# A Solution to Frequency Splitting in Magnetic Resonance Wireless Power Transfer Systems Using Double Sided Symmetric Capacitors

Thabat Thabet and John Woods

***Abstract* — The technology of wireless power transfer using magnetic resonance coupling has become a subject of interest for researchers with the proliferation of mobile. The maximum efficiency is achieved at a specific gap between the resonators in the system. However, the resonance frequency splits as the gap declines or gets smaller. Different methods have been studied to improve this such as frequency tracking and impedance matching, including capacitive tuning. However, the system has to maintain the same working frequency to avoid moving out of the license exempt industrial, scientific, and medical (ISM) band; and the efficiency must be as large as possible. In this paper, a symmetric capacitance tuning method is presented to achieve these two conditions and solve the splitting problem. In the proposed method, the maximum efficiency at one of the splitting frequencies is moved to match the original resonance frequency. By comparison to other works, both simulation and experiment show considerable improvements for the proposed method over existing frequency tracking and impedance matching methods. The paper also presents a proposal to apply this method automatically which can achieve wireless charging for electronic applications with high efficiency and through variable distance.**

***Index Terms* — Frequency splitting; frequency tracking; impedance matching (IM); magnetic coupling; maximum efficiency; mutual inductance; resonance frequency; symmetric capacitance tuning (SCT); wireless power transfer (WPT).**

## I. Introduction

Magnetic coupled wireless power transfer systems are a safe mode of power delivery [1], as well as being more convenient than wired systems. The method was inspired by Nikola Tesla at the beginning of the last century [2] and recently revisited by scientists at Massachusetts Institute of Technology (MIT) in 2007 [3], [4]. MIT announced a system that could transfer power wirelessly by magnetic resonance over two meters. The demand for wireless charging of vehicles and mobile devices has led to much academic effort to improve the overall performance of these systems [5]. The basis of magnetic resonant wireless power transfer is the interaction of a coil with the magnetic flux lines produced by another one [6]. The system in this technique consists of two coils (transmitter and receiver or primary and secondary), both of them have to resonate at the same frequency to obtain maximum transfer of wireless power between them [7], [8], as proofed later in this paper. That can be achieved by choosing the right capacitance for each coil to match the resonance frequency, as shown in Fig. 1.

The figure shows the equivalent circuit of the system where $V_S$ is the voltage source with an internal resistance $R_S$; $R_L$ is the load resistor; ($L_1$ & $C_1$) and ($L_2$ & $C_2$) are resonator1 and resonator2, respectively. The input impedance of the circuit is represented by $Z_{in}$. The currents $I_1$ and $I_2$ are relating to resonators 1 and 2, respectively. The efficiency of the magnetic power transfer system is influenced by several factors [9]: the resonant frequency, the inductor and capacitor values, and the mutual inductance between the two coils ($M$ in Fig. 1).

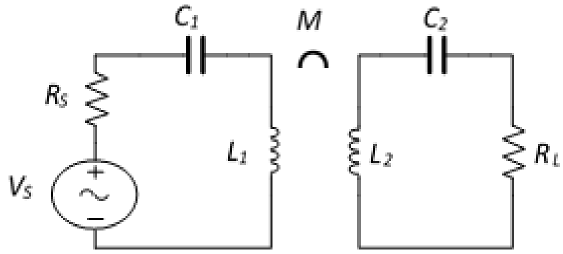


Fig. 1. Equivalent circuit of magnetic coupling wireless power transfer system.

The effect of the mutual inductance is producing electromotive force in a coil because of the change in the current in a coupled coil [10]. The mutual inductance is affected by the distance and the size of the two inductors. The mutual inductance can be calculated by the Neumann formula [11] or by Maxwell's method [12]. Although the system seems simple, its performance is more complicated than it might first appear. For each combination of coils and capacitors, there is a maximum transfer of power at a specific gap between the coils where the input impedance of the system matches the internal resistor of the source [13], [14]. At smaller gaps between the coils, there will be a splitting in the frequency response of the system (see later), and the maximum transfer of power happens at two different frequencies around the original resonant frequency ($f_0$) [15].

$$f_0 = \frac{1}{2\pi\sqrt{L_1C_1}} = \frac{1}{2\pi\sqrt{L_2C_2}} \qquad (1)$$

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In other words, if the resonators are coupled, the resonant frequencies split from the original one [16]. The explanation of this phenomenon is that the system reaches the resonant frequency in two cases [17]: 1) At frequency less than $f_0$, the two loops have a capacitive effect. Therefore, the reflected effect of the secondary is inductive in the primary. The resonance happens when they cancel each other. 2) At frequency larger than $f_0$, the two loops have inductive effect. Therefore, the reflected effect of the secondary is capacitive in the primary. Similarly, the resonance happens when they cancel each other. As the gap between a pair of coupled resonators, varies the frequency of resonance changes. Therefore, a re-statement of the problem is to maintain resonant frequency as the gap alters. Many researchers have worked on this to improve the efficiency of the system at different gaps. This can be done by several different methods [15]: Impedance matching [9], [18]-[20], frequency tracking [21], [22], and changing the parameters of the resonators or the coupling between them [23]. The last method is not practical because most systems consist of a fixed pair of resonators. Frequency tracking or frequency matching has the potential disadvantage of moving out of the used ISM (industrial, scientific, and medical) band [15]. Impedance matching can be implemented in a number of different ways. One of them is to place single turn coils in between turns of a spiral resonator coil [9]. The other one is to use an arbitrary number of flexible coils positioned to match the impedance [18]. The more commonly encountered method is to add an impedance matching circuit in the transmitter side and tune the additive capacitors accordingly [20]. This seems to be the best choice to improve the efficiency. However, using this method does not always offer full power transfer. This paper presents a new method to obtain maximum efficiency of power transfer in all cases without moving out of the used ISM band and without adding an impedance matching circuit. The paper also shows a comparison (section IV) with other studies in order to evaluate the performance. The proposed method is conducted by tuning the capacitors on both sides (transmitter and receiver) at the same time and maintaining the same values. By this method, one of the new resonant frequencies can be moved to match the original resonant frequency of the circuit and not violate the ISM band restrictions. The paper also presents a proposal to implement the new method.

## II. Theoretical Analysis

The circuit of Fig. 1 can be expressed as:

$$\begin{bmatrix} V_S \\ 0 \end{bmatrix} = \begin{bmatrix} Z_1 & -j\omega M \\ -j\omega M & Z_2 \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \end{bmatrix} \quad (2)$$

where the angular frequency is ω = 2$\pi f$, and the complex impedances for each circuit are:

$$Z_1 = R_S + j\left(\omega L_1 - \frac{1}{\omega C_1}\right) \quad (3a)$$

$$Z_2 = R_L + j\left(\omega L_2 - \frac{1}{\omega C_2}\right) \quad (3b)$$

The solutions to (2) can be found via Cramer's rule and are:

$$I_1 = \frac{Z_2 V_S}{Z_1 Z_2 + \omega^2 M^2} \quad (4a)$$

$$I_2 = \frac{j\omega M V_S}{Z_1 Z_2 + \omega^2 M^2} \quad (4b)$$

From (4a), the total impedance of the transmitter is defined as:

$$\frac{V_S}{I_1} = Z_1 + \frac{\omega^2 M}{Z_2} \quad (5)$$

and hence the input impedance seen by the source $Z_{in}$, as shown in Fig. 1, is found from:

$$Z_{in} = \frac{V_S}{I_1} - R_S \quad (6)$$

Using (4a), (3a) and (3b) leads to:

$$Z_{in} = \frac{\omega^2 M^2 R_L}{R_L^2 + \left(\omega L_2 - 1/\left(\omega C_2\right)\right)^2} + j\left[\omega L_1 - \frac{1}{\omega C_1} - \frac{\omega^2 M^2 \left(\omega L_2 - 1/\left(\omega C_2\right)\right)}{R_2^2 + \left(\omega L_2 - 1/\left(\omega C_2\right)\right)^2}\right] \quad (7)$$

According to the power transfer theorem for complex impedances, the maximum power will be transferred when:

$$Z_S = Z_{in}^* \quad (8)$$

Where $Z_S$ is the impedance of the source. In this case, we have $Z_S = R_S$, which is purely real, so the condition of (8) requires that the imaginary part of the input impedance given in (7) disappears. This is satisfied if $L_1 = L_2 = L$, $C_1 = C_2 = C$ and $\omega = \omega_0 = 1/\sqrt{LC}$ , the resonance angular frequency of the circuits. This means resonance is a condition and leads to:

$$Z_{in} = \frac{\omega_0^2 M^2}{R_2} = R_S \quad (9)$$

The condition for maximum power transfer is then:

$$\frac{\omega_0^2 M^2}{R_2 R_S} = 1 \quad (10)$$

Power transfer efficiency $\eta_0$ is defined in terms of the ratio of the output power to the input power under the condition of maximum power transfer.

$$\eta_0 = \frac{P_{out}}{P_{in,\max}} \tag{11}$$

where

$$P_{out} = \frac{1}{2}\left|I_2\right|^2 R_2 \tag{12}$$

From (11), $\eta_0$ is the percentage of the output power in terms of $P_{in}$ constrained to the value for the maximum power transfer. That is, we place $Z_{in} = R_S$ and $\left|I_1\right| = \left|V_s/(R_s + Z_{in})\right|$ obtain:

$$P_{in,\max} = \frac{V_S^2}{8R_S} \tag{13}$$

By substituting (4b), (12) and (13) in (11), the power transfer efficiency is then:

$$\eta_0 = \frac{4\omega^2 M^2 R_2 R_S}{\left|Z_1 Z_2 + \omega^2 M^2\right|^2} \tag{14}$$

where, for matched inductances and capacitances in the circuits:

$$\left|Z_1 Z_2 + \omega^2 M^2\right|^2 = \left[R_S R_2 + \omega^2 M^2 - \left(\omega L - \frac{1}{\omega C}\right)^2\right]^2 + \left[\left(R_S + R_2\right)\left(\omega L - \frac{1}{\omega C}\right)\right]^2 \tag{15}$$

When $\omega = \omega_0$, (15) reduces to:

$$\left|Z_1 Z_2 + \omega^2 M^2\right|^2 = \left(R_S R_2 + \omega^2 M^2\right)^2 \tag{16}$$

And then:

$$\eta_0 = \frac{4\omega_0^2 M^2 R_S R_2}{\left(R_S R_2 + \omega_0^2 M^2\right)^2} \tag{17}$$

Imposing the condition for maximum power transfer of (10) leads to $\eta_0$ = 100%.

The input impedance $Z_{in}$ of the system can be calculated as:

$$Z_{in} = \frac{V_S}{I_1} - R_S \tag{18}$$

Using (4a) and (18) leads to:

$$Z_{in} = \frac{\omega^2 M^2 R_L}{R_L^2 + \left(\omega L_2 - 1/(\omega C_2)\right)^2} + j\left[\omega L_1 - \frac{1}{\omega C_1} - \frac{\omega^2 M^2\left(\omega L_2 - 1/(\omega C_2)\right)}{R_2^2 + \left(\omega L_2 - 1/(\omega C_2)\right)^2}\right] \tag{19}$$

These equations have been used to study the performance of the wireless power transfer system in different cases and define the problem of frequency splitting and solve it.

## III. Results and Problem Definition

In this work a set of two solenoid coils (12.25 cm radius), with 8 turns and an inductance equal to 31.4 µH, are used in all experiments along with capacitors of 188 pF tuned to work at 2.1 MHz. The load resistor equals 50 Ω to match the internal resistor of the source. Starting with the basics, the efficiency of the system was calculated as a function of distance to show the maximum transfer of power at a specific distance which equals 10.5 cm in this combination as shown in Fig. 2. The theoretical results (Th) are compared with the experimental results (Exp) in the figure.

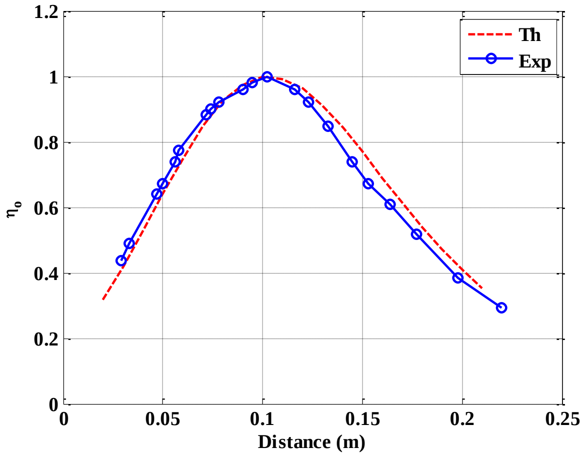


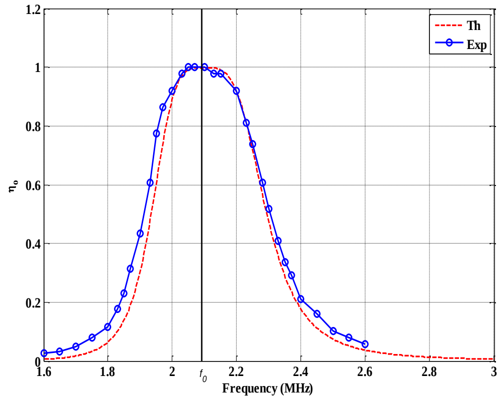

Fig. 2. Power transfer efficiency versus distance at resonance frequency 2.1MHz, RL = 50Ω.

Looking at this slightly differently, the efficiency was calculated as a function of frequency at different gaps to show the splitting in the resonant frequency. As seen in Fig. 3 (a), when the gap = 10.5 cm, the maximum efficiency of power transfer is at the original frequency of 2.1 MHz; as shown in Fig. 3(b) at gap = 7.5 cm, the maximum transfer of power will be at 1.98 MHz and 2.24 MHz, while Fig. 3(c) shows that at gap = 5 cm the system transfers the maximum power at the two new resonant frequencies 1.89 MHz and 2.35 MHz. It appears that the splitting frequencies diverge as long as the gap decreases between the two coils. These two new resonance frequencies can be estimated by:

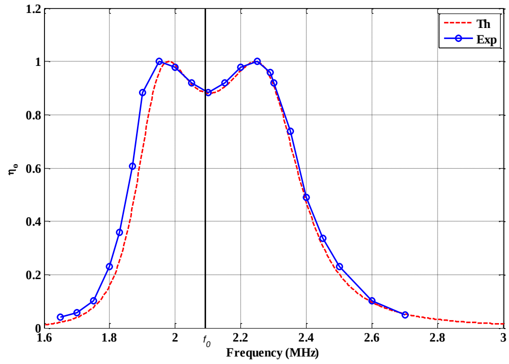
$$f_{1,2} = \frac{1}{2\pi\sqrt{(L_1 \pm M)C_1}} \tag{20}$$

where $f_1$ and $f_2$ are the new low and high frequencies, respectively.

To solve the problem of frequency splitting, capacitive tuning has been used to study its effect. Firstly, tuning one side either transmitter or receiver; then tuning both sides together to try to find the best solution.




(a)

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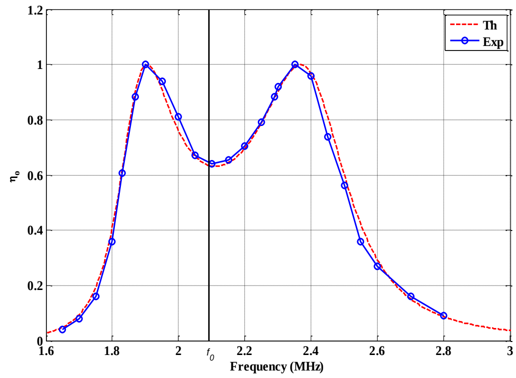



(c)

Fig. 3. Power transfer efficiency versus frequency at gap 10.5 cm (a), 7.5 cm (b) and 5 cm (c).

## A. *Tuning One Side Capacitor*

Tuning only one side by tuning either $C_1$ or $C_2$ shows that: an efficiency equal or less than the original at the resonant frequency is achieved as shown in Fig. 4. In the figure $C_1$ = 155 pF (less than the original capacitor value), 188 pF (the original value which equals $C_2$) and 238 pF (higher than the original capacitor value), the best case is when $C_1 = C_2$. This is also shown in Fig. 5 by tuning $C_2$.

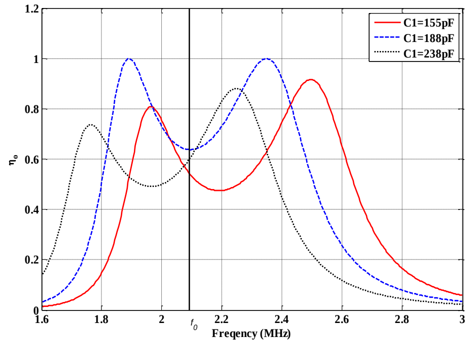



Fig. 4. Power transfer efficiency versus frequency at 5 cm distance tuning $C_1$ when $C_2$ = 188 pF.

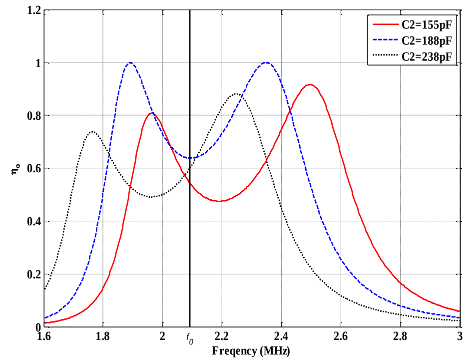



Fig. 5. Power transfer efficiency versus frequency at 5 cm distance tuning $C_2$ when $C_1$ = 188 pF.

From these two figures, it is clear that tuning only one of the capacitors is ill advised. Therefore, tuning the two capacitors together or Symmetric Capacitive Tuning (SCT) offers a solution.

## B. *Double Sided Symmetric Capacitive Tuning*

By tuning both receiver and transmitter capacitors together, it is possible to obtain maximum efficiency at two values of them, as seen in Fig. 6.

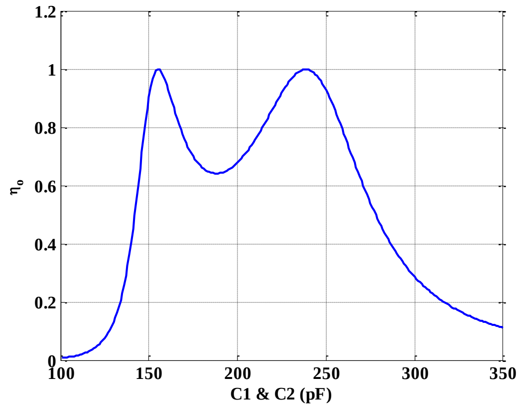



Fig. 6. Power transfer efficiency versus $C_1$ & $C_2$ together at gap = 5 cm, $f_0$ = 2.1 MHz.

Fig. 6 shows that maximum transference of power at gap=5cm, occurs when $C_1 = C_2$ = 155 pF = $C_{n1}$ and when $C_1 = C_2$ = 238 pF = $C_{n2}$. These two capacitors' values can be estimated by:

$$C_{n1,n2} = \frac{1}{(2\pi f_{1,2})^2 L_1} \tag{21}$$

where $C_{n1}$ and $C_{n2}$ are the small and large new capacitors which required for tuning to obtain maximum efficiency.

To find the effect of symmetric capacitive tuning on the input impedance of the system, equation (19) was used to plot Fig. 7 demonstrating the importance of the proposed method. It shows that the input impedance of the circuit is equal to 50 Ω purely resistance and the imaginary part equals zero at two specific values of $C_1$ & $C_2$ (155 pF and 238 pF in case of gap = 5 cm) i.e., impedance matching with the source internal resistance.

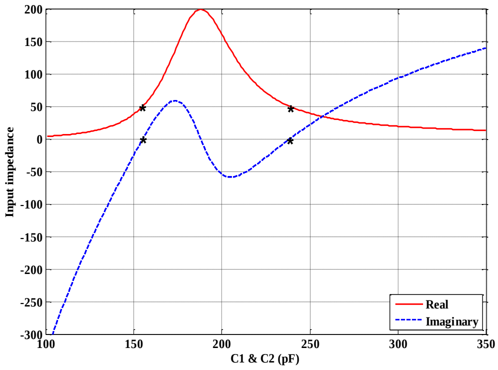
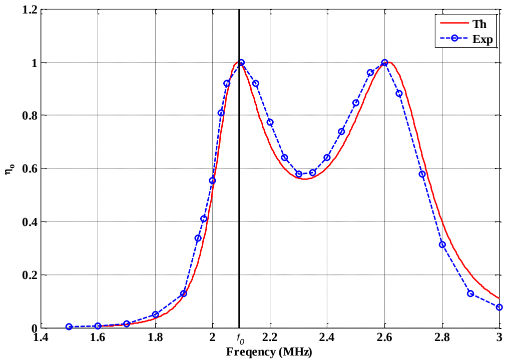
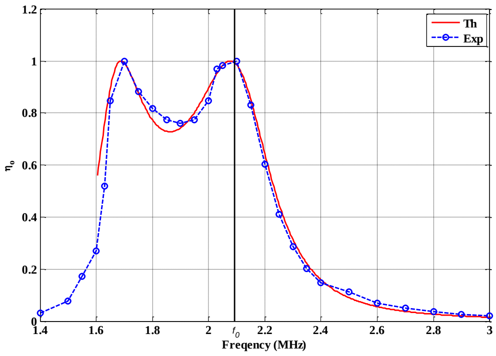



Fig. 7. Input impedance figure by tuning $C_1$ & $C_2$ together at gap = 5 cm, $f_0$ = 2.1 MHz.

These two values 155 pF and 238 pF can move the original splitting curve to the right or left, respectively at a 5cm gap between the resonators as shown in Fig. 8(a & b).




(a)




(b)

Fig. 8. Power transfer efficiency versus frequency at gap = 5 cm with $C_1$ & $C_2$ = 155pF (a) and $C_1$ & $C_2$ = 238 pF (b).

The figure demonstrates the idea of tuning both capacitors together. It shows how can a specific small value of $C_1$ & $C_2$ (155 pF) move the lower new resonant frequency (1.89 MHz) to match the original one (2.1 MHz), and a specific larger value of $C_1$ & $C_2$ (238 pF) move the higher new resonant frequency (2.35 MHz) to match the original. Fig. 8 shows good matching between the theoretical and experimental results.

In order to evaluate symmetric capacitive tuning method, we applied it on systems in other studies to compare its performance with their methods. The SCT method is applicable to other resonant frequencies as shown in the next section.

## IV. Comparison and Evaluation

The symmetric capacitance tuning method is superior to other methods such as impedance matching and frequency tracking. The proposed method is compared to other systems to evaluate efficiency whilst remaining inside the ISM band.

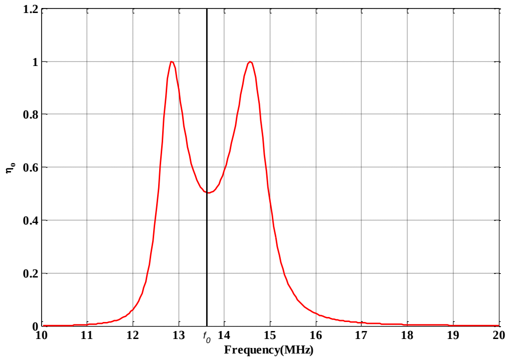
### *A. Impedance Matching*

This method works satisfactory, but it is not efficient in all cases as seen in [20]. There is 60% to 85% efficiency at a 9-20 cm gap between coils, and lower efficiency at smaller gaps. While, applying our proposed method to the same configuration we achieve higher efficiency at different gaps within the transfer distance, as shown in Fig. 9 and Fig. 10. The configuration consists of two similar resonators, each one has an inductor of 10.3 µH and a capacitance of 13.26 pF to work at a resonant frequency of 13.56 MHz [20]. Fig. 9(a) shows the splitting in the original resonant frequency to a new couple of frequencies, 12.84 MHz and 14.56 MHz. Due to these two frequencies, tuning both $C_1$ and $C_2$ to either 11.78 pF or to 15.1 pF achieves maximum transfer of power at resonance at gap = 9 cm as shown in Fig. 9(b & c). While Fig. 10(a) shows that at gap = 5 cm the two splitting frequencies diverge and achieving the maximum transfer of power at resonant frequency for this gap requires both $C_1$ and $C_2$ to be either 10.95 pF or to 16.75 pF. Therefore, it is possible to achieve the maximum transfer of power at the same resonant frequency at different gaps within the transfer distance of the system by symmetric tuning of the capacitors in both transmitter and receiver sides.

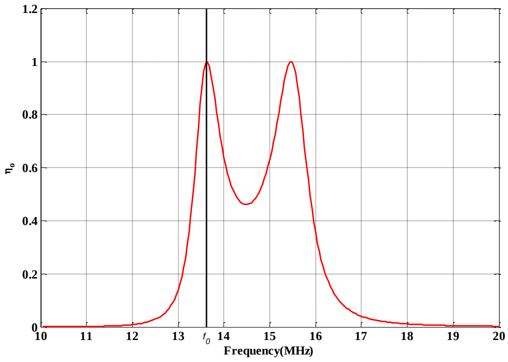
### *B. Frequency Tracking*

In this method, the frequency of the power source tracks one of the two maximum power transfer frequencies. However, it is more likely the system will wander out of the used ISM band especially at small gaps where the two splitting frequencies diverge. For example, in Fig.9 (a) the two splitting frequencies are 12.84 MHz and 14.56 MHz at gap = 9 cm and in Fig.10 (a) the two splitting frequencies are 12.4 MHz and 15.36 MHz at gap = 5 cm. In both cases, the tracking frequencies will be out of the ISM band, where the 13.56 MHz band has a frequency range of 13.553 MHz and 13.567 MHz [24].

Some researchers used a 1 MHz prototype system to explain the idea of the frequency tracking without regard to the ISM band [21]. Another group of researchers achieved around 70% efficiency within power transfer distances of 0.5 m and their system dropped to less than the minimum edge of the ISM band to reach 12.8 MHz [22].




(a)

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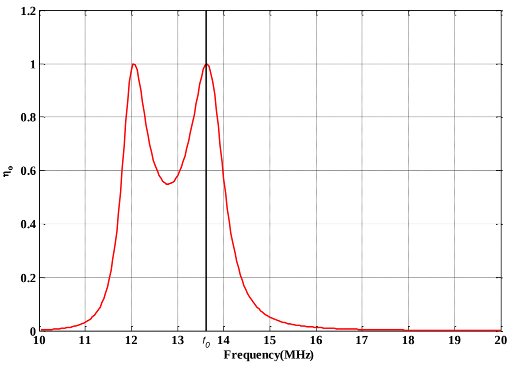
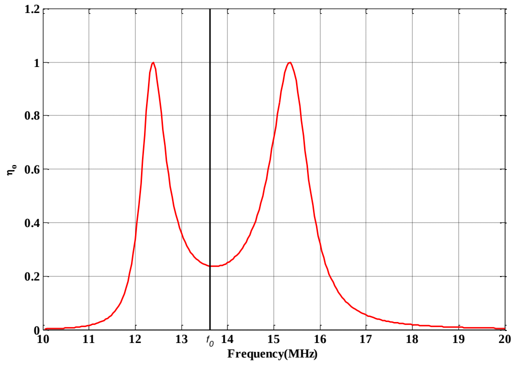



(c)

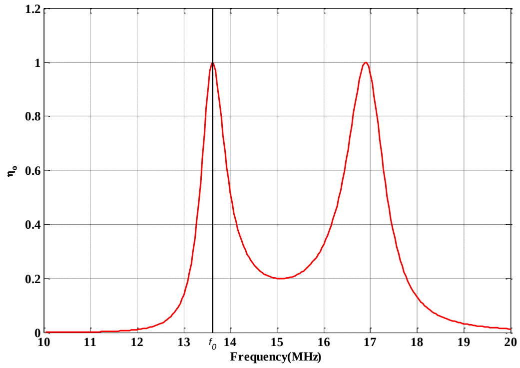
Fig. 9. Power transfer efficiency versus frequency at resonant frequency 13.56 MHz at gap 9 cm: (a) with original values of $C_1$ & $C_2$ = 13.26 pF; (b) by tuning $C_1$ & $C_2$ = 11.78 pF; (c) by tuning $C_1$ & $C_2$ = 15.1 pF.

## V. Implementation Proposal

In this section, a practical design is suggested to implement the symmetric capacitance tuning automatically. This is an efficient solution for the frequency splitting issue encountered in some applications such as wireless charging of electric vehicles. The block diagram of the suggested design is presented in Fig. 11. It shows that the transmitter consists of the power source, a directional coupler, a capacitor tuner, and a transmitting resonator. The receiver consists of a receiving resonator, a rectifier to provide the load with dc voltage, as well as the microcontroller with capacitor tuner. The system includes a microcontroller in both sides of the wireless power system because the assumption is that the microcontrollers can communicate with each other by wireless link in order to achieve the symmetric tuning.




(a)

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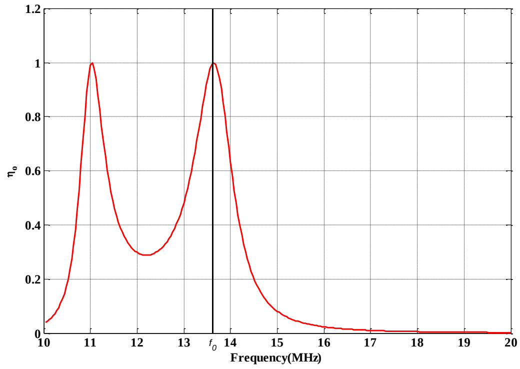


(c)

Fig. 10. Power transfer efficiency versus frequency at resonant frequency 13.56 MHz at gap 5 cm: (a) with original values of $C_1$ & $C_2$ = 13.26 pF; (b) by tuning $C_1$ & $C_2$ = 10.95 pF; (c) by tuning $C_1$ & $C_2$ = 16.75 pF.

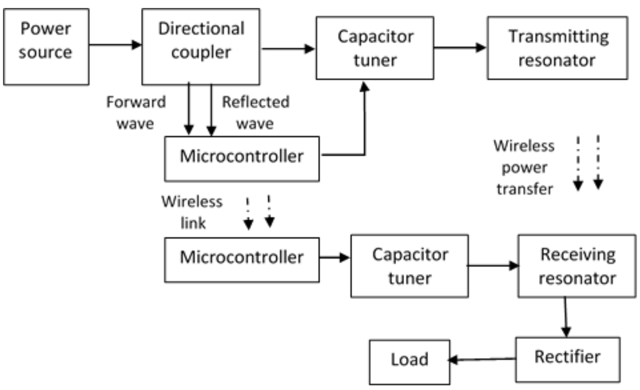


Fig. 11. Block diagram of the suggested symmetric capacitors tuning design.

## VI. CONCLUSION

Changing the gap between the two coupled resonators in magnetic resonant wireless power transfer systems affects the maximum efficiency. To solve the problem of splitting the original resonant frequency into two new resonant frequencies, the tuning of both capacitors simultaneously has been studied. The proposed method has more than one advantage when compared with other used methods in the literature: Compared to the existing frequency tracking method, there is no moving out the ISM band and the system keeps working at the same resonant frequency. Compared to the existing impedance matching method, maximum efficiency can be implemented easily for different gaps between the two resonators. Symmetric capacitance tuning is a promising way to keep maximum efficiency at resonance over variable distances for practical real-world systems. Simulation and experiment verify considerable improvements over existing frequency tracking and impedance matching methods. Adoption of the idea can achieve wireless charging for electronic applications with high efficiency through variable distances.

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