Resonant circuit topology Comparison and CC / CV Characteristic Evaluation Considering the Difference in Power Supply in Capacitive Wireless Power Transfer circuits

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***Abstract*— CPT is cheaper and lighter than Inductive Wireless Power Transfer (IPT). In addition, Capacitive Wireless Power Transfer (CPT) doesn't have risks of rising temperature of metallic foreign objects. Owing to these advantages, CPT will be able to use in various applications. But, No studies have made circuit comparisons considering differences between voltage and current sources. In this study, the typical circuits S-S, S-P, P-S and P-P circuits in CPT are compared, taking into consideration the difference in load value and the difference in power supply. In compensation condition, the conditions based on the gyrator characteristics and the ideal voltage transformer/current transformer characteristics are adopted. By satisfying this condition, CV characteristic or CC characteristic can be obtained in each circuit. As a result, it was found that the efficiency under the optimal load was the same value in all the circuits regardless of power supply, and the optimal load of S-S and P-S circuits was k^2 (coupling coefficient) times that of S-P and P-P circuits. When a voltage source is used, the output power of P-S and P-P circuits is k^2 times that of S-S and S-P circuits, and when a current source is used, the output power of S-S and S-P circuits is k^2 times that of P-S and P-P circuits. From the above results, it is concluded that when using a voltage source, S-S or S-P circuit should be selected. S-S should be selected when load resistance is low. S-P should be selected when load resistance is high. On the other hand, when using a current source, P-S or P-P circuit should be selected, P-S should be selected when load resistance is low. P-P should be selected when load resistance is high. These results could also be confirmed from experiments using actual circuits.**

I. Introduction

CPT is cheaper and lighter than Inductive Wireless Power Transfer (IPT). In addition, CPT doesn't have risks of rising temperature of metallic foreign objects. Owing to these advantages, CPT will be able to use in various applications. Therefore, there are a lot of research on CPT in recent years [1-10]. And a few studies compare circuits theoretically[11-12]. But, No studies have made circuit comparisons considering differences between voltage and current sources.

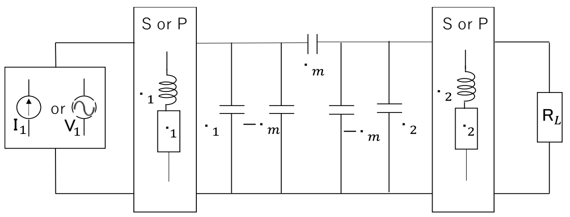


Fig .1 Circuit diagram of the CPT topology

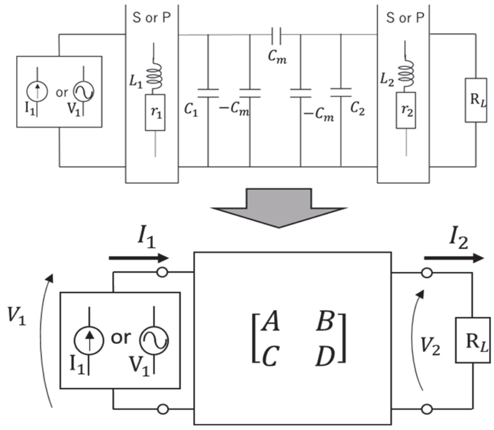


Fig .2 f-parameter of circuits

In this paper, we propose effective circuit selection among S-S, S-P, P-S and P-P topologies in CPT taking into consideration the difference in load value and power supply.

II. Reactance Compensation Conditions

The target circuit topology is shown in Fig .1. The target topologies are S-S, S-P, P-S and P-P.

In this section, Compensation conditions to meet gyrator characteristics and the ideal voltage transformer/current transformer characteristics are represented.

The gyrator characteristics and the ideal voltage transformer/current transformer characteristics is condition that can obtain the CC or CV characteristics. In addition to, the input power factor is 1. CC characteristic obtains that the current of the load is constant regardless of the load. CV characteristic obtains that the voltage of the load is constant regardless of the load. (**1**) is derived using f-parameter in Fig .2.

Table 1 Compensation conditions

	Primary condition	Secondary condition
S-S	$L_1 = \frac{1}{\omega^2 C_1(1-k^2)}$	$L_2 = \frac{1}{\omega^2 C_2(1-k^2)}$
S-P	$L_1 = \frac{1}{\omega^2 C_1}$	$L_2 = \frac{1}{\omega^2 C_2(1-k^2)}$
P-S	$L_1 = \frac{1}{\omega^2 C_1(1-k^2)}$	$L_2 = \frac{1}{\omega^2 C_2}$
P-P	$L_1 = \frac{1}{\omega^2 C_1}$	$L_2 = \frac{1}{\omega^2 C_2}$

Table 2 The relationship between four circuits and CV/CC characteristics

	S-S	S-P	P-S	P-P
Voltage source	CC	CV	CC	CV
Current source	CV	CC	CV	CC

In the type that meets A = D = 0, CC characteristics is satisfied using voltage source and CV characteristics is satisfied using

$$\begin{bmatrix} V_1 \\ I_1 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} V_2 \\ I_2 \end{bmatrix} \quad (1)$$

current source. This type are S-S and P-P.

In the type that meets B = C = 0, CV characteristic is satisfied using voltage source and CC characteristic is satisfied using current source. This type are S-P and P-S. Compensation conditions satisfying A = D = 0 or B = C = 0 are shown Table 1. Characteristics when compensation condition is satisfied are shown in Table 2.

III. Derivation of Equations

In this section, equations of efficiency, optimal load and output power are derived. And, the validity of these equations is shown by a bar graph based on the analysis results. Table 3 shows the parameters used in the analysis results. Efficiency η is defined (2).

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

Table 3 Analysis conditions

	f[kHz]	C_1[pF]	C_2[pF]	C_m[pF]	r_1[Ω]
S-S	450	400	400	40	2.23
S-P					2.21
P-S					2.23
P-P					2.21
	r_2[Ω]	L_1[μH]	L_2[μH]	$Q = Q_1 = Q_2$	k
S-S	2.23	316	316	300	0.1
S-P	2.23	313	316		
P-S	2.21	316	313		
P-P	2.21	313	313		

I_{r_1} is the current flowing into r_1. I_{r_2} is the current flowing into r_2. I_{R_L} is the current flowing into R_L. Optimal load $R_{L_{opt}}$ is load satisfied (3).

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

Output power P_{out} is defined (4)

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

δ_k is represented by (5)

$$\delta_k = \frac{k^2}{1-k^2} \quad (5)$$

Considering $\delta_k \cong k^2$ when the coupling coefficient is small, the maximum efficiency equations can be shown to (6).

$$\eta_{max}^{all} = \frac{k^2Q^2}{\left(1+\sqrt{1+k^2Q^2}\right)^2} \quad (6)$$

From (6), It can be seen that the maximum efficiency of each circuit is same value regardless of the difference in power supply. This result is also shown in Fig. 3. Optimal loads of S-S, S-P, P-S and P-P are derived to (7)(8).

$$R_{L_{opt}}^{S-S,P-S} = r_2\sqrt{1+k^2Q^2} \quad (7)$$

$$R_{L_{opt}}^{S-P,P-P} = \frac{r_2Q^2}{\sqrt{1+k^2Q^2}} \quad (8)$$

Considering $k^2Q^2 \gg 1$, the ratio of the optimal load is shown by (9).

$$R_{L_{opt}}^{S-S,P-S} : R_{L_{opt}}^{S-P,P-P} = 1 + k^2Q^2 : Q^2 \cong k^2 : 1 \quad (9)$$

From (9), optimal load of S-S and P-S are smaller than those of S-P and P-P. The ratio is about k^2: 1. This result is also shown in Fig. 4. Therefore, it is necessary to select the circuit according to the load value of the application.

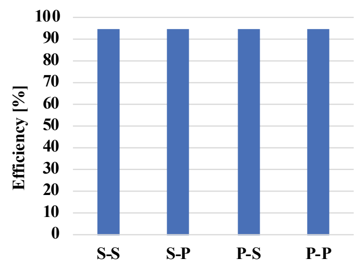


Fig .3 Bar graph of Efficiency by analysis

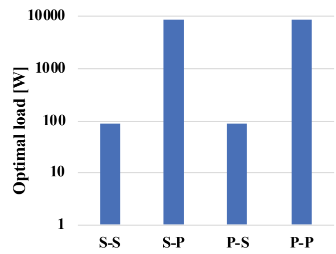


Fig .4 Bar graph of optimal load by analysis

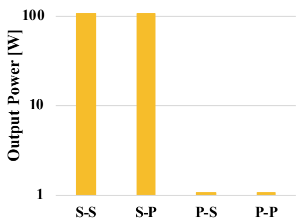


Fig .5 Bar graph of output power when using voltage source by analysis

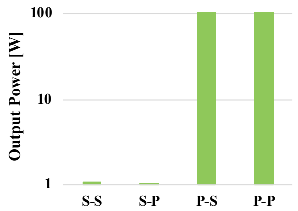


Fig .6 Bar graph of output power when using current source by analysis

Table 4 categorization of four circuits

		Resistance value of load	
		Low	High
Power supply	Voltage source	S-S	S-P
	Current source	P-S	P-P

Next, when using a voltage source, considering $\delta_k \cong k^2$ when the coupling coefficient is small, $P_{out,\eta max}$ of S-S and S-P and that of P-S and P-P are shown by (10)(11).

$$P_{out,\eta max}^{S-S,S-P} = \frac{\eta_{max}}{r_1\sqrt{1+k^2Q^2}}\left|\dot{V}_1\right|^2 \quad (10)$$

$$P_{out,\eta max}^{P-S,P-P} = \frac{\eta_{max}\sqrt{1+k^2Q^2}}{r_1Q^2}\left|\dot{V}_1\right|^2 \quad (11)$$

Considering that $k^2Q^2 \gg 1$, the ratio of the $P_{out,\eta max}$ is shown by (12).

$$\begin{aligned} P_{out,\eta max}^{S-S,S-P} : P_{out,\eta max}^{P-S,P-P} &= Q^2 : 1+k^2Q^2 \\ &\cong 1 : k^2 \end{aligned} \quad (12)$$

From (12), $P_{out,\eta max}$ of S-S and S-P are larger than those of P-S and P-P, the ratio is about $1{:}\,k^2$. This result is also shown in Fig. 5. Therefore, from the viewpoint of large power transmission., the S-S circuit and the S-P circuit have superior characteristics to the P-S circuit and the P-P circuit when the voltage source is used.

Next, when using a current source, considering $\delta_k \cong k^2$ when the coupling coefficient is small, $P_{out,\eta max}$ of S-S and S-P and that of P-S and P-P are shown by (13)(14).

$$P_{out,\eta max}^{S-S,S-P} = r_1\sqrt{1+k^2Q^2}\,\eta_{max}\left|\dot{I}_1\right|^2 \quad (13)$$

$$P_{out,\eta max}^{P-S,P-P} = \frac{r_1Q^2}{\sqrt{1+k^2Q^2}}\,\eta_{max}\left|\dot{I}_1\right|^2 \quad (14)$$

Considering that k^2Q^2 is sufficiently larger than 1, the ratio of the $P_{out,\eta max}$ is shown by (15).

$$\begin{aligned} P_{out,\eta max}^{S-S,S-P} : P_{out,\eta max}^{P-S,P-P} &= 1+k^2Q^2 : Q^2 \\ &\cong k^2 : 1 \end{aligned} \quad (15)$$

From (15), $P_{out,\eta max}$ of S-S and S-P are smaller than those of P-S and P-P. The ratio is about $k^2{:}\,1$. This result is also shown in Fig. 6. Therefore, from the viewpoint of large power transmission, P-S and P-P circuits have superior characteristics to S-S and S-P circuits when the current source is used. From above results, each circuit is categorized as Table 4 according to the difference in power supply and load resistance value.

IV. Power Transmission Characteristics When Load is Variable

In this section, characteristics of power factor, output current, output voltage, efficiency and output power are shown when load is variable. In power factor, characteristics are shown by analysis. Characteristic of output current, output voltage, efficiency and output power are shown by experiment.

A. Power factor, output voltage and output current in each circuit

In this section, considering the internal resistance, the analysis results show that the power factor, output voltage and output current. And The parameters are shown in Table 3.

Fig .7 shows the relationship between power factor $\cos\theta$ and load R_L. From Fig .7, it can be seen that power factor is almost 1 in all circuits, so power factor improvement can be achieved

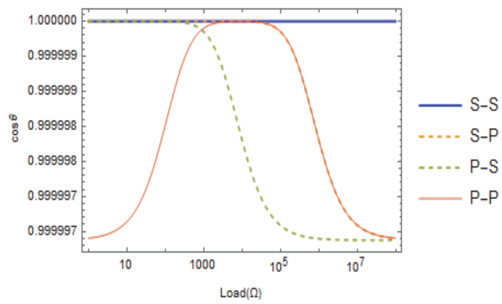
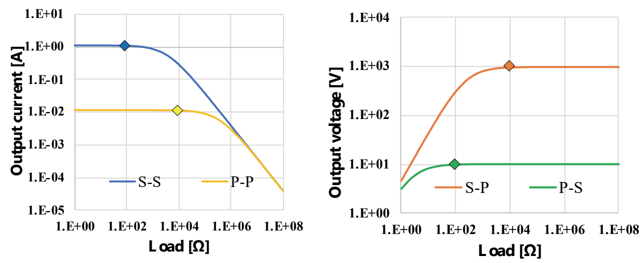


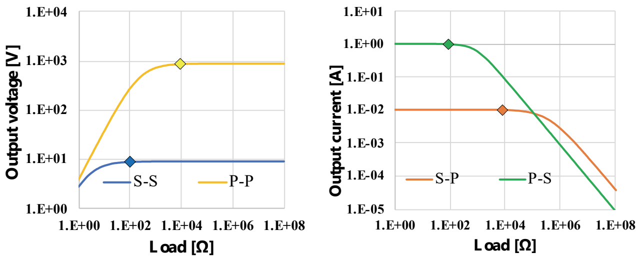
Fig .7 Calculation results of input power factor

in all circuits. Fig .8 shows the output current and output



(a) Output current (b) Output voltage

Fig .8 CC / CV characteristics of each circuit when using a voltage source voltage in each circuit when a voltage source is used, and Fig .9 shows the output current and output voltage in each circuit



(a) Output current (b) Output voltage

Fig .9 CC / CV characteristics of each circuit when using a current source

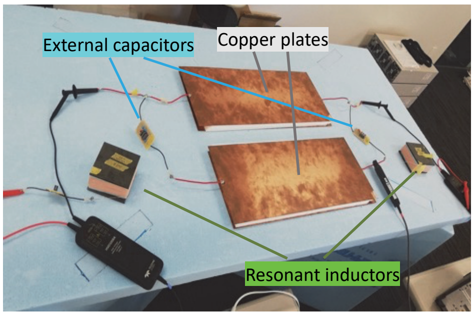


Fig .10 Experimental circuit （S-S)

Table 5 Parameter of experiment

	f[kHz]	C_1[pF]	C_2[pF]	C_m[pF]	r_1[Ω]
S-S	450	400	400	40	2.42
S-P					2.42
P-S					2.42
P-P					2.42
	r_2[Ω]	L_1[μH]	L_2[μH]	$Q = Q_1 = Q_2$	k
S-S	2.42	316	316	385	0.1
S-P	2.42	314	316		
P-S	2.42	316	314		
P-P	2.42	314	314		

when a current source is used. And, dot the position of the optimal load in Fig .8 and Fig .9.

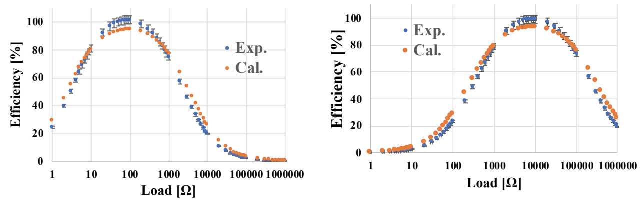
From Fig .8 (a), when a voltage source is used, the S-S and P-P circuits realize CC characteristics near the optimal load. In addition, from Fig .8 (b), when a voltage source is used, the S-P and P-S circuits realize CV characteristics near the optimal load. From Fig .9 (a), when a current source is used, the S-S and P-P circuits realize CV characteristics near the optimal load. In addition, from Fig .9 (b), when a current source is used, the S-P and P-S circuits realize CC characteristics near the optimal load. It can be seen that the above results are consistent with the results in Table 2 shown in Section Ⅱ.

B. Characteristics of efficiency and output power

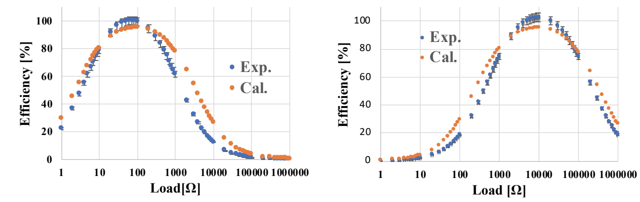
In this section, experimental results show that efficiency and output power in each circuit. The experimental result is a converted value obtained by measuring the f-parameter of the circuits. The state of the experiment is shown in Fig .10 and parameter in shown Table 5.

Next, Fig .11 and 12 show the efficiency in each circuit. And, in the experimental results shown in Fig. 11 and 12, an error of ± 1% was estimated in the measured value in consideration of the error of the voltage / current probe. From Fig .11 and 12, It can be seen that maximum efficiency is same value among each circuit. And the optimal load value is small for S-S and P-S, and the optimal load value is large for S-P and P-P, regardless of the difference in power supply. This ratio is k^2: 1. Therefore, it is necessary to select a circuit depending on the difference in the optimal load.

Next, Fig .13 and 14 show the output power at optimal load in each circuit. From Fig .13 and 14, When using a voltage source, S-S and S-P is superior to P-S and P-P in terms of power. This ratio is 1: k^2. On the other hand, when using a current source, P-S and P-P is superior to the S-S and S-P in terms of

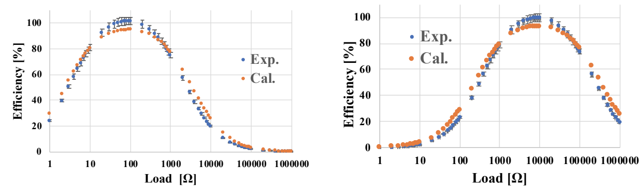


(a) Output current of S-S (b) Output voltage of S-P

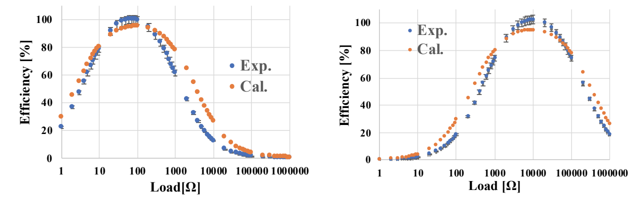


(c) Output voltage of P-S (d) Output current of P-P

Fig .11Efficiency of each circuit when using a voltage source



(a) Output current of S-S (b) Output voltage of S-P



(c) Output voltage of P-S (d) Output current of P-P

Fig .12 Efficiency of each circuit when using a current source

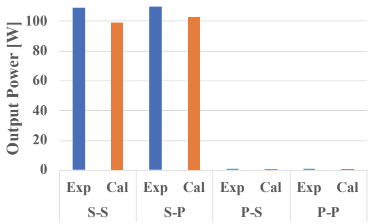


Fig .13 Transmission output power when using a voltage source

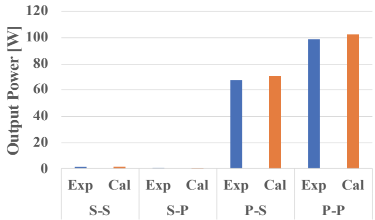


Fig .14 Transmission output power when using a current source

power. This ratio is $1{:}\,k^2$.Therefore, it is necessary to select a circuit depending on the difference in power supply.

V. Conclusion

In this study, the typical circuits S-S, S-P, P-S and P-P circuits in (CPT) are compared, taking into consideration the difference in load value and the difference in power supply. In compensation condition, the conditions based on the gyrator characteristics and the ideal voltage transformer/current transformer characteristics are adopted. By satisfying this condition, CV characteristic or CC characteristic can be obtained in each circuit. As a result, it was found that the efficiency under the optimal load was the same value in all the circuits regardless of power supply, and the optimal load of S-S and P-S circuits was k^2 (coupling coefficient) times that of S-P and P-P circuits. When a voltage source is used, the output power of P-S and P-P circuits is k^2 times that of S-S and S-P circuits, and when a current source is used, the output power of S-S and S-P circuits is k^2 times that of P-S and P-P circuits. From the above results, it is concluded that when using a voltage source, S-S or S-P circuit should be selected. S-S should be selected when load resistance is low. S-P should be selected when load resistance is high. On the other hand, when using a current source, P-S or P-P circuit should be selected, P-S should be selected when load resistance is low. P-P should be selected when load resistance is high. These results could also be confirmed from experiments using actual circuits.

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