A New Adaptive Efficiency Control of the Transmitter with Remote Monitoring of the Receiver Load for 6.78 MHz Class Wireless Power Transfer

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Abstract

Typically, the receiver of wireless power transfer (WPT) systems uses batteries for their energy storage. The power transfer efficiency depends on the load impedance of the battery, which varies according to the charging condition. The efficiency depends on the impedances of both the transmitter and receiver. However, for practical WPT systems, total load optimization is to be executed without directly monitoring the receiver load. This paper proposes a practical and effective method for an adaptive efficiency control of the transmitter with indirect monitoring of the receiver load.

1. Introduction

In recent years, magnetic-resonance-type wireless power transfer (WPT) has attracted attention as a technology that can improve the convenience of small devices and EV [1] - [4]. Load optimization is necessary for high-efficiency power transmission, because the transmission efficiency of the magnetic field resonance-type WPT depends on load conditions. [5] - [6]. The lithium ion storage battery has characteristics of high capacity and high power density, and is widely used as an electric storage device. The deterioration of the lithium ion storage battery can be suppressed during charging by optimizing the charging current and voltage according to the state of charge (SOC). However, this control lowers the transmission efficiency, because it causes impedance change. In other words, both the optimized charging of the storage battery and the maximization of the transmission efficiency of the WPT circuit are difficult to achieve. Therefore, a new WPT system is to be constructed for storage batteries. Previously, we proposed methods that are compatible with these controls [7] and required communications between the transmitting side and the receiving side. The receiving side system must be simplified for ultracompact devices such as sensor devices for IoT. Therefore, the elimination of communication is useful in such a system. In the proposed method, the state of the receiving side is estimated from the transmitting side information, and the transmission efficiency is maximized using this information.

2. Relationship between WPT and Battery Charging

2.1 Characteristics of WPT

The magnetic-resonance-type WPT transmits electrical power by exchanging the magnetic energy between the transmitting side and the receiving side LC resonator. The primary difference from the electromagnetic induction is the high transmission efficiency in the wide gap. Fig. 1 shows an example of a circuit used for a magnetic field resonance-type WPT. This circuit configuration is called an S/S method because the capacitors are connected in series. \( L_1 \) represents the power transmission coil; \( C_1 \) and \( C_2 \) represent the resonance capacitors; \( R_1 \) and \( R_2 \) represent the parasitic resistances of the transmission coils; \( L_2 \) represents the power reception coil. Further, \( k \) represents the coupling coefficient of the transmitting and receiving coil, and \( R_t \) represents the terminating load. In such a circuit configuration, the resonant frequency can be calculated from Eq. (1). Further, the resonant angular frequency is represented by \( \omega_0 \).

\[
\omega_0 = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}}
\] (1)

The transmission efficiency and transmission power of the magnetic-resonance-type WPT circuit can be expressed by Eqs. (2) to (5) [5].

\[
X = (R_t)(R_1 - R_2) + (\omega_0L_m)^2 - \left(\omega_0L_1 - \frac{1}{\omega_0C_1}\right)\left(\omega_0L_2 - \frac{1}{\omega_0C_2}\right)
\] (2)

\[
Y = (R_1)\left(\omega_0L_2 - \frac{1}{\omega_0C_2}\right) + (R_t + R_2)(\omega_0L_1 - \frac{1}{\omega_0C_1})
\] (3)
\[\eta = \frac{(R_l)(\omega L_m)^2}{(R_l + R_e)\frac{b}{\omega} + (R_e + R_e + \frac{a}{\omega})V_n^2}\]  \quad (4)

\[P = \frac{(R_l)(\omega L_m)^2}{\frac{b}{\omega} + \frac{a}{\omega}V_n^2}\]  \quad (5)

\[L_m\] in Eqs. (2) to (5) indicates the mutual inductance. Eq. (4) represents the transmission efficiency of the circuit shown in Fig. 1. In an actual operation, a DC power is supplied to the load by a rectifier. At this time, \(R_l\) in Eqs. (2) to (5) needs to be replaced with an AC load resistance of \(R_{ac}\) calculated from Eq. (6).

\[R_{ac} = R_l \cdot \frac{4}{\pi^2}\]  \quad (6)

2.2 Conventional wireless charger

As is apparent from Eqs. (4) to (5), the transmission state of the magnetic-resonance-type WPT system changes according to the output impedance value (= terminal load). Therefore, the transmission efficiency can be maximized by optimizing the output impedance. Nevertheless, the optimizations of the charging current and charging voltage are also important for optimum charging, as they affect the fluctuation of the output impedance. Fig. 2 shows the configuration of a typical wireless charger. The output impedance of the circuit configuration of Fig. 2 is represented by Eq. (7).

\[Z_{pl} = \frac{R_{charge}}{Duty^2} \cdot \frac{4}{\pi^2}\]  \quad (7)

Herein, let \(Z_{pl}\) be the apparent output impedance. Eq. (7) represents the case where the receiving side DC–DC converter is a step-down type. As is apparent in Eq. (7), the output impedance of the WPT circuit is determined by the values of the transformation ratio \(Duty\) and the charging current voltage ratio \(R_{charge}\). Therefore, the transmission efficiency and the output power of the WPT circuit depend on the charging state of the storage battery.

3. Proposed Method

3.1 Proposed wireless charger

In this section, we describe a method to suppress the efficiency reduction due to the load fluctuation caused by optimum charging. The circuit configuration used in this method is shown in Fig. 3. In this method, the load is optimized by adjusting the voltage applied to the WPT circuit. In the circuit configuration of Fig. 2, the output impedance is expressed by Eqs. (8) to (9).

\[Z_{pl} = \frac{(V_{out})^2}{P_{charge}} \cdot \frac{4}{\pi^2}\]  \quad (8)

\[P_{charge} = V_{charge} \cdot I_{charge}\]  \quad (9)

\(V_{out}\) in eq. (8) is calculated by equations (10) to (12).

\[V_{out} = A_v \cdot V_{in2}\]  \quad (10)

\[A_v = \frac{\omega L_m Z_{pl}}{R_1 Z_{pl} + R_2 + (\omega L_m)^2}\]  \quad (11)

\[V_{out} = (\frac{V_{in2}^2 \cdot R_2 \cdot V_{in2} \cdot R_2 + R_2 \cdot P_{charge} + R_2^2 \cdot A_v^2}{2 R_1}) + \frac{V_{in2}^2 \cdot R_2}{2 R_1}\]  \quad (12)

As is apparent from Eqs. (8) to (12), the output impedance can be optimized without interfering with the charge control by adjusting the input voltage \(V_{in2}\) to the WPT circuit.

3.2 Estimation using transmitting side information

In wireless charging, charging may be stopped because of insufficient power supply to the receiving side. In addition, feeding at the end of charging must be stopped to suppress magnetic field radiation. Therefore, the state of the receiving side must be understood.
The proposed method is a new method that does not require communications in the control of the transmission efficiency. Therefore, the power receiving state on the receiving side is to be estimated from the transmitting side information. The input impedance $Z_{\text{in2}}$, which is the transmitting side information can estimate the output impedance $Z_{\text{pl}}$. Eq. (13) is an equation to estimate the output impedance.

$$Z_{\text{pl}} = \frac{(2Z_{\text{in2}} - 2R_1 - R_2\pi^2)}{\pi^2} \quad (13)$$

$$Z_{\text{in2}} = \frac{V_{\text{in2}}}{I_{\text{in2}}} \quad (14)$$

In Eq. (13), $R_1$, $R_2$ represent the parasitic resistance value of the transmission coils. The input impedance can be calculated from $V_{\text{in2}}$ and $I_{\text{in2}}$ of the transmitting side information. Therefore, the transmission efficiency and the output power can be estimated from the information on the transmitting side. Further, the input impedance information can be used for efficiency control. From the above, the receiving side state can be estimated and can be adjusted to a value that maximizes the transmission efficiency from the transmitting side information.

4. Experiment

4.1 Verification by Matlab

We verified the correlation among the input impedance, transmission efficiency, and output power using Matlab. The simulation target is the circuit configuration of Fig. 3. The charging power is 4 V/50 mA. Figs. 4 and 5 show the results. The solid line shows the true value on the simulation and the dotted line shows the value estimated by Eq. (13). Fig. 4 shows that the transmission efficiency can be maximized by optimizing the input impedance. Fig. 5 shows that the state of the receiving side can be determined by monitoring the input impedance $Z_{\text{in2}}$.

4.2 Experimental condition

We verified whether the proposed method can achieve an improvement in the transmission efficiency without interfering with the charging operation. Table 1 shows the specifications of the circuit used for the verification, and Fig. 6 shows a photograph of the circuit. In this circuit, the output impedance becomes optimum when the input impedance $Z_{\text{in2}}$ is 188 Ω. The optimization control was constructed based on this characteristic. In this verification, we measured the fluctuation of the transmission efficiency by switching
the charging current. The transmission efficiency is defined as the transmission power ratio between transmission coils. The effective value of the high-frequency current and voltage flowing in the LC resonance part was measured using an oscilloscope. The circuit configuration to be compared is shown in Fig. 2. The input voltage to the comparison target circuit is 12 V.

| Table 1: Specifications of actual machine |
|------------------------------------------|
|                                         |
| Inductance (μH)                         | Transmitter | Receiver |
| Parasitic resistance of coil (Ω)        | 0.035       | 0.035    |
| Transmission distance (mm)              | 50          |
| Resonant capacitor (pF)                 | 81          |
| Operation Frequency (MHz)               | 6.78        |
| Inverter                                | Full Bridge by Gan FET |
| Rectifier                               | Full-wave rectification by SiC diode |
| DC–DC converter                         | Step-down chopper converter |

4.3 Experimental results

Fig. 7 shows the experimental results. The vertical axis of the graph shows the transmission efficiency whereas the horizontal axis shows the charging current $I_{\text{charge}}$. In the circuit without transmission efficiency improvement control, the transmission efficiency reduction due to the change in $I_{\text{charge}}$ is 26% at the maximum. However, the proposed method suppresses the decrease in transmission efficiency to 8%. Therefore, the proposed method can suppress the efficiency reduction due to the change in the charging power by using only the transmitting side information. This result shows that the proposed method can suppress the reduction in the transmission efficiency without interfering with the control when adding the optimum charge control function to the wireless charger.

5. Conclusion

We have proposed a practical and effective method for an adaptive efficiency control of the transmitter with the indirect monitoring of the receiver load. Since this architecture provides a simple and inexpensive structure of the edge, it is considered as an essential improvement in WPT systems that equip a battery at the edge. The experimental result shows the robustness of the efficiency against the change in charging condition of the battery.