# Modeling and Analysis of Series-Series and Series-Parallel Combined Topology for Wireless Power Transfer using Multiple Coupling Coefficients

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**Abstract:**
Wireless power transfer (WPT) using magnetic resonance coupling got significant importance in recent years. It is also known as a resonant wireless power transfer (RWPT). The efficiency of RWPT systems has appeared decreasing rapidly due to increase in distance between transmitters and receivers. Many circuit topologies have been employed for the efficiency improvement of RWPT system. This paper presents the modeling and efficiency analysis of RWPT system at different coupling coefficients using series-series (SS) and series-parallel (SP) combined topologies. Equations for power transfer efficiency are derived by circuit theory. In order to achieve the results, an Advanced Design System (ADS) software has been applied for analyzing the model. The model is tested by applying 48 V peak-to-peak input voltage. It is found that the efficiency of SP combined topology model is 77.669% at coupling coefficient of 0.0088, which is much better than SS topology model. Additionally, two coils structure of model is designed by Ansys software and coupling coefficient is calculated at different distances. It is found that at 12cm distance, the achieved coupling coefficient is 0.0088. Therefore, the model is appropriate for transferring power in centimeters range.

***Key words:***
*Power transfer efficiency analysis, Series-parallel-combined Topology, Wireless power transfer (WPT), Advanced Design System (ADS), Coupling Coefficient. Coil Structure.*

## 1. Introduction

Wireless power transfer (WPT) is the technique of transferring power from source to load using air as a medium. WPT is a promising choice in situations, where the wires can be unreliable and susceptible to failure. WPT can have a significant impact on the environmental safety by reducing the use of wires and batteries. The idea of WPT was initially presented by Nikola Tesla in the early 20th century [1]. WPT can be broadly segregated into two types; radiative or non-radiative. Radiative power can be defined as the transfer of power through air or vacuum using antenna over a long space in form of an electromagnetic wave [2]. It includes Microwave and Laser technologies, which uses Rectennas; and it has the operation range from several centimeters to few kilometers. It utilizes the frequency of several gigahertz to few terahertz. Moreover, the radiative power transfer also possesses a very high power transfer efficiency, but it requires clear line of sight (LOS), robust tracking and proper alignment for effective transfer of power. The radiative WPT technique is used for scientific, defense, industrial and medical purposes [3]. Note that because of unidirectional nature of radiative approach of WPT, it is affected by the trade-off between directionality and power transfer efficiency [4]. Moreover, the radiative approach of WPT can be hazardous for human health, therefore it is not prevalent choice for civilian use.

The non-radiative WPT employs inductive or resonant coupling and is appropriate for short distance and medium distance applications. The inductive wireless power transfer (IWPT) system functions on the basis of transformer, which utilizes an electromagnetic induction technique for transferring the power from primary coil to secondary coil. In a transformer the electromagnetic field is limited to a high permeability core, but in IWPT system the distance between the primary and secondary coils can be air or vacuum [5]. The resonant wireless power transfer (RWPT) can be particularized as an improved form of the IWPT technique, as it utilizes the magnetic resonance coupling to transfer the electrical power from the transmitting coil to receiving coil. Magnetic resonance coupling can be formed by employing the self-resonance of the spiral coils and the coils resonates at their self-inductance and parasitic capacitance. But when the parasitic capacitances of the coils are insufficient to create resonance at desired frequency, a peripheral lumped capacitor can be added to make the resonance between the coils [6].

After the Tesla's experiments, there has been slight research on WPT technology. However, for the last two decades, the IWPT technology received substantial consideration from researchers across the globe and the wireless charging of consumer electronic devices was primarily commercialized for small electric and electronic devices such as tooth-brushes, cell-phones and other identical devices [7].

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Moreover, the IWPT technique has also been employed for high power applications in kilowatts (kW) power level, such as charging of electrical vehicles [8]. After the development of wireless charging standards, the market of wireless charging has been grown swiftly. In the year 2015, around 140 million wireless receivers and approximately 50 million wireless chargers were sold. It is predicted that this quantity is going to be double in coming years [9]. Furthermore, in the year 2007, RWPT technology gathered much attention, when the researchers at Massachusetts Institute of Technology (MIT) successfully achieved the enhanced power transfer efficiency using magnetically coupled resonators [10]. In the experiment, they developed four coils WPT by putting together the source and load coils with the transmitting and the receiving coils. The experimental setup developed by MIT researchers is illustrated in Fig. 1. They realized a transfer efficiency of 40% to 60% using two self-resonant high quality factor (Q= 950) spiral coils with radius 30cm to light a 60W bulb at 2m air-gap [10, 11].

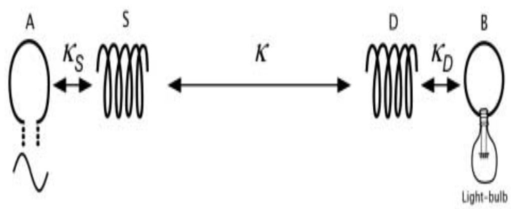



Fig. 1. Experimental setup by Massachusetts Institute of Technology (MIT) [10]

At present, many researchers are working on the enrichment of RWPT technology regarding power transfer efficiency and improvement of distance between the transmitting coil (Tx) and receiving coil (Rx). Misalignment between the Tx and Rx is also a point of concern for the researchers. As reported in [12, 13], the misalignment between Tx and Rx causes the reduction in power transfer efficiency. Many research studies reported different varieties of circuit topologies, as well as the control and frequency decrease analysis [14-16]. Additionally, the frequency splitting phenomenon often occurs in WPT systems with single or multi-transmitter and multi-receiver coils. Particularly, when two or more contiguous coils are placed in near vicinity having strong magnetic fields affecting each other, the frequency splits in two or more than two different peak values [17].

This paper presents the modeling and comparative analysis between series-series (SS) and series-parallel (SP) combined topologies for wireless power transfer at multiple coupling coefficients using advanced design system (ADS) software and circuit theory. This paper is organized in such a manner that the section 1 includes the Introduction. Section 2 consists of the comparative efficiency analysis of resonant wireless power transfer (RWPT) system between SS topology and SP combined topology. The simulation results are given in the section 3. The design of two coils structure of RWPT system and its results are provided in section 4. The conclusion is presented in section 5.

## 2. Comparative Efficiency Analysis of RWPT System

This section is segregated in three sub-sections.

### 2.1 Efficiency Analysis of Series-Parallel (SP) Combined Topology Model

The four circuit topologies are commonly used for circuit design. Which includes series-parallel, parallel-series, series-parallel and parallel-parallel. In this research, the RWPT model using SP combined topology is used to analyze the effects of circuit parameters on the overall performance of the system. The circuit model of SP combined topology system is depicted in Fig. 2. S-parameters are usually known as scattering parameters, which are often utilized for calculating the efficiency of WPT system. Therefore, in this research, the function of power transfer efficiency is expressed in S-parameters, which is given by (1),

$$\eta = |S_{21}|^2 \tag{1}$$

According to Chen et al [18], the equation of magnitude (S21) can be written as (2),

$$|S_{21}| = 2\,.\,\frac{U_L}{U_S}\,.\,\sqrt{\frac{R_S}{R_L}} = 2\,.\,\alpha\,.\,\beta\,.\,\gamma\,.\,\sqrt{\frac{R_S}{R_L}} \tag{2}$$

where, Us is the source voltage of the transmitter coil, the resonance frequency is ω. Moreover, $R_S$ and $R_L$ are the source and load resistances of transmitter and receiver coils, respectively. $U_L$ is the load voltage and it is the output voltage of the system. The equation for α, β and γ are provided by equations (3), (4) and (5), respectively.

$$\alpha = \frac{C_1}{C_1 + C_2 + j\omega C_1 C_2 R_s} \tag{3}$$

$$\beta = \frac{j\omega C_4 R_L}{1 + j\omega C_4 R_L + (j\omega C_3 + j\omega C_4 - \omega^2 C_3 C_4 R_L) R_2} \tag{4}$$

$$\gamma = \frac{A}{(B)(C) + D} \tag{5}$$

where,

$$A = \left(j\omega K\sqrt{L_1 L_2}(R_2 + \frac{1 + j\omega C_4 R_L}{j\omega C_3 + j\omega C_4 - \omega^2 C_3 C_4 R_L}\right)$$

$$B = \left(j\omega L_1 + R_1 + \frac{1 + j\omega C_1 R_s}{j\omega C_1 + j\omega C_2 - \omega^2 C_1 C_2 R_s}\right)$$

$$C = \left(j\omega L_2 + R_2 + \frac{1 + j\omega C_4 R_L}{j\omega C_3 + j\omega C_4 - \omega^2 C_3 C_4 R_L}\right)$$

$$D = (\omega K)^2 L_1 L_2$$

In the above equations $L_1$, $L_2$ are the inductances and $R_1$, $R_2$ are the characteristic resistances of transmitter and receiver coils, respectively. Now, the expression of efficiency η can be derived by putting the value of $|S_{21}|$ in equation (1) and now the efficiency can be calculated through (6).

$$\eta = \left(2\,.\;\alpha\,.\,\beta\,.\,\gamma\,.\sqrt{\frac{R_S}{R_L}}\right)^2 \tag{6}$$

From equation (6), the efficiency is related with the following parameters, which include inductances of the coils, resistances, coupling coefficient k, resonance frequency ω, and capacitances. Therefore, the proper selection and tuning of above mentioned parameters is mandatory in order to achieve higher efficiency.

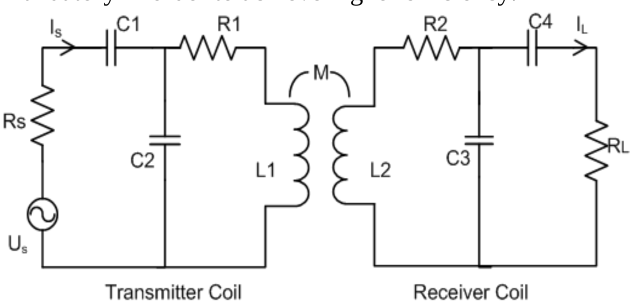



Fig. 2. Equivalent circuit of series-parallel-combined topology model

## 2.2 Efficiency Analysis of Series-Series (SS) Topology Model

In this section, the efficiency equation of SS topology model is derived in terms of S-parameters in order to carry out the fair comparison with SP combined topology model. Fig. 3 shows the equivalent circuit of SS topology model. By putting the values of $C_2$ and $C_3$ as zero in (6), the new equation of efficiency can be derived as (7),

$$\eta = \left(2\,.\;1\,.\frac{j\omega C_4 R_L}{1 + j\omega C_4 (R_L + R_2)}\cdot \Upsilon_{ss}\cdot\sqrt{\frac{R_S}{R_L}}\right)^2 \tag{7}$$

where,

$$\Upsilon_{ss} = \frac{\left(j\omega K\sqrt{L_1 L_2}(R_2 + \frac{1 + j\omega C_4 R_L}{j\omega C_4}\right)}{\left(j\omega L_1 + R_1 + \frac{1 + j\omega C_1 R_S}{j\omega C_1}\right)\left(j\omega L_2 + R_2 + \frac{1 + j\omega C_4 R_L}{j\omega C_4}\right) + (\omega K)^2 L_1 L_2}$$

Moreover, the two operating principles of WPT are suggested in the literature, i.e. maximum power transfer principle or maximum energy efficiency principle. The maximum power transfer theorem permits a flexible control of impedance matching in the model by adjusting two extra coupling coils to enhance the distance, but in this case efficiency will be compromised. If the relay resonators or domino resonators between the source and the load are deployed, a good compromise between efficiency and distance can be achieved, by using the maximum energy efficiency principle [2]. According to Alanson et al. [11], there is a critical coupling parameter for distance known as the point of critical coupling ($k_{critical}$), apart from that point the system cannot operate a prescribed load at the maximum efficiency. In series topology model, when the system is symmetrical, i.e. $R_1=R_2=R_X$ and $R_S=R_L=R$; then $k_{critical}$ and $S_{21(critical)}$ are given by equations (8) and (9), respectively;

$$K_{critical} = \frac{R + R_x}{\omega L} \tag{8}$$

$$S_{21(critical)} = \frac{R}{R + R_x} \tag{9}$$

Equation (8) illustrates that $k_{critical}$ is largely confined by ωL and the load resistance. Because of that reason, the SS topology model is unable to transfer electrical power at larger distance. From the above analytical equations, it can be concluded that SS topology model has their own advantages and disadvantages.

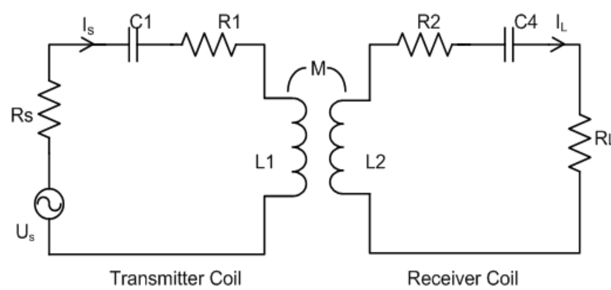



Fig. 3. Equivalent circuit of series-series topology model

The SS topology model presents large value of maximum transfer efficiency at small distances having less sensitivity for the parasitic resistance. But when the inductance is increased for realizing greater transfer distance; that will result in decreased efficiency due to more losses in parasitic resistance of large-sized coils. Whereas, the parallel-parallel circuit model can succeed in dealing with the limitations of the SS model, because its efficiency of power transfer is inversely related with the ratio L/C. But there are some limitations of parallel-parallel topology model, as it is bound to the parasitic resistance and its power transfer efficiency is extremely affected by change in the L/C ratio [18]. Therefore, by using SP combined topology, the advantages of both parallel and series topologies can be utilized to enrich the overall performance of the model.

Furthermore, the wireless power transfer system requires high frequency alternating current (HFAC) supply to create strong electromagnetic field, which propagates in the air or vacuum and captured by the receiving device. In order to capture maximum field; the transmitting and receiving device needs to resonate at identical frequency. Impedance matching network can be a promising technique to capture the maximum amount of electromagnetic field. HFAC supply can be produced by using an oscillator and inverter or power amplifier and inverter [6]. The present situation of HFAC supply in RWPT system is problematic due to losses in high frequency electronic devices. Thus, it is extremely important to decrease the operating frequency in order to reduce the losses in power electronics devices. Frequency decrease analysis in detail is presented in [19]. Here, the general equation of resonance frequency is given by,

$$\omega = \frac{1}{\sqrt{LC}} \tag{10}$$

The coupling coefficient (k) and mutual inductance (M) between the transmitter and the receiver coils can be formulated by equation (11),

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{11}$$

From equation (10), it can be concluded that the operating frequency can be reduced by enhancing the capacitance or the inductance value without affecting the condition of resonance. When inductance value is changed, it actually disturbs the coupling coefficient as provided by equation (11). Therefore, it is necessary to pick an optimized capacitance and inductance value to achieve the maximum efficiency.

## 2.3 Comparative Analysis and Modeling of SS and SP Combined Topology RWPT System

In this section, the modeling and simulation of SS and SP combined topologies are carried to compare the efficiency of both topologies at multiple coupling coefficients. Typically, the RWPT systems utilize above 10 MHz frequency to get higher efficiency and it is very difficult to implement such a high frequency because of many losses in high frequency alternating current supply. Therefore, a much lesser frequency of 1.805 MHz is used in the designed model. Fig. 4 shows the schematic diagram of SP combined topology model and the circuit parameters are given in Table 1. Moreover the schematic of SS topology model using ADS is shown in Fig. 5. The results of the study are presented in the next section. Note that the transient analysis is performed to achieve voltage and current waveforms, while S-parameter analysis is performed to analyze the efficiency of system.

Table 1. Parameters used in RWPT model

| ***Parameter Name*** | ***Corresponding Value*** |
|---|---|
| Frequency | 1.805 MHz |
| Voltage Amplitudes | 48 V |
| $R_S$ and $R_L$ | 50 ohm |
| C1 | 64 pF |
| C2 | 256 pF |
| L1 and L2 | 24.30 µH |
| C3 | 240 pF |
| C4 | 80 pF |
| k (coupling factor) | 0.0088 |

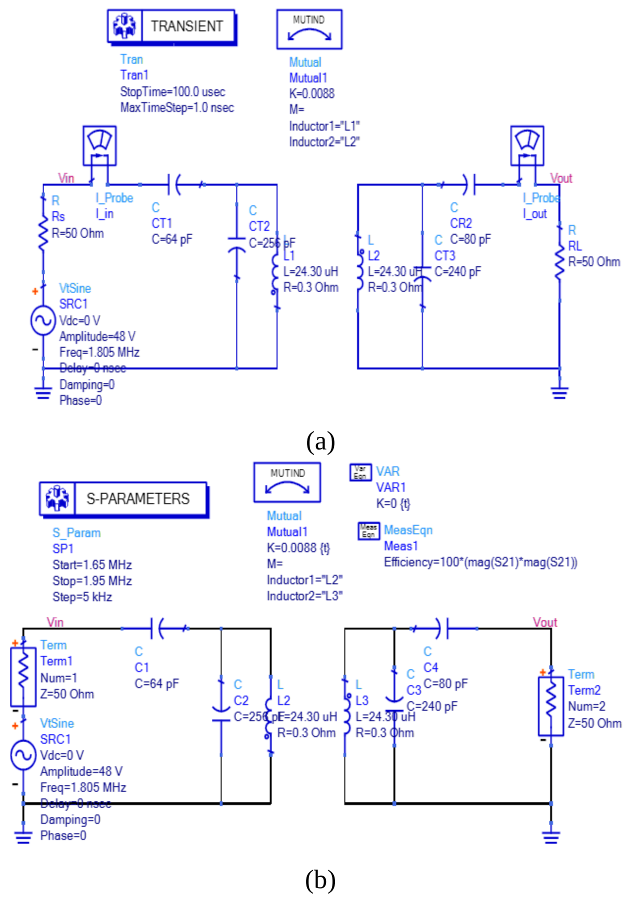
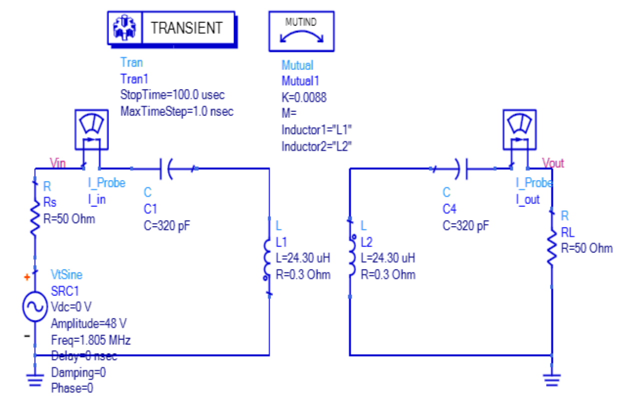
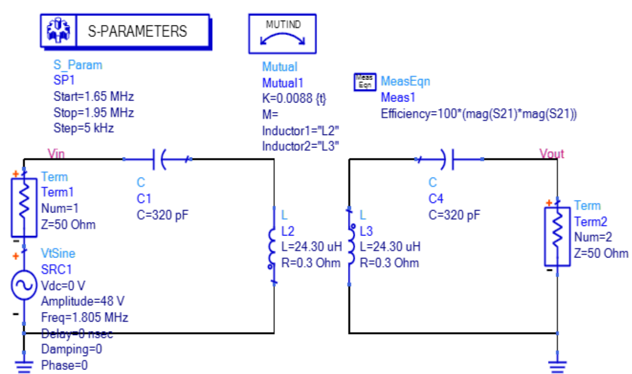



Fig. 4. Series-parallel combined topology model using ADS (a) Transient analysis (b) S-parameter analysis




(a)

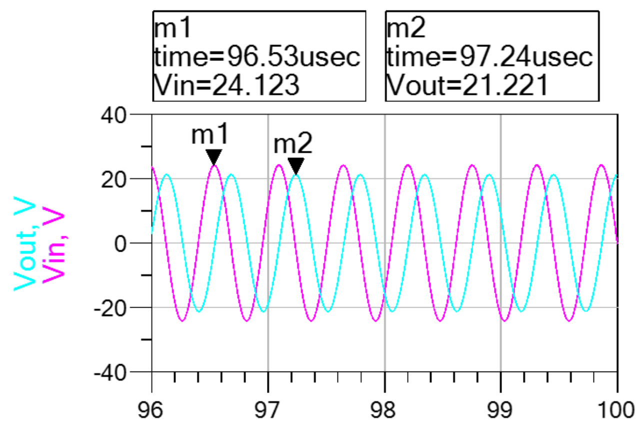



(b)

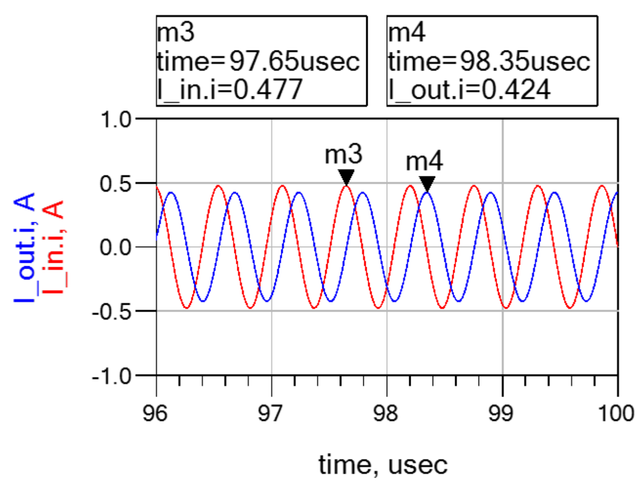
Fig. 5. Series-series topology model using ADS (a) Transient analysis (b) S-parameter analysis

## 3. Results and Discussion

The simulation results of the RWPT model are presented and discussed in this section. The analysis of the model is carried out by properly tuning the circuit parameters, which consist of resistances, inductances, capacitances, frequency and applied voltage. Both topology models are simulated using transient and S-parameter analysis. The S-parameter simulation is conducted to analyze the power transfer efficiency of the model. The schematics of the models as shown in Fig. 4 and Fig. 5 are simulated by applying 48 V input voltage amplitude. Fig. 6 shows the current and voltage waveforms for SP combined topology model. The peak values of voltage and currents are defined by markers m1, m2, m3 and m4. From these results, it can be seen that the peak values of the input and output voltage are appearing as 24.123 V and 21.221 V, respectively. On the other hand, the input and output peak values of current can be seen as 0.477 A and 0.424 A, respectively. Furthermore, from the Fig. 7, it is clear that the current and voltage waveforms values of SS topology model are much lesser than SP combined topology model. Furthermore, the S-parameter analysis results at multiple coupling coefficients of both mentioned topologies are illustrated in Fig. 8 and Fig. 9. It can be seen that, the efficiency varies at different coupling coefficients. When the coupling coefficient increases above 0.011, the splitting frequency phenomenon occurs in SP combined topology model. The frequency is divided in two peaks as depicted in Fig. 8. Although the frequency splitting does not occur at given coupling coefficients in SS topology model as illustrated in Fig. 9. The coupling factor (k), which defines the distance between the coils, has been kept 0.0088, which is equivalent to approximately 12 centimeter coupling distance. The overall result of SP combined topology model shows that the model has the power transfer efficiency of 77.669% at 12 centimeter distance, which is much better than SS topology model at the same distance. It is apparent from the transient analysis and S-parameter analysis results that SP combined topology model gives higher efficiency than SS topology model.

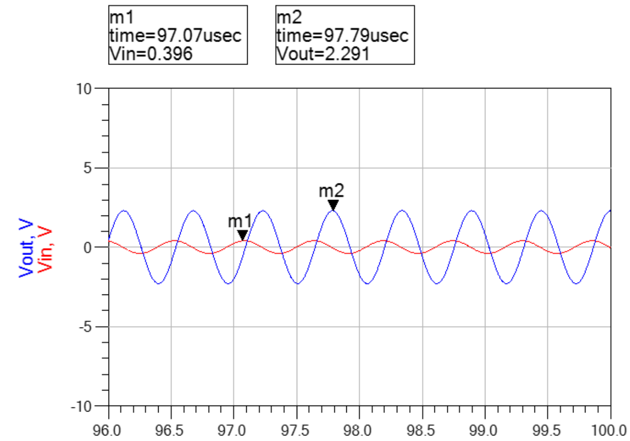



(a)

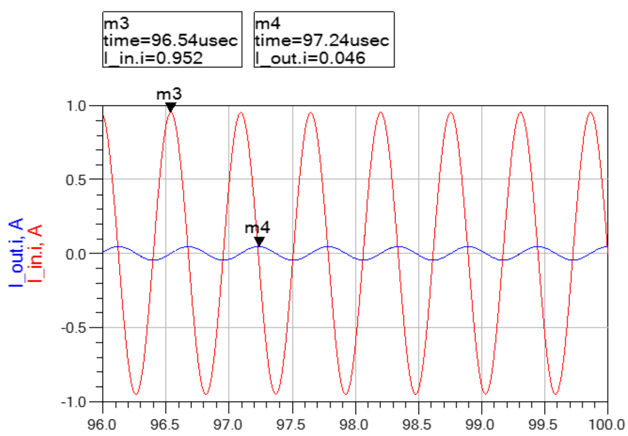



(b)

Fig. 6. Input and output voltage and current waveforms (a) Voltage waveforms (b) Current waveforms




(a)




(b)

Fig. 7. Input and output voltage and current waveforms of series-series topology model (a) Voltage waveforms (b) Current waveforms

## 4. Designing of Two Coil Structures for RWPT System

The spiral is a widely used structure in resonant wireless power transfer system due to its compact size and greatly constricted electromagnetic field characteristics. Because of these inherent advantages, the spiral coil is considered and designed in this research. The structure of coil is designed using Ansys software. The self-inductance, mutual inductance and coupling coefficient is calculated at several distances between the two coils. The behavior of magnetic field is also analyzed at 15mm distance between transmitter and receiver coil, which is depicted in Fig. 10. The parameters of the coil structure are given in Table 2 and measured values of inductance and coupling coefficient are provided in Table 3. Additionally, the behavior of distance vs coupling coefficient is illustrated in Fig. 11.

Table 2. Parameters of two coils structures

| ***Parameter*** | ***Name/Value*** |
|---|---|
| Material | Copper |
| Shape | Polygon Helix |
| Polygon Segments | 4 |
| Polygon Radius | 1 mm |
| Number of Turns | 20 |
| Start Helix Radius | 15 mm |
| Radius Change | 2.05 mm |
| Segments per Turn | 36 |
| Pitch | 0 |
| Distance between both coils | 15 mm |

Table 3. Self-inductance, mutual inductance and coupling coefficient between two circular coils

| ***S. No.*** | ***Distance [mm]*** | ***Self-inductance of both the coils [µH]*** | ***Mutual inductance between the coils [µH]*** | ***Coupling coefficient between the coils*** |
|---|---|---|---|---|
| 1 | 10.000 | 24.317 | 16.114 | 0.630 |
| 2 | 15.000 | 24.347 | 12.870 | 0.503 |
| 3 | 30.000 | 24.367 | 6.793 | 0.265 |
| 4 | 50.000 | 24.353 | 3.071 | 0.119 |
| 5 | 70.000 | 24.354 | 1.450 | 0.056 |
| 6 | 90.000 | 24.358 | 0.698 | 0.027 |
| 7 | 110.00 | 24.356 | 0.329 | 0.013 |
| 8 | 120.00 | 24.359 | 0.216 | 0.0088 |

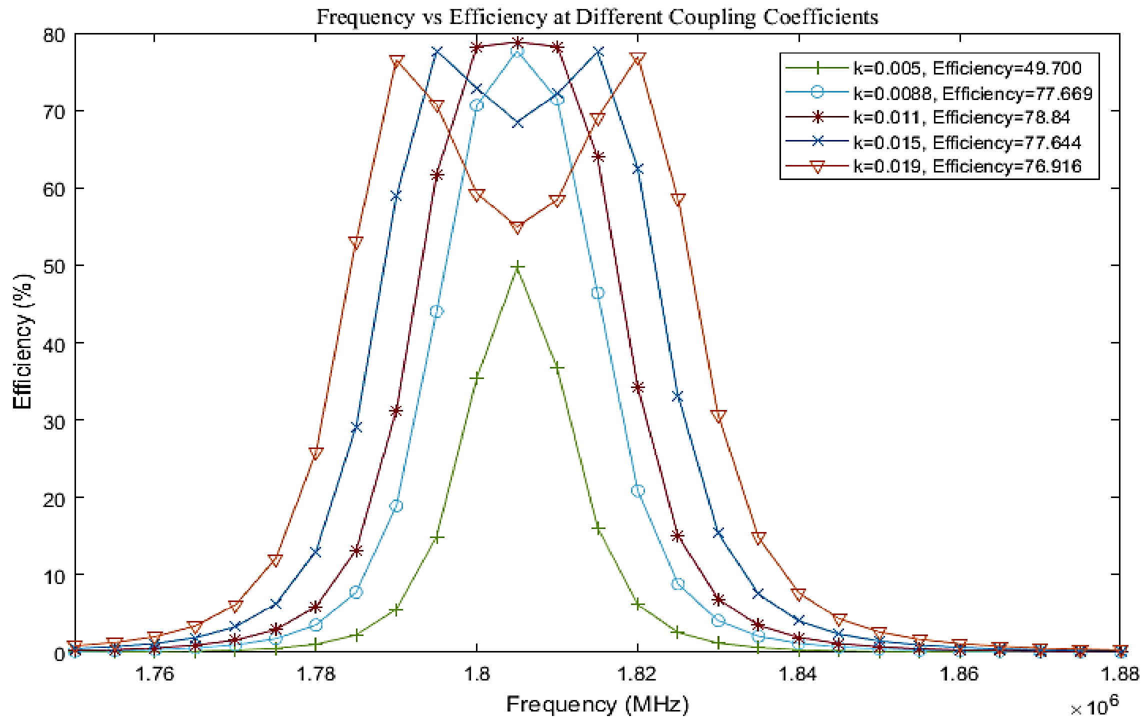



Fig. 8. Efficiency vs Frequency of series-parallel combined topology model at multiple coupling coefficients

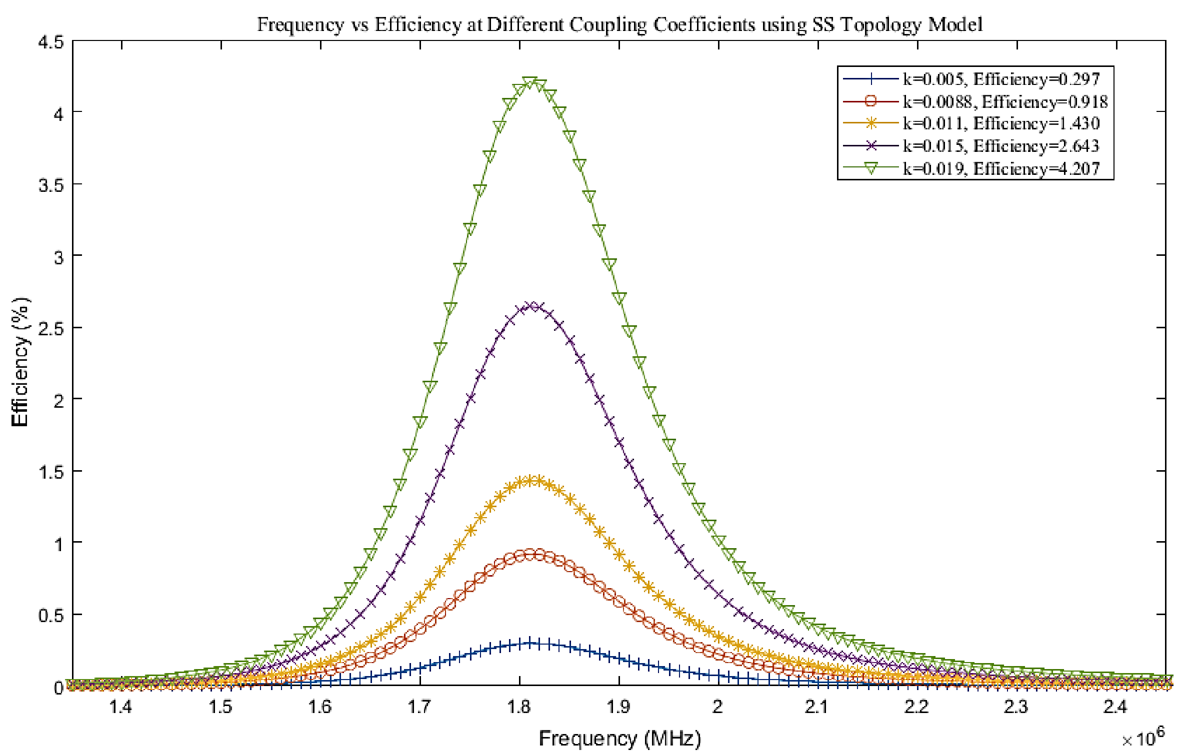



Fig. 9. Efficiency vs Frequency of series-series topology model at multiple coupling coefficients

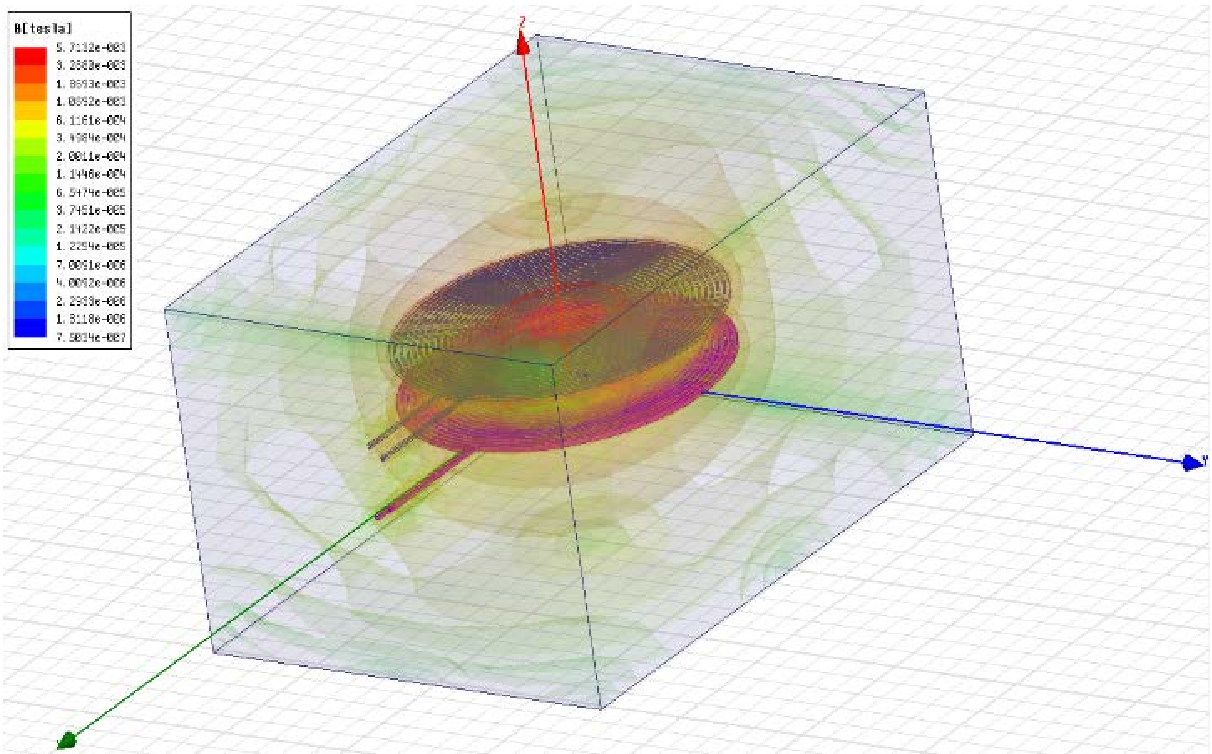



Fig. 10. Spiral coil structure of two coils and magnetic field calculation

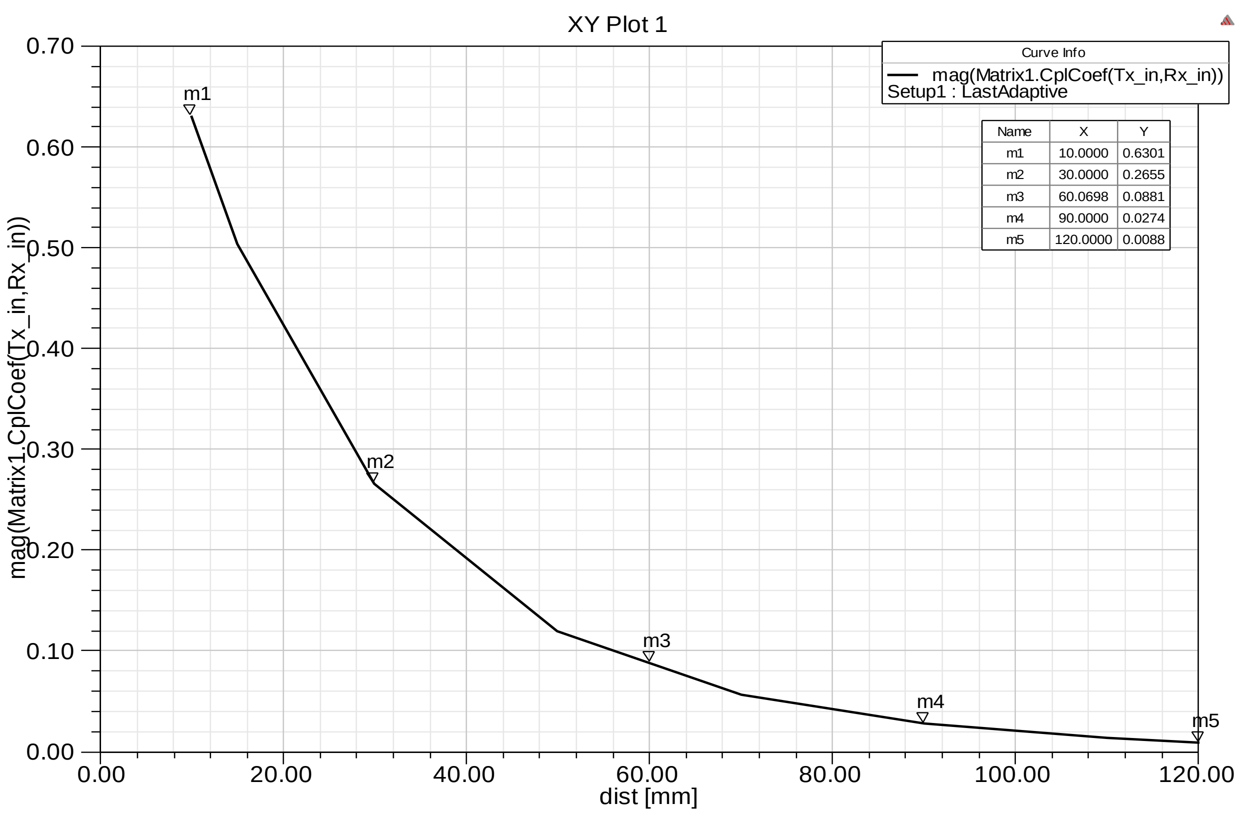



Fig. 11. Behavior of distance vs coupling coefficient

## 5. Conclusion

The modeling of resonant wireless power transfer system is carried out by ADS software. The equations of power transfer efficiency in terms of S-parameters and frequency are derived using circuit theory. The effects of various coupling coefficients on the efficiency of the WPT system are also analyzed. Moreover, the two coils structures for transmitter and receiver are designed by Ansys software. It is confirmed that with increasing distance between transmitter and receiver coil, the coupling coefficient is decreasing drastically. An input voltage amplitude of 48 V (peak-to-peak) has been employed to analyze the performance of the model. It is found that model is able to transfer power of 9 watts approximately at 12 centimeters distance. Therefore, the model is suitable for charging small consumer electronics devices. It is concluded that SP combined topology model is more efficient as compared to SS topology model for same load resistance and coupling coefficient. Future work may include the study of SP combined topology RWPT system using domino or relay resonators to increase the distance and optimization of coil structure for achieving uniform magnetic field.

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