Comparison of Multiple Circuits Including LCL in Inductive Power Transfer and Capacitive Power Transfer

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***Abstract*—Typical methods of wireless power transfer are Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT). Both have different characteristics such as transmission distance, cost, and impact of surrounding foreign matter. In addition, since transmission characteristics differ depending on the circuit. Therefore, in this paper, the design theory for selecting the appropriate circuit and method for various applications is made. The equations for transmission characteristics such as the compensation condition, CC(Constant Current)/CV(Constant Voltage) characteristic, efficiency, optimal load, and output power were calculated. As for compensation condition, it is found that S-P, P-S and P-P for IPT and S-S, S-P and P-S for CPT vary depending on the coupling factor. Substituting specific and impartial values into the calculated equations verified the following. As for the optimal load to achieve maximum efficiency, the value of optimal load in the receiver S is about k^2 times smaller than the others for IPT, and the value of optimal load in the receiver S and LCL are about k^2 times smaller than the others for CPT. Therefore, the circuits should be selected according to the value of the load for high efficiency transmission. As for the maximum efficiency, the efficiency does not depend on the transmission method or circuit, since it is the same for all circuits for both IPT and CPT. In terms of output power with voltage source, transmission S for IPT and transmission S and LCL for CPT can get about $1 / k^2$ larger power than the other circuits. Regarding the output power with current source, the transmitter P and LCL for IPT and the transmitter P for CPT can get about $1 / k^2$ larger power than the other circuits. Therefore, in order to get large power, an appropriate circuit should be selected depending on the type of the transmitter circuit, power source and method of transmission. Based on the above, it was found that LCL in IPT was same characteristic as S, but LCL in CPT was same characteristic as P. From the above, the design theory was made for optimal method and circuit selection by fairly evaluating representative circuits of both IPT and CPT methods under unified conditions.**

Keywords— Inductive Power Transfer, Capacitive Power Transfer, Circuit, Transmission Characteristics

I. Introduction

In recent years, electronic devices have become more and more widespread and opportunities for charging have increased year by year, there are problems with cable charging such as risk of electric shock, cable deterioration, and wire breakage. All of these problems can be solved by Wireless Power Transfer (WPT).

Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT) are representative WPT methods. The advantages of IPT are that it is easier to get higher power and has a longer transmission distance than CPT, while the advantages of CPT are that there is no risk of efficiency loss or heat generation due to foreign metal, it has a high degree of freedom in positioning, and it is inexpensive and lightweight due to the use of only metal plates. As described above, IPT and CPT have different advantages and should be used depending on the application.

For IPT, there are papers to compare the characteristics of each circuit [1], [2] and papers to select the appropriate circuit for a particular application.[3]-[8] For CPT, there are also papers to compare the characteristics of each circuit [9], [10] and papers to examine circuits for high power, which is the issue for CPT. [11]-[14] In addition, according to previous studies, SS and SP circuits are superior for both IPT and CPT. However, there are few studies that compare IPT and CPT together, and there are no studies that include even advanced circuits such as LCL. Therefore, in this paper, multiple circuits are compared in each of the IPT and CPT.

II. Compared Circuits

In this paper, 18 circuits are compared for IPT and CPT, including the circuits such as S, P, and LCL on the transmitter side and the circuits such as S, P, and LCL on the receiver side, as shown in Fig. 1-2.

S is the circuit which a resonant capacitor or resonant coil is connected in series with a transmission coil or transmission capacitor, and P is the circuit which a resonant capacitor or resonant coil is connected in parallel with a transmission coil or transmission capacitor. LCL in IPT is the circuit in which an additional coil is placed ahead of P. The advantage of LCL is that LCL-LCL have the same excellent characteristics as S-S and are more secure than S-S in the absence of receiver side. More specifically, for the transmitter side is S, there is only the internal resistance of the coil due to series resonance, which causes a large current to flow and dangerous. However, the transmitter LCL is safe because the input impedance becomes infinite and there is no large current flow in the absence of receiver side. As there is no established LCL in CPT, it is proposed here as a circuit in which an additional capacitor is placed ahead of S, as corresponding to LCL in IPT. The advantage of the LCL-LCL is that it has the same excellent characteristics as S-P, but the resonance conditions are independent of the coupling factor, as next chapters show.

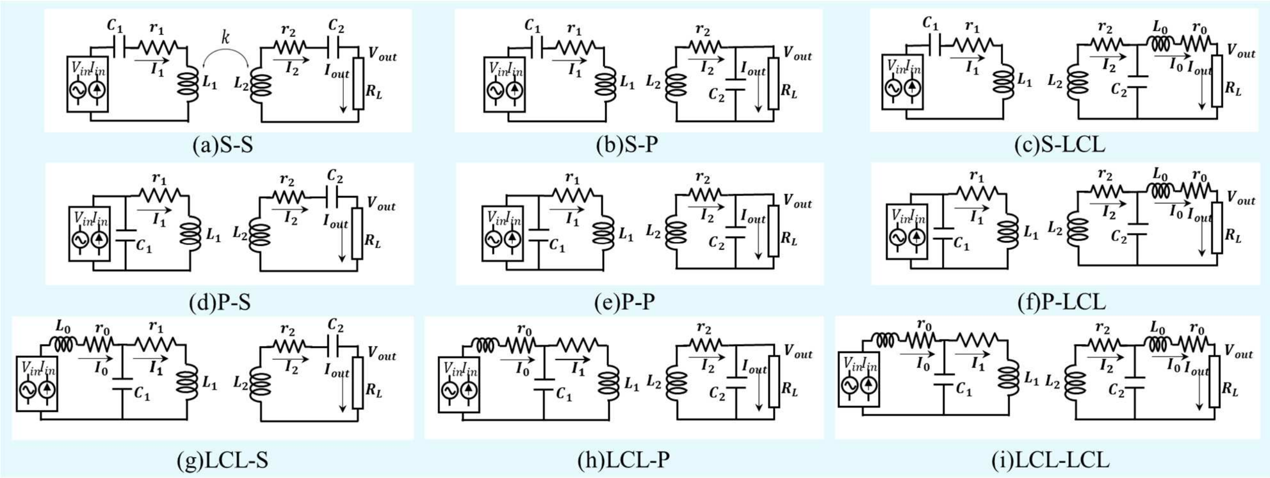


Fig. 1 Compared Circuits for IPT

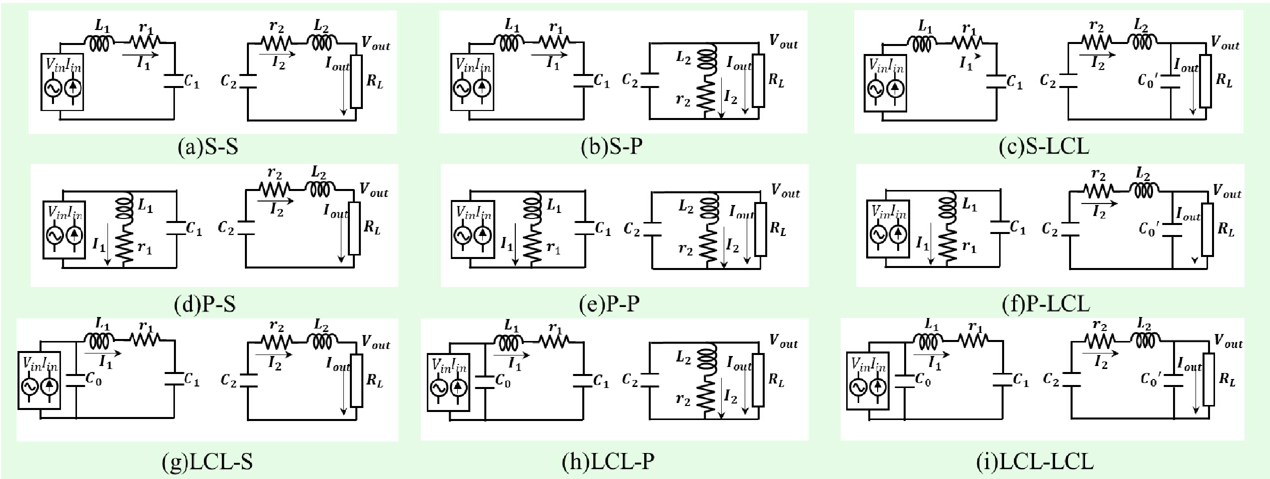


Fig. 2 Compared Circuits for CPT

III. EQUATIONS FOR TRANSMISSION CHARACTERISTICS

In this chapter, equations for transmission characteristics such as compensation condition, CC (Constant Current)/CV (Constant Voltage) characteristic, optimal load, efficiency, and output power are calculated for a total of 18 circuits shown in Fig. 1. $Q = \omega L/r$ a measure of coil performance evaluation, is used in the various equations for transmission characteristics.

First, the design condition equations for the compensation inductance and resonant capacitor are calculated assuming that the internal resistance is 0. The values of each element are shown in Table 1, based on the gyrator characteristic satisfying $B = C = 0$ and the ideal transformer characteristic satisfying $A = D = 0$ for the parameter in (1). Determining the value of the compensation element in the manner described above has the advantage of achieving power factor of 1 and high transmission efficiency, assuming the internal resistance of the coil is zero.

$$\begin{bmatrix} V_{in} \\ I_{in} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_{out} \\ I_{out} \end{bmatrix} \quad (1)$$

Table 1 shows that the resonance conditions for the S-P, P-S and P-P circuits of the IPT and the S-S, S-P and P-S circuits of the CPT vary with the coupling factor. Furthermore, Table 2 shows the CC/CV characteristic when the aforementioned conditions are applied.

TABLE I. COMPENSATION CONDITION

		Compensation Condition	
IPT	S-S	$C_1 = 1/\omega^2 L_1$	$C_2 = 1/\omega^2 L_2$
	S-P	$C_1 = 1/\omega^2(1-k^2)L_1$	$C_2 = 1/\omega^2 L_2$
	S-LCL	$C_1 = 1/\omega^2 L_1$	$C_2 = 1/\omega^2 L_2$
	P-S	$C_1 = 1/\omega^2 L_1$	$C_2 = 1/\omega^2(1-k^2)L_2$
	P-P	$C_1 = 1/\omega^2(1-k^2)L_1$	$C_2 = 1/\omega^2(1-k^2)L_2$
	P-LCL	$C_1 = 1/\omega^2 L_1$	$C_2 = 1/\omega^2 L_2$
	LCL-S	$C_1 = 1/\omega^2 L_1$	$C_2 = 1/\omega^2 L_2$
	LCL-P	$C_1 = 1/\omega^2 L_1$	$C_2 = 1/\omega^2 L_2$
	LCL-LCL	$C_1 = 1/\omega^2 L_1$	$C_2 = 1/\omega^2 L_2$
CPT	S-S	$L_1 = 1/\omega^2(1-k^2)C_1$	$L_2 = 1/\omega^2(1-k^2)C_2$
	S-P	$L_1 = 1/\omega^2 C_1$	$L_2 = 1/\omega^2(1-k^2)C_2$
	S-LCL	$L_1 = 1/\omega^2 C_1$	$L_2 = 1/\omega^2 C_2$
	P-S	$L_1 = 1/\omega^2(1-k^2)C_1$	$L_2 = 1/\omega^2 C_2$
	P-P	$L_1 = 1/\omega^2 C_1$	$L_2 = 1/\omega^2 C_2$
	P-LCL	$L_1 = 1/\omega^2 C_1$	$L_2 = 1/\omega^2 C_2$
	LCL-S	$L_1 = 1/\omega^2 C_1$	$L_2 = 1/\omega^2 C_2$
	LCL-P	$L_1 = 1/\omega^2 C_1$	$L_2 = 1/\omega^2 C_2$
	LCL-LCL	$L_1 = 1/\omega^2 C_1$	$L_2 = 1/\omega^2 C_2$

TABLE II. CC/CV CHARACTERISTIC

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

Next, after considering the internal resistance and satisfying compensation condition, Table 3 and 4 show the results of the equation of the efficiency and optimal load to get maximum efficiency, from (2) and (3).

$$\eta = \frac{R_L|I_{out}|^2}{r_0|I_0|^2 + r_1|I_1|^2 + r_2|I_2|^2 + {r_0'}^2|I_0'|^2 + R_L|I_{out}|^2} \quad (2)$$

$$\partial\eta/\partial R_L = 0 \quad (3)$$

The equation of the output power with voltage source and the output power with current source were got from (4) and (5). The results are shown in Table 5 and 6.

$$P_{out} = |V_{out}|^2/R_L \quad (4)$$

$$P_{out} = R_L|I_{out}|^2 \quad (5)$$

TABLE III. EFFICIENCY

		Efficiency
IPT	S-S	$\frac{k^2Q_1Q_2r_2R_L}{\{(1+k^2Q_1Q_2)r_2+R_L\}(r_2+R_L)}$
	S-P	$\frac{k^2Q_1Q_2^3r_2R_L}{(1+Q_2^2+k^2Q_1Q_2)Q_2^2r_2(r_2+R_L)+(1+k^2Q_1Q_2)R_L^2}$
	S-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{\{(1+Q_2^2)r_2+R_L\}\{(1+Q_2^2+k^2Q_1Q_2)r_2+(1+k^2Q_1Q_2)R_L\}}$
	P-S	$\frac{k^2Q_1Q_2r_2R_L}{\{(1+k^2Q_1Q_2)r_2+R_L\}(r_2+R_L)+k^4Q_2^2r_2^2}$
	P-P	$\frac{k^2(1-k^2)^2Q_1Q_2^3r_2R_L\{(1-k^2)^2Q_2^2r_2^2+R_L^2\}}{\{(1-k^2)^2Q_2^2r_2(r_2+R_L)+R_L^2\}[(1+k^2Q_1Q_2)\{(1-k^2)^2Q_2^2r_2^2+R_L^2\}+(1-k^2)^2Q_2^2r_2R_L] + Q_2^2\{(1-k^2)^2Q_2^2r_2^2+k^2R_L^2\}^2}$
	P-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{\{(1+Q_2^2)r_2+R_L\}\{(1+Q_2^2+k^2Q_1Q_2)r_2+(1+k^2Q_1Q_2)R_L\}}$
	LCL-S	$\frac{k^2Q_1^3Q_2r_2R_L}{\{(1+k^2Q_1Q_2)r_2+R_L\}\{(1+Q_1^2+k^2Q_1Q_2)r_2+(1+Q_1^2)R_L\}}$
	LCL-P	$\frac{k^2Q_1^3Q_2^3r_2R_L}{[\{(1+Q_1^2+k^2Q_1Q_2)\{(1+k^2Q_1Q_2)(Q_2^2r_2^2+R_L^2)+Q_2^2r_2R_L\} + (1+Q_1^2)Q_2^2r_2\{Q_2^2r_2+(1+k^2Q_1Q_2)R_L\}]}$
	LCL-LCL	$\frac{k^2Q_1^3Q_2^3r_2R_L}{\{(1+Q_2^2+k^2Q_1Q_2)r_2+(1+k^2Q_1Q_2)R_L\}[\{1+Q_1^2)(1+Q_2^2)+k^2Q_1Q_2\}r_2+(1+Q_1^2+k^2Q_1Q_2)R_L]}$
CPT	S-S	$\frac{k^2Q_1Q_2r_2R_L}{\{(1+k^2Q_1Q_2)r_2+R_L\}(r_2+R_L)}$
	S-P	$\frac{k^2Q_1Q_2[\{(1+Q_2^2)r_2+R_L\}^2+Q_2^2R_L^2}{(1-k^2)^2Q_2^2r_2^2\{(1+Q_2^2)r_2+2R_L\}^2 + \{(1+Q_2^2)r_2+R_L\}R_L\begin{bmatrix}(1-k^2)\{(1+Q_2^2)r_2+R_L\}R_L \\ +k^2Q_1Q_2\{(r_2+R_L)^2+Q_2^2r_2^2\}\end{bmatrix}}$
	S-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{\{Q_2^2r_2(r_2+R_L)+R_L^2\}\{(1-k^2)^2+k^2Q_1Q_2\} + Q_2^2\{(1-k^2)^2r_2R_L+k^4Q_2^2r_2^2+R_L^2\}}$
	P-S	$\frac{k^2Q_1Q_2r_2R_L}{\{(1-k^2)^2(r_2+R_L)+k^2Q_1Q_2r_2\}(r_2+R_L)+k^4Q_2^2r_2^2}$
	P-P	$\frac{k^2Q_1Q_2[\{(1+Q_2^2)r_2+R_L\}^2+Q_2^2R_L^2]r_2R_L}{Q_2^2\{(1+Q_2^2)r_2+2r_2R_L+k^2R_L\}^2 + \{(1+Q_2^2)r_2+R_L\}R_L\begin{bmatrix}(1-k^2)^2\{(1+Q_2^2)r_2+R_L\}R_L \\ +k^2Q_1Q_2\{(r_2+R_L)^2+Q_2^2r_2^2\}\end{bmatrix}}$
	P-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{\{Q_2^2r_2(r_2+R_L)+R_L^2\}\{(1-k^2)^2+k^2Q_1Q_2\} + Q_2^2\{(1-k^2)^2r_2R_L+k^4Q_2^2r_2^2+R_L^2\}}$
	LCL-S	$\frac{k^2Q_1Q_2r_2R_L}{\{(1-k^2)^2(r_2+R_L)+k^2Q_1Q_2r_2\}(r_2+R_L)+k^4Q_2^2r_2^2}$
	LCL-P	$\frac{k^2Q_1Q_2[\{(1+Q_2^2)r_2+R_L\}^2+Q_2^2R_L^2]r_2R_L}{Q_2^2\{(1+Q_2^2)r_2+2r_2R_L+k^2R_L\}^2 + \{(1+Q_2^2)r_2+R_L\}R_L\begin{bmatrix}k^2Q_1Q_2\{(r_2+R_L)^2+Q_2^2r_2^2\} \\ +(1-k^2)^2\{(1+Q_2^2)r_2+R_L\}R_L\end{bmatrix}}$
	LCL-LCL	$\frac{k^2Q_1Q_2^3r_2R_L}{\{Q_2^2r_2(r_2+R_L)+R_L^2\}\{(1-k^2)^2+k^2Q_1Q_2\} + Q_2^2\{(1-k^2)^2r_2R_L+k^4Q_2^2r_2^2+R_L^2\}}$

TABLE IV. OPTIMAL LOAD

		Optimal Load
IPT	S-S	$r_2\sqrt{1+k^2Q_1Q_2}$
	S-P	$r_2\sqrt{\frac{1+Q_2^2+k^2Q_1Q_2}{1+k^2Q_1Q_2}}$
	S-LCL	$r_2\sqrt{\frac{(1+Q_2^2)(1+Q_2^2+k^2Q_1Q_2)}{1+k^2Q_1Q_2}}$
	P-S	$r_2\sqrt{1+k^2Q_1Q_2+k^4Q_2^2}$
	P-P	$(1-k^2)Q_2r_2\sqrt{\frac{1+Q_2^2+k^2Q_1Q_2}{1+k^2Q_1Q_2+k^4Q_2^2}}$
	P-LCL	$r_2\sqrt{\frac{(1+Q_2^2)(1+Q_2^2+k^2Q_1Q_2)}{1+k^2Q_1Q_2}}$
	LCL-S	$r_2\sqrt{\frac{(1+k^2Q_1Q_2)(1+Q_1^2+k^2Q_1Q_2)}{1+Q_1^2}}$
	LCL-P	$Q_2r_2\sqrt{\frac{(1+k^2Q_1Q_2)(1+Q_1^2+k^2Q_1Q_2)+(1+Q_1^2)Q_2^2}{(1+k^2Q_1Q_2)(1+Q_1^2+k^2Q_1Q_2)}}$
	LCL-LCL	$r_2\sqrt{\frac{(1+Q_2^2+k^2Q_1Q_2)\{(1+Q_1^2)(1+Q_2^2)+k^2Q_1Q_2\}}{(1+k^2Q_1Q_2)(1+Q_1^2+k^2Q_1Q_2)}}$
CPT	S-S	$r_2\sqrt{1+k^2Q_1Q_2}$
	S-P	$Q_2r_2\sqrt{\frac{(1-k^2)(1+Q_2^2)}{1-k^2+k^2Q_1Q_2}}$
	S-LCL	$Q_2r_2\sqrt{\frac{(1-k^2)^2+k^2Q_1Q_2+k^4Q_2^2}{(1-k^2)^2+k^2Q_1Q_2+Q_2^2}}$
	P-S	$r_2\sqrt{\frac{(1-k^2)^2+k^2Q_1Q_2+k^4Q_2^2}{(1-k^2)^2}}$
	P-P	$Q_2r_2\sqrt{\frac{1+Q_2^2}{(1-k^2)^2+k^4Q_2^2+k^2Q_1Q_2}}$
	P-LCL	$Q_2r_2\sqrt{\frac{(1-k^2)^2+k^2Q_1Q_2+k^4Q_2^2}{(1-k^2)^2+k^2Q_1Q_2+Q_2^2}}$
	LCL-S	$r_2\sqrt{\frac{(1-k^2)^2+k^2Q_1Q_2+k^4Q_2^2}{(1-k^2)^2}}$
	LCL-P	$Q_2r_2\sqrt{\frac{1+Q_2^2}{(1-k^2)^2+k^4Q_2^2+k^2Q_1Q_2}}$
	LCL-LCL	$Q_2r_2\sqrt{\frac{(1-k^2)^2+k^2Q_1Q_2+k^4Q_2^2}{(1-k^2)^2+k^2Q_1Q_2+Q_2^2}}$

TABLE V. OUTPUT POWER WITH VOLTAGE SOURCE

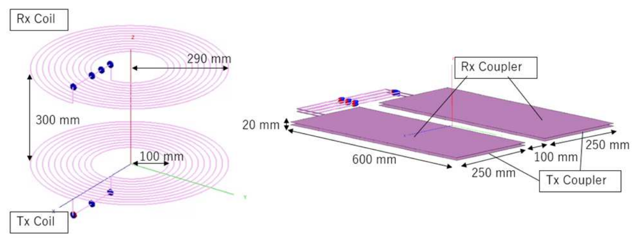
		Output Power connecting Voltage Source
IPT	S-S	$\frac{k^2Q_1Q_2r_2R_L}{r_1\{(1+k^2Q_1Q_2)r_2+R_L\}^2}\lvert V_{in}\rvert^2$
	S-P	$\frac{k^2Q_1Q_2^3r_2R_L}{r_1[\{Q_2^2r_2+R_L+k^2Q_1Q_2(r_2+R_L)\}^2+(Q_2r_2-k^2Q_1R_L)^2]}\lvert V_{in}\rvert^2$
	S-LCL	$\frac{k^2Q_1Q_2^3r_2R_L\lvert V_{in}\rvert^2}{r_1\{(r_2+R_L)(1+k^2Q_1Q_2)+Q_2^2r_2\}^2}$
	P-S	$\frac{k^2Q_1Q_2r_2R_L}{r_1[(r_2+R_L)^2+\{(Q_1+k^2Q_2)r_2+Q_1R_L\}^2]}\lvert V_{in}\rvert^2$
	P-P	$\frac{k^2(1-k^2)^2Q_1Q_2^3r_2R_L\lvert V_{in}\rvert^2}{r_1\begin{pmatrix}[(1-k^2)\{1-(1-k^2)Q_1Q_2\}Q_2r_2-\{(1-k^2)Q_1+k^2Q_2\}R_L]^2\\+[(1-k^2)(Q_1+Q_2)Q_2r_2+\{1-k^2(1+k^2Q_1Q_2)\}R_L]^2\end{pmatrix}}$
	P-LCL	$\frac{k^2Q_1Q_2^3r_2R_L\lvert V_{in}\rvert^2}{r_1[(r_2+R_L+k^2Q_1Q_2R_L+Q_2^2r_2)^2+Q_1^2\{(r_2+R_L)+Q_2^2r_2\}^2]}$
	LCL-S	$\frac{k^2Q_1^3Q_2r_2R_L\lvert V_{in}\rvert^2}{r_1\{(r_2+R_L)(1+Q_1^2)+k^2Q_1Q_2r_2\}^2}$
	LCL-P	$\frac{k^2Q_1^3Q_2^3r_2R_L\lvert V_{in}\rvert^2}{r_1[Q_2^2r_2^2(1+k^2Q_1Q_2+Q_1^2)^2+\{(1+Q_1^2)(Q_2^2r_2+R_L)+k^2Q_1Q_2R_L^2\}]}$
	LCL-LCL	$\frac{k^2Q_1^3Q_2^3r_2R_L\lvert V_{in}\rvert^2}{r_1\{(r_2+R_L+Q_2^2r_2)(1+Q_1^2)+k^2Q_1Q_2(r_2+R_L)\}^2}$
CPT	S-S	$\frac{k^2(1-k^2)^2Q_1Q_2r_1r_2R_L\lvert V_{in}\rvert^2}{r_1\{(1-k^2)(r_2+R_L)+k^2Q_1Q_2r_2\}^2}$
	S-P	$\frac{k^2(1-k^2)Q_1Q_2(1+Q_2^2)^2r_2R_L\lvert V_{in}\rvert^2}{\begin{gathered}r_1[k^4(1+Q_2^2)^2R_L^2\\+\{(1+Q_2^2)((1-k^2)Q_2r_2+k^2Q_1R_L)+(1-k^2)Q_2R_L\}^2]\end{gathered}}$
	S-LCL	$\frac{k^2Q_1Q_2^3r_2R_L\lvert V_{in}\rvert^2}{r_1\begin{bmatrix}\{(k^2Q_1+Q_2)R_L+(1-k^2+k^2Q_1Q_2)Q_2r_2\}^2\\+\{(1-k^2)R_L-k^2(Q_1+Q_2)Q_2r_2\}^2\end{bmatrix}}$
	P-S	$\frac{k^2Q_2r_2R_L\lvert V_{in}\rvert^2}{(1-k^2)Q_1r_1(r_2+R_L)^2}$
	P-P	$\frac{k^2(1+Q_2^2)Q_2r_2R_L\lvert V_{in}\rvert^2}{Q_1r_1[\{(1+Q_2^2)Q_2r_2+R_L\}^2+R_L^2]}$
	P-LCL	$\frac{k^2Q_2^3r_2R_L\lvert V_{in}\rvert^2}{Q_1r_1\{Q_2^2(r_2+R_L)^2+R_L^2\}}$
	LCL-S	$\frac{k^2Q_1Q_2r_2R_L\lvert V_{in}\rvert^2}{r_1[\{(1-k^2)(r_2+R_L)+k^2Q_1Q_2r_2\}^2+k^4\{Q_1(r_2+R_L)+Q_2r_2\}^2]}$
	LCL-P	$\frac{k^2Q_1Q_2(1+Q_2^2)^2r_2R_L\lvert V_{in}\rvert^2}{r_1\begin{bmatrix}\{1-k^2(1+Q_2^2)\}^2R_L^2\\+\{k^2Q_1(1+Q_2^2)R_L+Q_2(r_2+R_L)+Q_2^3r_2\}^2\end{bmatrix}}$
	LCL-LCL	$\frac{k^2Q_1Q_2^3r_2R_L\lvert V_{in}\rvert^2}{r_1\begin{bmatrix}\{(k^2Q_1+Q_2)R_L+(1-k^2+k^2Q_1Q_2)Q_2r_2\}^2\\+\{(1-k^2)R_L-k^2(Q_1+Q_2)Q_2r_2\}^2\end{bmatrix}}$

TABLE VI. OUTPUT POWER WITH CURRENT SOURCE

		Output Power connecting Current Source
IPT	S-S	$\frac{k^2Q_1Q_2r_1r_2R_L}{(r_2+R_L)^2}\lvert I_{in}\rvert^2$
	S-P	$\frac{k^2(1-k^2)Q_1^3Q_2r_1r_2R_L}{\{(1+k^2Q_1Q_2)r_2+R_L\}^2}\lvert I_{in}\rvert^2$
	S-LCL	$\frac{k^2Q_1Q_2^3r_1r_2R_L\lvert I_{in}\rvert^2}{(r_0+R_L+Q_2^2r_2)^2}$
	P-S	$\frac{k^2Q_1^3Q_2r_1r_2R_L}{\{(1+k^2Q_1Q_2)r_2+R_L\}^2+k^4Q_2^2r_2^2}\lvert I_{in}\rvert^2$
	P-P	$\frac{k^2(1-k^2)Q_1^3Q_2^3r_1r_2R_L\lvert I_{in}\rvert^2}{\begin{gathered}[(1-k^2)(k^2Q_1+Q_2)Q_2r_2+\{1+k^2(1-k^2)Q_1Q_2\}R_L]^2\\+\{(1-k^2)Q_2r_2-k^2(Q_1+Q_2)R_L\}^2\end{gathered}}$
	P-LCL	$\frac{k^2Q_1^3Q_2^3r_1^3r_2R_L\lvert I_{in}\rvert^2}{\{(1+Q_2^2+k^2Q_1Q_2)r_1r_2+(1+k^2Q_1Q_2)r_1R_L+r_2^2\}^2}$
	LCL-S	$\frac{k^2Q_1^3Q_2r_1r_2R_L\lvert I_{in}\rvert^2}{(r_2+R_L+k^2Q_1Q_2r_2)^2}$
	LCL-P	$\frac{k^2Q_1^3Q_2^3r_1r_2R_L\lvert I_{in}\rvert^2}{[(1+k^2Q_1Q_2)^2Q_2^2r_2^2+\{(1+k^2Q_1Q_2)R_L+Q_2^2r_2\}^2]}$
	LCL-LCL	$\frac{k^2Q_1^3Q_2^3r_1r_2R_L\lvert I_{in}\rvert^2}{\{(r_2+R_L)(1+k^2Q_1Q_2)+(1+Q_2^2)r_2\}^2}$
CPT	S-S	$\frac{k^2Q_1Q_2r_1r_2R_L\lvert I_{in}\rvert^2}{(r_2+R_L)^2}$
	S-P	$\frac{k^2Q_1Q_2(1+Q_2^2)^2r_1r_2R_L\lvert I_{in}\rvert^2}{(1-k^2)[Q_2^2\{(1+Q_2^2)r_2+R_L\}^2+R_L^2]}$
	S-LCL	$\frac{k^2Q_1Q_2^3r_1r_2R_L\lvert I_{in}\rvert^2}{\{k^2Q_2^2r_2-(1-k^2)R_L\}^2+Q_2^2\{(1-k^2)r_2+R_L\}^2}$
	P-S	$\frac{k^2(1-k^2)(1+Q_1^2)^2Q_1Q_2r_1r_2R_L\lvert I_{in}\rvert^2}{\{Q_1(r_2+R_L)+k^2(1+Q_1^2)Q_2r_2\}^2+k^4(1+Q_1^2)^2(r_2+R_L)^2}$
	P-P	$\frac{k^2(1+Q_1^2)^2(1+Q_2^2)^2Q_1Q_2r_1r_2R_L\lvert I_{in}\rvert^2}{\begin{gathered}[(1+Q_2^2)Q_1Q_2r_2+\{k^2(1+Q_1^2)(1+Q_2^2)+Q_1Q_2-1\}R_L]^2\\+\{(1+Q_2^2)Q_2r_2+(Q_1+Q_2)R_L\}^2\end{gathered}}$
	P-LCL	$\frac{k^2Q_1Q_2^3(1+Q_1^2)^2r_1r_2R_L\lvert I_{in}\rvert^2}{\begin{gathered}\{k^2(1+Q_1^2)(Q_2^2r_2+R_L)+Q_1Q_2(r_2+R_L)-R_L\}^2\\+\{(1-k^2-k^2Q_1Q_2)Q_2r_2+Q_1R_L\}^2\end{gathered}}$
	LCL-S	$\frac{k^2Q_1^3Q_2r_1r_2R_L\lvert I_{in}\rvert^2}{(1-k^2)(r_2+R_L)^2+\{Q_1(r_2+R_L)+k^2Q_2r_2\}^2}$
	LCL-P	$\frac{k^2Q_1^3Q_2(1+Q_2^2)^2r_1r_2R_L\lvert I_{in}\rvert^2}{\begin{gathered}\{Q_2(1+Q_2^2)r_2+(Q_1+Q_2)R_L\}^2\\+\{Q_1Q_2(1+Q_2^2)r_2-(1-k^2-Q_1Q_2-k^2Q_1Q_2)R_L\}^2\end{gathered}}$
	LCL-LCL	$\frac{k^2Q_1^3Q_2^3r_1r_2R_L\lvert I_{in}\rvert^2}{\begin{gathered}\{(Q_1+k^2Q_2)Q_2r_2-(1-k^2-Q_1Q_2)R_L\}^2\\+\{(1-k^2)Q_2r_2+(Q_1+Q_2)R_L\}^2\end{gathered}}$

IV. SIMULATION

In order to verify the correctness of the calculation results, a comparison with the results of the electromagnetic field analysis using the moment method is shown in Fig. 4-6. The coupler and parameter used in the analysis is shown in Fig. 3 and Table 7. Here, the values of supply voltage and current, coupler area, coupling factor and Q-value are set as common for a fair comparison between IPT and CPT. The value of the resonant capacitor in IPT and the resonant inductance in CPT are determined from the compensation conditions in Table 1.



(a)Transmission Coil for IPT (b)Transmission Plate for CPT

Fig. 3 Transmission Coupler

TABLE VII. SIMULATION PARAMETER

	Symbol	Value	
Voltage Source	V_{in}	30 V	
Current Source	I_{in}	1 A	
Coupling Factor	k	0.11	
Q value	Q_1, Q_2	231.02	
		IPT	CPT
Resonant Frequency	f	85 kHz	450 kHz
Inductance	L_1, L_2	51.85 μH	139.76 μH /138.05 μH
Internal Resistance	r_1, r_2	0.12 ohm	1.71 ohm /1.69 ohm
Capacitance	C_1, C_2	67.62 nF /68.41 nF	906.08 nF

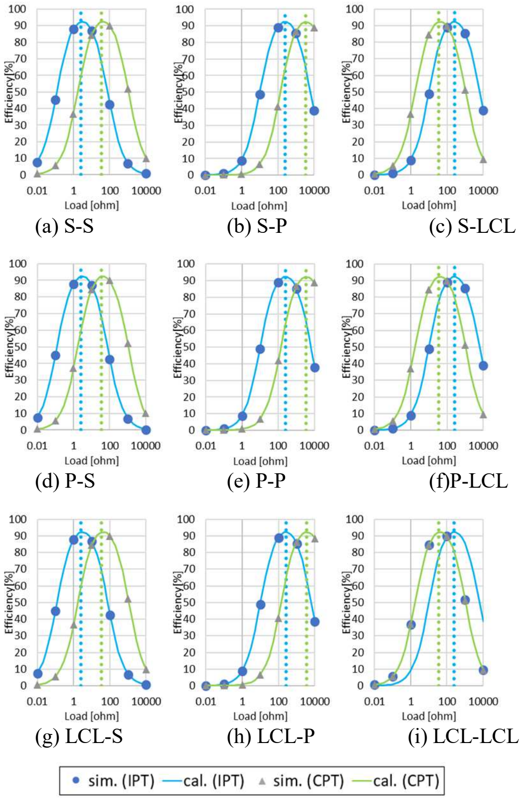


Fig. 4 Efficiency

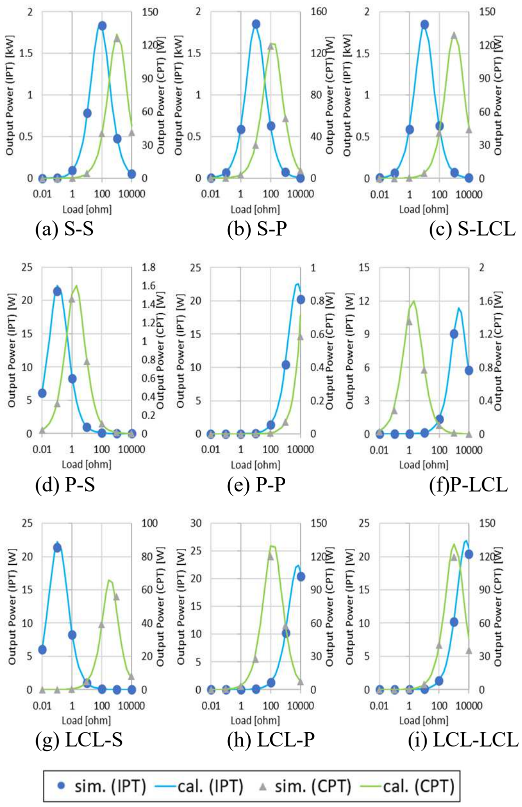


Fig. 5 Output Power Connecting Voltage Source

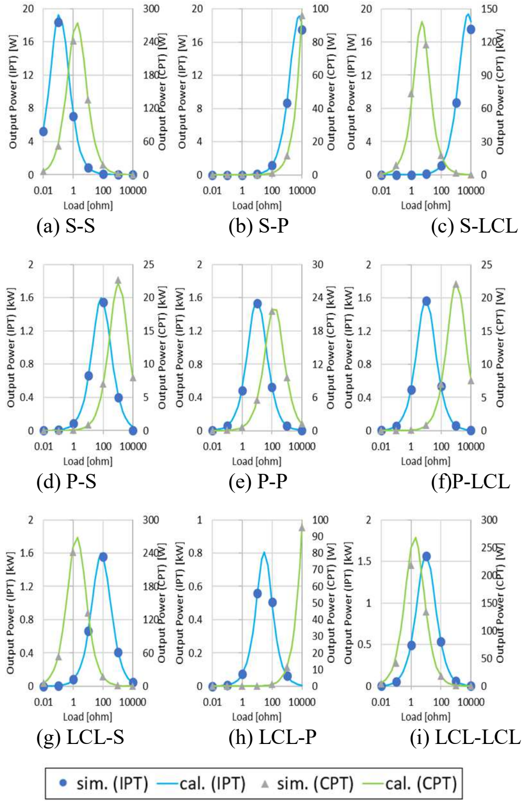


Fig. 6 Output Power Connecting Current Source

V. TRANSMISSION CHARACTERISTICS

The parameters of the analysis are then used to substitute into the equations for each transmission characteristics calculated in Chapter 2 and the results are compared.

A. Optimal Load

The optimal load for IPT and CPT are shown in Fig. 7. Optimal load value for IPT, the receiver S is smaller than the receiver P or LCL. On the other hand, optimal load value for CPT, the receiver S or LCL is smaller than the receiver P. In addition, due to the difference in the values of the internal resistance of the coils, the optimal load value for IPT is larger than the optimal load value for CPT.

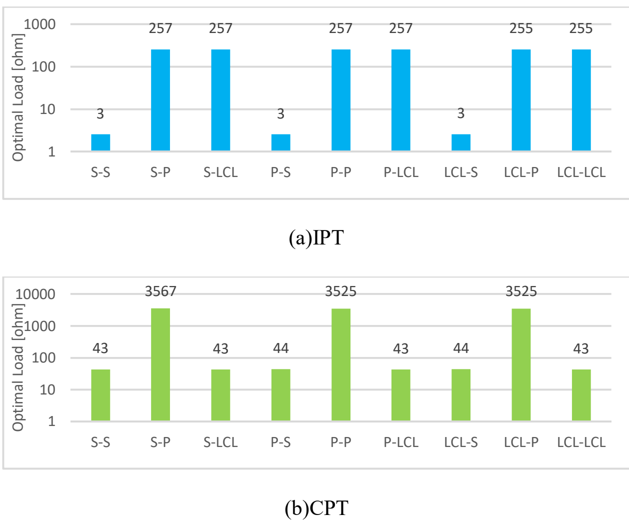


Fig. 7 Optimal Load

TABLE VIII. OPTIMAL LOAD UNDER APPROXIMATE CONDITION

	Transmitter	Receiver	Optimal Load
IPT		S	$r\sqrt{1+k^2Q^2}$
CPT		S, LCL	
IPT		P, LCL	$\frac{Q^2r}{\sqrt{1+k^2Q^2}}$
CPT		P	

Assuming that the Q value and internal resistance of all coils are the same, optimal load value in Table 4 can be approximated using (6) as shown in Table 8. Furthermore, when $\boldsymbol{k^2Q^2}$ is sufficiently large relative to 1, the ratio of optimal load can be approximated as in (7), which means that the smaller optimal load is $\boldsymbol{k^2}$ times the value of the larger optimal load.

$$1+k^2 \approx 1-k^2 \approx 1, 1+Q^2 \approx 1-Q^2 \approx Q^2 \tag{6}$$

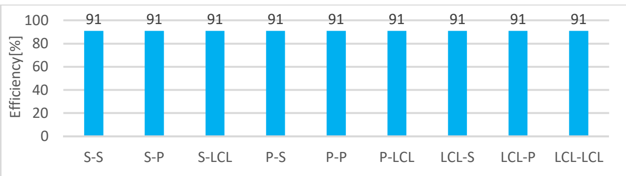
$$r\sqrt{1+k^2Q^2} : \frac{Q^2r}{\sqrt{1+k^2Q^2}} \approx k^2 : 1 \tag{7}$$

Therefore, for highly efficient transmission, the circuit must be appropriately selected according to the value of the load.

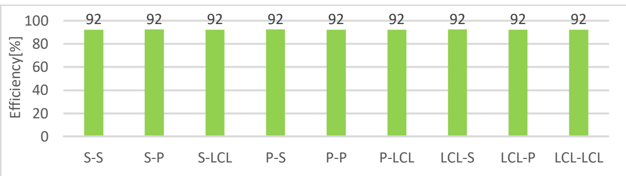
B. Maximum Efficiency

Fig. 8 shows the results of maximum efficiency. The results are similar for all circuits regardless of IPT or CPT. Also, using the approximation of (6) for the efficiency equation in Table 3, the maximum efficiency of all circuits for both IPT and CPT can be expressed as in (8). Therefore, the result is the same regardless of which circuit is selected, whether IPT or CPT, in terms of maximum efficiency.

$$\eta_{max}^{All\ circuits} = \frac{k^2Q^2}{\left(1+\sqrt{1+k^2Q^2}\right)^2} \tag{8}$$



(a)IPT



(b)CPT

Fig .8 Maximum Efficiency

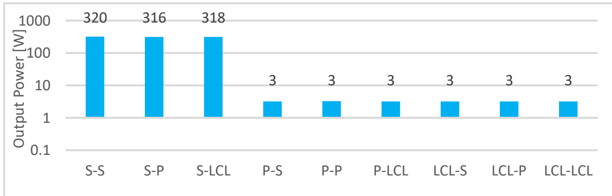
C. Output Power with Voltage Source

Fig. 9 shows the results for the output power with voltage source using the optimal load. For IPT, the transmitter S such as S-S, S-P and S-LCL get larger power than the transmitter P or LCL. For CPT, the transmitter S or LCL such as S-S, S-P, S-LCL, LCL-S, LCL-P and LCL-LCL get larger power than the transmitter P. Also, IPT get more power than CPT. As the Q value and coupling factor k of the parameters used in this study are the same, there is a difference in the magnitude of output power between IPT and CPT due to the internal resistance of the coil.

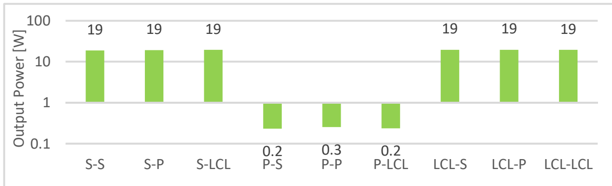
Assuming that the Q value and internal resistance of all coils are the same, the output power equation in Table 5 can be approximated using (6) as shown in Table 9. Furthermore, when k^2Q^2 is enough large relative to 1, the ratio of output power can be approximated as in (9), which shows that the larger power is $1/k^2$ times larger than the smaller power.

$$\frac{k^2Q^2}{r\sqrt{1+k^2Q^2}\left(1+\sqrt{1+k^2Q^2}\right)^2}|V_{in}|^2 : \frac{k^2\sqrt{1+k^2Q^2}}{r\left(1+\sqrt{1+k^2Q^2}\right)^2}|V_{in}|^2 = 1 : k^2 \tag{9}$$

Therefore, to get large power, the circuit on the transmitter S should be selected for IPT and the circuit on the transmitter side S or LCL should be selected for CPT.



(a)IPT



(b)CPT

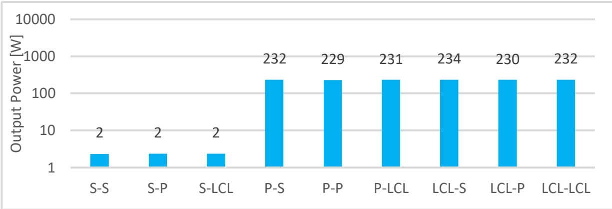
Fig. 9 Output Power Connecting Voltage Source

TABLE IX. OUTPUT POWER WITH VOLTAGE SOURCE UNDER APPROXIMATE CONDITION

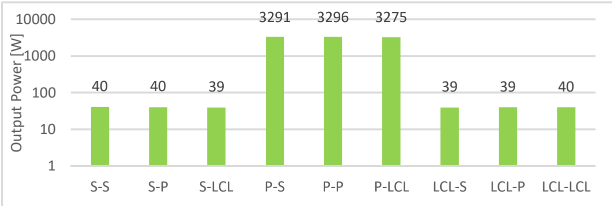
	Transmitter	Receiver	Optimal Load
IPT	S		$\frac{k^2Q^2}{r\sqrt{1+k^2Q^2}\left(1+\sqrt{1+k^2Q^2}\right)^2}\|V_{in}\|^2$
CPT	S, LCL		
IPT	P, LCL		$\frac{k^2\sqrt{1+k^2Q^2}}{r\left(1+\sqrt{1+k^2Q^2}\right)^2}\|V_{in}\|^2$
CPT	P		

D. Output Power with Current Source

Fig. 10 shows the results for the output power with current source using optimal load. For IPT, the transmitter P or LCL such as P-S, P-P, P-LCL, LCL-S, LCL-P and LCL-LCL get larger power than the transmitter S. For CPT, the transmitter P such as P-S, P-P, and P-LCL get larger power than the transmitter S or LCL. Also, CPT get more power than IPT. Since the Q value and coupling factor the parameters used in this study are the same, the internal resistance of the coils has an effect on the magnitude of the power as the output power with voltage source.



(a)IPT



(b)CPT

Fig. 10gi Output Power with Current Source

TABLE X. OUTPUT POWER WITH CURRENT SOURCE UNDER APPROXIMATE CONDITION

	Transmitter	Receiver	Optimal Load
IPT	S		$\frac{k^2Q^2r\sqrt{1+k^2Q^2}}{\left(1+\sqrt{1+k^2Q^2}\right)^2}\lvert I_{in}\rvert^2$
CPT	S, LCL		
IPT	P, LCL		$\frac{k^2Q^4r}{\sqrt{1+k^2Q^2}\left(1+\sqrt{1+k^2Q^2}\right)^2}\lvert I_{in}\rvert^2$
CPT	P		

Assuming that the Q value and internal resistance of all coils are the same, the output power equation in Table 6 can be approximated using (6) as shown in Table 10. Furthermore, when k^2Q^2 is sufficiently large with respect to 1, the ratio of output power with current source can be approximated as in equation (10), which shows that the larger power is $1\,/\,k^2$ times larger than the smaller power.

$$\frac{k^2Q^2r\sqrt{1+k^2Q^2}}{\left(1+\sqrt{1+k^2Q^2}\right)^2}\lvert I_{in}\rvert^2 : \frac{k^2Q^4r}{\sqrt{1+k^2Q^2}\left(1+\sqrt{1+k^2Q^2}\right)^2}\lvert I_{in}\rvert^2 = k^2 : 1 \quad (10)$$

Therefore, to get large power, the circuit on the transmitter P or LCL should be selected for IPT and the circuit on the transmitter side P should be selected for CPT.

VI. CONCLUSION

By calculating equations for the power transmission characteristics and comparing the characteristics, the differences between IPT and CPT circuits were clarified as the following. The resonance conditions of S-P, P-S and P-P in IPT and S-S, S-P and P-S in CPT vary depending on the coupling factor. As for the optimal load, the receiver S in IPT is about k^2 times smaller than other circuits. For CPT, the value of optimal load with the receiver S or LCL is about k^2 times smaller than other circuits, so the circuits should be selected according to the value of the load for high efficiency transmission. As for the maximum efficiency, the efficiency does not depend on the transmission method or circuit, since it is the same for all circuits for both IPT and CPT. In terms of output power with voltage source, the transmitter S in IPT and the transmitter S or LCL in CPT can get larger values, respectively. In terms of output power with current source, it was found that the transmitter P or LCL in IPT and the transmitter P can get larger values. Therefore, in order to get larger power, the appropriate circuit should be selected depending on the method of transmission, transmitter circuit and power source. Based on the above, it was verified that LCL in IPT was same characteristic as S, but LCL in CPT was same characteristic as P. In this paper, the design theory was made for optimal method and circuit selection by fairly evaluating representative circuits of both IPT and CPT methods under unified conditions.

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