Characteristic Comparison of 16 Circuits for Inductive Power Transfer

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***Abstract*— Past research on circuits for wireless power transfer was limited to the target applications or the compared circuits. Therefore, this study comprehensively compared the characteristics of 16 circuits by combining four circuits S, P, LCL and LCC on the transmitter and receiver sides. In addition, the equations for calculating the efficiency, Maximum Efficiency Load (MEL), output power, Maximum Power Load (MPL), and current for magnetic field review were derived. It was found that the efficiency of all circuits with MEL is independent of the circuit. It was also found that MEL became larger when the receiver side was P or LCL, and smaller when the receiver side was S. It was also found that the efficiency of all circuits with MPL is common the case that the coupling is small, but the case that it is large, high efficiency is obtained in P on the transmitter side such as S-P, P-S, P-P, P-LCL, and P-LCC. Therefore, it can be said that for high efficiency transfer, the circuit should be selected according to the value of the load. Since the output power of S on the transmitter circuit such as S-S, S-P, S-LCL, and S-LCC can get large power in all patterns regardless of MEL and MPL, so selecting S for the transmitter circuit is suitable for getting large power, but has the disadvantage of high current flow the case that the coupling is 0. On the other hand, the transmitter side P, LCL, and LCC have the advantage that large current does not flow even the coupling is zero, and since LCC on the transmitter side gets relatively large power, it is also appropriate to select LCC on the transmitter side according to the purpose. In the case of small coupling, the efficiency and output power with MEL and with MPL were found to be close. For the current value, there is no difference in the current value depending on the circuit with MEL, but with MPL, the ratio of the current flowing in the transmitter coil to that in the receiver coil differs depending on the circuit. From the above characteristics, the LCC on the transmitter side with MEL is suitable for symmetric coils with large coupling and asymmetric coils with smaller transmitter coil, while S on the transmitter side with MPL is suitable for symmetric coils with small coupling and asymmetric coils with smaller receiver coils. On the receiver side, the choice should depend on the value of the load.**

Keywords*— *Wireless Power Transfer, Comparison, Circuit, Maximum Power Load, Efficiency, Maximum Efficiency Load, Output Power, Current, Magnetic Field

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).

A typical circuit for Inductive Power Transfer (IPT) has four circuits such as S, P LCL, and LCC. S is the circuit that a capacitor is connected in series with the transmitter coil, P is the circuit that a capacitor is connected in parallel with the transmitter coil, LCL is the circuit that an additional coil is placed ahead of P and LCC is the circuit that another capacitor is placed in series with the transmitter coil of LCL. The advantages of LCL is discussed; consider the case that there is no receiver side, with $k = 0$ characteristic. For the transmitter circuit is S, input impedance is only the internal resistance of the coil due to series resonance, so a large current flows, which is dangerous. However, for the transmitter side is LCL or LCC, input impedance ideally becomes infinite, and there is the advantage that a large current does not flow even $k = 0$, and it is safe. The advantage of LCC circuit is that although the number of components increases compared to LCL, the inductance of the additional coils can be reduced, allowing for greater design flexibility.

There is the paper that compare for symmetric coils in IPT [1], some papers that compare circuits for electric vehicles [2], [3],[4] and implantable medical devices [5], and some papers that compare multiple circuits from various perspectives [6]-[9]. These studies have only one target application or are limited in the compared circuits. Therefore, this study comprehensively compares the transfer characteristics such as efficiency, Maximum Efficiency Load (MEL), output power, Maximum Power Load MPL) of 16 circuits, with S, P, LCL, and LCC as the transmitter side and receiver side. Furthermore, the currents flowing in the transmitter coil $|I_1|$ and the current flowing in receiver coil $|I_2|$ are compared. $|I_1|$ and $|I_2|$ mentioned here are obtained for the evaluation of the magnetic field, because he impact of magnetic fields on the surrounding human body and electronic equipment is often discussed in IPT and the magnetic field is proportional to the current from Biot-Savart Low. In addition, a comparison is made used between the case with MEL to get maximum efficiency and the case with MPL to get maximum power is used to clarify the difference in characteristics depending on the load. Furthermore, by setting different Q values and coupling factors, characteristics in each circuit are compared in multiple patterns, to make the design theory for selecting the optimal circuit for various applications.

II. DERIVATION OF EQUATION

The equations of the characteristics are derived, for 16 circuits as shown in Table 1. First of all, the design condition equation of the compensating element is designed by gyrator characteristics or ideal transformer characteristics. Gyrator characteristic is a design method that satisfies $A = D = 0$ in F parameter in shown (1), and the ideal transformer characteristic is a design method that satisfies $B = C = 0$ in F parameter. The equation obtained from the above characteristic conditions is shown in (2). Note that, $\omega_0$is the resonance angular frequency, L is a coil inductance and C is a resonance capacitance.

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

$$\omega_0 = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} = \frac{1}{\sqrt{L_0 C_1}} = \frac{1}{\sqrt{L_0' C_2}} = \frac{1}{\sqrt{L_1 \frac{C_{1s} C_{1P}}{C_{1s} + C_{1p}}}} = \frac{1}{\sqrt{L_2 \frac{C_{2s} C_{2P}}{C_{2s} + C_{2p}}}} \quad (2)$$

Next, using the element values obtained in (2), the equations for each characteristic are derived. Note that, Q is used as an indicator of the performance of the coil, $Q = \omega L / r$. The results of efficiency and Maximum Efficiency Load (MEL) are shown in Table 2 and 3. The results of the output power and Maximum Power Load (MPL) are shown in Table 4 and 5. Table 6. shows the results of deriving the equations for calculating the current in the transmitter coil $|I_1|$ and in the receiver coil $|I_2|$. Note that, LCL are omitted in Table 2-6 because the equations of LCL can be calculated by setting $Q_0 = Q_1, r_0 = r_1, Q_0' = Q_2, r_0' = r_2$ in the equations of LCC.

TABLE I. COMPARED CIRCUIT

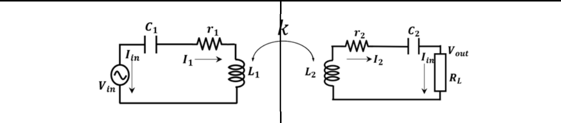
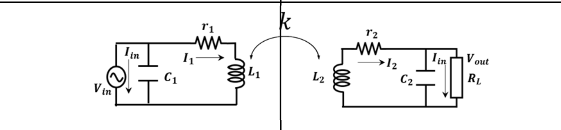
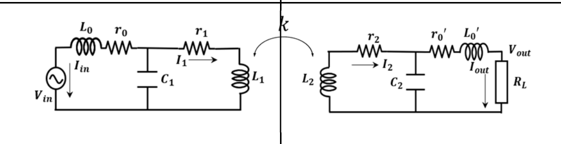
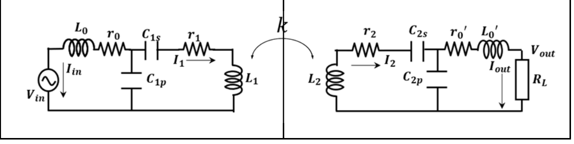
	Transmitter	Receiver
S		
P		
LCL		
LCC		

TABLE II. EQUATION OF EFFICIENCY

Circuit	Efficiency
S-S, P-S	$\frac{k^2 Q_1 Q_2 r_2 R_L}{\{(1+k^2Q_1Q_2)r_2 + R_L\}(r_2 + R_L)}$
S-P, P-P	$\frac{k^2 Q_1 Q_2^3 r_2 R_L}{(1 + Q_2^2 + k^2 Q_1 Q_2) Q_2^2 r_2 (r_2 + R_L) + (1 + k^2 Q_1 Q_2) R_L^2}$
LCC-S (LCL-S)	$\frac{k^2 Q_0^2 Q_1 Q_2 r_0 r_2 R_L}{\{(1+k^2Q_1Q_2)r_2 + R_L\}[\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}r_2 + (Q_0^2 r_0 + r_1)R_L]}$
LCC-P (LCL-P)	$\frac{k^2 Q_0^2 Q_1 Q_2^3 r_0 r_2 R_L}{\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}\{(1+k^2Q_1Q_2)(Q_2^2 r_2^2 + R_L^2) + Q_2^2 r_2 R_L\} + (r_1 + Q_0^2 r_0) Q_2^2 r_2 \{Q_2^2 r_2 + (1+k^2Q_1Q_2)R_L\}}$
S-LCC, P-LCC (S-LCL, PLCL)	$\frac{k^2 Q_0'^2 Q_1 Q_2 r_0'^2 r_2 R_L}{\{(r_2 + Q_0'^2 r_0')r_2 + r_2 R_L\}[\{(1+k^2Q_1Q_2)r_2 + Q_0'^2 r_0'\}r_0' + (1+k^2Q_2Q_2)r_2 R_L]}$
doubleLCC (LCL-LCL) (LCL-LCC) (LCC-LCL)	$\frac{k^2 Q_0^2 Q_1 Q_2 Q_0'^2 r_0 r_2 r_0'^2 R_L}{[\{(1+k^2Q_1Q_2)r_2 + Q_0'^2 r_0'\}r_0' + (1+k^2Q_1Q_2)r_2 R_L][\{(r_1 + Q_0^2 r_0)(r_2 + Q_0'^2 r_0') + k^2 Q_1 Q_2 r_1 r_2\}r_0' + \{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}R_L]}$

TABLE III. EQUATION OF MAXIMUM EFFICIENCY LOAD

Circuit	Maximum Efficiency Load
S-S, P-S	$r_2\sqrt{1 + k^2 Q_1 Q_2}$
S-P, P-P	$r_2\sqrt{\frac{1 + Q_2^2 + k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2}}$
LCC-S (LCL-S)	$r_2\sqrt{\frac{(1+k^2Q_1Q_2)\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}}{r_1 + Q_0^2 r_0}}$
LCC-P (LCL-P)	$Q_2 r_2\sqrt{\frac{(1+k^2Q_1Q_2)\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\} + Q_2^2(r_1 + Q_0^2 r_0)}{(1+k^2Q_1Q_2)\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}}}$
S-LCC, P-LCC (S-LCL, PLCL)	$\frac{r_0'}{r_2}\sqrt{\frac{(r_2 + Q_0'^2 r_0')\{(1+k^2Q_1Q_2)r_2 + Q_0'^2 r_0'\}}{1 + k^2 Q_1 Q_2}}$
doubleLCC (LCL-LCL) (LCL-LCC) (LCC-LCL)	$\frac{r_0'}{r_2}\sqrt{\frac{\{(1+k^2Q_1Q_2)r_2 + Q_0'^2 r_0'\}r_0'\{(r_1 + Q_0^2 r_0)(r_2 + Q_0'^2 r_0') + k^2 Q_1 Q_2 r_1 r_2\}}{(1+k^2Q_1Q_2)\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}}}$

TABLE IV. EQUATION OF OUTPUT POWER

Circuit	Output Power
S-S	$\frac{k^2 Q_1 Q_2 r_2 R_L}{r_1\{(1+k^2Q_1Q_2)r_2 + R_L\}^2}\lvert V_{in}\rvert^2$
P-S	$\frac{k^2 Q_1 Q_2^3 r_2 R_L}{r_1[\{Q_2^2 r_2 + (1+k^2Q_1Q_2)R_L\}^2 + (1+k^2Q_1Q_2)^2 Q_2^2 r_2^2]}\lvert V_{in}\rvert^2$
S-P	$\frac{k^2 Q_1 Q_2 r_2 R_L}{r_1[\{(1+k^2Q_1Q_2)r_2 + R_L\}^2 + Q_1^2(r_2 + R_L)^2]}\lvert V_{in}\rvert^2$
P-P	$\frac{k^2 Q_1 Q_2^3 r_2 R_L}{r_1\left[\{(Q_1+Q_2)r_2 + (1+k^2Q_1Q_2)R_L\}^2 + [\{1-(1-k^2)^2 Q_1 Q_2\}Q_2 r_2 - Q_1 R_L]^2\right]}\lvert V_{in}\rvert^2$
LCC-S (LCL-S)	$\frac{k^2 Q_0^2 Q_1 Q_2 r_1 r_2 R_L}{[\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}r_2 + (Q_0^2 r_0 + r_1)R_L]^2}\lvert V_{in}\rvert^2$
LCC-P (LCL-P)	$\frac{k^2 Q_0^2 Q_1 Q_2^3 r_1 r_2 R_L}{[(Q_0^2 r_0 + r_1)Q_2^2 r_2 + \{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}R_L]^2 + Q_2^2 r_2\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}^2}\lvert V_{in}\rvert^2$
S-LCC (S-LCL)	$\frac{k^2 Q_0'^2 Q_1 Q_2 r_0' r_2 R_L}{r_1[\{(1+k^2Q_1Q_2)r_2 + Q_0'^2 r_0'\}r_0' + (1+k^2Q_1Q_2)r_2 R_L]^2}\lvert V_{in}\rvert^2$
P-LCC (P-LCL)	$\frac{k^2 Q_1 Q_2 Q_0'^2 r_2 r_0' R_L}{r_1[\{(1+k^2Q_1Q_2)r_2(r_0' + R_L) + Q_0'^2 r_0'^2\}^2 + Q_1^2\{r_2(r_0' + R_L) + Q_0'^2 r_0'^2\}^2]}\lvert V_{in}\rvert^2$
doubleLCC (LCL-LCL) (LCL-LCC) (LCC-LCL)	$\frac{k^2 Q_0^2 Q_1 Q_2 Q_0'^2 r_0 r_1 r_2 R_L}{r_0\left[\{(Q_0^2 r_0 + r_1)(r_2 + Q_0'^2 r_0') + k^2 Q_1 Q_2 r_1 r_2\}r_0' + \{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}r_2 R_L\right]^2}\lvert V_{in}\rvert^2$

TABLE V. EQUATION OF MAXIMUM POWER LOAD

Circuit	Maximum Power Load
S-S	$r_2(1 + k^2 Q_1 Q_2)$
P-S	$\sqrt{\frac{(1+k^2Q_1Q_2)^2 + Q_1^2}{1 + Q_1^2}}$
S-P	$\frac{Q_2 r_2\sqrt{(1+k^2Q_1Q_2)^2 + Q_2^2}}{1 + k^2 Q_1 Q_2}$
P-P	$r_2\sqrt{\frac{(Q_1+Q_2)^2 + \{1-(1-k^2)Q_1Q_2\}^2 Q_2^2}{(1+k^2Q_1Q_2)^2 + Q_1^2}}$
LCC-S (LCL-S)	$\frac{\{(1+k^2Q_1Q_2)r_1 + Q_0^2 r_0\}r_2}{Q_0^2 r_0 + r_1}$
LCC-P (LCL-P)	$\frac{Q_2 r_2\sqrt{(r_1 + Q_0^2 r_0)^2 Q_2^2 + \{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}^2}}{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1}$
S-LCC (S-LCL)	$\frac{\{(1+k^2Q_1Q_2)r_2 + Q_0'^2 r_0'\}r_0'}{(1+k^2Q_1Q_2)r_2}$
P-LCC (P-LCL)	$\frac{r_0'}{r_2}\sqrt{\frac{\{(1+k^2Q_1Q_2)r_2 + Q_0'^2 r_0'^2\}^2 + Q_1^2(r_2 + Q_0'^2 r_0')^2}{(1+k^2Q_1Q_2)^2 + Q_1^2}}$
doubleLCC (LCL-LCL) (LCL-LCC) (LCC-LCL)	$\frac{\{(r_1 + Q_0^2 r_0)(r_2 + Q_0'^2 r_0') + k^2 Q_1 Q_2 r_1 r_2\}r_0'}{\{Q_0^2 r_0 + (1+k^2Q_1Q_2)r_1\}r_2}$

TABLE VI. EQUATION OF CURRENT

Circuit	Current in Transmitter Coil $\lvert I_1\rvert$	Current in Receiver Coil $\lvert I_2\rvert$
S-S	$\frac{1}{r_1}\frac{r_2+R_L}{(1+k^2Q_1Q_2)r_2+R_L}\lvert V_{in}\rvert$	$\frac{1}{r_1}\frac{\sqrt{k^2Q_1Q_2r_1r_2}}{(1+k^2Q_1Q_2)r_2+R_L}\lvert V_{in}\rvert$
P-S	$\frac{1}{r_1}\sqrt{\frac{(Q_2^2r_2^2+R_L^2+Q_2^2r_2R_L)^2+Q_2^6r_2^4}{\{(1+k^2Q_1Q_2)(Q_2^2r_2^2+R_L^2)+Q_2^2r_2R_L\}^2+Q_2^6r_2^4}}\lvert V_{in}\rvert$	$\frac{Q_2^2r_2^2+R_L^2}{r_1r_2}\sqrt{\frac{k^2Q_1Q_2r_1r_2}{\{(1+k^2Q_1Q_2)(Q_2^2r_2^2+R_L^2)+Q_2^2r_2R_L\}^2+Q_2^6r_2^4}}\lvert V_{in}\rvert$
S-P	$\frac{1}{r_1}\frac{r_2+R_L}{\sqrt{\{(1+k^2Q_1Q_2)r_2+R_L\}^2+Q_1^2(r_2+R_L)^2}}\lvert V_{in}\rvert$	$\frac{1}{r_1}\sqrt{\frac{k^2Q_1Q_2r_1r_2}{\{(1+k^2Q_1Q_2)r_2+R_L\}^2+Q_1^2(r_2+R_L)^2}}\lvert V_{in}\rvert$
P-P	$\frac{1}{r_1}\sqrt{\frac{[\{Q_2^2r_2(r_2+R_L)+R_L^2\}^2+Q_2^6r_2^4]}{\{Q_2^2r_2^2(1-Q_1Q_2+k^2Q_1Q_2)+(1+k^2Q_1Q_2)R_L^2+Q_2^2r_2R_L\}^2+\{Q_2^3r_2^2+Q_1(Q_2^2r_2^2+R_L^2+Q_2^2r_2R_L)\}^2}}\lvert V_{in}\rvert$	$\frac{Q_2^2r_2^2+R_L^2}{r_1r_2}\sqrt{\frac{k^2Q_1Q_2r_1r_2}{\{Q_2^2r_2^2(1-Q_1Q_2+k^2Q_1Q_2)+(1+k^2Q_1Q_2)R_L^2+Q_2^2r_2R_L\}^2+\{Q_2^3r_2^2+Q_1(Q_2^2r_2^2+R_L^2+Q_2^2r_2R_L)\}^2}}\lvert V_{in}\rvert$
LCC-S (LCL-S)	$\frac{Q_0(r_2+R_L)}{\{Q_0^2r_0+(1+k^2Q_1Q_2)r_1\}r_2+(Q_0^2r_0+r_1)R_L}\lvert V_{in}\rvert$	$\frac{Q_0\sqrt{k^2Q_1Q_2r_1r_2}}{\{Q_0^2r_0+(1+k^2Q_1Q_2)r_1\}r_2+(Q_0^2r_0+r_1)R_L}\lvert V_{in}\rvert$
LCC-P (LCL-P)	$Q_0\sqrt{\frac{(Q_2^2r_2^2+R_L^2+Q_2^2r_2R_L)^2+Q_2^6r_2^4}{[\{Q_0^2r_0+(1+k^2Q_1Q_2)r_1\}(Q_2^2r_2^2+R_L^2)+Q_2^2(Q_0^2r_0+r_1)r_2R_L]^2+Q_2^6(Q_0^2r_0+r_1)^2r_2^4}}\lvert V_{in}\rvert$	$\frac{Q_2^2r_2^2+R_L^2}{r_2}\sqrt{\frac{k^2Q_0^2Q_1Q_2r_1r_2}{[\{Q_0^2r_0+(1+k^2Q_1Q_2)r_1\}(Q_2^2r_2^2+R_L^2)+Q_2^2(Q_0^2r_0+r_1)r_2R_L]^2+Q_2^6(Q_0^2r_0+r_1)^2r_2^4}}\lvert V_{in}\rvert$
S-LCC (S-LCL)	$\frac{1}{r_1}\frac{r_2(r_0'+R_L)+Q_0'r_0'^2}{\{(1+k^2Q_1Q_2)r_2+Q_0'r_0'\}r_0'+(1+k^2Q_1Q_2)r_2R_L}\lvert V_{in}\rvert$	$\frac{r_2+R_L}{r_1}\frac{\sqrt{k^2Q_1Q_2r_1r_2}}{\{(1+k^2Q_1Q_2)r_2+Q_0'r_0'\}r_0'+(1+k^2Q_1Q_2)r_2R_L}\lvert V_{in}\rvert$
P-LCC (P-LCL)	$\frac{1}{r_1}\frac{r_2(r_0'+R_L)+{r_0'}^2}{\sqrt{[\{(1+k^2Q_1Q_2)r_2+Q_0'^2r_0'\}r_0'+(1+k^2Q_1Q_2)r_2R_L]^2+Q_1^2\{(r_2+Q_0'^2r_0')r_0'+r_2R_L\}^2}}\lvert V_{in}\rvert$	$\frac{r_0'+R_L}{r_1}\sqrt{\frac{k^2Q_1Q_2r_1r_2}{[\{(1+k^2Q_1Q_2)r_2+Q_0'^2r_0'\}r_0'+(1+k^2Q_1Q_2)r_2R_L]^2+Q_1^2\{(r_2+Q_0'^2r_0')r_0'+r_2R_L\}^2}}\lvert V_{in}\rvert$
doubleLCC (LCL-LCC) (LCC-LCL)	$\frac{Q_0\{r_2(r_0'+R_L)+Q_0'^2r_0'^2\}}{\{(r_1+Q_0^2r_0)(r_2+Q_0'^2r_0')+k^2Q_1Q_2r_1r_2\}r_0'+\{(1+k^2Q_1Q_2)r_1+Q_0^2r_0\}r_2R_L}\lvert V_{in}\rvert$	$\frac{(r_0'+R_L)\sqrt{k^2Q_0^2Q_1Q_2r_1r_2}}{\{(r_1+Q_0^2r_0)(r_2+Q_0'^2r_0')+k^2Q_1Q_2r_1r_2\}r_0'+\{(1+k^2Q_1Q_2)r_1+Q_0^2r_0\}r_2R_L}\lvert V_{in}\rvert$

III. SIMULATION

Using FEKO, which analyzes electromagnetic fields using MoM method, verified that the equations obtained in Chapter 2 were correct. The coil used in the analysis was shown in Fig. 1, and the parameters used in the analysis were shown in Table 7. The results of the analysis and calculations were in agreement with each other as shown in Fig. 2-3, which could confirm that the equations were correct.

TABLE VII. SIMULATION PARAMETER

Description	Symbol	Value	
Resonant Frequency	f	85 kHz	
Voltage Source	V_{in}	30 V	
Coupling Factor	k	0.03	
Inductance	L_1, L_2	51.85 µH, 4.95 µH	
Internal Resistance	r_1, r_2	0.12 Ω, 0.02 Ω	
Capacitance	C_1, C_2	67.62 nF, 707.61 nF	
Q value	Q_1, Q_2	230.95, 121.27	
		LCL	LCC
Inductance	L_0, L_0'	51.85 µH,4.95 µH	18.72 µH, 0.94 µH
Internal Resistance	r_0, r_0'	0.12 ohm, 0.02 ohm	0.10 ohm, 0.01 ohm
Capacitance	C_{1p}, C_{2p}	67.62 nF, 707.61 nF	187.34 nF, 3.74 µF
	C_{1s}, C_{2s}		105.84 nF 873.47 nF
Q value	Q_0, Q_0'	231.02, 121.27	100, 50

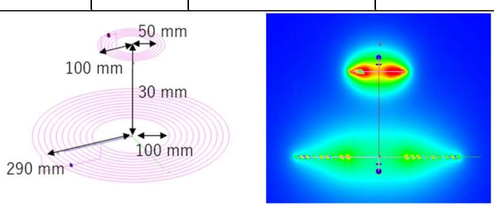


Fig. 1 Electromagnetic Simulation

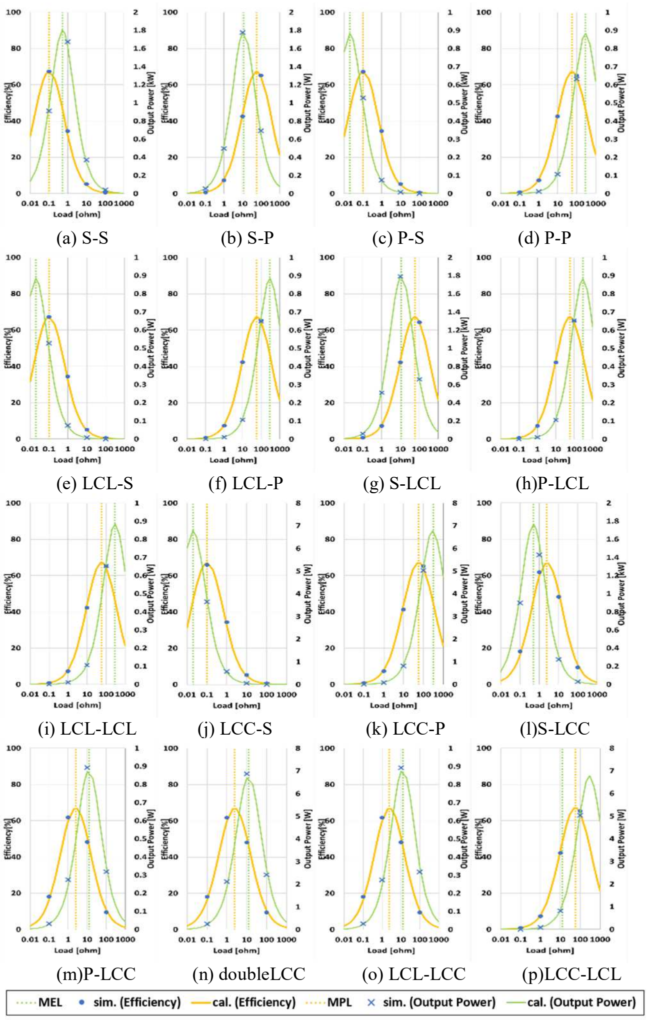


Fig. 2 Efficiency and Output Power

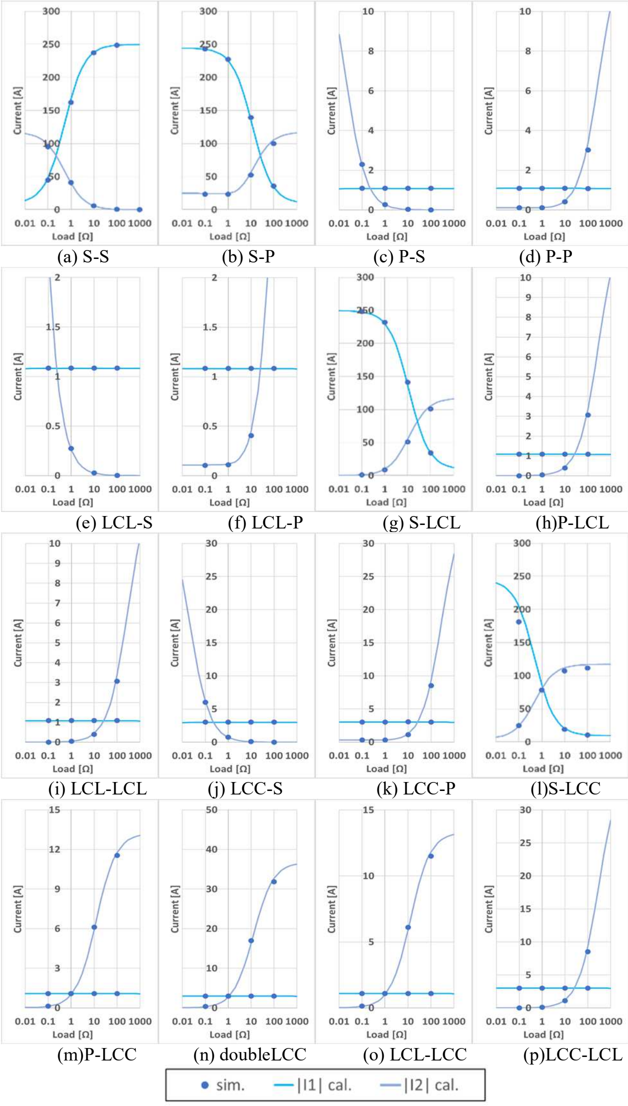


Fig. 3 Current

IV. Characteristic Comparison

The parameters of the Q value and coupling factor as shown in Table 8. were calculated by FEKO using coils of different sizes from Patterns 1-5. Patterns 1 and 2 are basic symmetrical coils, and the coupling factors are set to 0.1 and 0.01 considering the distance between the transmitter and the receiver coils in the two patterns. Patterns 3 and 4 are the case one coil is the same size as Patterns 1 and 2 and the other coil is smaller, and the values are set. Pattern 5 is the case that uses symmetry both coils are smaller than Pattern 1 and 2. Although the characteristics of LCC vary depending on the design, this time the Q value is set at about half that of the transmitter coil for the sake of comparison.

For the above 5 patterns, put the values of from Table 8. into the equations of Table 2-6, and used the specific values to calculate the maximum efficiency, MEL, output power, MPL, and the current value of the current flowing through the transmitter and receiver coil. The results were shown in Fig. 5 and Table 9. The current value was mentioned here, since the magnetic field and the power are proportional to the power of the square, in order to make a fair judgment, the value of the voltage source was derived from the output power equation in Table 3 assuming output power of 10 W.

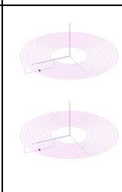
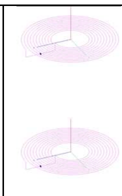
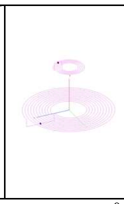
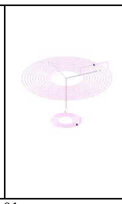
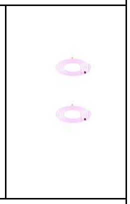
A. Maximum Efficiency Load (MEL)

The result of MEL were shown in Fig. 4. The comparison of the MEL values for the circuits showed that the values were small that the receiver side was S and large that the receiver side was P and LCL. Therefore, high-efficiency transfer is achieved by selecting the receiver circuit according to the value of the load.

B. Maximum Power Load (MPL)

The result of MEL were shown in Fig. 5. As for the value of MPL, it is classified by the configuration of the circuit on the receiver side, the value was vary, so more power can be got by selecting the circuit on both the transmitter and receiver sides according to the value of the load.

TABLE VIII. Parameter of Pattern

	Pattern 1 ($Q_1 = Q_2$)	**Pattern 2** ($Q_1 = Q_2$)	**Pattern 3** ($Q_1 > Q_2$)	**Pattern 4** ($Q_1 < Q_2$)	**Pattern 5** ($Q_1 = Q_2$)
f_0	85 kHz				
V_{in}	10 V				
					
k	0.1	0.01			
Q_1	231.02	231.02	121.27	231.02	121.27
Q_2	231.02	231.02	231.02	121.27	121.27
Q_0	100	100	50	100	50
Q_0'	100	100	100	50	50
r_1	0.12 ohm	0.12 ohm	0.02 ohm	0.12 ohm	0.02 ohm
r_2	0.12 ohm	0.12 ohm	0.12 ohm	0.02 ohm	0.02 ohm
r_0	0.10 ohm	0.10 ohm	0.01 ohm	0.10 ohm	0.01 ohm
r_0'	0.10 ohm	0.10 ohm	0.10 ohm	0.01 ohm	0.01 ohm

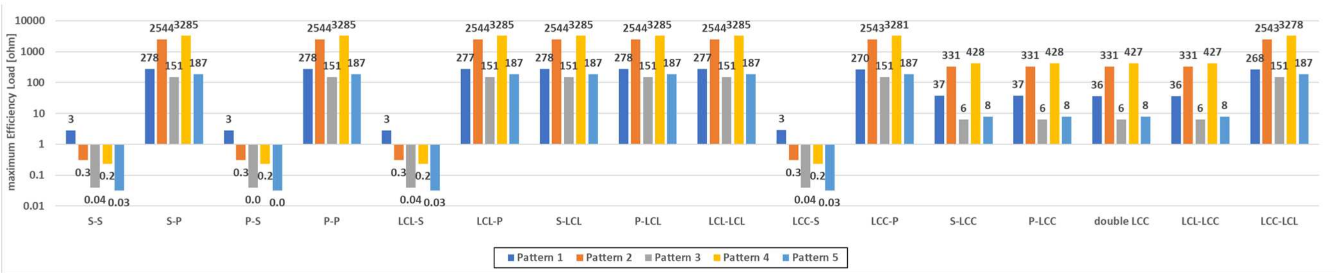


Fig. 4 Maximum Efficiency Load

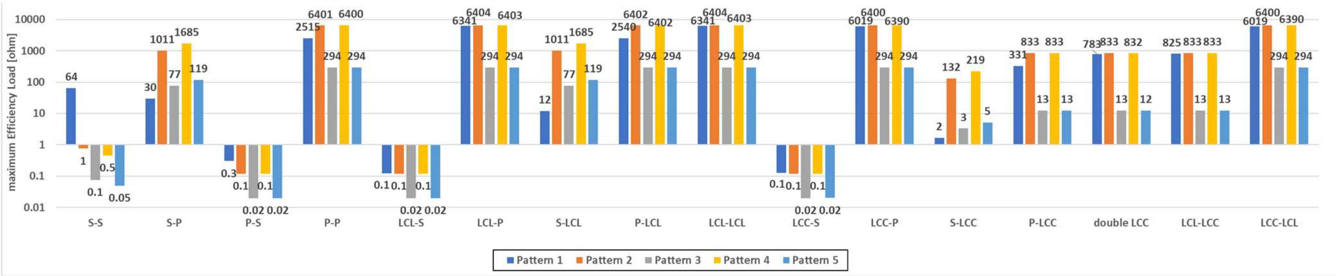


Fig. 5 Maximmum Power Load

V. Characteristic Comparison

		Circuit		$k = 0$	Efficiency	Output Power	Current	Evaluation
		Transmitter	Receiver					
Pattern 1	MEL	S	Anything	× Large Current	✓91-92%	✓32-33 W	✓$\lvert I_1\rvert = \lvert I_2\rvert$ =2 A	—
		P, LCL		✓Small Current		0.3 W		—
		LCC				✓2-3 W		✓
	MPL	S	P	× Large Current	✓70%	✓118 W	$\lvert I_1\rvert = 6$ A, $\lvert I_2\rvert = 0.9$ A	✓
			S, LCL, LCC		50%	✓208 W	$\lvert I_1\rvert = 9$ A, $\lvert I_2\rvert = 0.4$ A	×
		P	Anything	✓Small Current	71%	✓1-2 W	$\lvert I_1\rvert = 0.8$- 0.9 A, $\lvert I_2\rvert = 6$ A	—
		LCL			50%		$\lvert I_1\rvert = 0.8$- 0.9 A, $\lvert I_2\rvert = 9$ A	—
		LCC				✓15 W		×
Pattern 2	MEL	S	Anything	× Large Current	43%	✓143 W	$\lvert I_1\rvert = 9$ A, $\lvert I_2\rvert = 6$ A	—
		P, LCL		✓Small Current		×0.02 W		—
		LCC				0.1 W		—
	MPL	S		× Large Current	36%	✓175 W	✓$\lvert I_1\rvert = 12$ A, $\lvert I_2\rvert = 4$ A	✓
		P, LCL		✓Small Current		×0.02W	$\lvert I_1\rvert = 8$ A, $\lvert I_2\rvert = 9$ A	×
		LCC				0.2 W		×
Pattern 3	MEL	S	Anything	× Large Current	32%	✓137-138 W	$\lvert I_1\rvert = 12$ A, $\lvert I_2\rvert = 16$ A	✓
		P, LCL		✓Small Current		×0.01 W		×
		LCC				×0.08 W		×
	MPL	S		× Large Current	29%	✓153-154 W	$\lvert I_1\rvert = 13$ A, $\lvert I_2\rvert = 11$- 12 A	✓
		P, LCL		✓Small Current		×0.01 W	$\lvert I_1\rvert = 11$ A, $\lvert I_2\rvert = 22$- 23 A	×
		LCC				×0.08 W		×
Pattern 4	MEL	S	Anything	× Large Current	32%	✓826 W	$\lvert I_1\rvert = 28$ A, $\lvert I_2\rvert = 7$ A	—
		P, LCL		✓Small Current		0.2 W		×
		LCC				✓5 W		✓
	MPL	S		× Large Current	29%	✓921 W	$\lvert I_1\rvert = 33$ A, $\lvert I_2\rvert = 5$ A	—
		P, LCL		✓Small Current		0.2 W	$\lvert I_1\rvert = 27$ A, $\lvert I_2\rvert = 9$ A	×
		LCC				✓6 W		✓
Pattern 5	MEL	S	Anything	× Large Current	22%	✓706-707 W	$\lvert I_1\rvert = 38$ A, $\lvert I_2\rvert = 18$ A	—
		P, LCL		✓Small Current		0.1 W		×
		LCC				✓3 W		✓
	MPL	S		× Large Current	22%	✓743-744 W	$\lvert I_1\rvert = 41$ A, $\lvert I_2\rvert = 14$ A	—
		P, LCL		✓Small Current		0.1 W	$\lvert I_1\rvert = 37$ A, $\lvert I_2\rvert = 22$ A	×
		LCC				✓3 W		✓

A. *Efficiency*

As shown in Table. 9, the maximum efficiency with MEL is compared. Comparing Pattern 1 and 2, the parameters are the same except for coupling factor, but there is a large difference between the maximum efficiency of about 90% and 40%. Therefore, it can be seen that the coupling factor has a large impact on the maximum efficiency. On the other hand, since there is no difference depending on the circuit, the same maximum efficiency can be obtained regardless of which circuit is selected from the viewpoint of efficiency.

Regarding the efficiency with MPL, efficiency is lower for all circuits compared to the efficiency than with MEL in the all patterns. The case coupling factor is large in Pattern1, the efficiency with MPL is about half of the maximum efficiency when the transmitter side is S, LCL, or LCC, but when the transmitter side is P and S-P circuits have relatively high efficiency. In Patterns 2-5, the efficiencies are similar for all circuits and are closer to the maximum efficiency with MEL than in Pattern 1. Therefore, it can be said that when the case that coupling is small, there is no significant difference in efficiency whether MEL or MPL is used.

B. *Output Power*

As shown in Table. 9, it can be seen that regardless of MEL and MPL, all Patterns get higher power when the transmitter side is an S circuit. Comparing Patterns 2 and 4, Pattern 4 gets more power even though Q value and inner resistance of the receiver coil is the same. Therefore, it can be considered that the case that inner resistance of the transmitter coil is small, a larger current flows through the transmitter coil and a larger power can be got. Comparing the output power with MEL and with MPL, there is a large difference in Pattern 1, the case that the coupling is large, but the difference is smaller in Patterns 2-5. Therefore, the case coupling is small, the difference in efficiency and output power between with MEL and with MPL is small.

C. *Current*

As for the current value, since the magnetic field and power have a proportional relationship of the square, the characteristics are compared considering that the output power is used as 10 W common and the voltage source value is derived for fair judgment. As shown in Table 9, the results show that the current values with MEL are similar for all circuits. The case that there is a difference in Q value of the transmitter and receiver coils, a larger current flows to the one with the smaller Q value. The smaller the coupling factor, the larger the difference the currents flowing in the transmitter coil $|I_1|$ and the receiver coil $|I_2|$.

For the MPL, it varies by the transmitter circuit. In the case of symmetrical coils, the magnitudes of the magnetic field near the transmitter coil and the receiver coil are different because the ratio of the current flowing in the transmitter coil to that in the receiver coil varies depending on the transmitter circuit. Therefore, the impact of the magnetic field can be suppressed by using different circuits for different applications. For example, Pattern 1 and 2, the transmitter circuit is S, the current flowing to the receiver coil is small, so it is useful the case that there is concern about the impact of the magnetic field near the receiver coil.

VI. Pattern and Optimal Circuit

Based on the above, As shown in Table 9, the optimal circuit was evaluated as ✓ for good, - for moderate, and × for poor. For Pattern 1, most circuits have a trade-off relationship between high efficiency and high power depending on the load value. However, S-P with MPL, it achieves high efficiency and high power, so S-P circuit with MPL is effective in circuits with large coupling in Pattern 1. On the other hand, since higher efficiency is desirable to send large power, LCC on the transmitter circuit with MEL is also good for the safety of $k = 0$. For the case of small coupling with symmetrical coils in Pattern 2, the transmitter side is S such as S-S, S-P, S-LCL, and S-LCC with MPL are suitable. It should be noted that the value of the current flowing in the receiver. In IPT, the magnitude of the current flowing in the receiver is an important point because magnetic fields to the human body and electronic equipment near the receiver coil are often a concern. The transmitter side is S, there is no significant difference in the value of the current flowing to the transmitter coil and the receiver coil with MEL, but the current flowing to the receiver coil can be reduced by using MPL. Therefore, the transmitter side is S such as S-S, S-P, S-LCL, and S-LCC with MPL are particularly good in the case the influence of magnetic fields is a concern. For the case that the receiver coil is smaller than the transmitter coil in Patterns 3, the efficiency changes only 3% or so between MEL and MPL. In addition, the output power is harder to obtain than in the other patterns , so S-S, S-P, S-LCL, and S-LCC with MPL which can get larger output power are most suitable. The transmitter coil is small, as in Patterns 4 and 5, the transmitter LCC can get enough power. Therefore the transmitter LCC such as LCC-S, LCC-P, double-LCC, and doubleLCC is suitable for safety at $k = 0$. In common in Pattern1-5, MEL and MPL vary depending on the receiver circuit, so the receiver should be selected according to the load value.

VII. Conclusion

The characteristics of each circuit and each pattern were compared with MEL, MPL, efficiency, output power, and current. Since MEL varies depending on the receiver side circuit, it is necessary to select the receiver side circuit according to the load value for high-efficiency transfer. The MPL should be selected based on a more detailed classification because the value varies depending on the combination of the transmitter side and the receiver. The difference of efficiency between with MPL and MEL are smaller with a small coupling. For output power, it was found that for all Patterns, more power is got that the transmitter side is S. For the current, there is no difference by circuits with MEL, but there is a difference in the current with MPL depending on the circuit. Therefore it is necessary to select a more suitable circuit the case the magnetic field effect is a major concern. From the above characteristics, the LCC on the transmitter side with MEL is suitable for symmetric coils with large coupling and asymmetric coils with smaller transmitter coil, while S on the transmitter side with MPL is suitable for symmetric coils with small coupling and asymmetric coils with smaller receiver coils. On the receiver side, the choice should depend on the value of the load.

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