Coupling Coefficient Estimation for Wireless Power Transfer System at Constant Input Power Operation

Haruko Nawada, Yoshiaki Takahashi, Katsuhiro Hata,
Takehiro Imura, Hiroshi Fujimoto, Yoichi Hori
The University of Tokyo
Kashiwa, Japan
nawada.haruko18@ae.k.u-tokyo.ac.jp

Takuya Yabumoto
Advanced Technology R&D Center
Mitsubishi Electric Corporation
Amagasaki, Japan
Yabumoto.Takuya@ct.MitsubishiElectric.co.jp

***Abstract*—Dynamic Wireless Power Transfer (DWPT) system for electric vehicles (EVs) can extend their the driving distance or even provide an infinite driving range. The receiver-side voltage control is considered as one of the methods to achieve maximum transmission efficiency in DWPT system of EVs. Estimation of coupling coefficient is required for this control method. This paper proposes coupling coefficient estimation in wireless power transfer system at constant input power operation to control receiver-side voltage which maximizes transmission efficiency. The simulation and experimental results demonstrate that the proposed estimation method is significant because the estimated coupling coefficient value and the measured value is statistically equal.**

***Index Terms*—Wireless power transfer, Magnetic resonant coupling, Coupling coefficient estimation, Transmission efficiency**

I. INTRODUCTION

Electric vehicles (EVs) attract attention because of their low-emission of CO_2 and less non-renewable resources consumption. However, they have long charging time and short driving distance. Wireless power transfer (WPT) system is applied to solve these problems. Especially, Dynamic Wireless Power Transfer (DWPT) system is possible to extend the driving distance of EVs. DWPT system technology of EVs has been studying as one of the solutions to these problems [1].

WPT system via magnetic resonant coupling was invented in 2007 by MIT [2]. As a feature of this method, the performance of power transmission with high transmission efficiency is robust against horizontal misalignment between the transmitter-side and receiver-side. Therefore, magnetic resonant coupling system is suitable for DWPT system.

In this research, WPT system at constant input power operation is used. “SAE J 2954” [3] standard of EVs is applied in order to maintain compatibility in WPT system. Therefore, constant power source is able to adjust the transmission power to match this standard.

One of the methods to increase the transmission efficiency is communication between the power transmitter-side and receiver-side [4], [5]. However, communication between the transmitter and receiver coils is not suitable in DWPT system because of the interference by the magnetic field along with delay in communication.

Moreover, transmitter-side power control is also considered as another method to increase the transmission efficiency [6]. Still, the transmitter-side should be designed in simple model in order to reduce the cost in infrastructure.

For these reasons, DWPT system should not communicate between transmitter-side and receiver-side and should be controlled only on the power receiver-side. Therefore, DWPT system should use the information on the power receiver-side for the transmission efficiency optimization.

Transmission efficiency can be maximized by adjusting only the receiver-side voltage to optimal voltage [7], [8]. Accordingly, receiver-side voltage control is considered in this research. In order to calculate optimal voltage of receiver-side, coupling coefficient value is required. However, it cannot be directly measured and depends on the horizontal misalignment and the air gap. Thus, coupling coefficient estimation is necessary.

In this paper, coupling coefficient estimation method in constant power wireless power transfer system by magnetic resonant coupling is proposed. The circuit structure and circuit equation are explained in Section II to derive the estimation equation of the coupling coefficient at constant input power operation. The coupling coefficient estimation equation correctness is evaluated by simulation in Section III. The feasibility of the proposed method is verified by experiment in Section IV. Finally, conclusion and future works are summarized in Section V.

II. COUPLING COEFFICIENT ESTIMATION AT CONSTANT INPUT POWER

In this research, series-series (SS) compensated circuit topology of WPT via magnetic resonance coupling is applied because it does not affect the resonance condition by the variation of the coupling coefficient. The equivalent circuit of SS compensated WPT topology is shown in Fig. 1. These parameters are explained as follows.

R_L is the load resistance. V_1 and V_2 are the RMS values of the transmitter-side and receiver-side voltages, respectively. I_1 and I_2 are currents at the transmitter-side and receiver-side, respectively. P_1 and P_2 are the transmitting and receiving power, respectively. R_1 and R_2 are the internal resistances of the transmitter and receiver coils, respectively. L_1 and L_2 are

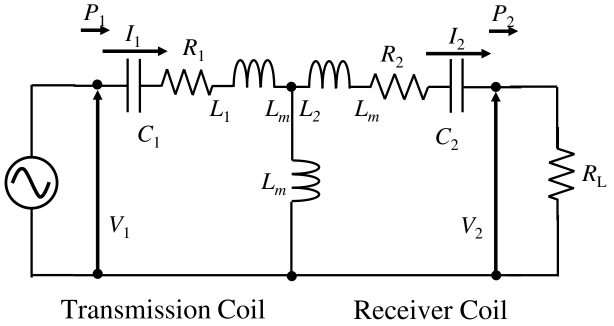


Fig. 1. T type equivalent circuit of SS system.

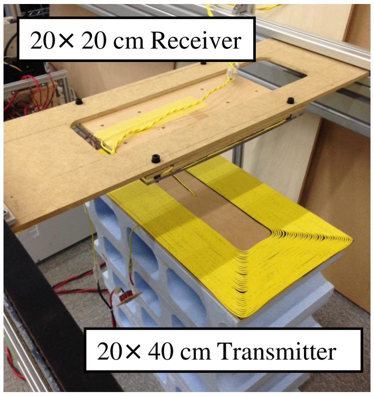


Fig. 2. Transmitter and Receiver Coils.

the self-inductance of the power transmitter and receiver coils, respectively. C_1 and C_2 are the capacitance of the transmitter and receiver capacitors, respectively. L_m is mutual inductance.

In the magnetic resonance coupling, since it is considered to operate under the resonance condition, the power source angular frequency ω_0 of the transmitter-side and the receiver-side is

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

Transmitter and receiver coils are designed to hold equation (1). The circuit equation of Fig. 1 is

$$\begin{bmatrix} V_1 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 & j\omega_0 L_m \\ j\omega_0 L_m & R_2 + R_L \end{bmatrix} \begin{bmatrix} I_1 \\ -I_2 \end{bmatrix}. \tag{2}$$

Considering $R_L = V_2/I_2$, from this circuit equation, the voltage ratio A_V and the current ratio A_I are

$$A_V = \frac{V_2}{V_1} = j\frac{\omega_0 L_m R_L}{R_1 R_2 + R_1 R_L + (\omega_0 L_m)^2} \tag{3}$$

$$A_I = \frac{I_2}{I_1} = j\frac{\omega_0 L_m}{R_2 + R_L}. \tag{4}$$

The transmission efficiency η is $A_V \cdot \overline{A_I}$. Considering that the power factor is 1, η can be derived as shown in the following equation (5).

$$\eta = \frac{P_2}{P_1} = \frac{V_2 I_2}{V_1 I_1} = \frac{(\omega_0 L_m)^2 R_L}{(R_2 + R_L)(R_1 R_2 + R_1 R_L + (\omega_0 L_m)^2)} \tag{5}$$

TABLE I
PARAMETERS USED FOR SIMULATION.

Parameter	Meaning	Value
f_0	Operating frequency	101 kHz
L_1	Transmitter inductance	419 μH
C_1	Transmitter capacitance	6.25 nF
R_1	Transmitter resistance	1.42 Ω
L_2	Receiver inductance	205 μH
C_2	Receiver capacitance	12.1 nF
R_2	Receiver resistance	1.09 Ω

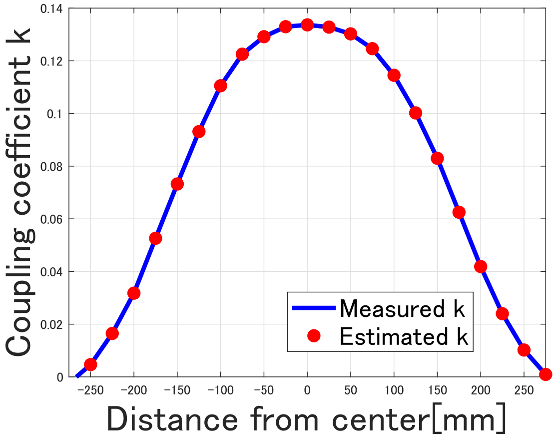


Fig. 3. Simulation result of coupling coefficient estimation ($P_1 = 10$ W).

Here, L_m is the mutual inductance between the transmitter coil and the receiver coil and can be obtained as follows:

$$L_m = k\sqrt{L_1 L_2}. \tag{6}$$

Thus, the estimated value of coupling coefficient $\hat{k}$ can be caluculated as follows:

$$\hat{k} = \sqrt{\frac{V_2 I_2 (R_2 + R_L)^2 R_1}{\{P_1 R_L - V_2 I_2 (R_2 + R_L)\}\omega_0^2 L_1 L_2}}. \tag{7}$$

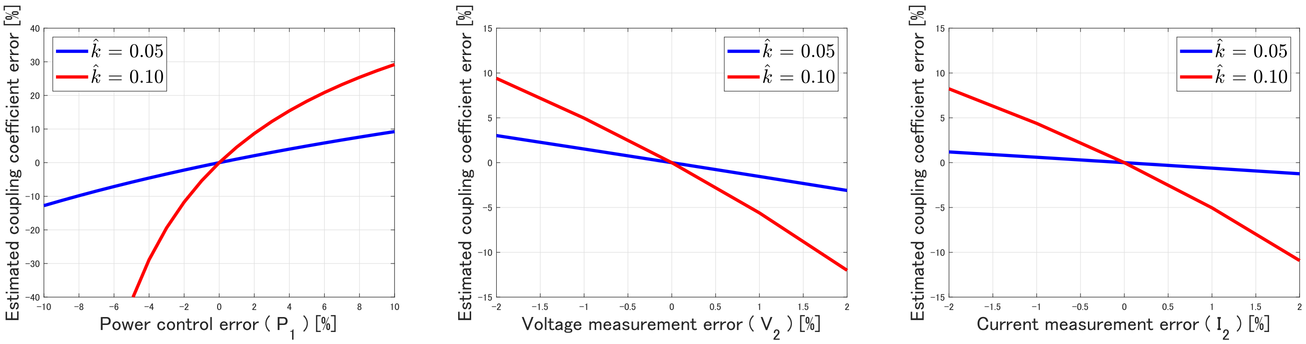
Assuming that input power is controlled to be constant, P_1 = P_{1ref}, and R_1 and L_1 are given as the known parameters. Therefore, it is possible to derive the coupling coefficient estimating equation by only the information on the secondary side.

III. THEORETICAL VALIDATION

A. Simulation

In order to evaluate the correctness of estimation equation (7) , simulation was conducted by MATLAB. In this simulation, the circuit shown in Fig. 1 is used. The transmitter and receiver coils are shown in Fig. 2, their parameters are listed in TABLE I, and R_L is constant. Coupling coefficient k is estimated under the condition that the input power is constant, so input power P_1 and P_{1ref} has been set to 10 W. Since the parameters of tranmitter side are given, k estimation only requires the receiver-side current I_2 and voltage V_2.

The simulation result of coupling coefficient estimation is shown in Fig. 3. From Fig. 3, the actual value and the



(a) Ratio of the power control error vs. the estimated coupling coefficient error.

(b) Ratio of the measurement error (V_2) vs. the estimated coupling coefficient error.

(c) Ratio of the measurement error (I_2) vs. the estimated coupling coefficient error.

Fig. 4. Error Analysis.

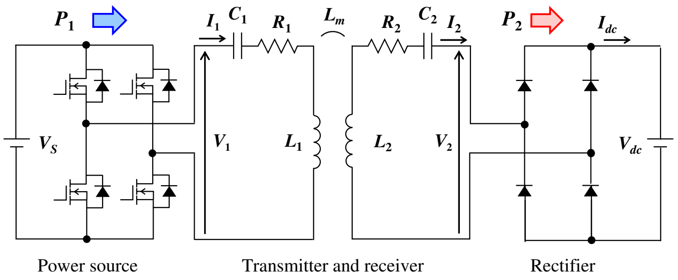


Fig. 5. Circuit structure.

estimated value match to each other. Therefore, it is implied the estimation equation (7) is correct.

B. Discussion of error

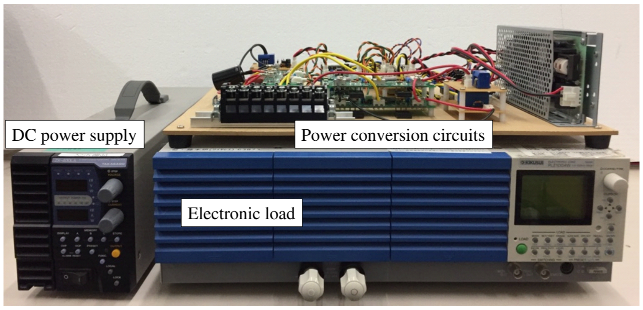
It is considered that estimated coupling coefficient $\hat{k}$ varies when the actual transmitted power P_1 deviates from the command value of the transmitted power P_{1ref}.

Also, the deviation of estimated coupling coefficient $\hat{k}$ from the actual value which is caused by the measurement error will be examined. In this discussion, let R_L is given as V_2/I_2. Error ratio analysis of $\hat{k}$ when there is error due to power control and measurement is shown in Fig. 4.

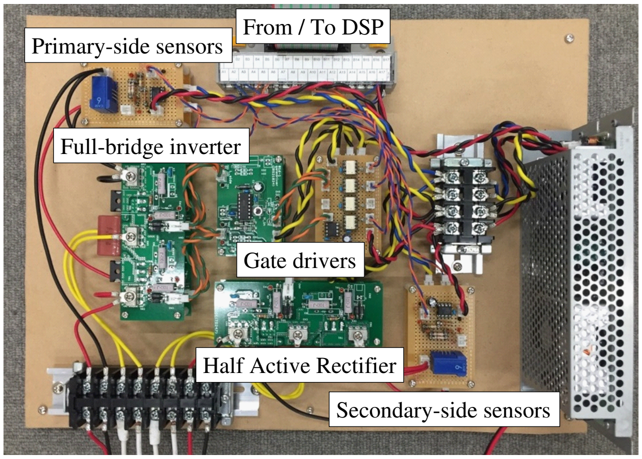
From Fig. 4 (a), the increase rate of the estimated coupling coefficient error increases more in the negative direction when the control error of P_1 becomes negative.

From Fig. 4 (b) and (c), the increase rate of the estimated coupling coefficient error increases in the negative direction when the measurement error of V_2, I_2 become positive. Also, when comparing Fig. 4 (b) and (c), the error rate of V_2 is slightly larger than the error rate of I_2. As the reason, from equation (7), it is considered that coupling coefficient estimation depends on V_2 rather than I_2.

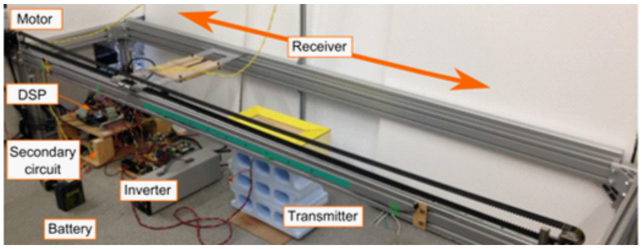
In addition, from Fig. 4, the error of the estimated coupling coefficient value due to the power control error and the measurement error also increases when the coupling coefficient increases. Therefore, it is necessary to precisely control power and measure the receiver-side current I_2 and receiver-side voltage V_2 when coupling coefficient becomes larger.



(a) Overview



(b) Power conversion circuit



(c) Equipment

Fig. 6. Equipment of wireless power transfer.

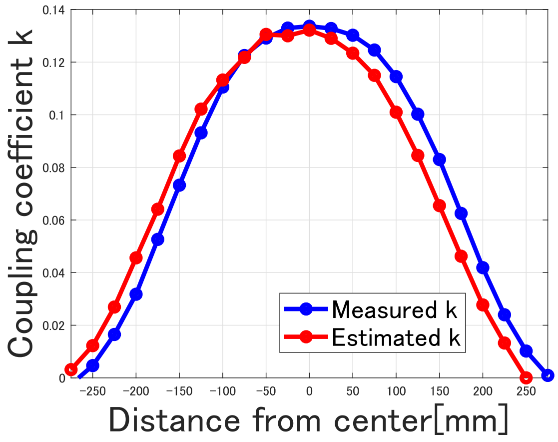


Fig. 7. Experimental result of coupling coefficient estimation ($P_1 = 10$ W).

IV. EXPERIMENT

In this section, the experimental verification of the proposed coupling coefficient estimation method is described. The circuit used for the experiment is shown in Fig. 5. The experimental equipment in Fig. 6 is designed to be about 1/3 of the actual EVs scale. The parameters of the experimental equipment are the same as those in TABLE. I. The effectiveness of the proposed method is verified by changing position of the receiver coil. The transmitter coil and the receiver coil have a gap length of 10 cm. The transmitter-side inverter is the rectangular wave voltage drive system, and the receiver-side converter is a diode rectification circuit.

The input voltage is adjusted to keep the transmission power constant ($P_1 = 10$ W). The values of the receiver-side voltage V_2 and the receiver-side current I_2 used for estimation at each measurement position were measured using a precision power analyzer (N4L PPA5500).

In addition, the receiver coil was moved by 2.5 cm intervals, and the coupling coefficient changed according to the receiver coil position. At this time, the actual value of the coupling coefficient was measured offline.

Experimental results are shown in Fig. 7. The actual value and the estimated value is approximately equal. As a result, the effectiveness and accuracy of the estimation equation were evaluated by the experiments.

The cause of error between the actual value and the experimental value is considered as the heat caused by driving the inverter for several hours and error due to coil position adjustment by hand.

However, even the largest error in this data (Distance from center = 200 mm), the transmission efficiency only changes within 18.6 % range.

V. CONCLUSION

In realistic WPT system, transmitter-side is ought to be simple in order to reduce the cost of infrastructure. Therefore, this research used only the information from the receiver-side. To achieve maximum transmission efficiency in DWPT system of EVs, the receiver-side voltage control is adapted.

To implement the receiver-side voltage control, estimation of coupling coefficient is required and this coupling coefficient is able to be estimated only by the information on the receiver-side.

In this paper, coupling coefficient estimation for WPT system at constant input power operation was implemented. It is confirmed that the estimation equation is effective by simulation and experimental validation.

As the future works, the method of high-precision constant power control of transmitter-side will be proposed and real-time maximum transmission efficiency control by receiver-side voltage adjustment with constant power supply will be performed in order to verify the practicality of this proposed method.

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