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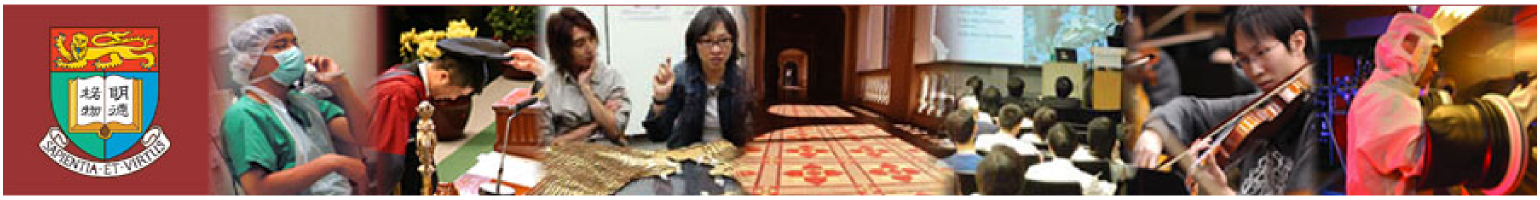

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Load Monitoring and Output Power Control of a Wireless Power Transfer System without Any Wireless Communication Feedback

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***Abstract*— For mid-range wireless power applications, the load is normally far away from the power source. In this project, a new method is proposed to determine the load impedance and load power without using any direct output feedback. Based only on the information of the input voltage and current, the load impedance and load power can be monitored and controlled without using any wired or wireless feedback from the load. This new method can therefore eliminate the need for any directly measured output feedback, which was previously thought to be essential. It also makes the power control of a wireless power transfer very simple. The concept is verified by the comparison between the computed results and practical results of an 8-ring domino wireless power transfer system. A good degree of accuracy has been achieved in the verification.**

Keywords—wireless power transfer; load monitoring; power control; magnetic resonance.

I. INTRODUCTION

Wireless power transfer based on the magnetic resonance and near-field coupling of two loop resonators was reported by Nicola Tesla a century ago [1]. From then on, a lot of research about transcutaneous energy systems for medical implants [2-4], the inductive power transfer (IPT) systems [5], and wireless charging systems for portable equipment such as mobile phones [6] have been summarized.

Recently, a lot of research efforts have been devoted to the improvement of the performance of wireless power transfer system such as to increase the transfer distance and to improve the overall system efficiency. Most of the projects have been extended from the traditional 2-coil systems to systems with more than two coils. For examples, 3-coil systems [7]-[9], 4-coil systems [10]-[12], systems with relay resonators [13]-[15] and domino-resonator systems [16]-[18] have emerged as variants of the wireless power transfer systems with potentials of simultaneously extending the transmission distance and overall system efficiency.

Among the recent publications, one article is related to the closed-loop control for frequency tracking of a 2-coil wireless power transfer system. A wireless communication system is used in [19] to send the output power feedback signal to the input power circuit for closed-loop control, because the optimal operating frequency is load dependent. In this paper, it is shown that such wireless feedback mechanism may not necessary. A theory is presented here to demonstrate that the load condition can be computed with the information of the input voltage and input current only, and the output power can be controlled without using any wireless communication feedback information [20]. The theory is verified by computer simulations based on the proven mathematical model previously reported [16] and practical measurements.

II. LOAD MONITORING

A. General Mathematical Model for an n-coil system

Consider a general wireless power transfer system with n-coils as shown in Figure.1, where the 1st coil is the transmitter and the nth coil is the receiver. Let L_i be the self-inductance, R_i be the coil resistance and C_i be the resonant capacitor of the ith coil; M_{ij} be the mutual-inductance between the ith coil and the jth coil; Z_L be the load impedance, then the system could be described using (1).

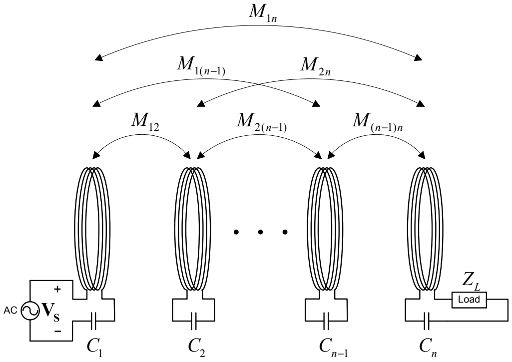

Figure.1 Schematic of an n-coil wireless power transfer system.

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$$\begin{bmatrix} \mathbf{U}_1 \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} R_1 + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) & j\omega M_{12} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ j\omega M_{21} & R_2 + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) & \cdots & j\omega M_{2(n-1)} & j\omega M_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{(n-1)1} & j\omega M_{(n-1)2} & \cdots & R_{n-1} + j\left(\omega L_{n-1} - \frac{1}{\omega C_{n-1}}\right) & j\omega M_{12} \\ j\omega M_{n1} & j\omega M_{(n-1)2} & \cdots & j\omega M_{(n-1)(n-1)} & R_n + Z_L + j\left(\omega L_n - \frac{1}{\omega C_n}\right) \end{bmatrix} \begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \vdots \\ \mathbf{I}_{(n-1)} \\ \mathbf{I}_n \end{bmatrix} \tag{1}$$

where $\mathbf{U_1}$ is the input voltage vector, $\mathbf{I_i}$ is the current vector in the i^{th} coil and ω is the angular frequency of $\mathbf{U_1}$.

In this system matrix equation, the dimension of the matrix is equal to the number of the coils used in system. In order to develop a new control method based on the input voltage and current, only $\mathbf{U_1}$ and $\mathbf{I_1}$ are measureable variables. If all system parameters such as winding self-inductance values, mutual inductance values, coil resistance values and resonant capacitance values are known, the remaining unknowns include the loop currents $\mathbf{I_2}$ to $\mathbf{I_n}$ and the load impedance Z_L. For closed-loop control purpose, it is necessary to compute $\mathbf{I_n}$ (which is the current in the receiver coil) and Z_L.

B. Load Estimation

If no sensor is used to monitor the output conditions such as output power, output voltage and current, one approach is to manipulate the matrix equation with the objective of transferring the required unknowns (i.e. $\mathbf{I_n}$ and Z_L) to become the subjects of the matrix equation. To facilitate this, equation (1) is first simplified as (2). Through the steps of writing (3) and (4), the measureable variables $\mathbf{U_1}$ and $\mathbf{I_1}$ are initially arranged to the left hand side of (4). This can be seen clearly when (4) is put into a matric form as shown in (5). Then by re-arranging the column vector of the right hand side of (5) to become the subject of (6), the equation (6) can now be computed with the known system parameters and the measureable variables of $\mathbf{U}_1$ and $\mathbf{I}_1$. $Z_{11}, Z_{12}, \ldots Z_{nn}$ in (6) are functions of the angular frequency. If such frequency has to be changed dynamically as part of an optimal operating strategy, the inverse system matrix in (6) has to be updated with any change of frequency.

$$\begin{bmatrix} \mathbf{U_1} \\ \mathbf{0} \\ \vdots \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & \cdots & Z_{1(n-1)} & Z_{1n} \\ Z_{21} & Z_{22} & \cdots & Z_{2(n-1)} & Z_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ Z_{(n-1)1} & Z_{(n-1)2} & \cdots & Z_{(n-1)(n-1)} & Z_{(n-1)n} \\ Z_{n1} & Z_{n2} & \cdots & Z_{n(n-1)} & Z_{nn} + Z_L \end{bmatrix} \begin{bmatrix} \mathbf{I_1} \\ \mathbf{I_2} \\ \vdots \\ \mathbf{I_{n-1}} \\ \mathbf{I_n} \end{bmatrix} \tag{2}$$

$$\begin{aligned} U_1 &= Z_{11}\mathbf{I_1} + Z_{12}\mathbf{I}_2 + \cdots + Z_{1(n-1)}\mathbf{I}_{(n-1)} + Z_{1n}\mathbf{I}_n \\ 0 &= Z_{21}\mathbf{I}_1 + Z_{22}\mathbf{I}_2 + \cdots + Z_{2(n-1)}\mathbf{I}_{(n-1)} + Z_{2n}\mathbf{I}_n \\ &\vdots \\ 0 &= Z_{(n-1)1}\mathbf{I}_1 + Z_{(n-1)2}\mathbf{I}_2 + \cdots + Z_{(n-1)(n-1)}\mathbf{I}_{(n-1)} + Z_{(n-1)n}\mathbf{I}_n \\ 0 &= Z_{n1}\mathbf{I}_1 + Z_{n2}\mathbf{I}_2 + \cdots + Z_{n(n-1)}\mathbf{I}_{(n-1)} + Z_{nn}\mathbf{I}_n + Z_L\mathbf{I}_n \end{aligned} \tag{3}$$

$$\begin{aligned} U_1 - Z_{11}\mathbf{I}_1 &= Z_{12}\mathbf{I}_2 + \cdots + Z_{1(n-1)}\mathbf{I}_{(n-1)} + Z_{1n}\mathbf{I}_n \\ -Z_{21}\mathbf{I}_1 &= Z_{22}\mathbf{I}_2 + \cdots + Z_{2(n-1)}\mathbf{I}_{(n-1)} + Z_{2n}\mathbf{I}_n \\ &\vdots \\ -Z_{(n-1)1}\mathbf{I}_1 &= Z_{(n-1)2}\mathbf{I}_2 + \cdots + Z_{(n-1)(n-1)}\mathbf{I}_{(n-1)} + Z_{(n-1)n}\mathbf{I}_n \\ -Z_{n1}\mathbf{I}_1 &= Z_{n2}\mathbf{I}_2 + \cdots + Z_{n(n-1)}\mathbf{I}_{(n-1)} + Z_{nn}\mathbf{I}_n + Z_L\mathbf{I}_n \end{aligned} \tag{4}$$

$$\begin{bmatrix} U_1 - Z_{11}\mathbf{I_1} \\ -Z_{21}\mathbf{I}_1 \\ \vdots \\ -Z_{(n-1)1}\mathbf{I}_1 \\ -Z_{n1}\mathbf{I}_1 \end{bmatrix} = \begin{bmatrix} Z_{12} & \cdots & Z_{1(n-1)} & Z_{1n} & 0 \\ Z_{22} & \cdots & Z_{2(n-1)} & Z_{2n} & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ Z_{(n-1)2} & \cdots & Z_{(n-1)(n-1)} & Z_{(n-1)n} & 0 \\ Z_{n2} & \cdots & Z_{n(n-1)} & Z_{nn} & 1 \end{bmatrix} \begin{bmatrix} \mathbf{I}_2 \\ \mathbf{I}_3 \\ \vdots \\ \mathbf{I}_n \\ Z_L\mathbf{I}_n \end{bmatrix} \tag{5}$$

$$\begin{bmatrix} \mathbf{I}_2 \\ \mathbf{I}_3 \\ \vdots \\ \mathbf{I}_n \\ Z_L\mathbf{I}_n \end{bmatrix} = \begin{bmatrix} Z_{12} & \cdots & Z_{1(n-1)} & Z_{1n} & 0 \\ Z_{22} & \cdots & Z_{2(n-1)} & Z_{2n} & 0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ Z_{(n-1)2} & \cdots & Z_{(n-1)(n-1)} & Z_{(n-1)n} & 0 \\ Z_{n2} & \cdots & Z_{n(n-1)} & Z_{nn} & 1 \end{bmatrix}^{-1} \begin{bmatrix} U_1 - Z_{11}\mathbf{I}_1 \\ -Z_{21}\mathbf{I}_1 \\ \vdots \\ -Z_{(n-1)1}\mathbf{I}_1 \\ -Z_{n1}\mathbf{I_1} \end{bmatrix} \tag{6}$$

From (6), the last two items, namely $\mathbf{I_n}$ and $Z_L\mathbf{I_n}$ can be computed based on known parameters and $\mathbf{U}_1$ and I_1. $\mathbf{I_n}$ is the load current in the setup of Figure.1. The value of $Z_L\mathbf{I}_n$ is the output voltage ($\mathbf{U_{out}}$) across the load. Both of $\mathbf{I_n}$ and $\mathbf{U_{out}}$ can be used by the driving circuit of the wireless power transfer system for output power control without the actual measurements. If load monitoring is required, the load impedance can also be determined as follows:

$$Z_L = \frac{Z_L\mathbf{I}_n}{\mathbf{I}_n} \tag{7}$$

C. Application to a Two-Coil System

For a two-coil system, the 1st coil is the transmitter coil with an input voltage $\mathbf{U_1}$, the 2nd coil is the receiver coil terminated with the load Z_L. The system equation of such a WPTS could be derived from (1) as:

$$\begin{bmatrix} \mathbf{U}_1 \\ \mathbf{0} \end{bmatrix} = \begin{pmatrix} R_1 + j\left(\omega L_1 - \dfrac{1}{\omega C_1}\right) & j\omega M_{12} \\ j\omega M_{21} & R_2 + Z_L + j\left(\omega L_2 - \dfrac{1}{\omega C_2}\right) \end{pmatrix} \begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \end{bmatrix} \tag{8}$$

and then arranged in the form of (6) as:

$$\begin{bmatrix} \mathbf{I}_2 \\ Z_L\mathbf{I}_2 \end{bmatrix} = \begin{bmatrix} Z_{12} & 0 \\ Z_{22} & 1 \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{U}_1 - Z_{11}\mathbf{I}_1 \\ -Z_{21}\mathbf{I_1} \end{bmatrix} \tag{9}$$

where Z_{11}, Z_{12}, Z_{21} and Z_{22} are functions of the angular frequency, coil resistance R_1, R_2, coil inductance L_1 and L_2 and mutual inductances between the 1st coil and the 2nd coil as listed in (10) to (13). Z_L is the load impedance at an angular frequency ω.

$$Z_{11} = R_1 + j(\omega L_1 - \frac{1}{\omega C_1}) \tag{10}$$

$$Z_{22} = R_2 + j(\omega L_2 - \frac{1}{\omega C_2}) \tag{11}$$

$$Z_{12} = j\omega M_{12} \tag{12}$$

$$Z_{21} = j\omega M_{21} \tag{13}$$

From (9), the load current and the output voltage can be obtained as expressed in (14) and (15), respectively.

$$\mathbf{I_2} = \frac{(\mathbf{U}_1 - Z_{11}\mathbf{I}_1)}{Z_{12}} \tag{14}$$

$$Z_L\mathbf{I}_2 = -Z_{21}\mathbf{I}_1 - \frac{(\mathbf{U}_1 - Z_{11}\mathbf{I}_1)Z_{22}}{Z_{12}} \tag{15}$$

Then the load impedance can be obtained as follows:

$$Z_L = \frac{-Z_{12}Z_{21}\mathbf{I}_1 - (\mathbf{U}_1 - Z_{11}\mathbf{I}_1)Z_{22}}{(\mathbf{U}_1 - Z_{11}\mathbf{I}_1)} \tag{16}$$

By substituting the parameters in (10) - (13) into (16), the solution of the load impedance becomes:

$$Z_L = \frac{(R_1 + j(\omega L_1 - \frac{1}{\omega C_1}))*(R_1 + j(\omega L_1 - \frac{1}{\omega C_1}))*\mathbf{I}_1 - \mathbf{U}_1 + \omega^2 M_{12}M_{21}\mathbf{I}_1}{\mathbf{U}_1 - (R_1 + j(\omega L_1 - \frac{1}{\omega C_1}))\mathbf{I}_1} \tag{17}$$

III. OUTPUT POWER CONTROL

The theory presented in section II shows that, for a wireless power transfer system with known system parameters, the load impedance Z_L could be computed easily by measuring the input voltage and input current. With Z_L determined, one could also calculate the coil currents $\mathbf{I}_1, \mathbf{I}_2, \dots \mathbf{I}_n$ by resolving the equation set (18).

In general, the coil current expression is

$$\mathbf{I}_i = f_i(\mathbf{U}_1, \omega, Z_L) \tag{19}$$

Other power information such as the input power of the power source (P_{in}), the output power of the load (P_{out}), and the power loss caused by each coil's resistance (P_{loss}) can be expressed in the following equations.

$$P_{in} = \mathrm{Re}(\mathbf{U}_1 \cdot \mathbf{I}_1^*) \tag{20}$$

$$P_{out} = [Abs(\mathbf{I}_n)]^2 \cdot \mathrm{Re}(Z_L) \tag{21}$$

$$P_{loss} = \sum_{i=1}^{n} ((Abs(\mathbf{I}_i))^2 \cdot R_i) \tag{22}$$

where I_1^* represents the conjugate of input current in complex form.

The overall system energy efficiency from the power source to the load is:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{[Abs(\mathbf{I}_n)]^2 \cdot \mathrm{Re}(Z_L)}{\mathrm{Re}(\mathbf{U}_1 \cdot \mathbf{I}_1^*)} \tag{23}$$

With the help of the full system model [16], it is possible to derive a look-up table for the optimal frequency versus the load resistance for a range of input impedance for achieving maximum energy efficiency. Therefore, one can adopt a frequency tracking method to adjust the operating frequency according to the load impedance. Unlike the proposal in [19] which requires wireless communication, this proposal enables the load impedance to be computed so that the appropriate operating frequency can be selected from the optimal frequency-load impedance mapping. Since the current of each coil, the input power and the output power can be calculated, one can adjust the input voltage to make the load power achieving the desired power output at the optimal frequency.

In summary, by using the proposed method, one may monitor the load changing and calculate the current, power and efficiency of the wireless power transfer system by measuring the input voltage and input current only, without any direct or indirect feedback from the load.

IV. SIMULATION RESULTS AND EXPERIMENTAL VERIFICATION

A. Load Monitoring Verification with Practical Resistive Bank

To verify the proposed ideas for identifying the load impedance for wireless power transfer system, an 8-coil wireless power domino-resonator system (Figure.1) is adopted in a simulation study. A practical resistor bank is used as the variable load. The system parameters and setup details are provided Table I to Table IV. The practical (nominal) values of the resistive load under different settings are listed and compared with the computed results in Table V.

It can be seen from Table V that the error between the computed and the practical load impedance and the measured resistance is less than 10 percent. Note that part of the error comes from the variations of the load resistance with temperature changes. In this preliminary verification process, a single set of input voltage and current measurements are used to calculate the load impedance. It can be expected that, the error between the calculated and measured load impedance will be further reduced if several sets of measurements are used with some averaging and/or filtering process in the computational process.

$$\begin{bmatrix} \mathbf{I}_1 \\ \mathbf{I}_2 \\ \vdots \\ \mathbf{I}_{(n-1)} \\ \mathbf{I}_n \end{bmatrix} = \begin{bmatrix} R_1 + j\left(\omega L_1 - \dfrac{1}{\omega C_1}\right) & j\omega M_{12} & \cdots & j\omega M_{1(n-1)} & j\omega M_{1n} \\ j\omega M_{21} & R_2 + j\left(\omega L_2 - \dfrac{1}{\omega C_2}\right) & \cdots & j\omega M_{2(n-1)} & j\omega M_{2n} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ j\omega M_{(n-1)1} & j\omega M_{(n-1)2} & \cdots & R_{n-1} + j\left(\omega L_{n-1} - \dfrac{1}{\omega C_{n-1}}\right) & j\omega M_{12} \\ j\omega M_{n1} & j\omega M_{(n-1)2} & \cdots & j\omega M_{(n-1)(n-1)} & R_n + Z_L + j\left(\omega L_n - \dfrac{1}{\omega C_n}\right) \end{bmatrix}^{-1} \begin{bmatrix} \mathbf{U}_1 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \tag{18}$$

TABLE I. SELF-INDUCTANCE OF EACH COIL OF THE 8-COIL DOMINO-RESONATOR SYSTEM

	L_1	L_2	L_3	L_4	L_5	L_6	L_7	L_8
Inductance (H)	8.204e-05	8.204e-05	8.204e-05	8.204e-05	8.204e-05	8.204e-05	8.204e-05	8.204e-05

TABLE II. MUTUAL-INDUCTANCE OF EACH PAIR OF COILS OF THE 8-COIL DOMINO-RESONATOR SYSTEM

	M_{12}	M_{13}	M_{14}	M_{15}	M_{16}	M_{17}	M_{18}
Inductance (H)	9.210e-06	2.588e-06	1.004e-06	4.733e-07	2.589e-07	1.555e-07	9.936e-08
	M_{23}	M_{24}	M_{25}	M_{26}	M_{27}	M_{28}	M_{34}
Inductance (H)	8.836e-06	2.5544e-06	9.887e-07	4.734e-07	2.584e-07	1.537e-07	9.048e-06
	M_{35}	M_{36}	M_{37}	M_{38}	M_{45}	M_{46}	M_{47}
Inductance (H)	2.582e-06	1.0126e-06	4.813e-07	2.589e-07	8.964e-06	2.616e-06	1.020e-06
	M_{48}	M_{56}	M_{57}	M_{58}	M_{67}	M_{68}	M_{78}
Inductance (H)	4.772e-07	9.212e-06	2.658e-06	1.015e-06	9.158e-06	2.5878e-06	8.885e-06

TABLE III. COPPER RESISTANCE OF EACH COIL OF THE 8-COIL DOMINO-RESONATOR SYSTEM

	R_1	R_2	R_3	R_4	R_5	R_6	R_7	R_8
Resistance (Ohm)	7.521e-01	7.521e-01	7.521e-01	7.521e-01	7.521e-01	7.521e-01	7.521e-01	7.521e-01

TABLE IV. CAPACITANCE VALUE OF EACH SERIES CAPACITOR OF THE 8-COIL DOMINO-RESONATOR SYSTEM

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Capacitance (nF)	1.020	1.004	1.009	9.992	9.960	1.002	1.012	1.065

TABLE V. COMPARISON OF CALCULATED IMPEDANCES AND EXPERIMENTAL IMPEDANCES

Measured load impedance (Ohm)	**Experimental Data from the transmitter**				**Calculated load impedances(Ohm)**		**Error (%)**
	Frequency (Hz)	$V_{in}(V)$	I_{in} (A)	***Phase angle (Degree)***	***Real part***	***Imaginary part***	
9.1	539751.57	1.507	0.0202	4.05	8.19	1.03	10.00
19.3	522452.52	1.2721	0.0315	-55.93	18.58	-4.71	3.73
19.3	535834.47	1.0658	0.0293	-9.34	18.43	-4.68	4.51
29.1	520632.39	1.3734	0.0264	-41.8	27.69	0.32	4.85
30	522739.37	1.3266	0.0285	-47.74	27.1	-0.46	9.67
39.3	521899.22	1.3136	0.0264	-34.75	36.86	-2.06	6.21
49.3	523702.25	1.3132	0.0258	-31.07	45.11	-6.62	8.50
59.2	523180.83	1.4107	0.0233	-25.78	56.64	-0.68	4.32
69.6	523512.07	1.4578	0.0221	-22.15	66.81	-3.08	4.01
79.5	523707.33	1.4909	0.021	-19.16	76.21	-3.58	4.14
99.6	523813.39	1.5872	0.0189	-17.07	94.99	-4.01	4.63
119.4	523887.33	1.6689	0.0172	-14.97	116.59	-3.49	2.35

B. *Power Control Verification*

A study has been conducted to verify the power control performance. A programmable ac voltage source is used to drive the transmitter coil at a frequency within the range of 495kHz to 525kHz. The load changing process is emulated with a programmable resistive bank. A control system is used to measure the input voltage and input current so as to calculate the load resistance, decide the operating frequency, and maintain the proper input voltage to make sure the load power be maintained at about 10W at the maximum energy efficiency.

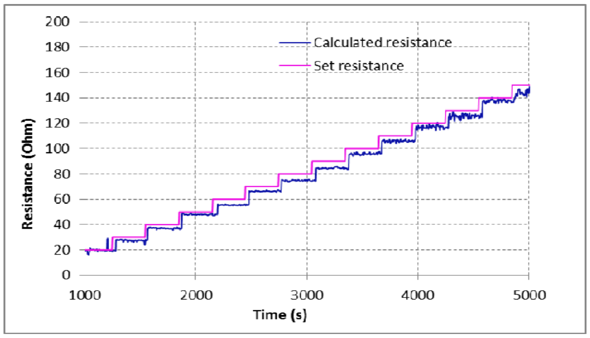

Figure. 2 Comparison of (practical) set resistance and calculated resistance.

Figure.2 shows the set resistance and the calculated resistance values over a period of time. The calculated results follow the resistance reference fairly closely. The load power can be maintained at around 10W despite the load changes. The theoretical energy efficiency and the computed one are plotted in Figure.3, together with the load power. The results indicate that a system efficiency of over 70% can be achieved for an output power of about 10W for a range of load impedance.

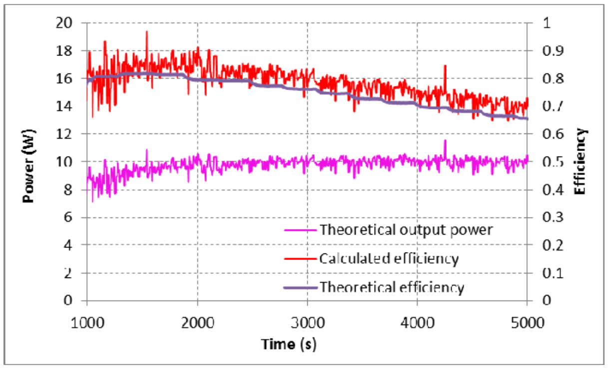

Figure. 3 Output power and theoretical and calculated energy efficiency.

V. CONCLUSION

A new approach of load monitoring and output power control of a wireless power system without using any direct measurements from the load is presented. Based on the input voltage and current measurements only, the proposed method can derive a range of variables such as the load impedance, output voltage, output current, output power and the loop currents. Other information such as power loss and energy efficiency can also be computed. The theory of this new approach has been presented and explained. It is demonstrated in an 8-coil wireless domino-resonator system and can in principle be applied to other wireless power systems.

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