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Auto tuning of frequency on wireless power transfer for an electric vehicle

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ABSTRACT

In these days, electric vehicles are enthusiastically researched as a countermeasure to air pollution, although these do not have practicality compared to gasoline-powered vehicles. The aim of this study is to transport energy wirelessly and efficiently to an electric vehicle. To accomplish this, we focused on frequency of an alternating current (AC) power supply, and suggested a method which determined the value of it constantly. In particular, a wireless power transfer circuit and a lithium-ion battery in an electric vehicle were expressed with an equivalent circuit, and efficiency of energy transfer was calculated. Furthermore, the optimal frequency which maximizes efficiency was found, and the behavior of voltage was demonstrated on a secondary circuit. Finally, we could obtain the larger electromotive force at the secondary inductor than an input voltage.

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1. INTRODUCTION

In these days, the effect of carbon dioxide (CO_2) is deeply concerned, and it is egested from gasoline-powered vehicles. This problem is the one of factor of global warming, and cars largely account for the rate in a variety of vehicles [1]. On the other hand, the electric vehicles (EV) on which do not egest CO_2 are focused, and it is forecasted that the egesting of CO_2 is reduced to 12 percent at 2050 in contrast with that of 2008 if the next-generation vehicles which contain those prevail in Japan [2]. Many eco-friendly EVs are frequently developed [3]-[5], and those are sold in the world [6], [7]. However, EVs have some problems, for example the spots to charge a lithium-ion battery in EVs are limited, and the time for charging it is considerably long [8]. Thus we can expect to solve those problems if the alternating current (AC) power supplies are set in loads, or on intersections, and moreover wireless power transfer (WPT) is realized from AC power supplies to a lithium-ion battery [9].

Kurs *et al.* [10] reported WPT via magnetic resonance, and it realized highly efficient energy transport. After that, many papers have reported WPT on various application, for example kitchen appliances [11], biomedical implants [12], [13], and satellites on space [14]. Particularly, many researchers are interested in EVs, and they use WPT to improve efficiency of energy transfer, oscillation problem, and atmospheric pollution [15]-[18]. As concrete solutions, [19] devised a configuration of inductors and controlled a phase, [20] controlled a duty cycle of square wave, and [21] utilized impedance matching.

For realizing efficient WPT, the adjustment of frequency of AC power supply is needed, and mutual inductance should be considered as the one of significant parameter. The mutual inductance changes according to the distance between an AC power supply and a lithium-ion battery [22]. It is important to measure the position of inductors, and calculate the mutual inductance constantly because there are many kinds of designs of vehicles.

In this study, an equivalent circuit of lithium-ion battery is designed by resistors and capacitors, and a WPT circuit is designed to charge and discharge the lithium-ion battery. Efficiency of transportation of electric power is found by the knowledge of control engineering. It proposes a method to determine frequency of AC power supply for highly efficient WPT.

2. DERIVATION OF THE OPTIMAL OPERATING FREQUENCY

2.1. Equivalent circuit of a lithium-ion battery

An equivalent circuit of a lithium-ion battery is designed as follows in Figure 1. It is equivalently expressed with capacitors and resistors, and moreover divided into fast dynamics part, slow dynamics part, and DC voltage source part. In Figure 1, $R_{\rm f} < R_{\rm s}, C_{\rm f} < C_{\rm s}$, and the time constant of slow dynamics part is approximately 10^3 times of that of fast dynamics part [23]-[26].

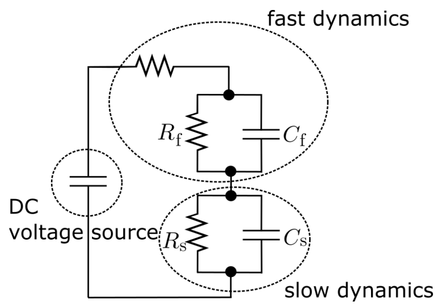

Figure 1. Equivalent circuit of a lithium-ion battery

2.2. Circuit of wireless power transfer and state equation

A WPT circuit to charge and discharge a lithium-ion battery is designed as follows in Figure 2. This circuit is divided into WPT part, rectifier circuit part to charge $C_{\rm ocv}$, and lithium-ion battery part. In WPT part, L_1, L_2, C_1, and C_2 are used to cause resonant phenomena, and M is the mutual inductance between L_1 and L_2. The optimal operating frequency of AC power supply u is determined by these values. Furthermore, the value of M changes in response to the distance between L_1 and L_2. If switch S is 1, $C_{\rm ocv}$ is charged by induced electromotive force which is rectified by full wave rectifier circuit. On the other hand, if switch S is 2, $C_{\rm ocv}$ discharges and drives the lithium-ion battery.

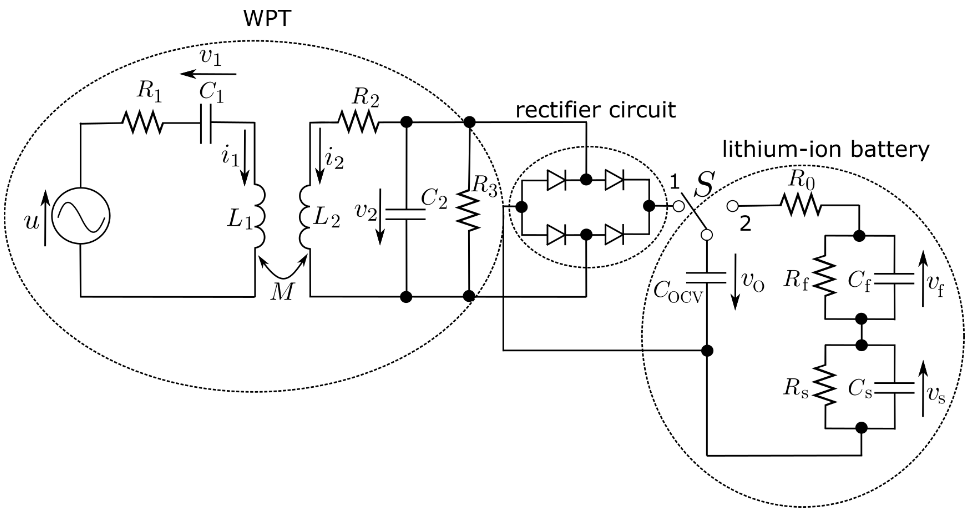

Figure 2. WPT circuit to charge and discharge a lithium-ion battery

The state equation in WPT part can be found by Figure 2 as (1) [26].

$$\dot{x} = Ax + Bu,\ x = \begin{bmatrix} v_1 & v_2 & i_1 & i_2 \end{bmatrix}^{\mathrm{T}}$$
$$A = \frac{1}{\Delta}\begin{bmatrix} 0 & 0 & \frac{\Delta}{C_1} & 0 \\ 0 & -\frac{\Delta}{R_3C_2} & 0 & \frac{\Delta}{C_2} \\ -L_2 & M & -R_1L_2 & R_2M \\ M & -L_1 & R_1M & -R_2L_1 \end{bmatrix},\ B = \frac{1}{\Delta}\begin{bmatrix} 0 \\ 0 \\ L_2 \\ -M \end{bmatrix}$$
$$\Delta = L_1L_2 - M^2 \tag{1}$$

Additionally, in the case of that S is 2, the state equation in lithium-ion battery part can be found as (2).

$$\dot{x} = Ax,\ x = \begin{bmatrix} \frac{dv_{\mathrm{o}}}{dt} & v_{\mathrm{f}} & v_{\mathrm{s}} \end{bmatrix}^{\mathrm{T}}$$
$$A = \begin{bmatrix} -\frac{1}{R_0C_{\mathrm{OCV}}}\left(1 + \frac{C_{\mathrm{OCV}}}{C_{\mathrm{f}}} + \frac{C_{\mathrm{OCV}}}{C_{\mathrm{s}}}\right) & \frac{1}{R_0R_{\mathrm{f}}C_{\mathrm{OCV}}C_{\mathrm{f}}} & \frac{1}{R_0R_{\mathrm{s}}C_{\mathrm{OCV}}C_{\mathrm{s}}} \\ \frac{C_{\mathrm{OCV}}}{C_{\mathrm{f}}} & -\frac{1}{R_{\mathrm{f}}C_{\mathrm{f}}} & 0 \\ \frac{C_{\mathrm{OCV}}}{C_{\mathrm{s}}} & 0 & -\frac{1}{R_{\mathrm{s}}C_{\mathrm{s}}} \end{bmatrix} \tag{2}$$

2.3. The optimal operating frequency to realize high efficiency

Power of power supply u and R_3 are defined as P_{in} and P_{out} respectively, and efficiency η of P_{out} to P_{in} is derived as (3):

$$\eta = \frac{R_3M^2\omega^2}{de(\omega)}$$
$$\begin{aligned} de(\omega) = {} & R_3^2C_2^2(R_1L_2^2 + R_2M^2)\omega^4 \\ & + [R_1(L_2^2 - 2R_3^2L_2C_2 + R_2^2R_3^2C_2^2) \\ & + (R_2 + R_3)M^2]\omega^2 \\ & + R_1(R_2 + R_3)^2 \end{aligned} \tag{3}$$

where ω is angular frequency of u. Hence, the optimal operating frequency f_{opt} which maximizes η is found as (4).

$$f_{\mathrm{opt}} = \frac{1}{2\pi}\sqrt{\frac{R_2 + R_3}{R_3C_2}}\left(\frac{R_1}{R_1L_2^2 + R_2M^2}\right)^{1/4} \tag{4}$$

Furthermore, M is expressed as (5) [27]:

$$M = \frac{\mu\pi n_1n_2r_1^2r_2^2}{2(r_1^2 + d^2)^{3/2}} \tag{5}$$

where μ is permeability, n_1 and n_2 are the winding numbers of L_1 and L_2, r_1 and r_2 are the radius of L_1 and L_2, and d is the distance between L_1 and L_2. Finally, f_{opt} is substituted as the function of d as (6).

$$f_{\mathrm{opt}} = \frac{1}{2\pi}\sqrt{\frac{R_2 + R_3}{R_3C_2}}\left(\frac{4(r_1^2 + d^2)^3R_1}{\mu^2\pi^2n_1^2n_2^2r_1^4r_2^4R_2 + 4(r_1^2 + d^2)^3R_1L_2^2}\right)^{1/4} \tag{6}$$

3. SIMULATION OF VOLTAGE ON RECEIVING CIRCUIT

3.1. Boad plot and steady voltage which is gained by receiving inductor

For numerical simulation, the values of elements are determined as Table 1. On this situation, mutual inductance M is calculated as 3 μH with the (5), and coupling coefficient $k(= M/\sqrt{L_1 L_2})$ is 0.1. Furthermore, $f_{\rm opt}$ is calculated with 29.1 kHz by the (4).

Table 1. Values of elements on the circuit

R_1, R_2	$1\ \Omega$	n_1, n_2	10
R_3	$100\ \Omega$	r_1, r_2	0.1 m
L_1, L_2	30 μH	d	0.158 m
C_1, C_2	1 μF	M	3 μH

The transfer function $G(s)$ from voltage of u to v_2 is calculated with the (1) as (7).

$$G(s) = -\frac{3.00 \times 10^{12} s^2}{891 s^4 + 6.89 \times 10^7 s^3 + 6.16 \times 10^{13} s^2 + 2.31 \times 10^{18} s + 1.01 \times 10^{24}} \tag{7}$$

Furthermore, bode plot is drawn as Figure 3.

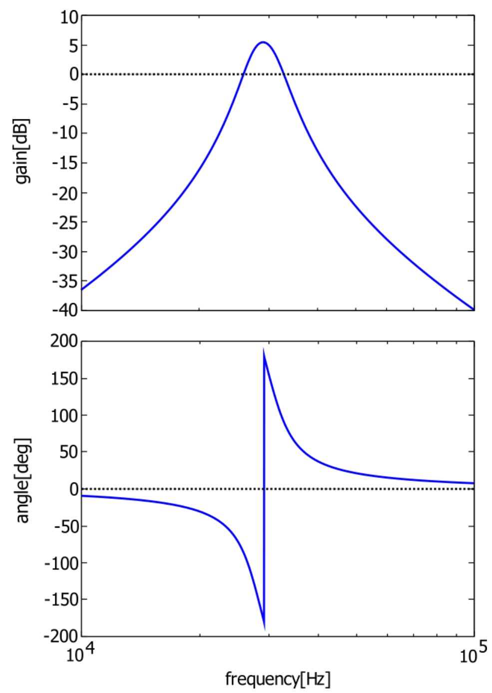

Figure 3. Bode plot from voltage of u to v_2

Moreover, steady solution $x_{\rm ss}$ is found from the state (1), and the stationary wave of open circuit voltage $v_{2\rm ss}$ is drawn in Figure 4. Where $E_{\rm m}$ is amplitude of u, and the value of it is $E_{\rm m} = 141$ V.

$$x_{\rm ss} = -E_{\rm m}(\omega I \cos \omega t + A \sin \omega t)(\omega^2 I + A^2)^{-1} B \tag{8}$$

3.2. Discussion

On this situation, gain is obtained as 5.45 dB, and the amplitude of $v_{2\rm ss}$ is calculated as 265 V by driving the circuit at 29.1 kHz. Therefore we can conclude that the higher voltage more than input voltage can be obtained at the secondary circuit. Moreover, the phase difference between u and $v_{2\rm ss}$ is approximately 0.

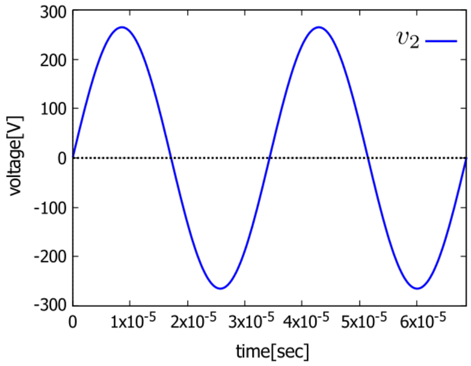

Figure 4. Steady voltage v_{2ss}

4. CONCLUSION

This study tried to improve efficiency of wireless power transmission for an electric vehicle. We certified the relationship between efficiency and distance of inductors because the optimal frequency to realize high power transmission depends on the distance. In the numerical simulation, we could verify that high induced electromotive force can be obtained if frequency of input is adjusted to appropriate value. In the future, the identification of internal systems is always needed to determine the optimal frequency even if the distance between a power supply and loads or the type of load change.

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