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Comparison of Series/Series and Parallel/Series Resonance Circuit in 1.5 kW Inductive Wireless Power Transfer for EV Applications

Bhukya Bhavsingh[1, *], G. Suresh Babu[2], B. Mangu[3]

[1]Department of Electrical Engineering, Rajiv Gandhi University of knowledge Technologies Basar, Telangana, India

[2]Department of Electrical and Electronics Engineering, Chaitanya Bharathi Institute of Technology (CBIT-A) Hyderabad, Telangana, India

[3]Department of Electrical Engineering, University College of Engineering, Osmania University, Hyderabad, Telangana, India

Email address:

bhavsingh205@gmail.com (Bhukya Bhavsingh), gsureshbabu_eee@cbit.ac.in (G. Suresh Babu), bmanguou@gmail.com (B. Mangu)

[*]Corresponding author

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Abstract: Wireless power transfer system plays a key role in the present and future days, because of their upgraded comfort and safety and their merits of less green-house gas (GHG) emissions, cell phones, laptops and electric vehicle charging. In this paper, the basic two resonance circuits were analyzed using an inductive wireless power transfer (IWPT) system, at 1.5 kW, 120-mm, and 85 kHz resonance frequencies. It includes analyzing, designing, and comparing this resonance circuit to choose a suitable resonant circuit for the particular application of an IWPT system. The main analysis and comparison were: Mutual Inductance Effect (Misalignment), stresses on the components, Effect of mutual inductance on the efficiency, Effect of distance on the efficiency, Effect of frequency on the efficiency, Effect of the coupling coefficient (k) on the efficiency and transferred power, Effect of coupling coefficient (k) on the input impedance, Effect of distance on the coupling coefficient (k) and Mutual inductance, and both S/S and P/S circuits have same battery output dc power, current, voltage levels. Both resonance circuits designing formulas derived, electrical parameters are calculated for the given wireless power charger level reaches SAEJ2954 standards. In the end, both resonance circuits are verified through MATLAB simulation of the equivalent circuits.

Keywords: Inductive Wireless Power Transfer (IWPT), Compensation, Resonance, Misalignments Effect, Power Transfer Capability

1. Introduction

The Popularity of Electric Vehicles (EVs) has increased noticeably over the past few years due to their favorable advantages which reduce pollution, the consumption of fuel, few requirements of maintenance, etc. [1]. The inductive wireless power transfer (IWPT) technology plays a key role in EVs. This technology avoids the safety concern and inconveniences which are caused by wired charging [2, 3]. The EV has many advantages such as charging cost, time, range, reliability, compatibility, high energy efficiency, environment friendliness, better performance, and reduced energy dependence on fossil fuels [1]. The basic diagram for the IWPT of EVs is presented in Figure 1.

In a IWPT system, the energy is transferred through the mutual inductance of the primary and secondary coils, whereas the leakage inductance does not have a direct contribution to the active power transfer. Because of the large gap between the primary and secondary coils, the coupling coefficient between the two coils is small, i.e., basically in the limit of 5%–30% depending on the air-gap between the coils, alignment, and size of the coils. This causes the Resonant Inductive Wireless Power Transfer (RIWPT) systems to have a large leakage inductance but a small mutual inductance. To increase the coupling, the coil design, without a doubt, is important [4]. Meanwhile, the compensation circuit, which is used to cancel the leakage inductance, is also of great importance and also reduces the VA rating and acts as a Zero Power Angle (ZPA). Usually, capacitors, which can be series or parallel, are added to both sides of the coil to form a resonant circuit.

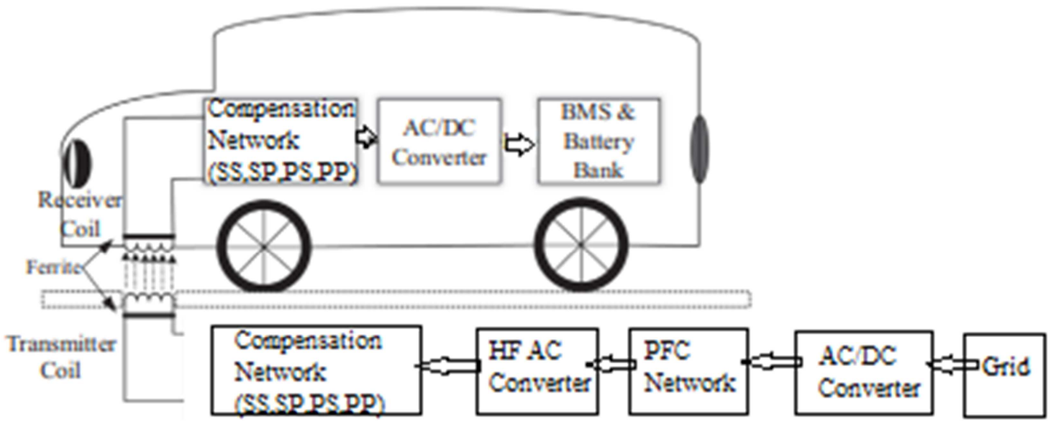


Figure 1. *Basic diagram for IWPT of EVs.*

Different compensation topologies for wireless charging topologies have been analyzed [5, 6]. There are four basic topologies, depending on capacitor position, there will be categorized by, series/series (S/S), series/parallel (S/P), parallel/series (P/S), and parallel/parallel (P/P) topologies [7, 8]. Some other novel topologies have also been proposed in the literature. In [9], like PS, PPS, LCL, LCC, LCC-S, and CLCL. The letter "S" and "P" refer to capacitance and inductors are connected in series and parallel. In the EV battery charging, either constant output voltage or constant current is required [4], therefore in this paper, only S/S and P/S compensation topologies are researched. Both topologies require voltage- source inverters, and remaining two are require current- source inverters [11]. From the basic fours resonant circuits, Series/series resonant circuit is best suitable for EVs, as the compensation capacitors are independent of coupling coefficient (k) and load, small and medium power transfer capability is suitable and less complex and size [12]. The main drawbacks of S/S resonant circuit are more voltage stress across compensation capacitors and converter switches. This becomes to the increased ratings of compensator capacitors and converter switches which effects the increase in losses and a reduced in overall power transfer efficiency [13]. Due to the above reason, the main focus on current-source P/S and P/P resonance circuit is increasing the demand. Simulations are performed in MATLAB Simulink, to verify the validity of evaluated the mathematical and simulated parameters.

Mathematical Analysis of the S/S Resonant Circuit is presented in section 2. Mathematical Analysis of the P/S Resonant Circuit is presented in section 3. The comparison of S/S and P/S resonant circuit is presented in section 4. And the conclusions are summarized in Section 5

2. Mathematical Analysis of the S/S Resonant Circuit

The output dc voltage and current ratings of the charger for EV which are considered are 280 V, 5.3A at 85 kHz resonance frequency, air gap of 120 mm distance, this distance is suitable for two wheeler and three-wheeler vehicles. The targeted dc power of IWBC is 1.5 KW for resonated circuit. The basic electrical network of IWBC with S/S resonance circuit for calculating electrical parameters is shown in Figure 2.

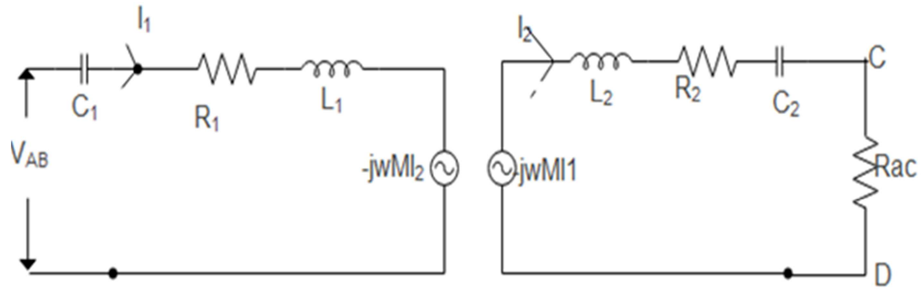


Figure 2. *Circuit of IPT with S/S resonance circuit.*

The simplified equivalent voltage- dependent network of the S/S IWBC system is shown in Figure2. In this section, the formulas for electrical parameters design used in [14] for S/S-IWPT topology are literature and derived using equivalent circuit shown in Figure 2. As per the wireless charging standards of Society of Automotive Engineers technical information report J2954, the resonant frequency should be in between the range 81.39-90 kHz [10, 15]. The electrical parameter values are calculated as follows and finally arranged in table 1.

As per output power 1.5 kW and 280 V, the R_O is the equivalent battery resistance.

$$R_0 = \frac{v_0^2}{P_0} = \frac{280*280}{1500} = 52\Omega; \tag{1}$$

The expression for transferring equivalent resistance is given by

$$R_{ac} = \left(\frac{8}{\pi^2}\right)* R_0 = \left(\frac{8}{\pi^2}\right)*52 = 42.19\Omega \tag{2}$$

From the quality factor (Q_2) formula, L_2 can be obtained.

$$Q_2 = \frac{w_0 L_2}{R_{ac}} \Rightarrow L_2 = Q_2 * \frac{R_{ac}}{w_0} = 6*\frac{42.12}{2*3.14*85000} = 474.22\mu H \tag{3}$$

To avoid the bifurcation, select suitable quality factor Q_2i.e 6. The secondary coil voltage and currents with compensation is given by

$$V_{srms} = \frac{2\sqrt{2}v_0}{\pi} = \frac{2\sqrt{2}*280}{\pi} = 252.21V \tag{4}$$

$$I_2 = \frac{V_2}{R_{ac}} = \frac{252.21}{42.19} = 5.97A \tag{5}$$

At resonance transferred Power should be equal to the supplied power. Then transmitting current (I_1) can be obtained as

$$I_1 = \frac{P_0}{V_{AC}} = \frac{1500}{200} = 7.5A \tag{6}$$

Apply KVL on receiving side at resonance gives

$$\left|jw_0 M I_1\right| == R_{ac}\left|I_2\right| \Rightarrow M = \frac{R_{ac}\left|I_2\right|}{w_0 I_1} = \frac{42.19*5.97}{2*3.14*85000*7.5} = 62.9\mu H \tag{7}$$

For bifurcation-free operation, must select k< k_c. The mathematical equation for the critical coupling coefficient [14] is obtained from Eq. 8.

$$k_c = \frac{1}{Q_2}\sqrt{1-\frac{1}{4Q_S^2}} = \frac{1}{6}\sqrt{1-\frac{1}{4*6^2}} = 0.16 \tag{8}$$

By using k, the value of primary coil inductance (L_1) can be obtained from the following Eq. 9.

$$M = k\sqrt{L_1 * L_2} \Rightarrow L_1 = \frac{M^2}{L_2 k^2} \Rightarrow \frac{\left(62.19*10^{-6}\right)^2}{\left(474.22*10^{-6}\right)*0.16^2} = 325\mu H \tag{9}$$

Both C_1 and C_2 can calculated from the below formula at resonant frequency which is given by

$$\begin{aligned} X_{L1} = X_{C1} \Rightarrow w_0 L_1 = \frac{1}{w_0 C_1} \Rightarrow C_1 = \frac{1}{w_0^2 L_1} \Rightarrow \frac{1}{\left(2*3.14*85000\right)^2 *325*10^{-6}} = 10.79nF \\ X_{L2} = X_{C2} \Rightarrow w_0 L_2 = \frac{1}{w_0 C_2} \Rightarrow C_2 = \frac{1}{w_0^2 L_2} \Rightarrow \frac{1}{\left(2*3.14*85000\right)^2 *474.22*10^{-6}} = 7.4nF \end{aligned} \tag{10}$$

$$M^2\left[\frac{R_L^2 I_2^2}{L_2^2 k^4} - w_0^2 I_2^2\right] = V_{AB}^2 \Rightarrow M^2\left[\frac{42.19^2 * 5.978}{\left(474.22*10^{-6}\right)*0.16^4} - \left(\left(2*3.14*85000\right)^2 * 5.978^2\right)\right] = 200^2 \Rightarrow 9.74\mu H \quad (11)$$

The calculated above circuit parameters for IWPT with S/S compensation are placed in Table 1.

To verify the above parameters, to simulate in MATLAB Simulink.The basic simulink mode which is considered for simulation is shown in Figure 3. The dc output voltage, current and Power are shown in Figure 4.

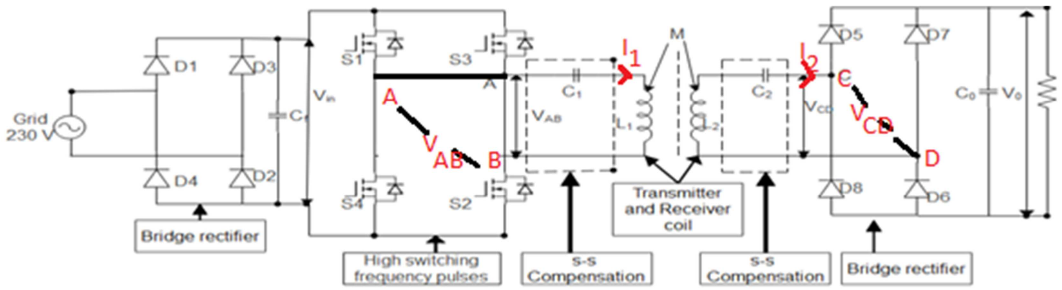


Figure 3. *Structure of S/S WPT system.*

In Figure 5, Secondary side parameters are same as S/S resonance circuit, only change in primary side, capacitor is replaced by parallel, Then Calculation of primary side parameters like L_1, C_1, and M is as follows:

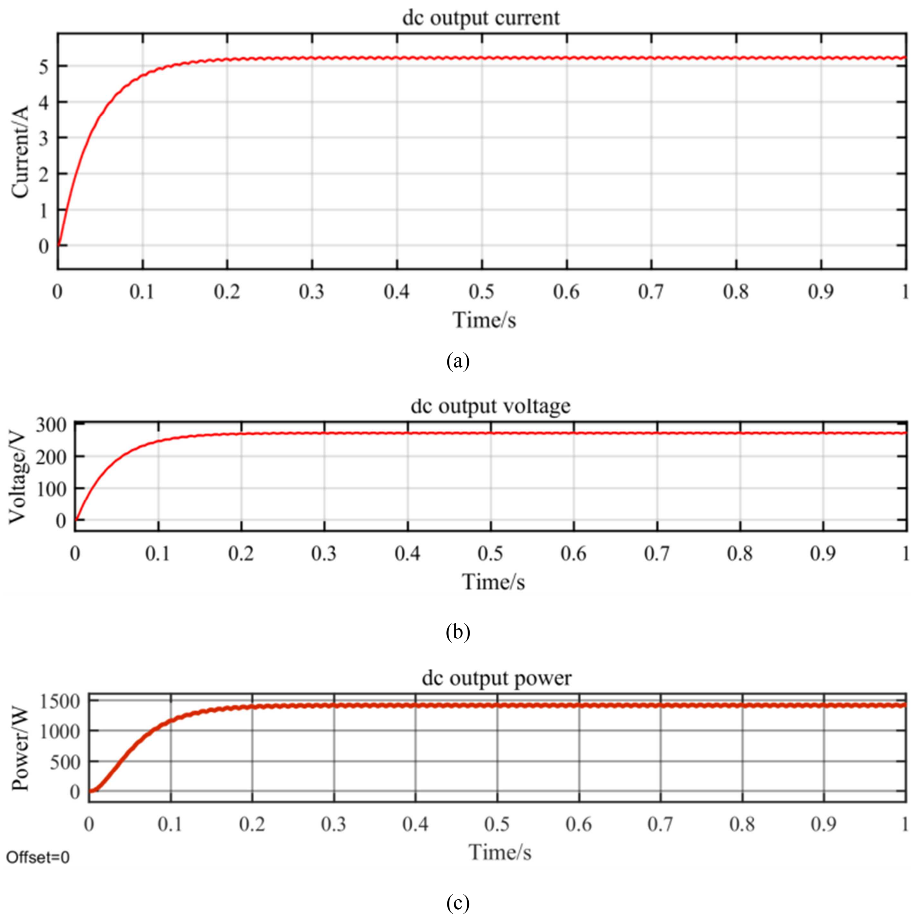


Figure 4. *S/S compensation circuit (a) Current (I_O); (b) Output Voltage (V_O); (c) Power (P_0)*

3. Mathematical Analysis of the P/S Resonant Circuit

The basic electrical circuit of the IWPT of P/S resonance circuit is shown in Figure 5.

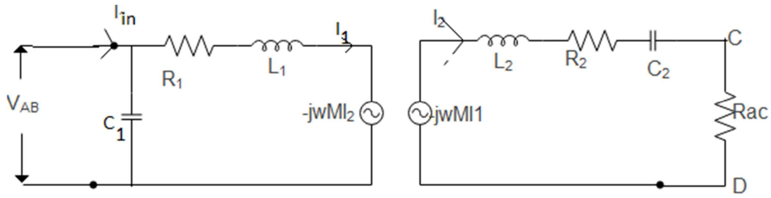


Figure 5. *Basic IPT with P/S topology.*

From equation (7), M can be calculated at the resonance frequency,

$$M^2\left[\frac{R_L^2 I_2^2}{L_2^2 k^4}-w_0^2 I_2^2\right]=V_{AB}^2 \Rightarrow M^2\left[\frac{42.19^2 * 5.978}{\left(474.22*10^{-6}\right)*0.16^4}-\left(\left(2*3.14*85000\right)^2 * 5.978^2\right)\right]=200^2 \Rightarrow 9.74\mu H \tag{12}$$

$$M=k\sqrt{L_1 * L_2} \Rightarrow L_1=\frac{M^2}{L_2 k^2} \Rightarrow \frac{\left(9.74*10^{-6}\right)^2}{\left(474.22*10^{-6}\right)*0.16^2}=7.814\mu H \tag{13}$$

$$X_{L1}=X_{C1} \Rightarrow w_0 L_1=\frac{1}{w_0 C_1} \Rightarrow C_1=\frac{1}{w_0^2 L_1} \Rightarrow \frac{1}{\left(2*3.14*85000\right)^2 * 7.814*10^{-6}}=449.1nF \tag{14}$$

Also I_{inv} can be found by Eq. 15,

$$\begin{aligned} I_{C1} &= V_{AB} w C_1 \Rightarrow 200*2*3.14*85000*449.1*10^{-9}=47.94A \\ I_{inv} &= \sqrt{I_{C1}^2+I_1^2} \Rightarrow \sqrt{47.94^2+7.5^2}=48.52A \end{aligned} \tag{15}$$

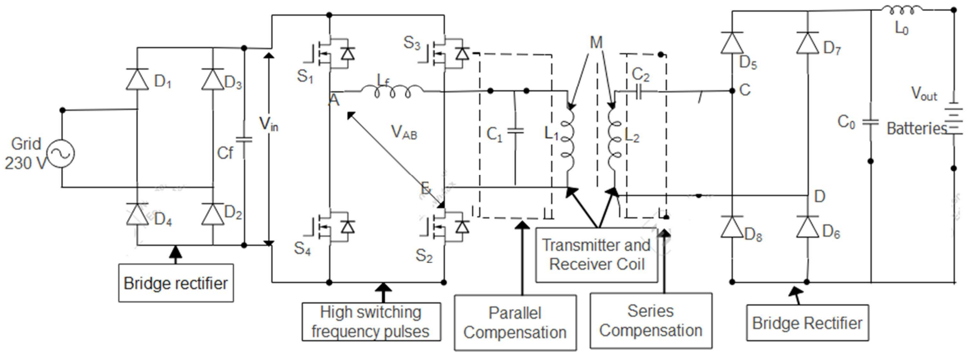
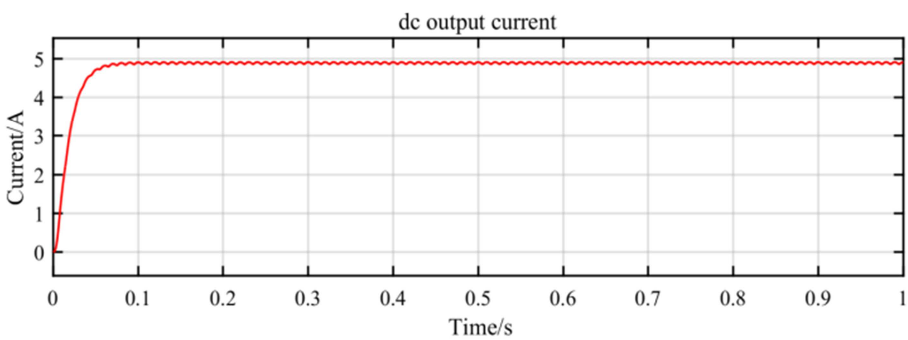
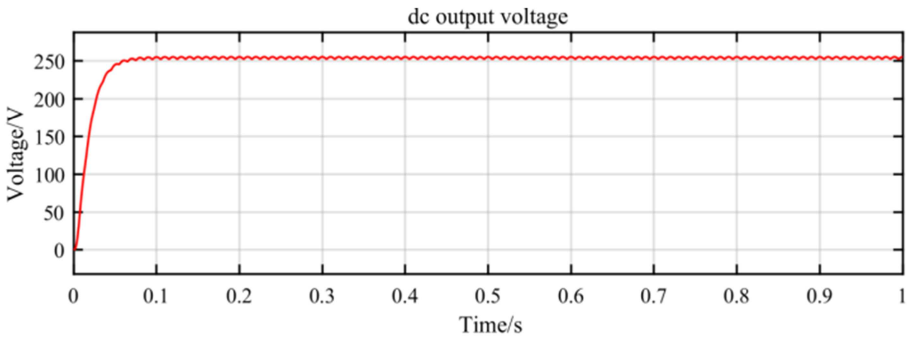


Figure 6. *Structure of P/S WPT system.*

To check the validity of the above components, all the calculated parameters is inserted in MATLAB Simulink. The simulink model for the simulation is shown in Figure 6. In Figure 6 series inductive (L_f) filter as P/S resonance circuit cannot be supplied directly from the voltage source, because P/S resonance circuit is a current-source circuit. From Figure 7 it can be noticed that dc output voltage, current and Power are almost matching with considered battery ratings.



(a)



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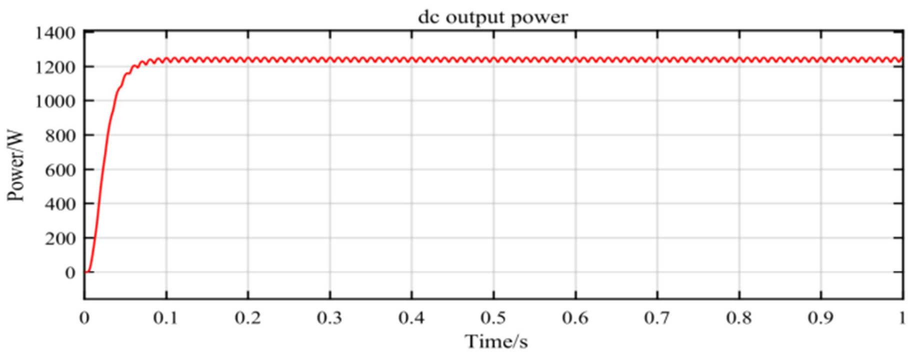


(c)

Figure 7. *P/S compensation circuit: (a) dc output Current (I_O); (b) dc Output Voltage (V_O); (c) dc Power (P_0)*

4. Comparison of Both Resonant Circuit

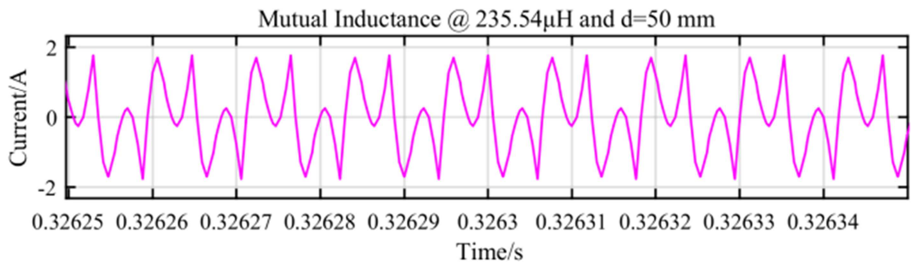
4.1. Mutual Inductance Effect (Misalignment)

Both Resonant circuits have been design and simulated in MATLAB simulink. The air gap between the coils is effected by different coupling coefficients, like k = 0.16, i.e., the mutual inductance M = 62.9 µH is considered for the study. The output voltage 280 V, 5.3 A is used for the simulation. The resonant frequency is the same as the inverter switching frequency i.e 85 kHz, at the end by using full bridge rectifier getting the dc output voltage.

Table 1. *Coils and Resonant circuit Parameters.*

Parameters	Symbol	Value for S/S Compensation	Value for P/SCompensation
DC supply voltage[V]	V_{in}	200	200
Output Power [kW]	P	1.5	1.5
Transmitter coil inductance [µH]	L_1	325	7.814
Receiver coil inductance [µH]	L_2	474.2	474.2
Transmitter side compensation capacitance [nF]	C_1	10.79	449.1
Receiver side compensation capacitance [nF]	C_2	7.4	7.4
Mutual Inductance [µH]	M	62.9	9.74
Resonant frequency [kHz]	f	85	85
Rectifier filter capacitance [µF]	C_0	180	180
DC output voltage [V_0]	V	280	280
Load Resistance [Ω]	R_L	52	52
Coil Resistance both side	R_1, R_2	0.1	0.1
Coupling coefficient	k	0.16	0.16
Ground clearance [mm]	D	120	120

Figures 8 and 9 define the primary current variation for bothproposed circuits with respect to variable mutual inductances. It is noticed that in S/S resonant circuit, the primary current changes with respect to the mutual inductance but in the case of P/S resonant circuit the primary current will change within small limits (Figures 8 and 9). It is notice that in the case of S/S resonant circuit if mutual inductance is decreasing, the current drawn from the source will increase but in the case of P/S resonant circuit, the source current will be within a small variation. Secondary current in the case of S/S resonant circuit, if mutual inductance is low, the source current as well as the primary current is also high compared to other higher mutual inductance conditions.



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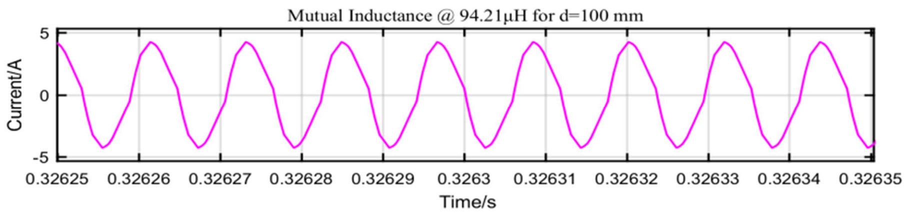

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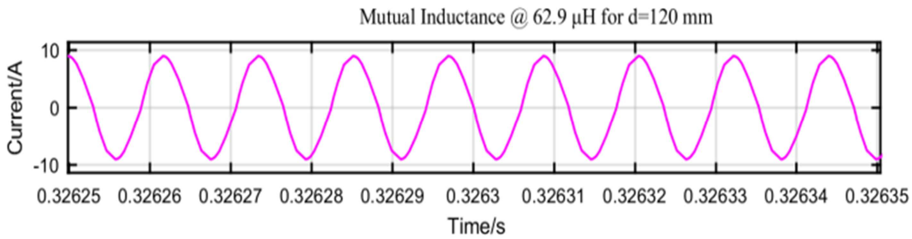

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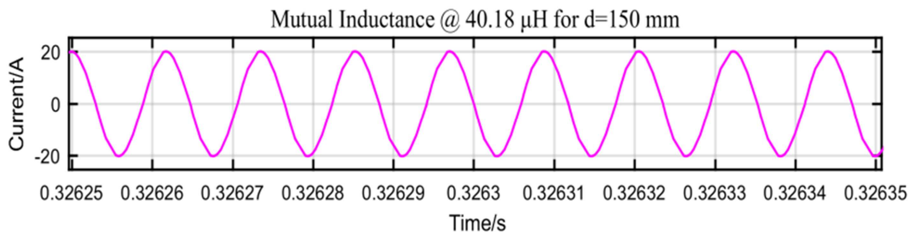

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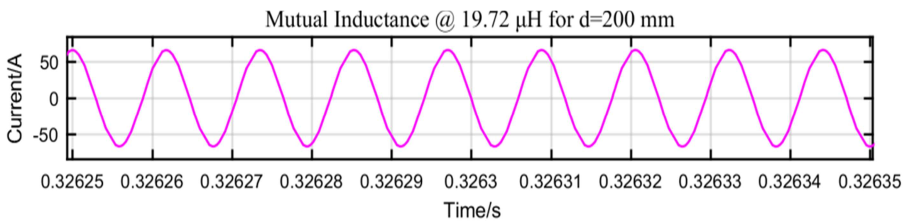
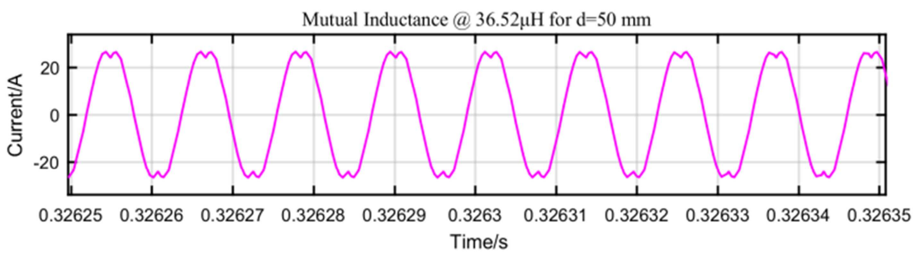


(e)

Figure 8. *Primary current of S/S resonance circuit (a) M = 235.54 μH; (b) M = 94.21 μH; (c) M = 62.9 μH; (d) M = 40.18 μH; (e) M = 19.72 μH*



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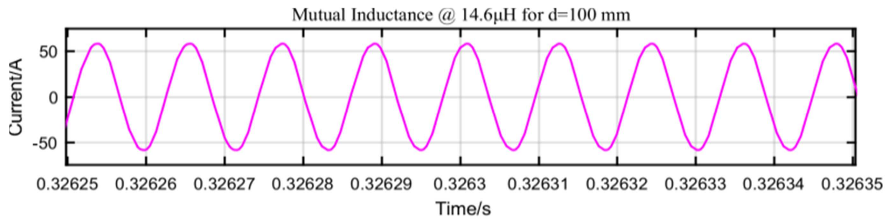

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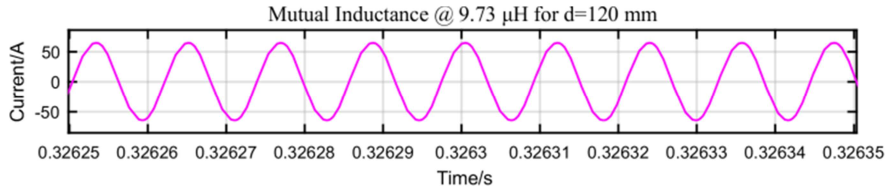

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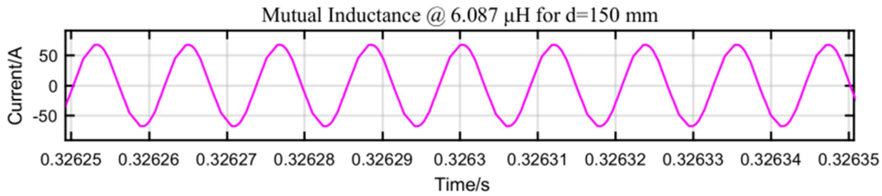

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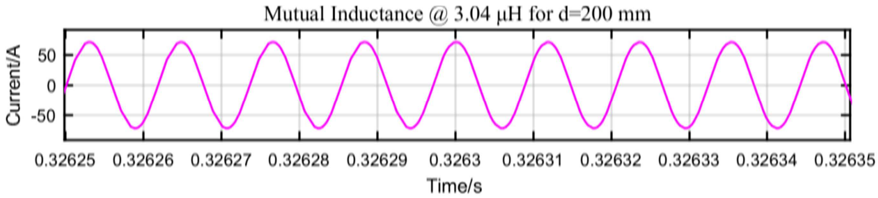


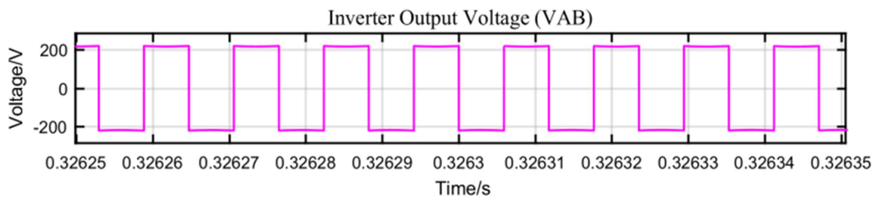
(e)

Figure 9. *Primary current P/S resonance circuit (a) M = 36.52 μH; (b) M = 14.6 μH; (c) M = 9.73 μH; (d) M = 6.087 μH: (e) M = 3.04 μH.*

4.2. Stresses on the Components

For the same Power level of both S/S and P/S resonant circuit, voltage and current stress on the primary and the secondary of the capacitors that is C_1 and C_2 in P/S resonant circuit is less compared to that in the S/S resonant circuit. Both secondary sides same but the primary side is different see Figure10.

From Figure 10 it can be found that voltage stress on primary side of capacitance and coil is very high. It is almost six times inverter output voltage. It can also be found that total primary current is transferred through inverter switches only.



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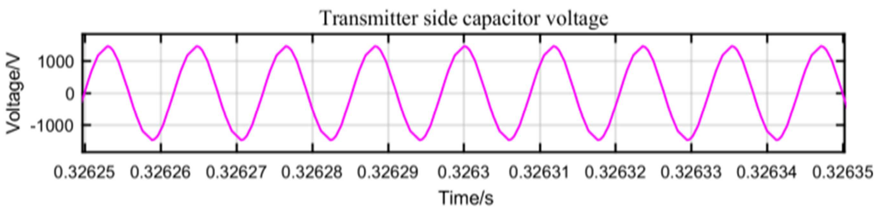

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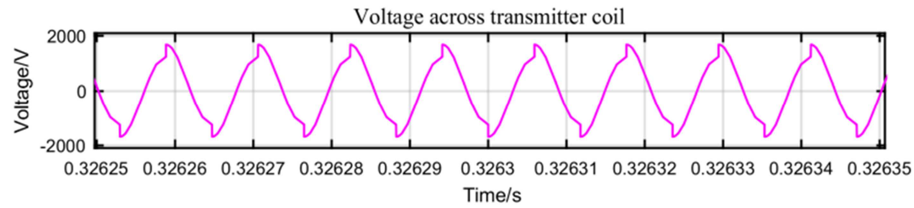

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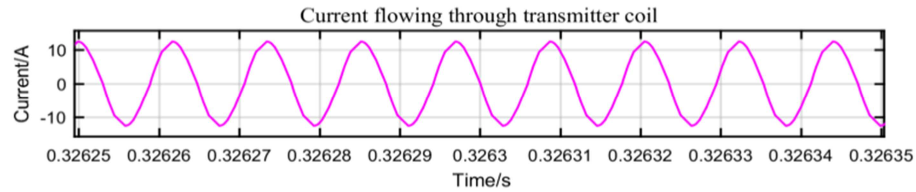
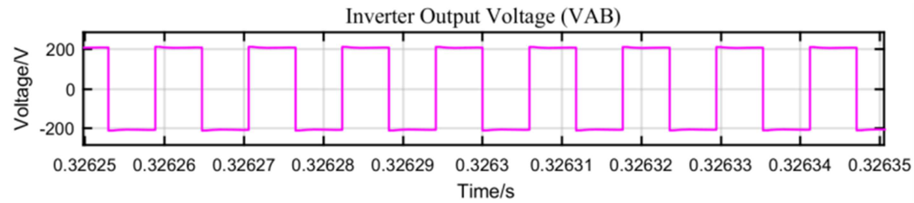


(d)

Figure 10. *For S/S resonance circuit: (a) Inverter output voltage (V_{AB}) (b) capacitor voltage (Vc1) (c) primary coil voltage (Vt) (d) primary coil current (It).*



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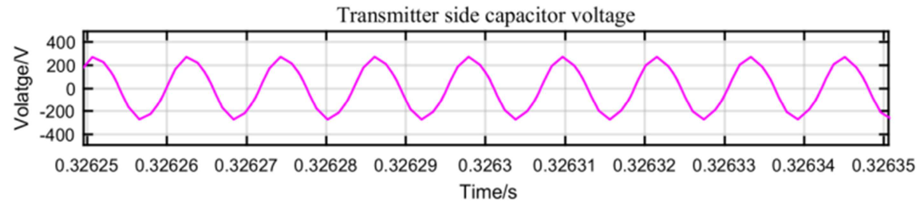

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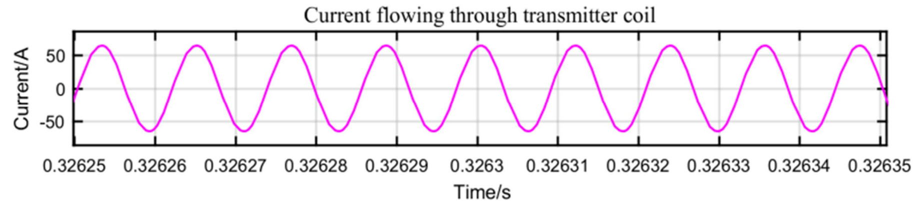

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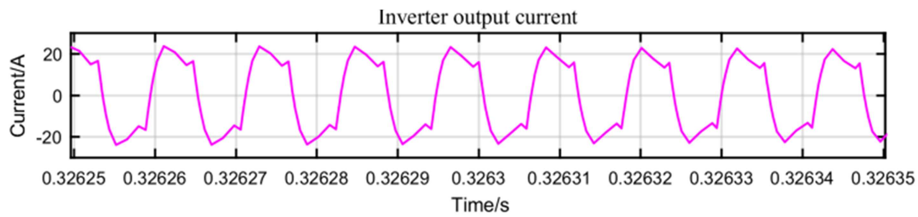

(d)

Figure 11. *P/S resonance circuit: (a) Inverter output voltage (V_{AB}) (b) capacitor voltage (Vc1) (c) primary coil current (It) (d) Inverter output current.*

4.3. Comparison of Efficiency and Transferred Power

For the study of efficiency the mutual inductance is the play key role. The efficiency of the S/S and P/S resonant circuit the mutual inductances high, efficiency also higher the value, even for a low coupling coefficient as shown in Figure 12, where the efficiency increases as the mutual inductance increases.

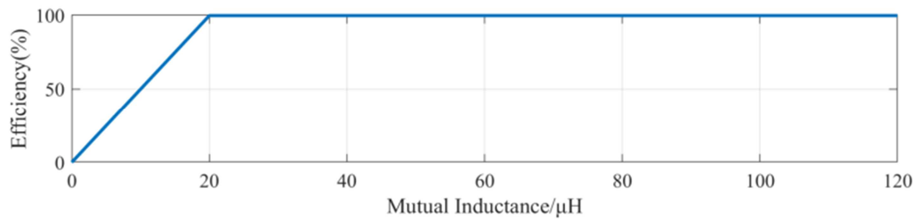

Figure 12. *Effect of misalignment on the efficiency.*

If the resonant capacitor is designed to make the primary and secondary sides both at the resonant state with a certain frequency, which means $Z_1=R_1$, $Z_2=R_2+R_{ac}$, the maximum efficiency of S/S compensation is obtained from Figure 2. $wL_1=\frac{1}{wC_1}$ and $wL_2=\frac{1}{wC_2}$.

$$\eta = \frac{R_{ac}}{(R_2+R_{ac})\left[1+\frac{R_1(R_{ac}+R_2)}{(wM)^2}\right]} \tag{16}$$

Also the maximum efficiency of P/S compensation is obtained from Figure5. $wL_1=\frac{1}{wC_1}$ and $wL_2=\frac{1}{wC_2}$

$$\eta = \frac{R_{ac}}{(R_2+R_{ac})\left[1+\frac{R_1(R_{ac}+R_2)}{(wM12)^2}\right]} \tag{17}$$

The maximum efficiency at resonance in both equations is almost the same, only the mutual inductance is a different value.

Also, see the resonance circuit parameters mentioned in Figure2 and Figure4 were computed by MATLAB from the equation defined in section-I. The calculated parameters like (L_1, L_2, and M) for each distance were inserted into MATLAB to compute their corresponding resonance parameters of each resonance circuit at 85 kHz. Then all parameters were inserted into MATLAB, and the dc-dc efficiency ($\eta=P_0/P_{in}$) is determined. The result is illustrated in Figure10.

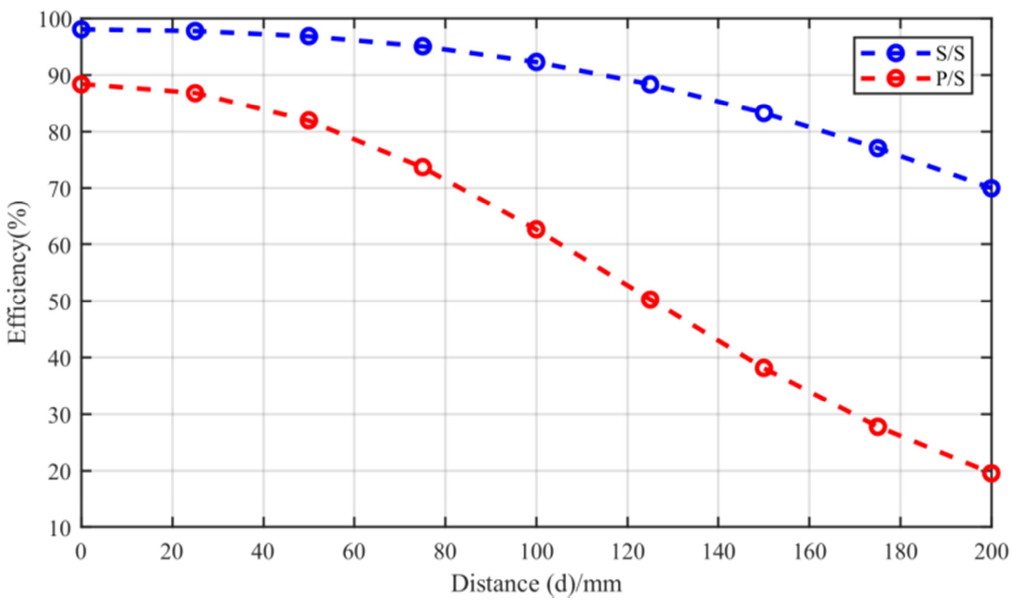

Figure 13. *Effect of d on the efficiency.*

Figure 13.Shows the effect of air-gap on the efficiency of the resonance network. In the S/S and P/S resonance circuit, efficiency decreases as distance d increases. For lower distance, higher the efficiency in SS compensation, but P/S compensation efficiency is low, so S/S compensation is best suitable for small and medium-range vehicles.

$$\eta_{\max} = \frac{k^2 Q_1 Q_2}{\left(1+\sqrt{1+k^2 Q_1 Q_2}\right)} \tag{18}$$

Equation 18, shows that Q1 is different for S/S and P/S compensation but Q2 is the same. Substitute the values found in Table 1 in the equation, and then we get Figure 10.

Maximum power transfer efficiency depends on Quality factors i.e

$Q_1=\frac{w_r L}{R_1}=\frac{2\pi f L}{R_1}$ (or) $\frac{1}{w_r RC}$ and $Q_2=\frac{w_r L}{R_2+R_{ac}}$coupling coefficient $k=\frac{M}{\sqrt{L_1 L_2}}$; where L_1=Transmitter side Inductance and L_2=Receiver side Inductance.

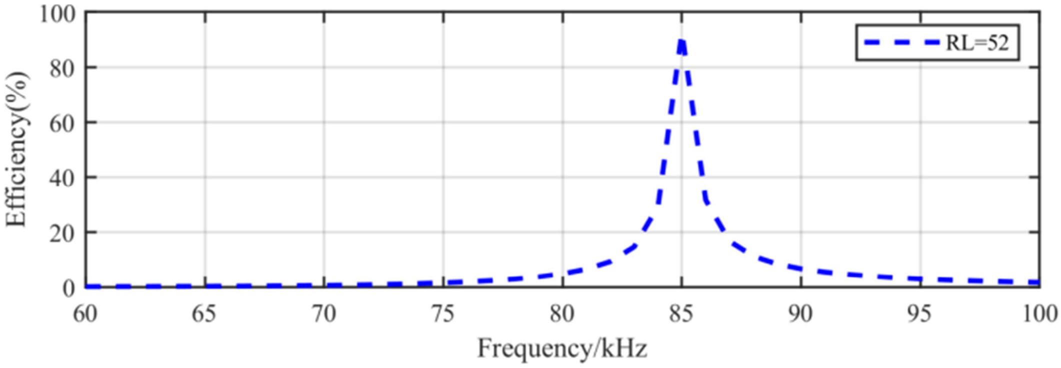

Figure 14. *Effect of frequency on the efficiency.*

As can see from Figure 14, where the efficiency decreases as the frequency increase after resonance. Also, see the frequency vs efficiency at resonance in Figure 15. It can be observed that the frequency increases both S/S and P/S resonance circuits are raising characteristics, but at 85 kHz, the efficiency of S/S resonance circuit is much higher than the P/S resonance circuit.

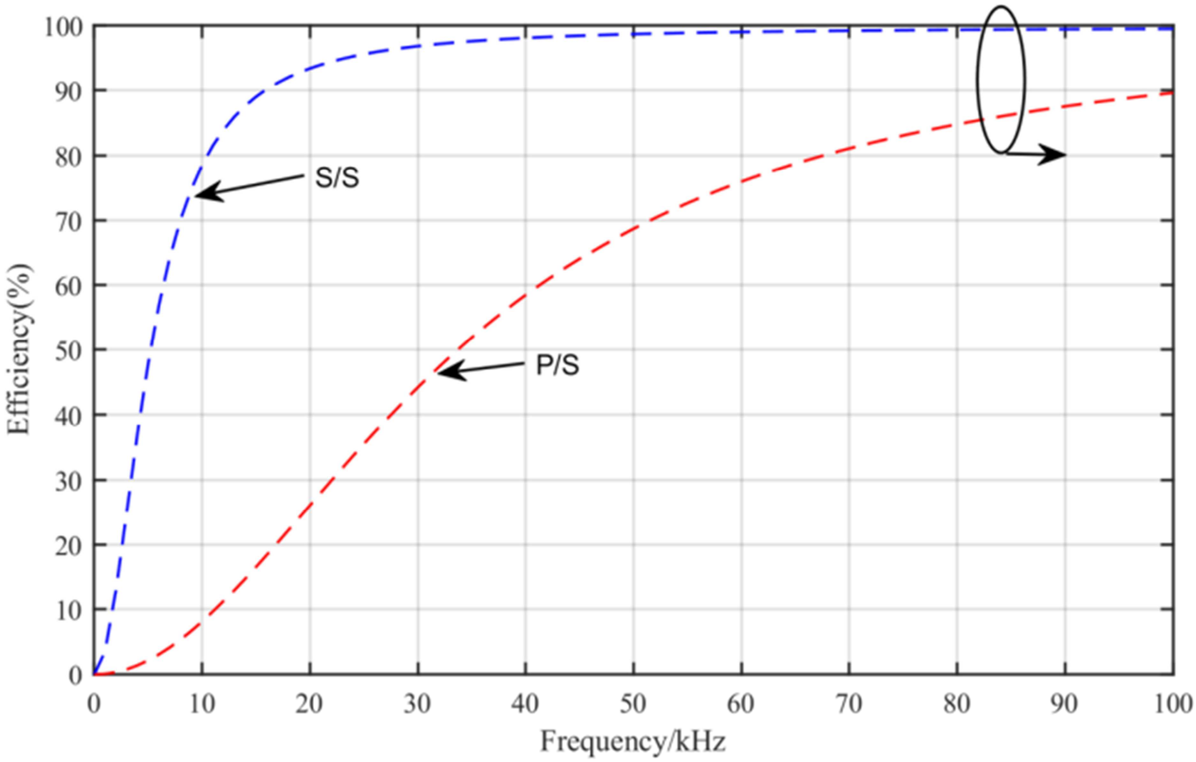

Figure 15. *Effect of frequency on the efficiency at resonance.*

Input impedance affects both the efficiency and transfer power, so we substitute all the parameters in the efficiency and transferred power equation (19, 20, 21, 22), Figure 16 shows the transferred power and efficiencies with respect to coupling coefficients for both circuits at their respective resonant frequencies. Higher input impedance reduces the input power to the coil which could result in lower transferred power. Also, it can be observed that the maximum power transfer points for the two circuits can be

$$P_t = I_2^2 R_{ac} = \left[\frac{wMV_{AB}}{R_1 \left(R_2 + R_{ac} \right) + \left(wM \right)^2} \right]^2 R_{ac} \tag{19}$$

$$P_t = I_2^2 R_{ac} = \left[\frac{wM_{12}V_{AB}}{R_1 \left(R_2 + R_{ac} \right) + \left(wM_{12} \right)^2} \right]^2 R_{ac} \tag{20}$$

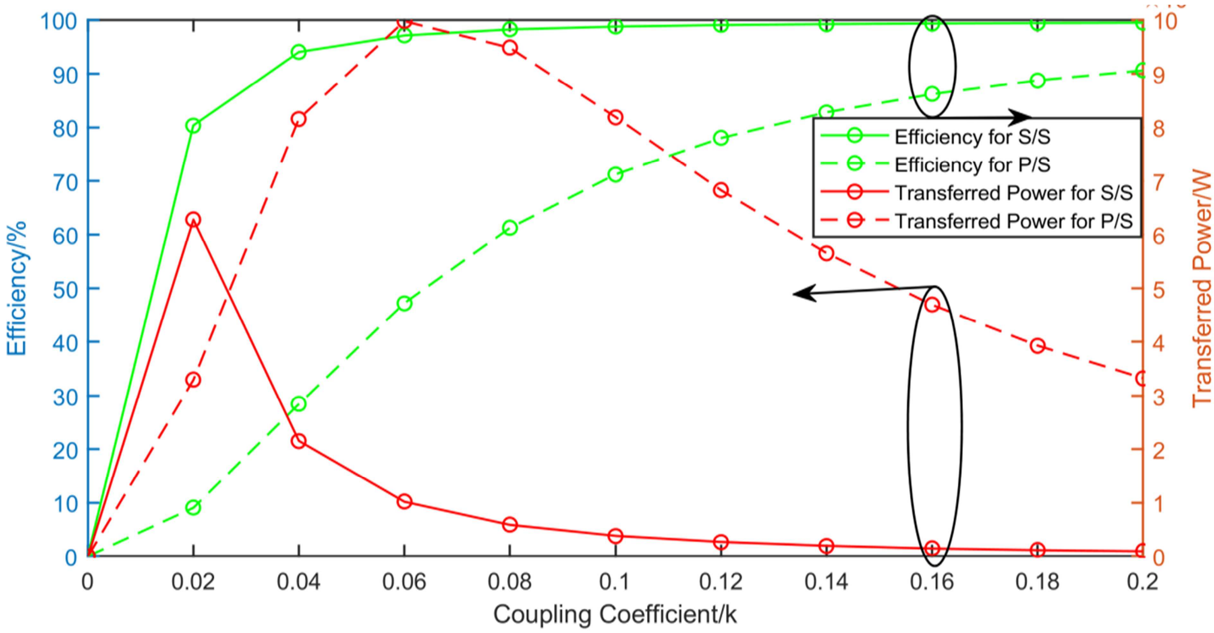

Figure 16. *Transferred powers and efficiencies with respect tocoupling coefficient (k) from 0.001 to 0.2.*

From the above comparison and analysis, it can be noticed that the transferred power of the P/S resonance circuit is better than that of the S/S resonance circuit. The voltage stresses of the P/S resonance circuit are lower than that of the S/S resonance circuit, but the current stress is vice-versa. But there is an advantage in S/S resonance circuit is lower distance, and the efficiency is high.

4.4. Impedance Frequency Response

The analyses of series/series compensation and parallel/series compensation circuit are performed using the simulation parameters from Table 1 and equations (21) and (22) respectively [16, 17].

$$Z_{inPP} = \frac{1}{R_1 + jwL_1 + \dfrac{w^2M^2}{R_1 + R_2 + j\left(wL_2 - \dfrac{1}{wC_2}\right)} + jwC_1} \quad (21)$$

$$Z_{inSP} = \left(R_1 + j\left(wL_1 - \frac{1}{wC_1}\right)\right) + \frac{w^2M^2}{R_1 + R_2 + j\left(wL_2 - \dfrac{1}{wC_2}\right)} \quad (22)$$

Figure 17 shows the frequency of the input impedances of the series compensated and Parallel compensated circuits with respect to the coupling coefficient.

5. Coupling Factor, Air Gap and Mutual Inductance

From Figure 18. It can be observed that distance increases between the coil, coupling factor and mutual inductance decreases. In case of of P/S compensation circuit same coupling coefficient at 0.16 for 120-mm distance, very small mutual inductance compare to S/S compensation circuit, so lesser mutual inductance larger power transfer capability.

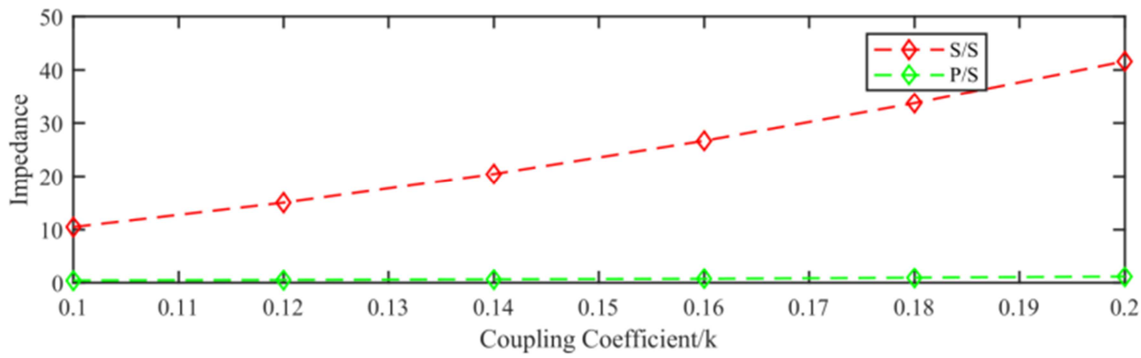

Figure 17. *Input impedances for series and Parallel resonance circuits with respect to coupling coefficient (k).*

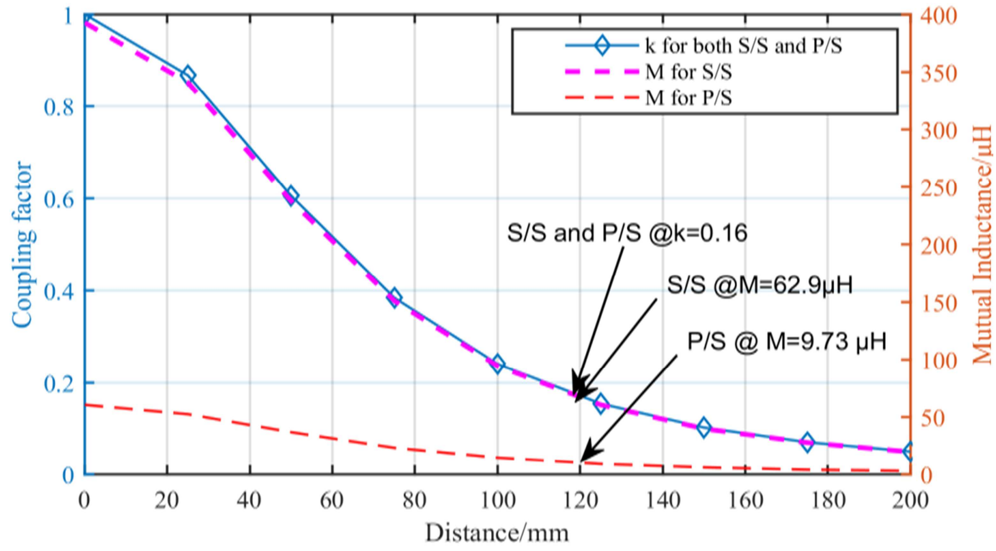

Figure 18. *Air gap Vs. Coupling coefficient and mutual inductance.*

6. Conclusion and Future Scope

Both resonance circuits has been proposed for IWPT systems. The variation in mutual inductance (misalignments), distance, efficiency and stresses affects the electrical characteristics of these two resonant circuits. The validation of calculated circuit components is checked through MATLAB Simulink, it is also noticed that the calculated electrical components are almost equal for the required magnitude of power level, and also seen in simulation, voltage and current stresses on coils, capacitors, and switches are done also Impedance effects on transferred power and efficiency. It is noticed that voltage stress on capacitor and coil in the S/S resonance circuit is high compared to P/S resonance circuit. Also observed is that current stress on capacitors and coil is high in P/S resonance circuit.

The future extension is possible to control the output power by using power electronic switches on the receiver side and maintain either constant voltage (CV) or constant current (CC) for Voltage Fed Converter (VFD) like S/S Compensator or Current Fed Converter (CFC) like P/S Compensator. We are developing small- scale wireless power transmission system in EV Battery charging in the laboratory.

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