Dynamic Contactless Power Transfer System using PS Topology Considering Mutual Coupling of Transmitter Coils

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ABSTRACT: The PS capacitor topology has been proposed as a method useful for dynamic contactless power transfer systems. In the PS capacitor topology, the input current is suppressed during the no-receiver-coil condition. When multiple transmitters are densely installed, mutual coupling between the coils must be considered. In this study, we analyzed the circuit considering mutual coupling and evaluated its characteristics. In addition, we evaluated the characteristics when the coil terminal not used for power supply was opened, and clarified the effect of mutual coupling.

KEY WORDS: dynamic contactless power transfer, electric vehicle, PS Capacitor topology, mutual coupling

1. INTRODUCTION

Electric vehicles are beginning to spread because of environmental and energy concerns, but they have problems such as short continuous cruising distance and long charging time. As a method to solve these problems, a dynamic contactless power transfer system with transmitter coils installed under the road as shown in Fig. 1 has been proposed(1). If the transmitter coils are installed densely so as to continuously supply power, mutual coupling between transmitter coils must be considered.

For a dynamic contactless power transfer system, the primary parallel and secondary series resonance capacitors topology (PS capacitor topology(2)) is useful. With the PS capacitor topology, the input impedance can be increased and the input current can be suppressed when there is a large misalignment or no receiver coil. In power transfer to a traveling vehicle, a large misalignment occurs only for a short time, so a PS capacitor topology that does not require a control mechanism is highly suitable.

Currently, in systems using PS capacitor topology, the power transmission characteristics using multiple transmitter coils and considering mutual coupling between the coils have not been clarified. In addition, although improvement in efficiency can be expected by connecting only the transmitter coil to be used, mutual coupling exists between the transmitter coils, so the effect of improving the efficiency is unknown.

In this study, we evaluated the dynamic contactless power transfer system considering mutual coupling between transmitter coils using PS capacitor topology. In addition, by focusing on the

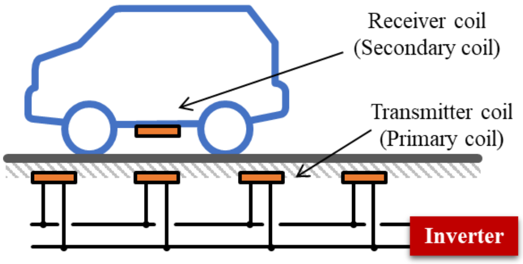


Fig. 1 Schematic of the dynamic contactless power transfer system.

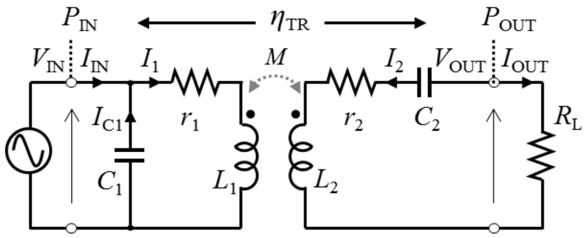


Fig. 2 PS capacitor topology (one-to-one).

Table 1 Capacitor values and characteristics of PS capacitor topology (one-to-one).

Topology	PS Capacitor
Capacitor	$\frac{1}{\omega C_1}=\omega L_1$, $\frac{1}{\omega C_2}=\omega L_2\left(1-k^2\right)$
I/O characteristics	$V_{IN}=a'V_{OUT}$, $I_{IN}=\frac{1}{a'}I_{OUT}$, $a'=\frac{L_1}{M}$
Input impedance	$Z_{IN}=\left(\frac{L_1}{M}\right)^2 R_L$

current of the transmitter coil, the characteristics were clarified when the terminal of the coil not used for power transfer is opened.

2. PS CAPACITOR TOPOLOGY

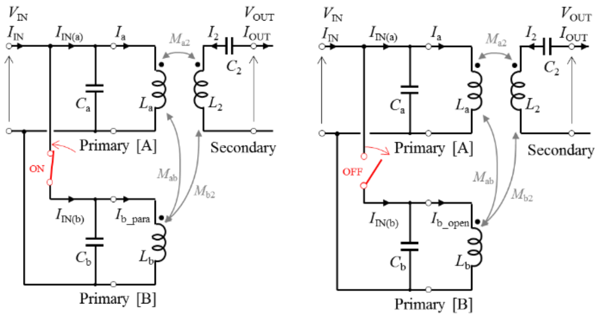
2.1. Primary 1 : Secondary 1

The circuit diagram of the PS capacitor topology is shown in Fig. 2; the capacitor values and characteristics are shown in Table 1.

The primary parallel capacitor C_1 is determined to achieve resonance with the primary self-inductance L_1, and the secondary series capacitor C_2 is determined so that the power factor is 1. The expression of the input/output characteristics derived from these conditions shows that it is the same as the ideal transformer of the voltage ratio *a*'. Because of the mutual inductance *M* in the denominator of the input impedance Z_{IN}, if *M* decreases because of misalignment, then Z_{IN} increases. Therefore, when the input voltage V_{IN} is constant, the input current can be suppressed.

2.2. Primary 2 : Secondary 1

We consider the case of using two primary transmitters as shown in Fig. 3. The primary [A] transmitter and secondary receiver are in a face-to-face condition. Each coil has mutual coupling. We evaluated the characteristics according to the connection method of the primary [B] transmitter.



(a) Parallel connection.

(b) Primary [B] terminal open.

Fig. 3 Connection method of primary [B].

2.2.1. Parallel connection of primary coils

Fig. 3(a) shows the parallel connection of primary [A] and [B]. When expressed by Equation (1), each capacitor can be approximated by Equation (2).

$$L_1 = L_a = L_b \tag{1}$$

$$\frac{1}{\omega C_a} = \frac{1}{\omega C_b} = \omega\left(L_1 + M_{ab}\right), \quad \frac{1}{\omega C_2} = \omega L_2\left(1 - k_{a2}^2\right) \tag{2}$$

As shown in Equation (2), the primary capacitors C_a and C_b have mutual inductance M_{ab} between the primary coils. When M_{ab} is sufficiently smaller than L_1, capacitors C_a and C_b have nearly the same value as in the one-to-one contactless power transfer case, and the power supply characteristics are nearly equal.

2.2.2. Primary [B] terminal opened

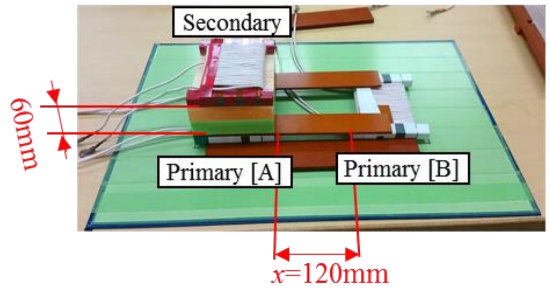
Primary [B] is little used for power transmission when primary [A] and the secondary are completely facing each other. Therefore, it is better to open the primary [B] terminal as shown in Fig. 3(b) and reduce the loss. The coil current I_{b_open} when the primary [B] terminal is opened is expressed by

$$I_{b\_open} = \frac{M_{a2}M_{b2} + jM_{ab}Z_2/\omega}{M_{a2}X_b/\omega + M_{ab}M_{b2}} I_{OUT} \tag{3}$$

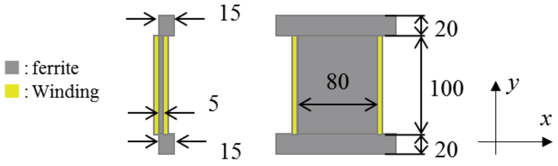
Z_2 is the impedance of the secondary, and X_b is the reactance of primary [B]; they are respectively expressed by

$$Z_2 = j\omega L_2 + \frac{1}{j\omega C_2} + R_L \tag{4}$$

$$X_b = \omega L_b - \frac{1}{\omega C_b} \tag{5}$$



(a) Outline.



(b) Dimension.

Fig. 4 Transformer outline and dimensions.

Table 2 Transformer parameters.

Topology	PS Capacitor
$N_{1(a)}$ / $N_{1(b)}$ / N_2 [Turns]	12 T / 12 T / 24 T
r_a / r_b / r_2 [mΩ]	42.57 / 45.00 / 96.63
L_a / L_b / L_2 [μH]	22.81 / 23.16 / 96.63
M_{ab} / M_{a2} / M_{b2} [μH]	−0.637 / 11.42 / 1.222
C_a / C_b / C_2 [μF]	0.1562 / 0.1487 / 0.0388
R_L [Ω]	16.0

Because I_{b_open} has reactance X_b, I_{b_open} greatly increases if primary [B] is in a resonance condition. If mutual coupling M_{ab} and M_{b2} with primary [B] are all 0, then I_{b_open} also becomes 0; otherwise, the reactance X_b greatly affects the efficiency. To improve efficiency, primary [B] should be placed at a position not affected by mutual coupling, or reactance X_b must be increased by changing capacitor C_b of primary [B].

3. EXPERIMENTS

3.1. Conditions

The outline and dimensions of the transformer are shown in Fig. 4. H-shaped solenoid transformers of the same shape as the primary and secondary transformers were used. An aluminum plate for magnetic shielding was installed on the back of each transformer. The magnetic gap was 60 mm, and we placed primary [A] and the secondary at completely opposite positions (standard condition). The distance between primary transmitters was 120 mm. The transformer parameters are shown in Table 2, and the experimental circuit diagram is shown in Fig. 5. In order to evaluate at the fundamental frequency f_0 = 85 kHz, an LC filter was used.

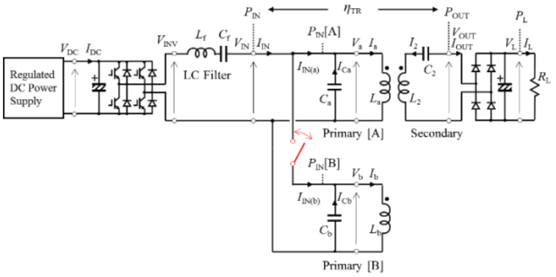


Fig. 5 Experimental circuit.

3.2. Parallel connection

3.2.1. With and without secondary

The primary transmitters were connected in parallel, and the input voltage and current were measured under the condition with and without the secondary receiver. The input voltage V_{IN} for a load power P_L of 1.5 kW in the standard condition was taken as the reference voltage. The power transfer results are shown in Table 3, and the input voltage and input current waveform are shown in Fig. 6. From Fig. 6(a), the input power factor in the standard condition is 0.95, which is close to 1. Because M_{ab} is smaller than L_a and L_b, the effect on power factor is small. As shown in Fig. 6(b), the input current without a secondary receiver is suppressed compared with the standard condition. The impedance in the standard condition was 34.5 Ω, which is small. Further, the impedance without a secondary receiver is 126.0 Ω, which is approximately 3.7 times that of the standard condition. The reason that the input current without a secondary receiver is suppressed is that the impedance has increased. The same characteristics as the one-to-one transformer were obtained.

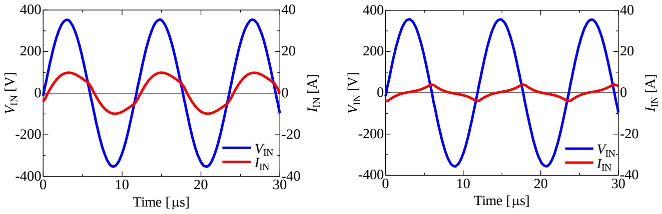
3.2.2. Misalignment characteristics

With the primary transmitters connected in parallel, the misalignment characteristics in the x (progressing) direction were measured. The power transfer experiment was performed at 30-mm intervals from x = −120 mm to 360 mm. The standard condition was that the secondary receiver was placed at x = 0 mm. The input voltage V_{IN} for a load power P_L of 1.5 kW in the standard condition was taken as the reference voltage. The efficiency and the output power are shown in Fig. 7(a). The input power of the primary transmitters is shown in Fig. 7(b). The input power factor of the primary transmitters is shown in Fig. 7(c).

From Fig. 7(a), the efficiency becomes a maximum at the positions (x = 0 mm, 240 mm) where the primary transmitters and secondary are completely opposite; it is 93.7% at x = 0 mm and 93.5% at x = 240 mm. The efficiency becomes a minimum at the

Table 3 Experimental results of parallel connection

Secondary coil	With	Without
V_{IN} [V]	248.6	248.6
I_{IN} [A]	7.20	1.97
pf_{IN}	0.95	0.13
$I_{IN(a)}$ / $I_{IN(b)}$[A]	5.97 / 1.71	1.21 / 0.90
$pf_{IN(a)}$ / $pf_{IN(b)}$	0.97 / 0.66	0.11 / 0.21
I_a / I_b[A]	22.6 / 20.9	17.8 / 16.9
V_D [V]	158.3	-
I_D [A]	11.1	-
P_{IN} [W]	1703	65.5
$P_{IN(a)}$ [W]	1438	33.2
$P_{IN(b)}$ [W]	266	32.3
P_D [W]	1597	-
P_L [W]	1500	-
η_{TR}	93.75	-
Z_{IN} [Ω]	34.5	126.0



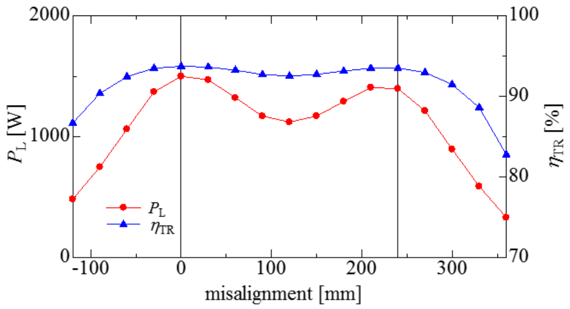
(a) With secondary coil. (b) Without secondary coil.

Fig. 6 Input waveform.

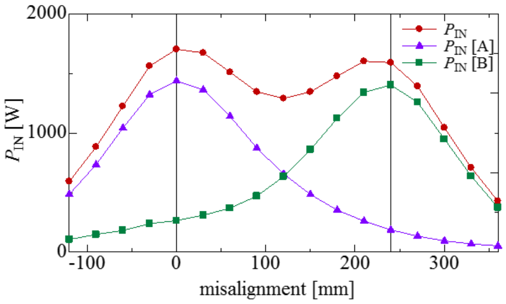
position (x = 120 mm) where the secondary is placed at the middle of the primary transmitters; the efficiency is 92.6%, which is approximately 1% lower than the maximum efficiency. The average efficiency is 93.2% between primary [A] and primary [B] (x = 0~240 mm), so it was found that power can be transferred with nearly constant efficiency. The output power becomes a minimum (1121 W) at x = 120 mm; the decline rate is 25.3%. The average output power between primary [A] and primary [B] is 1317W and the reduction rate is 12.2%.

From Fig. 7(b), the input power of the primary transmitters becomes a maximum at x = 0 mm, 240 mm, and the input power of each transmitter is nearly equal at x = 120 mm.

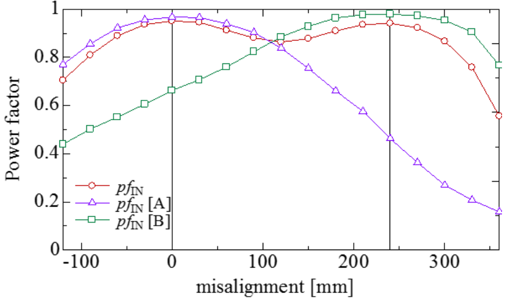
From Fig. 7(c), the input power factor of primary [A] is 0.97 at x = 0 mm and that of primary [B] is 0.98 at x = 240 mm. They are also close to 1. The input power factor of the primary transmitters becomes a maximum at x = 0 mm, 240 mm; and it is 0.95 at x = 0 mm and 0.94 at x = 240 mm. The minimum input power factor is 0.86 at x = 120 mm. The average input power factor is 93.2% between primary [A] and primary [B].



(a) Output power and efficiency.



(b) Input power.



(c) Power factor.

Fig. 7 Experimental results of misalignment.

3.3. Primary [B] terminal opened

We evaluated the characteristics when the primary [B] terminal was opened, in comparison with the results of the parallel connection. The load power P_L was 1.5 kW in the parallel connection. The input voltage with the terminal opened was the same input voltage as in the parallel connection. The experimental results are shown Table 4.

From the results, we found that when the primary [B] terminal is opened, the coil current I_b increases from 20.9 A to 28.5 A and the efficiency decreases from 93.75% to 85.68%, because the coil and the capacitor of primary [B] resonate.

Table 4 Experimental results with primary [B] terminal opened

Primary [B]	Parallel	Open
V_{IN} [V]	248.6	248.6
I_{IN} [A]	7.2	3.7
pf_{IN}	0.95	0.97
$I_{IN(a)}$ / $I_{IN(b)}$[A]	5.97 / 1.71	(3.7) / -
$pf_{IN(a)}$ / $pf_{IN(b)}$	0.97 / 0.66	(0.97) / -
I_a / I_b[A]	22.6 / 20.9	21.6 / 28.5
V_D [V]	158.3	110.1
I_D [A]	11.1	7.7
P_{IN} [W]	1703	895
$P_{IN(a)}$ [W]	1438	(895)
$P_{IN(b)}$ [W]	266	-
P_D [W]	1597	767
P_L [W]	1500	717
η_{TR}	93.75	85.68
Z_{IN} [Ω]	34.5	66.7

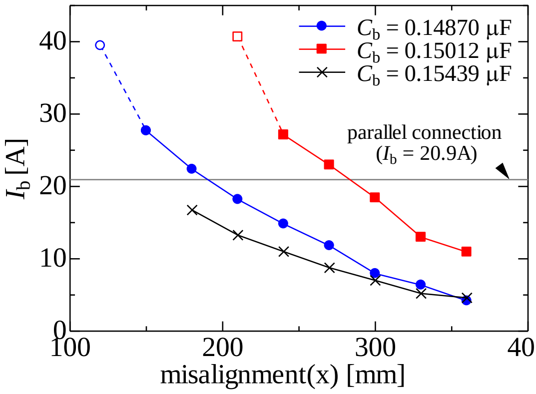
3.4 Increased interval of the primary transmitters

The power transfer experiment was performed by changing the interval of the primary transmitters and the capacitor C_b. Primary [B] was moved from x = 120 mm to 360 mm at an interval of 60 mm to feed 1.5 kW. In addition to the standard capacitors that were 0.1487 µF, two kinds of capacitors of 0.15012 µF and 0.15439 µF were prepared. The results are shown in Fig. 8. Fig. 8(a) shows the current I_b flowing through the coil of primary [B], and Fig. 8(b) shows the efficiency. The broken line in Fig. 8(a) is the value estimated on the basis of the I_b value at 1.0-kW power transfer. Because the broken line in Fig. 8(b) exceeded the upper limit of the coil current at 35 A, the data for 1.0-kW power transfer are posted as a reference. The relationship between capacitor C_b and the resonance frequency is shown in Table 5.

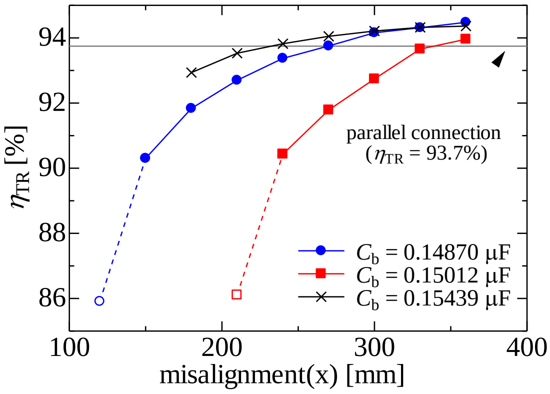
Table 5 Capacitor and resonance frequency.

C_b [μF]	Frequency [kHz]
0.1487	85.8
0.15012	85.4
0.15439	84.1

From the results, when the distance between the primary transmitters is small, the current I_b flowing through primary [B] increases and the efficiency decreases. When the capacitor was changed from $C_b = 0.1487$ μF to 0.15012 μF, I_b increased by nearly a factor of 2, and the efficiency greatly decreased. In addition, when C_b was changed to $C_b = 0.15439$ μF, conversely I_b decreased and efficiency improved. It is considered that the current I_b decreased because of the increase in the reactance of primary [B], and the efficiency was affected. From the data in Table 5, when C_b is 0.15012 μF, the resonance frequency is closest to the power transfer frequency of 85 kHz. Because the reactance reaches a minimum because of the resonance with L_b, the current I_b greatly increases according to Equations (5). As a result, the efficiency declines. On the contrary, when C_b is 0.15439 μF, the reactance of primary [B] reaches a maximum and efficiency improves because the resonance frequency is farthest from 85 kHz.



(a) Current I_b.



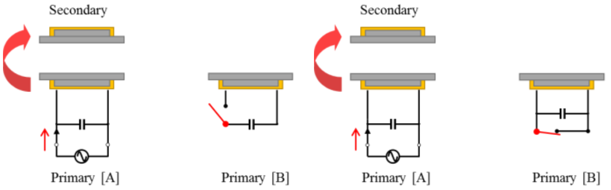
(b) Efficiency η.

Fig. 8 Experimental results when increasing the interval of the primary transmitters.

3.5 Connection method of the primary [B] terminal

Comparative experiments were performed to ascertain the effect of efficiency by connection method for primary [B]. For the primary transmitters, a power transfer experiment was conducted by two kinds of connection methods, as shown in Fig. 9. The load power P_L was 1.5 kW. The results are shown in Table 6. For reference, the results where the primary transmitters were connected in parallel are also included.

From the results, when the primary [B] terminal is opened, because current does not flow through the coil, the efficiency is improved. An efficiency improvement of approximately 1% was confirmed compared to the parallel condition. When the primary [B] terminals are shorted, the reactance of primary [B] increases because the coil does not resonate and little current I_b flows, according to Equation (5).



(a) Open. (b) Short.

Fig. 9 Connection state of primary [B] terminal.

Table 6 Experimental results of the primary [B] terminal connection method.

Type	Open	Short	Parallel
V_{IN} [V]	290.1	288.7	248.6
I_{IN} [A]	5.9	5.9	7.2
pf_{IN}	0.99	0.99	0.95
$I_{IN(a)}$ / $I_{IN(b)}$ [A]	(5.9) / -	(5.9) / -	5.97 / 1.71
$pf_{IN(a)}$ / $pf_{IN(b)}$	(0.99) / -	(0.99) / -	0.97 / 0.66
V_b [V]	15.8	1.0	(248.6)
I_a / I_b [A]	25.3 / 0.10	25.2 / 0.12	22.6 / 20.9
V_D [V]	158.5	158.4	158.3
I_D [A]	11.1	11.1	11.1
P_{IN} [W]	1684	1683	1703
$P_{IN(a)}$ [W]	(1684)	(1683)	1438
$P_{IN(b)}$ [W]	-	-	266
P_D [W]	1598	1598	1597
P_L [W]	1501	1500	1500
η_{TR}	94.91	94.97	93.75
Z_{IN} [Ω]	49.4	49.0	34.5

4. CONCLUSION

In this study, we examined the dynamic power transfer system using the PS capacitor topology with multiple transmitter coils, and confirmed the mutual coupling effect. We found that if the mutual coupling between the transmitter coils is small enough compared with the self-inductance, the characteristics in the parallel connection are nearly equal to those of the one-to-one transformer.

In the misalignment characteristic, the average efficiency is 93.2%, and the fluctuation in efficiency is approximately 1%, which is almost constant. However, the fluctuation of output power is large; it becomes a minimum (1121 W, a decline of 25.3%) at the position (x = 120 mm) where the secondary was placed at the middle of the primary transmitters. The average reduction rate of the output power between primary [A] and primary [B] is as large as 12.2%, and measures to suppress fluctuation are necessary for improving the output

When the terminals of primary transmitters that are rarely used for power transmission are released, the reactance of the primary transmitters is small; it was found that current flowed through the coil even when there was a small mutual coupling, causing efficiency reduction. When short-circuiting the coil terminals of the released primary transmitters, the reactance increased and the current flowing through the coil was suppressed. As a result, it was confirmed that efficiency was improved.

When power is transferred, it is necessary to design parallel or open connections of the primary transmitters that do not contribute to power transfer, considering the influence of mutual coupling and reactance, such as widening the arrangement interval or shorting the coil terminal.

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