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Study on Maximize Efficiency by Secondary Side Control Using DC-DC Converter in Wireless Power Transfer via Magnetic Resonant Coupling

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Abstract

Wireless power transfer via magnetic couple resonance has been widely studied as an attractive research target. In order to improve the transmitting efficiency, not only increasing performance of antenna is important but also controlling secondary (receiver) side input impedance value. As a method of controlling secondary input impedance, the method of using a DC-DC converter is proposed in previous research. Mutual inductance what related to transmitting distance and load resistance value is needed to know for control the DC-DC converter. Moreover, the transmitting distance and load resistance has changed in actual WPT situation. Therefore, control method for DC-DC convertor what keep best efficiency in actual WPT situation is needed. In this paper, the novel method of controlling a DC-DC converter for maximize efficiency which used for wireless power transfer via magnetic couple resonance is proposed. A mutual inductance can be known the voltage sensor in secondary side by setting power supply voltage constant. Furthermore, efficiency could be maximized regardless of the state of load by controlling a DC-DC converter so that the secondary side voltage constant value. This principle was explained by equation. Thereby, even when transmission distance and a load resistance value change, wireless power transfer system keep best efficiency automatically without communication between primary to secondary side.

Keywords: Wireless power transfer, magnetic resonant coupling, efficiency maximize, DC-DC converter

1 Introduction

Wireless Power Transfer (WPT) via magnetic resonant coupling which was first introduced in year 2007 [1]. With this method high transmission efficiency is obtainable over relatively larger gap compared to induction method. Potential application includes charging electric vehicles. The important feature of WPT is high efficiency at large transmission distance. For high transmission efficiency, not only improving the performance of transmitting and receiving antenna is important, but also optimal load impedance [2]. Impedance matching circuit is commonly used for changing load impedance [3] in radio engineering, but the circuit has mechanical element that causes slow response. Therefore, controlling load impedance with DC-DC converter is proposed. In paper [4], experiment shows that transmission efficiency is increased by DC-DC converter.

In actual WPT system, transmitting distance and load value has been changing by operating condition. Therefore, DC-DC converter needs control method which can achieve best efficiency when this changes. However, the control method for automatic adjustment in actual WPT system is not shown.

In this paper, the method for controlling DC-DC converter for WPT via magnetic resonant coupling is proposed. First, a characteristics of magnetic resonant coupling and relation between efficiency and load resistance is shown by equation and calculation. Next, basis of efficiency optimization using DC-DC converter is shown. Then, in an actual WPT system, control method of DC-DC converter for efficiency maximization automatically is explained. Finally, the proposed method is validated through experiment.

2 The Characteristics of Magnetic Resonant Coupling

2.1 Input Output Characteristics in Resonance Frequency

The magnetic couple resonance can be explained by equivalent circuit and equivalent circuit is proposed by past research. The equivalent circuit is illustrated in Figure 1 [5]. Term L_1, L_2 is primary and secondary coil of antenna inductance. C_1, C_2 is primary and secondary capacitance of antenna. R_1, R_2 is antenna resistance and related to antenna loss. These parameters are decided by antenna figure and does not have relation condition of WPT system as transmitting distance and load condition. Term L_m is mutual inductance which is related to transmission distance. Inductance and capacitance of transmitting antenna and receiving antenna satisfy (1) because WPT via magnetic couple resonance send the power by electrical resonance.

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \qquad (1)$$

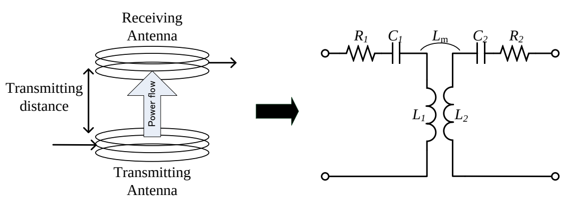


Figure 1: Equivalent circuit of magnetic resonant coupling

Figure 2 shows equivalent circuit of WPT system which connected power and load. Where V_1 is the primary side voltage, V_2 is the secondary side voltage, and R_L is load resistance. Term Z_{in2} is secondary side input impedance and equal to R_L in this figure.

In case transmitting frequency equal to resonance frequency which is shown in (1), transmission efficiency A_P is shown (2) and is equal to the ratio of secondary to primary power. Also A_V is the ratio of secondary to primary voltage as shown in (3).

$$A_P = \frac{(\omega_0 L_m)^2 R_L}{(R_L + R_2)\left(R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2\right)} \qquad (2)$$

$$A_V = \frac{\omega_0 L_m R_L}{R_1 R_L + R_1 R_2 + (\omega_0 L_m)^2} \qquad (3)$$

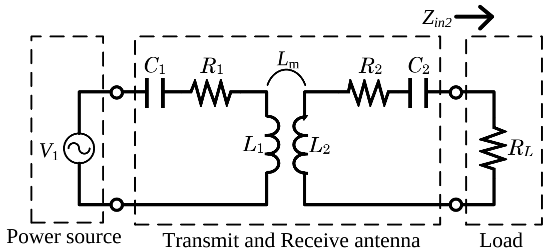


Figure 2: Equivalent circuit of magnetic resonant coupling with power source and load

2.2 Maximum Efficiency Secondary Input Impedance

Using the derived equations, the change of efficiency characteristic corresponding to load, R_L is calculated.

Figure 3 shows the antenna figure for calculation, and table 1 show the antenna specification and this antenna's parameter is shown in table 2. The antennas' parameters are set to be the same as the actual antennas. And Table 3 shows the L_m values of transmitting distances.

Figure 3: An antenna for Wireless power transfer

Table 1: Antenna specification

Description	Value
Outer diameter [mm]	450
Inner diameter [mm]	115
Number of turn [turn]	50
Pitch [mm]	3.4
Wire cross-section area [mm^2]	2.0

Table 2: Antenna parameters

Parameter	Value
L_1 [uH]	650
L_2 [uH]	650
C_1 [pF]	2000
C_2 [pF]	2000
R_1 [Ω]	1.4
R_2 [Ω]	1.4

Table 3: Relation between transmitting distance to mutual inductance

Transmitting distance [cm]	Mutual inductance L_m [uH]
20	86.3
30	41.4
40	22.2
50	12.9

Figure 3 shows the plot of A_P, corresponding to changing R_L. Figure 3 shows A_P is maximized at certain R_L values. Transmission efficiency is affected by load resistance. Therefore optimizing load value for high efficiency is important. The secondary side input impedance during maximum efficiency, $Z_{in2APmax}$ is shown by (4).

$$Z_{in2AP\max} = \sqrt{R_2\left(\frac{(\omega_0 L_m)^2}{R_1} + R_2\right)} \tag{4}$$

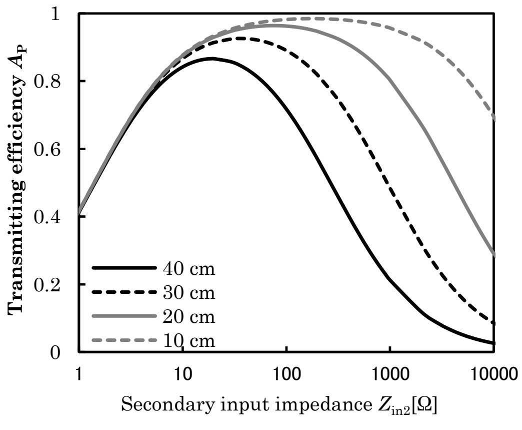


Figure 4: Relation efficiency and load resistance

3 Input Impedance Control by DC-DC Converter

The Load resistance R_L is determined by load condition and cannot be changed freely by WPT system. Therefore, a method to control the secondary side input impedance is needed. As a method of changing input impedance, DC-DC converter is more suitable for controlling secondary input impedance in WPT system because it has no mechanical elements and can fast response.

Figure 5 shows the block diagram of secondary impedance control with DC-DC converter. DC-DC converter can change secondary input impedance by changing switching duty ratio without changing R_L.

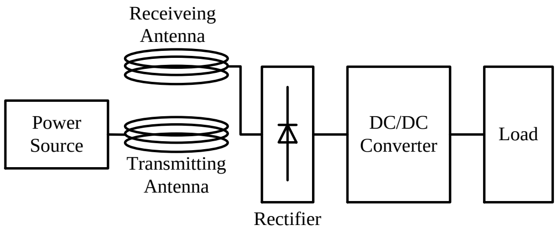


Figure 5: Impedance control by DC-DC converter

Figure 6 shows the circuit of buck converter. Buck converter converts input voltage into lower output voltage. Generated impedance is calculated by (5) where D is switching duty cycle and the impedance range is given by (6).

Equation (6) show Buck converter converts higher impedance than load resistance. In case of WPT for EV, R_L is smaller than $Z_{inAPmax}$ because EV needs high power charging. Therefore buck converter is suitable for high power WPT.

$$Z_{in2} = \frac{R_L}{D^2} \tag{5}$$

$$R_L \le Z_{in2} \le \infty \tag{6}$$

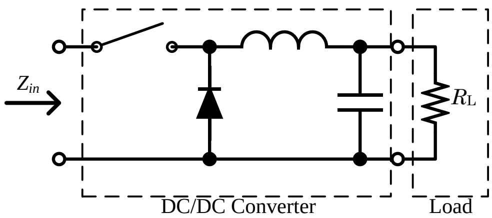


Figure 6: Buck converter

4 Control Method for DC-DC Converter

4.1 Problem of Conventional Method

Figure 7 shows the complete circuit of WPT system during actual application. The switching duty ratio of DC-DC converter is changed, so that Z_{IN2} with maximum efficiency is achieved.

Equation (5) cannot apply for actual DC-DC converter because (5) does not consider converter's loss and the loss of DC-DC converter changes depend on state, and are not constant. Moreover, (4) contains L_m. In order to obtain L_m, communication is needed between primary to secondary side.

4.2 Nobel Control Method

Then, novel control method is proposed. The primary voltage is set constant and efficiency maximization is attained by controlling secondary voltage.

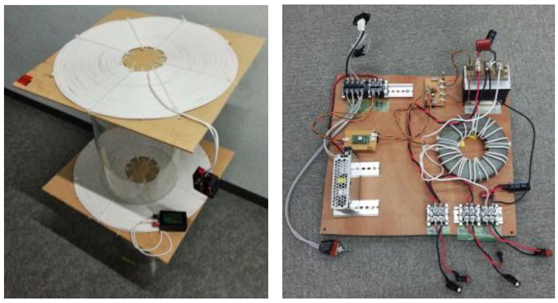
Maximum efficiency secondary voltage (V_2^*) is shown (7) from (3) and (4). By controlling a DC-DC converter so that secondary voltage becomes V_2^*, efficiency can be made into the maximum. When primary voltage (V_1) is constant value, L_m can be calculated by (4). This value represents the estimated mutual inductance from secondary side.

$$V_2^* = \sqrt{\frac{R_2}{R_1}} \frac{\omega_0 L_m}{\sqrt{(\omega_0 L_m)^2 + R_1 R_2} + \sqrt{R_1 R_2}} V_1 \quad (7)$$

$$L_m = \frac{\frac{V_1}{V_2} Z_{in2} + \sqrt{\left(\frac{V_1}{V_2} Z_{in2}\right)^2 - 4R_1(Z_{in2} + R_2)}}{2\omega_0} \quad (8)$$

4.3 Experimental Method

Experiment is performed. To confirm maximize efficiency by DC-DC converter when load resistance and transmitting distance. Transmitting distance is set to 20 cm and 40 cm. compare transmitting efficiency with DC-DC convertor to without DC-DC converter. V_1 set to constant value, and control duty cycle to become same value V_2 and V_2^*. The experimental experiment is shown in Figure 8. The antennas are same as for calculating in section 2.



(a) Antennas (b) DC-DC converter

Figure 8: Experimental equipment

4.4 Experimental Results

Experiment result is shown in Figure 9. In case DC-DC converter does not exist, Transmitting Efficiency is getting worse when load resistance is low. While on the other hand, in case apply the DC-DC converter with proposed control method, the efficiency keeps maximum value in low load resistance. From here this result indicates proposed control method of DC-DC converter is effective

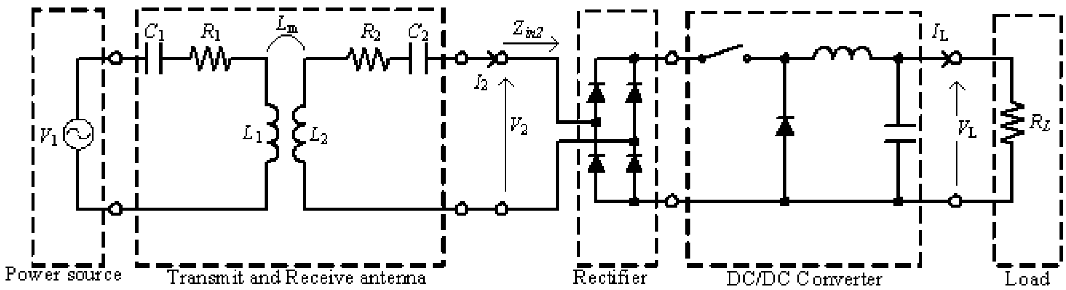


Figure:7 Circuit diagram of WPT system with DC-DC converter for maximize transmitting efficiency

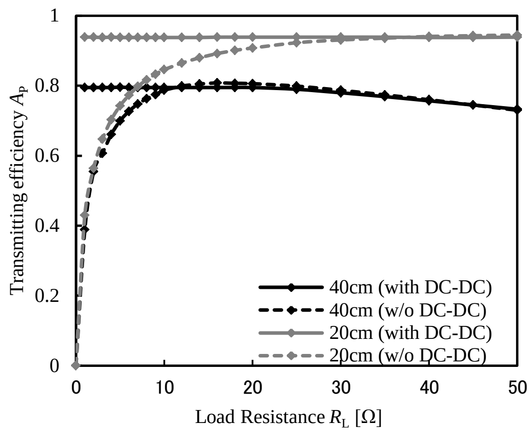


Figure 9: Experiment result

5 Conclusion

Method for transmission efficiency improvement using DC-DC converter for WPT via magnetic resonant coupling is proposed in this paper. The principle of DC-DC converter control method without communication between primary and secondary side is explained. And experiment is performed based on the control method, and confirm the method is effective.

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