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ARTICLE

Wireless Electricity Transmission by Coupled Magnetic Resonances

DaifAoulah Nassor, Ali Daroesho and **Abdalrahaman H. Alhashim**

Physics Department, Faculty of Science, Tishreen University, Lattakia, Syria.

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Abstract: In this work, we have experimentally demonstrated the ability of transferring electrical power wirelessly using coupled magnetic resonance technique. This technique has been improved by using four resonators, thus maintaining the efficiency of transferring electricity wirelessly during the change of the transfer distance between the transmitter and the receiver coils. We also introduce the concepts of this technique, analyze the used circuit and extract the theoretical model which agrees with experimental results. We have experimentally measured the efficiency of transferred electricity at various transfer distances beginning from 30 cm to 130 cm. The efficiency was more than 50% at a distance of less than 70 cm and 22% at a distance of 100 cm.

Keywords: Resonance, Coupled magnetic resonances, Resonant frequency, Coupling coefficient, Mutual induction.

Introduction

Since its discovery, electric power has been transferred *via* wires from energy resources to loads, which could be domestic or industrial devices…etc.

This method of transferring electric power is simple and efficient as long as the load is steady.

Because of the vast technological developments and the existence of many portable electronic gadgets, the interest in wireless electric transferring technique has recently increased. Many research studies and experiments have emerged in this field. There have been many terms to stand for wirelessly transferred electricity, like WPT (Wireless Power Transfer) and Witricity (Wireless electricity). The idea is not newborn; it dates back to the early twentieth century, even to the era before the existence of networks and electric devices, when Nicola Tesla made big steps in this field [1]. In our present time, there are many techniques to transfer electricity wirelessly; it's relevant to classify them according to efficiency and transfer distance. Techniques that use propagating electromagnetic waves work in the same way in which radio signals do. These techniques have been used successfully as the transfer distance for them was in the order of hundreds of meters. One of the most prominent problems for them was to trade efficiency with range, because transfer is multidirectional [2, 3]. Scientist Brown used this technology in 1964 to operate a 60-foot powered drone helicopter.There are also techniques like HF, RF and Microwaves which use antennas with high gain to wirelessly transfer electric power. These techniques have transfer ranges which reach up to several kilometers and have an efficiency of more than 90%.These systems need constant and complex monitoring alignment equipment to maintain a line-of-sight (point-to-point). This may be very relevant to the transfer of electricity wirelessly for vast distances in uninhabited areas and even to future projects to transfer energy from space to the earth and *vice versa* [4, 5]. In 1975, NASA and Goldstone used this technology in their well-known experiment, where they were able to transfer electricity with a transfer efficiency of about 82% for a transfer distance of 1.5 km. Unfortunately, the cost was high. In

Corresponding Author: Abdalrahaman H. Alhashim **Email**: abdalrahaman.hashim@gmail.com

return, the techniques that don't depend on propagating electromagnetic waves and work for distances less than the wave length of the sent signals, have a high efficiency, but their transfer range is limited; about several centimeters. Examples are inductive coupling and capacitive coupling which are used in many applications like rechargeable toothbrushes and power surfaces [6]. Finally, a new technique has been recently suggested. It depends on resonant inductive coupling or coupled magnetic resonances (CMR) [7]. This technique depends on the idea that two circuits with the same resonant frequency could exchange energy with high efficiency so that losses will be neglected. So, power transfer *via* this technique could be so efficient and multidirectional and the medium around the circuit won't affect the transfer process, because interferences and losses resulting from objects around will be small [8]. In 2007, a research team from the MIT (Massachusetts Institute of Technology) successfully performed the first attempt at wireless power transmission using this technique after scientist Tesla's attempts at the end of the 19^{th} century. They were able to transfer electricity wirelessly with a transfer efficiency of 40% and a transfer distance of about 2 meters. Therefore, they used four resonators including helical type as internal resonators (self-resonators) of relatively large size. The used resonant frequency was about 10 MHz and the theoretical model was based on the coupled theory. The article published in this research does not explain the equations necessary to calculate the parameters of the wireless power transfer system, such as coupling coefficient and mutual induction. However, their system didn't adapt with the change of transfer distance. Works in this field adopted various techniques, especially magnetic resonance technology, but most of these works did not explain the theoretical calculations of system parameters and relied on different and complex theories to describe the system, such as coupled mode theory, impedance theory and electromagnetic theory. The practical measurements of most of these works are based on expensive and generally unavailable devices such as VNA (victor network analyzer) and RF techniques for measuring circuit parameters such as Q and f_0. This research is distinguished for the use of simple physical equations to describe the circuit and system variables based on the laws of Kirchhoff and other simple circuit laws. It also uses flat spiral coils, because they occupy less space (relatively small dimensions). In our measurements, we used innovative methods, simple available devices, such as an oscilloscope and a high-frequency source to measure all the parameters, such as self-inductance L, capacitance C, resonant frequency f_0 and quality factor Q.

In this research, we will work on this technique, which consists of two or more magnetically coupled resonant circuits. Because of the high efficiency of this technique and its adaptation to the change of transfer distance as well as because of simplicity of its use and its low cost.

Research Importance

The importance of this research comes from the many important applications of it in our daily and future life, with the existence of many electronic gadgets, especially portable devices, such as mobiles and laptops, as well as electric vehicles and medical equipment, such as pulse regulator devices. Most of these devices need constant feeding of electric power to recharge their batteries; so the connectors will become removed as in electric vehicles. These connectors occupy a huge place of the circuit or device while the device is shrinking because of technological advance. The biggest importance comes in the medical field as in recharging the battery of a pulse regulator, which is usually fitted inside the patient's body. In the closer past, there was an inevitable need of surgery in order to recharge or replace that battery. Now, this battery is being recharged wirelessly. With the claim of utilizing electric vehicles to save the environment, the batteries of these vehicles can be recharged wirelessly while passing through a especially made area like a bus stop. Also, a mobile phone can be recharged wirelessly *via* merely putting it on the table or even, in the close future, *via* its existence in an area fitted with a wireless energy feeding system, … and so on for many other devices. According to what has preceded, the need of an efficient energy transfer system is shown. This research has theoretical and practical contributions to understanding and developing wireless power transfer technology, which has become desired in our days in many fields of application.

In this research, we used simple physical equations to describe the circuit and system variables. In our measurements, we used innovative methods and simple devices, as we mentioned earlier.

Research Purpose

This research aims to design and execute a circuit depending on wireless power transfer technology using coupled magnetic resonances. It aims to present the main concepts and parameters for this technique, such as transfer distance d, quality factor Q, coupling coefficient K and resonant frequency f_0. Besides of revealing this technique advantages and getting the maximum efficiency for variable transfer distance, starting from $30\ cm$ to $130\ cm$, this research aims to study the coil dimensions, the measurement of induction L(self-inductance), self-capacity $C_{\text{parasitic}}$ (parasitic capacity), quality factor Q and self-resonant frequency f_0, in addition to comparing these parameters to those obtained by theoretical calculations. In addition, transfer efficiency η is measured *via* distance variation and compared to theoretical values of efficiency.

Research Methodology

Throughout this research, we constructed a theoretical model, analyzed this model, executed the practical circuit, conducted measurements to this model parameters and its efficiency and compared the results. Coupled magnetic resonance occurs between two circuits when the magnetic field of the primary circuit interacts with the one of the secondary circuit, which produces an induced current in the secondary circuit. The two circuits exchange power *via* their shared magnetic field. This exchange will be at its maximum when the two circuits are in resonance. These two circuits are called (resonators) and the common frequency of these two circuits is called the resonant frequency f_0. The two circuits are now coupled, but coupled circuits can show resonance at more than one frequency such as standing waves in trumpets or straight chords [9].

Resonant frequency will change as a function of coupling between coils. This is called frequency splitting. When the amount of coupling is larger, frequency splitting gets clearer. Coupling amount follows the distance between coils. It determines the energy transfer ratio, not the efficiency [10], while the efficiency is determined *via* losses. To make these losses neglected, energy that can't be transferred to the receiver must stay in the transmitter. Even if the coupling was at its minimum, the efficiency could be very high for coils having a high quality factor Q. This result is somehow unexpected for wireless power transfer systems, while in multidirectional propagation electromagnetic waves technique, the efficiency will be coherent with $\frac{1}{d^2}$.

In inductive coupling technique, efficiency is coherent with $\frac{1}{d^3}$ [11]. In fact, there is a minimal amount of coupling; this will be necessary to each load in the receiver coil for efficiency to stay high and for the system to stay stable[12].

Analyzing the Applied Circuit

Fig. 1 shows a WPT system *via* CMR and Fig. 2 shows the equivalent circuit consisting of our coils (resonators).

Source coil (resonator 1) consists of a single copper loop with a resistor R_1 and self-inductance L_1connected to a high-frequency source with an internal resistor R_s and an electromotive force V_s and connected to capacitor C_1in series to make the coil resonant at the required frequency. Load coil (resonator 4) consists of a single copper loop with a resistor R_4 and self-inductance L_4 connected to capacitor C_4 in series. Two coils represent the internal resonators (resonators 3&4) called transmitter and receiver coils; they consist of a round copper conductor with flat spiral shape having number of turns N, resistors R_2, R_3, self-inductances L_2, L_3 and self-capacitances $C_{2,}C_3$, respectively. The geometry of each coil codetermines parasitic capacity and so it determines resonant frequency. As transmit and receive coils don't contain external resistances, their quality factor will be huge. The usage of two internal coils improves efficiency and range [13, 14].

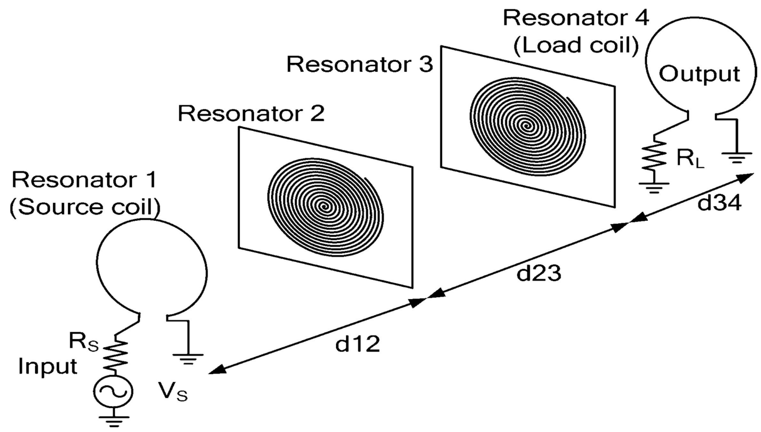

FIG. 1. WPT system *via* CMR.

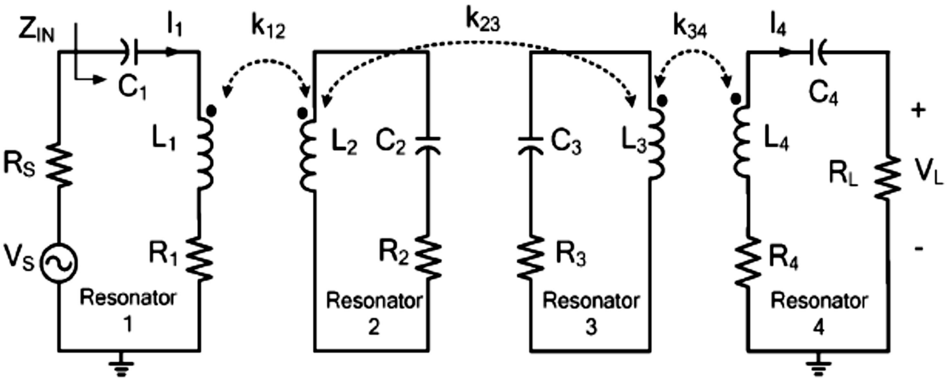

FIG. 2. Equivalent circuit of WPT system *via* CMR.

In addition, coupling coefficient between source coil and transmit coil on one hand and load coil and receiver coil on the other hand, can be controlled; so, distance change can be adapted without the need of an impedance matching network which can be used for the same purpose, but adding it will result in undesirable additional losses [15].

The suitable selection of the characteristics and geometry of transmitter and receiver coils plays the main role in improving efficiency and transfer range.

The distance between source coil and transmitter coil is d_{12} -Fig.1- and they are magnetically coupled with a coupling coefficient k_{12} as shown in the formula:

$$k_{i\,j} = \frac{M_{i\,j}}{\sqrt{L_i L_j}} \quad . \tag{1}$$

Here, M_{ij} is the mutual inductance between coils i and j. The subscripts i and j denote the circuit elements in Fig. 2. For example, i = 1 denotes the elements in the source coil (loop). In the same way, the distance between transmitter coil and receiver coil is d_{23} and they are magnetically coupled with a coupling coefficient k_{23}. The distance between receiver coil and load coil is d_{34} and they are magnetically coupled with a coupling coefficient k_{34}.

$$Q_i = \frac{\omega_i L_i}{R_i} \quad . \tag{2}$$

And the resonant frequency:

$$\omega_i = \frac{1}{\sqrt{L_i C_i}} \quad . \tag{3}$$

In this work, the cross-coupling terms k_{13}, k_{24}, k_{14} are neglected, because they are small and to make calculations easier.

Analyzing the previous circuits can be accomplished using many theories, but we will use Kirchhoff laws and simple circuit laws as mentioned earlier and write:

$$V_s = (R_s + R_1)I_1 + \left(j\omega L_1 - \frac{j}{\omega C_1}\right) I_1 + j\omega M_{12} I_2$$

$$0 = R_2 I_2 + \left(j\omega L_2 - \frac{j}{\omega C_2}\right) I_2 + j\omega M_{12} I_1 - j\omega M_{23} I_3$$

$$0 = R_3 I_3 + \left(j\omega L_3 - \frac{j}{\omega C_3}\right) I_3 + j\omega M_{34} I_4 - j\omega M_{23} I_2$$

$$0 = (R_L + R_4)I_4 + \left(j\omega L_4 - \frac{j}{\omega C_4}\right) I_4 + j\omega M_{34} I_3$$

When $\omega = \omega_0$ for each coil $\omega_i L_i = \frac{1}{\omega_i C_i}$

And $R_1 \ll R_s,\ R_4 \ll R_L \Longrightarrow$

$R_4 + R_L \cong R_L, R_1 + R_s \cong R_s \ \Longrightarrow$

$V_s = R_s I_1 + j\omega M_{12} I_2$

$0 = R_2 I_2 + j\omega(M_{12} I_1 - M_{23} I_3)$

$0 = R_3 I_3 + j\omega(M_{34} I_4 - M_{23} I_2)$

$0 = R_L I_4 + j\omega M_{34} I_3$

According to the previous equations, we calculate the current in each coil using Q_i and k_{ij}

$$I_1 = \frac{1+k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4}{[(1+k_{12}^2 Q_1 Q_2)(1+k_{34}^2 Q_3 Q_4)+k_{23}^2 Q_2 Q_3]} \frac{V_S}{R_s}$$

$$I_4 = \frac{k_{12} k_{23} k_{34} \sqrt{Q_1 Q_2}\sqrt{Q_2 Q_3}\sqrt{Q_3 Q_4}}{[(1+k_{12}^2 Q_1 Q_2)(1+k_{34}^2 Q_3 Q_4)+k_{23}^2 Q_2 Q_3]} \frac{jV_S}{\sqrt{R_S R_L}}$$

When $k_{12} = k_{34}, Q_2 = Q_3,\quad Q_1 = Q_4,$ the transfer function is:

$$\left|\frac{V_L}{V_S}\right| = \frac{k_{23} k_{12}^2 Q_1 Q_2^2}{(1+k_{12}^2 Q_1 Q_2)^2 + k_{23}^2 Q_2^2} \sqrt{\frac{R_L}{R_S}} \ . \qquad (4)$$

Here, V_L is the potential between load ends**.**

The input impedance is:

$$Z_{in} = \frac{V_{in}}{I_1} \Rightarrow Z_{in} = \frac{V_S - R_S I_1}{I_1} \ ; \qquad (5)$$

$$Z_{in} = R_S \frac{k_{12}^2 Q_1 Q_2 (1+k_{34}^2 Q_3 Q_4)}{1+k_{23}^2 Q_2 Q_3 + k_{34}^2 Q_3 Q_4}.$$

To reach maximum efficiency, we consider $Z_{in} = R_s$ and write:

$(k_{12}^2 Q_1 Q_2 - 1)(k_{34}^2 Q_3 Q_4 + 1) = k_{23}^2 Q_2 Q_3$. That is the impedance matching condition.

When $k_{12} = k_{34}, Q_2 = Q_3,\quad Q_1 = Q_4,$ we write:

$$k_{12}^2 = \frac{\sqrt{k_{23}^2 Q_2^2 + 1}}{Q_1 Q_2} \ . \qquad (6)$$

When we increase the transfer distance d_{23}, k_{23} will decrease and from the last equation, we notice that we should decrease k_{12} or Q_1 to keep the impedance matching condition and maintain efficiency high. Practically, k_{12} decreased when distance d_{12} increased; then, we could maintain efficiency high *via* variation of transfer distance d_{23} without using an impedance matching network. Back to Eq. (5), when $Z_{in} = R_s$, we found that $V_s = 2V_{in}$ is the practical condition to get high efficiency. We can write:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{\frac{V_L^2}{R_L}}{\frac{V_{in}^2}{R_S}} = \frac{\frac{V_L^2}{R_L}}{\frac{V_S^2}{4R_S}}$$

$$\eta = 4\left(\frac{V_L}{V_S}\right)^2 \frac{R_S}{R_L} \qquad (7)$$

From Eq. (4) and Eq. (7) and for $R_s = R_L$:

$$\eta = 4\left(\frac{k_{23} k_{12}^2 Q_1 Q_2^2}{(1+k_{12}^2 Q_1 Q_2)^2 + k_{23}^2 Q_2^2}\right)^2 \ . \qquad (8)$$

Measurement Ways and Devices

The research and measurements have been accomplished in the scientific laboratory- Physics Department, Science Faculty, Tishreen University, Lattakia, Syria.

We used in this research oscilloscope type HAMEG-HM400 -40MHz, which has an input impedance of $1M\Omega$ for all potential and frequency measurements. And we used a high-frequency generator type PHILIPS-PM 5321 HF GENERATOR giving frequencies from 0.15MHz to 108MHz.

The parameters of the circuit have been measured in more than a simple way. This is what distinguishes this research, as we previously mentioned, including:

A) Measuring L and Q

An LC circuit with an alternative source as in Fig. 3 was used. When the circuit is in resonance by changing the source frequency, the potential between the ends of the capacitor is the largest possible and greater than the potential between the ends of the source by Q times; so, we can measure quality factor $Q$and self-induction L for each coil from the equations:

$$\omega_0 = \frac{1}{\sqrt{LC}}, Q = \frac{V_c}{V_s}.$$

Here, the capacity C is known.

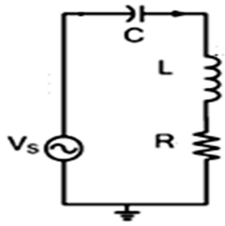

FIG. 3. RLC circuit.

B) Measuring Resonant Frequency of Internal Coils f_0 and Their Parasitic Capacitance $C_{\text{parasitic}}$

Measuring parasitic capacitance is not easy, because it is usually small and negligible. It appears in the equivalent circuit in parallel as in Fig. 4. However, the parasitic capacitance was successfully measured using the circuit described in Fig. 5.

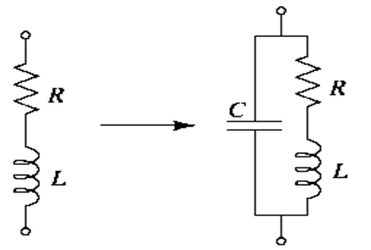

FIG. 4. Equivalent circuit for a coil at high frequency.

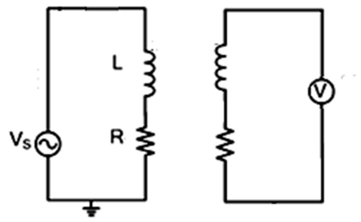

FIG. 5. Measuring resonant frequency.

When the source frequency is changed in the primary circuit (on the right), the potential is maximum in the secondary circuit, which consists of a coil both ends of which are connected to the oscilloscope at a definite frequency. Thus, the secondary circuit is in resonance. In this way, we could measure the resonant frequency. Knowing the self-inductance L of the coil and the resonant frequency, we could measure $C_{\text{parasitic}}$ from the equation:

$$\omega_0 = \frac{1}{\sqrt{LC_{parasitic}}} .$$

C) Measuring Efficiency η

Efficiency was measured by measuring the load potential V_L, the input potential V_{in} and the electromotive force V_s for each transfer distance. We get efficiency by applying the equation:

$$\eta = 4\left(\frac{V_L}{V_s}\right)^2 = \left(\frac{V_L}{V_{in}}\right)^2 .$$

Fig. 1 shows the practical circuit in which the high frequency source is connected to resonator 1 that consists of a source coil and a variable capacitor, so that resonator 1 is in resonance and the resonant frequency is the same frequency as the self-resonance frequency of the internal coils as well as the resonant frequency of resonator 4.

We could adjust resonator 1 to reach resonance by its variable capacitor.

The first channel of the oscilloscope is connected to the ends of the source in resonator 1; i.e., to the input.

The second channel of the oscilloscope is connected to the ends of the load in resonator 4; i.e., to the output.

What matters is the measurement of V_{in} to apply the practical impedance matching condition $V_{in} = \frac{V_s}{2}$; that is to make the input potential equal to a half of the electromotive force by changing the distance between the source coil and the transmitter coil d_{12} (the same distance between the load coil and the receiver coil).

Results and Discussion

Each of source coil and load coil consists of a single copper conductor with the section diameter of $w = 2r_c = 1.3\, mm$, round as a single ring with a radius $r_1 = 26\, cm$. Its inductance can be calculated from the formula [16, 17]:

$$L = \mu_0 r \left[\ln(\frac{8r}{r_c}) - 2\right] = 1.98\, \mu H .$$

Transmitter and receiver coil are made of single copper conductors with a section diameter of $w = 2r_c = 1.8\, mm$, round in flat spiral shape with a number of turns $N = 7.25$; outer diameter $D_0 = 70\, cm$, inner diameter $D_{in} = 53.5\, cm$, average radius $r_2 = 30.8\, cm$ and pitch $p = 1\, cm$. Its inductance is calculated from the formula [18]:

$$L = \frac{N^2[D_0 - N(w+p)]^2}{16D_0 + 28N(w+p)} \frac{39.37}{10^6} = 57.4\, \mu H .$$

We calculate the resonant frequency for transmitter and receiver coils that is driven by parasitic capacitance from the derived formula:

$$f_0 = \frac{c}{8\pi r N} = 5.34\, MHz .$$

Here, c is the speed of light in free space.

We calculate self-capacitance (parasitic capacitance) $C_{parasitic}$ from:

$$C_P = \frac{1}{\omega^2 L} = 15.4\, PF .$$

The resistance includes ohm resistance and radiation resistance which are calculated for all coils from [19, 20]:

$$R_{rad} = \sqrt{\frac{\mu_0}{\varepsilon_0}}\left[\frac{\pi}{12}N^2\left(\frac{\omega r}{c}\right)^4\right]$$

$$R_{ohm} = R_{DC}\frac{2r_c}{4\delta}, \delta = \frac{1}{\sqrt{\pi f_0 \mu_0 \sigma}}$$

$$\Rightarrow R_{ohm} = \sqrt{\pi f_0 \mu_0 \rho}\, N\frac{r}{r_c}.$$

Here, μ_0 is the magnetic permeability of free space, ε_0 is the electrical insulation of free space, δ is the skin depth and $\rho = \frac{1}{\sigma}$ the resistance of the conductor (copper).

$\Rightarrow R_1 = R_4 = 0.24\,\Omega\; R_2 = R_3 = 1.54\,\Omega$.

We have neglected radiation resistance for its smallness (it is $0.006\,\Omega$ for coils 2&3). Source resistance and load resistance are $R_s = R_L = 65\,\Omega$.

The theoretically calculated parameters for the resonators are given in Table 1.

Table 2 shows the experimentally determined parameters for the resonators.

TABLE 1. Theoretically calculated parameters for the resonators.

	$L\,(\mu H)$	$C\,(PF)$	$f_0\,(MHz)$	$Q_{unloaded}$	Q_{loaded}
Resonator 1 (loop)	1.98	429	5.34	276.8	1.16
Resonator 2 (coil)	57.4	15.4	5.34	1250.5	–
Resonator 3 (coil)	57.4	15.4	5.34	1250.5	–
Resonator 4 (loop)	1.98	429	5.34	276.8	1.16

TABLE 2. Experimentally determined parameters for the resonators.

	$L\,(\mu H)$	$C\,(PF)$	$f_0\,(MHz)$	$Q_{unloaded}$	Q_{loaded}
Resonator 1 (loop)	1.95	398.4	5.71	35	1.22
Resonator 2 (coil)	63	12.33	5.71	150	–
Resonator 3 (coil)	62	12.53	5.71	150	–
Resonator 4 (loop)	1.93	402.5	5.71	34	1.20

Comparing the two tables, we notice the great difference in Q value because of the difference between calculated resistance and measured resistance due to mechanic deformation in the conductor [21]. Bad conductive oxide layer (copper oxide) on the surface of the conductor affects the skin depth making current more limited causing higher resistance [22] and proximity effect makes the same effect on the current. This effect makes precise resistance calculation very difficult [19]. So, we will use the parameters in Table (2) to calculate efficiency.

We calculate coupling coefficient from Eq. (1) and mutual inductance from Neumann's formula [21]:

$$M_{i,j} = \frac{\mu_0 \pi N_i N_j r_i^2 r_j^2}{2d_{i,j}^3}; r_i r_j \ll d_{i,j}\ .$$

But this formula is limited the in last condition; so, we will use another formula which depends on elliptic integral:

$$M_{i,j} = 2\mu_0\frac{\sqrt{a+b}}{b}\left[\left(1-\frac{\beta^2}{2}\right)\mathrm{K}(\beta) - E(\beta)\right]$$

Here:

$$a = \frac{r_i^2+r_j^2+d_{i,j}^2}{r_i^2+r_j^2}, b = \frac{2}{r_i r_j}, \beta = \sqrt{\frac{2b}{a+b}}$$

$\mathrm{r_i}$ is the radius of loop i of the first coil, r_j is the radius of loop j of the second coil, $d_{i,j}$ is the distance between loop i and loop j and $E(\beta)$ and $\mathrm{K}(\beta)$ are the first and second kind elliptic integral:

$$K(\beta) = \int_0^1 \frac{dt}{\sqrt{(1-t^2)(1-\beta^2 t^2)}}$$

$$E(\beta) = \int_0^1 \sqrt{\frac{(1-\beta^2 t^2)}{(1-t^2)}}\, dt$$

These can be found in the elliptic integral table [25].

Then, the mutual inductance between first and second coils is:

$$M_{a,b} = \sum_{i=1}^{N}\sum_{j=1}^{M} M_{i,j}\ .$$

Here, N and M represent the number of turns for first and second coil, respectively.

Fig. 6 shows the coupling coefficient k_{12} as a function of distance d_{12}, which has been theoretically calculated from the mutual induction between the coils M_{12} and according to Eq. (1) and Table 2.

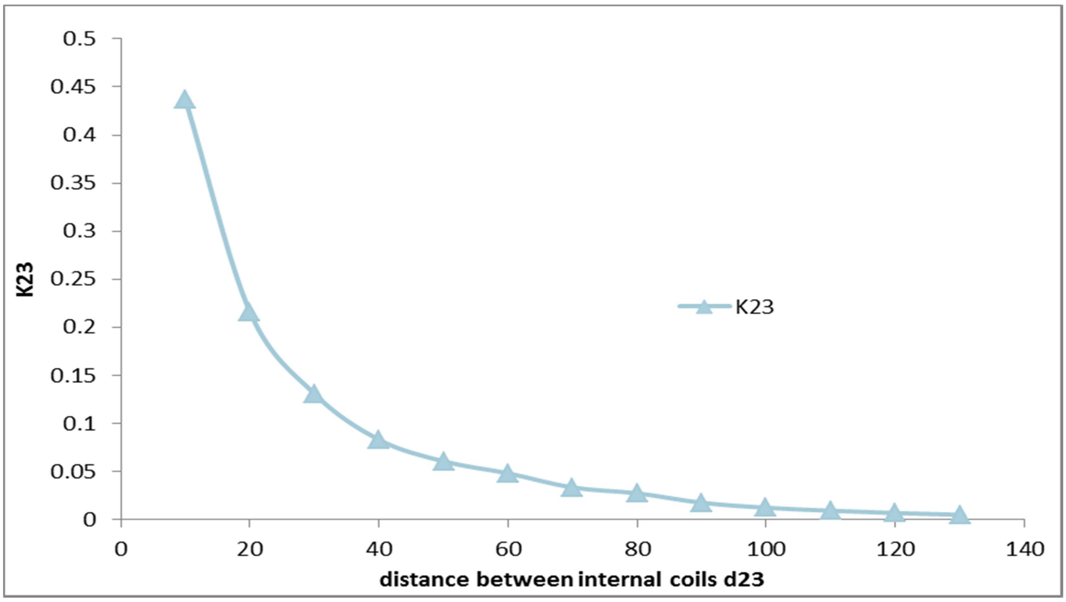

FIG. (6) Coupling coefficient $\boldsymbol{k_{23}}$ *versus* $\boldsymbol{d_{23}}$.

Fig. 7 shows the coupling coefficient k_{23} as a function of distance d_{23}, which also has been theoretically calculated from the mutual induction between the coils M_{23} and according to Eq. (1) and Table (2).

From Figs. 6 and 7, we notice a decrease in coupling coefficient by increasing the distance between coils.

Efficiency is theoretically calculated using Eq. (8) and Table 2 parameters in two cases:

The first case: The distance between the source coil and the transmitter coil d_{12} (the same distance between the load coil and the receiver coil) is fixed ($d_{12} = const = 15.5\ cm$); i.e., $k_{12} = const$.

Thus, in Eq. (8), efficiency η and k_{23} remain variable. In this case, there is no impedance matching condition.

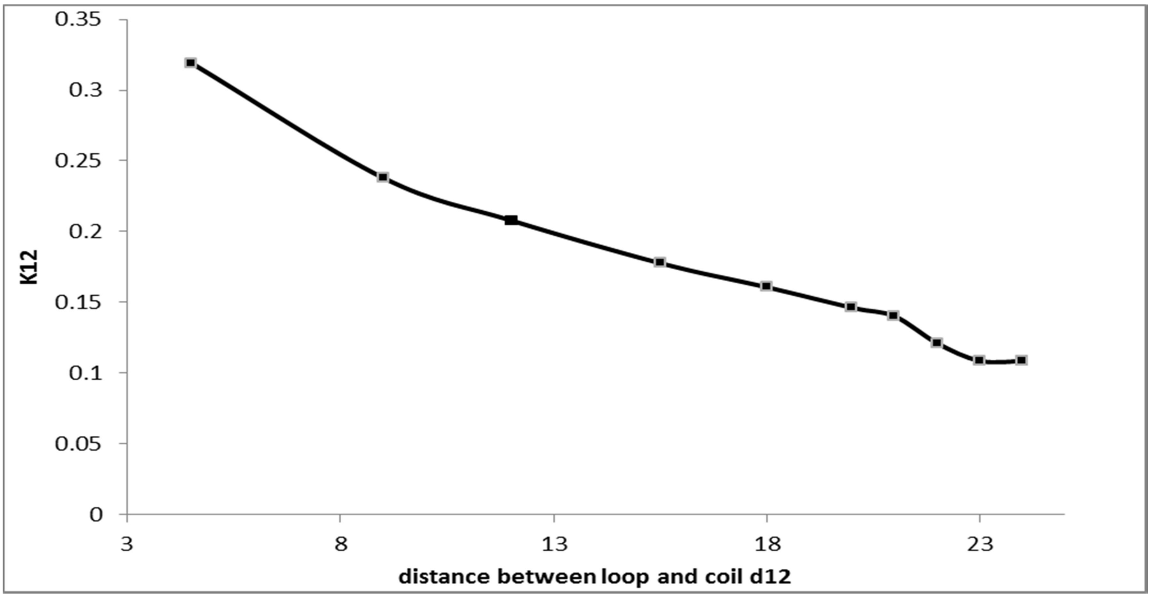

FIG. 7. Coupling coefficient $\boldsymbol{k_{12}}$ *versus* $\boldsymbol{d_{12}}$.

The second case: The distance d_{12} is variable by changing the transfer distance d_{23}; i.e., k_{12} is variable when k_{23} changes according to the impedance matching condition in Eq. (6), where by increasing the transfer distance $d_{23,}$ k_{23} will decrease. Therefore, k_{12} should be decreased (i.e., the distance d_{12} should be increased) to keep the efficiency at its maximum as mentioned above. Thus, we calculate the efficiency according to Eqs. (8) and (6). Here, Eq. (8) also has two variables, η and k_{23}, because, according to Eq. (6), k_{12} is related to k_{23}.

Fig. 8 shows the results of theoretical calculation of efficiency in the two preceding cases ($k_{12} = const$, $k_{12} = variable$).

From Fig. 8, we note the improvement in efficiency in the second case; i.e., the application of impedance matching condition.

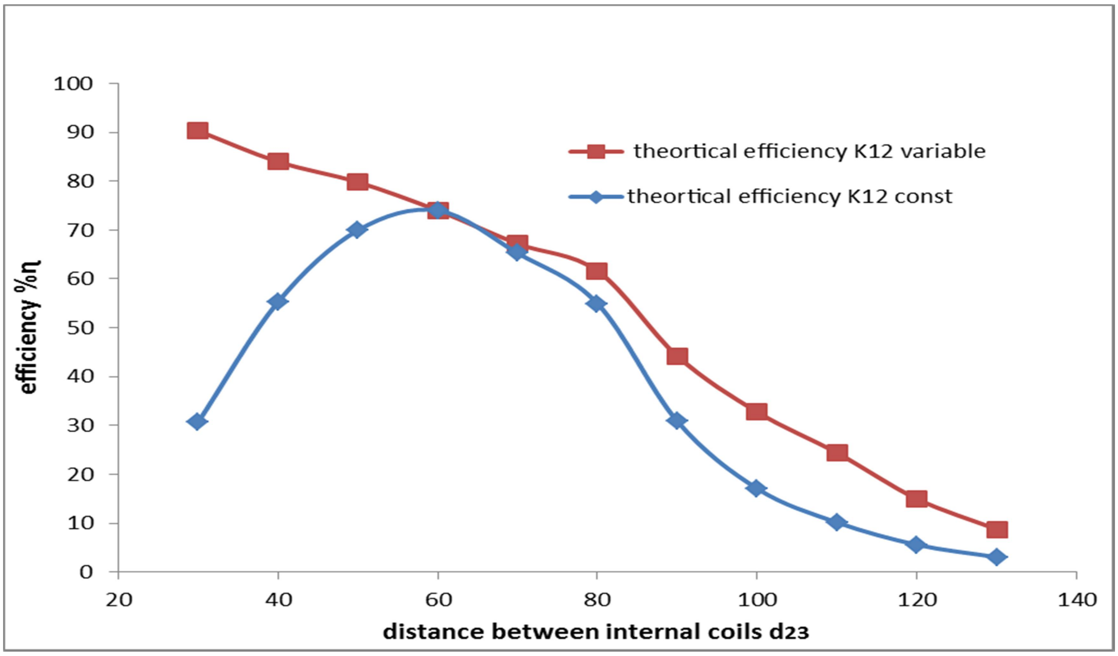

FIG. 8. Theoretical efficiency *versus* $\boldsymbol{d_{23}}$.

Efficiency has been measured in two cases and compared to theoretical efficiency:

First: by fixing d_{12}; i.e., $k_{12} = const$.

Second: by changing $d_{12;}$ i.e., $k_{12} = variable$, according to the practical impedance matching condition $V_s = 2V_{in}$ which improves the efficiency and keeps it high by changing the transfer distance.

Fig. 9 illustrates the practical efficiency in the previous two cases. From the figure, we note the improvement in efficiency by applying the impedance matching condition.

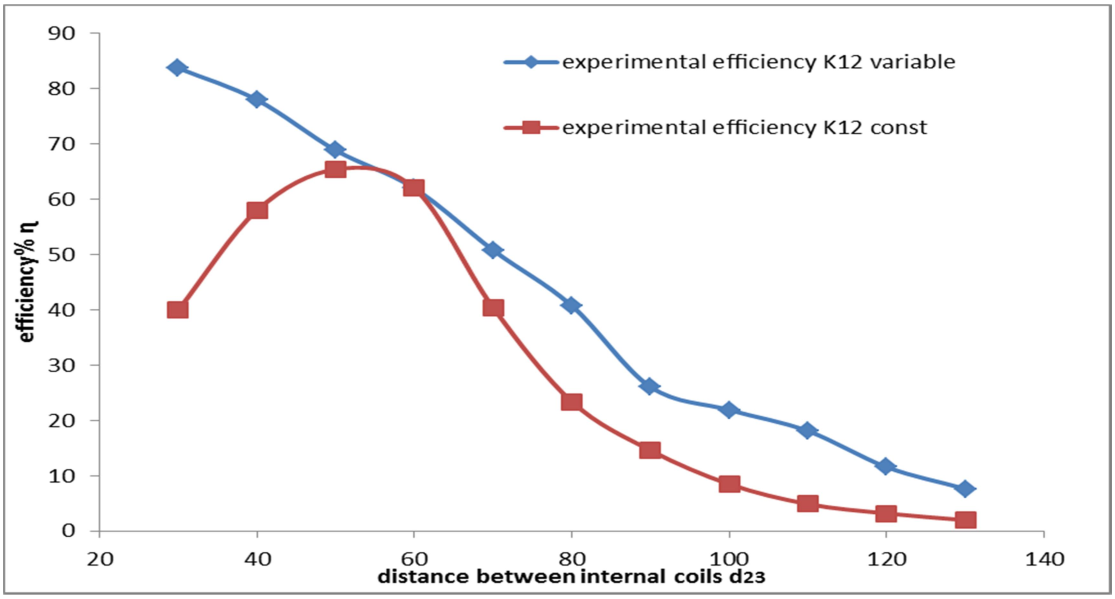

FIG. 9. Experimental efficiency *versus* $\boldsymbol{d_{23}}$.

Fig. 10 shows a comparison between theoretical efficiency and practical efficiency in the case of the application of impedance matching condition; i.e., k_{12} is related to k_{23}.

Experimental and theoretical results show that WPT technique *via* Coupled Magnetic Resonances could be efficient for medium ranges and for the case of distance change throughout using the concept of impedance matching (using four coils), where coupling coefficient k_{12} can be changed by changing the distance d_{12}.

We have experimentally measured the maximum efficiency at a distance $d_{23} = 30cm$ between the two internal resonators and a whole distance $d = 40cm$ form source coil to load coil. It was found that $\eta = 83.7\%$ and at distances less than $d_{23} = 70cm, d = 106cm$, it was more than 50%.

$\eta = 22\%$ at a distance $d_{23} = 100cm$ and a whole distance $d = 142cm$ and $\eta = 7.6\%$ at a distance $d_{23} = 130cm$ and a whole distance $d = 178cm$.

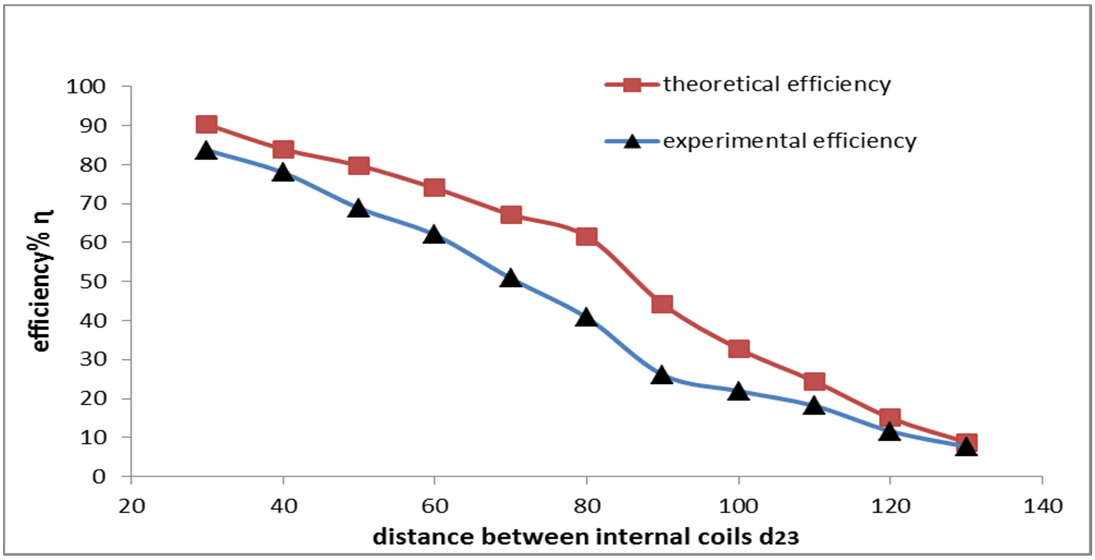

FIG. 10. Experimental and theoretical efficiency *versus* $\mathbf{d_{23}}$.

Conclusions and Recommendations

This work insures the comprehension of WPT *via* Coupled Magnetic Resonances. In addition, the theoretical results approximately match the experimental measurements. It determines the parameters that play vital roles in transfer efficiency and range, such as Q. Bigger Q means higher efficiency. Q is related to coil inductance, coil capacitance, resonant frequency and losses like Ohmic Resistance, which is mainly responsible for quality factor decrease. In the future, we intend to work on coils that have high quality factor values and fewer losses which means high efficiency and range, working on the coil shape and geometry besides a full theoretical model that is more compatible to experimental measurement.

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