Start-Up Current Control with Fast Settling by Time-Adjustment of Active Rectification for Wireless Power Transfer Systems

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***Abstract*—The paper proposes a method to improve transient characteristics such as current overshoot and oscillation at the start of power transmission for wireless power transfer systems to running electric vehicles. In the system, reducing the settling time as short as possible and ensuring a stable power supply without overshoot is important. However, conventional methods of current overshoot suppression have a slow response on the receiving side. In this paper, by focusing on the superposition of responses of transmitting-side and receiving-side voltages and applying the receiving-side voltage appropriately, the oscillations in the transient section are effectively suppressed. The proposed method is simple in that it only switches at the steady-state value of the receiving-side current. The proposed method was verified by experiments. As a result, the proposed method reduces the current overshoot to 3%, while the conventional method causes 78% overshoot. Also, the settling time of the receiving-side current is short.**

***Index Terms*—Electric Vehicle, Wireless Power Transfer, Transient Control, Active Rectification, Inductive Power Transfer**

I. Introduction

Wireless power transfer (WPT) technologies using magnetic resonance coupling are widely studied [1], [2]. They are considered in a variety of industries applications [3], [4]. One example is electric vehicles (EVs), which are also attracting attention [5], [6]. The use of EVs is expected to increase instead of internal combustion engine vehicles in the future because of their eco-friendliness. However, EVs have some problems such as a shorter cruising range and longer charging time compared to the conventional vehicles. Therefore, a dynamic wireless power transfer (DWPT) system, which applies WPT technologies to running EVs, has been studied as a drastic solution to this problem. In addition, the DWPT system can reduce the battery capacity on EVs since the consumed energy can be immediately charged from the road, which will lead to cost reduction [7].

The DWPT system has some challenges. One of the challenges is the need for power transmission in a limited time. For example, if the vehicle is traveling at a speed of 80 km/h on the highway and the charging range of a transmitter coil is 1 m, the time of the power transmission is only 45 ms. Thus, it is important to keep the settling time as short as possible and to ensure a stable power supply without overshoot. Overshooting beyond the rated current not only increases the stress on the power switching devices but also causes extremely high voltages on the coils and resonant capacitors. Therefore, it is necessary to secure a large amount of power while avoiding high currents.

Many researchers have studied for improving the characteristic of transient response. One of the simplest methods is to suppress the current overshoot by using phase-shift control in a full-bridge inverter [8]. Also, a method that combines the phase-shift method with frequency control has been proposed [9]. For analyzing high-frequency transient responses in the WPT system, the method focusing on its envelope has been widely studied in different circuit schemes such as S-S and LCC [10]–[12]. There are several control methods for the transient response, such as pulse density modulation and dc-dc converter after the rectifier [13], [14].

In the previous studies focusing on the start of power transmission, most of the papers deal with transmitting-side control such as phase-shift control. The research in [15] and [16] proposed control methods that have a characteristic of no overshoot by focusing on the moment when the diode rectifier conducts. These methods suppress the current overshoot by reducing the voltage in the transient section. However, in these methods, the time for the receiving side to reach a steady-state value is longer because of the smaller voltage. In the case of [15] and [16], the settling time of the receiving-side current is on the order of several ms. As mentioned above, the settling time is an important factor for the DWPT system. Therefore, this paper proposes a simple transient response control method with a fast settling time of about the order of μs at the start of power transmission. The characteristic of the method is using a receiving-side active rectifier.

This paper is organized as follows: first, section II explains the response analysis of a simple envelope model and the proposed method based on time-adjustment of active rectification. This method focuses on the superposition of responses and cancels the overshoot by applying the receiving-side voltage appropriately, referred to as time-adjustment of active

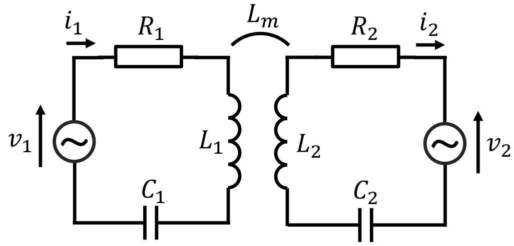


Fig. 1. SS-compensated circuit for WPT.

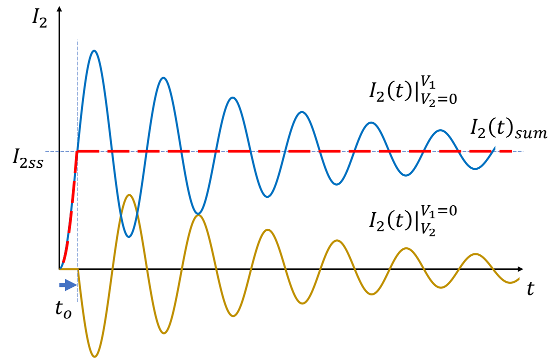


Fig. 2. Diagram of time-adjustment of active rectification: shows envelop model step responses $I_2(t)|_{V_2=0}^{V_1}$ and $I_2(t)|_{V_2}^{V_1=0}$. Sum of each response $I_2(t)_{sum}$ is an actual circuit response.

rectification. In section III and IV, the experimental setup and the results of the experiments using the proposed method are demonstrated respectively. As a result, the current overshoot rate was improved by about 75% and the fast response is verified. Finally, In section V, conclusions are presented.

II. Strategy for start-up current control

Fig. 1 shows a WPT circuit model of a series-series compensated resonant topology. R_1 and R_2 are the internal resistance of the coils, and L_1 and L_2 are the self-inductance.

L_m is the mutual inductance and has a relationship with coupling coefficient k as

$$k = \frac{L_m}{\sqrt{L_1 L_2}}. \tag{1}$$

C_1 and C_2 are the resonance capacitors and are designed to satisfy the following resonance conditions:

$$\omega = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}}. \tag{2}$$

The transmitting-side voltage v_1 operates at the same operating frequency ω_o as the resonant frequency ω. Also, due to a bandpass characteristic of the WPT circuit, the paper focuses on only the fundamental component of AC waveform.

In the resonant condition, the phase of the transmitting-side current i_1 is the same as one of v_1 and can be written as

$$i_1 = I_1 \sin \omega t, \tag{3}$$

where I_1 is the amplitude of i_1.

In addition, the receiving-side current i_2 leads v_1 by 90 degrees, so i_2 can be expressed as

$$i_2 = I_2 \cos \omega t, \tag{4}$$

where I_2 is the amplitude of i_2.

Under the assumption of $\omega_o = \omega$, if the operating frequency ω is sufficiently large, an envelope model can be expressed as follows [11]:

$$\begin{cases} 2L_1 \dfrac{dI_1}{dt} + R_1 I_1 = V_1 - \omega L_m I_2, \\ 2L_2 \dfrac{dI_2}{dt} + R_2 I_2 = \omega L_m I_1 - V_2. \end{cases} \tag{5}$$

As the input variable is the voltage amplitude $(V_1, V_2)^{\mathrm{T}}$ and the output variable is the current amplitude $(I_1, I_2)^{\mathrm{T}}$, the Laplace transform of (5) is calculated as

$$\begin{pmatrix} I_1 \\ I_2 \end{pmatrix} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2 + \alpha_1\alpha_2} \cdot \begin{pmatrix} \frac{1}{2L_1}\frac{1}{\omega_n^2}(s+\alpha_2) & \frac{1}{\omega L_m} \\ \frac{1}{\omega L_m} & -\frac{1}{2L_2}\frac{1}{\omega_n^2}(s+\alpha_1) \end{pmatrix} \begin{pmatrix} V_1 \\ V_2 \end{pmatrix}, \tag{6}$$

where

$$\alpha_1 = \frac{R_1}{2L_1}; \quad \alpha_2 = \frac{R_2}{2L_2}; \tag{7}$$

$$\omega_n = \frac{\omega k}{2}; \quad \zeta = \frac{1}{2}\left(\frac{1}{Q_1} + \frac{1}{Q_2}\right)\frac{1}{k}; \tag{8}$$

$$Q_1 = \frac{\omega L_1}{R_1}; \quad Q_2 = \frac{\omega L_2}{R_2}. \tag{9}$$

(6) is a second-order system, and the current envelope oscillates at the frequency ω_d which is expressed as

$$\omega_d = \sqrt{(1-\zeta^2)\omega_n^2 + \alpha_1\alpha_2} \approx \omega_n. \tag{10}$$

The proposed method focuses on canceling current overshoot and oscillation by adding responses of I_2 calculated from V_1 and V_2 at the appropriate time. This proposal is called as time-adjustment of active rectification.

Step responses $I_2(t)|_{V_2=0}^{V_1}$ and $I_2(t)|_{V_2}^{V_1=0}$ are respectively calculated as follows:

$$\begin{aligned} I_2(t)|_{V_2=0}^{V_1} &= \frac{V_1}{\omega L_m}\left(1 - e^{-\zeta\omega_n t}\cos\omega_d t - \frac{\zeta}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\sin\omega_d t\right) \\ &\approx \frac{V_1}{\omega L_m}\left(1 - e^{-\zeta\omega_n t}\cos\omega_n t\right), \qquad (\because \zeta \ll 1) \end{aligned} \tag{11}$$

$$\begin{aligned} &I_2(t)|_{V_2}^{V_1=0} \\ &= -\frac{R_1 V_2}{\omega^2 L_m^2}\left(1 - e^{-\zeta\omega_n t}\cos\omega_d t + \left(\frac{\omega_n}{\alpha_1} - \zeta\right)\frac{1}{\sqrt{1-\zeta^2}} e^{-\zeta\omega_n t}\sin\omega_d t\right) \\ &\approx -\frac{R_1 V_2}{\omega^2 L_m^2}\frac{\omega_n}{\alpha_1} e^{-\zeta\omega_n t}\sin\omega_n t. \qquad \left(\because \frac{\omega_n}{\alpha_1} \gg 1\right) \end{aligned} \tag{12}$$

I_2 is a superposition of (11) and (12). Fig. 2 shows a diagram of each response. Since $I_2(t)|_{V_2}^{V_1=0}$ oscillates from the negative

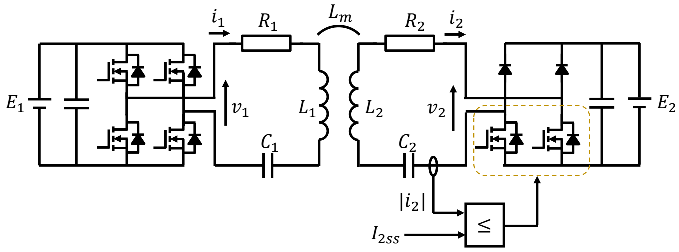


Fig. 3. WPT circuit configuration for experiment.

TABLE I
PARAMETERS IN THE EXPERIMENT

Symbol	Definition	Value
f_o	Operating frequency	85 kHz
L_1	Transmitter inductance	233.96 μH
R_1	Transmitter resistance	141.34 mΩ
L_2	Receiver inductance	97.60 μH
R_2	Receiver resistance	53.26 mΩ
k	Coupling coefficient	0.088
L_m	Mutual inductance	13.38 μH
E_1	Transmitting-side DC-link voltage	30 V
E_2	Receiving-side DC-link voltage	15 V

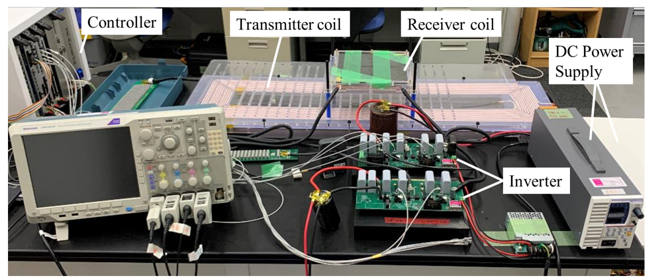


Fig. 4. Experimental setup.

direction, it is possible to suppress the oscillation by applying V_2 at the steady-state current amplitude expressed as

$$I_{2ss} = \frac{V_1}{\omega L_m}. \tag{13}$$

Also, the input time t_o can be calculated from (11) as

$$t_o = \frac{\pi}{2\omega_n} = \frac{\pi}{\omega k}. \tag{14}$$

Furthermore, considering conditions in which the transient response can be completely canceled, it is expressed as

$$I_2(t+t_o)\big|_{V_2=0}^{V_1} + I_2(t)\big|_{V_2}^{V_1=0} = I_{2ss}. \tag{15}$$

From (11)-(15), the following constraint can be obtained:

$$V_2 = \sqrt{\frac{L_2}{L_1}} V_1. \tag{16}$$

Thus, in the case of (16) satisfied, current overshoots and oscillations can be completely canceled by applying V_2 at I_{2ss}.

The proposed method is limited by (16). However, an optimal voltage $V_{2\eta opt}$ which realizes maximum efficiency is expressed as [17]

$$V_{2\eta opt} = \sqrt{\frac{R_2}{R_1}} \frac{\omega L_m}{\sqrt{R_1 R_2 + \omega^2 L_m^2} + \sqrt{R_1 R_2}} V_1 \approx \sqrt{\frac{R_2}{R_1}} V_1. \tag{17}$$

Therefore, if assuming R is proportional to L, note that the constraint is realistic.

III. Experimental setup

The proposed method was verified by the experiment. Fig. 3 shows the schematic diagram of the experimental circuit. The receiving side has a constant voltage load through a rectifier. Fig. 4 shows the experimental setup and inverters used for the transmitting and the receiving side, respectively. The inverter on the transmitting side outputs an AC voltage. The active rectifier on the receiving side controls the timing of voltage input by turning on and off the lower switch. As the lower switches are off, the rectifier behaves as a full-bridge diode rectifier, referred to as the rectification mode. As the lower switches are on, the AC voltage v_2 is zero, referred to as the short mode. By switching from the short mode to the rectification mode, the voltage on the load side is applied at the moment of conduction, thus realizing the step input of voltage. To determine the switching, a current sensor measures the current i_2 with 4.2 MHz sampling. Then, the FPGA-based controller compares the absolute value and the steady-value I_{2ss} and outputs the switching signal.

Table I shows the circuit parameters. The DC voltage on the receiving side is the value that satisfies (16), and the drop voltage during diode conduction is taken into account.

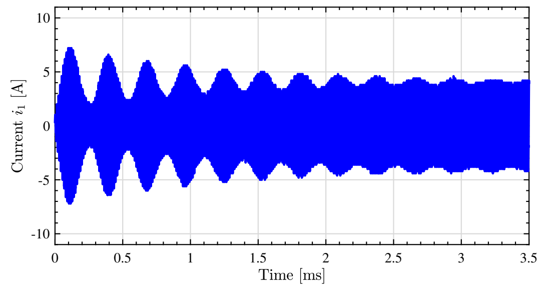
IV. Experimental results

The experiments was run under the following two conditions. In the conventional method, the rectifier works as a full-bridge diode rectifier. In the proposed method, the active rectifier waits in the short mode and switches to the rectification mode as the current reaches the steady-state value $I_{2ss} = 5.3$A.

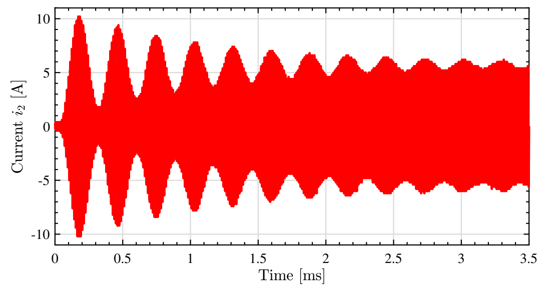
Figs. 5, 6 show the experimental results of the conventional method and proposed method, respectively. In the response of the conventional method shown, an overshoot of 78% was observed in the transmitting-side and receiving-side currents, respectively. On the other hand, in the proposed method shown in Fig. 6, by switching from the short mode to the rectification mode at I_{2ss}, the overshoot is reduced to 3% and the oscillation is suppressed effectively. In addition, the proposed method has an advantage in terms of the settling time of the response.

V. Conclusion

The paper proposes the method to suppress current overshoot and oscillation at the start of power transmission by time-adjustment of active rectification for wireless power transfer systems. The proposed method focuses on the superposition of the response from V_1 to I_2 and from V_2 to I_2. This method is simple, requiring only switching at steady-state values, and has a short settling time. The proposed method was verified by experiments comparing the diode rectifier. As

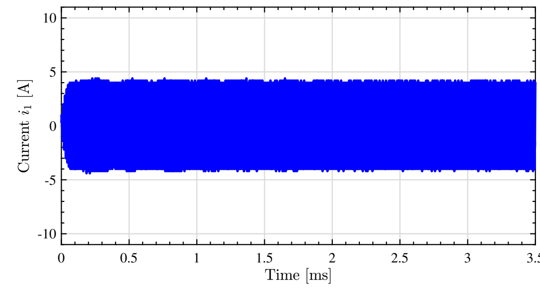


(a) Transmitting-side current.

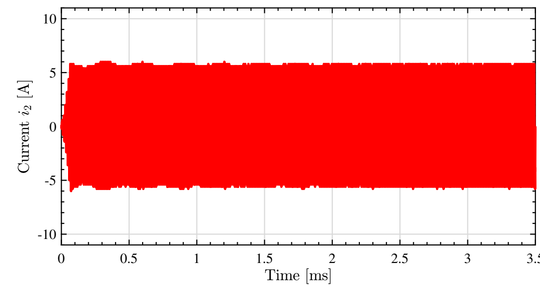


(b) Receiving-side current.

Fig. 5. Experimental results of conventional method.



(a) Transmitting-side current.



(b) Receiving-side current.

Fig. 6. Experimental results of proposed method.

a result, the current overshoot rate was improved by about 75%.

One of the disadvantages of the proposed method is that it is limited to (16) as an applicable condition. However, it is expected to effectively reduce the current overshoot even when the constraint is violated, except for the large gap of self-inductance.

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