Maximum Output Power Design Considering the Efficiency in Wireless Power Transfer Coils

Yuto Yamada
Faculty of Science and Technology
Tokyo University of Science
Noda city, Chiba, Japan

Takehiro Imura
Faculty of Science and Technology
Tokyo University of Science
Noda city, Chiba, Japan

***Abstract*—Wireless power transfer has been attracting a lot of attention in recent years to improve our convenience. Wireless power transfer to electric vehicles is very important to contribute to the spread of electric vehicles and to reduce global warming. Since power supply to electric vehicles often requires high output power, it is essential to design coils to increase the output power by focusing on the coupler part in a specific frequency band from the viewpoint of practicality. In this study, based on SAE J2954 Test station GA-WPT1 and Test station VA-WPT1/Z3 at 85kHz band, we propose a coil design method to obtain the output power while maintaining the efficiency within the required coil size. Although the WPT1 requires 3.3 kW output, the highest efficiency of 99.2% was achieved at 10.9 kW with 600 V input in the simulation. It also achieved 99.0% efficiency at 20.2kW output. The simulation and measurement results show that the inductance of the coil on the transmission side has a significant effect on the output power, which is applied to all wireless power transfer in SS circuits.**

Keywords—Wireless Power Transfer, Coil design, Electric Vehicle, Output Power

I. INTRODUCTION

Research on Wireless Power Transfer (WPT), which is the transmission of power to any device without cables, is becoming more and more active [1]. WPT for electric vehicles is attracting attention as a means to solve many of the problems that electric vehicles are currently facing, and is expected to be very popular in the future [2-4]. Although SAE J2954 is the standard for Static Wireless Power Transfer (SWPT) of electric vehicles, it does not specify the exact design within the specified coil size and is still a subject of research [5]. SAE J2954 divides the classes according to the input power, and describes up to 60 kVA, which is WPT5 class. In recent years, some quick chargers using cables have exceeded 100 kW, and a high power output of WPT5 or higher is required for power supply to electric vehicles [6]. High power WPT is also very important for dynamic wireless power transfer because it is necessary to supply power within a short time when the car passes over the coil. Most of the previous researches used parametric analysis to study the optimum circuit elements for high power, or looked at the response of power transfer due to changes in frequency or coupling coefficient [7] [8]. Electromagnetic field analysis is already a well-established and reliable method, but it does not show accurate results because it is difficult to predict changes in the environment considering that the coil is actually buried in the ground [9]. It is very important to deepen the theorization of the parameters of the coil and to evaluate them

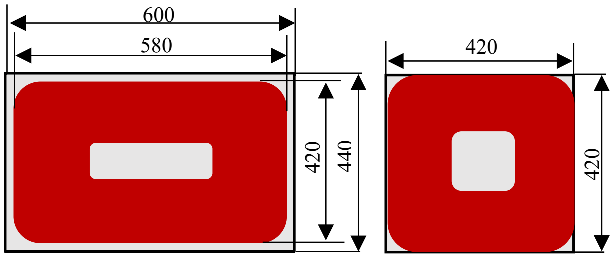


Fig. 1 Test station GA-WPT1, VA-WPT1/Z3

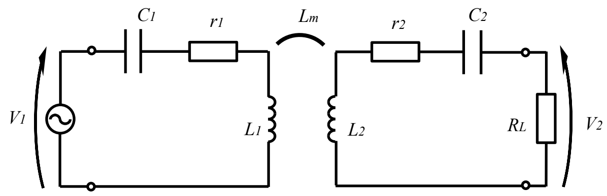


Fig. 2 Equivalent circuit in magnetic field resonance coupling of (S-S).

easily by numerical analysis in order to better understand the characteristics of the coil.

Although the trade-off between efficiency and power is widely known, there are few papers that have theoretically presented and examined the design of coils that achieve the required power without compromising the transmission efficiency [10]. In some literatures, researches to maximize the efficiency by using kQ product are introduced, but in many cases, the output power cannot be obtained [11-13]. In this study, a coil design method to increase the output power is discussed assuming the coil size of Test station GA-WPT1 and Test station VA-WPT1/Z3 of SAE J2954 [5]. Each size of Test station is shown in Fig. 1. The theory is presented in chapter II, the relationship between efficiency and power is visualized in chapter III, and the conclusion is given in chapter IV. The theory presented in chapter II can be applied to all kinds of coils, so it can be applied to various coil designs.

II. THEORY

In this study, S-S (Series-Series) magnetic field resonant coupling [14], in which an inductor and a capacitor are connected in series and resonate, is used for wireless power transfer. The circuit diagram is shown in Fig. 2. Each parameter is defined as the internal resistance r_1 and r_2 of the transmission and receiving coils, the self-inductance L_1 and L_2 of the transmission and receiving coils, each resonant capacitor C_1 and C_2, and the load resistance R_L.

Since the reactance due to the self-inductance L_1 and L_2 and the reactance due to the capacitance C_1 and C_2 cancel each

$$P_{2,\eta max} = \frac{k^2Q_1Q_2\sqrt{1+k^2Q_1Q_2}}{r_1\left\{(k^2Q_1Q_2)^2 + 3k^2Q_1Q_2 + 2(1+k^2Q_1Q_2)\sqrt{1+k^2Q_1Q_2} + 2\right\}} V_1^2 \quad (12)$$

other out under the resonance condition, the resonance angular frequency ω_0 can be expressed as follows

$$\omega_0 = 2\pi f = \frac{1}{\sqrt{L_1C_1}} = \frac{1}{\sqrt{L_2C_2}} \quad (1)$$

The efficiency η can be expressed as follows

$$\eta = \frac{R_L(\omega_0L_m)^2}{(r_2+R_L)\{r_1(r_2+R_L)+(\omega_0L_m)^2\}} \quad (2)$$

From the following conditional equation (3), the maximum efficiency η_{max} can be expressed as (5) by introducing the optimal load $R_{L,\eta max}$ (4), which maximizes the efficiency.

$$\frac{\partial\eta}{\partial R_L} = 0 \quad (3)$$

$$R_{L,\eta max} = r_2\sqrt{1+\frac{(\omega_0L_m)^2}{r_1r_2}} \quad (4)$$

$$\eta_{max} = \frac{(\omega_0L_m)^2}{\left(\sqrt{r_1r_2}+\sqrt{r_1r_2+(\omega_0L_m)^2}\right)^2} \quad (5)$$

The output power P_2 discussed in this study can be expressed by the following equation.

$$P_2 = \frac{R_L(\omega_0L_m)^2}{\{r_1(r_2+R_L)+(\omega_0L_m)^2\}^2}V_1^2 \quad (6)$$

Next, introducing the coupling coefficient k and the quality factors Q_1 and Q_2, the kQ product can be expressed as (9).

$$k = \frac{L_m}{\sqrt{L_1L_2}} \quad (7)$$

$$Q = \frac{\omega_0L_i}{r_i} \quad (8)$$

$$k^2Q_1Q_2 = \frac{(\omega_0L_m)^2}{r_1r_2} \quad (9)$$

From (9), (4) and (5) can be expressed as follows

$$R_{L,\eta max} = r_2\sqrt{1+k^2Q_1Q_2} \quad (10)$$

$$\eta_{max} = \frac{k^2Q_1Q_2}{(1+\sqrt{1+k^2Q_1Q_2})^2} \quad (11)$$

Equation (12) is then obtained from (6) (9) and (10).

From (11), it can be seen that the efficiency η_{max} can be improved by increasing the kQ product, but from (12), it can be seen that if the kQ product is increased, the output power P_2 will decrease. Also, the design of the transmission coil is important because of the internal resistance r_1 term. Now, by introducing the following approximation, equation (12) can be shown as (13).

$$1 \ll k^2Q_1Q_2$$

$$P_{2,\eta max} = \frac{1}{r_1(\sqrt{k^2Q_1Q_2}+2)}V_1^2 \quad (13)$$

More, equation (13) can be transformed into the following

$$P_{2,\eta max} = \frac{1}{\omega_0 k\sqrt{\frac{r_1L_1L_2}{r_2}}+2r_1} \quad (14)$$

From (14), it can be seen that in order to increase the output power $P_{2,\eta max}$, the inductance should be reduced and the coupling coefficient k should be decreased. However, since both of them decrease the efficiency η_{max}, it is important to decrease the number of turns on the transmission side, which can effectively increase the output $P_{2,\eta max}$ when the pitch is fixed.

Reducing the inductance of the receiving coil L_2 can also increase the output power $P_{2,\eta max}$, but it is not effective because the internal resistance r_2 decreases with the decrease in inductance L_2.

III. Measurement Results

Based on Test station GA-WPT1 and Test station VA-WPT1/Z3 of SAE J2954, five coils on the transmission side and five coils on the receiving side were made, and the output power values at the optimum load at 600V input were derived, and the theoretical values were compared with the measured values. The frequency was set to 85 kHz.

However, the output power P_2 at 600V input was output using equation (12) from the results obtained using a vector network analyzer : VNA(KEYSIGHT E5061B).

Fig. 3 shows the measurement scenery. The comparison between the analyzed and measured values of coil resistance

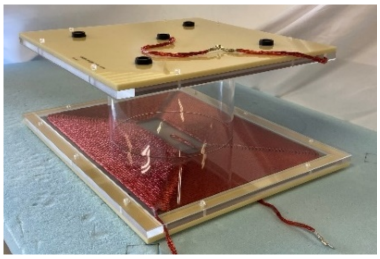


Fig. 3 Measurement of efficiency and power between coils (airgap = 200 mm).

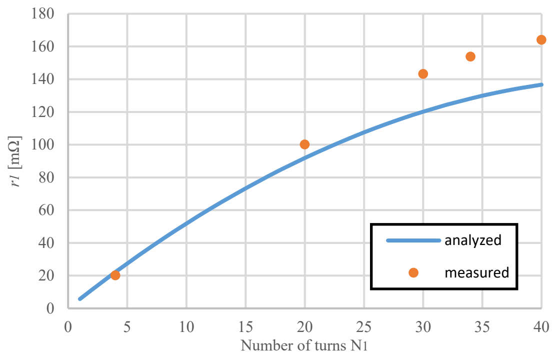


Fig. 4 Resistance of transmission coil.

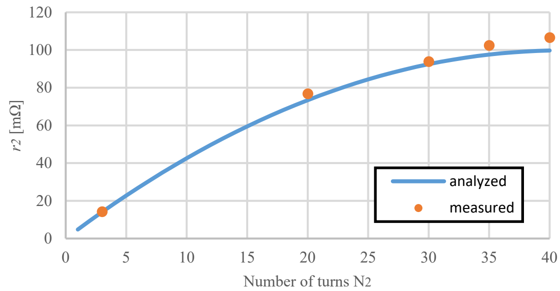


Fig. 5 Resistance of the receiving coil.

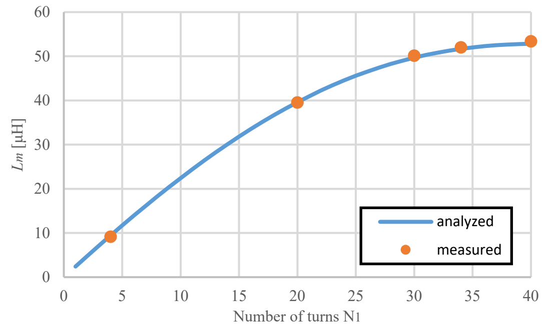


Fig. 6 Comparison between analyzed and measured values of mutual inductance L_m (N_2=30).

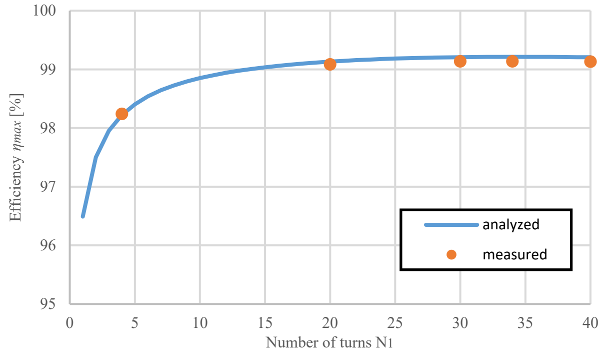


Fig. 7 Efficiency η_{max} at number of turns at 30 on the receiving side.

and mutual inductance is shown in Fig. 4, Fig. 5, and Fig. 6, respectively. Fig. 7 shows the comparison between the analytical and simulated values for the change in the number of turns on the transmission side with 30 turns on the receiving side. The measurements in Fig. 7 are based on the use of an ideal capacitor for the coil that was created.

The analyzed and measured values are in very good agreement, and the point of maximum efficiency is the same. In Fig.3 and Fig.4, there is a slight error between the analyzed and measurement values of the internal resistance of the coils, but the coils made this time were made with a wire-to-wire distance of 0 mm to emphasize efficiency. However, the efficiency shown in Fig. 7 was evaluated with almost no error. In order to further increase the transmission power between coils, a wire-to-wire distance should be increased, which will enable more accurate analysis.

Fig. 8 and Fig. 9 shows the created coil. The PEEC method [15] [16] was used to analyze the internal resistance of the coil, and the Neumann equation was used to derive the mutual inductance.

Deriving the kQ product, efficiency η_{max}, and output P_2 for each combination of the number of turns on the transmission side and the receiving side, it can be shown as Fig. 10, Fig. 11 and Fig. 12. The area where the allowable current of the used Litz wire is exceeded is indicated by a shaded line. The highest efficiency can be obtained with the number of turns of ★. The point proposed in this paper, where output can be obtained without loss of efficiency, is the number of turns of ☆.

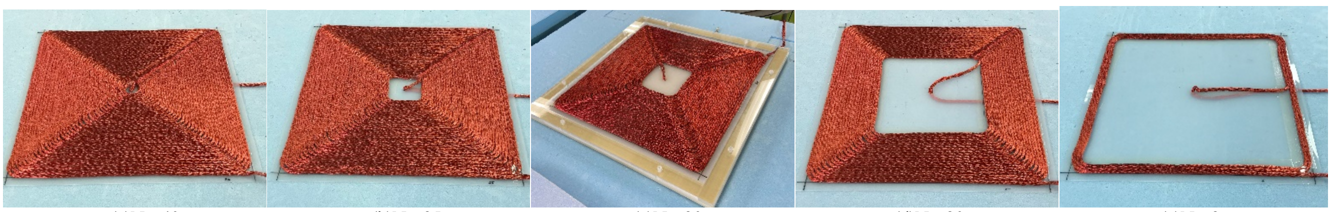
The U.S. Department of Energy (DOE) Electrical Safety Guidelines and the Occupational Safety and Health Administration, as well as Japan's Ministry of Economy, Trade and Industry, have set 600V as the boundary between low voltage and high voltage. In this paper, 600V is set as the input voltage for quick charging in commercial facilities and homes. However, SAE J2954 sets the upper limit of battery voltage for loads at 420V. Since the optimal load resistor is connected to the load instead of the battery, we cannot discuss the details, but we also studied the case where the load voltage is limited to 420V.

Fig. 10 and Fig. 11 shows that the efficiency is higher when the number of turns on both the transmission and the receiving sides are large, but Fig. 12 shows that the output power is higher when the number of turns is small, and the effect of the number of turns on the transmission side is particularly large. This is exactly what the theory showed.

Fig. 13 shows the region when the input voltage is 600V and the load voltage is within 420V. It is a very narrow area, but with 28 turns on the transmission side and 14 turns on the receiving side, the efficiency is 99.0% and the output is 14.1kW. On the other hand, Fig.14 shows the area where the input voltage is 420V and the load voltage is within 420V. Although the range is wider than Fig. 13, it can be seen that when there are 14 turns on the transmission side and 16 turns on the receiving side, the efficiency is 98.9% and the output is 13.6 kW, which is inferior to the input voltage of 600V. This indicates that in order to achieve both efficiency and output, it is better to increase the input voltage as much as possible, even if it reduces the number of available turns.

(a)N_1=40 (b)N_1=34 (c)N_1=30 (d)N_1=20 (e)N_1=4

Fig. 8 Created transmission side coil (580×420mm).



(a)N_2=40 (b)N_2=35 (c)N_2=30 (d)N_2=20 (e)N_2=3

Fig. 9 Created receiving side coil (420×420mm)

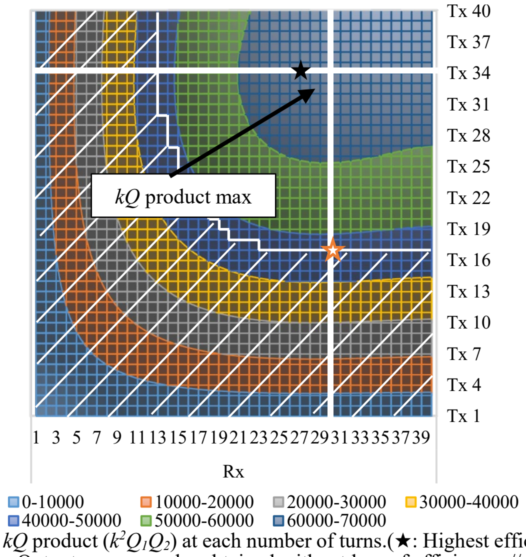


Fig. 10 *kQ* product ($k^2Q_1Q_2$) at each number of turns.(★: Highest efficiency point. ☆: Output power can be obtained without loss of efficiency. // : Area exceeding allowable current of Litz wire at input voltage of 600V.)

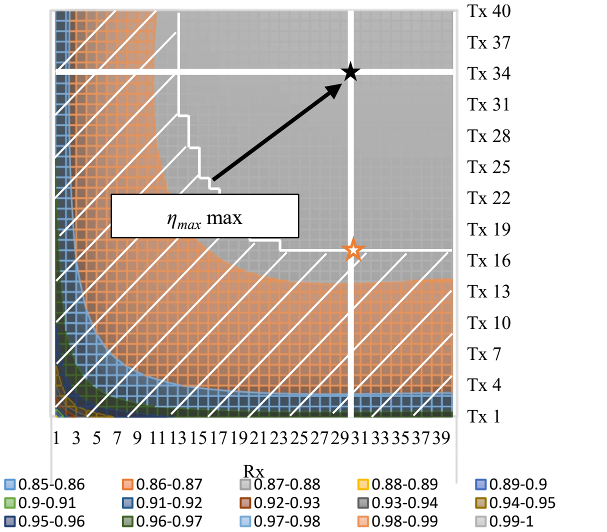


Fig. 11 Maximum efficiency η_{max} at each number of turns. (★: Highest efficiency point. ☆: Output power can be obtained without loss of efficiency. // : Area exceeding allowable current of Litz wire at input voltage of 600V.)

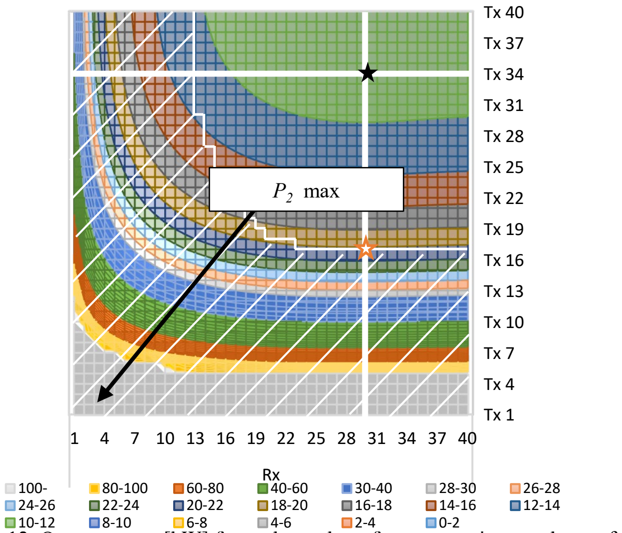


Fig. 12 Output power [kW] for each number of turns at an input voltage of 600 V. (★: Highest efficiency point. ☆: Output power can be obtained without loss of efficiency. // : Area exceeding allowable current of Litz wire at input voltage of 600V.)

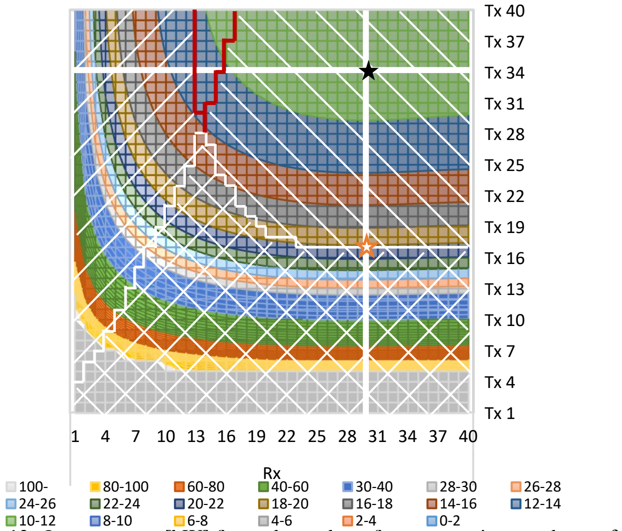


Fig. 13 Output power [kW] for each number of turns at an input voltage of 600 V. (★: Highest efficiency point. ☆: Output power can be obtained without loss of efficiency. // : Area exceeding allowable current of litz wire at input voltage of 600V. \\ : The area where the load voltage exceeds 420V at an input voltage of 600V)

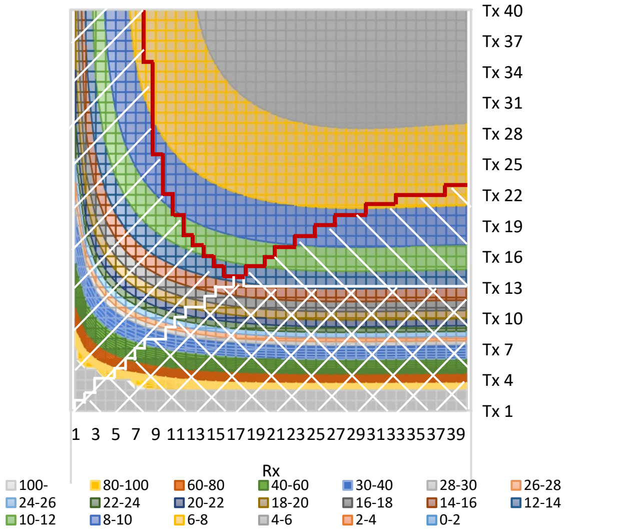


Fig. 14 Output power [kW] for each number of turns at an input voltage of 420 V. (★: Highest efficiency point. // : Area exceeding allowable current of litz wire at input voltage of 420V. \\ : The area where the load voltage exceeds 420V at an input voltage of 420V)

The maximum efficiency and output power are summarized in Fig. 15 and Fig.16 along with the data of the coils produced. It can be seen that the power movement on the transmission side is large, and the transmission side coil is very important to obtain the output power in the coil design. In the analysis, the ESR of the resonant capacitor was assumed to be negligibly small, but in reality, many resonant capacitors have the same level of resistance as the coil, and the measured efficiency was lower than the analyzed value.

Table 1 Created coil and capacitor data.

N_1	r_1 [mΩ]	L_1 [μH]	Q	C_1[nF]	r_{C1}[mΩ]
40	164.03	452.40	1473.3	7.73	245.66
34	153.72	428.27	1487.9	8.33	151.25
30	143.17	391.63	1460.9	8.90	128.81
20	100.04	262.94	1403.8	13.37	92.46
4	20.09	21.39	568.5	169.35	34.44
N_2	r_2 [mΩ]	L_2 [μH]	Q	C_1[nF]	r_{C2}[mΩ]
40	106.67	296.32	1483.6	11.49	31.36
35	102.47	286.17	1491.1	12.29	147.44
30	93.93	266.00	1512.4	13.36	231.69
20	76.90	186.37	1294.2	18.91	23.01
3	14.29	10.89	407.1	334.42	10.74

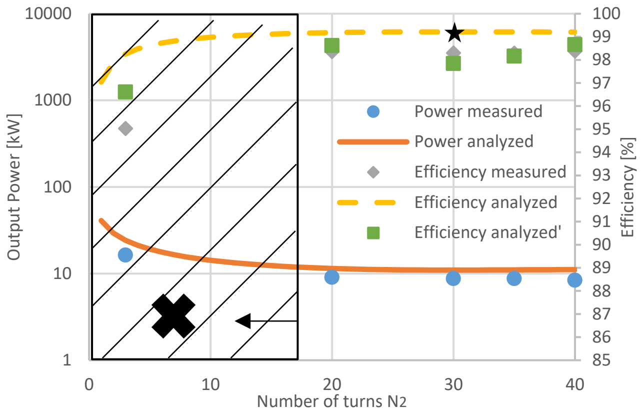


Fig. 15 Relationship between efficiency and output power of receiving side coil at N_1=34. (●:Power obtained from VNA, —: Power obtained from equation(12), ◆: Efficiency obtained from VNA, - -: Efficiency obtained from equation(11),■: Efficiency obtained from equation(11) include the resistance of capacitor. ×: Area exceeding the allowable current, ★: Maximum efficiency point.)

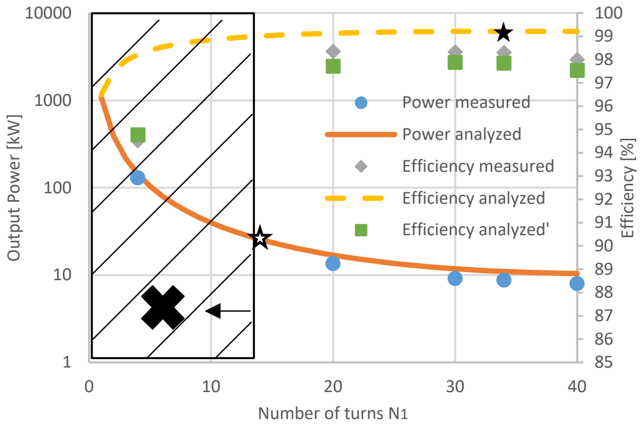


Fig. 16 Relationship between efficiency and output power of transmission side coil at N_2=30. (●:Power obtained from VNA, —: Power obtained from equation(12), ◆: Efficiency obtained from VNA, - -: Efficiency obtained from equation(11),■: Efficiency obtained from equation(11) include the resistance of capacitor. ×: Area exceeding the allowable current, ★: Maximum efficiency point, ☆: Maximum output power.)

Therefore, the data of the coils and capacitors used are shown in Table 1, and the analytical value of the efficiency when the resistance of the capacitor is taken into account is also shown in Fig. 15 and Fig. 16. This shows that the measured and analyzed values are very close.

Although the error in efficiency was noticeable due to the use of poor-quality capacitors, the results were in line with the theory for the power described in this paper.

When the input voltage is 600V, the simulation results show that the efficiency is 99.2% and the output power is 10.2kW with 34 turns on the transmission side and 30 turns on the receiving side. When the number of turns on the transmission side was reduced in consideration of the allowable current of the Litz wire, an efficiency of 99.0% and an output of 20.2 kW were obtained. When the number of turns on the power receiving side was reduced, an efficiency of 99.0% and an output of 12.9 kW were obtained. These values show that reducing the number of turns on the transmission side is very effective.

IV. Conclusion

Coupler optimization is a very important topic in wireless power transfer. In its optimization, it is essential to achieve high efficiency and high power under the specified coil size and frequency. In this paper, under the specified coil size and frequency of SAE J2954, the relationship between the output power and the number of turns is shown in the case of an air core, and a method to extend the output power without significantly reducing the efficiency is proposed. Under the input voltage of 600V, an efficiency of 99.2% and an output power of 10.9kW were obtained with 34 turns on the transmission side and 30 turns on the receiving side. 3.3kW output power is required for WPT1, which is well achieved. Considering the allowable current of the Litz wire, an efficiency of 99.0% and an output power of 20.2 kW were obtained with 17 turns on the transmission side and 30 turns on the receiving side. Although these are all simulated values and the efficiency is expected to decrease by about 1% when the power is actually transmitted, it can be seen that both the efficiency and power follow each other very well.

Therefore, it can be said that in order to obtain output power without a significant reduction in efficiency, the number of turns on the transmission side should be reduced to the allowable current of the Litz wire, and the number of turns on the receiving side should be set to the highest efficiency.

The coil we made this time has a wire-to-wire distance of 0 mm in order to obtain the highest efficiency. From (13), it can be seen that the output power can be increased in the same way by just taking the distance between the wires and reducing the Q value of the coil, and similarly, the effect of the change in the transmission side coil is significant.

In addition, SAE J2954 stipulates that the battery voltage should be less than 420V for safety reasons and other reasons. In practice, it is difficult to say for sure because of heat generation and inverter problems, but we found that it is better to increase the input voltage as much as possible even when the load voltage is limited.

This study was significant because SAE J2954 is a standard for supplying power while the vehicle is stationary, but even large power is required to supply power while driving. Ferrite is used in the WPT of electric vehicles, but theoretically it is the same and the same results can be expected. This time, the comparison was focused on the number of turns on the transmission side, but since the pitch of the transmission side also has a significant impact on the output, we will study this in the future. Another important issue is to counter the leakage magnetic field of the air-core coil.

Acknowledgment

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