Wireless Power Transfer System whose Input / Output Ratio is Determined Only by Self-Inductance

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***Abstract*—Wireless power transfer (WPT) technology is a power transmission system that does not necessitate an electrical contact. This study focuses on a simple design for WPT products through an analysis of a series/series-parallel (S/SP) WPT circuit scheme that exhibits the same input/output (I/O) characteristics as ideal transformers. S/SP is a circuit topology characterized by capacitors connected in series to a primary coil and in series-parallel to a secondary coil. Moreover, even with the inductor-capacitor-capacitor/series (LCC/S) scheme, determining a specific value for the compensation coil results in ideal transformer characteristics. To validate the theoretical results of the study, an experiment and a simulation are conducted, where solenoid type coils of the same shape and external dimension for the primary and secondary sides are applied for the S/SP and LCC/S WPT systems. Specifically, the experimental and simulated findings confirm that the winding number ratio of the coils and the I/O voltage ratio of the WPT system are in agreement.**

Keywords—wireless power transfer, compensation capacitor, input/output characteristics, ideal transformer characteristics, S/SP system, LCC/S system

I. INTRODUCTION

From the point of view of environmental problems and efficient energy utilization, plug-in hybrid vehicles and electric vehicles (EVs) have recently been attracting attention. Nevertheless, such vehicles may be characterized by significant mechanical drawbacks. For instance, EVs operate on electricity supplied via electric cables and connectors, a conductive method that invites the danger of electric shock during recharge in rainy weather. Needless to say, the charging cable needs to be connected to the car body daily, which can create a sense of annoyance for the EV user. In addition, the momentum of motorization is increasing in all markets, as shown by the spread of electric-assisted bicycles and the expansive distribution of automated guided vehicles in factories, as well as the palpable rise in the demand for electronic appliances, such as smart phones and wearable devices. In other words, expectations for wireless power transfer (WPT) technology are increasing. This study aims to promote the introduction of WPT products to the market by focusing on the ease of design.

In contrast to the conductive charging method, WPT is a transmission system that does not need an electrical contact, thereby preventing the danger of electric shock. It is a convenient charging method in which power is supplied to a vehicle simply by parking the vehicle, and to a device only by placing it on the wireless charger. In a WPT based on a magnetic field coupling system (which is also called inductive power transfer), the method of connecting inductors and capacitors in series or in parallel to the transmitting and receiving coils, respectively, is commonly observed [1-3]. Moreover, through the application of compensation circuits, devices can be designed to achieve specific characteristics, such as efficiency improvement and power factor compensation. The S/SP method [4-6], in which compensation capacitors are connected in series to the primary coil and in series-parallel to the secondary coil, provides constant voltage (CV) output during CV driving, so the output voltage can be kept constant against load fluctuation. Moreover, it is also reported that the CV output can be maintained even if the coupling coefficient fluctuates due to positional deviation [4,5], indicating the superiority of the topology.

In this study, by newly analyzing the circuit using an F-matrix, the method for deciding the compensation capacitors is clearly presented, and it is shown that the input/output (I/O) relation of the circuit is equivalent to the ideal transformer. Theoretical formulas are also derived for maximum efficiency and optimum load, which takes maximum efficiency. In addition, under limited conditions, as with the general transformer, it is possible to determine the I/O voltage/current ratio using only the turn ratio of the coils, demonstrating that it is an advantageous circuit system in product design.

Moreover, we show that the ideal transformer characteristics can likewise be obtained by the inductor-capacitor-capacitor/series (LCC/S) method [7,8]. WPT by LCC compensation has been regarded as an effective circuit topology for dynamic wireless power transfer in EVs [7-9]. In particular, the LCC/S scheme has been reported to have excellent characteristics as well as CV output [2,7,8]. The compensation inductor used for the LCC method is not in a coupled state with the transmitting and receiving coils but is determined to have an arbitrary value. In addition, because it is a parameter contributing to the I/O ratio, by taking a certain value, the ideal transformer characteristics can also be obtained in the LCC/S system.

The remainder of this paper is organized as follows. Section II analyzes the series/series (S/S) topology which is the most basic circuit of WPT, briefly describes the characteristics, and showed the problems of the system. Section III presents an analysis of the WPT circuit, which takes on ideal transformer characteristics. Section IV discusses the simulation and the experimental results verifying the analysis. Finally, Section V emphasizes specific conclusions and states the direction of our future work.

II. S/S WPT System

The S/S method has been widely studied and used because it has excellent circuit characteristics, such as a simple circuit structure, as well as a theoretical maximum efficiency and an input power factor of 1. Fig. 1 shows a simplified S/S type WPT circuit. L_1, L_2, and M indicate the self-inductance and mutual inductance of the primary and secondary side coils, respectively, which follows relationship (1) via the coupling coefficient k:

$$M = k\sqrt{L_1 L_2}\,. \tag{1}$$

A. *Constant Current Output of S/S System*

In (2), capacitances C_1 and C_2 on the primary and secondary sides, respectively, are determined to resonate with L_1 and L_2 at the resonant frequency $\omega = 2\pi f$:

$$C_1 = \frac{1}{\omega^2 L_1},\ C_2 = \frac{1}{\omega^2 L_2}\,. \tag{2}$$

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

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} 0 & -j\omega M \\ -j\dfrac{1}{\omega M} & 0 \end{pmatrix} \begin{pmatrix} V_d \\ I_d \end{pmatrix}. \tag{3}$$

In a two-port network, by expressing the I/O relationship of the circuit by the F-matrix, the output characteristics when driven by a CV (or Constant Current (CC)) can be easily confirmed. In addition, if the diagonal elements (or non-diagonal elements) of the matrix are all 0, it can be determined that the input power factor is 1, and zero-voltage switching (ZVS) is possible. When the capacitances are determined by (2), the output becomes CC with CV driving, as shown in (3). Therefore, it is difficult to keep the output voltage constant against load fluctuation and to obtain I/O voltage and power with the desired values.

In practice, a DC–DC converter is applied to the output of the WPT circuit to control the voltage and power applied to the load [10, 11]. On the contrary, a circuit design that considers the output eliminates feedback control. This makes it possible

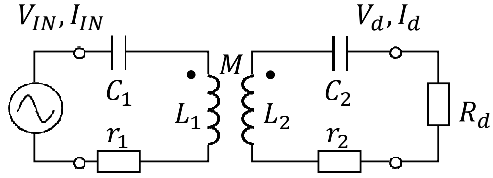


Fig. 1 WPT circuit with S/S method

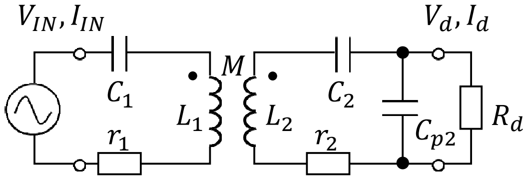


Fig. 2 WPT circuit with S/SP method

to use a general-purpose DC–DC converter, which is advantageous in mass production and cost reduction.

B. *Constant Voltage Output of S/S System*

Contrary to the discussion in Section II-A, it has been reported that by driving the power supply at offset frequencies with respect to f, the output characteristics can be changed, and a CV output is obtained at certain frequencies [2,12,13]. In [12,13], it is shown that by driving at the frequency $\omega_1 = 2\pi f_1$ represented by (4), the I/O relationship of CV can be obtained even in an S/S system:

$$f_1 = \frac{1}{\sqrt{1 \pm k}} f\,. \tag{4}$$

Shifting the power supply frequency is equivalent to shifting the resonant frequency of the compensation capacitors. That is, 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 in (5):

$$\begin{cases} C_1 = \dfrac{1}{\omega^2 (1 \pm k) L_1} \\ C_2 = \dfrac{1}{\omega^2 (1 \pm k) L_2} \end{cases}. \tag{5}$$

Consequently, the I/O characteristics of the circuit are given by:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \mp\sqrt{\dfrac{L_1}{L_2}} & 0 \\ -j\dfrac{1}{\omega M} & \mp\sqrt{\dfrac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_d \\ I_d \end{pmatrix}. \tag{6}$$

Specifically, (6) shows CV output under CV driving. Moreover, as the non-diagonal components are not all 0, the input power factor is not 1.

III. WPT Systems with Ideal Transformer Characteristics

A. Analysis of S/SP System

Fig. 2 shows the WPT circuit of the S/SP system. When C_1 and C_2 are determined as in (5), the I/O relationships of the system can be obtained through:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \mp\sqrt{\frac{L_1}{L_2}} & 0 \\ -j\frac{1}{\omega M} \mp j\omega C_{p2}\sqrt{\frac{L_2}{L_1}} & \mp\sqrt{\frac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_d \\ I_d \end{pmatrix}. \quad (7)$$

Correspondingly, C_{p2} is determined so that the non-diagonal component becomes 0. Considering $C_{p2} > 0$, each capacitance is respectively determined by:

$$\begin{cases} C_1 = \dfrac{1}{\omega^2(1-k)L_1} \\ C_2 = \dfrac{1}{\omega^2(1-k)L_2}, \\ C_{p2} = \dfrac{1}{\omega^2 k L_2} \end{cases} \quad (8)$$

and the I/O characteristics are expressed by:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{L_1}{L_2}} & 0 \\ 0 & \sqrt{\frac{L_2}{L_1}} \end{pmatrix} \begin{pmatrix} V_d \\ I_d \end{pmatrix}. \quad (9)$$

Equation (9) shows that the I/O characteristics of the S/SP system are determined only by the self-inductances of the coils. Because it does not include parameters that are determined by the positional relationship of the coils, such as the coupling coefficient (or mutual inductance), this topology is simpler than the previously proposed WPT topologies in terms of product design and production.

Next, we show the power transfer efficiency of the S/SP method. By the loss generated in the coils and the power consumed by the load resistance, the efficiency is expressed as:

$$\eta_{TR} = \frac{R_d I_d^2}{r_1 I_1^2 + r_2 I_2^2 + R_d I_d^2} = \frac{R_d}{\frac{1}{r_2}\left(\frac{1}{kQ_2}\right)^2 R_d^2 + R_d + r_2\left(1+\frac{Q_2}{Q_1}\right)}. \quad (10)$$

Here, I_1 and I_2 are the current flowing through the primary and secondary coils, respectively, and Q ($= \omega L / r$) is the index that represents the performance of the coil. From $\partial\eta_{TR} / \partial R_d = 0$, the optimal load R_{dopt} and the maximum efficiency η_{TRmax} are, respectively:

$$R_{dopt} = kQ_2 r_2\sqrt{1+\frac{Q_2}{Q_1}} \quad (11)$$

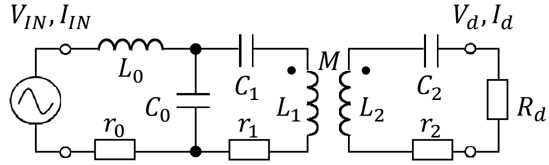


Fig. 3 WPT circuit with LCC/S method

and

$$\eta_{TR\max} = \frac{1}{1+\frac{2}{kQ_2}\sqrt{1+\frac{Q_2}{Q_1}}}. \quad (12)$$

B. Analysis of LCC/S System

Fig. 3 displays a simplified WPT circuit diagram of the LCC/S system, where C_0, L_0, and r_0 are the compensation capacitor, inductor, and its winding resistance on the primary side, respectively. Based on [7,8], each capacitance is determined by:

$$\begin{cases} C_0 = \dfrac{1}{\omega^2 L_0} \\ C_1 = \dfrac{1}{\omega^2(L_1 - L_0)}. \\ C_2 = \dfrac{1}{\omega^2 L_2} \end{cases} \quad (13)$$

At this stage, the I/O relationships of the circuit are expressed by:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \frac{L_0}{k\sqrt{L_1 L_2}} & 0 \\ 0 & \frac{k\sqrt{L_1 L_2}}{L_0} \end{pmatrix} \begin{pmatrix} V_d \\ I_d \end{pmatrix}. \quad (14)$$

The compensating inductor L_0 does not couple with the transmitting and receiving coils via a toroidal core or the like. That is, as its value can be arbitrarily determined, the I/O voltage (/current) ratio has a high design freedom. Specifically, determining L_0 as in (15), transforms the I/O relationships, as in (9), and provides the ideal transformer characteristics, even in the LCC/S system:

$$L_0 = kL_1. \quad (15)$$

IV. Verification by Experiment and Simulation

Guided by the theory proposed in Section III, we conducted a power feeding experiment to validate the SS/P scheme, along with a power feeding simulation for the LCC/S method via the circuit simulation software PSIM. Solenoid coils as shown in Fig. 4 (a) were created. The relationship between the self-inductance of the solenoid coil and the number of turns of the coil is expressed as:

Table I. Transformer parameters

N_1 [Turn]	42	L_1 [μH]	230
N_2 [Turn]	12	L_2 [μH]	18.3
k	0.487	M [μH]	31.6
Q_1	511	r_1 [Ω]	0.240
Q_2	213	r_2 [Ω]	0.0456
N_1 / N_2	3.50	$\sqrt{L_1/L_2}$	3.56

Table II. Experimental/simulation conditions

Method	SS/P	LCC/S
f [kHz]	85.0	
R_L [Ω]	4.83	7.49
L_0 [μH]	-	112
r_0 [Ω]	-	0.567
C_0 [μF]	-	0.0314
C_1 [μF]	0.0297	0.0283
C_2 [μF]	0.373	0.192
C_{p2} [μF]	0.403	-

$$L_i = \frac{\mu_{0i} S_i}{l_i} N_i^2 \qquad (i \in 1,2) \tag{16}$$

Here, μ_0 is the permeability, S is the cross-sectional area of the coil, and l is the coil length. If these parameters hold:

$$\mu_{01} = \mu_{02}, S_1 = S_2, l_1 = l_2, \tag{17}$$

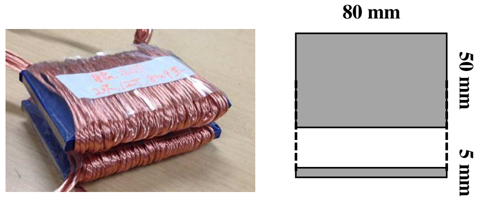
and (9) can be rewritten as:

$$\begin{pmatrix} V_{IN} \\ I_{IN} \end{pmatrix} = \begin{pmatrix} \frac{N_1}{N_2} & 0 \\ 0 & \frac{N_2}{N_1} \end{pmatrix} \begin{pmatrix} V_d \\ I_d \end{pmatrix}. \tag{18}$$

That is, when coils having the same shape and dimensions on the primary side and the secondary side are used, the I/O ratio of the WPT circuit can be determined by the turn ratio of the coils alone, as in a general transformer.

In this experiment, litz wire with 42 turns on the primary side and 12 turns on the secondary side was wound around a ferrite core, as shown in Fig. 4 (b), and coils with a turn ratio of 3.50 were created. The distance from the center of the primary coil to the center of the secondary coil is 15 mm, and every parameter for the coils in this setup was as shown in Table I. Fig. 5 shows the simulation and experimental circuit structures, with the conditions as shown in Table II. The input voltage V_{IN} was adjusted so that the power P_L applied to the load resistance was 150 W.

The waveforms of the I/O voltage and current are shown in Fig. 6 and Fig.7. In both S/SP and LCC/S systems, the input current I_{IN} has a delayed power factor with respect to V_{IN}, and it can be seen that ZVS can be realized. V_{IN} in both methods, and the output voltage V_d in the LCC/S method are square waves. Table III shows the root mean square (RMS) value of each parameter result. Because V_{IN} in both methods and V_d in the LCC/S method are square waves, the I/O voltage ratio was



(a) Coils (b) Ferrite core

Fig. 4 Solenoid-type coil and core

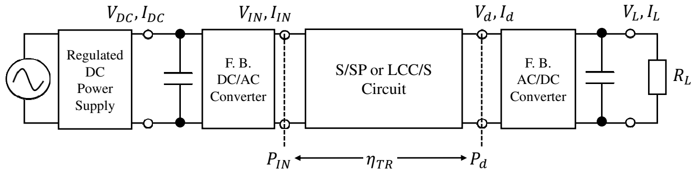
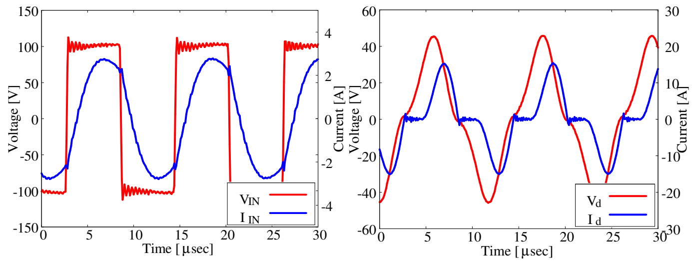
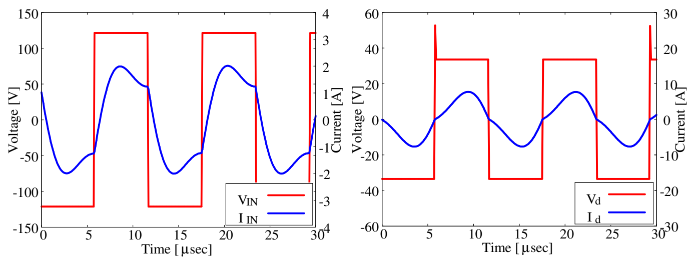


Fig. 5 Experimental/simulation circuit



(a) Input (b) Output

Fig. 6 Voltage/current waveforms of S/SP system



(a) Input (b) Output

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

Table III. Experimental/simulation results

Method	SS/P	LCC/S
V_{IN} [V]	108	121
I_{IN} [A]	2.11	1.51
pf	0.728	0.862
V_d [V]	27.4	33.8
I_d [A]	8.08	5.18
η_{TR} [%]	97.3	96.7
V_{IN} / V_d	3.54	3.60

calculated using 0.9 times the RMS value of the square wave, which is the RMS value of the fundamental wave. In the S/SP method, the difference between the voltage ratio and the square root (SQRT) of the self-inductance ratio is -0.574%, and the difference between the voltage ratio and the turns ratio is +1.04%. In the LCC/S method, difference between the voltage ratio and the SQRT of the self-inductance ratio is +1.41%, and the difference between the voltage ratio and the turns ratio is +2.86%. Both systems are generally consistent, demonstrating the validity of the theory.

In addition, in the S/SP system, the same power supply experiment was conducted under load fluctuation. Fig. 8 shows the I/O voltage ratio when the load resistance changes, and also displays the SQRT of the self-inductance ratio and the turns ratio. The voltage ratio did not change significantly, even when load fluctuation occurred, and the results were roughly consistent with the theory.

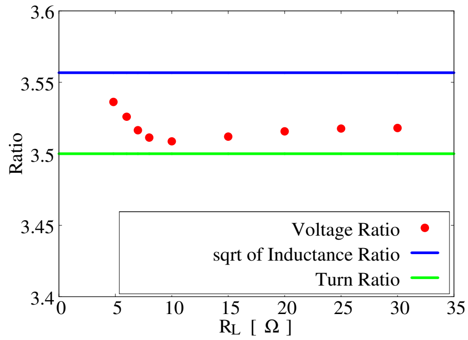


Fig. 8 Lad fluctuation characteristics of ratio

V. Conclusion

We focused on ease in designing WPT products, and showed how to select the compensation capacitor and inductor so that the I/O ratio could be determined solely by the self-inductances of the coils through an analysis of the S/SP and LCC/S systems. Results of the power supply experiment and simulation carried out for S/SP and LCC/S methods indicated that the I/O voltage ratio matched the turns ratio of coils having the same shape and dimensions on the primary side and the secondary side. The experiment also showed that the voltage ratio did not change even when the load resistance fluctuated. Similar experiments must be conducted in the future when gap changes occur.

In this study, the power feeding experiment and simulation were performed with solenoid type coils, but in the case of WPT where mounting in small products and EVs is taken into account circular coils have been extensively employed. Our future work investigates whether the I/O ratio can be obtained based on the turn ratio of the coils in the case of using circular coils as well.

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