Comparison Between Three- and Four-coil Wireless Power Transfer Systems with Resonant Coils

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Abstract– **In this paper, it is demonstrated that the efficiency and ability to transfer power to the load in three-coil wireless power transfer (WPT) systems are always higher than in equivalent four-coil ones. On the other hand, it is shown that there are features attainable in four-coil WPT system that are not in three-coil ones. For instance, in a four-coil WPT system, which can be divided into source, two communication, and load circuits, it is possible to devise a method for which the maximum power transferred to the load circuit or the maximum efficiency do not depend on the mutual inductance between the two communication coils, independently of the load resistance value. The necessary conditions to achieve the above feature together with the overall circuit analysis are discussed in details and practical results presented.**

Index Terms– four-coil, power transfer efficiency, three-coil, wireless power transfer systems.

I. Introduction

Among the several forms of energy, whenever possible, the electrical one is preferable as produces less pollution comparatively, it is easier to handle, and mainly because it can be transmitted more efficiently. The usual method to transmit electrical energy from the source to the load is via cables or wires. However, from the very beginning of electrical energy distribution history, it was recognized that wireless methods to transmit it would be comparatively more convenient [1].

Nevertheless, after the pioneering work of Tesla, which used an inductive link, composed of two coils tuned at the same resonance frequency to transmit electrical energy at a given distance [2], the investigation of the so-called wireless power transfer (WPT) systems was almost neglected for several years, but by some sparse works [3]–[9]. In fact, only about a decade ago the three- [10]–[18], and four-coil [19]–[30] WPT systems had been introduced. WPT systems using more than four coils had also been investigated, but most of the research effort in the area had been focused in the three- and four-coil configurations [25], [31], [32]. Here it is important to emphasize that the three- and four-coil WPT systems are, in some aspects, similar to the two-coil WPT systems, e.g., they have one coil connected to the source and one connected to the load. The differences are that the three-coil WPT systems have one additional (communication) coil and the four-coil WPT systems have two additional (communication) coils. Moreover, following Tesla's original approach [2], all coils are tuned at the same resonance frequency and mutual inductance of non-adjacent coils are made as small as possible.

Anyway, perhaps because it is a relatively recent circuit configuration, the three- and four-coil WPT systems characteristics are still object of studies. For example, in a recent paper it was demonstrated

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that in a three-coil WPT system both the maximum efficiency ($\eta 3_{max}$) and maximum power transferred to the load ($P3_{max}$) depend on neither the mutual inductance between the coils of the communication and load circuits nor the load resistance value (R_L) [17]. This means that $\eta 3_{max}$ and $P3_{max}$ are only determined by the source and communication circuits parameters, a feature that may be relevant to those involved in the circuit implementation. However, this also means that given a load resistance value there is only one value of the mutual inductance between the coils of the communication and load circuits, and vice-versa, for which either the maximum power transferred to the load circuit or the efficiency are maximum, restricting its practical application.

The aim of this work is to show that in four-coil WPT systems the maximum efficiency or maximum power transferred to the load do not depend on mutual inductance between the coils of the communication circuits (M23) independently of the load resistance value, and vice-versa. This is done by adjusting the mutual inductance between the coil at the last communication circuit and that at the load circuit (M34). In order to demonstrate this feature it is important to compare the three- and four-coil WPT systems, for it is demonstrated that the efficiency and the ability to transfer power to the load in three-coil WPT systems are always higher than in equivalent four-coil ones. Thus, the mutual inductance (proportional to distance in a coaxial arrangement) between the coils of the communication circuits were preserved in both three- and four-coil WPT systems. The necessary conditions to attain the above feature as well as the overall circuit analysis are discussed in details and experimental results, used to validate the theoretical analysis, presented.

II. Circuit Analysis

Figure 1 shows the schematic view of a four-coil WPT system. Following Tesla's original approach [2], all circuits should be tuned at the same resonance angular frequency ($\omega_0^{-1} = \sqrt{L_1C_1} = \sqrt{L_2C_2} = \sqrt{L_3C_3} = \sqrt{L_4C_4}$), and the mutual inductances between non-adjacent coils should be as small as possible ($M_{13} = M_{14} = M_{24} = 0$). Under the above conditions, the currents and voltages at each coil circuit are in phase so that possible losses due to reactive effects are reduced.

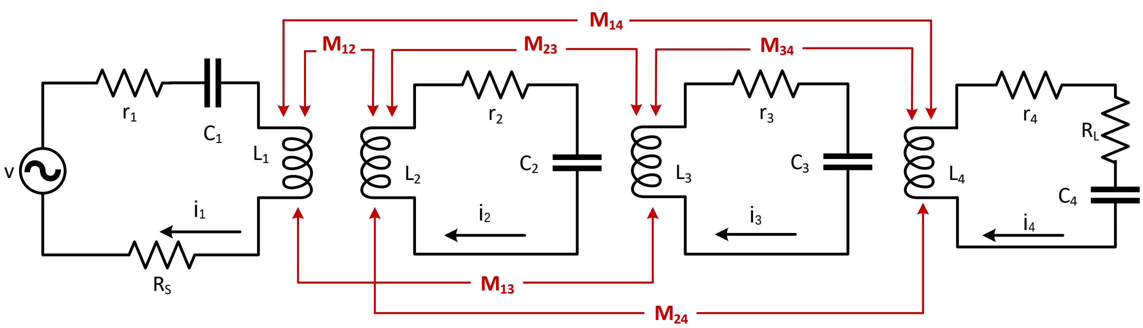

Fig. 1. Schematic representation of a four-coil wireless power transfer system.

These considerations allow to write the power dissipated at the load circuit (P_4) as

$$P_4 = R_4.|i_4|^2 = \frac{R_4 v^2 \omega_0^2 M_{12}^2 \omega_0^2 M_{23}^2 \omega_0^2 M_{34}^2}{\left(\left(R_1 r_2 + \omega_0^2 M_{12}^2\right)\left(r_3 R_4 + \omega_0^2 M_{34}^2\right) + R_1 R_4 \omega_0^2 M_{23}^2\right)^2}, \quad (1)$$

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where M_{12}, M_{23}, and M_{34} are the remaining mutual inductances, v the source open-terminal voltage (when $i_1 = 0$), R_1 the sum of the source resistance and the total internal resistance of L_1 and C_1 ($R_1 = R_s + r_1$), r_2 and r_3 the total internal resistances of L_2 and C_2, and L_3 and C_3, respectively, and R_4 the sum of the load resistance and the total internal resistance of L_4 and C_4 ($R_4 = R_L + r_4$).

The total power supplied by the voltage source can be easily calculated ($P_T = v.i_1$) giving

$$P_T = \frac{r_2 r_3 R_4 + r_2 \omega_0^2 M_{34}^2 + R_4 \omega_0^2 M_{23}^2}{\left(R_1 r_2 + \omega_0^2 M_{12}^2\right)\left(r_3 R_4 + \omega_0^2 M_{34}^2\right) + R_1 R_4 \omega_0^2 M_{23}^2}. \tag{2}$$

Thus, the system efficiency ($\eta = P_4/P_T$) can be written as

$$\eta = \frac{R_4 \omega_0^2 M_{12}^2 \omega_0^2 M_{23}^2 \omega_0^2 M_{34}^2}{\left(\left(R_1 r_2 + \omega_0^2 M_{12}^2\right)\left(r_3 R_4 + \omega_0^2 M_{34}^2\right) + R_1 R_4 \omega_0^2 M_{23}^2\right)\left(r_2 r_3 R_4 + r_2 \omega_0^2 M_{34}^2 + R_4 \omega_0^2 M_{23}^2\right)} \tag{3}$$

It is important to emphasize that if one calculates the efficiency considering only the power delivered to the load (η_L), since the same current i_4 flows through r_4 and R_L, the power P_4 can be splitted using the ratio of a voltage divider. Thus, $P_{RL} = P_4.R_L/(R_L+r_4)$ and the efficiency is $\eta_L = \eta.R_L/(R_L+r_4)$. In a similar manner, if only the efficiency of the link transmission (η_{LINK}) is to be analyzed (excluding the generator resistance, R_S), it can be written $\eta = \eta_{LINK}.R_1^*/(R_S + R_1^*)$, where R_1^* is the sum of r_1 and the reflected resistance [33] from communication and load circuits into the source circuit. Moreover, at first glance, the WPT systems should be designed to transmit the maximum amount of power from the source to the load (located as far as possible) with maximum efficiency. However, the maximum power transfer theorem teaches that the maximum transference of power is attained with an overall system efficiency of only 50%, higher efficiencies meaning a relatively reduced amount of power transferred to the load [25], [26], [34]. Thus, it is necessary to know a priori whether the WPT system is designed to optimize efficiency or if the amount of power transferred to load is to be the maximum [26].

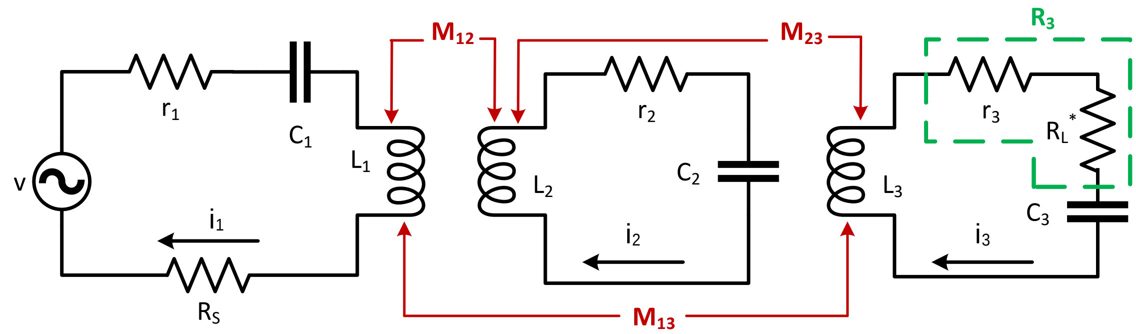

Fig. 2. Schematic representation of a three-coil wireless power transfer system.

Anyway, in order to help a comparative analysis, figure 2 shows the schematic view of the three-coil WPT system. Observe that the four-coil WPT system can be transformed into a three-coil equivalent one, reflecting R_4 [33] into the second communication circuit (see figure 2). In other words, both three-coil and four-coil WPT systems are equivalent whenever (see figure 2)

$$R_L^* = \frac{\omega_0^2 M_{34}^2}{R_4}. \tag{4}$$

In addition, it is possible to define

$$R_3 = r_3 + R_L^*, \tag{5}$$

so that the power transferred to R_3 in a three-coil WPT system (P_3) and efficiency (η_3) can be given by

$$P_3 = R_3.|i_3|^2 = \frac{R_3 v^2 \omega_0^2 M_{12}^2 \omega_0^2 M_{23}^2}{\left(\left(R_1 r_2 + \omega_0^2 M_{12}^2\right) R_3 + R_1 \omega_0^2 M_{23}^2\right)^2}, \tag{6}$$

and

$$\eta_3 = \frac{R_3 \omega_0^2 M_{12}^2 \omega_0^2 M_{23}^2}{\left(\left(R_1 r_2 + \omega_0^2 M_{12}^2\right) R_3 + R_1 \omega_0^2 M_{23}^2\right)\left(r_2 R_3 + \omega_0^2 M_{23}^2\right)}, \tag{7}$$

respectively.

Dividing (1) by (6) and (3) by (7), and using (4) and (5) yield

$$\frac{P_4}{P_3} = \frac{\eta_4}{\eta_3} = \frac{\dfrac{\omega_0^2 M_{34}^2}{R_4}}{r_3 + \dfrac{\omega_0^2 M_{34}^2}{R_4}}. \tag{8}$$

Therefore, the three-coil WPT systems always present better performance than the four-coil ones ($P_3 > P_4$ and $\eta_3 > \eta_4$).

However, there are situations that performance should be relegated to a second plan to attend some practical demand. For instance, it can be easily demonstrated that in the three-coil WPT system the M_{23} for maximum power transferred to R_3 ($M_{23-P_{3MAX}}$) and M_{23} for maximum efficiency ($M_{23-\eta_{3MAX}}$) can be written [17] as

$$M_{23-P_{3MAX}} = \frac{1}{\omega_0}\sqrt{\frac{R_1 r_2 + \omega_0^2 M_{12}^2}{R_1} R_3}\quad, \tag{9}$$

and

$$M_{23-\eta_{3MAX}} = \frac{1}{\omega_0}\sqrt{\sqrt{\frac{r_2}{R_1}}\sqrt{R_1 r_2 + \omega_0^2 M_{12}^2} R_3}\quad, \tag{10}$$

respectively.

Substituting (9) and (10) into (6) and (7) yield

$$P_{3MAX} = \frac{v^2}{4R_1}\frac{\omega_0^2 M_{12}^2}{R_1 r_2 + \omega_0^2 M_{12}^2}\,, \tag{11}$$

and

$$\eta_{3MAX} = \frac{\omega_0^2 M_{12}^2}{\left(\sqrt{R_1 r_2} + \sqrt{R_1 r_2 + \omega_0^2 M_{12}^2}\right)^2}\,, \tag{12}$$

respectively.

Note that, as already pointed out in [17], (11) and (12) are independent on either M_{23} and R_3, i.e., P_{3MAX} or η_{3MAX} are determined exclusively by the source and communication circuits' parameters. However, (9) and (10) show also that for a given R_3, and consequently for a given load $R_L^* = R_L$, there is only one value of M_{23} for which P_3 or η_3 can be maximum, and this specific value of M_{23} may not be attainable.

On the other hand, in four-coil WPT systems, using (4) and (5) into (9), and substituting (11) into (8), and using $R_4 = r_4 + R_L$, yield

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$$M_{23-P_{4MAX}} = \frac{1}{\omega_0}\sqrt{\left(\frac{R_1 r_2 + \omega_0^2 M_{12}^2}{R_1}\right)\left(r_3 + \frac{\omega_0^2 M_{34}^2}{r_4 + R_L}\right)} \quad , \tag{13}$$

and

$$P_{4MAX} = \frac{v^2}{4R_1}\frac{\omega_0^2 M_{12}^2}{R_1 r_2 + \omega_0^2 M_{12}^2}\frac{\frac{\omega_0^2 M_{34}^2}{r_4 + R_L}}{r_3 + \frac{\omega_0^2 M_{34}^2}{r_4 + R_L}} \quad , \tag{14}$$

respectively, whereas using (4) and (5) into (10), and substituting (12) into (8), and also using $R_4 = r_4 + R_L$, give

$$M_{23-\eta_{4MAX}} = \frac{1}{\omega_0}\sqrt{\sqrt{\frac{r_2}{R_1}}\sqrt{R_1 r_2 + \omega_0^2 M_{12}^2}\left(r_3 + \frac{\omega_0^2 M_{34}^2}{r_4 + R_L}\right)} \quad , \tag{15}$$

and

$$\eta_{4MAX} = \frac{\omega_0^2 M_{12}^2}{\left(\sqrt{R_1 r_2} + \sqrt{R_1 r_2 + \omega_0^2 M_{12}^2}\right)^2}\frac{\frac{\omega_0^2 M_{34}^2}{r_4 + R_L}}{r_3 + \frac{\omega_0^2 M_{34}^2}{r_4 + R_L}}, \tag{16}$$

respectively.

Observe that independently of R_L used, the value of M_{34} might be adjusted so that an adequate value of M_{23} may be obtained, allowing P_4 or η_4 to be maximum. In other words, in a four-coil WPT system the M_{34} can be used as an "impedance match" circuit desvinculating the actual R_L value from the determination of M_{23} which allows P_4 or η_4 to be maximum.

III. Experimental Results

For the experimental evaluation of the mathematical analysis, four coils with equal dimensions and shapes were built. The coils are circular with diameter of 150 mm and 22 mm of length, wound with 23 turns of enameled copper 20 AWG wire in a single layer way. The coils have self-inductance of 138.67 ± 0.21 μH with internal resistances of 3.41 ± 0.09Ω. All measurements were made using an Agilent precision vector impedance analyzer (model 4294A) operating at 552kHz. In order to obtain the practical value of the mutual inductance the coils were arranged coaxially, the value of the coupling coefficient (k) was measured, and then using $M_{ps} = k\sqrt{L_p L_s}$ the mutual inductance was determined as follows: the primary coil was excited by a signal generator (Rigol model DG1022) with a voltage vp, whereas the open-terminal voltage of the secondary coil, vs, was taken. Both voltages were measured with the aid of a digital oscilloscope (Tektronix model TDS2012C). The frequency of the exciting voltage was adjusted to a relatively low value (≈ 10kHz) to reduce the possible influence of the coils' stray capacitances. It can be easily demonstrated that $k = v_p/v_s$, whenever $L_p \approxeq L_s$ [26]. Figure 3 shows the measured mutual inductance as a function of the distance between the coils coaxially aligned.

Commercial capacitors of 560pF were used to tune the circuits (the practical values was 556 $\pm 7pF$), with a variable capacitor (trimmer) in parallel, achieving the series resonance value of 552kHz. This frequency has been selected due to its handiness in tuning the circuits, and because it does not present adverse health effects [35], [36]. The resistances of the capacitors at 552kHz were neglected because they were in order of milliohms.

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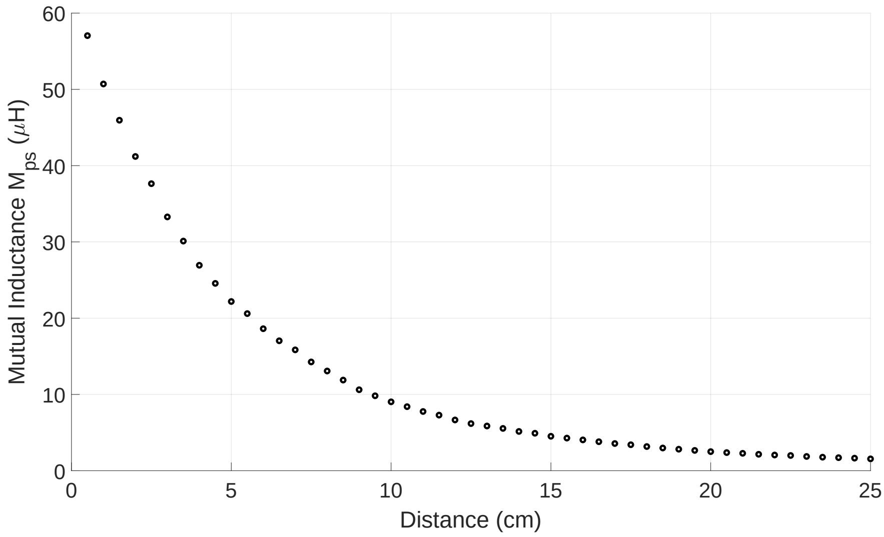

Fig. 3. Experimental mutual inductance in function of distance for coils coaxially aligned.

The measured (at 552kHz) values of the load (R_L) used in the experiments were 5.67Ω, 8.24Ω, 9.97Ω, 12.03Ω, 17.98Ω, 21.77Ω and 46.95Ω. The parasitic self-inductance of the resistors were neglected because they were in order of nanohenry.

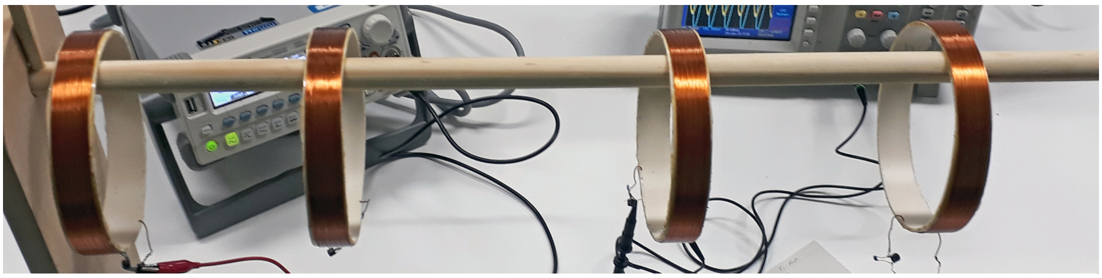

Fig. 4. Experimental setup of the four-coil wireless power transfer system.

Figure 4 shows the implemented four-coil WPT system. The coil of the source circuit was fixed to the left end of a wood support, whereas the second coil was fixed 12.5cm apart. The value of M_{12} was $6.18\mu H$ (see figure 3). A sinusoidal voltage signal (v) of 7.1 V_{RMS} with a frequency of 552kHz, internal resistance (R_s) of 50.53Ω (Rigol signal generator - DG1022) was used as the voltage source. The current at the source circuit (i_1) was determined to measure the voltage at a series resistor (r = 1.02Ω). Therefore, the value of R_1 (= $r_1 + r + R_s$) used in the calculations was 54.89Ω. During the experiments the phase between v and i_1 was continuously monitored (ideally it must be zero) to certify that the influence of M_{13}, M_{14}, and M_{24} could in fact be neglected.

The value of i_3 in the three-coil and i_4 in the four-coil WPT systems, respectively, were determined by measuring the voltages at the used loads, and the powers at the load circuits ($P_3 = R_3.|i_3|^2$ and $P_4 = R_4.|i_4|^2$) were calculated.

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From equations (14) and (16) it can be defined as a multiplying factor (F)

$$F = \frac{\frac{\omega_0^2 M_{34}^2}{r_4 + R_L}}{r_3 + \frac{\omega_0^2 M_{34}^2}{r_4 + R_L}}. \tag{17}$$

The maximum power transferred to the load circuit (P_{4MAX}), and the maximum efficiency (η_{4MAX}), both as a function of R_L for F equal to 1/2, 2/3 and 5/6, are shown in figures 5(a) and 5(b), respectively. Firstly, the experiments were performed keeping M_{23} fixed at 3.4μH. Then, just to check the independence between R_L and M_{23} the experiments were repeated keeping M_{23} fixed at 5.55μH. In addition, for comparison purposes, the values of P_{3MAX} and η_{3MAX} for M_{23} = 3.4μH and M_{23} = 5.55μH were also plotted in figures 5(a) and 5(b), respectively.

Evidently, in the four-coil WPT system each time R_L was changed the relative position of L_4 was modified so that $\left(\omega_0^2 M_{34}^2\right) / \left(R_L + r_4\right)$ was kept constant.

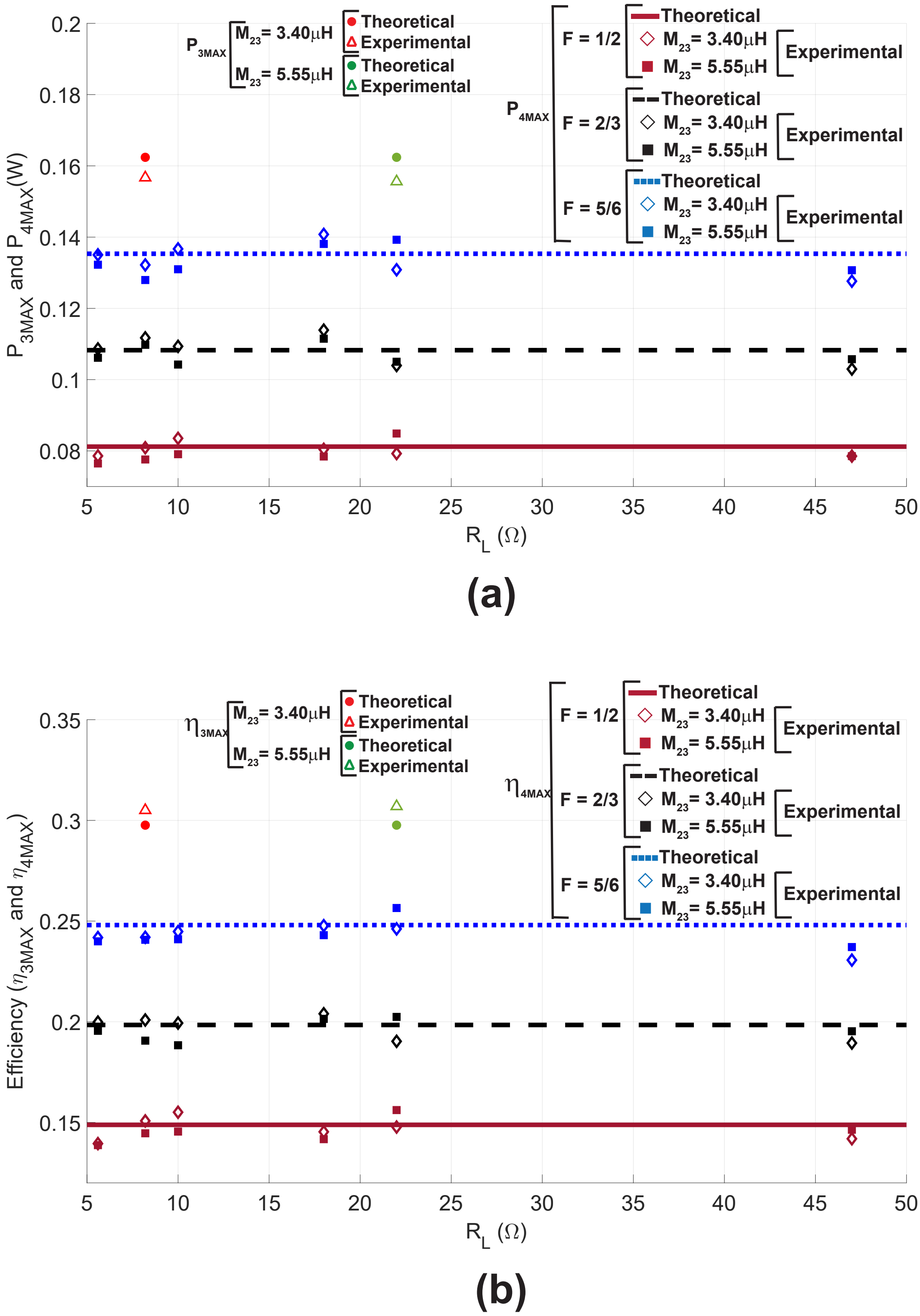

Fig. 5. Experimental results of (a) maximum power transferred to the load circuit and (b) maximum efficiency, both as a function of R_L in a four-coil WPT system. For comparison purposes the values of P_{3MAX} and η_{3MAX} for $M_{23} = 3.4\mu H$ and $M_{23} = 5.55\mu H$ were also plotted in figures 5(a) and 5(b), respectively.

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IV. CONCLUSION

The three- and four-coil WPT systems have been compared, showing that in the four-coil ones neither the maximum power transferred to the load nor the maximum efficiency depends on the mutual inductance regardless of the on load resistance value, provided $(\omega^2 M_{34}^2)/(R_L + r_4)$ is kept constant. Although the maximum power transferred to the load or maximum efficiency of four-coil are always smaller than those of three-coil WPT systems, the demonstrated feature allows designing optimized WPT systems independent on load resistance value whenever the four-coil configuration is used, which is not possible with three-coil WPT systems.

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