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Modelling and Efficiency-Analysis of Wireless Power Transfer using Magnetic Resonance Coupling

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Abstract

Wireless power transfer (WPT) system has got significant attention in recent years due to its applications in consumer electronics, medical implants and electric vehicles etc. WPT is a promising choice in situations, where the physical connectors can be unreliable and susceptible to failure. The efficiency of WPT system decreasing rapidly with increasing air-gap. Many circuit topologies have been employed to enhance the efficiency of the WPT system. This paper presents the modelling and performance analysis of resonant wireless power transfer (RWPT) system using series-parallel-mixed topology. The power transfer efficiency analysis of the model is investigated via circuit theory. S-parameters have been used for measuring power transfer efficiency. Transient analysis is performed to realize the behavior of voltage and current waveforms using advanced design system (ADS) software. The proposed model is tested with two amplitudes i.e. 100 V peak-to-peak and 110 V peak-to-peak at the same frequency of 365.1 kHz. The overall result shows that the series-parallel-mixed topology model has higher efficiency at low coupling factor (K) for both voltage amplitudes.

Keywords*: Wireless power transfer, Resonant wireless power transfer, Power transfer efficiency analysis, Transient analysis*

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1. Introduction

Wireless power transfer (WPT) Wireless power transfer (WPT) is the method of transferring the electrical power from supply to load without using physical connectors. The idea of wireless power transfer was given by Nikola Tesla about a century ago [1]. WPT technology can have an adequate impact on the environment because the use of wires and batteries can be reduced significantly by using this technology. According to the power transfer mechanism, there are two types of WPT i.e. radiative or non-radiative. Radiative power relies on far-field and it can be defined as the transfer of electrical energy through a medium such as air using a transmitting coil over a long distance as an electromagnetic wave [2]. This approach of WPT is used for industrial, scientific, defense and medical purposes [3]. The non-radiative wireless power transfer employs near-field inductive or resonant coupling and is suitable for short-range and mid-range applications. The radiative power includes microwave and laser technology. Nevertheless, the remarkable research has been carried out in the field of radiative WPT, still this radiative approach suffers from the trade-off between directionality and transmission efficiency [4]. Moreover, the radiative approach of transferring power is hazardous for human health therefore it is not a prevalent choice.

Recent research in non-radiative WPT has outlined the potential benefits and methods of wireless power transfer using inductive coupling and magnetic resonant coupling. The WPT system using inductive coupling works like the basic transformer, which uses electromagnetic induction method for transferring the power from primary to secondary coil and can be called as inductive wireless power transfer (IWPT). In a transformer the magnetic field is typically confined to a high permeability core. However in IWPT technique, the region between the primary and secondary coils can be simply air or vacuum [5]. The WPT using magnetic coupled can be called as resonant wireless power transfer (RWPT). Magnetic resonance coupling can be created by using self-resonance of the spiral conductors, which resonates with its self-inductance and parasitic capacitance. But when the parasitic capacitance of the conductors are insufficient to make resonance at desired frequency, an external capacitor can be added to

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build the resonance conductors [6]. In the RWPT technique, the leakage inductance is compensated by combining the techniques of magnetic coupling and resonance together to ensure the improved power transfer efficiency.

After the Tesla's experiments, there has been little research on wireless power transfer since several decades. In the late 20th century, the IWPT technology received significant attention from the researchers [7] and the wireless charging of portable consumer devices was initially commercialized for charging small electric devices like tooth brushes, cell phones [8] and other similar devices. Furthermore, the IWPT method has also been deployed for high power applications in kilowatts (KW) range, such as charging of electric vehicles [9]. After the wireless charging is standardized universally, the market of wireless charging has been grown rapidly. In the year 2007, RWPT technology caught the world's attention, when the team of researchers at Massachusetts Institute of Technology (MIT) developed a magnetic resonant coupled scheme to enhance the transmission efficiency [10, 11]. They demonstrated the feasibility of WPT by using two self-resonant high quality factor (Q= 950) spiral coils with radius 30cm to light a 60W bulb with 2m air gap. The experiment was successful with transfer efficiency of 40% to 60% [11, 12].

Presently, many researchers are working on the enhancement of efficiency and air-gap of RWPT technology. The efficiency of RWPT systems decreases drastically with increasing air-gap and misalignment between transmitter and receiver coils. The research on misalignment of coils is presented in [13-15], which concluded that the misalignment can significantly impair the power transfer efficiency and the efficiency can be improved by optimizing the design of coil. A lot of interesting works have been accomplished with different kinds of innovative circuits as well as the system analysis and control in [5, 11, 16-18]. The detailed discussion has been presented for multi-dimensional WPT structure in [19]. Furthermore, the frequency splitting phenomenon frequently occurs in the WPT systems with multi-transmitter and multi-receiver coils, when two or more adjacent coils are in close vicinity that they have strong relative magnetic fields. This phenomenon of splitting frequency has been discussed and analyzed in [20]. Furthermore, in [21], it is concluded that the maximum distance between transmitter and receiver is related to the radius and number of turns of the coils. The operation of RWPT system with multiple transmitters and receivers is investigated in [22]. It was examined that due to multiple couplings, the actual resonant frequency of the transmitter or the receiver are altered. In order to compensate the alteration of frequencies, the necessary adjustments are provided. By utilizing the proposed frequency adjustments, 51 to 65 W powers are transferred with efficiency of 45% to 57% at coupling coefficients of 0.025 to 0.063, respectively.The research reported in [23] proposed an optimizable WPT model for acquiring high power transfer efficiency. The efficiency of 85% for the air-gap of 10 centimeters and the efficiency of 45% for the air-gap of 20 centimeters was realized. In [24] ,the authors have conducted research on WPT with metamaterial. From the computational results they relalized that the range of power transfer can be increased using WPT with metamaterial.The focus of their research was only on range but the efficiency was not discussed. While the work presented in this paper discusses the efficiency as well as frequency analysis.

This paper presents the modelling and efficiency analysis of wireless power transfer using magnetic resonance coupling. Initially, the expressions of the model are achieved by circuit theory. Thereafter, simulation of series-parallel-mixed topology is performed by advanced design system (ADS) software. S-parameter and transient analysis of the model are carried out to analyze the performance of the model.

2. Research Method

This section consists of three sub-sections, which are given below.

2.1. Power Transfer Efficiency Analysis

In order to carry out the power transfer efficiency analysis, the series-parallel-mixed topology model is illustrated in Figure 1. Note that WPT system needs high frequency (HF) alternating current (AC) supply. HF AC supply can be created by using an inverter and power amplifier or inverter and oscillator.

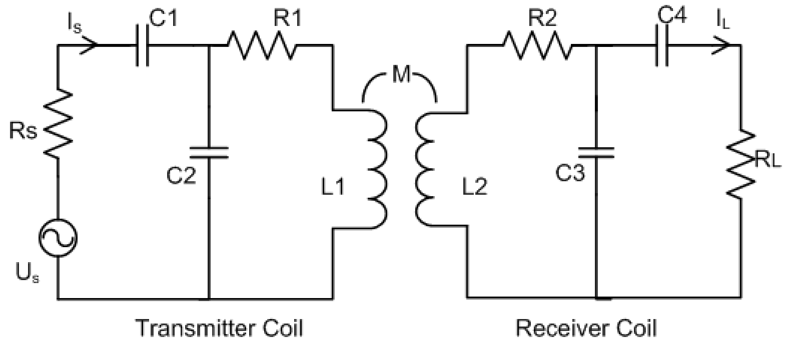


Figure 1. Series-parallel-mixed circuit model of two coils WPT system

According to S-parameters, which are often called scattering parameters, the function of power transfer efficiency is expressed as,

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

The expression of magnitude (S21) has been derived by Chen et al. [23], which is given by,

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

where, Us is the source voltage applied on the transmitting coil at resonance frequency *ω*, and R_S and R_L are the source and load resistances of transmitting and receiving coils, respectively. The expressions for *α*,*β and γ* are given by (3), (4) and (5), respectively.

$$\alpha = \frac{C_1}{C_1+C_3+j\omega C_1C_3R_S} \tag{3}$$

$$\beta = \frac{j\omega C_4R_L}{1+j\omega C_4R_L+(j\omega C_3+j\omega C_4-\omega^2C_3C_4R_L)R_2} \tag{4}$$

$$\gamma = \frac{j\omega K\sqrt{L_1L_2}\left(R_2+\frac{1+j\omega C_4R_L}{j\omega C_4+j\omega C_3-\omega^2C_3C_4R_L}\right)}{\left(j\omega L_1+R_1+\frac{1+j\omega C_1R_S}{j\omega C_1+j\omega C_2-\omega^2C_1C_2R_S}\right)\left(j\omega L_2+R_2+\frac{1+j\omega C_4R_L}{j\omega C_3+j\omega C_4-\omega^2C_3C_4R_L}\right)+\omega^2K^2L_1L_2} \tag{5}$$

In the above equations R_1 and R_2 are the characteristic resistances of transmitting and receiving coils, respectively. Now, the equation of efficiency *η* can be achieved by substituting the value of $|S_{21}|$ in (1) and is given by (6).

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

By using the equivalent circuit method, the voltages and efficiency can be calculated. From (6), it can be extracted that efficiency is associated with the parameters such as coupling factor *K*, resonance frequency *ω*, resistances, capacitances and inductances of the coils. Therefore, by tuning the above circuit parameters efficiency can be improved. Furthermore, Impedance matching and adaptive shifting frequency method can be used to improve the efficiency. Additionally, the two operating principles of WPT are suggested in the literature, i.e. maximum power transfer principle or maximum energy efficiency principle.

Maximum power transfer theorem permits a flexible control of impedance matching in the model by adjusting two extra coupling coils to enhance the air gap, 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 air gap can be achieved, by using the maximum energy efficiency principle [2]. Furthermore, according to the research reported in [25] 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 given load at the maximum efficiency. In series resonant model, when the system is symmetrical, i.e. $R_1=R_2=R_x$ and $R_S=R_L=R$; Then K_{critical} and $S_{21\ (critical)}$ is given by (7) and (8) respectively;

$$K_{critical} = \frac{R+R_x}{\omega L} \quad (7)$$

$$S_{21(critical)} = \frac{R}{R+R_x} \quad (8)$$

From the above equations, it can be seen that K_{critical} is dependent on ωL and the load resistance. For this reason, the series-series model is not capable of transferring power at large distance. It is worth mentioning that both series and parallel topology models have their own advantages and disadvantages. The series-series circuit model can give the higher value of maximum transfer efficiency because of the lower sensitivity for the parasitic resistance. Moreover, the transfer distance can be increased by increasing inductor value of series-series model, but it will lead to decrease the efficiency because of larger parasitic resistance loss of large-sized coils. On the other hand, the parallel-parallel circuit model has ability to overcome the flaws of series-series circuit model. But parallel-parallel topology model has its own limitations, as it is bound to the parasitic resistance and its efficiency is seriously affected by an increase in the *L/C* ratio [23]. Therefore, by mixing series and parallel topologies, the advantages of both can be achieved to enhance the overall performance of WPT system.

2.2. Frequency Analysis

The present situation of high frequency in the resonant wireless power transfer (RWPT) system creates the problems, because it is difficult to generate high frequency (HF) alternating current (AC) supply. Therefore, it is of great importance to reduce the resonant frequency to get easy excess to power electronics inverters. It is worth noting that when the resonance condition occurs, the reactive impedance of the coil becomes zero, In that condition, the resonance frequency of the transmitting and receiving coils can be calculated as,

$$\omega = \frac{1}{\sqrt{LC}} \quad (9)$$

The coupling factor (K) between the transmitting and the receiving coils mutual inductance (M) between the transmitting and the receiving coils is formulated in terms of coupling factor (K) and inductances of coils, which is given by (10),

$$K = \frac{M}{\sqrt{L_1 L_2}} \quad (10)$$

From (9), it can be comprehended that the operating frequency can be decreased by increasing the inductance or the capacitance without changing the condition of resonance. When inductance value is changed it actually affects the coupling factor according to (10). Therefore, it is essential to choose an optimized value of inductance and capacitance in order to maintain the constant efficiency.

2.3. Design and Simulation of the Proposed Model

This section presents the modelling and simulation of series-parallel-mixed WPT system using magnetic resonance coupling. The model is simulated for two input voltages i.e. 100 V peak-to-peak and 110 V peak to peak. Usually, the RWPT system requires a very high frequency up to several MHz to get higher efficiency. But in this research, a comparatively low frequency of 365.1 kHz is used, because implementation of a high frequency is difficult and it has many losses. Figure 2 and Figure 3 show the schematic diagrams of model for performing S-parameters and Transient analysis, respectively. The proposed circuit parameters are provided in Table 1.

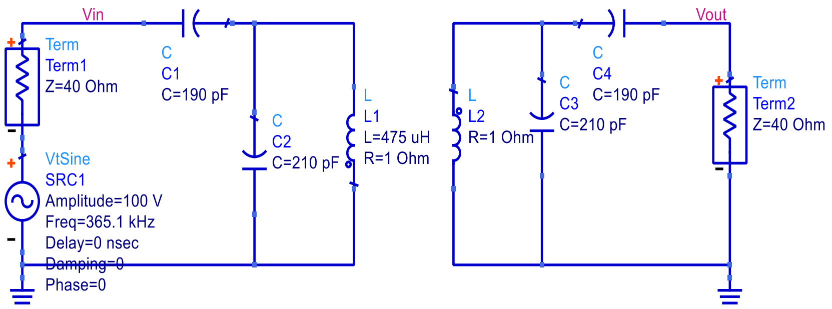


Figure 2. Schematic of designed model using ADS for finding S-parameters

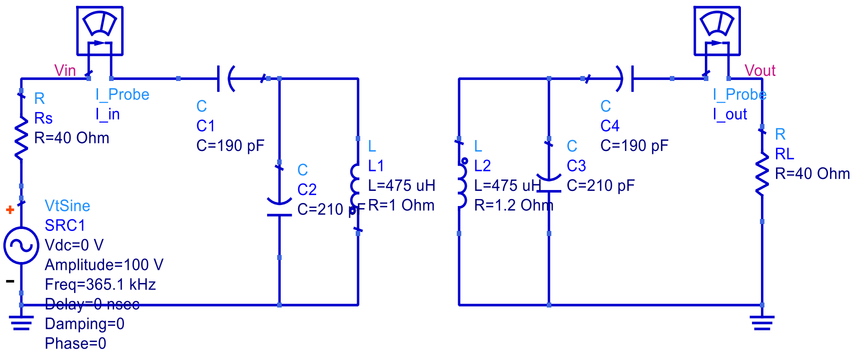


Figure 3. Schematic of designed model using ADS for Transient analysis

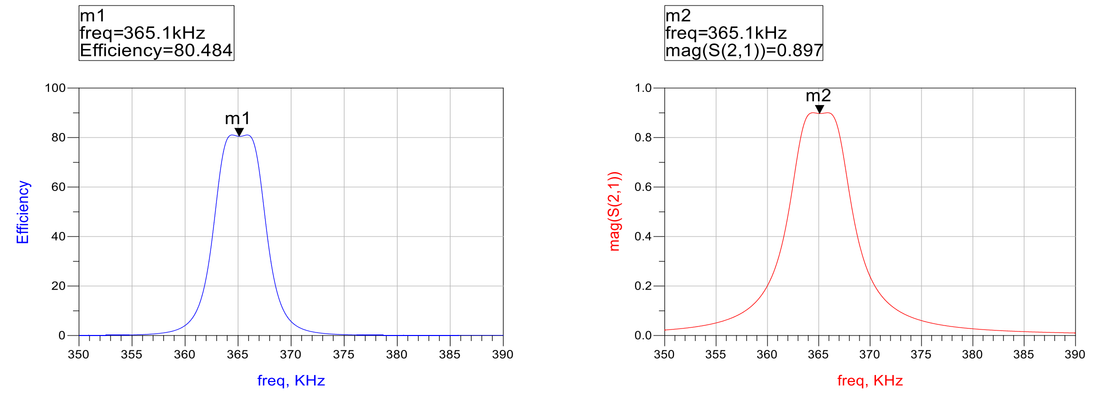
Table 1. Parameters used in proposed model

Parameter Name	Corresponding Value
Frequency	365.1 kHz
Voltage Amplitude	100 V and 110 V peak-to-
R_S and R_L	40 Ω
C1 and C4	190 pF
C2 and C3	210 pF
L1 and L2	475 µH
K (coupling factor)	0.01

By applying the above parameters the transient and S-parameter analysis is performed by using advanced design system (ADS) software. The results of the study are described and discussed in later section.

3. Results and Analysis

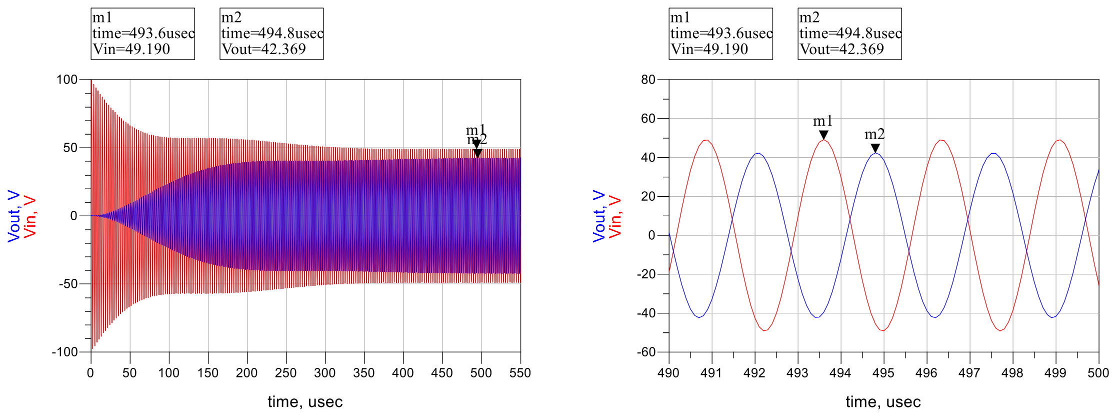
In this This section emphasizes on the modelling and simulation results of series-parallel-mixed topology model. The tuning of the model is performed by varying the circuit parameters including capacitance, inductance and resistances to obtain the better efficiency. S-parameter and transient analysis are carried by applying two input amplitudes i.e. 100 V peak-to-peak and 110 V peak-to-peak. As shown in Figure 4(a) and 4(b) 80.48% efficiency and 0.897 S (2, 1) magnitude is achieved for both input amplitudes. Moreover, transient analysis results for 100 V peak-to-peak amplitude are depicted in Figure 5 and Figure 6. While, for 110 V peak-to-peak amplitude the results are shown in Figure 7 to Figure 8. The markers m1 and m2 are the corresponding peak values of efficiency, magnitude and waveforms.



(a) (b)

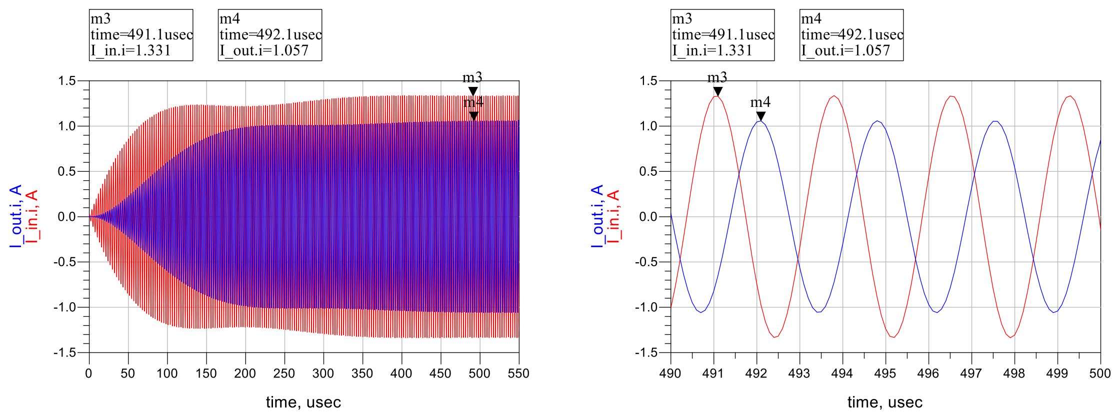
Figure 4. (a) Efficiency of the model using S-parameter analysis
(b) Figure 5. S (2, 1) magnitude of the model

The results of model for 100 V peak-to-peak amplitude are shown in Figure 5 and Figure 6. The obtained peak values of the input voltage and current are 49.190 V and 1.331 A, respectively. On the other hand, the output voltage and current values are 42.369 V and 1.057 A, respectively.



(a) (b)

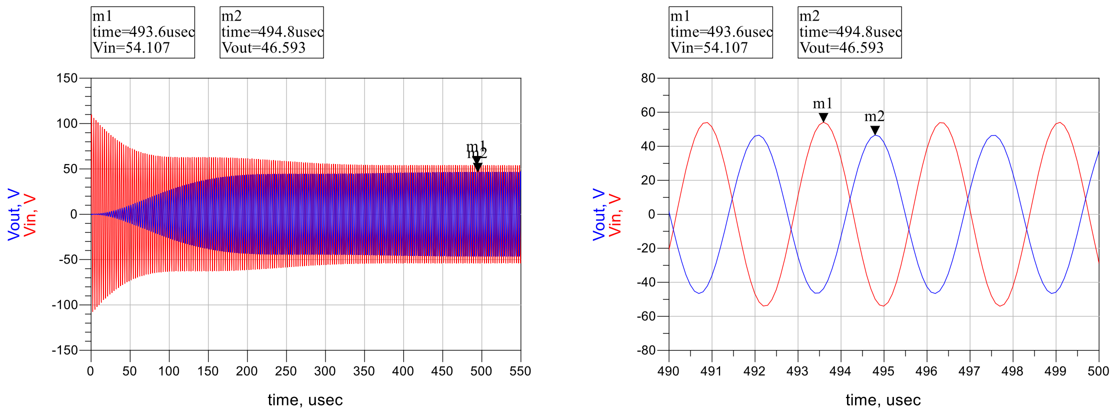
Figure 5. Input and output voltage waveforms using 100 V peak-to-peak amplitude
(a) Full view (b) Zoom in view



(a) (b)

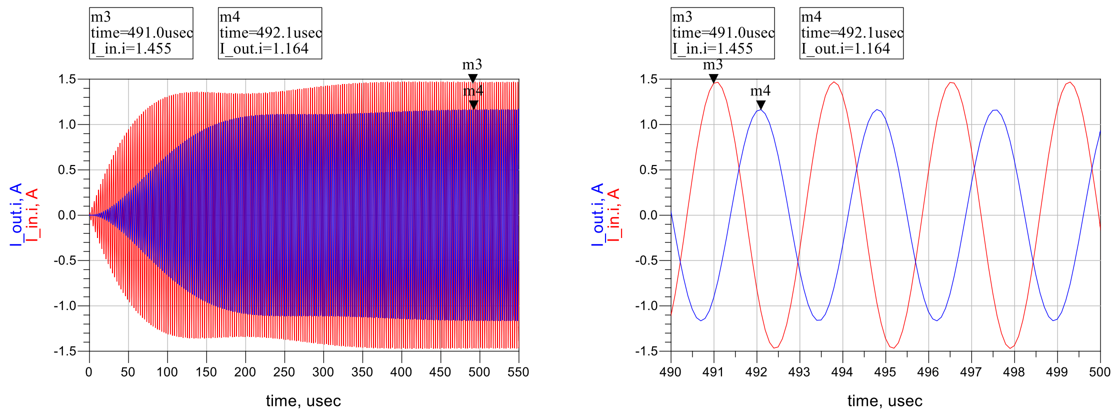
Figure 6. Input and output current waveforms using 100 V peak-to-peak amplitude
(a) Full view (b) Zoom in view

Using 110 V peak-to-peak amplitude, the results are illustrated in Figure 7 and Figure 8. The obtained input and output peak voltages are 54.107 V and 46.593 V, respectively. On the other hand, the input and output peak currents can be seen as 1.455 A and 1.164 A, respectively. From the full view of waveforms, it is seen that there is a distrortion in voltage and current waveforms upto 150 micro seconds approximately, afterwards the waveforms have been stabilized automatically. This distortion for small time occurs because of the transient behavior and non-linearity of the system.



(a) (b)

Figure 7. Input and output voltage waveforms using 110 V peak-to-peak amplitude
(a) Full view (b) Zoom in view



(a) (b)

Figure 8. Input and output current waveforms using 110 V peak-to-peak amplitude
(a) Full view (b) Zoom in view

It is apparent from the results that series-parallel-mixed topology model can work for different voltage levels with good efficiency. Furthermore, the designed model can be further optimized for achieving better results.

4. Conclusion

In this paper, the modeling of wireless power transfer system is carried out by using ADS simulation software. The efficiency analysis of the model is conducted using circuit theory. Equation of efficiency in terms of S-parameter is also provided. The effects of reducing the operating frequency without affecting the efficiency of the RWPT system are also discussed. The analysis of the series-parallel-mixed topology model shows that its performance is promising at different voltage levels. From the S-parameter analysis of the model, the efficiency of about 80.48% is realized for two input amplitudes i.e. 100 V and 110 V peak-to-peak. Future work may include the investigation on mid-range wireless power transfer by employing impedance matching and adaptive shifting of frequency.

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