Wireless Power Transfer System with Ideal Transformer Characteristics Determined Solely by Coil Turns Ratio

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To manufacture wireless power transfer (WPT) products, not only in-depth knowledge of WPT but also various factors, such as power supply, charging circuit, and battery, must be considered, and the complexity is a barrier to the spread of WPT technology. Therefore, if the voltage is easily stepped up/down by the WPT circuit section, a general-purpose power supply and charging circuit can be used, leading to simplification of the system. The S/SP method proposed in this study exhibits the same input/output (I/O) characteristic of an ideal transformer, and the I/O ratio of the WPT circuit is determined from the turn ratio of the coils, similar to a general transformer. In a power feeding experiment, the I/O voltage ratio of the WPT circuit matched the turn ratio of the coils. The power transfer efficiency of the S/SP system was lower than that of the S/P system, but the difference was only 1.0%. Through a secondary side misalignment experiment, we confirmed that the I/O relation was maintained to an extent. In addition, the S/SP method was clarified to have better displacement characteristics than those of the S/P method.

Keywords: wireless power transfer, constant voltage output, S/SP system, ideal transformer, circuit design

1. Introduction

Wireless power transfer (WPT) is being considered to be a promising technology. It is a convenient charging way in which power is supplied to a portable device such as a smartphone and laptop computer by just placing it on a wireless charger⁽¹⁾⁽²⁾. Also, if it can be mounted on desktop devices such as TVs and desktop computers, WPT technology increases installation flexibility of the devices and simplify the complicated power cables behind the desk.

In WPT based on magnetic field coupling, which is called inductive power transfer⁽³⁾, inductors and capacitors are generally connected in series or parallel to transmitting and receiving coils to improve circuit characteristics⁽⁴⁾⁽⁵⁾. The series/series (S/S) WPT system has been widely studied⁽⁶⁾ because of its excellent circuit characteristics such as a theoretical maximum efficiency and input power factor (PF_{IN}) of 1. However, with a constant voltage (CV) power supply driving, the output of the S/S circuit is a constant current (CC). Hence, the output voltage changes due to battery load fluctuations. Therefore, it is necessary to control a converter connected to the charging circuit to prevent the voltage from changing considerably. In addition, it is necessary to obtain a circuit design that does not exceed the rated voltage and

current of a power supply, charging circuit, and battery, and the complexity limits the spread of WPT technology. If the voltage is easily stepped up/down by the WPT circuit section, a general-purpose power supply and charging circuit can be used, resulting in a simpler system. Also, in the case that the I/O voltage can be determined and fixed in the WPT section, a voltage control or a converter for the voltage control can be omitted, which leads to simplification, miniaturization and high efficiency of the system.

Therefore, in this paper, we present a solution to promote the introduction of WPT technology by proposing WPT circuits that it is easy to convert voltage in WPT section. Here, designability is defined as follows, and WPT circuits are proposed and evaluated based on them.

- 1) The output of WPT circuit is constant voltage.
- 2) WPT systems do not require a voltage control.
- 3) Input/output voltage can be determined arbitrarily.

Our team studied a WPT circuit with the ideal transformer characteristics as a circuit that satisfies the above conditions⁽⁷⁾. In that research, we proposed a new S/SP compensation method in which the I/O voltage ratio is determined from the self-inductance or turn ratio of the coils alone. Although the S/SP method was dealt with in a few studies^{(8)–(10)}, no comparison of transmitting efficiency and experimental comparison of secondary misalignment were made with the S/P method⁽¹¹⁾⁽¹²⁾ whose circuit configuration and circuit characteristics are similar. In this study, these two topologies are compared and evaluated through simulations and experiments. In addition, our previous work is extended to examine the change due to the secondary coil displacement, and the superiority of the S/SP method is clarified.

The remainder of this paper is organized as follows:

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Fig. 1. WPT circuit with S/S method

Fig. 2. WPT circuit with S/P method

section 2 analyzes the S/S and S/P topology and describes the characteristics of CC and CV output. Section 3 presents an analysis of a WPT circuit which takes on the characteristic of an ideal transformer. Section 4 discusses the simulation and experimental results verifying the analysis and compares S/SP and S/P topologies. Furthermore, the characteristics of secondary misalignment are clarified by simulation and experiment, comparing both approaches. Finally, section 5 concludes the study and states the direction of our future work.

2. Conventional WPT System

Figure 1 shows a simplified S/S WPT circuit. L_1 , L_2 , and M are the self-inductance and mutual inductance of the primary and secondary side coils, respectively. These follow relationship (1) via the coupling coefficient k :

$$M = k \sqrt{L_1 L_2} \dots \dots \dots (1)$$

2.1 S/S WPT System with Constant Current Output

In (2), capacitances C_{s1} and C_{s2} on the primary and secondary sides resonate with L_1 and L_2 respectively at the resonant frequency $\omega = 2\pi f$:

$$C_{s1} = \frac{1}{\omega^2 L_1}, \quad C_{s2} = \frac{1}{\omega^2 L_2} \dots \dots \dots (2)$$

If the winding resistances r_1 and r_2 are sufficiently small with respect to the reactance component that they can be ignored, the I/O characteristic of the circuit is expressed by (3) using the F-matrix. Here, V_{IN} , V_{OUT} , I_{IN} and I_{OUT} represent input voltage, output voltage, input, current and output current, respectively:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} 0 & -j\omega M \\ \frac{1}{j\omega M} & 0 \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix} \dots \dots \dots (3)$$

When the capacitances are determined by (2), the output becomes CC with CV driving, as shown in (3). Therefore, it is difficult to keep maintain output voltage against load fluctuation and to obtain I/O output and power with the desired value. In practice, a DC-DC converter is used at the output of the WPT circuit to control the voltage and power applied to the load^{(13)–(16)}. In contrast, a WPT circuit with CV output eliminates feedback control at the output. This makes it possible to use a general-purpose converter or omit a converter itself, which is advantageous in system simplicity and cost reduction.

2.2 S/P WPT System The S/P method shown in Fig. 2 is a typical WPT circuit topology with CV output during CV driving. By determining compensation capacitors as shown in (4), a high efficiency, high PF_{IN} , and CV output system can be achieved:

$$C_{s1} = \frac{1}{\omega^2(1-k^2)L_1}, \quad C_{p2} = \frac{1}{\omega^2 L_2} \dots \dots \dots (4)$$

The I/O characteristic of S/P circuit is expressed by (5):

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \frac{M}{L_2} & 0 \\ 0 & \frac{L_2}{M} \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix} \dots \dots \dots (5)$$

There is no voltage fluctuation due to the load change because the S/P method has a CV output characteristic as seen from (5). However, since the voltage gain includes the mutual inductance, coils having the same specification cannot be used for products having different distances between power transmission and reception side, which is disadvantageous for mass production.

2.3 S/S WPT System with Constant Voltage Output

Contrary to the discussion in section 2.1, it has been reported that by driving the power supply at offset frequencies with respect to the resonant frequency f , the output characteristic is changed, and a CV output is obtained at certain frequencies⁽⁷⁾⁽¹⁷⁾⁽¹⁸⁾. In those works, it was shown that by driving at the frequency $\omega_1 = 2\pi f_1$ represented by (6), the I/O relationship of CV is obtained even in the S/S system:

$$f_1 = \frac{1}{\sqrt{1 \pm k}} f \dots \dots \dots (6)$$

Shifting the power supply frequency is equivalent to shifting the resonant frequency of the compensation capacitors. In other words, when the power supply is driven at f in the S/S system, a CV output can be obtained by determining the compensation capacitors as follows:

$$C_{s1} = \frac{1}{\omega^2(1 \pm k)L_1}, \quad C_{s2} = \frac{1}{\omega^2(1 \pm k)L_2} \dots \dots \dots (7)$$

Consequently, the I/O characteristic of the circuit is given by:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \mp \sqrt{\frac{L_1}{L_2}} & 0 \\ \frac{1}{j\omega M} & \mp \sqrt{\frac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix} \dots \dots \dots (8)$$

Equation (8) shows a CV output under CV driving. Moreover, as the non-diagonal components are not all 0, PF_{IN} is not 1.

3. WPT Systems with Ideal Transformer Characteristics

3.1 Analysis of Proposed WPT Circuits When C_{s1} and C_{s2} are determined using (7), it can be seen that the input impedance of the WPT circuit includes an imaginary component and PF_{IN} is not 1. Therefore, an impedance Z_p , in the form of an inductor or capacitor, is connected for power factor compensation such that the non-diagonal component of (8) is 0. As shown in Fig. 3, the I/O characteristics of the circuit are expressed as (9) and (10) by connecting an impedance in parallel on the power supply side or the load side. Here, (9) and (10) correspond to Figs. 3(a) and 3(b),

Fig. 3. WPT circuit with CV output based on S/S method

respectively:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \mp \sqrt{\frac{L_1}{L_2}} & 0 \\ \frac{1}{j\omega M} \mp \frac{1}{Z_{p1}} \sqrt{\frac{L_1}{L_2}} & \mp \sqrt{\frac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix}, \dots \quad (9)$$

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \mp \sqrt{\frac{L_1}{L_2}} & 0 \\ \frac{1}{j\omega M} \mp \frac{1}{Z_{p2}} \sqrt{\frac{L_2}{L_1}} & \mp \sqrt{\frac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix}, \dots \quad (10)$$

Z_{p1} and Z_{p2} are adjusted appropriately so that the non-diagonal component is 0. When $Z_p > 0$, an inductor should be connected, and when $Z_p < 0$, a capacitor should be connected. Table 1 summarizes each compensation method and I/O relationship.

In the circuit shown in Fig. 3, when the compensation circuit conforms to Table 1, the I/O relation of the WPT circuit has the same characteristic as an ideal transformer. Thus, the voltage ratio can be determined solely from the self-inductance. Since it does not include parameters that are determined by the positional relationship of the coils, such as the coupling coefficient (or the mutual inductance), a circuit design using this topology is straightforward. In the previously proposed WPT topologies, the I/O relationship depends on the coupling coefficient, so it is necessary to temporarily create coils, measure the coupling factor, and rewind the coils when performing voltage step up/down in the WPT circuit section. On the other hand, our proposed method does not require such a rewinding (or temporary creation) process. Furthermore, unlike the S/P method, a coil that achieves a certain design requirement can satisfy the same requirement even for products with different gaps between transmitting and receiving coils, simply by changing capacitors.

Here, four WPT topologies have been proposed; however, it is generally more difficult to obtain an inductor with a desired value than a capacitor. Only compensation by capacitors is considered because this study focuses on the ease of

design. In addition, when a parallel capacitor is connected to the first compensation circuit, as viewed from the power supply, the fundamental input impedance is larger than the impedance to the harmonics. This is not suitable for a square wave input. Therefore, the following discussion deals with the S/SP WPT system (which is listed in Table 1 as case D).

3.2 Condition of Ideal Transformer Characteristics

A condition that I/O relationship of S/SP system is determined by the turn ratio of coils is mentioned using solenoid type coils in this section. The relationship between the self-inductance of the solenoid coil and the number of turns of the coil is expressed as:

$$L_i = \frac{\mu_0 i S_i}{l_i} N_i^2, \dots \quad (11)$$

Here, i is 1 or 2, indicating the transmitting or receiving side, μ_0 is the permeability, S is the cross-sectional area of the coil, and l is the coil length. If these parameters are equal for both sides, that is:

$$\mu_{01} = \mu_{02}, \quad S_1 = S_2, \quad l_1 = l_2, \dots \quad (12)$$

then the I/O characteristic of proposed circuit is rewritten as below:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \frac{N_1}{N_2} & 0 \\ 0 & \frac{N_2}{N_1} \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix}, \dots \quad (13)$$

That is, when the capacitances of S/SP circuit are determined as Table 1 and coils with the same shape and dimensions are used on both the primary and secondary sides, the I/O ratio of the WPT circuit can be determined by the turn ratio of the coils alone, as in a general transformer.

4. Verification by Experiment and Simulation

Based on the theory proposed in Section 3, we conducted power feeding experiments and simulations. Solenoid coils as shown in Fig. 4 were created. Litz wire with 22 turns on the primary side and 11 turns on the secondary side was wound around a Mn-Zn ferrite core (NJ Components Co., Ltd., 6H45). Turn ratio of the coils was 2.00. The distance from the center of the primary coil to the center of the secondary coil was 25 mm. Every parameter for the coils in this condition is listed in Table 2. We also conducted the same experiments and simulations for the S/P system and the S/S system with CV output (S/S (CV) system) and compared it with the S/SP system. Figure 5 shows the experimental and simulation circuit structures with the conditions listed in Table 3. In the transmitting side, DC voltage made by regulated power supply was converted to square AC voltage by the full-bridge DC/AC converter with MOSFET module

Table 1. Compensation method for ideal transformer characteristic and its I/O relation

Case	Parallel impedance	Parallel inductor/capacitor	Series capacitor	I/O relation
A	$Z_p = j\omega L_p$	$L_{p1} = kL_1$	$C_{s1} = \frac{1}{\omega^2(1+k)L_1}$	$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} -\sqrt{\frac{L_1}{L_2}} & 0 \\ 0 & -\sqrt{\frac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix}$
B		$L_{p2} = kL_2$	$C_{s2} = \frac{1}{\omega^2(1+k)L_2}$	
C	$Z_p = \frac{1}{j\omega C_p}$	$C_{p1} = \frac{1}{\omega^2 k L_1}$	$C_{s1} = \frac{1}{\omega^2(1-k)L_1}$	$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{L_1}{L_2}} & 0 \\ 0 & \sqrt{\frac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_{OUT} \\ I_{OUT} \end{pmatrix}$
D		$C_{p2} = \frac{1}{\omega^2 k L_2}$	$C_{s2} = \frac{1}{\omega^2(1-k)L_2}$

Fig. 4. Solenoid-type coil

Table 2. Coil parameters

Parameter	Value	Parameter	Value
N_1 [Turn]	22	L_1 [μ H]	85.1
N_2 [Turn]	11	L_2 [μ H]	21.6
k	0.455	M [μ H]	19.5
Q_1	465	r_1 [Ω]	0.0977
Q_2	446	r_2 [Ω]	0.0259
N_1/N_2	2.00	$\sqrt{L_1/L_2}$	1.98

Fig. 5. Experimental/simulation circuit

(SPC Electronics Co., SFM60-11). Behind of WPT circuit, AC voltage was converted to DC voltage by the full-bridge rectifier with fast recovery diode (STMicroelectronics N. V., STTH12012TV1) and by LC smoothing filter whose values were 60 μ H on the inductor and 1000 μ F on the capacitor. In the simulations and experiments, the same DC power supply, DC/AC converter, coil, rectifier, and smoothing filter were used even in each method, but there was no smoothing inductor in the S/S(CV) system because the output current of S/S(CV) WPT circuit was square wave without L_f . The power supply frequency was 85.0 kHz. Table 3 also shows the theoretical optimum output resistance R_{OUTopt} and maximum efficiency η_{max} . R_{OUTopt} of each circuit was calculated based on Ref. (7) and Ref. (12). The load resistance R_L was determined so that R_{OUTopt} was equal to the equivalent AC resistance $^{(19)(20)}$. Hence, R_L was determined as:

$$R_{OUTopt} = \frac{\pi^2}{8} R_L \dots \dots \dots (14)$$

for S/SP and S/P method and as:

$$R_{OUTopt} = \frac{8}{\pi^2} R_L \dots \dots \dots (15)$$

for S/S (CV) method. η_{max} of the S/SP method was 98.5%, which was lower than that of S/P method, but the difference was only 0.4%, and it can be said that the S/SP is a highly efficient circuit topology.

4.1 Power Feeding in Secondary Alignment The power feeding experiment was performed when the primary and secondary coils were facing each other. Here, the DC input voltage V_{DC} was adjusted so that the load power P_L applied to the load resistance was 800 W. Table 4 lists the root

Table 3. Experimental/simulation conditions and theoretical optimal load and maximum efficiency

Parameter	S/SP	S/P	S/S (CV)
f [kHz]	85.0	85.0	85.0
R_L [Ω]	5.91	21.9	9.37
C_{s1} [μ F]	0.0755	0.0526	0.0755
C_{s2} [μ F]	0.299	-	0.299
C_{p2} [μ F]	0.367	0.161	-
R_{OUTopt} [Ω]	7.29	27.0	7.59
η_{max} [%]	98.5	98.9	98.6

Table 4. Experimental result

Parameter	S/SP	S/P	S/S (CV)
V_{DC} [V]	194	166	195
I_{DC} [A]	4.36	5.02	4.53
V_{IN} [V]	189	162	187
I_{IN} [A]	5.32	6.03	9.77
PF_{IN}	0.839	0.847	0.456
V_{OUT} [V]	85.7	161	92.0
I_{OUT} [A]	10.8	5.91	9.66
V_L [V]	72.8	141	91.1
I_L [A]	11.0	5.69	8.79
V_{IN}/V_{OUT}	1.98	0.908	2.03

Fig. 6. Voltage/current waveforms of S/S (CV) system

Fig. 7. Voltage/current waveforms of S/SP system

mean square (RMS) values of each parameter. The square wave parameters were calculated and listed as the square wave RMS values. As shown in Table 4, PF_{IN} of the S/S (CV) system was 0.456, whereas that of the S/SP system was 0.839. This indicates that the power factor was improved by the parallel capacitor. The waveforms of the I/O voltage and current of the S/S (CV) and S/SP system are shown in Figs. 6 and 7, respectively. From Figs. 6(a) and 7(a), it can be seen that PF_{IN} was increased as well. In addition, the input current I_{IN} had a delayed power factor with respect to V_{IN} , and it can be observed that zero voltage switching is realized $^{(21)}$. The I/O voltage ratio of the S/SP WPT circuit was 1.98, which is consistent with the self-inductance ratio and almost the same as the turn ratio, validating the theory. Here, because V_{IN} in each method and V_{OUT} in the S/S (CV) method were square waves, the I/O voltage ratio was calculated using 0.9 times the RMS value of the square wave, which is the RMS value of the fundamental wave.

Figure 8 shows the power transmitting efficiency of the three topologies. In comparison to the S/S (CV) method, the S/SP method showed higher values for both the transformer

Fig. 8. Efficiency of three topologies

Fig. 9. Fluctuation of coil parameter

Fig. 10. Fluctuation of DC input current

Fig. 11. Fluctuation of load power

efficiency η_{TR} and DC efficiency η_{DC} . In contrast, compared with the S/P method, the power transfer efficiency of the S/SP system was lower than that of the S/P system, but the difference was only 0.6% for η_{TR} and 1.0% for η_{DC} . The result of η_{TR} was in accordance with theory. It is considered that the difference in η_{DC} was larger than the difference in η_{TR} because PF_{IN} of the S/P system was higher than that of the S/SP system.

4.2 Power Feeding in Secondary Misalignment

Although our proposed method is intended for an application that is powered by placing it on a wireless charger, imagining an actual charging situation, since the device is roughly placed on the charger, it is essential to clarify power feeding characteristics during displacement. Therefore, we also evaluated the characteristics under the secondary coil misalignment through simulation and experiment. Figure 9 shows the fluctuation of each inductance and coupling coefficient when the secondary coil was displaced in the X direction. The coupling coefficient k decreased with the positional deviation and became almost zero at 60 mm. The value of each inductance also decreased. The value of capacitors and load resistance were fixed at the value when there was no displacement.

Power supply simulation of the misalignment was performed using the circuit simulation software PSIM. In this simulation, V_{DC} was adjusted to obtain P_L of 200 W at the secondary alignment. V_{DC} was kept constant in the case of positional deviation. Fluctuations of the DC input current I_{DC} and P_L during this simulation are shown in Fig. 10 and Fig. 11 respectively. I_{DC} of both the S/P and S/SP systems increased according to the position shift. At the secondary alignment, the DC input current was $I_{DC} = 2.81$ A for the S/P system and was $I_{DC} = 2.47$ A for the S/SP system. At a position shift of 50 mm, these were $I_{DC} = 27.8$ A for the S/P system and $I_{DC} =$

6.64 A for the S/SP system. In the S/P system, the current at 50 mm was 9.90 times the current at the secondary coil alignment, while it was suppressed to 2.69 times in the S/SP system. In addition, the maximum load power was $P_L = 668$ W at 40 mm for the S/P system and was $P_L = 276$ W at 30 mm for the S/SP. It can be said that the S/SP system, with a small increase in input current and load power, is superior than the S/P system in terms of secondary displacement. On the other hand, in the S/S (CV) system, I_{DC} was almost constant but P_L decreased according to the displacement. This was because the imaginary component of the input impedance increased and PF_{IN} decreased in addition to the effect of the efficiency reduction.

Finally, we also conducted the experiment for secondary misalignment and compared the I/O voltage ratio and the power transmitting efficiency of the three topologies. In this experiment, V_{DC} was varied to keep P_L as always 200 W even in the case of displacement. This was done to prevent element breakdown owing to an increase in input current and unfairness due to differences in feeding power. The experimental results are summarized in Figs. 12, 13, 14, and 15. Although the compensation capacitances were fixed in the experiment, Fig. 12 showed that C_{p2} reduced the imaginary component of the input impedance even during displacement state. It is considered that this result was the reason why the fluctuation of the S/SP system with respect to the position shift was smaller than that of the S/S (CV) system. Figure 13 shows the I/O voltage ratio during misalignment. The S/S (CV) and S/SP method have the same I/O relation during CV driving; however, the S/SP system has a smaller voltage fluctuation with respect to the secondary displacement. In the S/SP method, the voltage ratio changed to smaller values due to the displacement, but the minimum value was

Fig. 12. Fluctuation of input power factor

Fig. 15. Fluctuation of DC efficiency

Fig. 13. Fluctuation of I/O voltage ratio

Fig. 16. Fluctuation of theoretical optimum resistance

Fig. 14. Fluctuation of AC efficiency

1.86 at 20 mm. Also, the ratio gradually increased as the displacement further advanced, reaching 2.37 at 40 mm and 4.30 at 50 mm. The voltage difference between at 0 mm and at 20 mm was 8.58 V, and the one between at 0 mm and at 40 mm was 22.5 V. A general-purpose charging circuit usually has an operating voltage range of 20 V to 30 V, so that there is a possibility that the S/SP method can be used even when the displacement is large.

Figure 14 shows that the fluctuation of transformer efficiency was smaller in the S/SP system than in the S/P system. Figure 15 displays that the DC efficiency was up to 2.40% higher in the S/P system. However, the difference between the two efficiencies became smaller, and above 40 mm, the S/SP system was more efficient. This was because that the fluctuation of the optimum resistance in S/P method with respect to the displacement was bigger than that in S/SP method as shown in Fig. 16. These experimental results show that the S/SP system has better characteristics for secondary misalignment than the S/P system.

5. Conclusion

As a solution to promote the introduction of WPT technology, we examined the WPT system that can use a general-purpose DC power supply and charging converter. The proposed WPT circuit with the ideal transformer characteristics can easily step up/down the voltage by the WPT circuit section because the I/O ratio of the WPT circuit is determined solely by the coils turn ratio, as in a general transformer. In the power feeding experiment for secondary alignment, the I/O voltage ratio and self-inductance ratio coincided, and the value almost matched the turn ratio of the coils. In addition, compared with the S/P system with similar circuit configuration and characteristics as the S/SP system, the power transfer efficiency of the S/SP system was lower than that of the S/P system. However, the difference was only 0.6% for the AC efficiency and 1.0% for the DC efficiency, and it can be said that the S/SP method has the same power feeding capacity as the S/P method. Moreover, in simulation and experiment assuming secondary misalignment, the S/SP method showed little change with respect to displacement in terms of input current, load power and efficiency, and thus exhibited superior characteristics to the S/P system.

In this study, the power feeding experiments and simulations were performed with solenoid type coils, but in the case of WPT where mounting in small products is taken into account circular coils, like a Qi standard⁽¹⁾, have been extensively employed. Our future work investigates whether the I/O ratio is obtained based on the turn ratio of the coils in the case of using circular coils as well.

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