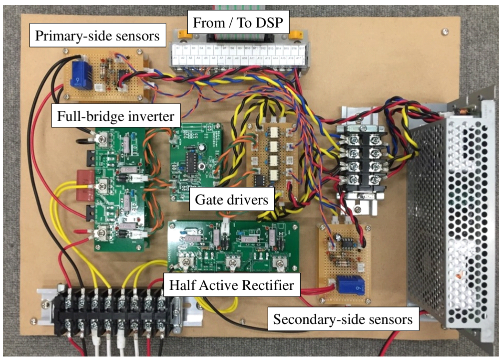
Fig. 1 Circuit diagram of the wireless power transfer system using Half Active Rectifier.



(a) Overview.

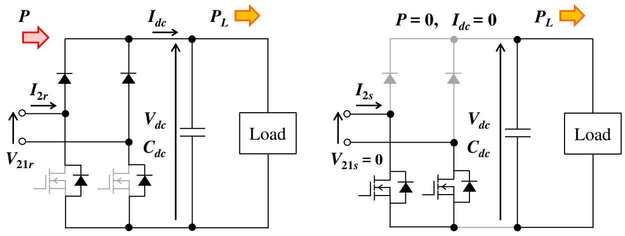


(b) Transmitter and receiver coils.



(c) Power conversion circuits.

Fig. 2 Experimental equipment.



(a) Rectification mode. (b) Short mode.

Fig. 3 Operation modes of Half Active Rectifier.

Table 1 Specifications of coils.

	Primary side	Secondary side
Resistance R_1, R_2	1.19 Ω	1.23 Ω
Inductance L_1, L_2	617 μH	617 μH
Capacitance C_1, C_2	4000 pF	4000 pF
Resonance frequency f_1, f_2	101.3 kHz	101.3 kHz
Mutual inductance L_m	37.3 μH	
Coupling coefficient k	0.060	
Outer diameter	440 mm	
Number of turns	50 turns	
Transmitting gap	300 mm	

3. Circuit Analysis

3.1 Fundamental voltages and currents

Assuming that iron losses are negligible, the equivalent circuit of WPT via magnetic resonance coupling is shown in Fig. 4 [6]. Since the primary-side inverter generates a square voltage wave, the RMS value of the fundamental primary voltage V_{11} is calculated as follows:

$$V_{11} = \frac{2\sqrt{2}}{\pi} V_1 = \frac{2\sqrt{2}}{\pi} V_S. \tag{2}$$

Additionally, the load is assumed to be a constant voltage load because the DC link voltage is controlled by HAR. If fluctuations in the DC link voltage are negligible small, the secondary voltage is assumed to be a square wave with the same amplitude as the DC link voltage V_{dc} during the rectification mode [7]. On the other hand, the amplitude of the secondary voltage becomes 0 during the short mode. As a result, the fundamental voltages of the during each operation modes V_{21r}, V_{21s} are expressed as follows:

$$V_{21r} = \frac{2\sqrt{2}}{\pi} V_{2r} = \frac{2\sqrt{2}}{\pi}(V_{dc} + 2V_f) \tag{3}$$

$$V_{21s} = \frac{2\sqrt{2}}{\pi} V_{2s} = 0 \tag{4}$$

where, V_f is the forward voltage of the diodes.

Since the phase difference between the primary voltage and the secondary voltage is 90 degrees [7], the circuit equation gives the RMS values of the primary current I_1 and the secondary current I_2, which are described as follows:

$$I_1 = \frac{R_2 V_{11} + \omega_0 L_m V_{21}}{R_1 R_2 + (\omega_0 L_m)^2} \tag{5}$$

$$I_2 = \frac{\omega_0 L_m V_{11} - R_1 V_{21}}{R_1 R_2 + (\omega_0 L_m)^2}. \tag{6}$$

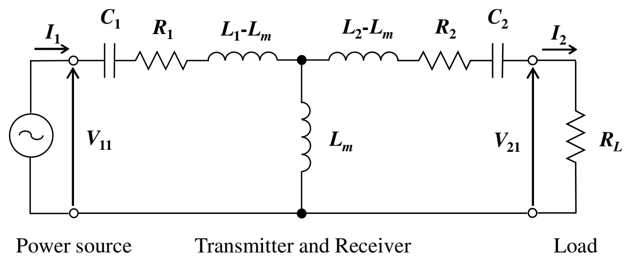


Fig. 4 Equivalent circuit of wireless power transfer via magnetic resonance coupling.

3.2 Efficiency maximization on the primary side

The transmitting efficiency η is determined not only by the coil parameters but also by the load resistance R_L [8]. From eq. (6), R_L is defined as follows:

$$R_L = \frac{V_{21}}{I_2} = \frac{\{R_1R_2 + (\omega_0 L_m)^2\}V_{21}}{\omega_0 L_m V_{11} - R_1 V_{21}}. \tag{7}$$

Then, the voltage ratio A_V and the current ratio A_I between the primary side and the secondary side are given as follows:

$$A_V = \frac{V_{21}}{V_{11}} = \frac{\omega_0 L_m R_L}{R_1(R_2 + R_L) + (\omega_0 L_m)^2} \tag{8}$$

$$A_I = \frac{I_2}{I_1} = \frac{\omega_0 L_m}{R_2 + R_L}. \tag{9}$$

By multiplying these equations, the transmitting efficiency η is expressed as follows:

$$\eta = \frac{(\omega_0 L_m)^2 R_L}{(R_2 + R_L)\{R_1(R_2 + R_L) + (\omega_0 L_m)^2\}}. \tag{10}$$

For efficiency maximization, the load resistance R_L has to be equal to $R_{L\eta\max}$, which is given as follows [8]:

$$R_{L\eta\max} = R_2\sqrt{1 + \frac{(\omega_0 L_m)^2}{R_1R_2}} = R_2\sqrt{1 + k^2Q_1Q_2} \tag{11}$$

where k is coupling coefficient between the transmitter and the receiver coils. Q_1 and Q_2 are the quality factors of these coils.

By substituting eq. (11) into eq. (8), $A_{V\eta\max}$, which maximizes the transmitting efficiency, is obtained as follows:

$$A_{V\eta\max} = \frac{V_{21}}{V_{11\eta\max}} = \frac{1}{1 + \sqrt{1 + k^2Q_1Q_2}}\frac{\omega_0 L_m}{R_1}. \tag{12}$$

Therefore, $V_{11\eta\max}$ is expressed as follows:

$$V_{11\eta\max} = \left(1 + \sqrt{1 + k^2Q_1Q_2}\right)\frac{R_1V_{21}}{\omega_0 L_m}. \tag{13}$$

From eq. (6), in order to transfer power to the secondary side, V_{11} has to be larger than $V_{11\min}$, which is given as follows:

$$V_{11\min} = \frac{R_1V_{21}}{\omega_0 L_m}. \tag{14}$$

Consequently, the reference voltage of the fundamental primary voltage $V_{11\eta\max}$ is described as follows:

$$V_{11\eta\max} = \left(1 + \sqrt{1 + k^2Q_1Q_2}\right)V_{11\min}. \tag{15}$$

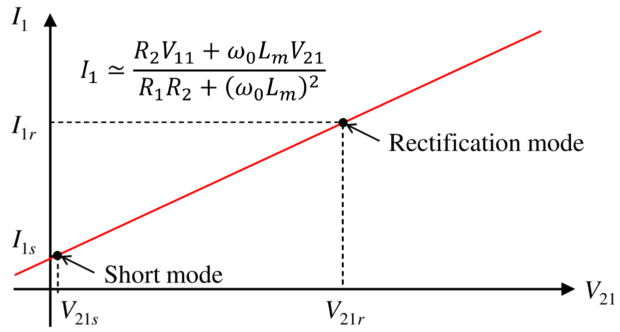


Fig. 5 Primary current I_1 in each modes of HAR.

4. Reference voltage calculation based on primary current measurement

In order to achieve efficiency maximization without signal communication, eq. (15) has to be derived based on primary-side information. In this paper, the reference voltage is calculated from the transmitter coil resistance R_1 and the measured primary currents during each operation modes I_{1r}, I_{1s}.

Fig. 5 shows the fundamental secondary voltage V_{21} versus the primary current I_1. By substituting eq. (3) and eq. (4) into eq. (5), I_{1r}, I_{1s} are given as follows:

$$I_{1r} = \frac{R_2V_{11} + \omega_0 L_m V_{21r}}{R_1R_2 + (\omega_0 L_m)^2} \tag{16}$$

$$I_{1s} = \frac{R_2V_{11}}{R_1R_2 + (\omega_0 L_m)^2}. \tag{17}$$

Then, eq. (17) is transformed as follows:

$$I_{1s} = \frac{1}{1 + k^2Q_1Q_2}\frac{V_{11}}{R_1}. \tag{18}$$

As a result, the following equations can be obtained based on primary-side information.

$$1 + k^2Q_1Q_2 = \frac{V_{11}}{R_1I_{1s}} \tag{19}$$

$$k^2Q_1Q_2 = \frac{V_{11}}{R_1I_{1s}} - 1 = \frac{V_{11} - R_1I_{1s}}{R_1I_{1s}} \tag{20}$$

In addition, eq. (18) gives the following equation.

$$I_{1r} = \frac{1}{1 + k^2Q_1Q_2}\left(\frac{V_{11}}{R_1} + \frac{k^2Q_1Q_2}{R_1}V_{11\min}\right) \tag{21}$$

Then, $V_{11\min}$ is described as follows:

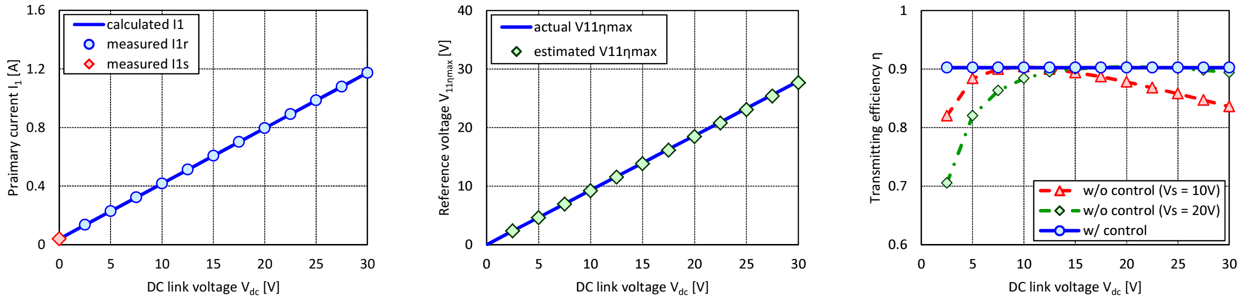
$$V_{11\min} = \frac{R_1I_{1r}(1 + k^2Q_1Q_2) - V_{11}}{k^2Q_1Q_2}. \tag{22}$$

By substituting eq. (19) and eq. (20) into eq. (22), $V_{11\min}$ is given as follows:

$$V_{11\min} = \frac{V_{11}(R_1I_{1r} - R_1I_{1s})}{V_{11} - R_1I_{1s}}. \tag{23}$$

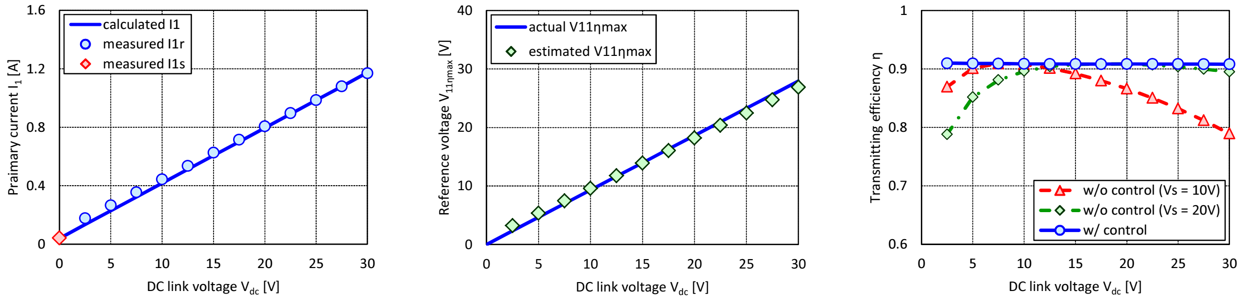
Therefore, $V_{11\eta\max}$ can be obtained as follows:

$$V_{11\eta\max} = \left(1 + \sqrt{\frac{V_{11}}{R_1I_{1s}}}\right)\frac{V_{11}(R_1I_{1r} - R_1I_{1s})}{V_{11} - R_1I_{1s}}. \tag{24}$$



(a) Primary current I_1 (b) Reference voltage $V_{11\eta\mathrm{max}}$ (c) Transmitting efficiency η

Fig. 6 Simulation results of reference voltage calculation and efficiency maximization.



(a) Primary current I_1 (b) Reference voltage $V_{11\eta\mathrm{max}}$ (c) Transmitting efficiency η

Fig. 7 Experimental results of reference voltage calculation and efficiency maximization.

5. Simulation and experiment

In order to verify the effectiveness of the proposed method, simulations and experiments were demonstrated using experimental equipment, which are shown in Fig. 1. The DC link voltage V_{dc} was regulated by an electronic load from 2.5 V to 30 V. The primary current I_1 was measured during each operation modes of HAR and the reference voltage $V_{11\eta\mathrm{max}}$ was calculated based on the measured I_{1r} and I_{1s}. Then, efficiency improvement with the control was verified.

Fig. 6 shows the simulation results of the reference voltage calculation and efficiency maximization. Fig. 6(b) indicates that the reference voltage $V_{11\eta\mathrm{max}}$ is suitably calculated based on the measured primary current, which are shown in Fig. 6(a). Additionally, the transmitting efficiency η is maximized by controlling V_{11} to $V_{11\eta\mathrm{max}}$ as shown in Fig. 6(c).

Fig. 7 shows the experimental results of the reference voltage calculation and efficiency maximization. Fig. 7(b) and Fig. 7(c) certifies that the proposed method can obtain the reference voltage with satisfactory accuracy and maximize the transmitting efficiency η regardless of changes in V_{dc}.

6. Conclusion

This paper proposed an efficiency maximization method of a WPT system with HAR based on the primary current measurement. The reference value of the primary voltage was calculated based on the measured primary current during the rectification mode and during the short mode of HAR. The simulations and the experiments demonstrated the effectiveness of the proposed method.

Cooperative control of the primary side and the secondary side for maximum efficiency and the desired power will be implemented and demonstrated based on the proposed method in the future.

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