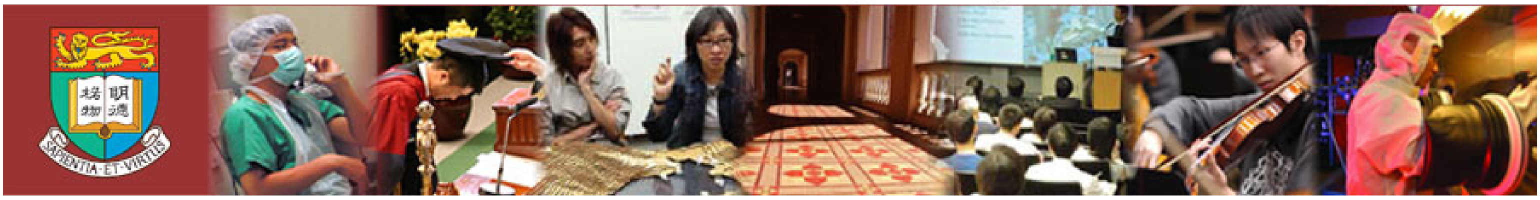

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Parameter Identification of Wireless Power Transfer Systems Using Input Voltage and Current

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***Abstract*—Wireless power transfer (WPT) systems based on the use of resonators with high quality factors are highly sensitive to the parameters of the resonant tanks. While the inductance terms can be theoretically calculated, the mutual inductance terms require very accurate measurements of the coil dimensions, locations and orientations. Slight deviations of these measurements could therefore lead to significant errors. In addition, capacitors have fairly large tolerance in terms of their capacitance, making it difficult to assume their rated values in the determination of the optimal operating frequency of the WPT systems. In this paper, a parameter identification method for WPT systems based on the measurements of the input voltage and current is presented. Using an evolutionary algorithm, accurate parameter values required for modeling the WPT system can be determined. This method has been successfully illustrated in a 3-coil WPT system. Good agreements between calculated and measured parameters have been achieved.**

I. INTRODUCTION

Wireless power transfer based on near-field magnetic coupling and resonance of two loop resonators was reported by Nicola Tesla a century ago [1]. From then on, a lot of research efforts about transcutaneous energy systems for medical implants [2-6], the inductive power transfer (IPT) systems [7-14], and wireless charging systems for portable equipment such as mobile phones [15-20] have been reported. Recently, a lot of research activities are focused on improving the performance of wireless power transfer systems, such as extending the transfer distance, improving energy efficiency and widening the operating frequency. Most of these projects assume that all the parameters of the system are known or can be calculated or measured [19, 21]. If such assumption is valid, one can choose proper operating frequency and input voltage/current to make the system operate at the optimal point of maximum efficiency, or maximum power transfer, or other reasonable purposes, e.g., to transfer constant power to the load.

As more complex WPT systems with multiple coil resonators are being investigated, sometimes it is difficult to calculate or measure all the parameters of the wireless power transfer system accurately. Let assume a wireless power transfer system with multiple coils, such as with domino resonators [21, 22], or have complicated structure [23], the calculation or measurement of mutual inductances between each two coils will be extremely difficult because the mutual inductance values are highly sensitive to coil dimensions, locations and orientations. Any slight changes in the distance or orientation of the resonators may lead to significant errors in the mutual inductance values. In addition, the capacitance of the resonant capacitors used in the wireless power transfer system is usually close but not exactly equal to the rated value. For these reasons, using nominal values of the system parameters of the wireless power transfer systems will not lead to accurate prediction of optimal operating frequency and system analysis.

In this paper, a method to identify the system parameters based on the input voltage and current measurements and the use of a Genetic Algorithm (GA) [24-26] is presented. This method avoids the requirements of prior knowledge of all parameter measurements and overcomes the component tolerance issue In order to simplify the analysis, a wireless power transfer systems with 3 identical resonators as shown in Fig.1 is used to verify the proposed concept. However, the method can be applied to any wireless power transfer systems in principle. The information of the coils is given in Table I. In Fig.1, all the coils are coaxial to each other. The 1st coil on the left is the transmitter, and it connected to the power source. The 3rd coil is the receiver which is connected to a resistor box as the load.

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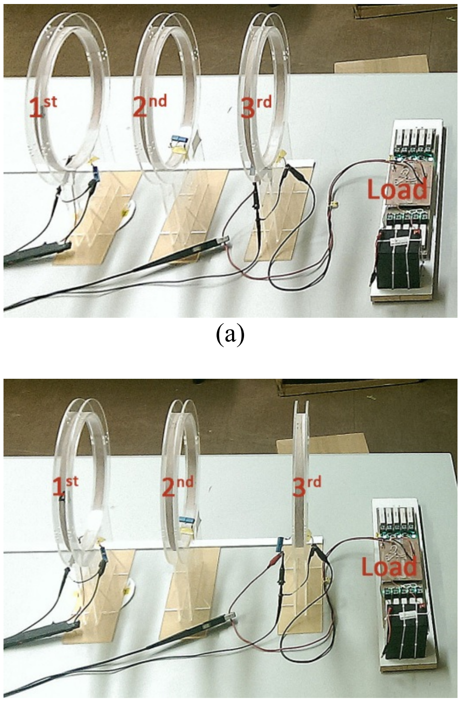

(a)

(b)

Fig.1 A wireless power transfer system with 3 resonators: (a) d_{12}=0.2m, d_{23}=0.2m; (b) d_{12}=0.2m, d_{23}=0.25m. (Please refer to Table III)

TABLE I. PRAMETERS OF THE RESONATORS

Radius of Windings	150mm
Number os tuns	11
Layer of the wire	1
Axial lenth of the wire	15mm
Structure of the Litz wire	Φ0.1mm*120strans Outer Φ1.7㎜
Inductance (Calculated)	82.03uH
Capcitance (Nominal value) #1 through #11	1nF
Wire resistance (at 530kHz)	0.9998 Ohm

II. IDEAS AND ASUMPTIONS

Consider a wireless power transfer system consisting of n coils as shown in Fig.2, if L_i is the self-inductance of the i^{th} coil, R_i is the coil resistance of the i^{th} coil, and M_{ij} is the mutual-inductance between the i^{th} coil and the j^{th} coil, then the system could be described in a matrix equation (1).

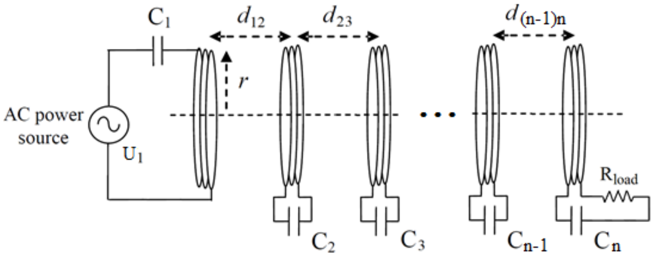

Fig.2 An n-coil domino system for wireless power transfer

If all the parameters in the matrix in (1) are known for a given frequency f, one can get the input impedance of the system by giving a certain input of U_{1f}, calculating the input current I_{1f}, and then,

$$Z_f = \frac{U_{1_f}}{I_{1_f}} \tag{2}$$

Hence, a set of impedance values at different frequencies along the frequency axis: $Z_{f_1}, Z_{f_2}, \cdots, Z_{f_m}$ can be obtained, where f_i is one of the different frequencies, and Z_{f_i} is the input impedance at f_i.

$$(Z_{f_1}, Z_{f_2}, \cdots, Z_{f_m}) = f\left(\begin{array}{l} L_1, L_2, \cdots, L_n, \\ M_{12}, M_{23}, \cdots, M_{(n-1)n}, \\ C_1, C_2, \cdots, C_n, \\ R_1, R_2, \cdots, R_n, \\ R_{load} \end{array}\right) \tag{3}$$

$$\begin{bmatrix} U_1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) & j\omega M_{12} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ j\omega M_{21} & R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) & \cdots & j\omega M_{2(n-1)} & j\omega M_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{(n-1)1} & j\omega M_{(n-1)2} & \cdots & R_{n-1} + j\left(\omega L_{n-1} - \frac{1}{\omega C_{n-1}}\right) & j\omega M_{12} \\ j\omega M_{n1} & j\omega M_{(n-1)2} & \cdots & j\omega M_{(n-1)(n-1)} & R_n + R_l + j\left(\omega L_n - \frac{1}{\omega C_n}\right) \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_{n-1} \\ I_n \end{bmatrix} \tag{1}$$

Since the coils in the 3-coil system are identical to each other, the self-inductance L_1 through L_n can be treated as a constant value, and it could be accurately calculated [27]. The coil resistance, R_1 through R_n, can be considered as identical too, and it can be measured at the most probably resonant frequency of the resonator (i.e. 530 kHz in this design). The coil resistance is regarded as a constant value since the wireless power transfer system is operated at or around the resonant frequency because the resistance change caused by skin effect is nearly the same over a very small frequency range. All the measured parameters or the nominal value of the resonators are shown in Table I. Meanwhile, the mutual inductances M_{12}, M_{23}, …, $M_{(n-1)n}$ are expressed as functions of distances between each coil pair, d_{12}, d_{23},…,$d_{(n-1)n}$ [27]. So equation (3) may be replaced by equation (4):

$$(Z_{f_1}, Z_{f_2}, \cdots, Z_{f_{m-1}}, Z_{f_m}) = f\begin{pmatrix} L_1, L_2, \cdots, L_n, \\ d_{12}, d_{23}, \cdots, d_{(n-1)n}, \\ C_1, C_2, \cdots, C_n, \\ R_1, R_2, \cdots, R_n, \\ R_{load} \end{pmatrix} \qquad (4)$$

For a given system, the input impedance set $Z_{f_1}, Z_{f_2}, \cdots, Z_{f_m}$ could be experimentally measured easily. The Genetic Algorithm (GA) approach is used to search for the most probably values of d_{12}, d_{23},…,$d_{(n-1)n}$ and C_1, C_2,…,C_n with the help of a set of measured input impedance $Z_{f_1}, Z_{f_2}, \cdots, Z_{f_m}$ at different frequencies. GA is used to obtain the optimum solutions for the following optimum problem:

$$J\begin{pmatrix} d_{12}, d_{23}, \cdots, d_{(n-1)n}, \\ C_1, C_2, \cdots, C_n, \end{pmatrix} = \min[\sum_{1}^{m}((|Z_{f_i}| - |Z^*_{f_i}|)^2 + (\theta_{f_i} - \theta^*_{f_i})^2)] \qquad (5)$$

where $|Z_{f_i}|$ and θ_{f_i} are the magnitude and angular values of the measured input impedance at frequency f_i, while $|Z^*_{f_i}|$ and $\theta^*_{f_i}$ are calculated magnitude and angular values of the input impedance at frequency f_i from equation (3) using calculated parameters inductance L_1 through L_n, measured parameters R_1 through R_n, and predicted parameters d_{12}, d_{23},…,$d_{(n-1)n}$. A set of { $d_{12}, d_{23}, \cdots, d_{(n-1)n}, C_1, C_2, \cdots, C_n$ } should be searched in a space of potential solutions, so that the right-hand side of (5) will be minimized. Each parameter has a lower bound and an upper bound as shown in Table II, which forms a search space for the GA operation.

TABLE II. LOWER BOUND AND UPPER BOUND FOR PARAMETERS

	Lower bound	Upper bound
$d_{12}, d_{23}, \cdots, d_{(n-1)n}$	0.1 (m)	0.3 (m)
$C_1, C_2, \cdots, C_n$	0.5 (nF)	1.5 (nF)

III. SIMULATION RESULTS AND EXPERIEMNTAL VERIFICATION

A 3-coil system is used to verify the proposed concept for identifying the parameters for wireless power transfer system by using the GA. Different load resistance values are used to check whether this method could be used at different conditions or not. The different experimental conditions and measured parameters are listed in Table III and the predicted parameters are listed in Table IV.

Input impedances from 450 kHz to 580 kHz, stepping every 1 kHz, are measured for the 4 conditions as shown in Table III. Only the distance between the 2nd coil and the 3rd coil and the load resistance are adjusted, and their values are measured and noted in Table III. The GA approach has been run for each condition to identify the parameters of d_{12}, d_{23} and C_1, C_2, C_3, and the output are recorded in Table IV.

It can be seen from Table III that, for each load resistance (11.8 Ohm or 49.9 Ohm, marked in yellow) , d_{12} is always 0.2m, but d_{23} differs from 0.2 m to 0.25 m (marked in shaded boxes). These highlighted values will be used as references to check if the proposed method could predict the parameters or not. By comparing the predicted parameters in Table IV and measured parameters in Table III, one can see that the predicted parameters are very close to the nominal values (for the capacitances) and measured values (for the coil distances). The standard deviations (SD) for the 3 capacitances predicted for the 4 conditions are also listed in Table IV and they are very small, therefore confirming the validity of the proposed method.

TABLE III. MEASURED PARAMETERS OF 3-COIL SYSTEM

No.	**c1**	**c2**	**c3**	**d_{12}**	**d_{23}**	**R_{load}**
1	#1	#2	#3	0.20 (m)	0.20 (m)	11.8 (Ohm)
2	#1	#2	#3	0.20 (m)	0.25 (m)	11.8 (Ohm)
3	#1	#2	#3	0.20 (m)	0.20 (m)	49.9 (Ohm)
4	#1	#2	#3	0.20 (m)	0.25 (m)	49.9 (Ohm)

TABLE IV. PREDICTED PARAMETERS OF 3-COIL SYSTEM

No.	c_1 (nF)	c_2 (nF)	c_3 (nF)	d_{12} (m)	d_{23} (m)
1	1.0191	1.0040	1.0197	0.2021	0.1984
2	1.0180	1.0040	1.0195	0.2016	0.2494
3	1.0192	1.0031	1.0215	0.1890	0.2167
4	1.0192	1.0036	1.0211	0.2042	0.2531
SD	0.000585	0.000427	0.000998		

Fig.4 through Fig.7 are the comparisons of experimental and simulated amplitude-frequency characteristics and phase-frequency characteristics of input impedance for 3-coil systems. The curves labelled as “z_exp” and “z_sim” are the results for experimental and simulated impedance amplitude-frequency characteristics respectively. The curves labelled as “ph_exp” and “ph_sim” are the results for experimental and simulated phase-frequency characteristics. From the figures, it is clear that the simulated and experimental curves fit very well for each test condition. Also the simulated energy efficiency versus frequency curves are plotted in these figures so that one can use the efficiency-frequency curves to choose the optimal operating frequency for maximum efficiency or other optimizing purposes.

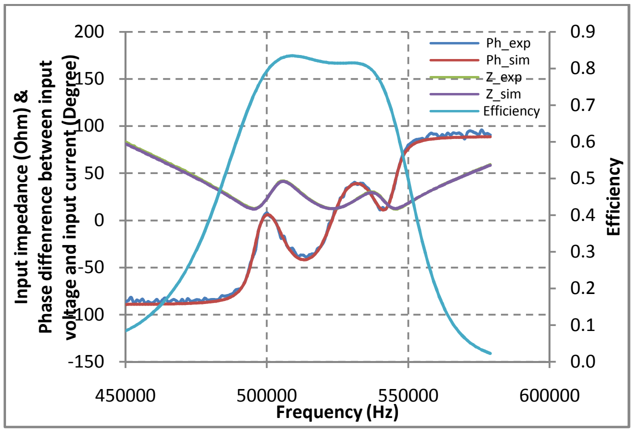

Fig.4 experimental and simulated input impedance comparison of No.1 experiment in Table III for wireless power transfer system with 3 resonators

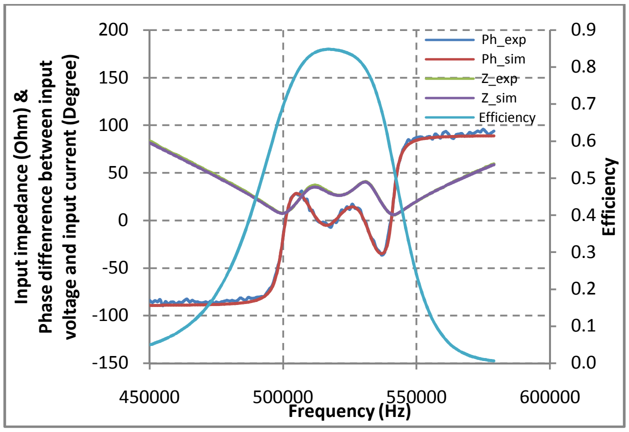

Fig.5 experimental and simulated input impedance comparison No.2 experiment in Table III for wireless power transfer system with 3 resonators

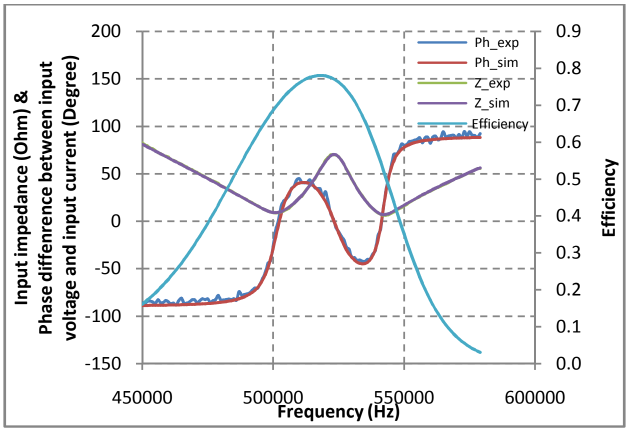

Fig.6 experimental and simulated input impedance comparison of No.3 experiment in Table III for wireless power transfer system with 3 resonators

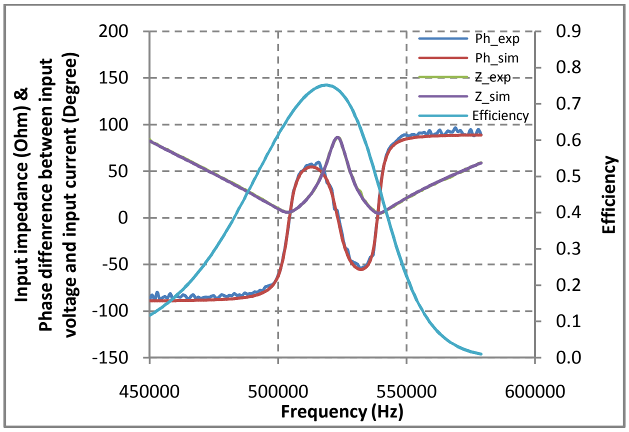

Fig.7 experimental and simulated input impedance comparison of No.4 experiment in Table III for wireless power transfer system with 3 resonators

IV. CONCLUSION

In this paper, a method for identifying the parameters of wireless power transfer systems is proposed. With the help of an evolutionary algorithm, one can use only the measured input voltage and the input current information to predict the system parameters for a wireless power transfer system. The method has been demonstrated in a 3-coil system. The good agreements between measurements and predictions have confirmed the validity of the proposed method. In principle, this method can be applied to a wireless power transfer system with any number of coils, although the equations will become more complex with increasing number of coils. The key advantages of this method are that it does not require the prior knowledge of all parameters and that it can overcome the problems of measurement accuracy of the coil locations and orientations and also the tolerance of the components of the resonators.

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