Front-end Monitoring of Multiple Loads in Wireless Power Transfer Systems Without Wireless Communication Systems

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Abstract— This paper describes a method for monitoring multiple loads from the front-end of a wireless power transfer system without using any wireless communication systems. A mathematical approach based on scanning the frequency around the resonant frequency has been developed for deriving the load conditions. The proposal requires only information of the input voltage and current only, therefore eliminating the requirements of using wireless communication systems for feedback control. The proposal has been practically confirmed in hardware prototype with acceptable results.

Index Terms—Load monitoring, wireless power transfer, tesla's resonators.

I. INTRODUCTION

Nicola Tesla investigated the fundamental principles of wireless power transfer based on the magnetic resonance and near-field coupling a century ago [1]. With the availability of power electronics as an enabling technology, wireless power transfer has re-emerged as a hot research topic in recent years, covering biomedical implant devices [2]-[10], inductive power transfer [11]-[13] and wireless charging techniques [14]-[19]. Due to the wireless nature of the system, wireless communication system has been proposed to feed back the load measurements for closed-loop control purpose [20]. However, it is preferable to remove this wireless communication link between the transmitter coil and the receiver coil in order to reduce system cost and complexity. A number of research efforts have been attempted to implement load detection methods on the transmitter side in a two-coil wireless power transfer (WPT) system with a single load [21]-[26]. Recently, reference [27] shows that it is possible to estimate the load variation based on the measurement of input voltage and current in a single load system. In some applications, there is a need for powering multiple loads simultaneously from the

power source. Therefore WPT systems consisting of multiple receiver coils have been investigated in recent years [28]-[33].

Two camps of wireless power, namely the Wireless Power Consortium (WPC) and the Alliance for Wireless Power (A4WP) have been targeting wireless charging of multiple devices and wireless charging with spatial freedom. For the WPC, one of the major milestones for Version 1.2 of the Qi standard is "multi-device V.1.2 receivers charging on a V.1.2 transmitter with one inverter, delivering lowest cost designs" [34]. For the Rezence standard promoted by the A4WP, multi-device charging is highlighted as a technical specification [35]. In fact, wireless charging pads for multiple devices have been launched commercially. An example of a wireless charging pad capable of charging up to 5 devices simultaneously is shown in Fig.1.

Fig. 1 An example of wireless charging pad for multiple devices (courtesy of ConvenientPower Ltd.).

In this project, a novel computational load estimation method is reported and demonstrated in a WPT system with two loads. The proposed method can manage nonlinear and time-varying input information in order to determine the multiple-load conditions without using any direct output feedback from the loads. This work is an extended version of [36], and it includes new implementation details and practical measurements under static and dynamic load conditions. This method is simple and time-efficient especially for large systems with several magnetic resonators and longer transmission distance. This computational approach is explained and practically verified with measurements obtained from a 4-coil WPT system under both static and dynamic load conditions. The proposal can greatly reduce the system cost and complexity by eliminating the requirements of any wireless communication systems that are often used in WPT systems for output feedback purposes [20],[37].

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II. MATHEMATICAL MODEL

Fig. 2 An n-coil wireless power transfer system with two loads.

Fig. 2 illustrates a general WPT system consisting of n coils, where an AC sinusoidal voltage source with a root-mean-square amplitude V_s and an angular frequency ω is applied to the transmitter coil-1 on the input side. Two load resistors R_{L1} and R_{L2} are connected respectively to coil- $(n-1)$ and coil- n on the output sides. In principle, the two loads can be connected to any pair of coils in the system except the transmitter coil-1. In this case, the coil-1 is the transmitter coil, the coil- $(n-1)$ and coil- n are the receiver coils. The other coils with indices from 2 to $n-2$ are the relay coils. A capacitor is connected in series with each coil to form a resonator so as to enhance the power transfer capability. The resonant frequency of each coil resonator should match the input frequency of the power source. Since every coil resonator forms a closed circuit loop itself, by applying the Kirchhoff's Voltage Law to the n coils the system matrix equation can be expressed as (1).

$$\begin{bmatrix} V_s \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & j\omega M_{12} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ j\omega M_{12} & Z_2 & \cdots & j\omega M_{2(n-1)} & j\omega M_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{1(n-1)} & j\omega M_{2(n-1)} & \cdots & Z_{n-1} + R_{L1} & j\omega M_{(n-1)n} \\ j\omega M_{1n} & j\omega M_{2n} & \cdots & j\omega M_{(n-1)n} & Z_n + R_{L2} \end{bmatrix} \times \begin{bmatrix} I_1 \\ I_2 \\ \vdots \\ I_{n-1} \\ I_n \end{bmatrix} \quad (1)$$

where $Z_i = R_i + j(\omega L_i - \frac{1}{\omega C_i})$ is the total impedance, R_i is the equivalent resistance, L_i is the self-inductance, and C_i is the capacitance of the coil- i ; I_i is the current phasor flowing in

the coil- i ; M_{ij} is the mutual inductance between the coil- i and coil - j ($M_{ij}=M_{ji}$), $1 \leq i \leq n, 1 \leq j \leq n$.

Some assumptions are made in the following analysis:

- All the parameters of the coils can be measured or calculated. Since the positions of coils are fixed, the mutual inductance of every pair of coils is also constant and can be measured accurately or calculated mathematically. (Note: this assumption can be justified as a patent-pending technique [38] has been developed for real-time identification of system parameters including the mutual inductance terms in the system matrix of (1).)
- The input voltage phasor V_s and current phasor I_1 in the coil-1 can be measured in real time.

III. COMPUTATIONAL APPROACH FOR DOUBLE LOAD APPLICATION

A. Steps to Re-arrange the System Equations

Now (1) can be re-arranged in the following steps:

$$\begin{cases} V_s = Z_1 I_1 + j\omega M_{12} I_2 + \cdots + j\omega M_{1n} I_n \\ 0 = j\omega M_{12} I_1 + Z_2 I_2 + \cdots + j\omega M_{2n} I_n \\ \vdots \\ 0 = j\omega M_{1(n-1)} I_1 + j\omega M_{2(n-1)} I_2 + \cdots + j\omega M_{(n-1)n} I_n + R_{L1} I_{n-1} \\ 0 = j\omega M_{1n} I_1 + j\omega M_{2n} I_2 + \cdots + Z_n I_n + R_{L2} I_n \end{cases} \quad (2)$$

The unknowns in above equations are $I_2, I_3, \dots, I_n, R_{L1}$ and R_{L2} . By transferring all the known terms (which are the terms with I_1) from the right hand side of (2) to the left hand side and leaving only unknown terms on the right hand side, (2) can be re-written as (3).

$$\begin{cases} V_s - Z_1 I_1 = j\omega M_{12} I_2 + \cdots + j\omega M_{1(n-1)} I_{n-1} + j\omega M_{1n} I_n \\ -j\omega M_{12} I_1 = Z_2 I_2 + \cdots + j\omega M_{2(n-1)} I_{n-1} + j\omega M_{2n} I_n \\ \vdots \\ -j\omega M_{1(n-1)} I_1 = j\omega M_{2(n-1)} I_2 + \cdots + j\omega M_{(n-1)n} I_n + Z_{L1} I_{n-1} \\ -j\omega M_{1n} I_1 = j\omega M_{2n} I_2 + \cdots + Z_n I_n + Z_{L2} I_n \end{cases} \quad (3)$$

Equation (3) is nonlinear because it consists of the products of two unknowns $R_{L1} I_{n-1}$ and $R_{L2} I_n$. If one regard the terms $R_{L1} I_{n-1}$ and $R_{L2} I_n$ as two new unknowns, the original $n+1$ unknowns (i.e. $I_2, I_3, \dots, I_n, R_{L1}$ and R_{L2}) will become $I_2, I_3, \dots, I_n, R_{L1} I_{n-1}$ and $R_{L2} I_n$. Then (3) can be transformed into a linear form as shown in (4). However the solutions to (4) are not unique, because there are n equations and $n+1$ unknowns. By putting the term $R_{L1} I_{n-1}$ on the left hand side of the equation in the form of (5), then the unknowns of (5) can be placed on the left hand side of (6).

$$\begin{bmatrix} \mathbf{V}_s - Z_1 \mathbf{I}_1 \\ -j\omega M_{12} \mathbf{I}_1 \\ \vdots \\ -j\omega M_{1(n-1)} \mathbf{I}_1 \\ -j\omega M_{1n} \mathbf{I}_1 \end{bmatrix} = \begin{bmatrix} j\omega M_{12} & j\omega M_{13} & \cdots & j\omega M_{1n} & 0 & 0 \\ Z_2 & j\omega M_{23} & \cdots & j\omega M_{2n} & 0 & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots & \vdots \\ j\omega M_{2(n-1)} & j\omega M_{3(n-1)} & \cdots & j\omega M_{(n-1)n} & 1 & 0 \\ j\omega M_{2n} & j\omega M_{3n} & \cdots & Z_n & 0 & 1 \end{bmatrix} \times \begin{bmatrix} \mathbf{I}_2 \\ \vdots \\ \mathbf{I}_n \\ R_{L1} \mathbf{I}_{n-1} \\ R_{L2} \mathbf{I}_n \end{bmatrix} \quad (4)$$

$$\begin{bmatrix} \mathbf{V}_s - Z_1 \mathbf{I}_1 \\ -j\omega M_{12} \mathbf{I}_1 \\ \vdots \\ -j\omega M_{1(n-1)} \mathbf{I}_1 - R_{L1} \mathbf{I}_{n-1} \\ -j\omega M_{1n} \mathbf{I}_1 \end{bmatrix} = \begin{bmatrix} j\omega M_{12} & j\omega M_{13} & \cdots & j\omega M_{1n} & 0 \\ Z_2 & j\omega M_{23} & \cdots & j\omega M_{2n} & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{2(n-1)} & j\omega M_{3(n-1)} & \cdots & j\omega M_{(n-1)n} & 0 \\ j\omega M_{2n} & j\omega M_{3n} & \cdots & Z_n & 1 \end{bmatrix} \times \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{I}_3 \\ \vdots \\ \mathbf{I}_n \\ R_{L2} \mathbf{I}_n \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} \mathbf{I}_2 \\ \mathbf{I}_3 \\ \vdots \\ \mathbf{I}_n \\ R_{L2} \mathbf{I}_n \end{bmatrix} = \mathbf{P} \times \begin{bmatrix} \mathbf{V}_s - Z_1 \mathbf{I}_1 \\ -j\omega M_{12} \mathbf{I}_1 \\ \vdots \\ -j\omega M_{1(n-1)} \mathbf{I}_1 - R_{L1} \mathbf{I}_{n-1} \\ -j\omega M_{1n} \mathbf{I}_1 \end{bmatrix} \quad (6)$$

where $\mathbf{P}$ is the inverse matrix of the coefficient matrix in (5) and

$$\mathbf{P} = \begin{bmatrix} j\omega M_{12} & j\omega M_{13} & \cdots & j\omega M_{1n} & 0 \\ Z_2 & j\omega M_{23} & \cdots & j\omega M_{2n} & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{2(n-1)} & j\omega M_{3(n-1)} & \cdots & j\omega M_{(n-1)n} & 0 \\ j\omega M_{2n} & j\omega M_{3n} & \cdots & Z_n & 1 \end{bmatrix}^{-1} \quad (7)$$

Note that the last 3 equations of the matrix equation (6) are:

$$\mathbf{I}_{n-1} = a + b R_{L1} \mathbf{I}_{n-1} \quad (8)$$

$$\mathbf{I}_n = c + d R_{L1} \mathbf{I}_{n-1} \quad (9)$$

$$R_{L2} \mathbf{I}_n = e + f R_{L1} \mathbf{I}_{n-1} \quad (10)$$

where

$$\begin{cases} a = \mathbf{P}_{n-2} \mathbf{V} \\ b = -p_{(n-2)(n-1)} \\ c = \mathbf{P}_{n-1} \mathbf{V} \\ d = -p_{(n-1)(n-1)} \\ e = \mathbf{P}_n \mathbf{V} \\ f = -p_{n(n-1)} \end{cases} \quad (11)$$

$$\mathbf{V} = \begin{bmatrix} \mathbf{V}_s - Z_1 \mathbf{I}_1 \\ -j\omega M_{12} \mathbf{I}_1 \\ \vdots \\ -j\omega M_{1(n-1)} \mathbf{I}_1 \\ -j\omega M_{1n} \mathbf{I}_1 \end{bmatrix} \quad (12)$$

$\mathbf{P}_i$ is the i -th row vector in matrix $\mathbf{P}$, and p_{ij} is the element on the i -th row and j -th column in the $\mathbf{P}$ matrix. From (8),

$$\mathbf{I}_{n-1} = \frac{a}{1 - b R_{L1}} \quad (13)$$

Substituting (13) into (9),

$$\mathbf{I}_n = c + \frac{ad R_{L1}}{1 - b R_{L1}} \quad (14)$$

Substituting (13) and (14) into (10), the R_{L1} - R_{L2} relationship is:

$$A R_{L1} R_{L2} + B R_{L1} + C R_{L2} + D = 0 \quad (15)$$

where,

$$\begin{cases} A = ad - bc = \alpha_A + j\beta_A \\ B = be - af = \alpha_B + j\beta_B \\ C = c = \alpha_C + j\beta_C \\ D = -e = \alpha_D + j\beta_D \end{cases} \quad (16)$$

Here the four coefficients A, B, C, D are complex numbers whereas the two unknowns R_{L1} and R_{L2} are real. By comparing the coefficients of the real and the imaginary parts in (15), it can be shown that:

$$\alpha_A R_{L1} R_{L2} + \alpha_B R_{L1} + \alpha_C R_{L2} = -\alpha_D \quad (17)$$

$$\beta_A R_{L1} R_{L2} + \beta_B R_{L1} + \beta_C R_{L2} = -\beta_D \quad (18)$$

With some mathematical manipulations of (17) and (18) to eliminate the nonlinear term $R_{L1} R_{L2}$,

$$(\alpha_B \beta_A - \alpha_A \beta_B) R_{L1} + (\alpha_C \beta_A - \alpha_A \beta_C) R_{L2} = \alpha_A \beta_D - \alpha_D \beta_A \quad (19)$$

In (19), there are two independent unknowns R_{L1} and R_{L2} with real coefficients related to the measurements of $\mathbf{V}_s$ and $\mathbf{I}_1$ for one specific frequency. If the frequency is changed to another value, a new set of coefficients will be obtained. Theoretically, only two sets of $\mathbf{V}_s$ and $\mathbf{I}_1$ measurements obtained at two different frequencies are sufficient in order to

calculate the two load resistance values, provided that there is no parameter tolerance and measurement errors. In practice, one cannot avoid measurement noise and error. It will be shown that data sets obtained from more than two different frequencies are needed in order to reduce the estimation errors.

B. A Typical Case: Three-Coil System

The proposed method can be illustrated with a three-coil WPT system where the coil-1 is the transmitter. The two loads R_{L1} and R_{L2} are connected to coil-2 and coil-3 respectively. For such a system, the inverse matrix $\mathbf{P}$ in the form of (7) can be expressed as (20)

$$\mathbf{P} = \begin{bmatrix} \frac{M_{23}}{M_{12}(j\omega M_{23} - \frac{M_{13}Z_2}{M_{12}})} & -\frac{\frac{M_{13}}{M_{12}}}{j\omega M_{23} - \frac{M_{13}Z_2}{M_{12}}} & 0 \\ -\frac{Z_2}{j\omega M_{12}(j\omega M_{23} - \frac{M_{13}Z_2}{M_{12}})} & \frac{1}{j\omega M_{23} - \frac{M_{13}Z_2}{M_{12}}} & 0 \\ \frac{Z_2Z_3 - (j\omega M_{23})^2}{j\omega M_{12}(j\omega M_{23} - \frac{M_{13}Z_2}{M_{12}})} & -\frac{Z_3 - \frac{j\omega M_{13}M_{23}}{M_{12}}}{j\omega M_{23} - \frac{M_{13}Z_2}{M_{12}}} & 1 \end{bmatrix} \quad (20)$$

The results of (20) are essential to the proposed calculation procedure. For example, the intermediate coefficients a, b, c, d, e, f in (11) and A, B, C, D in (16) are obtained with the help of (20). Finally the two load resistances in (19) can be found.

C. Least Square Approximation

In order to overcome the problems arising from the measurement errors and parameter tolerance, it is necessary to use more than two sets of measured input voltage and current data obtained at different frequencies. Equation (19) can be described as a straight line in an x-y coordinate plane. Imagine a general multiple-coil WPT system with two loads (say both 10 Ohms). If it is under the ideal condition that the system parameters are and the input measurements of $\mathbf{V}_s$ and $\mathbf{I}_1$ are accurate, all the R_{L1} - R_{L2} lines described by (19) for different input frequencies should intersect at one point as shown in Fig. 3. Such single intersection point should provide the unique solutions for (19). In practice, there are tolerance in systems parameters and noise in measurements. In this case the R_{L1} - R_{L2} lines described by (19) for different input frequencies will have multiple intersection points as shown in Fig. 4. So one cannot rely on the use of data sets obtained from only two frequencies to find the correct solution. In this study, the least square method is used to obtain the solution with improved accuracy.

The least square theorem [39] can be described as follows: let $\mathbf{A}$ be a $m \times n$ matrix, the least square solution to the system $\mathbf{A}\hat{\mathbf{x}} = \mathbf{b}$ can be expressed as

$$\hat{\mathbf{x}} = (\mathbf{A}^T \mathbf{A})^{-1} \mathbf{A}^T \mathbf{b} \quad (21)$$

where $\hat{\mathbf{x}}$ is the column matrix having n elements, and $\mathbf{b}$ is the column matrix consisting of m elements. With respect to (19) in this study,

$$\mathbf{A} = \begin{bmatrix} \alpha_{B1}\beta_{A1} - \alpha_{A1}\beta_{B1} & \alpha_{C1}\beta_{A1} - \alpha_{A1}\beta_{C1} \\ \alpha_{B2}\beta_{A2} - \alpha_{A2}\beta_{B2} & \alpha_{C2}\beta_{A2} - \alpha_{A2}\beta_{C2} \\ \vdots & \vdots \\ \alpha_{Bm}\beta_{Am} - \alpha_{Am}\beta_{Bm} & \alpha_{Cm}\beta_{Am} - \alpha_{Am}\beta_{Cm} \end{bmatrix} \quad (22)$$

$$\hat{\mathbf{x}} = \begin{bmatrix} R_{L1} \\ R_{L2} \end{bmatrix} \quad (23)$$

$$\mathbf{b} = \begin{bmatrix} \alpha_{A1}\beta_{D1} - \alpha_{D1}\beta_{A1} \\ \alpha_{A2}\beta_{D2} - \alpha_{D2}\beta_{A2} \\ \vdots \\ \alpha_{Am}\beta_{Dm} - \alpha_{Dm}\beta_{Am} \end{bmatrix} \quad (24)$$

The number of equations used is m . The geometric meaning of the least square operation here is to find an optimum equivalent point among all the intersection points of the m straight lines. Such point should have the nearest distance to all of the m straight lines.

Fig. 3 Unique intersection under ideal condition.

Fig. 4 Multiple intersections under practical conditions.

D. An Exceptional Case

Theoretically, it seems that this method cannot work under the conditions of a symmetric geometrical structure and identical load circuit parameters. Take a three-coil system depicted in Fig. 5 as an example. The coil-1 is the transmitter coil. If two identical receiver coil resonators (i.e. coil-2 and coil-3) are located symmetrically with respect to the coil-1, then $M_{12}=M_{13}$, $R_2=R_3$, $L_2=L_3$ and $C_2=C_3$. If the loads R_{L1} and R_{L2} are connected to coil-2 and coil-3 respectively, a pair of input voltage and current measurements can be obtained in the coil-1. If the two loads are interchanged, i.e. connecting R_{L1} to the coil-3 and R_{L2} to the coil-2, there will not be any change in the input voltage and current. Thus under such situation, although a unique pair of load solutions for R_{L1} and R_{L2} can still be obtained, one cannot tell which value is for R_{L1} and which for R_{L2} . Therefore in practical applications, the symmetric structure such as the one in Fig. 5 should be avoided in the system design stage.

Fig. 5 A symmetric 3-coil wireless power transfer system with two loads.

IV. EXPERIMENTAL VERIFICATION

In order to verify the proposed computational method for identifying the load resistance values, a 4-coil wireless power domino-resonator system is adopted in the experimental study. Each coil has the same parameters ($R_{1\sim4}=0.6788 \Omega$, $L_{1\sim4}=82.03 \mu\text{H}$). The coil diameter is 30 cm, and the number of turns is 11. The details of the system parameters are provided in Tables I and II. The system setup is illustrated in Fig. 6. The four coils are aligned along one direction with even distance of about 10 cm. The first coil is the transmitter, the coil-3 is connected to one load R_{L1} , and the coil-4 is connected to the other load R_{L2} . The input voltage is supplied by the function generator Tektronix AFG 3102. The input voltage and current are captured by the oscilloscope Agilent OSO-X 3034A. The instantaneous measured data are transferred to the computer which calculates the load resistance values.

Table I Mutual-inductance of each pair of coils of the 4-coil domino-resonator system.

	M_{12}	M_{13}	M_{14}	M_{23}	M_{24}	M_{34}
Inductance (μH)	15.45	5.863	2.645	15.43	5.769	15.13

Table II Capacitance Value of each series capacitor of the 4-coil domino-resonator system.

	C_1	C_2	C_3	C_4
Capacitance (nF)	1.029	1.024	1.013	1.046

Fig. 6 Experiment setup.

A. Constant Load Detection

Tests have been conducted by connecting two resistors R_{L1} and R_{L2} to the coil-3 and coil-4 respectively. By sweeping the input frequency from 470 kHz to 630 kHz to estimate the resistor values using the least square method, Fig. 7 illustrates the calculated load values based on the data sets obtained from 2 to 40 frequency scans for three different load resistance combinations (i.e. (i) $R_{L1} = 0$ Ohms, $R_{L2} = 10$ Ohms; (ii) $R_{L1} = 10$ Ohms, $R_{L2} = 10$ Ohms; (iii) $R_{L1} = 50$ Ohms, $R_{L2} = 20$ Ohms). When the information from only two frequencies is applied to find the load solutions, the results are far from satisfactory. This observation highlights the effects of the parameter tolerance (error) and measurement noise. The least square method enables the solutions to converge to the reference values when more data sets obtained from the frequency scans are used. The number of frequency scans for accurate estimations depends on the practical system configuration. In this study, reasonably accurate values of the load resistance can be obtained with estimated values calculated from 20 different frequencies.

The time for calculating the load values can be estimated. In general, five cycles of measurements are used for each frequency scan. For the frequency range from 470 kHz to 630 kHz, the time for 5 cycles of an average frequency of 500 kHz is only 40 μ s. So it takes typically less than 50 μ s to obtain the required data sets for load estimation. To solve the equations of this method, typical computational time by microprocessors is less than a few milliseconds (depending on the type of processor). For the load monitoring of multiple loads under static charging, the load conditions do not change quickly. If the load monitoring is carried out every 3 seconds, for example, the time of a few milliseconds required for checking the load conditions is negligible.

(a) $RL1=0$, $RL2=10$ Ohms.

(b) $RL1=RL2=10$ Ohms.

(c) $RL1=50$, $RL2=20$ Ohms.

Fig. 7 Estimated load resistances using more than two frequencies.

B. Variable Load Detection

Another set of tests have been conducted by using two variable resistors connected to the coil-3 and coil-4. For each frequency scan, the measured waveforms of input voltage and current are transmitted to the computer so that the amplitudes and phase difference can be calculated. Then the R_{L1} - R_{L2} equation (19) can be solved with data obtained from different frequencies. When the threshold number of the frequency scans is reached, the solutions should converge to the reference values.

Fig. 8 shows the estimated load results when one of the two resistive loads is kept constant and the other is varied in steps with time. The dotted curves represent the reference values, and the solid curves represent the estimated resistance values. Here the threshold number of adopted frequencies is 20. It can be observed that there is a transient time period when the estimated load value is changing from one to another level. The less data sets are used, the shorter the transient time period becomes. However if the number of data sets is not sufficient, the calculated resistor values will be far from the reference values.

Fig. 9 depicts the new case where both of the load resistors are changing and the estimated load resistances are calculated with 30 frequency scans. As more equations are involved, the transient time in Fig. 9 is longer than that in Fig. 8. However the load curves in Fig. 9 are smoother than those in Fig. 8 because more data are used now. In the middle of the test in Fig. 9, R_{L1} is deliberately reduced to zero (i.e. to simulate a short circuit fault at the terminals of the coil-3). The estimated results of R_{L1} in Fig. 9 indicate that the proposed approach can detect such conditions in a WPT system.

Fig. 8 Calculated resistances with 20 equations when load is changing.

Fig. 9 Calculated resistances with 30 equations when load is changing.

V. CONCLUSION

In this paper, a new method is presented for monitoring two loads in a wireless power transfer system, using only the input voltage and input current measurements. The method overcomes the errors introduced by the parameter tolerance and measurement noise by solving the proposed equation set with a number of frequency scans and using the least square approximation method to obtain the estimated load values with reasonably good accuracy. This approach has the advantage of eliminating the need for a wireless communication system on the receiver side of the system, therefore reducing the cost and circuit complexity of the receiver circuits in wireless power systems. The proposed method has been practically demonstrated in a 4-coil wireless power transfer system with two loads of various combinations of resistance values. For the experimental setup with four coils and two loads, it is found that about 20 sets of data (obtained at 20 different frequencies around the resonant frequency of the resonators) are sufficient to obtain results with good accuracy. Of course, the speed of the implementation depends on the speed of the processor. In this study, the input voltage and current waveforms are sampled by a digital oscilloscope and the sampled data are exported to an external computer for monitoring the load resistance values. If faster response is required for other purpose such as real-time control, the input voltage and current can be captured directly by a fast processor. Since the time required for the frequency scans and calculating the load values is typically less than a few milliseconds, the proposed method will not affect the time for wireless power transfer significantly even if the load monitoring is applied regularly.

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