A Method for Determining Resonant Elements Considering the Requirements of Double-LCC Circuits in Dynamic Wireless Power Transfer

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***Abstract*—Wireless power transfer technology is attracting attention as a means of charging electric vehicles while driving. Compared to the SS circuit, in which the coils and capacitors required for power transfer are connected in series and resonate, the Double-LCC circuit, in which capacitors are inserted in parallel on both the power transmitting and receiving sides, is more resistant to misalignment and has less standby loss. On the other hand, due to the complexity of the circuit and the increase in the degree of freedom, the optimization of the circuit has become very complicated and its determination method has not been established yet. In this study, when the coils to be used for transmitting and receiving power have already been determined, the optimal combination of resonant elements was determined considering all requirements such as allowable current, capacitor withstand voltage, required power transmission efficiency, required power, required secondary side power, etc. As a result, a resonant element was proposed that satisfies 98.0% efficiency and 31.2 kW of power, considering all requirements of the circuit in the simulated values. The validity of the proposed method was also shown by experiments.**

Keywords— Wireless Power Transfer, Dynamic Wireless Power Transfer, Electric Vehicle, Double-LCC

I. INTRODUCTION

Wireless Power Transfer (WPT) [1] supplies power to any device wirelessly, without the need for a plug, and recently wireless power transfer to electric vehicles has been attracting attention. Wireless power transfer to electric vehicles is said to solve all the problems that current EVs are facing [2]. In particular, Dynamic Wireless Power Transfer (DWPT) is the ultimate technology that will greatly contribute to the decarbonization of the world, not only because of the convenience of wireless power transfer, but also because it extends the cruising range while reducing the on-board battery [3-5]. The standard for wireless power transfer while electric vehicles are stationary was established by SAE J2954 in October 2020 [6], and is now somewhat firmly established. However, the technical standard for Dynamic Wireless Power Transfer has not yet been determined, and research is still underway. Until now, wireless power transfer to EVs has been done when the vehicle is stationary, so misalignment has not been considered a problem, and the SS circuit, in which a resonant capacitor is connected in series with the coil used to transmit and receive power, has been widely used. However, the SS circuit generates excessive current during misalignment, which is considered to be a problem [7], and the Double-LCC circuit [8-11] is increasingly used. The Double-LCC circuit has been attracting attention because of its filtering effect and low standby loss when dynamic wireless power transfer is implemented. However, compared to the SS circuit, the Double-LCC circuit has a larger number of elements, and the optimization of the resonant elements, as well as the optimization of the coils, greatly affects the efficiency and power of the circuit, but it has not been generalized yet. In addition, papers using Double-LCC circuits often complicate the circuit and simplify the equivalent circuit.

In this study, a theoretical equation that takes into account the resistance component of the resonant inductance is presented. Assuming that the main coils, the power transmission coil and the power receiving coil, have already been determined, a method is presented to determine the resonant element that can obtain the most power with the constraints of efficiency, allowable current of each element, and withstand voltage of the capacitor. In chapter II, the theoretical equation and the points to be considered in designing the Double-LCC circuit are presented. In chapter III, the optimal resonant element is proposed for the main coil actually produced, and the conclusion is given in chapter IV.

II. DERIVATION OF THEORETICAL EQUATIONS AND DESIGN POINTS FOR DOUBLE-LCC CIRCUITS

In this chapter, the theoretical equation of the Double-LCC circuit is presented, and the method of taking power and efficiency when designing the circuit is shown. Fig 1 shows the equivalent circuit used in this study, which includes the input voltage v_1, power transmission coil L_1, internal resistance of the power transmission coil r_1, resonant capacitors C_{1s} and C_{1p} on the power transmission side, power receiving coil L_2, internal resistance of the power receiving coil r_2, and resonant capacitors C_{2s} and C_{2p} on the power receiving side. In dynamic wireless power transfer, the AC power transmitted to the secondary side is actually converted by a rectifier and DC/DC converter and supplied to the battery, but for the purpose of determining the resonant element this time, the load R_L is directly connected. In many previous papers, the resistance of the resonant element has been neglected due to the complexity of the circuit. In this study, the resistances of the primary and secondary resonant coils, r_o and r_o', are taken into account. As for the capacitor, it is assumed to be ideal.

Considering the circuit equation for each current loop in Fig 1 and canceling the imaginary part, the resonance condition can be expressed as (1).

$$\omega_0 = \frac{1}{\sqrt{L_0 C_{1p}}} = \sqrt{\frac{C_{1p}+C_{1s}}{L_1 C_{1p} C_{1s}}} = \frac{1}{\sqrt{L_0' C_{2p}}} = \sqrt{\frac{C_{2p}+C_{2s}}{L_2 C_{2p} C_{2s}}} \quad (1)$$

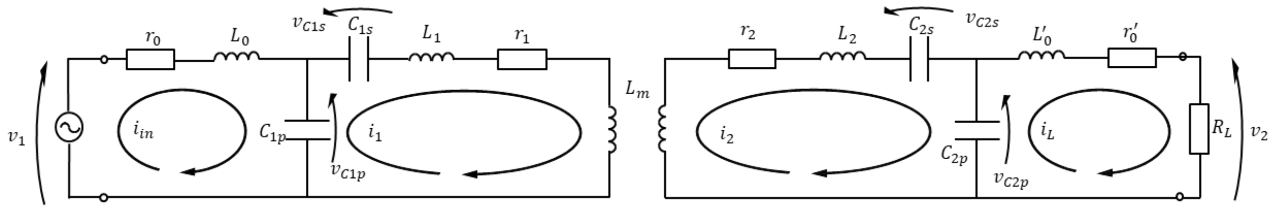


Fig 1 Equivalent circuit of Double-LCC

Table 1 List of theoretical equations in double LCC circuits.

$$i_{in} = \frac{\omega_0^2 C_{1p}^2\{\omega_0^2 C_{2p}^2 (r_0' + R_L)(r_1 r_2 + \omega_0^2 L_m^2) + r_1\}}{\omega_0^2 C_{2p}^2 (r_0' + R_L)\{r_2(\omega_0^2 C_{1p}^2 r_0 r_1 + 1) + \omega_0^4 L_m^2 C_{1p}^2 r_0\} + \omega_0^2 C_{1p}^2 r_0 r_1 + 1} v_1 \quad (2)$$

$$i_1 = -j\frac{\omega_0 C_{1p}\{\omega_0^2 C_{2p}^2 r_2 (r_0' + R_L) + 1\}}{\omega_0^2 C_{2p}^2 (r_0' + R_L)\{r_2(\omega_0^2 C_{1p}^2 r_0 r_1 + 1) + \omega_0^4 L_m^2 C_{1p}^2 r_0\} + \omega_0^2 C_{1p}^2 r_0 r_1 + 1} v_1 \quad (3)$$

$$i_2 = \frac{\omega_0^4 L_m C_{1p} C_{2p}^2 (r_0' + R_L)}{\omega_0^2 C_{2p}^2 (r_0' + R_L)\{r_2(\omega_0^2 C_{1p}^2 r_0 r_1 + 1) + \omega_0^4 L_m^2 C_{1p}^2 r_0\} + \omega_0^2 C_{1p}^2 r_0 r_1 + 1} v_1 \quad (4)$$

$$i_L = -j\frac{\omega_0^3 L_m C_{1p} C_{2p}}{\omega_0^2 C_{2p}^2 (r_0' + R_L)\{r_2(\omega_0^2 C_{1p}^2 r_0 r_1 + 1) + \omega_0^4 L_m^2 C_{1p}^2 r_0\} + \omega_0^2 C_{1p}^2 r_0 r_1 + 1} v_1 \quad (5)$$

$$\eta = \frac{R_L |i_L|^2}{v_1 |i_{in}|} = \frac{\omega_0^4 L_m^2 C_{2p}^2 R_L}{[\omega_0^2 C_{2p}^2 (r_0' + R_L)\{r_2(\omega_0^2 C_{1p}^2 r_0 r_1 + 1) + \omega_0^4 L_m^2 C_{1p}^2 r_0\} + \omega_0^2 C_{1p}^2 r_0 r_1 + 1]\{\omega_0^2 C_{2p}^2 (r_0' + R_L)(r_1 r_2 + \omega_0^2 L_m^2) + r_1\}} \quad (6)$$

$$\frac{\partial \eta}{\partial R_L} = 0 \quad (7)$$

$$R_{L,\eta max} = \frac{1}{\omega_0^2 C_{2p}^2}\sqrt{\frac{[\omega_0^2 C_{2p}^2 r_0'\{r_2(\omega_0^2 C_{1p}^2 r_0 r_1 + 1) + \omega_0^4 L_m^2 C_{1p}^2 r_0\} + \omega_0^2 C_{1p}^2 r_0 r_1 + 1]\{\omega_0^2 C_{2p}^2 r_0'(r_1 r_2 + \omega_0^2 L_m^2) + r_1\}}{\{r_2(\omega_0^2 C_{1p}^2 r_0 r_1 + 1) + \omega_0^4 L_m^2 C_{1p}^2 r_0\}(r_1 r_2 + \omega_0^2 L_m^2)}} \quad (8)$$

$$A = \omega_0^2 C_{2p}^2, B = \omega_0^2 C_{1p}^2 \quad (9)$$

$$P_2 = \sqrt{\frac{(Ar_0' r_2 k^2 Q_1 Q_2 + 1)k^2 Q_1 Q_2}{B r_0 r_1 k^2 Q_1 Q_2 + 1}} \cdot \frac{B r_1 k^2 Q_1 Q_2}{k^2 Q_1 Q_2 + 2\sqrt{(Ar_0' r_2 k^2 Q_1 Q_2 + 1)(B r_0 r_1 k^2 Q_1 Q_2 + 1)k^2 Q_1 Q_2}} \cdot v_1^2 \quad (10)$$

$$\eta_{max} = \frac{k^2 Q_1 Q_2}{2(Ar_0' r_2 k^2 Q_1 Q_2 + 1)(B r_0 r_1 k^2 Q_1 Q_2 + 1) + k^2 Q_1 Q_2 + 2\sqrt{(Ar_0' r_2 k^2 Q_1 Q_2 + 1)(B r_0 r_1 k^2 Q_1 Q_2 + 1)k^2 Q_1 Q_2}} \quad (11)$$

Table 1 summarizes the theoretical equations used in the double LCC circuit.

The current in each loop during resonance is represented by (2)-(5).The power transmission efficiency η is expressed by (6). Derive for $R_{L,\eta max}$ where the efficiency η is maximized. R_L for which (7) holds can be expressed by (8). Here, let A and B be (9) and approximating $k^2 Q_1 Q_2 \gg 1, Ar_0' r_2 \ll 1, Br_0 r_1 \ll 1$, the received power P_2 and the maximum efficiency η_{max} are expressed by (10) and (11).

Using the Q values of the power transmission and receiving coils and the coupling coefficient k between the coils, the kQ product ($k^2 Q_1 Q_2$) can be expressed as follows.

$$Q_i = \frac{\omega_0 L_i}{r_i} \quad (i = 1,2) \quad (12)$$

$$\frac{\omega_0^2 L_m^2}{r_1 r_2} = k^2 Q_1 Q_2 \quad (13)$$

From (9) and (10), it can be seen that in order to obtain power, it is effective to make C_{1p} large. In other words, from the resonance condition, it is necessary to design L_0 to be small. It is also effective to increase the kQ product.

As shown in (9) and(11), there is no difference in efficiency between the primary and secondary resonators, so making C_{1p} and C_{2p} small, i.e, designing L_0 and L_0' as large as possible, leads to improvement in efficiency. It can also be seen that a larger kQ product improves the efficiency because the effect of the denominator in (11) becomes smaller.

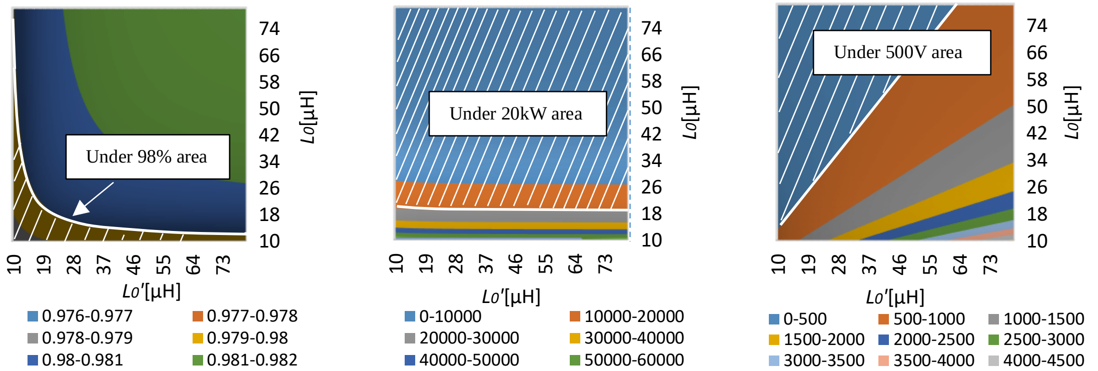
From the above, it is proposed to design L_0 as small as possible for high power in Double-LCC circuit, and to design L_0' as large as possible for efficiency. Furthermore, it is important to increase the kQ product of the main coil.

III. SIMULATION AND EXPERIMENTAL VALIDATION

After confirming the theory presented in Chapter II, we describe the method for determining the optimum resonant element that satisfies all the requirements for wireless power transfer.

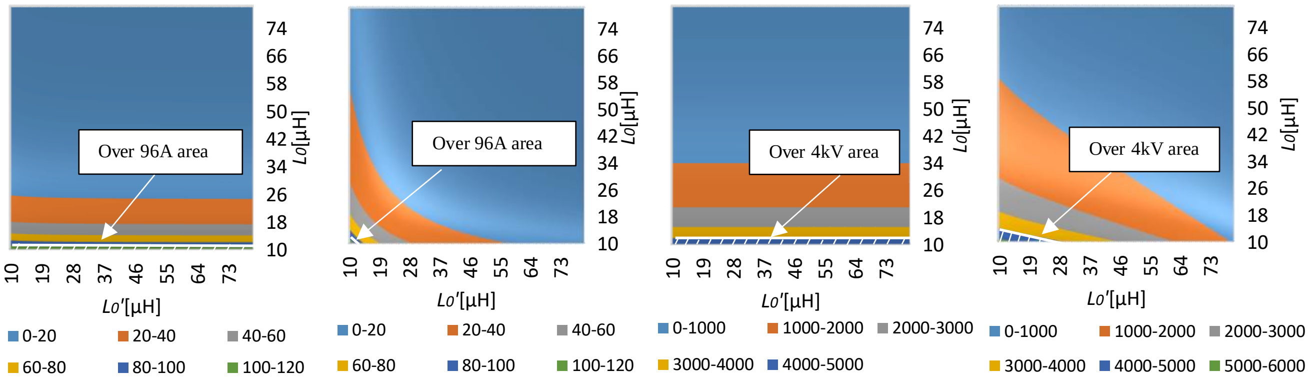
A. *Assumed WPT environment*

The WPT situation assumed in determining the optimum resonant element is confirmed. Since the purpose of this research is to determine the resonant element of the Double-LCC circuit when the main coil has already been determined, all the power supplies used are AC, and resistive loads are connected. The size of the transmission coil is 1300 × 600 mm and the receiving coil is 580 × 420 mm. The input voltage was



(i) η [-] (ii) $\boldsymbol{P_2}$ [W] (iii) $\boldsymbol{v_2}$ [V]

Fig 2 Relation of η, $\boldsymbol{P_2}$ and $\boldsymbol{v_2}$ to the change in $\boldsymbol{L_0}$ and $\boldsymbol{L_0'}$.



(i) $\boldsymbol{i_L}$ [A] (ii) $\boldsymbol{i_L}$ [A] (iii) $\boldsymbol{v_{C1s}}$ [V] (iv) $\boldsymbol{v_{C2s}}$ [V]

Fig 3 Relation of $\boldsymbol{i_{in}}$, $\boldsymbol{i_L}$, $\boldsymbol{v_{C1s}}$ and $\boldsymbol{v_{C2s}}$ to the change in $\boldsymbol{L_0}$ and $\boldsymbol{L_0'}$.

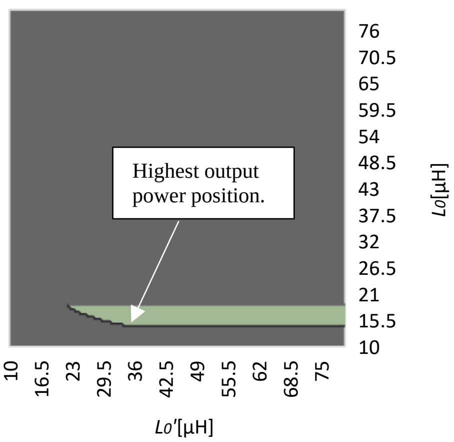


Fig 4 Area that can be used as design values that take into account all requirements. ($\boldsymbol{i_{in} < i_{in,max}, i_1 < i_{1,max}, i_2 < i_{2,max}, i_L < i_{L,max}, i_{c1p} < i_{c1p,max}, i_{c2p} < i_{c2p,max}, v_{c1p} < v_{c1p,max}, v_{c1s} < v_{c1s,max}, v_{c2p} < v_{c2p,max}, v_{c2s} < v_{c2s,max}, v_2 > V_{batt}, \eta > \eta_{min}, P_2 > P_{2,min}}$)

600 V, which is the boundary between high and low voltage, and the frequency was 85 kHz. In the experiment, a small signal is input from VNA and converted to 600 V. The allowable current for each branch current is 96A, which is the allowable current of the Litz wire used. If the allowable current differs depending on the element used, the same constraint can be set by setting each one. The capacitors were ideal and the withstand voltage was set to 4 kV. Since the size of the resonant coil is smaller than that of the main coil and it is difficult to derive the resistance value by simulation, the Q value was set to 500 in this case. These information is summarized in the Table 2. In this study, the Q value of the resonant inductance is set to 500, and a discussion of cases in which this Q value deviates significantly is presented in the Appendix.

B. *Determination of the optimum resonant element*

The parameters to be changed are L_0 and L_0', which are the resonant coils of the primary and secondary sides, respectively. There are other resonant elements such as C_{1p}, C_{1s}, C_{2p} and C_{2s}, but these are uniquely determined by the resonance conditions shown in (1), so there is no need to

Table 2 Assumed WPT environment and requirements.

Input voltage v_1 [V]	600 V
Operating frequency	85 kHz
Transmission distance	250 mm
Inductance of L_1	90.5 μH
Inductance of L_2	96.1 μH
Coupling coefficient k	0.11
Allowable current	Under 96 [A]
Capacitors withstand voltage	Under 4 [kV]
Required transmission power $P_{2,min}$	Over 20 [kW]
Required efficiency η_{min} (AC to AC)	Over 98 [%]
Q value of resonant coil	500
Load voltage	Over 500 [V]

specify them as parameters to be changed. Once the coil to be used and the transmission distance are determined, the mutual inductance L_m can be obtained. This allows us to calculate all the circuit information using the theoretical equation shown in section II. As the changing parameters, L_0 and L_0' were varied from 10 μH to 80 μH by 0.5 μH respectively, and the best combination was determined among them.

Fig 3 below shows the relationship when the main parameters, L_0 and L_0', are changed. Here, the allowable currents of input current i_{in}, primary coil current i_1, secondary coil current i_2, output current i_L, branch current i_{c1p} flowing through C_{1p}, and branch current i_{c2p} flowing through C_{2p} are $i_{in,max}$, $i_{1,max}$, $i_{2,max}$, $i_{L,max}$, $i_{c1p,max}$ and $i_{c2p,max}$, respectively. The maximum values of the voltages v_{c1p}, v_{c1s}, v_{c2s} and v_{c2p} applied to each capacitor C_{1p}, C_{1s}, C_{2s} and C_{2p} are $v_{c1p,max}$, $v_{c1s,max}$, $v_{c2s,max}$, $v_{c2p,max}$, respectively. The minimum power transmission efficiency to be achieved is η_{min}, and the minimum secondary power to be achieved is $P_{2,min}$. In this study, a resistive load is connected as the load, but assuming that it is a battery load, the load voltage v_2 should be higher than the battery voltage V_{batt} so that it can be easily stepped down by the DC/DC converter. The region where all the above conditions are taken into account is shown in Fig 4

C. Comparison with experiment

In the measurement environment shown in the Fig 5, several resonators were changed and the input current i_{in}, output current i_{out}, power transmission efficiency η, and output power P_2 were measured using a vector network analyzer (VNA: KEYSIGHT E5061B). Since it can be seen from Fig 2 that the output power P_2 varies greatly with the change in L_0, i_{in}, i_L, P_2, and η for a change in L_0 when L_0' is 35.5 μH are shown in Fig 6. This figure shows very good agreement with the change in L_0. Fig 7 shows the variation of i_{in}, i_L, P_2, and η with respect to the variation of L_0' when L_0 is 26.1 μH. From Fig 6 and Fig 7, it can be seen that the equations presented in Chapter II are correct, and that it is important to design L_0 smaller to take power and L_0' larger to increase efficiency.

This study assumes dynamic wireless power transfer to EVs. Since the increase in the amount of power obtained from wireless power transfer often outweighs the decrease in efficiency during the design phase, and since studies have shown that greater power significantly reduces infrastructure costs [12], the optimal design value is the combination of L_0 and L_0' that provides the most power within the range shown in Fig 4. When L_0=14.9 μH, L_0'=35.5 μH, the allowable current, withstand voltage, efficiency, and secondary side voltage were all satisfied, and the AC power transmission of 31.2kW 98.0% was found to be possible. On the other hand, the measured values were power transmission efficiency η = 96.4% and transmission power P_2 = 28.0 kW.

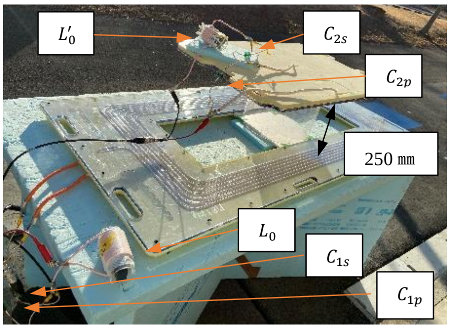
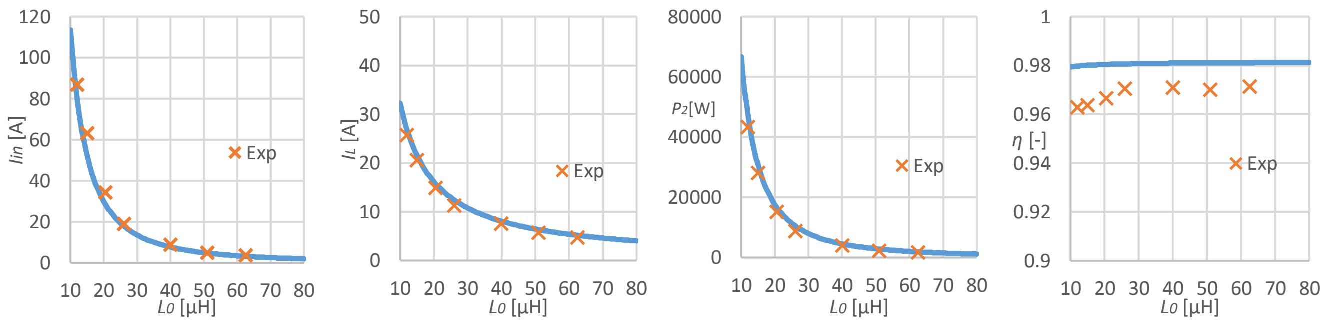
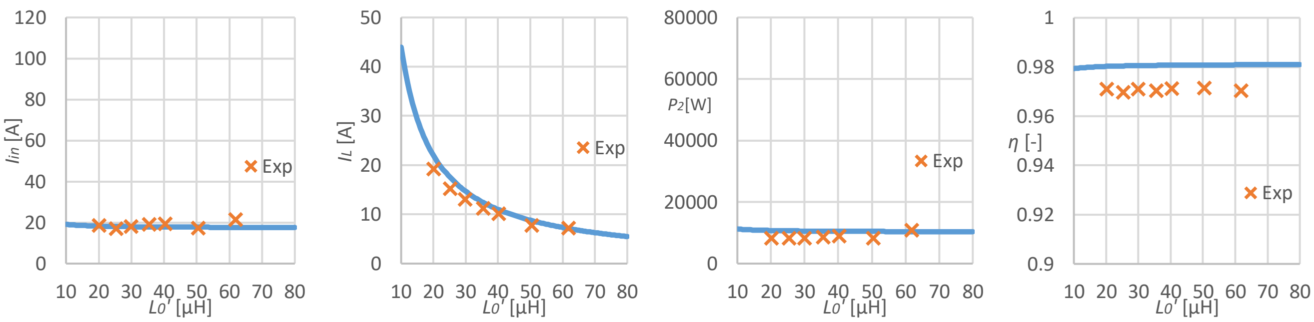


Fig 5 Measurement scenery



(i) i_{in} (ii) i_L (iii) P_2 (iv) η

Fig 6 Comparison of design and measured values for a change in $\boldsymbol{L_0}$ when $\boldsymbol{L_0'}$=35.5μH.



(i) i_{in} (ii) i_L (iii) P_2 (iv) η

Fig 7 Comparison of design and measured values for a change in $\boldsymbol{L_0'}$ when $\boldsymbol{L_0}$=26.1μH.

The errors in efficiency and power can be attributed to the fact that the Double-LCC circuit could not be fully resonated in all loops simultaneously. Although both efficiency and power are a little lower than in the simulation, the theoretical equations revealed in this study are in good agreement, and we were able to show how to determine the resonant elements in the Double-LCC circuit.

IV. Conclusion

In this study, the theoretical equation considering the resistance of the resonant element of the Double-LCC circuit was presented, and it was shown that it is effective to make L_0 as small as possible in order to increase the output power in the Double-LCC circuit. In order to increase the efficiency, the inductance of the resonant coil should be made as large as possible, but from the viewpoint of output, the inductance of L_0 should be small, so it is effective to make L_0' large. Furthermore, increasing the kQ product of the coil improves both the efficiency and power of the circuit, so it is important to use a coil with strong coupling and high Q value. However, based on the research [12] that reducing the investment cost of infrastructure is more important than the loss of electricity due to the loss of efficiency in dynamic wireless power transfer, this research has chosen the resonant element with the highest output power that meets all the requirements as the optimal one.

As a result, 31.2 kW of AC power transmission and 98.0 % efficiency were achieved in the simulation when L_0 = 14.9 μH and L_0' = 35.5 μH. On the other hand, the measured power and efficiency were 28 kW and 96.4%, respectively. The graphs agree well, although the efficiency dropped significantly because perfect resonance was not obtained.

This research has clarified the method of determining the resonant element, which has been complicated in the past, and has shown that it is possible to redesign the resonant element to achieve the desired circuit characteristics even after the main coil is determined. This is a very important achievement for the future infrastructure of dynamic wireless power transfer.

Appendix

1) Is the approximation of $k^2Q_1Q_2 \gg 1$ valid?

In (10) and (11), the approximation $k^2Q_1Q_2 \gg 1$ was used to indicate power and power transmission efficiency. Generally, the Q value of coils used for wireless power transmission is 500 or higher, and the coupling coefficient

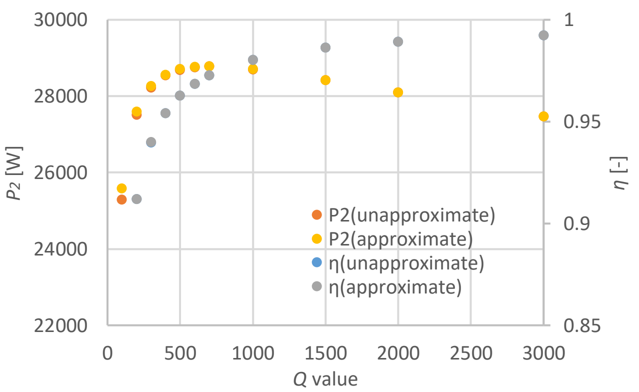


Fig 8 Comparison of approximated and unapproximated values for efficiency and power.

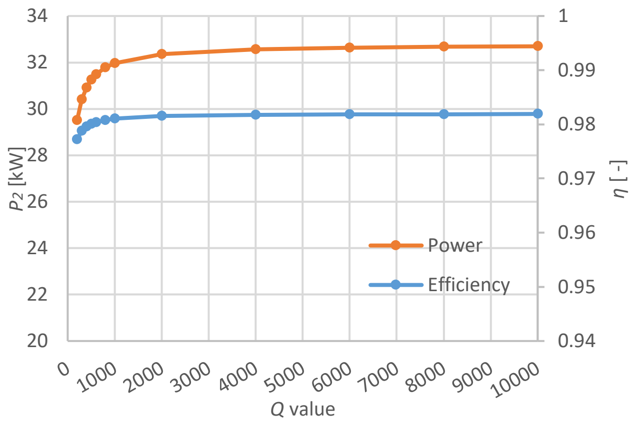


Fig 9 Effect of Q value of resonant coil on power and efficiency.

k is often 0.01 or higher. In this case, at least $k^2Q_1Q_2$ is 2500, which is sufficiently larger than 1. Fig 8 shows the effectiveness of the approximation in terms of efficiency and power when the Q value of the main coil is varied from 100 to 3000, when k is set to 0.11, the coupling coefficient of the coils used in this study. For simplicity, the primary and secondary Q value are assumed to be equal. Fig 8 shows that the values for the approximation and without approximation are in excellent agreement, indicating that equations (10) and (11) are correct.

2) Influence of Q-value of resonator

For simplicity, the resonator coil in this paper was designed with a Q value of 500. In reality, however, changes in the Q value can be expected due to changes in the magnetic permeability of the ferrite and an increase in the resistance of the Litz wire after prolonged operation. When the Q value is 500, the efficiency and power are 98.0 % and 31.2 kW, respectively, in the analyzed values, whereas when the Q value is reduced to 300, the efficiency and power drop to 97.9 % and 30.4 kW, respectively. Although the fluctuations appear to be larger than in Fig 9, we do not consider it problematic to set the Q value of the resonant coil at 500 because the power is reduced to less than 3 % for a 40 % reduction in the Q value of the resonant element.

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