Parametric Study of Magnetic Resonance Coupling for Mid-Range Wireless Charging of Portable Devices

Sayed Abdullah Hussain, Yasir Saleem, M Usman Iftikhar, M Saleem Mian, Ahsan Raza, Umer Farooque

***Abstract*—Transfer of electrical power from source to load through wires is a conventional and well-known technology. However, in recent years wireless power transfer has gained interest especially in charging applications of portable devices such as smart phones, PDAs and digital cameras etc. Such devices are equipped with small batteries which often require frequent charging. Existing wireless chargers work on the principle of mutual induction, which requires charging device to be properly placed on a charging pad for charging purpose. However, these wireless chargers can transmit power efficiently to a distance of only up to a few millimeters. Transmission of power to relatively longer distances (i.e. up to about 1 meter) requires larger diameter of coils making it impractical for use in portable devices due to their inherent small size. Magnetic resonance coupling technique is a potential candidate for such mid-range applications. In this paper, authors have investigated interdependence of various parameters affecting the power transfer efficiency of magnetic resonance coupling. The main aim of the work is to achieve a practically realizable wireless charging system while optimizing various factors such as distance, resonator size, conductor size and resonance frequency. Resonating two coils at same frequency having significant difference in sizes is a challenge. This is achieved with external LC impedance matching circuit and is simulated in this paper. Based on the results, a wireless charger design is proposed to achieve maximum efficiency using smaller coil size on the receiver side, making it suitable for portable devices.**

***Index Terms*—Efficiency Maximization, Impedance Matching, Magnetic Resonance Coupling, Mid-Range Wireless Charging, Small Receiver.**

I. Introduction

WIRELESS power transfer means transmitting power from source to load wirelessly without any physical medium between them [1] [2]. In early twentieth century, Nikola Tesla started developing a system for transferring large amounts of power wirelessly over large distances. His main goal was to avoid electrical-wire grids, but unfortunately this project could not be completed due to a number of technical and financial difficulties. In recent years use of portable devices like laptops, cameras, cell phones etc. has become widespread. As these devices need to be charged frequently, so the importance of wireless power charging has re-emerged.

Wireless power transfer can be categorized into long-range, mid-range and short-range depending upon the distance over which power is transferred efficiently [3]. Based on these categories, various options of wireless charging technologies have been studied [4]. Long range transmission involves wireless power transmission up to several kilometers. Microwave radiation and laser beams are used for such long range transmission. Although power can be transferred up to kilometers using this technology but it has some limitations like need of large antenna, high path losses and condition of line of sight between transmitter and receiver in case of laser beam. Short range transmission involves wireless power transfer up to a few inches only. This transmission is based on the phenomenon of mutual induction or electromagnetic induction. This technology is now in practical implementation phase and is most commonly employed to power up portable devices wirelessly [5].

Mid-range power transmission involves wireless power transfer up to several meters. Electromagnetic radiation and ultrasonic transmission are the natural candidates for wireless power transfer over mid-range or longer distances [6]. Despite its suitability for transmitting information/data, radiative transfer has a lot of difficulties for power transfer applications. Its major drawbacks are low efficiency in case of omni-directional transmission and requirement of continuous line of sight and sophisticated tracking mechanism if radiation is unidirectional [7]. Similarly, for small sized portable devices it is difficult to generate enough power for charging.

An efficient technique for wireless power transfer in mid-range is magnetic resonance coupling [8] [9]. According to magnetic resonance coupling principle if two objects (transmitter and receiver) are tuned at same frequency they tend to couple strongly with each other and couple weakly to other off resonant objects [10]. Therefore, if power is to be received through this technique, the receiver is to be tuned at transmitter

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frequency. Using this technique, power can be transferred wirelessly up to meters with a reasonable power level [11].

Although wireless power technologies have been developed for various commercial applications but there are still many areas that need improvements. For instance, circuit modeling and investigation of mathematical equations and parameters for optimization of power transfer efficiency remained an area of research for a long time [12] [13] [14] [15] [16]. Nevertheless, mid-range power transfer with reasonable efficiency while having a small receiver size is an area that lacks attention. In this regard, a number of prototypes have been developed by researchers with large and identical sized transmitter and receiver coils. The first prominent effort was made by MIT scientists in 2007. They developed a prototype to transmit power efficiently through strongly coupled magnetic resonance [17]. They succeeded in transmitting about 60W power to a distance of 2 meters with 40% efficiency. However, the two coils used by them were similar in size and had a radius of 30cm each which is not feasible for portable devices. A research published in 2011 proposed a design of wireless power delivery systems for biomedical implants [18]. They implemented four-coil system with coil diameter of transmitter and receiver as 64mm and 22mm, respectively. They achieved an efficiency of about 72% at a transfer distance of 32mm only. Similarly, in a recent research a wireless power transfer system was demonstrated with 30cm radius coil size of both transmitter and receiver [19]. An efficiency of around 70% was achieved in this effort at a distance of 1m. Although they achieved promising efficiency at mid-range transmission distance but the size of receiver coil is still not small enough to be implemented in portable devices. A latest research implements wireless charging application for robots using multi-layer coil structure and compensation topology [20]. The experimental results are successful and replace the traditional contact charging technology by transferring power up-to a distance of about 15 cm with an efficiency of around 56% at a resonance frequency of 516.5KHz.

Reducing the size of coils decreases the transmission efficiency at comparatively larger distances. In 2012, some authors presented a design of wireless power system with small resonator size but they restricted the transmission distance within few centimeters only [21]. The challenge is to implement wireless power transfer in portable devices over larger charging distances.

A latest work in the field of magnetic resonance coupling presented design and analysis of a wireless power transfer system with 6.78MHz resonance frequency for less than 100W charging applications [22]. They designed transmitter and receiver coils of same radius of 100mm and simulated it for 40mm distance between transmitter and receiver coil. The size of receiver coil is comparatively small but transmission distance is very less.

In this paper, the authors have focused on reducing the receiver coil size while still achieving meaningful power transfer efficiency over a practically useful distance. In this context, the power transfer efficiency has also been investigated in relation with various system parameters such as distance, number of turns of resonator coil, conductor diameter and coil radius etc. Based on these results an optimum selection of system parameters is proposed which leads to the design of a practically realizable charger for portable devices that can charge efficiently up to 0.6m distance wirelessly.

The novelty of this work lies in the fact that practically realizable system parameters have been focused for maximizing the efficiency. The interdependence of various parameters has been studied and the impact of each parameter on power transfer efficiency is quantified.

II. Feasibility of Magnetic Resonance Coupling For Wireless Power

Due to the limitations of radiative modes of power transfer, the non-radiative modes are feasible for wireless power. Several schemes of non-radiative modes exist but they have limitations of short range and low transfer efficiency. Moreover, these schemes are only suitable for information or signal transfer over medium or long range wherein only small power is required to be transmitted. Magnetic resonance coupling is a non-radiative efficient wireless power transfer scheme suitable for mid-range applications. In magnetic resonance coupling, transmitter emits power at a particular frequency. All those nearby objects which are tuned at that frequency will strongly couple with this transmitter and the objects which are not tuned at that frequency give little response to that frequency [23]. In magnetic resonance coupling, magnetic field is used for power transfer in the near field region [24]. The stationary (lossless) and omni-directional nature of the near field makes this scheme suitable for portable wireless receivers.

III. Magnetic Resonance Coupling System Modeling

A wireless power transfer system based on the principle of magnetic resonance coupling comprises of a transmitting and a receiving section. A resonator is a key element of both sections. A resonator comprises of inductance, capacitance and resistance and it can be tuned to its fundamental frequency to achieve the optimum output. In order to analyze the system for efficient performance a comprehensive mathematical model is needed. There are many factors involved in generating magnetic field from an inductor. In this paper, the circuit shown in Fig. 1 has been analyzed and its mathematical model has been developed to calculate the received power with respect to various system parameters like distance, resonator size and resonance frequency. In this circuit L_s, C_s and R_s are the inductance, capacitance and resistance of transmitter (source) resonator and L_r, C_r and R_r are the inductance, capacitance and resistance of the receiver resonator. M is the mutual coupling and D is the distance between transmitter and receiver.

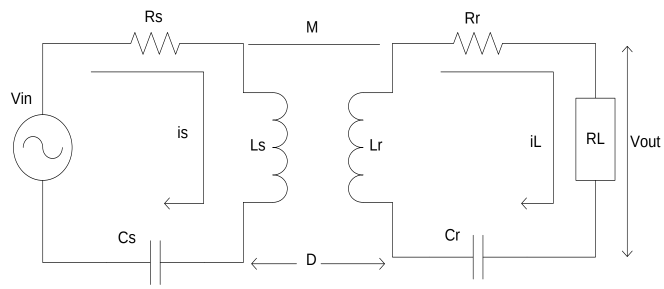

Fig. 1 Magnetic Resonance Coupling Model

$$Z_s = R_s + j\omega L_s + \frac{1}{j\omega C_s} \qquad (1)$$

$$Z_r = R_L + j\omega L_r + \frac{1}{j\omega C_r} \qquad (2)$$

Z_s and Z_r are the impedances of transmitting and receiving sections.

From Kirchoff's law:

$$V_{in} = Z_s i_s - j\omega M i_L \qquad (3)$$

$$0 = Z_r i_L - j\omega M i_s \qquad (4)$$

Hence, from equation (4) the expression for i_s and i_L can be derived as:

$$i_s = \frac{Z_L i_L}{j\omega M} \qquad (5)$$

$$i_L = \frac{j\omega M i_S}{Z_r} \qquad (6)$$

From equation (3), the expression of i_s and i_L can be derived as:

$$i_s = \frac{V_{in} + j\omega M i_L}{Z_s} \qquad (7)$$

$$i_L = \frac{-V_{in} + Z_s i_s}{j\omega M} \qquad (8)$$

Comparing equation (5) and (7)

$$i_s = \frac{V_{in} Z_r}{Z_s Z_r + \omega^2 M^2} \qquad (9)$$

Similarly comparing equation (6) and (8)

$$i_L = \frac{V_{in} j\omega M}{Z_s Z_r + \omega^2 M^2} \qquad (10)$$

(11)

$$V_{out} = \left(\frac{V_{in} j\omega M}{Z_s Z_r + \omega^2 M^2}\right) R_L$$

Hence the expression for efficiency can be derived as follows:

$$P_{in} = \frac{{V_{in}}^2 Z_r}{Z_s Z_r + \omega^2 M^2} \qquad (12)$$

$$P_{out} = \frac{-{V_{in}}^2 \omega^2 M^2 R_L}{(Z_s Z_r + \omega^2 M^2)^2} \qquad (13)$$

$$|\eta| = \left|\frac{\omega^2 M^2 R_L}{Z_r (Z_s Z_r + \omega^2 M^2)}\right| \qquad (14)$$

At resonance frequency f_r, $\omega = \omega_r$, $Z_s = R_s$, $Z_L = R_r + R_L$. Hence the impedances become minimum and power efficiency becomes maximum.

$$|V_{out}|_{\omega_r} = \frac{\omega_r M V_{in} R_L}{R_s R_r + {\omega_r}^2 M^2} \qquad (15)$$

$$\eta = \frac{{\omega_r}^2 M^2 R_L}{R_L + R_r[R_s(R_L + R_r) + {\omega_r}^2 M^2]} \qquad (16)$$

Mutual coupling between transmitter and receiver coil is approximated as [21]:

$$M = \frac{\pi}{4} \mu_o N_s N_r \frac{{r_s}^2 {r_r}^2}{D^3} \qquad (17)$$

Hence the expression for efficiency becomes:

$$\eta = \frac{\pi^4 {\mu_o}^2 {f_r}^2 {N_s}^2 {N_r}^2 {r_s}^4 {r_r}^4 R_L}{\pi^4 {\mu_o}^2 {f_r}^2 {N_s}^2 {N_r}^2 {r_s}^4 {r_r}^4 [R_L + R_r] + 4D^6 [R_L + R_r]^2 R_s} \qquad (18)$$

IV. Parametric Relationships and Optimization

In the last section, a mathematical relationship for efficiency has been derived which involves various system parameters. In this section, the effects of these parameters on system efficiency have been analyzed. The parameters of the system assumed are tabulated in .

TABLE I
ASSUMED PARAMETERS FOR PARAMETRIC STUDY

Parameter	Assumed Value
Number of turns of transmitter	20
Number of turns of receiver	20
Conductor radius of transmitter	2mm
Conductor radius of receiver	2mm
Radius of transmitter coil	100mm
Radius of receiver coil	100mm
Distance between transmitter and receiver	500mm
Resonance frequency	15MHz
Load Resistance	50Ω

The parameter under study is varied over a certain range and the corresponding efficiency of the system is calculated and plotted in the subsequent sections.

A. Efficiency vs Number of Turns of Transmitter (N_s) and Receiver (N_r)

Number of turns of coils is an important factor in design consideration. Fig. 2 shows the relationship of power transfer efficiency with number of turns of receiver for different number of turns of transmitter. This relationship shows that if the number of turns of coils is increased the efficiency increases and its quantitative trend is depicted in Fig. 2. It means that for the system under study an addition of two turns in receiver coil results in about 5 to 7% efficiency boost. When the number of turns of receiver exceeds 20, the increase in efficiency is less significant. Similarly an addition of two turns in transmitter coil results in 5 to 8% efficiency increase. However this is true up-till about 14 turns of transmitter. Beyond that, little increase in efficiency is obtained with these system parameters.

B. Efficiency vs Coil Distance (D)

Coil distance directly affects the power transfer efficiency because the magnetic coupling between the coils decreases with distance. The relationship of coil distance and power transfer efficiency is shown in the Fig. 3(a). This graph shows how the efficiency decreases as the coil distance increases. This trend shows that for the given system the efficiency remains somewhat unaffected by the distance up-till 450mm and then it drops significantly if the distance between the coils is further increased.

C. Efficiency vs Receiver Coil Size (r_L)

Receiver coil size is the most critical factor in wireless charger design. As the proposed wireless charger is aimed for portable devices, the size of receiver coil should be kept as small as possible. The relationship between power transfer efficiency and receiver coil size is shown in Fig. 3(b). From this plot, it is clear that efficiency of the system initially increases with increase in size of resonator but afterwards it starts decreasing with further increase in size. This behavior is attributed to the increase in inductance and ohmic resistance of coil with increased radius.

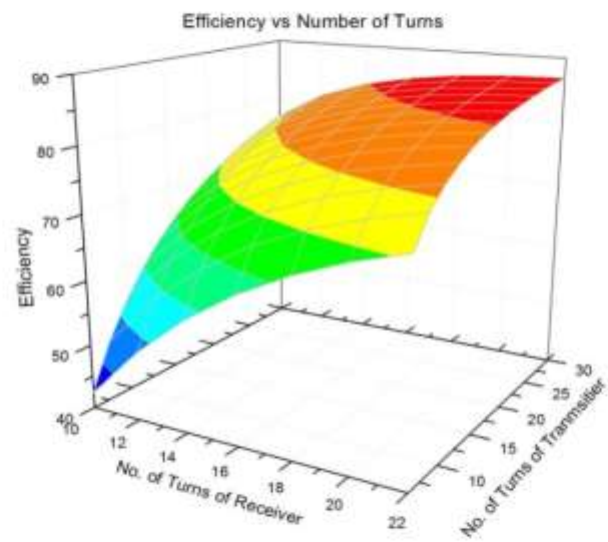

Fig. 2 Efficiency vs Number of Turns

D. Efficiency vs Resonance Frequency (f_r)

Resonance frequency has inverse relationship with capacitance and inductance. So, if we increase the resonance frequency the coil size can be reduced with same parameters. Similarly, if we fix the coil size, the efficiency of the system increases with increase in frequency. However, for magnetic resonance coupling the operating frequency should be less than 40MHz. This is because the magnetic field is dominant in near field region of EM waves. This near field region lies within a distance of about 0.16λ from the source. For portable devices receiver coil size should be small. Therefore, in order to transmit reasonable power up to about 1-meter distance we have to increase the size of transmitter coil. The relationship between frequency and efficiency of the system is shown in Fig. 3(c).

E. Efficiency vs Load Resistance (R_L)

Efficiency of the system is maximum for a particular value of load resistance. Efficiency decreases as we increase or decrease the value of load resistance. The relationship of efficiency with load resistance is shown in Fig. 3(d). This shows that for this system maximum efficiency can be achieved with a load resistance of 30Ω.

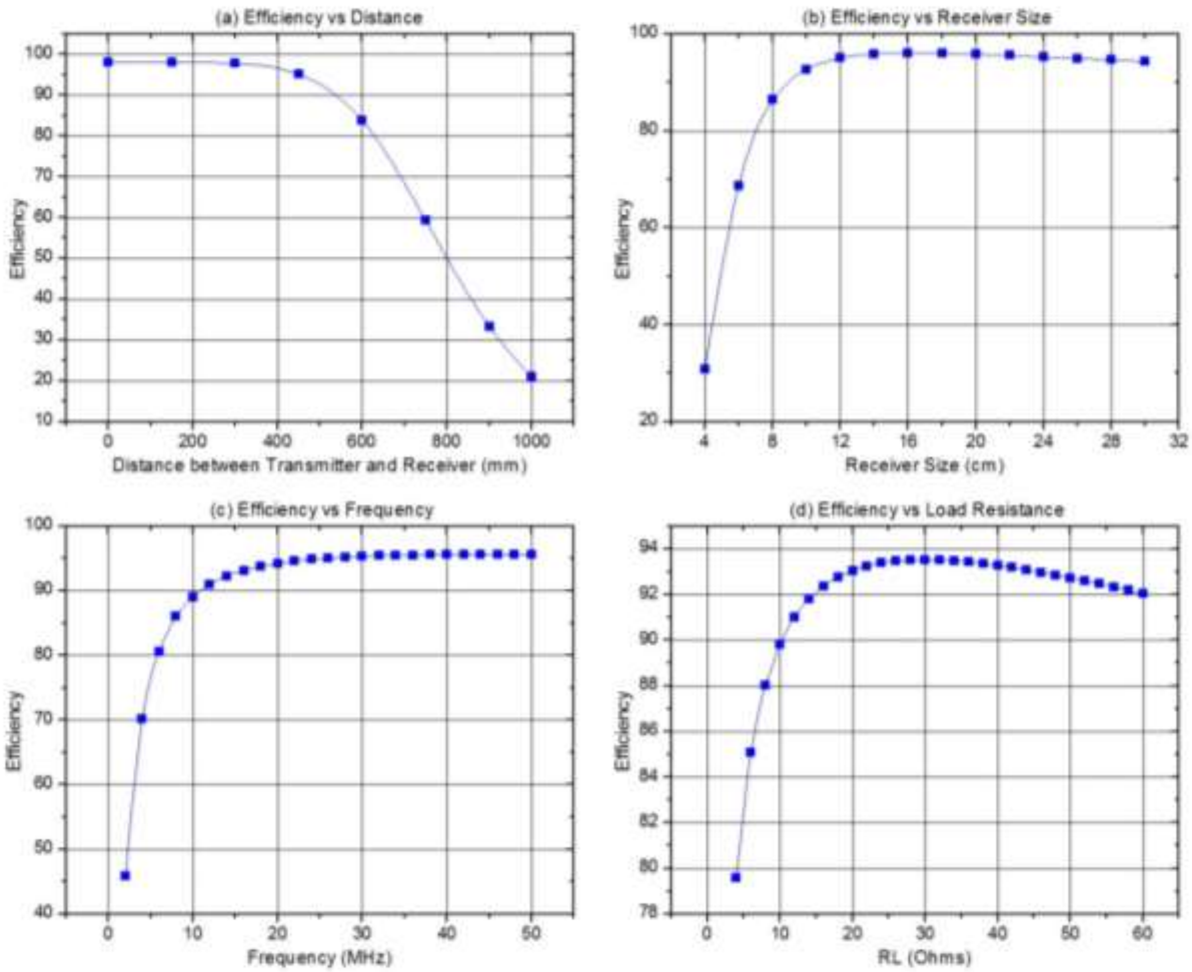

Fig. 3 Parametric Relationship of Magnetic Resonance Coupling

V. SYSTEM DESIGN

A. System Parameters

The expressions of system parameters for the system design are given as under:

Inductance [25]:

$$L = \mu_o N^2 r \left[ln\left(\frac{8r}{a}\right) - 2 \right]$$

Capacitance:

$$C = \frac{1}{4\pi^2 L \omega_r{}^2}$$

At high frequencies, the inductance loss resistance is given by [17]:

$$R = \frac{Nr}{a}\sqrt{\frac{\omega_r \mu_o}{2\sigma}}$$

In view of the parametric relationships and simulation results presented in preceding sections, following system parameters are proposed for practical implementation of the wireless charger:

Number of Turns of Transmitter (N_s) *and Receiver* (N_r)

For portable devices we limit the number of turns of receiver coil to 20 with conductor radius of 0.2mm. These parameters can be easily implemented in any portable electronic device. Number of turns of transmitter are 10 with conductor radius of 4mm.

Coil Size (r_L)

For practical consideration, radius of receiver coil is taken as 5cm. This size can be implemented in smartphones and laptops. Radius of transmitter coil is taken as 0.3m.

Resonance Frequency (f_r)

Resonance frequency of the system is taken as 10MHz.

Load Resistance (R_L*)*

For practical and simulation purpose, the load resistance is taken as 50Ω.

TABLE II
SELECTED SYSTEM PARAMETERS

System Parameters	Transmitter Coil	Receiver Coil
Number of Turns (N)	10	20
Radius of Coil (r)	300mm	50mm
Radius of Conductor (a)	4mm	0.2mm
Inductance	192uH	140uH
Conductor Material	Copper (σ = 5.96 x 10^7 S/m)	Copper (σ = 5.96 x 10^7 S/m)
Load Resistance (R_L)	50Ω	
Resonance Frequency	10MHz	
Distance between Transmitter and Receiver	600mm	
Efficiency (Theoretical)	77.2%	

B. Charger Design

If 5V input signal is applied to transmitter, then at resonance frequency the output voltage (from eq. (15)) would be around 20V. The hardware requires a matching circuit for both transmitter and receiver at resonance frequency. Moreover, high power amplifier (HPA) and oscillator circuits are required to properly transmit the power. The 20V signal received at receiver requires rectification and filtration. Depending upon the application, the filtered output can be converted to a regulated 5V or 9V DC via switching regulator. This final output can be utilized to charge the batteries of portable devices. The conceptual block diagram of the proposed charging system is shown in Fig. 4.

VI. SIMULATIONS

The simulations were run on CST Microwave Studio-high frequency. First of all, a 3D model as shown in Fig. 4 was build. The radius of primary transmitter coil is taken to be 300mm with conductor radius of 4mm while that of receiver coil is designed with 50mm radius and 0.2mm conductor radius. The distance between transmitter and receiver coil is adjusted to 600mm. First of all its s-parameters were observed for a frequency range of 2 to 50MHz for any possible match of resonance frequency. A resonance was observed at a frequency of 9.44MHz.

C. Impedance Matching

When a high frequency signal is propagated through a conductor of significant length, it is vitally important that transmission medium is matched to its termination. Without proper impedance matching the signal reflection occurs that result in degradation of amplitude and phase accuracy. The purpose of impedance matching is to match the impedances of the coil with external 50Ω port for maximum power transfer [26] [27]. A simple inductor-capacitor (LC) circuit can be used to match impedance. Impedance matching was performed at this frequency with the help of "Opteni Lab" software. This impedance matching makes the two coils tune at same frequency called the resonance frequency. The schematic after impedance matching is shown in Fig. 5.

D. S_{21} Parameters

This matching circuit is simulated and the s-parameters were plotted against frequency. The results are shown in Fig. 6. S-parameters depict the input-output relationship between the terminals. S_{21} represents the power transferred from port 2 to port 1 which in our case is the measure of the efficiency of the system. The parameter $|S_{21}|^2$ shows the efficiency of the system. The efficiency of the system is calculated as $(0.86)^2$ which equals 74.2%. This result is very close to the mathematical result of 76.2% at the same resonance frequency (f_r = 9.44MHz).

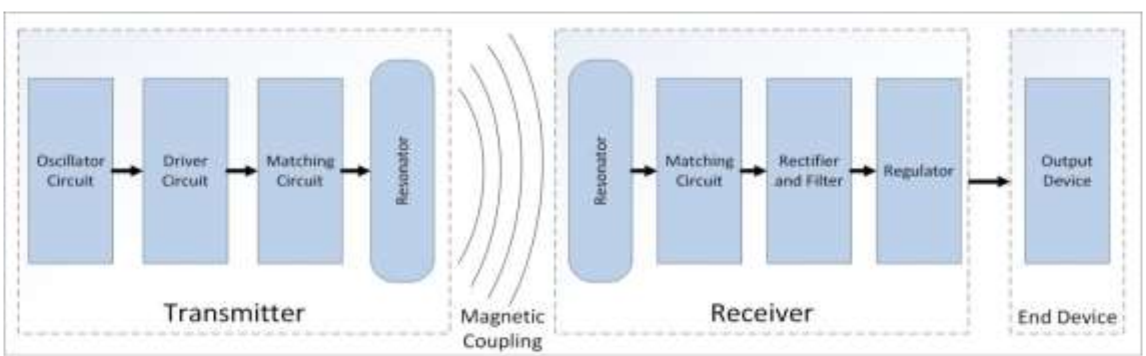

Fig. 4 Conceptual Block Diagram of the System

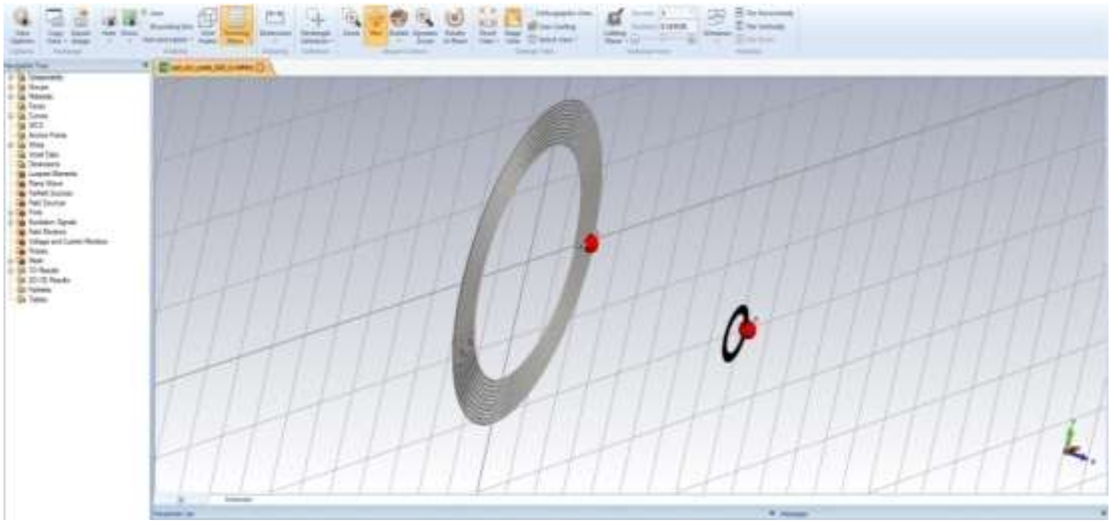

Fig. 4 3D Model of System (CST Studio)

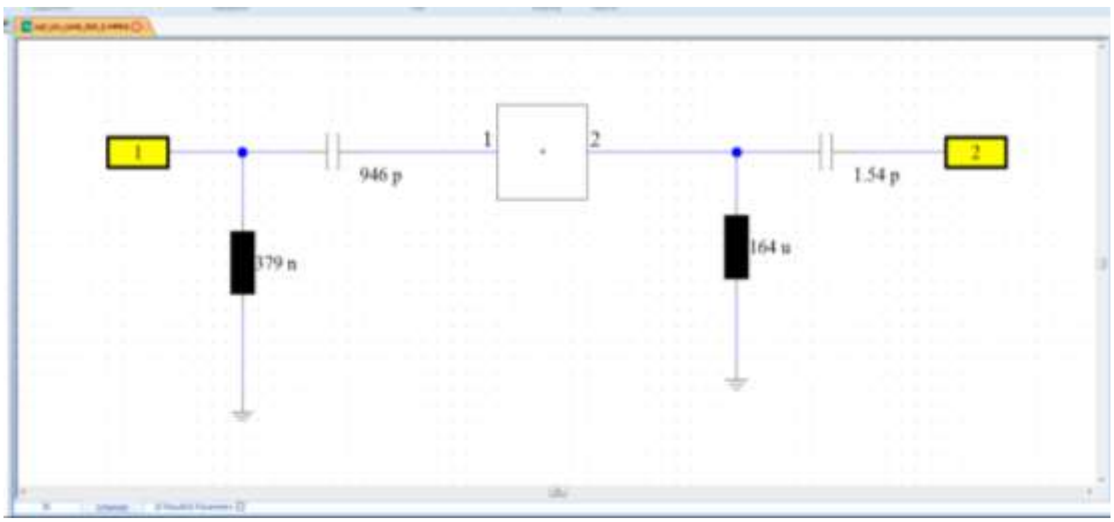

Fig. 5 Schematics after Impedance Matching

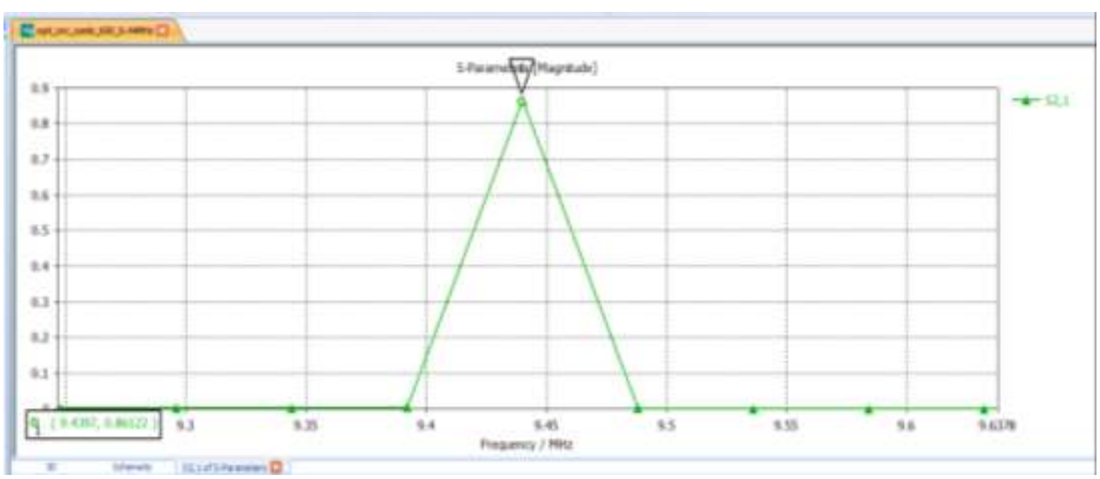

Fig. 6 S_{21} Parameter after Matching

VII. Results and Discussion

The key results achieved in this study are listed below:

- It has been demonstrated that useful resonance can be achieved even with significant difference in coil sizes for transmitter and receiver.
- Furthermore the resonance is achieved with external LC impedance matching circuit.
- The efficiency of 74.2% can be achieved using practically feasible and realistic system parameters.
- The performance of resonance coupling is adequate (practically useful) while using a reduced coil radius at receiver end (i.e. about 5cm) which makes it suitable for implementation in portable devices.

Nevertheless, it is pertinent to mention here that this parametric study has been performed while keeping the transmitter and receiver coils aligned in the same axis. This effect of coil misalignment and placement of coils along different axis could be the scope of future research. However, the present work has clearly demonstrated the existing potential in the resonance coupling technology for practical use in smart devices and application. The presented model can be used as a baseline for further investigations in this direction.

VIII. Conclusion

In this paper practical feasibility of magnetic resonance coupling for wireless charging of portable devices has been analyzed. It is obvious that power transfer efficiency can be considerably improved by increasing coil radius, increasing number of turns of resonator coils, increasing frequency and decreasing distance between transmitter and receiver coils. However, for portable devices resonator size cannot be increased beyond certain limits. Therefore, a trade-off is needed among various parameters in order to achieve a practically realizable system of wireless power transfer while still achieving adequate efficiency. Authors have demonstrated that an efficiency of 74.2% can be achieved with a small receiver coil of radius 50mm (5cm) at a resonance frequency of 9.44MHz for 600mm transmission distance, making it practical for portable devices.

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