A Simple Method to Determine the Performance of Two-Coil Wireless Power Transfer Systems without Direct Output Measurement

Lucas Ricken Garcia and Paulo J. Abatti

Abstract— Two-coil wireless power transfer (WPT) systems are composed of two circuits tuned at the same resonance frequency, one containing the source, and other containing the load, both connected to each other by the mutual inductance. The power delivered to the load circuit (P_o) divided by the total power supplied by the source (P_T) and by the maximum ideal amount of power which can be delivered to the load circuit are usual figures of merit known as efficiency (η) and power transfer capability (P^*), respectively. Additionally, it can be defined a third figure of merit (I^*) as the power dissipated at the source circuit divided by P_T . It has been recently demonstrated that η and P^* are related to I^* . In this paper, it is presented a simple method to monitor I^* , allowing consequently the determination of η and/or P^* without any direct measurement at the load circuit. The qualities and limitations of the proposed method are discussed in details. Practical results are included to verify the proposal.

Index Terms— Wireless power transfer, inductive power transfer, figures of merit, efficiency, power transfer capability.

I. INTRODUCTION

WIRELESS power transfer (WPT) systems via inductive coupling was first reported by Tesla more than a century ago [1]. The simplest WPT systems are composed of only two resonant circuits tuned at the same resonance frequency, one containing the source, and other containing the load, which are magnetically connected by the mutual inductance. Due to its safety, flexibility, and reliability, WPT systems have become a key technology in several fields, such as, for instance, power charging electric vehicles and implantable medical devices [2]–[7].

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Perhaps because of their increasing importance, a lot of research efforts have been devoted to the improvement of the overall system efficiency and/or power transfer capability [7]–[13]. The WPT system's efficiency (η) can be defined as the power delivered to the load circuit (P_o) divided by the total power supplied by the source (P_T), whereas its power transfer capability (P^*) can be defined as P_o divided the maximum ideal amount of power which can be delivered to the load circuit [11].

Independently of the figure of merit used to characterize the WPT system, in some applications the relative position of coils is not fixed, which means that the mutual inductance between them may have a different value each time. In the same way, load characteristics may be dependent of the employed remote device or may vary with time. Implantable medical devices and electric vehicles, which employ WPT systems, are obvious instances of such applications [14]–[17]. Thus, as η and P^* depend on mutual inductance and/or load value, feedback strategies to allow the WPT system's control have been devised. For example, in [18] and [19] wireless communication scheme had been used to monitor selected parameters at the load circuit and send the information back to the source circuit for control purposes. Unfortunately, classical feedback procedures require additional communication circuits between the source and load ones, increasing consequently the system complexity, volume, and cost [20]. Alternatively, techniques to allow the control and optimization of WPT systems using exclusively information obtained at the source circuit had been proposed [20]–[25]. For instance, if the current in the source circuit depends on the load value, it can be monitored, and this information used to compensate any possible variation on η and P^* caused by load value modification. However, if the current in the source circuit depends on two elements of the WPT system, such as load and mutual inductance values, it is necessary to monitor at the source circuit at least two independent parameters (equivalent to describe the WPT system from the source circuit using two independent equations). This can be done, for instance, relating load and mutual inductance values to the real and imaginary parts of the reflected impedance [20]–[25]. In this way, provided all other parameters are known, the circuit is completely determined, so that the WPT system's η and/or P^* can be promptly calculated, and control procedures

implemented.

However, the WPT systems must present minimum losses, so a basic guideline used in their implementation is to minimize the reactive effects. Of course, such a WPT system does not present imaginary part of reflected impedance at the source circuit; therefore, the just described technique (see [20]–[25]) is not anymore applicable. Thus, to preserve the advantages of minimum losses with the possibility of output control using only information obtained at the source circuit a novel approach is necessary.

It has been recently demonstrated that using a third figure of merit (I^*), which can be defined as the power dissipated at the source circuit divided by P_T , $P^* = 4\eta I^*$ and that for two-coil WPT systems $\eta = (1 - I^*)$, opening up the possibility to determine η and/or P^* without any direct measurement at the load circuit [26].

The aim of this paper is to present a simple method to monitor I^* of a typical two-coil WPT system with both source and load as series circuits, allowing therefore the determination of η and P^* using only information obtained at the source circuit. The qualities and limitations of the proposed method are discussed in details. Practical results are included to validate the presented theory.

II. THEORY

Fig. 1 shows the schematic view of a typical two-coil WPT system with both source and load as series circuits.

As aforementioned, possible losses due to reactive effects should be reduced. Thus, it is usual to consider all circuits tuned at the same angular frequency ($\omega^{-1} = \sqrt{L_1 C_1} = \sqrt{L_2 C_2}$), because under this condition the voltages and currents in each circuit are in phase.

Fig. 1. Schematic diagram of a typical two-coil WPT system with both source and load as series circuits.

Therefore, the two-coil WPT system in practice is composed by two individual circuits with their inductances (L_1 and L_2) tuned by their respective capacitances (C_1 and C_2), magnetically connected through the mutual inductance M_{12} . The losses at each circuit are represented by the resistances R_1 and R_2 , which are the sum of the internal resistance of C_1 - L_1 (r_1) and the internal resistance of the source (R_s), and the sum of the internal resistance of C_2 - L_2 (r_2) and the load resistance (R_L), respectively.

These considerations allow to write

$$i_1 = \frac{v}{R_1 (1 + Q_{12})}, \quad (1)$$

where Q_{12} is defined as

$$Q_{12} = \frac{\omega^2 M_{12}^2}{R_1 R_2}. \quad (2)$$

Clearly, if $M_{12} = 0$, i.e. $Q_{12} = 0$, i_1 is maximum (i_{1MAX}), which is given by

$$i_{1MAX} = \frac{v}{R_1}. \quad (3)$$

The power dissipated at the source (P_1) and load (P_o) circuits can be written as

$$P_1 = \frac{v^2}{R_1 (1 + Q_{12})^2}, \quad (4)$$

and

$$P_o = \frac{v^2}{R_1 (1 + Q_{12})^2} Q_{12}. \quad (5)$$

The optimal value of Q_{12} that maximizes P_o can be obtained solving $dP_o/dQ_{12} = 0$, yielding $Q_{12} = 1$. Therefore, using $Q_{12} = 1$ in (5) the maximum power which can be delivered to the load circuit is $P_{oMAX} = v^2/4R_1$.

The total power delivered by the source (P_T) can be calculated using (4) and (5) yielding

$$P_T = v i_1 = P_1 + P_o = \frac{v^2}{R_1 (1 + Q_{12})}. \quad (6)$$

The efficiency (η) and the power transfer capability (P^*) can be given, using (4), (5), (6) and P_{oMAX} , by

$$\eta = \frac{P_o}{P_T} = \frac{Q_{12}}{1 + Q_{12}}, \quad (7)$$

and

$$P^* = \frac{P_o}{P_{oMAX}} = \frac{P_o}{(v^2/4R_1)} = 4 \frac{Q_{12}}{(1 + Q_{12})^2}, \quad (8)$$

respectively.

Observe that dividing (6) by P_T gives

$$1 = \frac{P_1}{P_T} + \frac{P_o}{P_T}. \quad (9)$$

The relation $P_1/P_T (= I^*)$ can be calculated dividing (4) by (6) and using (3) yielding

$$I^* = \frac{P_1}{P_T} = \frac{1}{1 + Q_{12}} = \frac{R_1 i_1^2}{v i_1} = \frac{i_1}{(v/R_1)} = \frac{i_1}{i_{1MAX}}. \quad (10)$$

Finally, using (7) and (10) into (9) and (8) it can be written

$$\eta = 1 - I^*, \quad (11)$$

and

$$P^* = 4 \eta I^* = 4(1 - I^*)I^*, \quad (12)$$

respectively.

Equations (11) and (12) show that η and P^* can be determined using only information obtained at the source circuit, i.e. monitoring I^* . In addition, (10) shows that if i_{1MAX}

is known, I^* can be experimentally determined measuring i_1 .

It was just demonstrated that P_O is maximum ($P_{O_{MAX}}$) whenever $Q_{12} = 1$. Consequently, using (8), the maximum power transfer capability of a two-coil WPT system (P_{MAX}^*) is also equal to 1. Additionally, using $Q_{12} = 1$ into (10) and (11) gives $I^* = 1/2$ and $\eta = 1/2$, respectively. Thus, following the maximum power transfer theorem maximum $P_{MAX}^* = 1$ implies $\eta = 1/2$ [7], [11], and these values can be easily determined since for them necessarily $I^* = 1/2$, or $i_1 = i_{1_{MAX}}/2$.

Moreover, note that $P_{MAX}^* = 1$, $\eta = 1/2$, and $I^* = 1/2$ values do not depend on the individual values of M_{12} , R_L , and R_1 since there are innumerable combinations of $M_{12} - R_L - R_1$ for which $Q_{12} = 1$. In other words, independently of M_{12} , R_L , and R_1 values, whenever $Q_{12} = 1$, $P_{MAX}^* = 1$, $\eta = 1/2$, and $I^* = 1/2$. In fact, each value of Q_{12} correspond to a unique combination of P^* , η , and I^* values, whereas innumerable combinations of $M_{12} - R_L - R_1$ can result a single Q_{12} value.

There is not an optimal value of Q_{12} that maximizes η , because it monotonically increases as Q_{12} increases (see (7)). Therefore, η can be only determined in a trade-off basis, because to increase it ($\eta > 1/2$) it is necessary to decrease the value of P^* from its maximum value ($P^* < 1$). For instance, adjusting $Q_{12} = 3$ makes $P^* = \eta = 3/4$, and $I^* = 1/4$, or $i_1 = i_{1_{MAX}}/4$.

At this point it must be emphasized that P^* and η are related to the power transferred to the load circuit ($r_2 + R_L$) not to the power transferred to load (R_L). As load circuit is a series one, the two-coil WPT system “load power transfer capability” (P_L^*) and “load efficiency” (η_L) are respectively related to P^* and η as

$$P_L^* = \frac{R_L}{r_2 + R_L} P^* = \frac{1}{1 + \frac{r_2}{R_L}} P^*, \quad (13)$$

and

$$\eta_L = \frac{R_L}{r_2 + R_L} \eta = \frac{1}{1 + \frac{r_2}{R_L}} \eta. \quad (14)$$

Note that in practice as r_2/R_L decreases, P_L^* approaches P^* as well as η_L approaches η , whereas, I^* is not influenced by the relation r_2/R_L . Therefore, multiplying (12) by $R_L/(r_2 + R_L)$ and using (13) and (14) it can be written

$$P_L^* = 4 \eta_L I^*, \quad (15)$$

Summing up, the performance (represented by I^* , P^* and/or η) of the two-coil WPT system is determined in a unique form by the Q_{12} value. Moreover, perhaps more important from practical point of view, P^* and η , as well as the relationship between P_L^* and η_L , can be determined uniquely by I^* (see (11) and (12)), and (15)), since Q_{12} has a univocal relation to I^* . On the other hand, innumerable combinations of $M_{12} - R_L - R_1$ can yield a given value of Q_{12} . However, the absolute value of P_O is determined, given a voltage source with amplitude “ v ” and a Q_{12} value, by R_1 (see (5)) and, from the P^* and η values, r_2/R_L determines P_L^* and/or η_L (see (13) and (14)),

respectively. Although the presented analysis was developed for both source and load as series circuits, evidently it can be adapted to most of the other configurations (series-parallel, etc., see for example [23]) calculating the equivalent series circuit.

Clearly, the presented method does allow to easily determine P^* and η by monitoring I^* , being recommended whenever the values of R_L and/or M_{12} are known or their individual determination are not necessary and/or required.

III. EXPERIMENTAL VALIDATION

The experiments were performed using two circular coils with 62 turns of enameled copper wire of 35 AWG, both with diameter of 40 mm. The coils have self-inductances of $217 \pm 2.4 \mu H$ with internal resistances of $9.25 \pm 0.25 \Omega$. To monitor the current in the source circuit, a resistance (R_0) of 4.9Ω (measured at 530 kHz) was added in series. All these measurements were done using an Agilent 4294A vector impedance analyzer operating at 530 kHz.

The source was a Minipa MFG-4201A function generator (internal resistance R_s equal to 50Ω) and the voltages were measured using a Tektronix 2002B oscilloscope.

Both circuits had been empirically tuned at a resonance frequency of 530 kHz using associations of capacitors ($411 \pm 4.2 pF$). The resistances of the capacitors at 530 kHz were neglected because they were in order of milliohms.

After tuning, the resistances of each circuit yield $R_1 = 63.9 \Omega$, and as three different values of R_L were used, 9.9 Ω , 47.1 Ω and 98.8 Ω , the load circuit resistances ($R_2 = r_2 + R_L$) were 19.4 Ω , 56.6 Ω and 108.3 Ω , respectively. All experiments were performed keeping the source circuit unchanged and modifying only R_L in the load circuit. Fig. 2 illustrates the experimental setup of the implemented two-coil WPT system.

Fig. 2. Experimental setup showing the implemented two-coil WPT system.

In all experiments the mutual inductance M_{12} was gradually varied from 56.5 μH to 1.4 μH . In a coaxial arrangement these mutual inductances values are related to $L_1 - L_2$ distances (measured between the last turn of L_1 and first turn of L_2) of 4 mm and 80 mm, respectively.

Practical data were obtained by measuring the voltages over R_0 and the load to determine source and load circuit currents, respectively. Theoretical values were calculated using

Neumann equation to determine the mutual inductance and (7), (8), and (10) to obtain η , P^* , and I^* , respectively.

The i_{1MAX} was measured by placing L_2 sufficiently far away so that $M_{12} \approx 0$ ($Q_{12} \approx 0$). The data via I^* were obtained dividing i_1 by i_{1MAX} and applying (11) and (12) to obtain η and P^* , respectively. These values of η and P^* and those of r_2/R_L according to the selected R_L were used in (13) and (14) to compute η_L and P_L^* , respectively.

Fig. 3 presents the theoretical (lines) and experimental (points) results of P^* , η , and I^* as function of Q_{12} , for $R_1 = 63.9 \Omega$, and R_2 equal to 19.4 Ω , 56.6 Ω and 108.3 Ω .

The practical, both via direct load circuit measurements and using only measured values of I^* in (11) and (12), and theoretical results of I^* , P^* , and η as function of M_{12} are presented in Fig. 4, for $R_1 = 63.9 \Omega$, and R_2 equal to 19.4 Ω , 56.6 Ω and 108.3 Ω .

Fig. 3. Theoretical and practical results of P^* , η , and I^* as function of Q_{12} , for $R_1 = 63.9 \Omega$, and R_2 equal to 19.4 Ω , 56.6 Ω and 108.3 Ω . The points for Q_{12} equal to 1 and 3 are indicated by vertical dashed lines, whereas horizontal dashed lines indicate the correspondent values of P^* , η , and/or I^* .

Clearly, the only difference between Fig. 3 and 4 is that, as I^* , P^* , and η are plotted as function of M_{12} , the results are split into three curves, one for each R_2 selected value. Fig. 4 shows also that as R_2 increases a higher value of M_{12} is necessary for P^* to reach its maximum value. For example, for R_2 equal to 19.4 Ω and 56.6 Ω the implemented two-coil WPT system reaches P_{MAX}^* for $M_{12} \approx 11.4 \mu H$ and $M_{12} \approx 18.1 \mu H$, respectively.

The influence of R_L on the results can be analyzed plotting P_L^* and/or η_L in Fig. 3 and/or 4. However, as I^* is not influenced by r_2/R_L , perhaps the most appropriate manner to discuss the qualities and limitations of the proposed method is using a graph I^* versus P_L^* and η_L (Fig. 5), where for comparison purposes, P^* and η are also presented. In this figure, it had been used the values of r_2/R_L of approximately 0.96, 0.20, and 0.10, corresponding to $r_2 = 9.5 \Omega$, and R_L equal to 9.9 Ω , 47.1 Ω and 98.8 Ω , respectively, whereas P^* and η are presented as r_2/R_L equal to zero.

Fig. 4. Practical using direct output measurements and via I^* and theoretical results for the two-coil WPT system's (a) I^* , (b) P^* and (c) η for $R_1 = 63.9 \Omega$, and R_2 equal to 19.4 Ω , 56.6 Ω and 108.3 Ω .

Fig. 5. Behavior of P_L^* and η_L relative to I^* for different r_2/R_L : approximately 0.96, 0.20, and 0.10, corresponding to $r_2 = 9.5 \Omega$, and R_L equal to 9.9 Ω , 47.1 Ω and 98.8 Ω . For comparison purposes, P^* and η are also presented as r_2/R_L equal to zero.

This figure summarizes the objective of the present work. For instance, it can be easily observed that if $I^* = 0.25$, $P_L^* = \eta_L$ equal to 0.38, 0.62 and 0.68 for r_2/R_L equal to 0.96, 0.2

and 0.1, respectively, i.e. as r_2/R_L decreases $P_L^* = \eta_L$ approaches $P^* = \eta$, in this case 0.75. Moreover, if one want to operate the WPT system with an efficiency η_L higher than 0.75 (75 %) and knows that the maximum value of r_2/R_L in this system is 0.1, then he or she may modify the relative position of the coils modifying M_{12} , so that I^* is adjusted to be always smaller than 0.175.

Finally, it is possible to verify that P^* and η , as well as P_L^* and η_L , present, for all values of R_2 , r_2 , and R_L utilized, a correlation higher than 0.996 between theoretical and experimental (both direct load circuit measurement and determined via I^*) data.

IV. CONCLUSION

In this paper it was presented a simple method to monitor I^* of a typical two-coil WPT system with both source and load as series circuits, allowing therefore the determination of η and P^* using only information obtained at the source circuit.

In fact, it was demonstrated that typical two-coil WPT systems have unique set of I^* , P^* and η as function of Q_{12} , and as the relation between Q_{12} and I^* is univocal, determining I^* , means that both P^* and η can be determined. It was also shown that the influence of R_L can be calculated comparing it with r_2 so that the performance of practical WPT systems can be conveniently represented by P_L^* and/or η_L (see (13) and (14)). The diagram I^* versus P_L^* and η_L illustrates the proposed method (see Fig. 5). It must be emphasized however that innumerable combinations of $M_{12} - R_L - R_1$ can yield a given value of Q_{12} so indirectly I^* . This means that P_L^* and η_L are not determined by the individual values of M_{12} , R_L and R_1 (see (15)); the individual influence of R_1 is mainly on the absolute value of P_O (see (5)), whereas, as just mentioned, R_L , compared with r_2 , allows to compute P_L^* and η_L from P^* and η values, respectively.

It must be emphasized that, after a simple procedure to determine the amplitude of i_{1MAX} , I^* can be promptly determined monitoring the amplitude of i_1 , facilitating any scheme of P^* and/or η (or even of P_L^* and/or η_L if r_2/R_L is known) control. Moreover, as most of two-coil WPT system configurations can be converted into source and load series circuits, the developed analysis can be adapted to most of the practical circuit.

The authors hope that the presented work may be useful to those interested in design and implementation of WPT systems.

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