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:

$$\omega_0 = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}$$

where $\omega_0$ 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 charging 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.
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:

$$V_{11} = \frac{2\sqrt{2}}{\pi} V_1 = \frac{2\sqrt{2}}{\pi} V_2. \quad (2)$$

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:

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

$$V_{21s} = 2\frac{\sqrt{2}}{\pi} V_{2s} = 0 \quad (4)$$

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:

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

$$I_2 = \frac{\omega_0 L_m V_{11} - R_1 V_{21}}{R_1 R_2 + (\omega_0 L_m)^2}. \quad (6)$$
3.2 Efficiency maximization on the primary side

The transmitting efficiency $\eta$ 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:

$$ R_L = \frac{V_{21}}{I_2} = \frac{\{R_1R_2 + (\omega_0L_m)^2\}V_{21}}{\omega_0L_mV_{11} - R_1V_{21}}. $$

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

$$ A_V = \frac{V_{21}}{V_{11}} = \frac{\omega_0L_mR_L}{R_1(R_2 + R_L) + (\omega_0L_m)^2}, $$

$$ A_I = \frac{I_2}{I_1} = \frac{\omega_0L_m}{R_2 + R_L}. $$

By multiplying these equations, the transmitting efficiency $\eta$ is expressed as follows:

$$ \eta = \frac{(\omega_0L_m)^2R_L}{(R_2 + R_L)(R_1(R_2 + R_L) + (\omega_0L_m)^2)}. $$

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

$$ R_{L_{\text{ymax}}} = R_2\sqrt{1 + \frac{(\omega_0L_m)^2}{R_1(R_2 + R_L)}} = R_2\sqrt{1 + k^2Q_1Q_2} $$

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), $A_{V_{\text{ymax}}}$, which maximizes the transmitting efficiency, is obtained as follows:

$$ A_{V_{\text{ymax}}} = \frac{V_{21}}{V_{11_{\text{ymax}}}} = \frac{1}{1 + \sqrt{1 + k^2Q_1Q_2}} \frac{\omega_0L_m}{R_1}. $$

Therefore, $V_{11_{\text{ymax}}}$ is expressed as follows:

$$ V_{11_{\text{ymax}}} = \left(1 + \sqrt{1 + k^2Q_1Q_2}\right) \frac{R_1V_{21}}{\omega_0L_m}. $$

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

$$ V_{11_{\text{min}}} = \frac{R_1V_{21}}{\omega_0L_m}. $$

Consequently, the reference voltage of the fundamental primary voltage $V_{11_{\text{ymax}}}$ is described as follows:

$$ V_{11_{\text{ymax}}} = \left(1 + \sqrt{1 + k^2Q_1Q_2}\right) V_{11_{\text{min}}}. $$

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:

$$ I_{1r} = \frac{R_3V_{11} + \omega_0L_mV_{21r}}{R_1 + (\omega_0L_m)^2}, $$

$$ I_{1s} = \frac{R_2V_{11}}{R_1 + R_2 + (\omega_0L_m)^2}. $$

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

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

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

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

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

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

$$ I_{1r} = \frac{1}{1 + k^2Q_1Q_2} \frac{V_{11}}{R_1} + k^2Q_1Q_2 \frac{V_{11_{\text{min}}}}{R_1}. $$

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

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

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

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

Therefore, $V_{11_{\text{ymax}}}$ can be obtained as follows:

$$ V_{11_{\text{ymax}}} = \left(1 + \sqrt{\frac{V_{11}}{R_1I_{1s}}}\right) \frac{V_{11}(R_1I_{1r} - R_1I_{1s})}{V_{11} - R_1I_{1s}}. $$
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 $V_{11\text{max}}$ was calculated based on the measured $I_1$. 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 $V_{11\text{max}}$ is suitably calculated based on the measured primary current, which are shown in Fig. 6(a). Additionally, the transmitting efficiency $\eta$ is maximized by controlling $V_{11}$ to $V_{11\text{max}}$ 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 $\eta$ 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.

References