Magnetic Field Resonant Coupling in Wireless Power Transfer Comparison of Multiple Circuits Using LCL

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***Abstract*— The purpose of this study is to develop a theory for design circuits depending on the application for LCL-S, LCL-P, S-LCL, P-LCL, and LCL-LCL circuits in Inductive Power Transfer (IPT) of Wireless Power Transfer (WPT). Under unified conditions, transmission characteristics were compared in terms of Constant Voltage (CV) characteristics, Constant Current (CC) characteristics, transmission efficiency, optimum load, output power, and coupling factor $k = 0$ characteristic. The results show that the optimal load of the LCL-S circuit is about k^2 times that of LCL-P, S-LCL, P-LCL, and LCL-LCL circuits. S-LCL circuit can get more power when a voltage source is connected, and LCL-S, LCL-P, P-LCL, and LCL-LCL circuits can get more power when a current source is connected. Furthermore, it was found that each circuit has a different tendency to change in efficiency and power with load variations.**

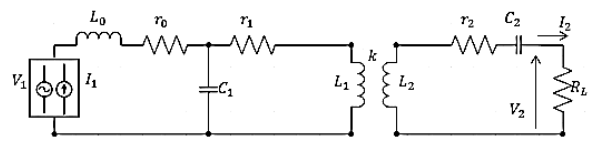
Keywords—Wireless Power Transfer, Inductive Power Transfer, LCL circuit

I. Introduction

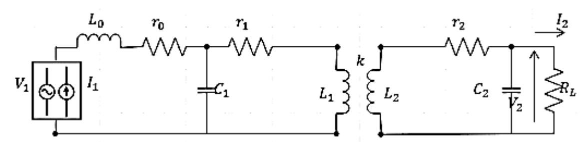
In recent years, when electronic devices have become even more widespread and opportunities for charging have increased. The problems with cable charging are lack of durability, risk of electric shock, cable deterioration and disconnection. They are all solved by WPT that is a technology for transmitting electrical power without wires. IPT has higher efficiency and longer transmission distance than Capacitive Power Transfer (CPT), making IPT increasingly useful.

There are papers that compare IPT and CPT [1] and typical circuit configurations of IPT, such as S-S and S-P circuits [2][3][4]. There are also papers comparing SS, LCL and LCC circuits. [5][6][7][8] Although S-S and S-P are considered better for IPT, LCL circuits are proposed because of the danger of high current flow at zero coupling.

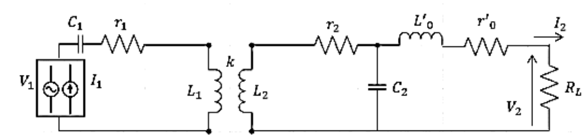
In this paper, we developed a design theory for optimal circuit selection by comparing characteristics such as CC/CV characteristics, transmission efficiency, optimal load, and output power for a total of five circuits, LCL-S, LCL-P, S-LCL, P-LCL, and LCL-LCL, as shown in Fig. 1, under unified conditions of coupling coefficient, Q value, and internal resistance.



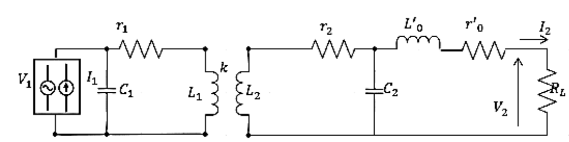
(a) LCL-S circuit



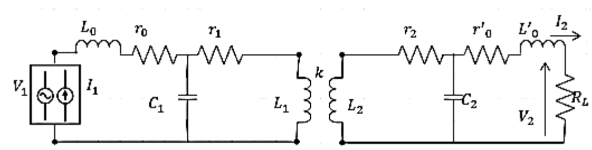
(b) LCL-P circuit



(c) S-LCL circuit



(d) P-LCL circuit



(e) LCL-LCL circuit

Fig. 1 Each Circuit

II. Derivation of the Respective Equations for Transmission Characteristics

A. Element Compensation Conditional Equations and CC/CV Characteristics

Compensation conditions are the conditions for determining the inductance L_0, L_0' of the additional coils and the capacitors C_1, C_2 of the resonant capacitor, when properly set, enable high efficiency and high power transmission. In this study, the design is made to satisfy the gyrator characteristics shown in (2) or the ideal transformer characteristics shown in (3). In the absence of internal resistance, an input power factor $cos\theta_{in} = 1$ is achieved.

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} 0 & \pm jZ_0 \\ \pm j\dfrac{1}{Z_0} & 0 \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} \pm jZ_0 & 0 \\ 0 & \pm j\dfrac{1}{Z_0} \end{bmatrix} \begin{bmatrix} V_1 \\ I_2 \end{bmatrix} \tag{3}$$

From (2) and (3), I_2, V_2 can be rewritten as (4) and (5), indicating that the Constant Current (CC) and Constant Voltage (CV) characteristics do not depend on the load R_L when a constant voltage source is connected.

$$I_2 = \pm j\frac{1}{Z_0}V_1 \tag{4}$$

$$V_2 = \pm j\frac{1}{Z_0}V_1 \tag{5}$$

From the above, the design condition equations for the additional inductances L_0, L_0' and C_1, C_2 resonant capacitors are derived based on gyrator and ideal transformer characteristics with internal resistance as 0, as shown in Table 1. Table 2 also shows the CC/CV characteristics when the aforementioned conditions are applied.

From Table 1, the design condition equation consists only of the resonant angular frequency ω and the coils L_1, L_2 used for power transmission.

TABLE I. Element Conditional Equation

	L_0	$L_0{}'$	C_1	C_2
LCL-S	L_1		$\frac{1}{\omega^2 L_1}$	$\frac{1}{\omega^2 L_1}$
LCL-P	L_1		$\frac{1}{\omega^2 L_1}$	$\frac{1}{\omega^2 L_1}$
S-LCL		L_2	$\frac{1}{\omega^2 L_1}$	$\frac{1}{\omega^2 L_1}$
P-LCL		L_2	$\frac{1}{\omega^2 L_1}$	$\frac{1}{\omega^2 L_1}$
LCL-LCL	L_1	L_2	$\frac{1}{\omega^2 L_1}$	$\frac{1}{\omega^2 L_1}$

TABLE II. CC/CV characteristic

	Voltage Source	Current Source
LCL-S	CV	CC
LCL-P	CC	
S-LCL	CV	CC
P-LCL		CV
LCL-LCL	CC	CV

B. Power Transmission Efficiency and Optimum Load

Next, taking into account the internal resistance, the power transmission characteristics of the devices in Table 1 are obtained when the conditions are applied. The power transmission efficiency is obtained from (6). The optimal load is R_L such that the condition in (7) is satisfied, and the result is shown in Table 3. Here, $r_0 = r_1, r_0' = r_2$ to match the Q values.

$$\eta = \frac{P_{R_L}}{P_{r_0} + P_{r_1} + P_{r_2} + P_{r_0'}} = \frac{R_L|I_R|^2}{r_0|I_0|^2 + r_1|I_1|^2 + r_2|I_2|^2 + r_0'|I_0'|^2} \tag{6}$$

$$\frac{\partial\eta}{\partial R_L} = 0 \tag{7}$$

Furthermore, for comparison, the optimal load is calculated by applying the condition in (8) and obtaining the ratio as shown in (9).

$$r = r_1 = r_2, Q = Q_1 = Q_2, 1 + k^2 \approx 1, 1 + Q^2 \approx 1, 1 \ll k^2Q^2 \tag{8}$$

$$R_{Lopt}^{LCL-S} : R_{Lopt}^{LCL-P,S-LCL,P-LCL,LCL-LCL} = 1 + k^2Q^2 : Q^2 = k^2 : 1 \tag{9}$$

Since the coupling factor k is smaller than 1, the optimum load for the LCL-S circuit is k^2 times as small as than for the LCL-P, S-LCL, P-LCL, and LCL-LCL circuits. Therefore, for high efficiency transmission, it is necessary to select circuit according to the value of the load.

C. Output Power

Next, the output power P_{out_V} when a voltage source is connected and P_{out_I} when a current source is connected to the power supply are calculated.

First, P_{out_V} is as shown in Table 4. Furthermore, when the approximation in (8) is applied, the ratio of output power can be expressed as (10).

$$P_{out_V}^{LCL-S,LCL-P,P-LCL,LCL-LCL} : P_{out_V}^{S-LCL} = 1 + k^2Q^2 : Q^2 \approx k^2 : 1 \tag{10}$$

From $k^2 < 1$, S-LCL circuit can get power $1 / k^2$ times as high as other circuits when a voltage source is connected. Next, when a current source is connected, the output power P_{out_I} is obtained in the same way, as shown in Table 4, and using the approximation in (8), (11) is obtained.

$$P_{out_I}^{LCL-S,LCL-P,P-LCL,LCL-LCL} : P_{out_I}^{S-LCL} = Q^2 : 1 + k^2Q^2 \approx 1 : k^2 \tag{11}$$

LCL-S, LCL-P, P-LCL, and LCL-LCL circuits can get $1 / k^2$ times more power than the S-LCL circuit when a current source is connected.

D. $k = 0$ Characteristic

The safety when the coupling is 0, $k = 0$, characteristic is discussed. The currents I_S, I_P, and I_{LCL} when $k = 0$ flowing in the circuit configuration of the transmission side for S, P, and LCL, respectively, are as (12) and when approximated using (9). From the above, it can be seen that the S-LCL circuit having S on the power transmission side is dangerous because a large current flows at $k = 0$.

$$I_S : I_P : I_{LCL} = \frac{1}{r_1} : \frac{1}{Q_1 r_1\sqrt{1 + Q_1^2}} : \frac{1}{r_1\sqrt{1 + Q_1^2}} = Q_1^2 : 1 : Q_1 \tag{12}$$

TABLE III. EFFICIENCY AND OPTIMAL LOAD

	η	R_{Lopt}
LCL-S	$\frac{k^2Q_1^3Q_2r_2R_L}{(r_2+R_L+k^2Q_1Q_2r_2)\{(r_2+R_L)(1+Q_1^2)+k^2Q_1Q_2r_2\}}$	$r_2\sqrt{\frac{(1+k^2Q_1Q_2)(1+k^2Q_1Q_2+Q_1^2)}{1+Q_1^2}}$
LCL-P	$\frac{k^2Q_1^3Q_2^3(Q_2^2r_2^2+R_L^2)r_2R_L}{\{(1+k^2Q_1Q_2)(Q_2^2r_2^2+R_L^2)+Q_2r_2R_L\}^2+Q_2^3r_2^4+Q_1^2Q_2^6r_2^4 +Q_1^2\{Q_2^2r_2(r_2+R_L)+R_L^2\}\{(1+k^2Q_1Q_2)(Q_2^2r_2^2+R_L^2)+Q_2r_2R_L\}}$	$Q_2r_2\sqrt{\frac{(1+Q_1^2)(1+k^2Q_1Q_2+Q_2^2)+k^2Q_1Q_2(1+k^2Q_1Q_2)}{(1+k^2Q_1Q_2+Q_1^2)(1+k^2Q_1Q_2)}}$
S-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{(r_2+R_L+Q_2^2r_2)\{(r_2+R_L)(1+k^2Q_1Q_2)+Q_2^2r_2\}}$	$r_2\sqrt{\frac{(1+Q_2^2)(1+k^2Q_1Q_2+Q_2^2)}{1+k^2Q_1Q_2}}$
P-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{(r_2+R_L+Q_2^2r_2)\{(r_2+R_L)(1+k^2Q_1Q_2)+Q_2^2r_2\}}$	$r_2\sqrt{\frac{(1+Q_2^2)(1+k^2Q_1Q_2+Q_2^2)}{1+k^2Q_1Q_2}}$
LCL-LCL	$\frac{k^2Q_1^3Q_2^3r_2R_L}{\{(r_2+R_L)(1+k^2Q_1Q_2+Q_1^2)+Q_2^2r_2(1+Q_1^2)\}\{(r_2+R_L)(1+k^2Q_1Q_2)+Q_2^2r_2\}}$	$r_2\sqrt{\frac{(1+k^2Q_1Q_2+Q_2^2)\{1+k^2Q_1Q_2+Q_1^2+Q_2^2(1+Q_1^2)\}}{(1+k^2Q_1Q_2+Q_1^2)(1+k^2Q_1Q_2)}}$

TABLE IV. OUTPUT POWER

	P_{out_V}	P_{out_I}
LCL-S	$\frac{k^2Q_1^3Q_2r_2R_L}{r_1\{(r_2+R_L)(1+Q_1^2)+k^2Q_1Q_2r_2\}^2}\lvert V_1\rvert^2$	$\frac{k^2Q_1^3Q_2r_1r_2R_L}{(r_2+R_L+k^2Q_1Q_2r_2)^2}\lvert I_1\rvert^2$
LCL-P	$\frac{k^2Q_1^3Q_2^3r_2R_L\lvert V_1\rvert^2}{[Q_2^2r_1r_2^2(1+k^2Q_1Q_2+Q_1^2)^2 +r_1\{R_L(1+k^2Q_1Q_2+Q_1^2)+Q_2^2r_2(Q_1^2+1)\}^2]}$	$\frac{k^2Q_1^3Q_2^3r_1r_2R_L}{[(1+k^2Q_1Q_2)^2Q_2^2r_2^2 +\{(1+k^2Q_1Q_2)R_L+Q_2^2r_2\}^2]}\lvert I_1\rvert^2$
S-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{r_1\{(r_2+R_L)(1+k^2Q_1Q_2)+Q_2^2r_2\}^2}\lvert V_1\rvert^2$	$\frac{k^2Q_1Q_2^3r_1r_2R_L}{(r_0+R_L+Q_2^2r_2)^2}\lvert I_1\rvert^2$
P-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{r_1[(r_2+R_L+k^2Q_1Q_2R_L+Q_2^2r_2)^2 +\{(r_2+R_L)Q_1+Q_1Q_2^2r_2\}^2]}\lvert V_1\rvert^2$	$\frac{k^2Q_1^3Q_2^3r_1^3r_2R_L}{\{(r_2+R_L)k^2Q_1Q_2r_1+(Q_2^2r_2+R_L)r_1+r_2^2\}^2}\lvert I_1\rvert^2$
LCL-LCL	$\frac{k^2Q_1^3Q_2^3r_2R_L}{r_1\{(r_2+R_L+Q_2^2r_2)(1+Q_1^2)+k^2Q_1Q_2(r_2+R_L)\}^2}\lvert V_1\rvert^2$	$\frac{k^2Q_1^3Q_2^3r_1r_2R_L}{\{(r_2+R_L)(1+k^2Q_1Q_2)+(Q_2^2+1)r_2\}^2}\lvert I_1\rvert^2$

III. COMPARISON OF CALCULATED AND ANALYTICAL RESULTS

Next, an analysis was performed using electromagnetic field analysis software by MoM to demonstrate the validity of the calculation results. The coil used in the analysis is a symmetrical coil as shown in Fig. 2, and the parameters are shown in Table 5. The resonant frequency is 85 kHz, and voltage source is 30 V or current source is 1A connected.

TABLE V. PARAMETERS USED IN THE ANALYSIS

Symbol	Description	Value
f	Resonant frequency	85 kHz
V_1	Voltage Source	30 V
I_1	Current Source	1 A
$L_0, L_1, L_2, L_0{}'$	Inductance	51.85 µH
C_1, C_2	Capacitance	67.62 nF
$r_0, r_1, r_2, r_0{}'$	Inner Resistance	0.12 Ω
k	Coupling Factor	0.11
Q	Q Value	231.02

Fig. 3-5 shows the calculation and analysis results for the efficiency η and the output power P_{out_V}, P_{out_I} when the load value is changed. Figure 3-5 shows that the calculation formulas are correct because the trends of the calculation and analysis results are consistent.

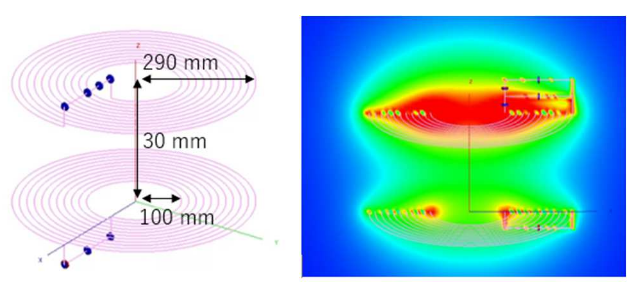


Fig. 2 Electromagnetic Field Analysis

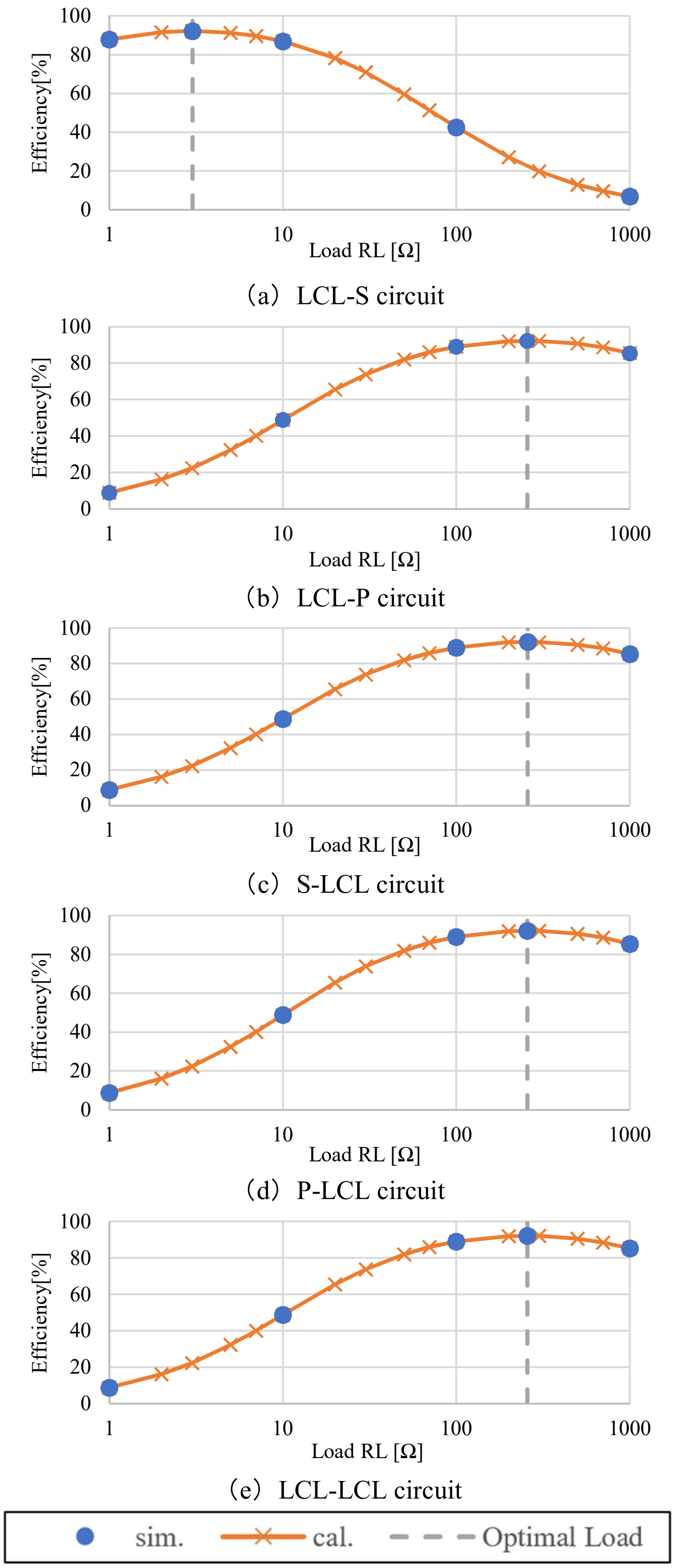


Fig. 3 Comparison of Calculated and Analytical Results in Efficiency
(Independent of Power Supply Type)

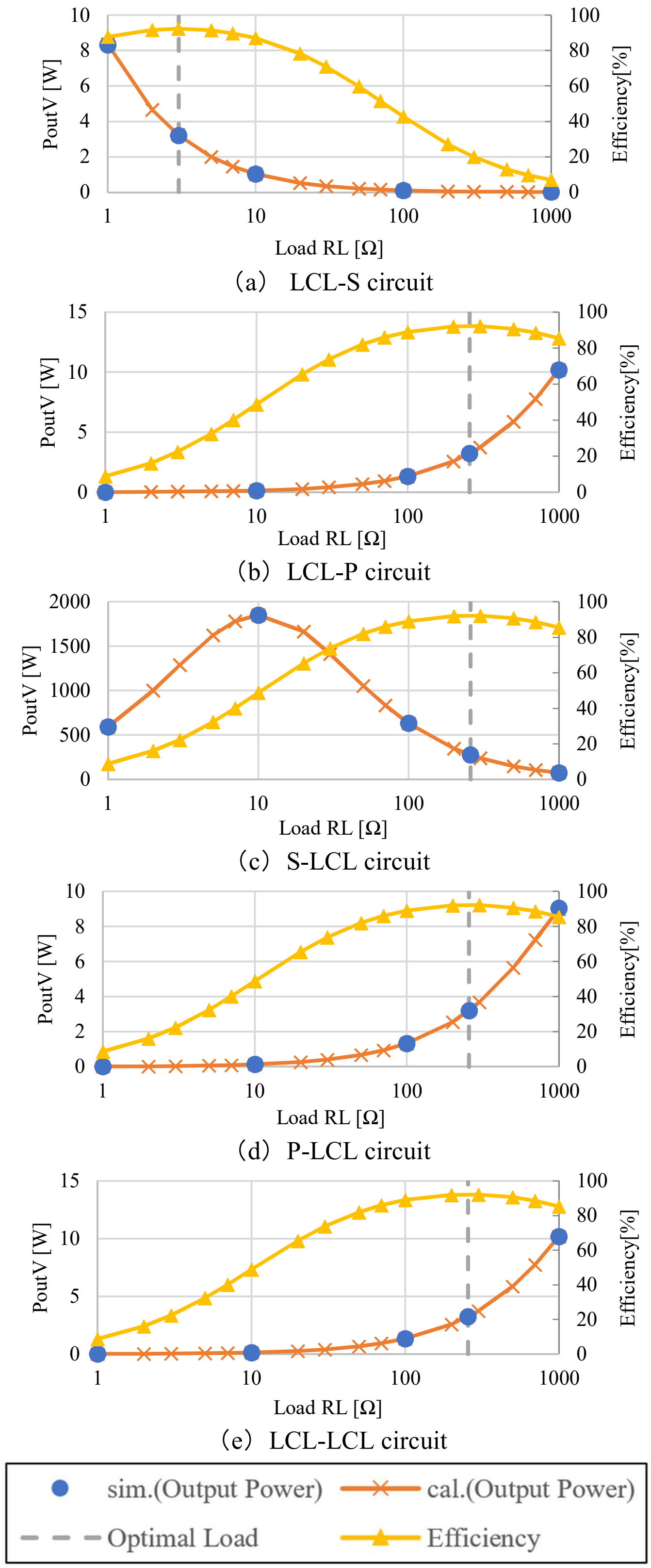
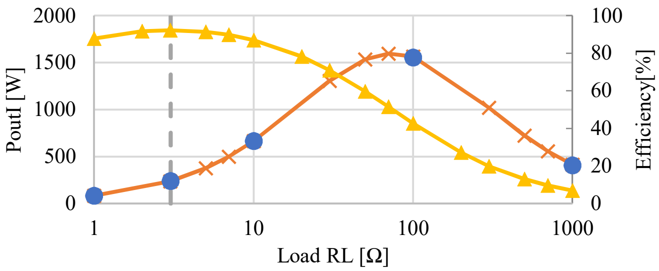
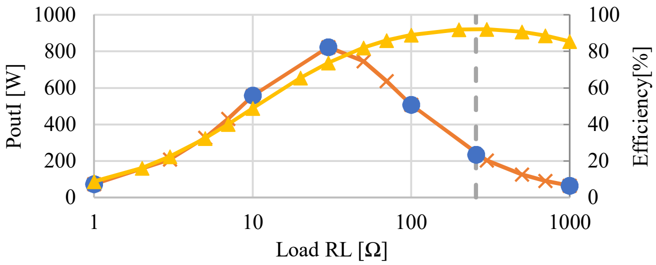


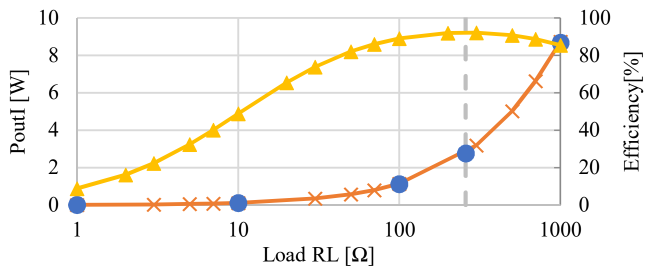
Fig. 4 Comparison of Calculated and Analytical Results in Power
(Voltage source)



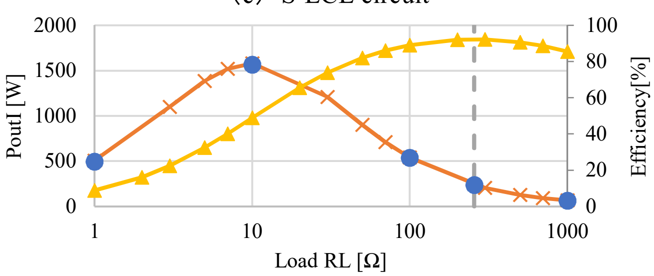
(a) LCL-S circuit



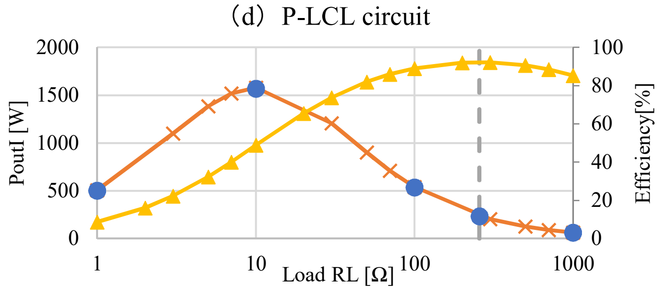
(b) LCL-P circuit



(c) S-LCL circuit



(d) P-LCL circuit



(e) LCL-LCL circuit

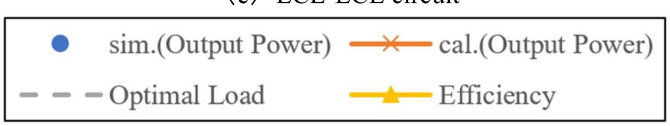


Fig. 5 Comparison of Calculated and Analytical Results in Output Power (Current Source)

A. Maximum Efficiency

The efficiency and optimal load obtained from Table 3 are shown in Figure 6 for each circuit when the optimal load is used. Here, the efficiency and optimum load are the same regardless of the type of power supply. Figure 6 shows that the efficiency of all circuits with optimal load is more than 90%. Therefore, the maximum efficiency is high regardless of the circuit. For all of the circuits, the stability of efficiency is observed around the optimal load. In particular, LCL-S, LCL-P, P-LCL, and LCL-LCL circuits with large optimal load values show stable efficiency for load variations.

B. Optimal Load

The optimal load of LCL-S circuit is smaller than that of LCL-P, S-LCL, P-LCL, and LCL-LCL circuits, as described in Chapter 2, so the circuit must be selected according to the load value for high-efficiency transmission. Therefore, for high efficiency transmission, it is necessary to select the circuit according to the load value.

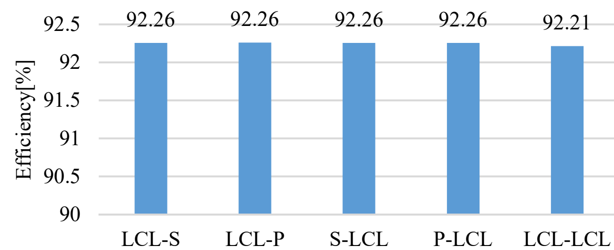


Fig. 6 Maximum Efficiency in Each Circuit (Independent of Power Supply Type)

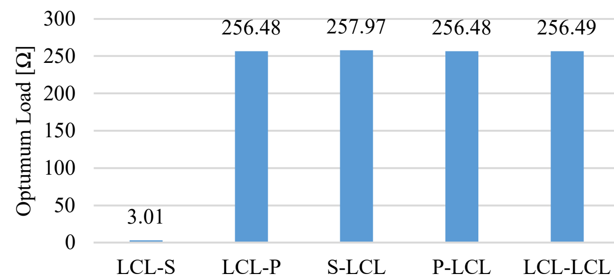


Fig. 7 Optimum Load for Each Circuit (Independent of Power Supply Type)

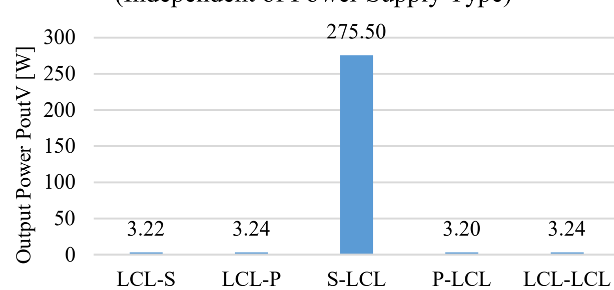


Fig. 8 Output Power P_{out_V} (Voltage Source)

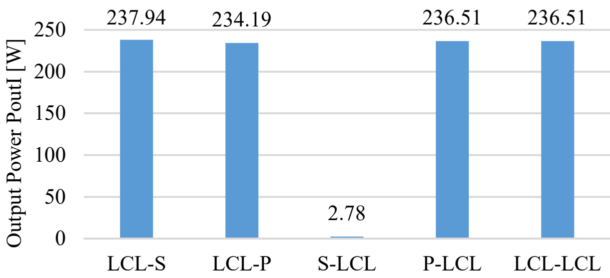


Fig. 9 Output Power P_{out_I}
（Current Source）

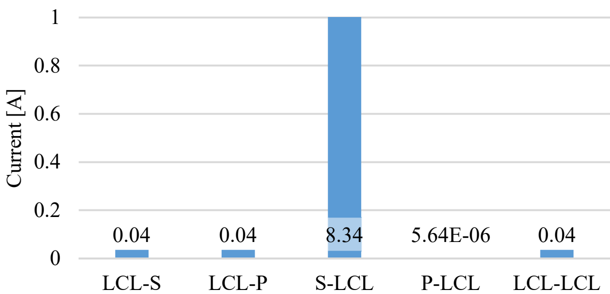


Fig. 10 Current when $k = 0$
（Voltage Source）

C. Output Power

Using the formulas in Table 4. and the parameters in Table 5, the output power P_{out_V} and P_{out_I} are calculated as shown in Fig. 8. Fig. 8 shows that S-LCL circuit is suitable when a voltage source is used, and LCL-S, LCL-P, P-LCL, and LCL-LCL circuits are suitable when a current source is used under the purpose of getting large power. The relationship between load regulation and output power and the relationship between load regulation and output power in Fig. 4 and 5 show that there is a difference between the load that can take the most power and the optimum load for any of these circuits.

D. $k = 0$ Characteristic

Substituting the values in Table 5. into (12), the current is calculated in Fig. 10. From Fig. 10, it can be seen that at $k = 0$, the S-LCL circuit is dangerous because a large current flows.

IV. Concluusion

The transmission characteristics of LCL-S, S-LCL, LCL-P, P-LCL, and LCL-LCL circuits were compared. It was found that LCL-S circuit is suitable for WPT with high efficiency when the load value is small, while the LCL-P, S-LCL, P-LCL, and LCL-LCL are suitable when the load value is large. For getting more output power S-LCL circuit is more suitable when a voltage source is connected, and the LCL-S, LCL-P, P-LCL, and LCL-LCL circuits are more suitable when a current source is

TABLE VI. Characteristics of each circuit

	LCL-S	LCL-P	S-LCL	P-LCL	LCL-LCL
CC/CV Characteristic (Voltage Source)	CV	CC	CV		CC
CC/CV Characteristic (Current Source)	CC		CC	CV	CV
Efficiency	Good	Good	Good	Good	Good
Optimum Load	Low	High	High	High	High
Output Power (Voltage Source)	Poor	Poor	Good	Poor	Poor
Output Power (Current Source)	Good	Good	Poor	Good	Good
Safety ($k = 0$)	Good	Good	Poor	Good	Good

connected. Based on the above, Table 6 summarizes the characteristics of each circuit

From the above, we have developed a design theory to use different circuits for different applications, since the power transmission characteristics such as optimal load, efficiency, and output power.

Future work will include comparisons with circuits containing LCC and field coupling methods, as well as comparisons when coupling coefficients and Q values are varied. In addition, comparisons with CPT will be conducted.

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