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Optimized wireless power transfer for moving electric vehicles by real-time modification of frequency and estimation of coupling coefficient

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ABSTRACT

In order to prevent global warming, electric vehicles are increasingly recommended than gasoline-powered vehicles that have been widely used in the past. However, problems peculiar to electric vehicles exists, and their widespread utilize is not progressing in Japan and other developed countries. This study performed wireless power transfer assuming that electric vehicles are stationary on a road at some distance from an AC power supply. Frequency of a power supply has significant influence on efficiency of wireless power transfer, and it is important to adjust this value on any situation. Therefore, an experiment was conducted based on the optimal frequency expression derived in the past to confirm the correctness of the expression, finally it achieved 60% transport efficiency. Moreover, since the expression includes coupling coefficient between transmission and receiving inductors, its value must be estimated accurately. In this study, an experiment was conducted to estimate value of coupling coefficient using current and voltage values measured from outside circuits, and it was compared with a theoretical expression obtained from laws on electromagnetics.

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1. INTRODUCTION

Recently, along with industrial development, various environmental problems such as global warming and consumption of fossil fuels have been pointed out [1], [2]. Many methods have been tried around the world to solve these problems. Among them, electric vehicles (EVs) are noticed as contributing to solving problems without reducing the quality of the modern transportation environment. In Europe, the U.S., and China, EVs account for a large percentage of all new vehicles, and made widely in there area globally [3]. On the other hand, there are area, including Japan, where EVs have not been widely adopted even in developed countries, mainly due to their short cruising range and lack of recharging locations. As a method to solve those problems, wireless power transfer (WPT) is expected to be utilized.

The basic principle of WPT is based on electromagnetic induction proposed by Faraday and Henry [4]. Strong resonance by reactance adjustment to realize high power WPTs have greatly advanced WPT field [5]. The inductance has been evaluated analytically and numerically to supply power to automobiles [6], the rotating magnetic field has been applied to automated guided vehicles (AGVs) by devising a topology [7], and photovoltaic power generation is concomitant used for WPT [8]. In addition to land-based transports, airborne applications are also advancing. Communication technology optimize UAVs in the power transport space [9], expansion of the charge capacity of UAVs can be realized by reducing current ripple [10], and study [11] proposed for methods to improve energy transport efficiency to UAVs by optimizing their placement. Furthermore, its applications are not limited on the earth, antenna design for WPT in space [12] and design of focusing lenses for harvesting space sunlight [13] are reported.

A load which is charged by WPT must always take into account changes in position. This means that the coupling coefficient between the transmission and charging circuits is constantly changing, and the frequency must be adjusted to the optimal value each time [14]. Alternatively, the optimum frequency varies depending on elements such as inductors and capacitors that make up the load. Currently, a method to calculate coupling coefficient using the parameters on the transmitter and receiver has been proposed [15], although a method to calculate it in real time and to always use the optimal frequency has not been established. On the other hand, attempts have been made to achieve efficient power transmission by fixing a position of load at the circuit design and devising inductors and Q values [16], [17].

In this paper, the optimal frequency is calculated and controlled, and the value is required by an inverter on WPT circuit. The optimal frequency is defined as the value which maximizes efficiency, and efficiency is defined the ratio of transmitting and receiving power. Simulations and experiments are conducted around the optimal frequency, and it can be confirmed that the power transmission efficiency is maximum near the optimal frequency in both cases. However, the expression for the optimal frequency includes the coupling coefficient between inductors in addition to the circuit constants, and this value must be accurately determined. The coupling coefficient can be expressed using the magnetic flux obtained from Biot-Savart's law, although the expression includes parameters related to a shape of the inductor, such as radius and cross-sectional area, and there may not be confirmed from outside a circuit. Hence this study attempts a method to calculate the value from externally measured currents and voltages, and compares it with the expression obtained from theory.

2. AUTOMATIC FREQUENCY TUNING FOR IMPROVEMENT TRANSMITTION EFFICIENCY

2.1. Transmission circuit and efficiency

The circuit of this study and parameters are shown in Figure 1 and Table 1. This circuit is largely composed of an inverter section and a mutual induction section. The inverter section is consisted of four MOSFETs, which are controlled by the switching IC TL494. Furthermore, the TL494 is controlled by a microcontroller through the digital potentiometer AD8400, and the microcontroller controls the frequency of the inverter section consequently.

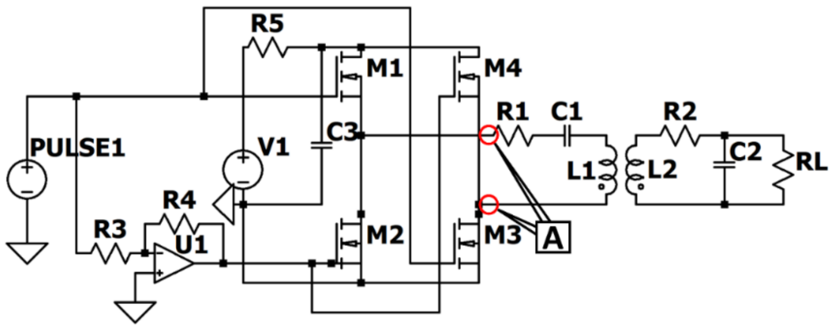

Figure 1. The circuit of WPT with frequency auto tuning

Table 1. Parameters on the circuit

Parameters	Values	Parameters	Values
PULSE 1	−5 to 5 V	R_4, R_5	1 Ω
V1	5 V	C_2, C_3	0.047 μF
R_1, R_2, R_3	1 Ω	L_1, L_2	25 μH
C_1	1 nF	R_L	100 Ω

For highly efficient WPT, it is important to determine the frequency of the inverter section. In this study, the frequency is adopted such that the ratio of load power to transmission power is maximized. If point A in Figure 1 is the transmission voltage, the frequency is calculated as (1) [18].

$$f = \frac{1}{2\pi}\sqrt{\frac{R_2+R_L}{R_L C_2}\left(\frac{R_1}{R_1 L_2{}^2+R_2 k^2 L_1 L_2}\right)^{\frac{1}{4}}} \tag{1}$$

Then k is coupling coefficient between L_1 and L_2. Moreover, since k is obtained by the positional relationship between L_1 and L_2 as shown in (2), and this positional relationship determines the optimal frequency [19].

$$k = \frac{\mu S_1 S_2}{2\pi\sqrt{L_1 L_2}(r_1{}^2+d_x{}^2+d_y{}^2+d_z{}^2)^{\frac{3}{2}}} \tag{2}$$

Then μ is the magnetic permeability, S_1 and S_2 are the total area of each inductor, r_1 is the radius of L_1, and d_x, d_y, d_z are the center position of L_2 with L_1 as the origin. Based on the above information, this study constructed a system in which a microcontroller performs optimal frequency control in real time when the d_z position is changed. Figure 2 shows the experiment on our laboratory, and Figures 3(a) and 3(b) show the calculated and measured efficiency - frequency relationships each other at $d_z = 10$ mm. The dashed lines in Figure 3 shows the optimum frequency at $d_z = 10$ mm obtained from (1).

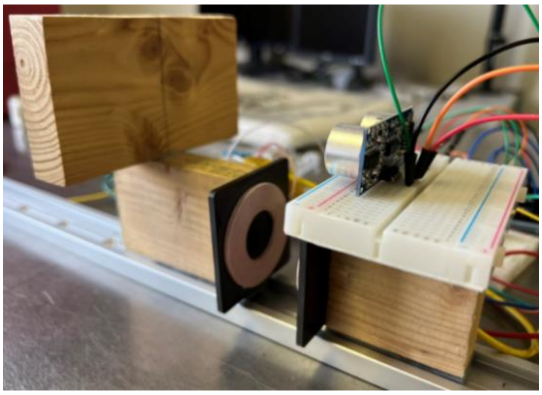

Figure 2. Experiments on automatic frequency tuning according to distance

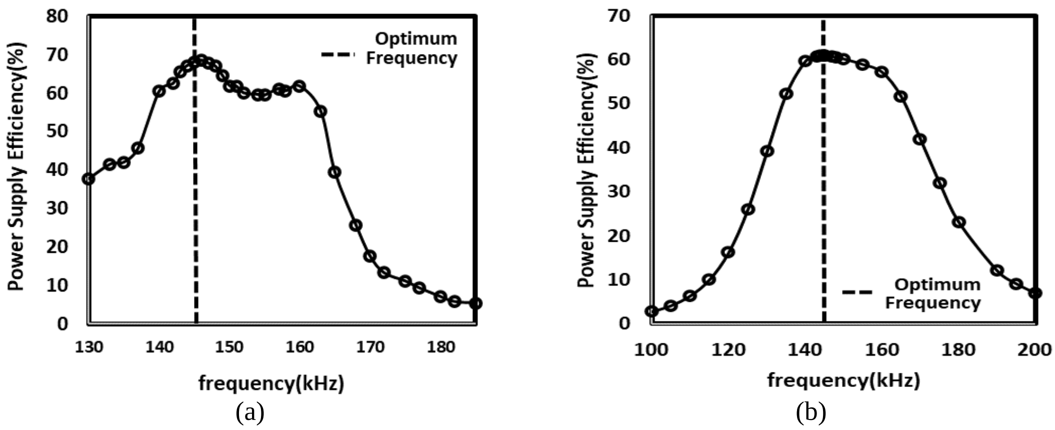

Figure 3. Variation of efficiency versus frequency and optimum frequency (a) calculated values and (b) measured values

2.2. Discussion

From (1), the optimum frequency is calculated to be 145 kHz at $d_z = 10$ mm. Figure 3(b) shows that efficiency at the frequency is 60.9%, which is the highest value compared to other frequencies. From above result, it is concluded that (1) correctly achieves high-efficiency WPT. On the other hand, the result based on the calculated values shown in Figure 3(a) indicate that there are two extreme values of efficiency.

This is due to the fact that (1) is derived by a method that finds extreme values of efficiency, and the number of the values increases with the number of inductor-capacitor pairs [20].

3. ACCURATE ESTIMATION OF COUPLING COEFFICIENT FOR CORRECT CALCULATION OF FREQUENCY

In the previous section, it is argued that frequency should be adjusted according to the positional relationship between the inductors. On the other hand, the formula for correct frequency calculation includes coupling coefficient. Therefore, if this value cannot be accurately measured, the optimal frequency cannot be calculated. This section measures the voltage at each element externally and measures the coupling coefficient from the results. In addition, it is compared with the coupling coefficient derived from the theory described in the previous section.

3.1. A circuit to measure mutual inductance

A circuit to measure coupling coefficient correctly is shown in Figure 4. From Figure 4, the following circuit (3) can be obtained.

$$\begin{bmatrix} \dot{V}_1 \\ j\dot{V}_2 \end{bmatrix} = \begin{bmatrix} R_1 & -\omega_0 k\sqrt{L_1 L_2} \\ -\omega_0 k\sqrt{L_1 L_2} & -R_2 \end{bmatrix} \begin{bmatrix} \dot{I}_1 \\ j\dot{I}_2 \end{bmatrix} \tag{3}$$

When ω_0 satisfies the following (4).

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{4}$$

From the above conditions, the coupling coefficient k is obtained as (5).

$$k = \frac{V_1 \pm \sqrt{V_1^2 - 4R_1 I_2 (R_2 I_2 + V_2)}}{2\omega_0 \sqrt{L_1 L_2} I_2} \tag{5}$$

In (5), since a designer can determine the value of $\dot{V}_1$, k can be estimated by measuring the current $\dot{I}_2$ and voltage $\dot{V}_2$ of R_{L}. Also (5) has two solutions, but takes positive values when k is large and negative values when k is small [21]. In this section, (5) which is obtained from the measured values is compared with (2), which is obtained from the inductor configurations and distance between inductors. The configurations of inductors used in this experiment is shown in Figure 5 and Table 2. This inductor is wound horizontally and consists of two vertical layers. Therefore the value of the radius varies from place to place, and as a result, the area in a loop changes each place [22].

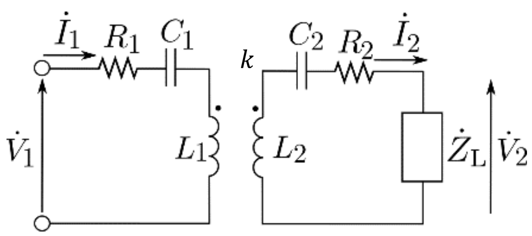

Figure 4. A circuit for estimating coupling coefficient based on experimental values

Table 2. Configuration of inductor

Inner radius	Turn number	Self-inductance
10 mm	21	25.1 μH

Experimental and theorical values of the variation of k with distance between inductors are shown in Figure 6. Considering the size of the inductors, the range of distances between inductors is 0 to 20 mm. The values for each element are shown in the Table 3.

Figure 5. Inductor used on experiment

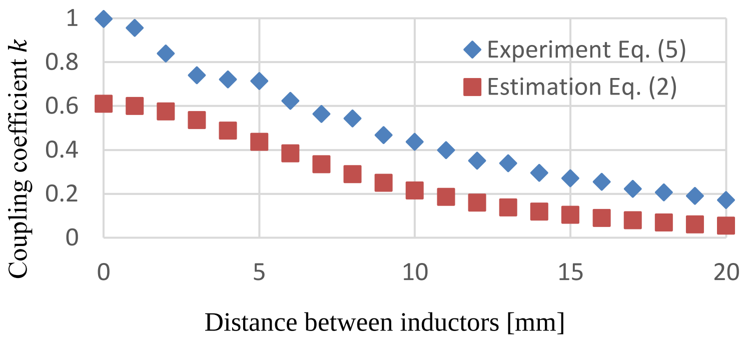

Figure 6. Comparison of experimental and estimated values of coupling coefficients

Table 3. Values of elements on an experimental circuit

Parameters	Values	Parameters	Values
V_1	10 V	C_2	39 nF
C_1	39 nF	L_2	28 μH
L_1	27.9 μH	R_2	10.3 Ω
R_1	50 Ω	R_L	100.2 Ω

3.2. Discussion

From coupling coefficient estimation, it is found that the coupling coefficient decreases gradually as the distance between inductors increases, as shown in the Figure 6 for both experimental and estimated values. However large errors can be observed, especially in the range of large distance. In a situation where the inductors are almost separated, an error of over 200% is observed. This is due to the fact that the cube of the position is included in (2), and the values of current and voltage used in the calculation in (5) are small. When WPT is applied to EVs, the distance between a power supply and a load is often large, thus it is necessary to consider the validity of the approximation accuracy and to increase size of an inductor on power supply circuit [23]. Moreover, in this study, an ultrasonic sensor was used to measure the distance, but if speed of a target is fast, feedback takes time and the optimum frequency adjustment may not be made in time. Therefore a more immediate response sensor is required [24], [25], or a sensor should be installed in a location where the EVs are moving at a sufficiently low speed.

4. CONCLUSION

In this paper, an inverter circuit and a mutual induction circuit that constitute WPT system were designed. The inverter circuit was controlled by a microcontroller, and frequency was programmed to always adopt the optimum value. As a result, the power transport efficiency was greater when the optimal frequency was adopted than at other frequencies.

The frequency autotuning method successfully improved efficiency, but errors between experimental and theoretical values were confirmed in the previous section. To improve the error, an expression for coupling coefficient was calculated from circuit equation, and its value was estimated from experimental values. The estimation results show that the error tends to be large, especially in the range where the distance between inductors is large.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Haruto Terada	✓	✓	✓		✓	✓		✓	✓	✓	✓			
Ryusei Okamura	✓	✓	✓		✓	✓		✓	✓		✓			
Kenichi Iida						✓			✓			✓		

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The evidences of some data on this study can be submitted by HT and RO if those are required.

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