Development of an Optimal Wireless Power Transfer System for Lithium-Ion Battery Charge

Yuto HONDA, Lei LIN, Masahiro FUKUI

Graduate school of Science and Engineering
Ritsumeikan University
Shiga, Japan, 525-0058
Email:mfukui@se.ritsumei.ac.jp

Abstract - We describe the development of the optimal wireless power transfer system for lithium-ion battery charge. Changing the charging current cause variation of the load value of the wireless power transmission circuit. This behavior reduces the transmission efficiency of wireless power transfer. Therefore, we have developed a wireless battery charger that achieve both of improvement the transmission efficiency and optimum charging of the Li-ion rechargeable battery.

I. INTRODUCTION

In recent years, wireless power transmission (WPT) technique is studied in order to increase convenience of EV and portable devices. In the wireless power transfer circuit using magnetic resonance, when the load resistance value is not optimum, the transmitting efficiency decreases [1,2]. If the charging control of the Li-ion battery is not optimized, the deterioration of the Li-ion battery to proceed by heat generation [3,4]. If the wireless charger uses the charging method of suppressing the deterioration during charging by controlling the charging current, the wireless transmission efficiency goes down. This is because the value of the charge load on the secondary-side is deviated from the optimum load resistance value when changing the charging current. The efficiency reduction improvement technique of the wireless power transmission already has been proposed [5-7]. However, several approach is not suitable for wireless charging of the Li-ion battery. This is because the efficiency control determines the output voltage. In this study, we propose the new wireless charging system. This system establish both of the suppressing reduction of the transmission efficiency of wireless power transmission and the optimization of charging to the Li-ion battery. This system has the DC/DC converter in both of the secondary-side (receiving-side) and the primary-side (transmitting-side). Secondary-side optimize charging current and voltage to the Li-ion battery. DC/DC converter on the primary side is indirectly improve efficiency by optimizing the DC/DC converter duty on the secondary side. To develop the proposed system, we analyzed the proposed method by finding out the optimum condition, modeling of the load, computing the numerical value. Additionally, we experimented by using prototyping the system to show the effectiveness of this method.

II. CONVENTIONAL METHOD OF EFFICIENCY IMPROVEMENT AND PROBLEMS

In the magnetic field resonance type wireless power transmission circuit, the transmission efficiency is reduced when the resistance value of the connected load is not at the optimum value. Here shows a method of suppressing using wireless power transmission DC/DC converter on the secondary-side a decrease in transmission efficiency due to the load fluctuation [7]. Fig.1 represents the circuit construction of this technique. HF is a high frequency power source, R is the load resistance, the *Duty* is the duty ratio of the DC/DC converter on the secondary-side in the figure. In this approach, the resistance of the load connected to the wireless power transmission circuit is a load resistance value of the virtual. Then, this method can maximize the transmission efficiency even if R is not the optimal value when the pretense load resistance value is optimum. R_{PL} is calculated by equation (1).

$$R_{PL} = \frac{R}{Duty^2} \quad (1)$$

R is the resistance value of the load connected to the secondary-side DC/DC converter, the *Duty* is the duty ratio of the secondary-side DC/DC converter. In this approach, R_{PL} becomes the load resistance value in the wireless power transmission circuit. In other words, even if the variation in the value of R, the transmission efficiency is maximized if the R_{PL} is the optimal value. However, this method cannot adapt to the charger. Fig.2 is an equivalent circuit model of a Li-ion battery [8]. In this model, R_{seriese} is internal resistance $R_{\text{transient\_}L}$, $C_{\text{transient\_L}}$, $R_{\text{transient\_}S}$, $C_{\text{transient\_}S}$ reproduce the impedance characteristics. V_{SOC} reproduces the voltage corresponding to the state of charge(SOC).

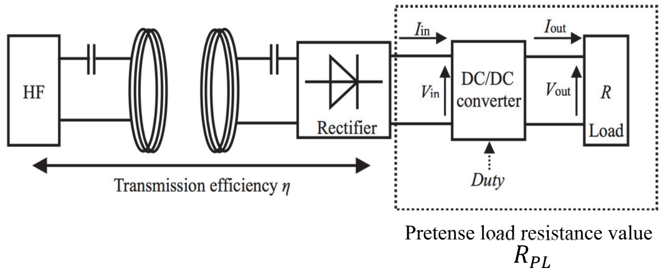


Fig. 1 Efficiency Improvement Method Using DC/DC Converter on the Secondary-side

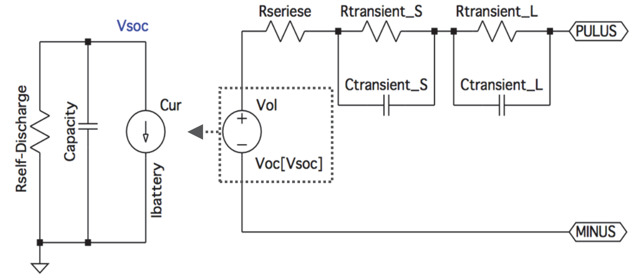


Fig.2 Equivalent circuit model of a Li-ion battery

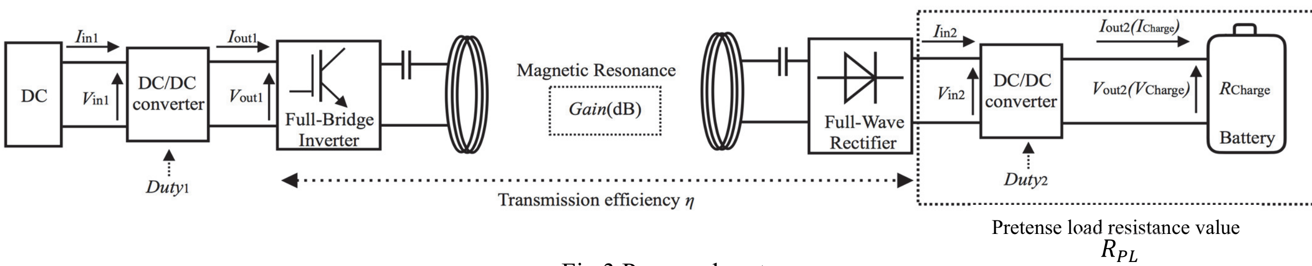


Fig.3 Proposed system

As can be seen from this equivalent circuit model, the current-voltage characteristic in charging is determined by the internal impedance and the SOC. Consider a case connected to the DC/DC converter to the equivalent circuit model as a black box. In this case, a Li ion battery is a load determined uniquely the charging voltage or charging current when gave charging current or the charging voltage. Equation (2) represents the load of the battery charger when charging the battery.

$$R_{\mathrm{Charge}} = \frac{V_{\mathrm{Charge}}}{I_{\mathrm{Charge}}} \tag{2}$$

V_{Charge} is a charging voltage, I_{Charge} is a charging current. In charging the Li-ion battery, it is important to management of the charging voltage and the charging current. Considering the suppression of deterioration and safety, it is necessary to adjust the value of the charging voltage V_{Charge} and charging current I_{Charge} according to the state of the storage battery to an optimum. Thus, *Duty* and *R* of formula (1) is dependent on the charging conditions. In other words, the pretense load resistance value R_{PL} is dependent on the charging conditions. Therefore, the conventional method cannot improve efficiency because the equation (1) cannot optimize R_{PL}.

III. PROPOSED METHOD

We propose the method of compatible optimum charging of the high-efficiency and storage batteries of wireless power transmission by extending the equation (1)

A. The configuration of the proposed circuit

Fig.3 shows the proposed circuit configuration. Proposed circuit has a DC/DC converter in both of the primary-side and the secondary-side. DC/DC converter on the primary-side adjust the V_{out1}. In this case, the duty ratio of the DC/DC converter on the secondary-side is expressed by equation (3).

$$Duty_2 = \frac{V_{out2}}{Duty_1 \times Gain \times V_{\mathrm{in1}}} \tag{3}$$

$Duty_1$ is the duty ratio of DC/DC converter on the primary-side. *Gain* is the gain of the voltage of the wireless power transmission circuit. In this way, the duty ratio of the DC/DC converter on the secondary-side can be expressed by using the duty ratio of the primary-side. Equation (3) can convert equation (1) into equation (4).

$$R_{PL} = \frac{R_{Charge}(Duty_1 \times Gain \times V_{in1})^2}{V_{out2}^{\;2}} \quad (4)$$

In equation (4), pretense load resistance value R_{PL} can controlled by the duty ratio of the DC/DC converter on the primary-side. Therefore, adjusting the DC/DC converter of the primary-side can improve the transmission efficiency.

IV. CIRCUIT DESIGN OF WIRELESS POWER SUPPLY

The optimum value of the element and the operating frequency of the wireless power transmission circuit can be determined with numerical calculations based on the transmission conditions such as transmission power, transmission distance, load resistance value. This chapter will be discussed with the magnetic field simulation, numerical analysis using the F parameter, the derivation of the resonance condition based on kQ product, and considering of the optimum circuit configuration.

TABLE I
Simulation condition

	Primary-side	Secondary-side
Diameter (mm)	300	300
Number of turns	20	20
Material	Cu	Cu
Wire diameter (mm)	10	10
The distance between the coils (mm)	50	
Ambient condition	Air	

TABLE Ⅱ
Magnetic field simulation result

	Primary-side	Secondary-side
Inductance (μF)	328	329
Parastic capacitance(nF)	0.207	0.207
Coupling coefficient	0.266	

TABLE Ⅲ
Measurement result of the production coils

	Primary-side	Secondary-side
Inductance (μF)	316	316
Parastic capacitance(nF)	0.268	0.240
Coupling coefficient	0.317	

A. *Magnetic field simulation*

Magnetic field simulation can reveal a certain amount of property before making the production of coil. We have run the magnetic field simulation on the basis of the transmission distance and the coil size, which had been decided in order to know the characteristics of the coil of the plan to manufacture. In this simulation, we use the Femtet manufactured by Murata software Corporation. Table Ⅰ-Ⅲ shows specifications of coils of the simulation, analysis results, and the value of the fabricated coils.

B. *Circuit analysis*

We analyzed the resonant circuit based on the fabricated coil characteristics by F-parameters and kQ product. Then, we derive the optimum value of the resonance frequency and the value of the resonance capacitor.

First, calculate the kQ product, and to derive the optimum operating frequency. kQ product is represented by the multiplication of coupling coefficients k and the Q value (Quality Factor). Coupling coefficient k represents the strength of coupling of the two coils. In wireless power transmission circuit of the magnetic field resonance, Q value is derived from the equation (5) and (6).

$$Q_{tx} = \frac{\omega \cdot L}{\frac{(\omega \cdot L_m)^2}{R}} \quad (5)$$

$$Q_{rx} = \frac{\omega \cdot L}{R} \quad (6)$$

In the formula (5), Q_{tx} represents the Q value of the transmission side. In the formula (6), Q_{rx} represents the Q value of the secondary-side. ω is the angular frequency of the operating frequency, L is the self-inductance, L_m is the mutual inductance, R is a load connected to the secondary-side. Equation (10), (11) represents the optimum value of k-Q product.

Critical coupling : $k^2 \cdot Q_{tx} \cdot Q_{rx} = 1$ (7)

Unimodal characteristic: $k \cdot Q_{tx} = k \cdot Q_{rx} = 1$ (8)

The frequency characteristic of the wireless power transmission circuit is a single peak characteristic and the critical characteristic when satisfying the condition of formula (7) (8). As a result, the output and efficiency is increased [4]. In other words, the output and efficiency of the wireless power transmission circuit can be improved when the relationship between the load resistance value and the coil characteristics and the operating frequency are optimal. We derive the optimal resonance condition by substituting the measured values of the coil in the formula (5) to (8). It was calculated using the values in Table . The graph of Fig.5 shows the calculation results. y-axis is load resistance value connected to the secondary-side, x-axis is k-Q product.

Analyzing the LC resonance circuit by using F-parameters [9]. This analysis can be derived optimum value of the resonance frequency and the resonance capacitor. Transfer coil of the magnetic field resonance wireless power transmission circuit is represented as a transformer. However, this is a factor that makes difficult to analyze the circuit in F-parameter. So representing the resonant circuit in the T-type equivalent circuit. General resonance circuit and the T-type equivalent circuit shown in figs 6 and 7. Analyzing the resonant circuit by using the equivalent circuit in fig 7 and F- parameters. In the following formula, jω = s. Circuit of the primary-side (transmitting-side) is represented as four matrices is shown in Equation (9).

$$M_{\mathrm{tx1}} = \begin{bmatrix} 1 & \frac{1}{sC_1} \\ 0 & 1 \end{bmatrix} \qquad M_{\mathrm{tx2}} = \begin{bmatrix} 1 & 0 \\ sC_{\mathrm{p1}} & 1 \end{bmatrix}$$
$$M_{\mathrm{tx3}} = \begin{bmatrix} 1 & sL_1 + R_1 \\ 0 & 1 \end{bmatrix} \qquad M_{\mathrm{tx4}} = \begin{bmatrix} 1 & 0 \\ \frac{1}{2sL_{\mathrm{m}}} & 1 \end{bmatrix} \tag{9}$$

Circuit of the secondary-side (receiver-side) is represented by five matrices is shown in Equation (10).

$$M_{\mathrm{rx1}} = \begin{bmatrix} 1 & 0 \\ \frac{1}{2sL_{\mathrm{m}}} & 1 \end{bmatrix} \qquad M_{\mathrm{rx2}} = \begin{bmatrix} 1 & sL_2 + R_2 \\ 0 & 1 \end{bmatrix}$$
$$M_{\mathrm{rx3}} = \begin{bmatrix} 1 & 0 \\ sC_{\mathrm{p2}} & 1 \end{bmatrix} \qquad M_{\mathrm{rx4}} = \begin{bmatrix} 1 & \frac{1}{sC_2} \\ 0 & 1 \end{bmatrix}$$
$$M_{\mathrm{rx5}} = \begin{bmatrix} 1 & 0 \\ R & 1 \end{bmatrix} \tag{10}$$

Multiplying equations (9) and (10) by equation (11). Set the calculation results as the matrix of *F*.

$$F = M_{\mathrm{tx1}} \cdot M_{\mathrm{tx2}} \cdot M_{\mathrm{tx3}} \cdot M_{\mathrm{tx4}} \cdot M_{\mathrm{rx1}} \cdot M_{\mathrm{rx2}} \cdot M_{\mathrm{rx3}} \cdot M_{\mathrm{rx4}} \cdot M_{\mathrm{rx5}} \tag{11}$$

Each element of the matrix *F* is calculated by equation (12) (13). In these equations, *Z* represents impedance, *Gain* represents the voltage gain.

$$Z = \frac{|F_{1,1}|}{|F_{2,2}|} \tag{12}$$

$$Gain = \frac{|1|}{|F_{1,1}|} \tag{13}$$

We have to derive the optimum conditions at the time of transmission by the coil fabricated using the formula (9) to (13).

C. Experiment and conditions

We have confirmed the efficiency improvement by the proposed method in experiments using the prototype. Fig.8 shows the prototype, and the specifications shown in Table Ⅳ . Load is an electronic load. Operating mode is set to CC mode. The output voltage of the DC/DC converter on the secondary-side was fixed at 3.7V. This reproduce the charge in the storage battery. Transmission efficiency was calculated by the equation (14).

$$\eta = \frac{V_{\mathrm{in2}} \times I_{\mathrm{in2}}}{V_{\mathrm{out1}} \times I_{\mathrm{out1}}} \tag{14}$$

We verified the efficiency improvement by the proposed method through experimentation.

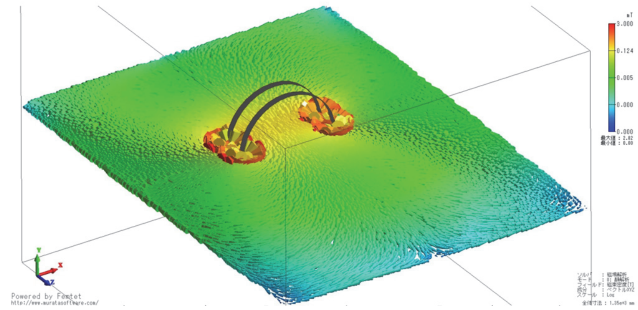


Fig. 4 Simulation result of the magnetic field

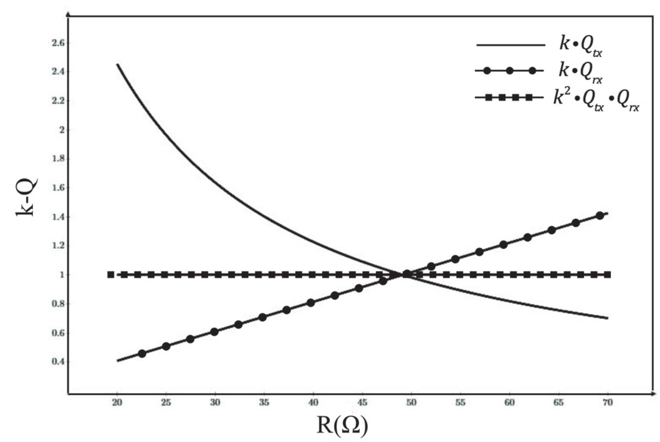


Fig. 5 Calculation result of k-Q product

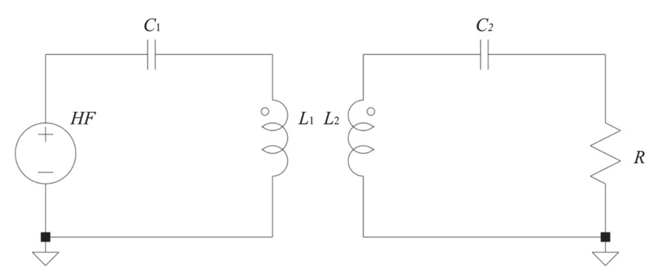


Fig. 6 Circuit of the WPT using magnetic resonant coupling

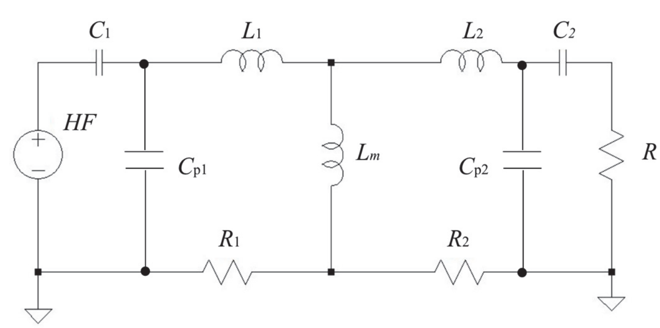
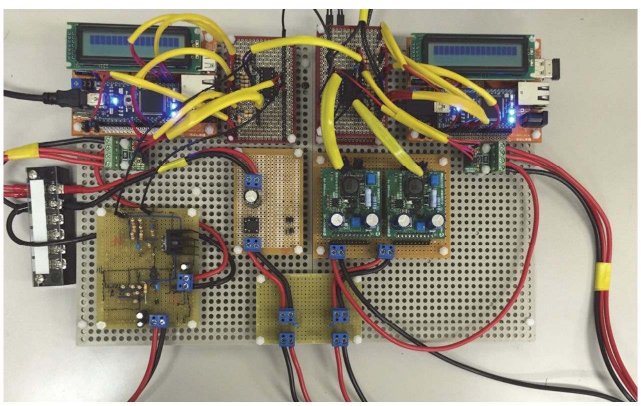


Fig. 7 T type equivalent circuit of WPT using magnetic resonant coupling

D. Experimental Results

Graph plotting experimental results is shown in fig 9. y-axis represents the transmission efficiency η, x-axis represents the output current I_{out2} the secondary-side. The white bar charts indicate the efficiency in the case of fixing the input voltage to the full bridge inverter to 16V, the gray bar charts indicate the efficiency of the case of fixing the input voltage to the full bridge inverter to 13V. In the case the circuit dose not have DC/DC converter on the primary-side, the transmission efficiency is dependent on I_{out2}. When the input voltage to the full bridge inverter to compare the case of 13V and the case of 16V, the value of I_{out2} that maximizes the transmission efficiency is different. This means that the optimum value of the input voltage to the full bridge inverter are different depending on the value of the charging current.

When compare of the proposed method and the conventional method, 12% efficiency improvement at the maximum can be seen in the proposed method. Moreover, efficiency degradation is up to 16% in the case of WPT without primary-side DC/DC converter. However, the efficiency degradation of proposed method is 4.4%. In other words, this experiment showed that the efficiency degradation of proposed method is nearly a quarter as low as conventional method. Thus, these result proved the proposed method can maintain efficiency when switching charging current.



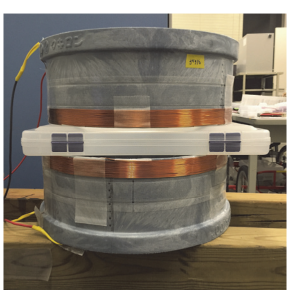


Fig.8 Prototype of proposed system

TABLE IV
Specification of prototype

	Primary-side	Secondary-side
Inductance (μF)	316	317
Parasitic capacitance (nF)	0.268	0.240
Parasitic resistance (Ω)	0.458	0.456
The number of turns of the coils (turns)	10	
Coil diameter (mm)	300	
Wire diameter (mm)	1	
Distance (mm)	50	
Coil material	Cu	
Resonance capacitor (μF)	0.01	
Frequency (kHz)	79.8	

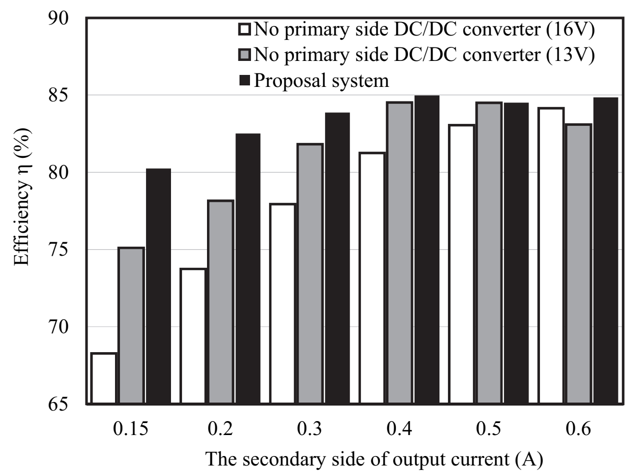


Fig.9 Comparative transmission efficiency

V. SUMMARY

This paper showed the development of the optimal wireless power transfer system for the lithium-ion battery charge. First, we showed the problems of the charging of the Li-ion battery using the WPT. Extend the equations used in the conventional method, and proposed a method that can suppress a decrease in efficiency in charging a wide charging current. From the results of experiments with a prototype circuit, we proved that the proposed method is able to improve the reduction in the efficiency in charging a wide current range. In other words, the results proved that proposed system is able to achieve both of the transmission efficiency improvement and the optimum charge. In the future, analyzing each efficiency of each module, and increasing the operating frequency for reducing the size of the system.

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