

Global Sensitivity Analysis of Wireless Power Transfer System in Domino Structure

Xinyu Hou , Member, IEEE, Hui Xia , and Yong Shi , Member, IEEE

Abstract—This article proposes a global sensitivity analysis method of a wireless power transfer (WPT) system in domino structure. The sensitivity of system characteristics to capacitor deviations is studied to identify sensitive parameters that cause significant uncertainty in the output. The effect of capacitor deviations on output current, power transfer efficiency, and power factor is comprehensively investigated. Interactions between capacitors are considered, and the main effect index S and the total effect index S_T are calculated by Sobol' method. Its results indicate that the output current, power factor, and efficiency are slightly affected by the deviation of the capacitor in series with the receiving coil. Interaction between capacitors has a significant effect on the output current and power factor. Finally, the experimental setups of the three-coil and four-coil WPT systems are built. The experimental results show that when the resonant capacitor on the receiving side is varied within $\pm 10\%$, the fluctuation of the output current is less than 1.5%, the maximum variation in efficiency is less than 2%, and the power factor remains almost above 0.9. The validity of the proposed global sensitivity analysis method is verified.

Index Terms—Domino structure, global sensitivity analysis, wireless power transfer.

I. INTRODUCTION

WIRELESS power transfer (WPT) systems are widely used in many fields, such as electric vehicles [1], unmanned aerial vehicles [2], and biomedical implants [3]. Two-coil WPT system is very common in short-distance applications. For mid-range applications, multicoil WPT system in domino structure is more suitable [4]. Nowadays, WPT system in domino structure has been a research hotspot [5]. The excellent characteristics of the domino structure WPT system were analyzed, assuming that the circuit parameters are equal to their nominal value [6]. However, nonideal compensation is a common problem for WPT systems. Due to cost limitations and manufacturing errors, parameter variations in their nominal values are inevitable. Besides, there are also variations in parameters due to changes in operating temperature and other reasons [7], [8]. Variations in component parameters can affect the transfer

efficiency and output characteristics of the WPT system [9], [10], [11].

Some researchers have studied the sensitivity of the WPT system to parameter variations. In [12], the effect of compensation capacitance errors on the output characteristics of the series-series compensated WPT system was analyzed. In [13], the sensitivity of the constant current characteristic of the *LCL*-P compensated WPT system to the deviation of compensation inductors and capacitors was analyzed. Li et al. [14] studied the sensitivity of constant current/constant voltage output characteristics of the double-sided *LCC* compensation network to topology parameters. Liu et al. [15] compared the sensitivity of higher order compensation topologies with the basic second-order compensation circuits in terms of primary inductance change and compensation capacitor change. In [16], the three-coil WPT system was analyzed in terms of the sensitivity of the constant current characteristic to changes in compensation parameters. However, the above literature studied the sensitivity by changing one-factor-at-a-time (OAT), which is not suitable for visualizing the effects of parameter deviations on the domino structure WPT system with multiple parameters. Moreover, capacitors are more susceptible to environmental factors than inductors. So, more attention has been paid to the output characteristics under capacitance variations.

Some scholars have studied the effect of capacitor deviation on system performances using numerical analysis methods. In [17], the sensitivity of *LCC-LCC* compensated topology was investigated through the singular values analysis. In [18], the Monte Carlo method was used to investigate the effect of compensation component deviations on *SS*- and *LCC*-compensated WPT systems. In [19], the sensitivity of output power and efficiency to variations of resonant parameters in the *LCC*-compensated WPT system was studied. For single-parameter variation, the LT spice simulation method is used. For multiparameter variations, exhaustive analysis and Monte Carlo methods are applied. Wang et al. [20] studied the sensitivity of *LCC-S* compensated WPT system performance to capacitor errors through the numerical methodology and Sobol' sensitivity method. All the above studies are based on the two-coil structure WPT system and did not discuss the effect of interactions between capacitors on the system. For the domino structure WPT system with complex coupling, the effect of interactions between capacitors on system performance needs to be considered. Therefore, a global sensitivity analysis is required.

This article presents a global sensitivity analysis of the domino structure WPT system based Sobol' method. Taking into account

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The authors are with the School of Electrical and Control Engineering, Shaanxi University of Science and Technology, Xian 710000, China (e-mail: houxinyu@sust.edu.cn; 220611006@sust.edu.cn; shiyong@sust.edu.cn).

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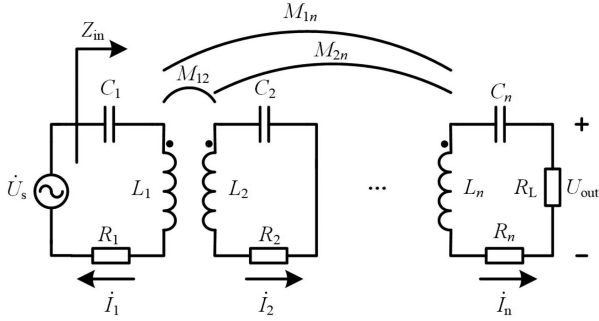


Fig. 1. Equivalent circuit diagram of wireless power transfer in domino Structure.

interactions between capacitors, the main effect index S and the total effect index S_T together quantify the sensitivity of the WPT system in domino structure to capacitor deviations. The effect of capacitor deviations on output current, power transfer efficiency, and power factor is studied. The robustness of the domino structure WPT system is tested in the presence of capacitor deviations. The most sensitive and least sensitive parameters of the domino structure WPT system can be found. It can help to ease the calibration stage by focusing on the sensitive parameters without spending time on nonsensitive ones.

The rest of this article is organized as follows. In Section II, the domino structure WPT system is modeled and capacitor deviation analysis is performed. In Section III, the effect of capacitor deviation on output current, transfer efficiency, and power factor is studied by Sobol' method. In Section IV, the experimental prototype is built to validate the feasibility of theoretical analysis. Finally, Section V concludes this article.

II. SYSTEM MODELING AND CAPACITOR DEVIATION ANALYSIS

A. Domino Structure WPT System Modeling

The equivalent circuit of wireless power transfer in domino structure is shown in Fig. 1. L_i and R_i represent the inductance and the equivalent series resistance (ESR) of the coil i . C_i represents the compensation capacitance of coil i . \dot{U}_s represents ac power supply. \dot{I}_i represents the induced current in the coil i . R_L represents the load resistance. M_{ij} represents the mutual inductance of coil i and coil j . The input impedance of the system is represented by Z_{in} .

This article defines matrix \mathbf{L} , \mathbf{R} , and \mathbf{C} as

$$\mathbf{L} = \begin{bmatrix} L_1 & M_{12} & \cdots & M_{1n} \\ M_{21} & L_2 & \cdots & M_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ M_{n1} & M_{n2} & \cdots & L_n \end{bmatrix} \quad (1)$$

$$\mathbf{R} = \begin{bmatrix} R_1 & 0 & \cdots & 0 \\ 0 & R_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & R_n + R_L \end{bmatrix} \quad (2)$$

$$\mathbf{C} = \begin{bmatrix} C_1^{-1} & 0 & \cdots & 0 \\ 0 & C_2^{-1} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & C_n^{-1} \end{bmatrix}. \quad (3)$$

Based on Kirchhoff's voltage law and first harmonic analysis theory, we establish a matrix model in the steady-state domain of the wireless power transfer system in domino structure

$$\begin{bmatrix} \dot{U}_s \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \left(j\omega\mathbf{L} + \mathbf{R} + \frac{1}{j\omega}\mathbf{C} \right) \begin{bmatrix} \dot{I}_1 \\ \dot{I}_2 \\ \vdots \\ \dot{I}_n \end{bmatrix}. \quad (4)$$

When input voltage U_s , load resistance R_L , and operating frequencies ω are given, we can calculate the current in coils by (4). Output current I_{out} , output voltage U_{out} , and output power P_{out} can be obtained by

$$\begin{cases} I_{out} = |\dot{I}_n| \\ U_{out} = |\dot{I}_n| R_L \\ P_{out} = |\dot{I}_n|^2 R_L. \end{cases} \quad (5)$$

The load impedance of ac power supply Z_{in} is written by

$$Z_{in} = \frac{\dot{U}_s}{\dot{I}_1}. \quad (6)$$

The power factor δ can be calculated by

$$\delta = \frac{\text{Re}(Z_{in})}{|Z_{in}|}. \quad (7)$$

The power transfer efficiency η can be calculated by

$$\eta = \frac{I_n^2 R_L}{I_1^2 R_1 + I_2^2 R_2 + \cdots + I_n^2 R_n + I_n^2 R_L} \times 100\%. \quad (8)$$

It should be noted that the ideal inverter and the ideal rectifier are used in the modeling process to simplify the system model expression. The losses in the inverter, the rectifier, and the compensation capacitors are ignored in the theoretical analysis.

B. Capacitor Deviation Analysis of WPT System

It can be found from (1), (2), and (3) that there are three types of parameters (inductance, resistance, and capacitance) in the WPT system. The factors that affect parameter deviation mainly include tolerance, temperature, humidity, and aging. In most WPT systems, capacitors (capacitance) are more susceptible to temperature, humidity, and aging compared with inductors (inductance and resistance). Therefore, only capacitor deviation analysis is studied in this article.

Common capacitor tolerances include J ($\pm 5\%$), K ($\pm 10\%$), and M ($\pm 20\%$). In terms of temperature, C0G (NP0) capacitors have the best temperature characteristics, the temperature character of the capacitor is 30 ppm/ $^\circ\text{C}$ with temperature ranges from $-55\text{ }^\circ\text{C}$ to $+125\text{ }^\circ\text{C}$. In addition, the X7R capacitor is also commonly used, with a variation range of $\pm 15\%$ when the temperature ranges from $-55\text{ }^\circ\text{C}$ to $+125\text{ }^\circ\text{C}$. Therefore,

the sensitivity analysis in this article is based on a capacitor deviation range of $\pm 10\%$.

For wireless power transfer system in domino structure, the capacitor deviation analysis is very challenging because there are multiple compensation capacitors in the coupler, each coil is connected in series with a capacitor, and there are many complex cross-coupling mutual inductances between coils. In addition, it is also necessary to consider the interactions between capacitors.

Common sensitivity analysis methods include scatter plots, OAT, derivative-based local methods. The OAT methods are that each time one design variable is changed over its entire range while all other parameters are held fixed at their initial value. Local derivative-based methods involve taking the partial derivative of the output with respect to an input factor. The above methods cannot detect the presence of interactions between input variables and is unsuitable for nonlinear models. For the WPT system in domino structure, it can be seen from Fig. 1 and (4) that the relationship between the system output and the capacitor deviation is clearly nonlinear. The global sensitivity analysis method is more appropriate when the model response is nonlinear with respect to its inputs.

III. SENSITIVITY ANALYSIS

In this article, the main purpose of the sensitivity analysis is uncertainty assessment and deeper understanding. First, the robustness of the system output is tested in the presence of uncertainty. The uncertainty is reduced by identifying model inputs that cause significant uncertainty in the output. This input is focused on during the design of the system parameters to improve the system robustness. Second, sensitivity analysis is used to deepen the understanding of the relationship between system inputs and outputs. The primary sensitivity analysis allows for the identification of sensitive parameters that need to be focused on, without spending time on nonsensitive parameters.

A. Variance-Based Sensitivity Analysis

Variance-based sensitivity analysis is one of the common global sensitivity analysis methods. It is often referred to as the Sobol' method or Sobol' indices, after Ilya Meyerovich Sobol'. Its main advantage is that it allows full exploration of the input space, accounting for interactions, and nonlinear responses. The sensitivity of the domino structure WPT system can be analyzed more precisely and comprehensively by the variance-based sensitivity analysis method. In addition, the variation in the output caused by varying each of the parameters alone can be measured by the main effect sensitivity index S_i , and the interactions between parameters can be measured by the total effect sensitivity index S_{Ti} . The high- and low-sensitivity parameters of the domino structure WPT system can be easily identified by the sensitivity indices.

From the black box perspective, any model of the wireless power transfer in domino structure can be seen as a function Y . X is a vector of m uncertain inputs X_1, X_2, \dots, X_m . Y is a chosen model output. For WPT system in domino structure, uncertain inputs X is the capacitor deviation, and Y can be $U_{\text{out}}, I_{\text{out}}, P_{\text{out}}, \delta$, or η . The proposed global sensitivity analysis

scheme of WPT system in domino structure is shown in Fig. 2. It should be noted that the multiple outputs can be analyzed by multiple sensitivity analyses, respectively. For most wireless power transfer systems, the uncertain inputs are independently and uniformly distributed. Y may be decomposed as

$$Y = f(\mathbf{X}) = f_0 + \sum_{i=1}^m f_i(X_i) + \sum_{i < j}^m f_{ij}(X_i, X_j) + \dots + f_{1,2,\dots,m}(X_1, X_2, \dots, X_m) \quad (9)$$

where f_0 is a constant, f_i is a function of X_i , and f_{ij} is a function of X_i and X_j .

It can be seen from (9) that f_i represents the effect of varying X_i alone, and f_{ij} represents the effect of varying X_i and X_j simultaneously, additional to the effect of their individual variations. Variance expression of Y can be decomposed in (10) the following way:

$$\text{Var}(Y) = \sum_{i=1}^m V_i + \sum_{i < j}^m V_{ij} + V_{12\dots m} \quad (10)$$

where

$$\begin{cases} V_i = \text{Var}_{X_i}(E_{X_{\sim i}}(Y | X_i)) \\ V_{ij} = \text{Var}_{X_{ij}}(E_{X_{\sim ij}}(Y | X_i, X_j)) - V_i - V_j \\ \dots \end{cases} \quad (11)$$

$X_{\sim i}$ represents the set of all variables except X_i . By variance decomposition, the variance attributed to each input and their interaction effects are obtained.

S_i , called first-order sensitivity index or main effect index, is shown in

$$S_i = \frac{V_i}{\text{Var}(Y)}. \quad (12)$$

S_i represents the main contribution to the output variance of the main effect of X_i . The effect of deviations in C_i on the system output can be quantified by S_i . However, all capacitors deviate from their nominal values with almost the same tendency when environmental parameters change. Therefore, the effect of the interaction between capacitors on the system output should be of concern. High sensitivity indexes S_{ij}, S_{ijk} , and so on should be analyzed. However, for a WPT system in domino structure, the number of variables is large, the cross-coupling between coils is complex, which could be computationally demanding.

Therefore, S_{Ti} , called total effect index or total order index, is introduced, as shown in (13). All variance caused by its interactions with any other input variables is included, as shown in (14)

$$S_{Ti} = \frac{E_{X_{\sim i}}(\text{Var}_{X_i}(Y | X_{\sim i}))}{\text{Var}(Y)} = 1 - \frac{\text{Var}_{X_{\sim i}}(E_{X_i}(Y | X_{\sim i}))}{\text{Var}(Y)} \quad (13)$$

$$S_{Ti} = S_i + \sum_{i \neq j} S_{ij} + \sum_{i \neq j \neq k} S_{ijk} + \dots + S_{12\dots m}. \quad (14)$$

The calculation process of Sobol indices is summarized below.

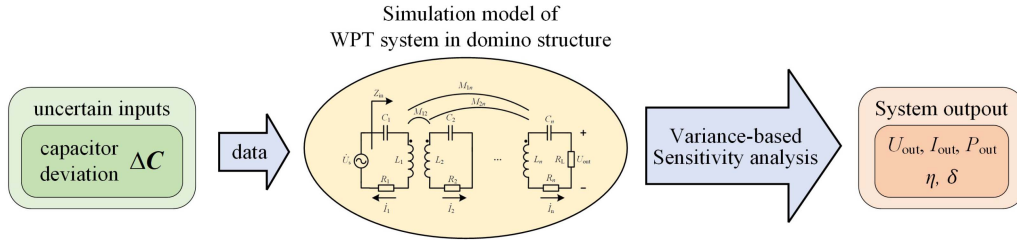


Fig. 2. Proposed global sensitivity analysis scheme of WPT system in domino structure.

TABLE I
SYSTEM PARAMETERS OF SIMULATION MODEL

Parameter	Value	Parameter	Value
Dc power supply	30 V	inductance L_i	340.1 μH
Load resistance R_L	250 Ω	Capacitance C_i	3 nF
Number of turns	30	M_{12}, M_{23}, M_{34}	73.27 μH
Layer of the coil	1	M_{13}, M_{24}	25.05 μH
Radii of the coil	150 mm	M_{14}	10.67 μH
Transmission distance	100 mm	ESR of the coil	0.5 Ω

- Specify the number of variables m and sampling ranges. For the n -coil WPT system, there are n input variables, C_1, C_2, \dots, C_n . The number of variables m is equal to the number of coils n , and capacitance sampling ranges are $\pm 10\%$ of nominal.
- Generate an $N \times 2m$ sample matrix from the Sobol sequence. N is the number of sampling points and is 10^5 in this article to ensure accuracy.
- Construct the calculation matrix according to the sampling matrix and calculate output current I_{out} , efficiency η , and power factor δ separately at each point.
- Calculate the main effect index S and the total effect index S_T using the Monte Carlo estimator.

The methodology of the proposed global sensitivity analysis is demonstrated with the use of a three-coil and four-coil WPT system in domino structure. The system parameters are listed in Table I. The operating frequency is selected as the constant current frequency. The constant current frequencies can be obtained according to [6]. With the parameters of the coupler fixed, the sensitivity of system performance to capacitor deviation is analyzed in this article. The proposed method can also be used to analyze the sensitivity of the domino WPT system when the coupler parameters are changed.

B. Effect of Capacitor Deviation on Output Current

For the WPT system, the stability of the output current or voltage of the system is very important. The main effect index S and the total effect index S_T of output current I_{out} are calculated when the three-coil and four-coil WPT systems operate at a constant current frequency. The results are shown in Fig. 3.

For the three-coil WPT system, there are two constant current frequencies, 142.91 kHz and 177.87 kHz, respectively. When the

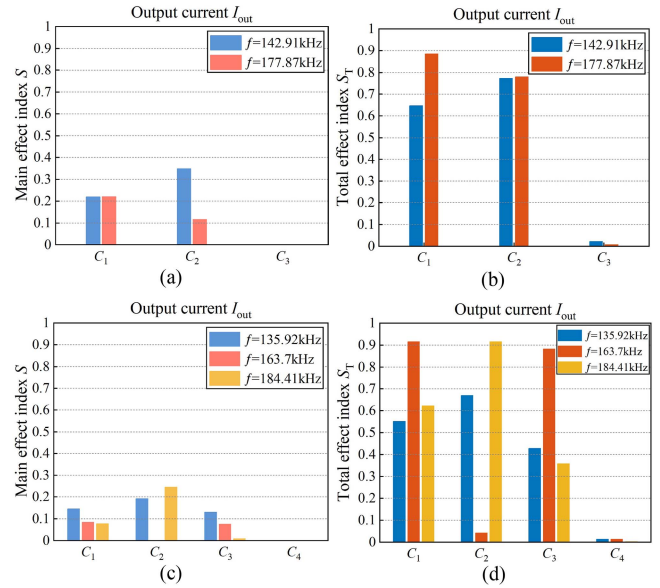


Fig. 3. Sobol indices of output current I_{out} . (a) Main effect index S for three-coil WPT system. (b) Total effect index S_T for three-coil WPT system. (c) Main effect index S for four-coil WPT system. (d) Total effect index S_T for four-coil WPT system.

three-coil WPT system operates at constant current frequency, the output current is affected by deviations in C_1 or C_2 , and hardly affected by deviations in C_3 . In terms of C_1 and C_2 , it can be seen that the total effect index S_T is higher than the main effect index S , as shown in Fig. 3(a) and (b). Therefore, the output current is greatly affected by the interaction between C_1 and C_2 . A large fluctuation in the output current may be caused if both C_1 and C_2 deviate from their nominal value.

For the four-coil WPT system, there are three constant current frequencies, 135.92 kHz, 163.7 kHz, and 184.41 kHz. When the four-coil WPT system operates at 135.92 kHz, the output current is affected by deviations in C_1, C_2 , or C_3 . However, the output current is almost unaffected by deviations in C_4 . When the four-coil WPT system operates at 163.7 kHz, the output current is affected by deviations in C_1 or C_3 , while the output current is hardly affected by deviations in C_2 or C_4 . When the four-coil WPT system operates at 184.41 kHz, the output current is affected by deviations in C_1, C_2 , or C_3 , and almost unaffected by deviations in C_4 . As shown in Fig. 3(c) and (d), the total effect index S_T is significantly higher than the main effect index S . Thus, the output current is greatly affected by

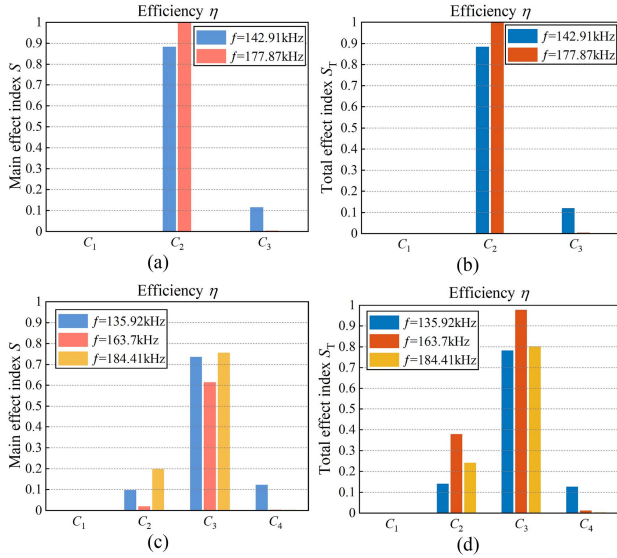


Fig. 4. Sobol indices of power transfer efficiency η . (a) Main effect index S for three-coil WPT system. (b) Total effect index S_T for three-coil WPT system. (c) Main effect index S for four-coil WPT system. (d) Total effect index S_T for four-coil WPT system.

the interactions between C_1 , C_2 , and C_3 . Only the effect of the interaction between C_1 and C_3 on the output current needs to be considered when the four-coil WPT system operates at a fixed constant current frequency of 163.7 kHz.

As shown in Fig. 3, C_3 in the three-coil WPT system and C_4 in the four-coil WPT system have small main and total effect indices. Therefore, the output current is almost unaffected by deviations in the capacitor connected to the receiving coil. By comparing the main effect index S and the total effect index S_T , it can be found that interaction between capacitors has a significant effect on the output current. The conclusion is still valid even if the number of coils increases or the load resistance changes. Besides, the effect of capacitor deviation on the transmitting coil current or relay coil current can also be analyzed by the proposed method.

C. Effect of Capacitor Deviation on Power Transfer Efficiency

The effect of capacitor deviation on power transfer efficiency η is analyzed here. Fig. 4 presents the bars showing the main effect index S and the total effect index S_T of power transfer efficiency η when the three-coil and four-coil WPT systems operate at constant current frequency.

In the three-coil WPT system, when the operating frequency is 142.91 kHz, the deviation of C_2 has the greatest effect on efficiency, the deviation of C_3 has less effect on efficiency, and the deviation of C_1 hardly affects power transfer efficiency. When the operating frequency is 177.87 kHz, efficiency is only affected by the deviation of C_2 . As shown in Fig. 4(a) and (b), the main effect index S and the total effect index S_T are fairly the same. The interactions between capacitors have a negligible effect on the efficiency.

In the four-coil WPT system, when the operating frequency is 135.92 kHz, the deviation of C_3 has the greatest effect on

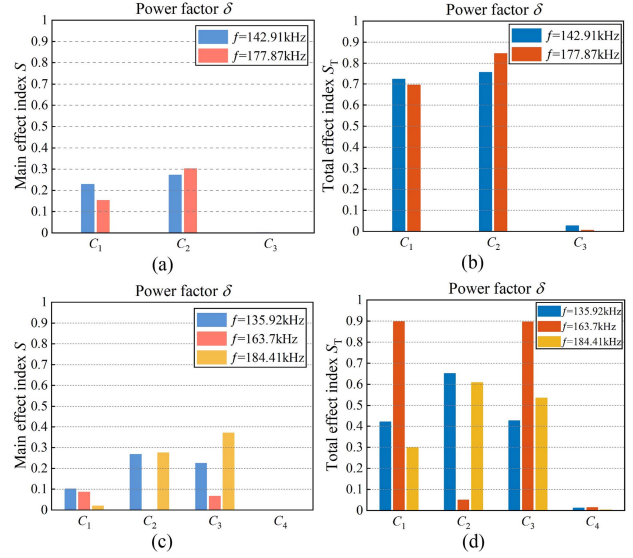


Fig. 5. Sobol indices of power factor δ . (a) Main effect index S for three-coil WPT system. (b) Total effect index S_T for three-coil WPT system. (c) Main effect index S for four-coil WPT system. (d) Total effect index S_T for four-coil WPT system.

efficiency, the deviation of C_2 or C_4 has less effect on efficiency, and the deviation of C_1 hardly affects power transfer efficiency. When the operating frequency is 163.7 kHz or 184.41 kHz, the deviation of C_3 has the greatest effect on efficiency, and the deviation of C_2 has less effect on efficiency. The efficiency is almost unaffected by deviations in C_1 or C_4 . When the operating frequency is 135.92 kHz or 184.41 kHz, the total effect index S_T is almost the same as the main effect index S . However, the total effect index S_T is higher than the main effect index S at 163.7 kHz. Therefore, when the four-coil WPT system operates at 163.7 kHz, the effect of the interaction between C_2 and C_3 on the efficiency is not negligible.

For the three-coil WPT system, the efficiency is greatly affected by the deviation of C_2 . For the four-coil WPT system, the efficiency is greatly affected by the deviation of C_3 . However, power transfer efficiency is almost unaffected by the deviation of the capacitor in series with the transmitter coil, and slightly affected by the deviations in the capacitor in series with the receiving coil. It should be noted that the sensitivity of efficiency may be changed when the system parameters are changed. When the load resistance is small, the effect of the deviation of the capacitor in series with the receiving coil on the efficiency is greater and cannot be neglected.

D. Effect of Capacitor Deviation on Power Factor

The reactive power caused by capacitor deviation may not be neglected, the effect of capacitor deviation on power factor should also be studied. Fig. 5 presents the bars showing the main effect index S and the total effect index S_T of power factor δ when the three-coil and four-coil WPT systems operate at constant current frequency.

When the three-coil WPT system operates at 142.91 kHz or 177.87 kHz, the power factor is affected by the deviation of C_1

or C_2 . However, the power factor is almost unaffected by the deviation of C_3 . In comparison with Fig. 4(a) and (b), it can be found that the total effect index S_T is higher than the main effect index S . The composite effects between C_1 and C_2 are strong in terms of power factor. A significant reduction in power factor may occur if C_1 or C_2 are both deviated.

For the four-coil WPT system, when the operating frequency is 135.92 kHz or 184.41 kHz, the power factor is affected by deviations in C_1 , C_2 , or C_3 . However, the deviation of C_4 has little effect on the power factor. When the operating frequency is 163.7 kHz, the power factor is affected by deviations in C_1 or C_3 while the power factor is hardly affected by deviations in C_2 or C_4 . From Fig. 5(c) and (d), the total effect indices S_T is higher than the main effect indices S , especially at 163.7 kHz. Therefore, the interaction between C_1 and C_3 has a significant effect on the power factor at the operating frequency of 163.7 kHz. Besides, when the four-coil WPT system operates at 135.92 kHz or 184.41 kHz, the effect of interactions between C_1 , C_2 , and C_3 on the power factor cannot be ignored.

As shown in Fig. 5, the power factor is almost unaffected by the deviation of C_3 in the three-coil and C_4 in the four-coil WPT system. It is concluded that the power factor is almost unaffected by deviations in the capacitor connected to the receiving coil. However, the power factor is greatly affected by the interactions between the capacitors.

In the above analysis, it is worth noting that the output current and power factor are almost unaffected by the deviation of the capacitor in series with the receiving coil. The transfer efficiency is hardly affected by the deviation of the capacitor in series with the transmitter coil, and is slightly affected by deviations of the capacitor in series with the receiving coil. The interactions between the capacitors greatly affect output current and power factor, and slightly affect efficiency. This conclusion is valid for the domino structure WPT system with any number of coils. However, it should be noted that the sensitivity of the domino structure WPT system is affected by many factors, such as distance between coils and relative position. Thus, a specific WPT system needs to be analyzed comprehensively using the proposed method to identify the high- and low-sensitive parameters.

When the domino WPT system is in constant current mode, the overall system performance can be evaluated by output current, efficiency, and power factor. According to the above sensitivity analyses of the three indicators, it can be concluded that the deviation of C_3 has the least effect on the overall performance of the three-coil WPT system. A capacitor with relatively low accuracy can be used for C_3 to reduce the product cost, and high precision capacitors should be used for C_1 and C_2 to avoid deterioration of system performance caused by capacitor deviation. For the four-coil WPT system, when the operating frequency is 135.92 kHz or 184.41 kHz, the system performance is affected by deviations in C_1 , C_2 , or C_3 . However, only deviations in C_1 or C_3 affect the system performance at 163.7 kHz. When the four-coil WPT system operates at a fixed constant current frequency of 163.7 kHz, capacitors with relatively low accuracy can be used for C_2 and C_3 , and high-precision capacitors should be used for C_1 and C_3 .

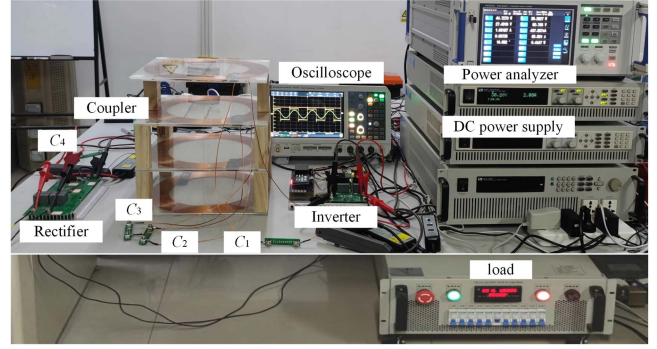


Fig. 6. Photograph of the experimental setup.

TABLE II
PARAMETERS OF THE EXPERIMENTAL SETUP

Parameter	Value	Parameter	Value
Dc power supply	30 V	load resistance	250Ω
L_1	355.2 μH	C_1	2.967 nF
L_2	357.1 μH	C_2	2.964 nF
L_3	359.9 μH	C_3	2.972 nF
L_4	360.1 μH	C_4	2.952 nF

IV. EXPERIMENT VERIFICATION

An experimental setup of the WPT system in domino structure is built, as shown in Fig. 6, to verify the sensitivity analysis method proposed in this article. The supply voltage is 30 V. The load resistance is 250 Ω. All the coils are fabricated by litz wire with a single wire diameter of 1.5 mm. Each coil has 30 turns and a radius of 15 cm. Distance between adjacent coils is 10 cm. An LCR meter was used to measure coils' self-inductance, mutual inductance, and capacitance. The parameters of the experimental setup are listed in Table II.

As shown in Tables I and II, the parameters of the experimental setup are different from those of the simulation model, and thus the experimental operating frequency has a certain deviation from the simulation one. For the three-coil WPT system, the simulated frequency is 142.91 kHz, while the experimental frequency is 141.638 kHz. For the four-coil WPT system, the simulated frequency is 163.7 kHz, while the experimental frequency is 158.723 kHz. Fig. 7 illustrates the experimental waves of the inverter output voltage u_s , inverter output current i_1 , and output voltage u_o . As shown in Fig. 7(a), when the three-coil WPT system operates at the constant current frequency of 141.638 kHz, the output power is 23.4 W, and the dc–dc efficiency is 80.32%. As shown in Fig. 7(b), when the four-coil WPT system operates at the constant current frequency of 158.723 kHz, the output power is 37.1 W, and the dc–dc efficiency is 80.64%.

Figs. 8 and 9 show the transfer characteristics versus compensation capacitance for the three-coil and four-coil WPT system, respectively. When the resonant capacitor has a value of 2.66 nF, 2.88 nF, 2.96 nF, 3.14 nF, 3.32 nF, respectively, the output current, the ac–ac efficiency, and the power factor can be measured

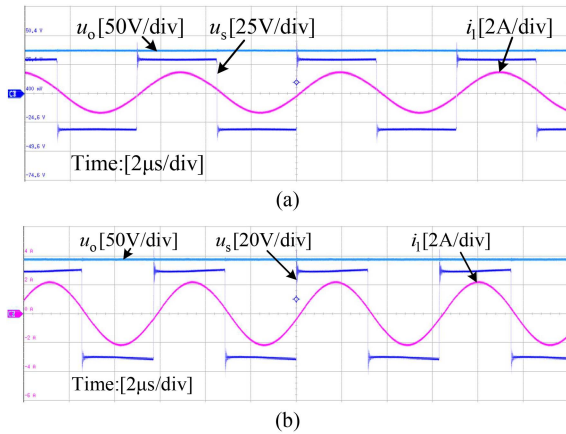


Fig. 7. Experimental waveforms of u_s , i_1 , and u_o . (a) Three-coil WPT system at $f = 141.638$ kHz. (b) Four-coil WPT system at $f = 158.723$ kHz.

by the power analyzer, the experimental results are plot in Figs. 8 and 9.

As shown in Fig. 8(a), when C_3 is varied within $\pm 10\%$, the output current of the three-coil WPT system is almost maintained at 0.33 A, and the fluctuation of the output current is less than 1.5%. However, with a 10% deviation in C_1 or C_2 , the output current drops below 0.2 A. For the four-coil WPT system, it can be seen from Fig. 9(a) that the output current is almost maintained at 0.44 A with a fluctuation of 1.5% when C_2 or C_4 is changed. However, when C_1 or C_3 is varied within $\pm 10\%$, the fluctuation of the output current is more than 50%.

It can be seen from Fig. 8(b) that changes in C_3 have the least effect on the experimental efficiency of the three-coil WPT system. When C_3 is varied within $\pm 10\%$, the maximum variation of efficiency is less than 2%. However, the maximum variation of efficiency is more than 5% when C_1 or C_2 is varied. As shown in Fig. 9(b), changes in C_2 or C_4 have the least effect on the experimental efficiency of the four-coil WPT system. When C_2 or C_4 is varied within $\pm 10\%$, the maximum variation of efficiency is less than 1.5%. It should be noted that there is an error between the experiment and the simulation. The simulation efficiency does not vary with C_1 , but the experimental efficiency is affected by changes in C_1 . This is because changes in C_1 cause a drop in power factor, as shown in Figs. 8(c) and 9(c), which will cause the primary inverter's current to increase, resulting in a large change in efficiency. For the three-coil WPT system, Fig. 8(c) shows that the power factor remains almost above 0.9 when C_3 is varied within $\pm 10\%$. However, a 10% deviation in C_1 causes the power factor to drop below 0.6. The power factor will also be significantly reduced when C_2 is lower than its nominal value. For the four-coil WPT system, Fig. 9(c) shows that the power factor remains almost above 0.95 when C_2 or C_4 is varied within $\pm 10\%$. However, changes in C_1 or C_3 cause a significant reduction in the power factor. With a 10% deviation in C_1 or C_3 , the power factor drops below 0.5.

The experimental results show that the transfer characteristics of the three-coil WPT system are almost affected by the variation of C_3 . The transfer characteristics of the four-coil WPT system are slightly affected by changes in C_2 or C_4 . However, variations

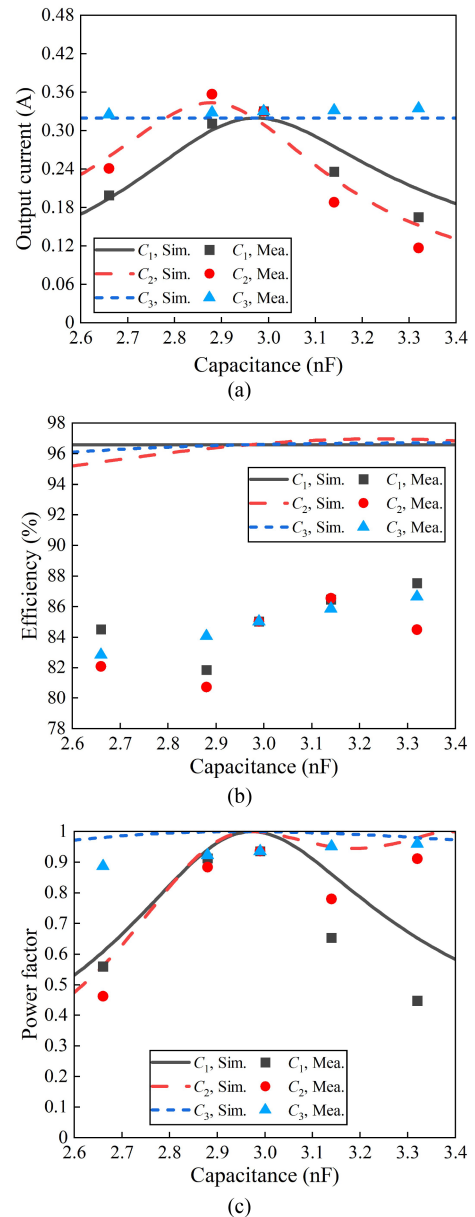


Fig. 8. Simulation and experimental results of the transfer characteristics versus compensation capacitance for three-coil WPT system. (a) Output power. (b) Power transfer efficiency. (c) Power factor.

in C_1 or C_3 cause significant reductions in the output current and power factor of the four-coil system. The experimental results match well with the theoretical analysis. It should be mentioned that there are some errors between the experimental and simulation results. The main reason for the errors is that the parameters of the experimental setup cannot be completely the same as those of the simulation model, as shown in Tables I and II. On the other hand, the losses of converters, rectifiers, and compensation capacitors are ignored in the simulation. Domino structure WPT system modeling is not completely accurate due to ignoring parasitic parameters. However, the experimental results have the same trend as the simulation results although there exist some discrepancies between the simulations and the measurements.

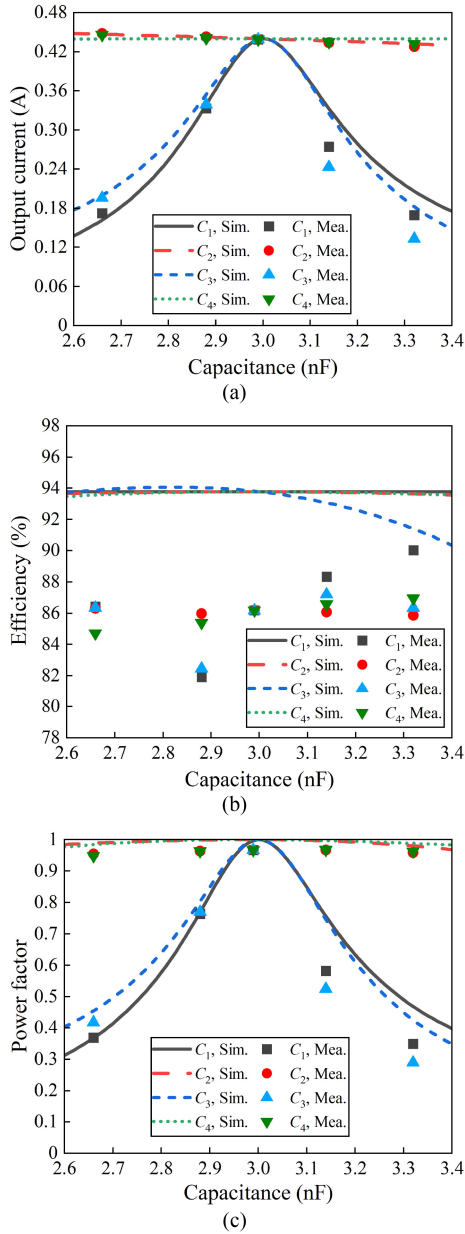


Fig. 9 Simulation and experimental results of the transfer characteristics versus compensation capacitance for four-coil WPT system. (a) Output power. (b) Power transfer efficiency. (c) Power factor.

V. CONCLUSION

In this article, the global sensitivity of the WPT system in domino structure was studied based on Sobol' method. The effect of capacitor deviations on the output current, transfer efficiency, and power factor was analyzed in detail. The effect of interactions between capacitors on system performance was considered, and the main effect index S and the total effect index S_T were calculated to quantify the effect of capacitor deviation on the system performance. Its results show that the output current, power factor, and efficiency are almost unaffected by deviations in the capacitor connected to the receiving coil. The interactions between the capacitors greatly affect output current

and power factor, and slightly affect efficiency. The experimental results show that when the resonant capacitor on the receiving side, C_3 in the three-coil system and C_4 in the four-coil system, is varied within $\pm 10\%$, the fluctuation of the output current is less than 1.5%, the maximum variation of efficiency is less than 2%, and the power factor remains almost above 0.9. The experimental results are consistent with the theoretical analysis. The feasibility of the proposed global sensitivity analysis method is verified.

REFERENCES

- [1] K. Li, J. Chen, X. Sun, G. Lei, Y. Cai, and L. Chen, "Application of wireless energy transmission technology in electric vehicles," *Renewable Sustain. Energy Rev.*, vol. 184, Sep. 2023, Art. no. 113569.
- [2] H. Ren, Z. Zhang, Z. Peng, L. Li, and C. Pan, "Energy minimization in RIS-assisted UAV-enabled wireless power transfer systems," *IEEE Internet Things J.*, vol. 10, no. 7, pp. 5794–5809, Apr. 2023.
- [3] H. Le-Huu and C. Seo, "Dual-band transmitter for wireless power transfer to biomedical implant applications," *IEEE Antennas Wireless Propag. Lett.*, vol. 22, no. 6, pp. 1461–1465, Jun. 2023.
- [4] P. Vishnuram et al., "Review of wireless charging system: Magnetic materials, coil configurations, challenges, and future perspectives," *Energies*, vol. 16, no. 10, May 2023, Art. no. 4020.
- [5] X. Hou, J. Su, H. Hu, Y. Sun, and Y. Su, "A multirelay magnetic coupling wireless power transfer system with hybrid output characteristics," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 11, no. 6, pp. 6150–6158, Dec. 2023.
- [6] X. Hou, Y. Su, Z. Zuo, X. Dai, and Y. Fei, "A novel analysis method based on quadratic eigenvalue problem for multirelay magnetic coupling wireless power transfer," *IEEE Trans. Power Electron.*, vol. 36, no. 9, pp. 9907–9917, Sep. 2021.
- [7] H. Patel, L. Levesque, L. Dunleavy, H. Morales, and M. Laps, "Centering simulation model based on actual versus nominal capacitance value," in *Proc. IEEE 17th Annu. Wireless Microw. Technol. Conf.*, 2016, pp. 1–4.
- [8] M. H. El-Husseini, P. Venet, G. Rojat, and M. Fathallah, "Effect of the geometry on the aging of metalized polypropylene film capacitors," in *Proc. IEEE 32nd Annu. Power Electron. Specialists Conf.*, 2001, pp. 2061–2066.
- [9] A. Hakemi, D. Jovanovic, D. M. Vilathgamuwa, G. Walker, and J. Pauls, "Generic uncertainty parameter analysis and optimization of series-series wireless power transfer system for robust controller design," *IEEE Trans. Ind. Electron.*, vol. 69, no. 4, pp. 4107–4118, Apr. 2022.
- [10] Y. Cheng, G. Qian, G. Chen, H. Sun, and G. Wang, "Sensitivity analysis of L-type impedance matching circuits for inductively coupled wireless power transfer," *Int. J. Appl. Electromagn. Mech.*, vol. 61, no. 1, pp. 1–11, Aug. 2019.
- [11] A. K. Swain, S. Devarakonda, and U. K. Madawala, "Modeling, sensitivity analysis, and controller synthesis of multipickup bidirectional inductive power transfer systems," *IEEE Trans. Ind. Inform.*, vol. 10, no. 2, pp. 1372–1380, May 2014.
- [12] Y. Wang, F. Lin, Z. Yang, and Z. Liu, "Analysis of the influence of compensation capacitance errors of a wireless power transfer system with SS topology," *Energies*, vol. 10, no. 12, Dec. 2017, Art. no. 2177.
- [13] Y. Yao, X. Liu, Y. Wang, and D. Xu, "Modified parameter tuning method for LCL/P compensation topology featured with load-independent and LCT-unconstrained output current," *IET Power Electron.*, vol. 11, no. 8, pp. 1483–1491, Jul. 2018.
- [14] D. Li, X. Wu, J. Gao, J. Lu, and W. Gao, "Sensitivity analysis and parameter optimization of inductive power transfer," *IEEE Access*, vol. 9, pp. 166951–166961, 2021.
- [15] Y. C. Liu, J. Zhang, C. K. Tse, C. Zhu, and S. -C. Wong, "General pathways to a higher order compensation circuits for IPT converters via sensitivity analysis," *IEEE Trans. Power Electron.*, vol. 36, no. 9, pp. 9897–9906, Sep. 2021.
- [16] L. Yang, X. Li, Z. Xu, S. Liu, Z. Dong, and Y. Wu, "Analysis and design of a high-efficiency three-coil WPT system with constant current output," *IET Electric Power Appl.*, vol. 14, no. 10, pp. 1933–1943, Oct. 2020.
- [17] J. Deng et al., "Frequency and parameter combined tuning method of LCC-LCC compensated resonant converter with wide coupling variation for EV wireless charger," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 10, no. 1, pp. 956–968, Feb. 2022.

- [18] F. J. López-Alcolea, J. Vázquez, E. J. Molina-Martínez, P. Roncero-Sánchez, and A. P. Torres, "Monte-carlo analysis of the influence of the electrical component tolerances on the behavior of series-series- and LCC-compensated IPT systems," *Energies*, vol. 13, no. 14, Jul. 2020, Art. no. 3663.
- [19] Y. Wang, A. Mostafa, H. Zhang, Y. Mei, C. Zhu, and F. Lu, "Sensitivity investigation and mitigation on power and efficiency to resonant parameters in an LCC network for inductive power transfer," *IEEE J. Emerg. Sel. Topics Power Electron.*, vol. 3, no. 3, pp. 443–453, Jul. 2022.
- [20] Y. Wang, Z. Yang, F. Lin, J. Dong, and P. Bauer, "Frequency tracking method and compensation parameters optimization to improve capacitor deviation tolerance of the wireless power transfer system," *IEEE Trans. Ind. Electron.*, vol. 70, no. 12, pp. 12244–12253, Dec. 2023.



Xinyu Hou (Member, IEEE) received the B.S. degree in automation and the Ph.D. degree in control theory and control engineering from Chongqing University, Chongqing, China, in 2017 and 2022, respectively.

He is currently a Lecturer with the School of Electrical and Control Engineering, Shaanxi University of Science and Technology, Xi'an, China. His current research interests include inductive power transfer technology and power electronics.



Hui Xia received B.S. degree in electrical engineering and its automation from Chongqing Jiaotong University, Chongqing, China, in 2020. She is currently working toward the M.Sc. degree in electrical engineering from the Shaanxi University of Science and Technology, Xi'an, China.

Her current research interests include inductive power transfer technology.



Yong Shi (Member, IEEE) was born in Henan, China, in 1974. He received the B.S. degree in industrial electrical automation from Xi'an Architecture and Technology University, Xi'an, China, and the M.Sc. and Ph.D. degrees in electrical engineering from Xi'an Jiaotong University, China, in 2002 and 2005, respectively.

From 2005 to 2007, he was a Lecturer with Shanghai Jiaotong University, Shanghai, China. From 2007 to 2016, he was a Senior Engineer with Xi'an Action Power Electrical Company Ltd., Xi'an, China. Since

2016, he has been a member of College of Electrical and Control Engineering, Shaanxi University of Science and Technology, Xi'an, China, where is currently a Professor. He has authored and coauthored more than 50 papers in journals and conferences in power electronics.

His main research interests include soft-switching dc–dc converters, power factor correction converters, matrix converter, and multilevel converter.