Basic Study on Reduction of Reflected Power Using DC/DC Converters in Wireless Power Transfer System via Magnetic Resonant Coupling

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***Abstract*— Nowadays, wireless power transfer via magnetic resonance coupling is researched and developed actively. This method enables power transfer with high efficiency across large air gap and is robust to displacement compared to traditional method. One of the problems for realization of such system is the increase of reflected power due to load variation and displacement. Reflected power will become loss in power source and result in declining efficiency of the power transfer. Therefore, impedance matching circuit becomes crucial for realization of high efficiency wireless power systems. In this paper, a novel method for reduction of reflected power using DC/DC converter is proposed. DC/DC converter operates like variable impedance by changing duty cycle of switching devices and therefore functions as impedance matching circuit. As a basic phase, reduction of reflected power and efficiency improvement by proposed method are investigated by experiment.**

***Keywords;* wireless power transfer, magnetic resonant coupling, DC/DC converter**

I. INTRODUCTION

Recently, mobile devices such as mobile phones and laptop PCs are widely spread. These devices are powered by batteries or capacitors, which have low energy density and need to be charged constantly. The need for a technique to wirelessly charge these devices has been on the rise. Until now, various methods of wireless power transfer have been investigated in research community. Especially, the novel method using electromagnetic resonant coupling, which enables mid-range wireless power transfer with high efficiency while being robust to antennas' displacement, has recently been researched and developed more actively[1]. In resonant coupling method, size and weight of the antenna depend on resonant frequency range of the power source to which the antenna will be applied. Antennas in MHz range are relatively small in size, and therefore are suitable for broad applications (such as mobile phones, laptop PCs and home electronics). In particular, the system operating at 13.56MHz, which is the frequency limited by ISM band (Industrial Science Medical band), is studied actively.

Wireless power transfer using magnetic resonance coupling, however, contains some problems in realization. Power transfer efficiency is decreased due to displacement and load variation. Impedance mismatch causes reflected power to increase. Reflected power becomes loss in source and cause distorted waveform, and therefore should be reduced in order to achieve high efficiency power transmission. Antenna's parameter optimization methods for fixed load have been proposed in the past study [2]. However, in real application (such as motor or capacitor), load variation and displacement is unavoidable, hence high efficiency system which is robust to load variation and displacement is essential. Therefore, impedance matching circuit is crucial for realization of high efficiency wireless power systems. In the past, impedance matching circuit has been implemented using variable capacitor and inductor [3]. However, the problem of this method is that matching time is too slow for energy transfer in applications with rapid load variation such as capacitor and motor.

In this paper, a novel method for reduction of reflected power using DC/DC converter is proposed. DC/DC converter operates like variable impedance by changing duty cycle of switching MOSFET and therefore functions as impedance matching circuit. As a result, the amount of reflected power is reduced hence high efficiency for power transfer is achieved regardless of load variation. As a basic phase, reduction of reflected power and efficiency improvement by proposed method are investigated by experiment.

II. WIRELESS POWER TRANSFER VIA MAGNETIC RESONANT COUPLING

A. *Equivalent Circuit and Efficiency Calculation*

In this section, equivalent circuit which is a basic theory of this research is explained. Magnetic resonant coupling method, which is presented by MIT in 2007, is explained by mode coupling theory [1]. However, this theory is difficult to comprehend, and therefore, not suitable for designing electrical circuit. Therefore, system analysis in terms of electrical circuit is necessary. Since magnetic resonant coupling involves creating LC resonance, equivalent circuit can be expressed by simple RLC circuit as shown in Fig.1.

The efficiency of power transfer is calculated based on equivalent circuit parameters. S_{11} is the reflected power ratio. S_{21} is the transmitted wave ratio. The definitions of S_{11} and S_{21} are expressed in equation (1), (2), (3). Necessary matching condition in order to reduce reflected power is explained in terms of Z_0 and Z_{in} as shown in equation (4). Impedance matching circuit operates based on equation (4) to realize high efficiency energy transfer.

$$S_{21}(\omega)=\frac{2j\omega L_m\sqrt{Z_0 Z_L}}{\left(Z_0+R+j\omega L+\frac{1}{j\omega C}\right)\left(Z_L+R+j\omega L+\frac{1}{j\omega C}\right)+L_m{}^2\omega^2} \qquad (1)$$

$$\eta_{21}=|S_{21}|^2\times 100 \quad [\%] \qquad (2)$$

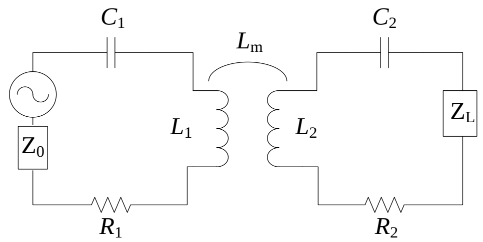
$$\eta_{11}=|S_{11}|^2\times 100 \quad [\%] \qquad (3)$$

$$Z_0=Z_{in} \qquad (4)$$

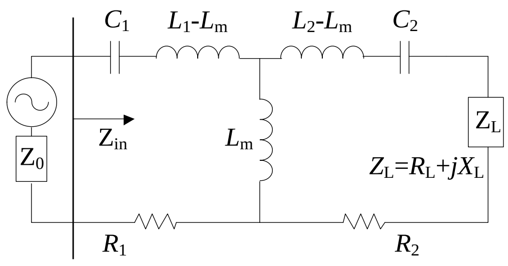
B. *Efficiency with Respect to Load Variation*

This section presents efficiency characteristic with respect to load variation calculated by simulation program. The resonant frequency of wireless power transfer system used in this study is 13.56 MHz. Each parameter of the wireless power transfer system is shown in Table.1. In order to show the effect on antenna characteristics due to load variation only, transmitting distance is set to a constant value. And load impedance Z_L is purely resistive as shown in equation (5). Fig. 2 shows characteristics of S_{21} and S_{11} due to load variation.

$$Z_L=R_L \quad (X_L=0) \qquad (5)$$



(a)Equivalent circuit



(b)T-type equivalent circuit

Fig. 1 Equivalent circuit for magnetic resonant coupling.

Table1. Antenna Parameters

Resonant frequency [MHz]	13.56	Inductance L [μH]	11.0
Antenna diameter [mm]	300	Capacitance C [pF]	12.5
Transmitting air gap[mm]	250	Internal resistance R [Ω]	1.53
Coupling coefficient k	0.037	Characteristic impedance Z_0[Ω]	50

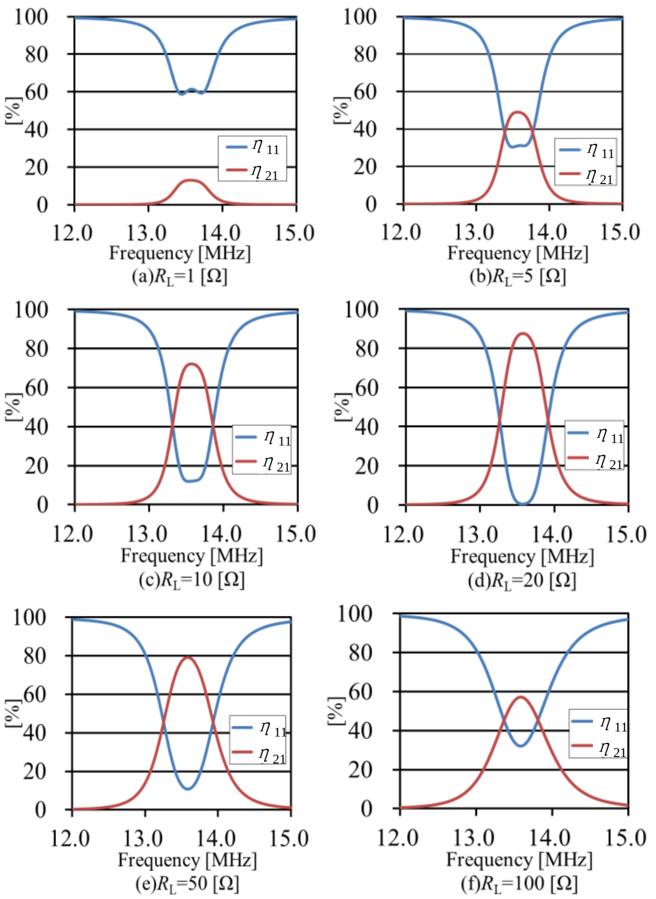


Fig. 2 Efficiency vs. Load resistance.

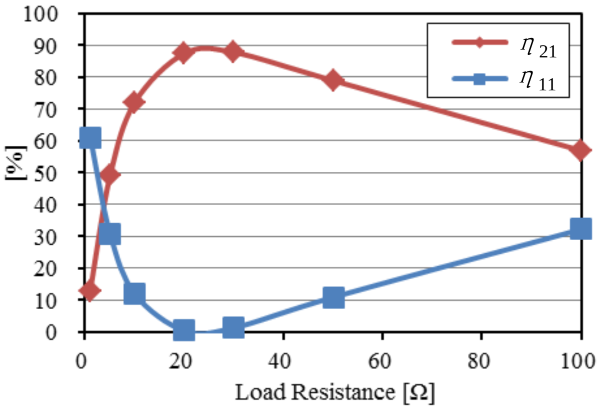


Fig. 3 Efficiency vs. Load resistance (13.56 MHz).

Fig. 2 shows that reflected power and efficiency is affected and antenna characteristic changes when load resistance is changed. Efficiency and reflected power at 13.56 MHz are shown in Fig.3. Maximum efficiency occurs at the point with minimum reflected power ratio. Therefore, this system requires impedance matching circuit which makes load impedance become 20 Ω to realize high efficiency power transmitting.

C. Effect of Diode Rectifier

In MHz range, loss in diode rectifier is significant. Therefore, power transmitting efficiency is severely affected by rectifier. In this section, efficiency including loss due to diode rectifier is investigated. Transmitting efficiency is redefined in equation (6). Experimental system and result are shown in Fig.4 and Fig.5. Note that the rectifier circuit consists of SiC schottky barrier diodes.

$$\eta_L = \frac{P_L}{P_f} \tag{6}$$

The efficiency shown in Fig.5 is compared to efficiency in Fig.3. For power transfer in MHz range, the efficiency drops to approximately 60 % mainly due to loss in rectifier diode.

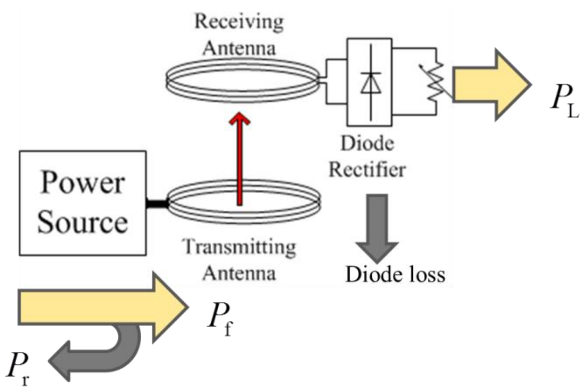


Fig. 4 Experimental system of power transfer efficiency including diode rectifier loss.

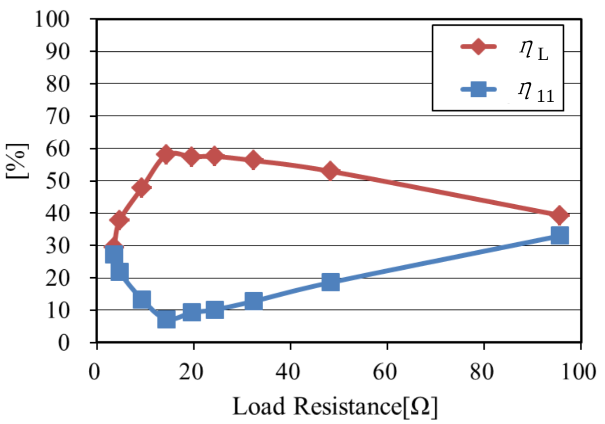


Fig. 5 Efficiency including loss due to diode rectifier vs. Load resistance (13.56 MHz).

III. IMPEDANCE MATCHING USING DC/DC CONVERTER

In this section, impedance matching system using DC/DC converter is proposed. A DC/DC converter changes DC voltage from one level to another. By such functionality, DC/DC converter operates like variable impedance circuit by controlling duty cycle of switching MOSFET. Three simple converter circuits are shown in Fig.6. Impedance value can be calculated from duty cycle and relation between input and output power. Impedance ranges that can be generated by each converter are shown as follows.

1) Buck Converter

A buck converter is a circuit which converts input voltage into lower output voltage expressed in terms of switching duty cycle D ($0 < D < 1$) in equation (7). And relation between input power and output power is shown in equation (8). Relation between output voltage, output current and load resistance is expressed in equation (9). Using equation (7), (8), (9), generated impedance is calculated by equation (10). Additionally, the range of generated input impedance relative to load resistance is shown in equation (11). Input impedance value becomes larger than load resistance.

$$V_{\text{out}} = DV_{\text{in}} \tag{7}$$

$$V_{\text{in}} I_{\text{in}} = V_{\text{out}} I_{\text{out}} \tag{8}$$

$$V_{\text{out}} = R_{\text{L}} I_{\text{out}} \tag{9}$$

$$Z_{\text{L}} = \frac{V_{\text{in}}}{I_{\text{in}}} = \frac{R_L}{D^2} \tag{10}$$

$$R_{\text{L}} \le Z_{\text{L}} \le \infty \tag{11}$$

2) Boost Converter

A boost converter is a circuit which converts input voltage into lower output voltage expressed in terms of switching duty cycle D ($0 < D < 1$) in equation (12). And relation between input power and output power is shown in equation (13). Relation between output voltage, output current and load resistance is expressed in equation (14). Using equation (12), (13), (14), generated impedance is calculated by equation (15). Additionally, the range of generated input impedance relative to load resistance is shown in equation (16). Input impedance value becomes smaller than load resistance.

$$V_{\text{out}} = \frac{1}{1-D} V_{\text{in}} \tag{12}$$

$$V_{\text{in}} I_{\text{in}} = V_{\text{out}} I_{\text{out}} \tag{13}$$

$$V_{\text{out}} = R_{\text{L}} I_{\text{out}} \tag{14}$$

$$Z_{\text{L}} = \frac{V_{\text{in}}}{I_{\text{in}}} = (1-D)^2 R_{\text{L}} \tag{15}$$

$$0 \le Z_{\text{L}} \le R_{\text{L}} \tag{16}$$

3) Buck-boost Converter

A buck-boost converter is a circuit which converts input voltage into lower output voltage expressed in terms of switching duty cycle D ($0 < D < 1$) in equation (17). And relation between input power and output power is shown in equation (18). Relation between output voltage, output current and load resistance is expressed in equation (19). Using equation (17), (18), (19), generated impedance is calculated by equation (20). Additionally, the range of generated input impedance relative to load resistance is shown in equation (21). Input impedance value can become either smaller or larger than load resistance.

$$V_{out} = \frac{D}{1-D} V_{in} \quad (17)$$

$$V_{in} I_{in} = V_{out} I_{out} \quad (18)$$

$$V_{out} = R_L I_{out} \quad (19)$$

$$Z_L = \frac{V_{in}}{I_{in}} = \frac{(1-D)^2}{D^2} R_L \quad (20)$$

$$0 \le Z_L \le \infty \quad (21)$$

The relation between variable impedance range and voltage ratio by each converter is summarized in Table.2. It is necessary to choose a suitable converter for each application in order to achieve high efficiency power transmission.

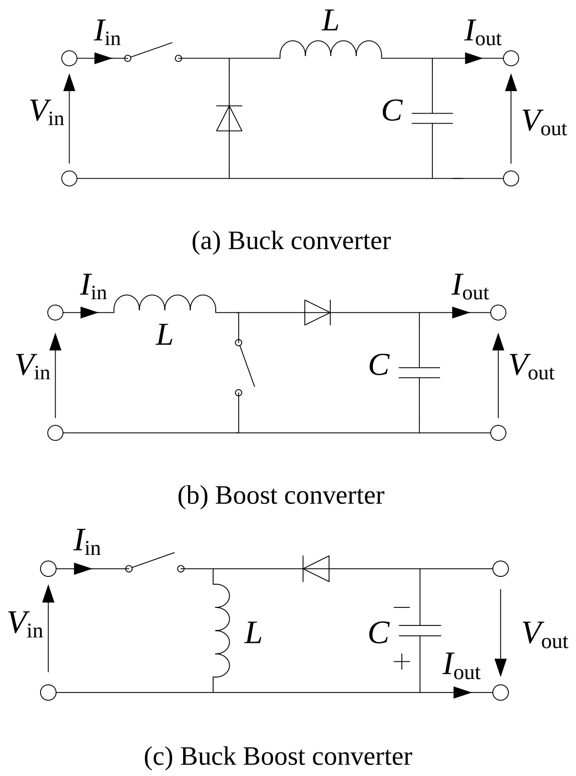


Fig. 6 DC/DC converters.

IV. EXPERIMENT

A. Exprimental System

Experimental system is set up as shown in Fig.7. In this study, impedance matching circuit using buck converter is investigated. The 13.56 MHz sinusoidal signal produced by function generator is amplified to 20 W by linear amplifier. Next, amplified power is fed into the directional coupler which is then connected to the transmitting antenna. The directional coupler divides input wave into forward wave P_f and reflected wave P_r, and only forward wave will propagate into the transmitting antenna and be transmitted to the receiving antenna. P_f and P_r are measured by power meter. AC power received in the receiving antenna is rectified to DC power by diode bridge circuit. Afterward, DC power is connected load resistance through DC/DC converter. DC/DC converter's switching frequency is 10 kHz. Load power P_L is calculated by measuring load voltage V_L. Power transmitting efficiency is then calculated by the relation defined in equation (6).

B. Realization of Impedance Matching Circuit Using DC/DC Converter

The possibility of realizing the variable impedance by using DC/DC converter needs to be verified. The change in transmitting efficiency and reduction of reflected power by changing duty cycle D, when load resistance is constant (R_L = 4.7 Ω), is investigated. The experimental result is displayed in Fig. 8.

Fig. 8 shows that reflected power ratio and transmitting efficiency are varied by duty cycle. Furthermore, minimum

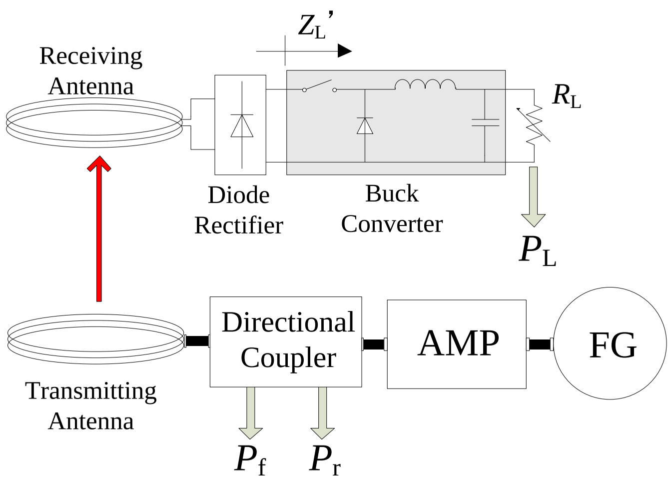


Fig. 7 Experimental system.

Table.3 DC/DC Converters & variable impedance

	Input & Output Voltage	Generated Impedance	Variable Range
Buck Converter	$V_{out} = DV_{in}$	$Z_L = R_L / D^2$	$R_L < Z_L < \infty$
Boost Converter	$V_{out} = 1 / (1-D) \cdot V_{in}$	$Z_L = (1-D)^2 R_L$	$0 < Z_L < R_L$
Buck-Boost Converter	$V_{out} = D / (1-D) \cdot V_{in}$	$Z_L = (1-D)^2 / D^2 \cdot R_L$	$0 < Z_L < \infty$

reflected power ratio and maximum transmitting efficiency occurs when duty cycle D is 0.6. At this point, Z_L = 4.7 / 0.62 = 13.1, according to equation (10). It is proved that high efficiency can be maintained by switching at optimal duty cycle regardless of load value.

C. Reduction of Reflected Power by Impedance Matching Circuit

Next, comparison study of power transfer system with and without matching circuit for each load resistance (R_L=4.7~50 Ω) is shown. The experimental result is displayed in Fig. 9. In Fig. 9, the experimental result in the case with matching circuit, the proposed method is able to reduced reflected power η_{11} during when load value is smaller than the optimal load value to the same level as when the optimal load value for power transfer is used. Therefore, when load variation occurs, the proposed method using DC/DC converter is proved to be effective in reducing reflected power.

D. Efficiency Improving by Matching Circuit

Consistent with the result shown in section *C*, the proposed method is able to improve efficiency of power transmission η_L from 5% to 20% when load value is smaller than the optimal load value. Therefore, as a result of reflected power reduction by impedance matching circuit using DC/DC converter, efficiency is improved.

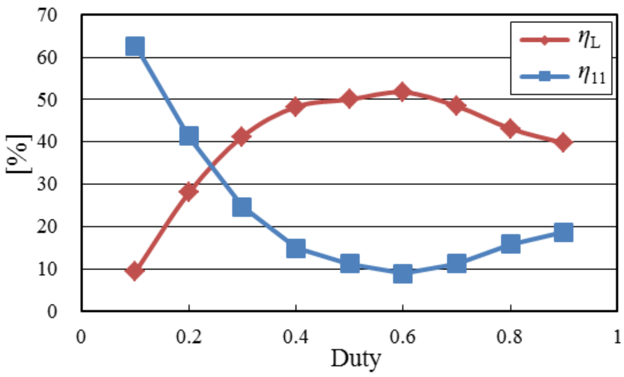


Fig. 8 Efficiency vs. Duty cycle.

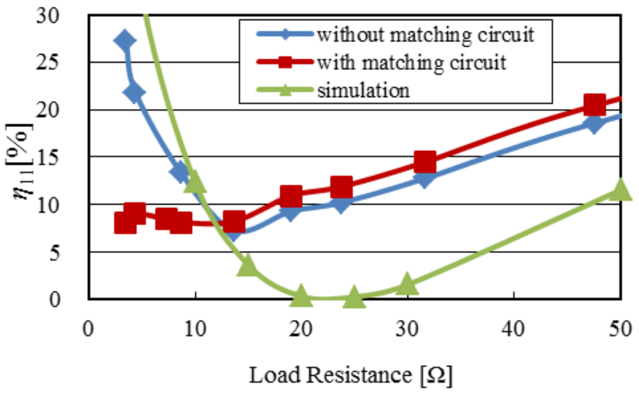


Fig. 9 Reduction of reflected power by matching.

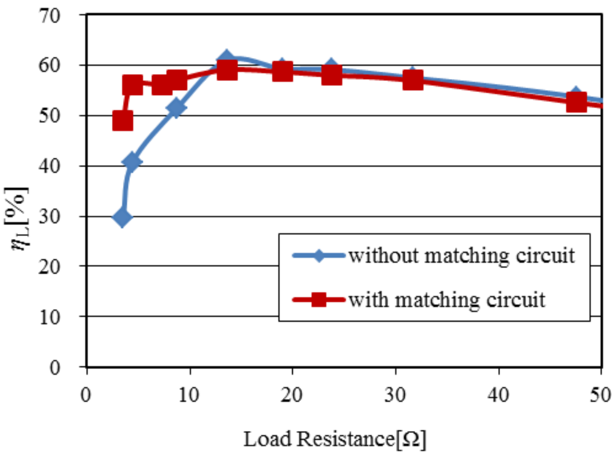


Fig. 10 Efficiency improving by matching.

V. CONCLUSION

In this paper, a novel impedance matching method using DC/DC converter in wireless power system via magnetic resonant coupling is proposed. The reduction of reflected power using DC/DC converter is proved to be effective by experiment. For Buck converter, the proposed method is effective only for the case when load resistance value is lower than optimal point in case of no matching circuit, due to the characteristics of Buck converter.

As the next step, the proposed impedance matching system built with boost or buck boost converter will be investigated. Automatic matching system will be proposed in order to examine matching speed using DC/DC converter.

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