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A Study on Performances of Different Compensation Topologies for Loosely Coupled Inductive Power Transfer System

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***Abstract*— This paper investigates the performance of different compensation topologies of loosely coupled inductive power transfer system at 1MHz using Class E Amplifier. The capacitor compensation technique is regularly used in inductive power transfer to solve the problem of large leakage inductance and get the maximum power transfer when reach the resonant inductive coupling. In this paper, the analysis of efficiency of power transfer for four compensation topologies will be considered, which are primary series-secondary series (SS), primary series-secondary parallel (SP), primary parallel-secondary series (PS) and primary parallel-secondary parallel (PP). The performance of such topologies is evaluated through the simulation results.**

***Index Terms*— Loosely Coupled Inductive Power Transfer, Compensation Capacitor, Class E Amplifier**

I. INTRODUCTION

Throughout all the technological advances in recent years, most electric vehicles [1], medical implants [2], and mobile phones [3] have been continuing to grow and develop by making them more reliable, convenient, effective and comprehensive. In order to achieve them, wireless power transfer has been introduced and become popular among researchers. The first idea of transmitting power without direct contact has been pioneered by Tesla which is more than century old [4]. Hence, in this context, the wireless power transfer or also known as a contactless power transfer responsible to transmit electrical energy from one part to another part (at a small distance range) without direct wire connection. This wireless power transfer can be realized by few techniques which are inductive power transfer (IPT), capacitive power transfer (CPT) and microwave power transfer [5]. In this paper, the IPT is considered due to its high power transfer.

The inductive power transfer is based on the Ampere's Law and Faraday's Law which is the changing of magnetic field that is created due to the alternating current through the primary side that induced a voltage onto the secondary side [6]. There are two types of inductive power transfer systems either closely coupled system like transformer or loosely coupled system. The closely coupled system is the conventional method of inductive power transfer that has been widely used since decades ago because it offers a perfect coupling factor and very efficient transmission energy with the physical contact. However, loosely coupled system is a non-contact power transfer with a small gap between primary and secondary side that is suitable to be used for moving objects especially charging system [7]. Therefore, this type of IPT systems has gained more attention among researchers. However, the main problem of loosely coupled system is poor coupling of the separable transformer [8]. In addition, there is a large leakage inductance in the contactless transformer [9]. To overcome the aforementioned problems, an external capacitor is proposed to be added at the primary or secondary side [8] [9], this significantly helps to improve its performance. The external capacitor is commonly known as a capacitor compensation which can be connected in series or parallel at primary or secondary side to achieve resonance conditions [10]. Therefore, this paper aims to investigate the performance of different compensation topologies of the loosely coupled IPT system at 1MHz using Class E Amplifier.

II. IPT SYSTEM MODEL

Loosely coupled IPT system, commonly, consists of two coils that are transmitter, T_x (primary side) and a receiver, R_x (secondary side) and separated by an air gap [10]. Since loosely coupled is a contactless transformer with a weak of mutual coupling, so, it must work at high frequency [11][12]. The IPT system that is considered in this paper is shown in Fig. 1 where the AC source is generated by Class E Amplifier. As we know, in IPT system, the mutual coupling effect exists when the primary and secondary inductors are interdependent of each other, see Fig. 1. Due to this behavior, the dependent voltage sources, V_{12} exists at primary side which is induced by I_2 where

$$V_{12} = -j\omega M I_2 \tag{1}$$

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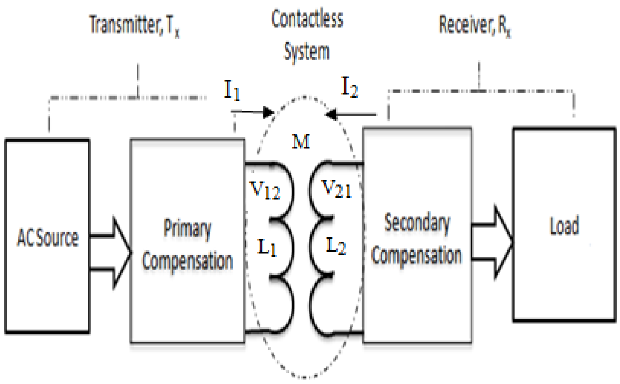


Fig. 1. General Block Diagram of IPT System

Then, while dependent voltage sources, V_{21} is induced by I_1 as shown in the following equation,

$$V_{21} = j\omega M I_1 \tag{2}$$

The mutual inductance coupling can be related to their self inductance by coupling coefficient, *k* as follows:

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{3}$$

where, M is the mutual inductance between primary coil, L_1 and secondary coil, L_2. The coupling coefficient of the loosely coupled IPT system is normally less than one. A low coupling between coils needs a high current in the primary side for transferring the necessary energy [2].

A. Class E Power Amplifier

The IPT system needs a high frequency to generate a magnetic field, typically 10k-10MHz. To achieve this, the power amplifier is commonly used. To date, there are several classes of power amplifiers available such as Class A, Class AB, Class C, Class D and Class E. Among these, Class D and Class E amplifiers are the mostly used at high frequency because of their ability to provide a great efficiency at such frequency [13]. In this paper, the Class E Amplifier is used in the IPT system due to its simplicity [14] and 100% theoretical efficiency [2]. The topology of Class E Amplifier is shown in Fig. 2.

Based on the Fig. 2, the MOSFET operates as an on/off switch of Class E Amplifier. Meanwhile, L_{choke} acts as current source when the switch is off that is to limit the input current to be a constant current. The shunt capacitor across the switch is to shape drain voltage and current waveform during on to off transition and a net series load inductance offer the required phase shift for the fundamental wave and behave as a harmonic open circuit [14]. Current and voltage in the inductor, L and capacitor, C_{series} branch are nearly sinusoidal at the resonant frequency of the tank circuit. This condition is only held for high power factor, Q coils [2].

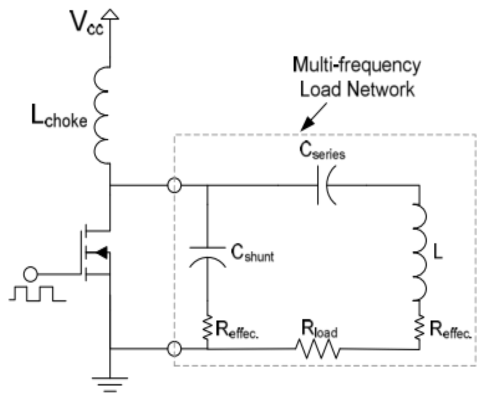


Fig. 2. Class E Topology [2]

The current drawn from the DC supply, V_{cc} can be derived as follows:

$$I_o = \frac{P_{load}}{V_{cc}} \tag{4}$$

To note here that P_{load} is stand for the power at 50Ω load resistance. Then, the shunt capacitor, C_{shunt} can be calculated as follows:

$$C_{shunt} = \frac{I_o}{2\pi^2 f V_{cc}} \tag{5}$$

where *f* is the operating frequency. The required load resistance, R can be calculated as follows:

$$R = \frac{8V_{cc}^2}{(\pi^2+4)P_{load}} \tag{6}$$

Furthermore, by assuming the quality factor, Q, the series capacitor, C_{series} and series resonant inductor, L_{res} can be computed as follows:

$$C_{series} = \frac{1}{2\pi f Q R} \tag{7}$$

$$L_{res} = \frac{QR}{2\pi f} \tag{8}$$

The excess series inductance, L_{ext} is found from

$$L_{ext} = \frac{1.153R}{2\pi f} \tag{9}$$

Thus, the value of series inductor, L is just the sum of resonant inductor, L_{res} and series loading inductor, L_{ext} [14], where

$$L = L_{res} + L_{ext} \tag{10}$$

B. Capacitor Compensation

The technique of capacitor compensation is not a new method to overcome the problem of leakage inductance in IPT system. It is regularly used to achieve the resonant inductive coupling.

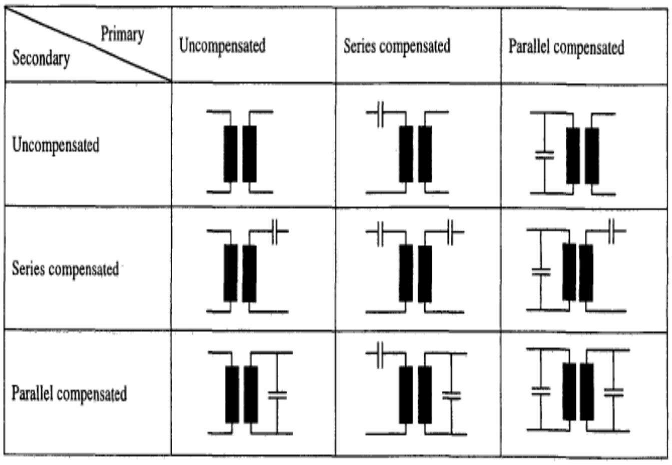
Basically, the resonant inductive coupling is essential in an IPT system to ensure the maximum power transfer. This is happened when all the reactive components cancel out each other, which is the inductive and capacitive reactance are equal in magnitude and in phase at the resonant frequency, ω_o. Normally, the primary and secondary resonant frequencies are identical as shown in the following equation [10],

$$\omega_o = \frac{1}{\sqrt{L_1 C_1}} = \frac{1}{\sqrt{L_2 C_2}} \tag{11}$$

where L_1 is primary inductance, C_1 is primary capacitance, L_2 is secondary inductance, and C_2 is secondary capacitance.

At present, there are various topologies of capacitor compensation available; see Table 1 and out of that topologies, four topologies will be investigated in this paper, which are SS, SP, PS and PP. The reason of choosing such topologies is because they are widely used in the framework of the IPT system at various frequency levels.

TABLE I. NINE COMPENSATION TOPOLOGIES [7]



Due to the fact that every topology has their own strength and weaknesses, in this paper, we attempt to investigate the performance of these different topologies in term of the output power and efficiency of power transfer of loosely coupled IPT systems at 1 MHz frequency using Class E Amplifier. The detail discussion regarding this can be found in the following text.

III. CIRCUIT DESIGN

In this section, the design of Class E Power Amplifier circuit is provided first. Then, the IPT system is designed based on the mentioned topologies with Class E Power Amplifier Circuit.

C. Class E Power Amplifier Circuit

The Class E Amplifier circuit designed is shown in Fig. 3. The function of Class E Amplifier is to generate a very high frequency, 1 MHz in our case here, for IPT system. The reason for selecting this type of power amplifier circuit has been provided in Section II (A), hence omitted here. The design of this Class E Amplifier is based on the parameters that are shown in Table II.

TABLE II. CLASS E AMPLIFER PARAMETERS

Parameters	Values
Operating Frequency	1MHz
Rated Power	25W
Quality Factor, Q	10
DC Voltage	25V
RF Choke Inductor, L_{choke}	100µH
Shunt Capacitor, C_{shunt}	2.03nF
Series Capacitor, C_{series}	1.11nF
Series Inductance, L	25.57µH
R_{load}	50Ω

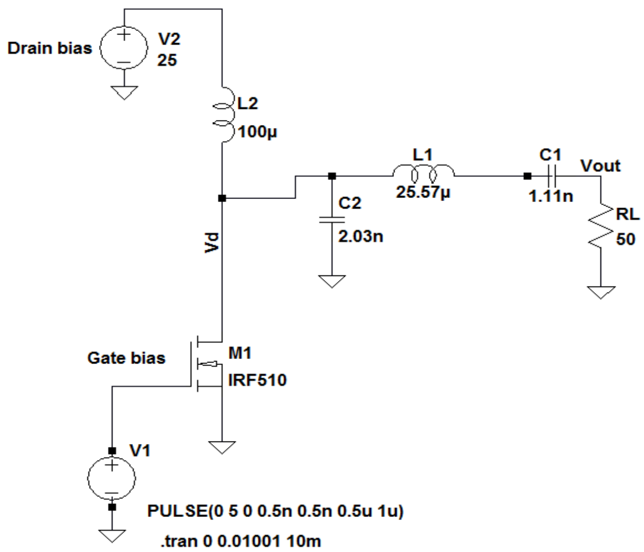


Fig. 3. Class E Amplifier Circuit at 1MHz

D. Loosely Coupled IPT with Class E Amplifier

Now, using the proposed Class E Amplifier, the loosely coupled IPT system is designed, see Fig. 4 (for example of SS topology). Then, the compensation circuits are included. For the SS topology, the capacitor is located in series of inductive coupling for both primary and secondary winding. The parameters that are used are provided in the Table III. The voltage and current across the load are interested to be analyzed.

Fig. 5 illustrates the SP topology of the loosely coupled IPT system with Class E Amplifier. Notice that, for this topology the capacitor at primary side is placed in series connection while the capacitor at secondary side is in parallel connection of inductive coupling.

TABLE III. LOOSELY COUPLED IPT SYSTEM SPECIFICATION

Parameters	Values
Operating Frequency	1MHz
DC Voltage	25V
Coupling coefficient	0.95
Primary coil resistance	1.2Ω
Primary coil inductance	30µH
Secondary coil resistance	0.5Ω
Primary coil inductance	30µH
Capacitor compensation	844nF

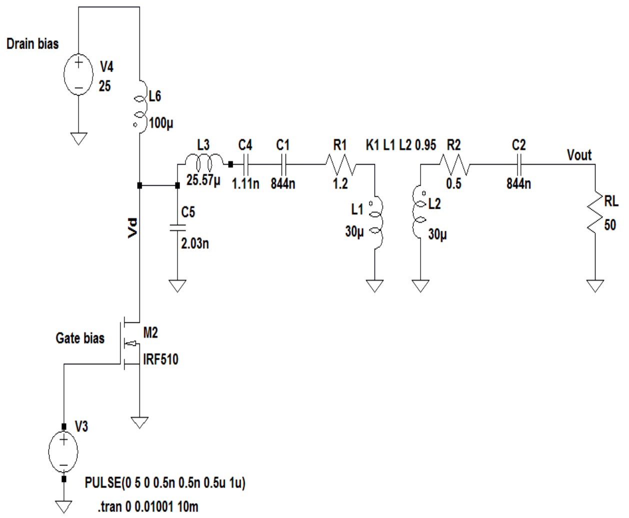


Fig. 4. SS Topology of Loosely Coupled IPT System

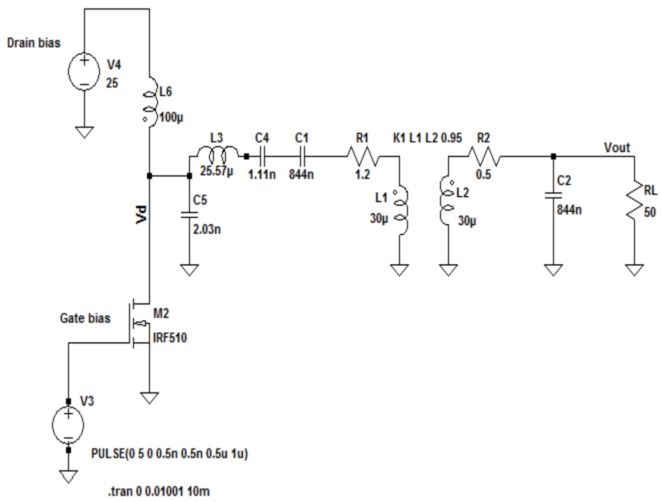


Fig. 5. SP Topology of Loosely Coupled IPT System

Next, Fig. 6 illustrates the PS topology of the loosely coupled IPT system with Class E Amplifier. For this topology, the capacitor at primary side is located in parallel connection while the capacitor at secondary side is placed in series connection of inductive coupling.

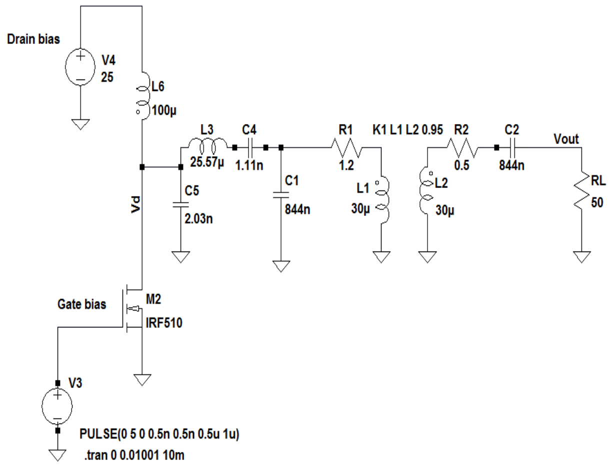


Fig. 6. PS Topology of Loosely Coupled IPT System

On the other hand, Fig. 7 illustrates the PP topology of the loosely coupled IPT system with Class E Amplifier. The capacitor at primary side is in parallel connection while the capacitor at secondary side is in parallel connection of inductive coupling.

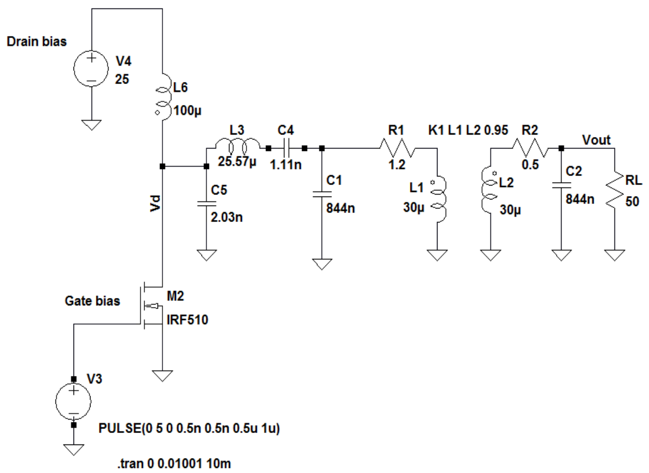


Fig.7. PP Topology of Loosely Coupled IPT System

Using the presented four topologies of compensation techniques, the efficiency of every circuit will be given next, and the comparison among them will be provided. Through this, the best compensation technique to be used for 1 MHz frequency can be suggested accordingly.

IV. RESULTS AND DISCUSSION

This section discusses the obtained results based on the provided circuits shown in the previous section. The analysis of efficiency of every compensation technique is also given in this section.

We begin this section by providing the Class E Amplifier output (see Fig. 3 for the circuit) – see Fig. 8. The waveform on the upper graph depicts the drain to source voltage, V_{DS} of the IRF510 MOSFET, whereas the lower graph shows the drain current.

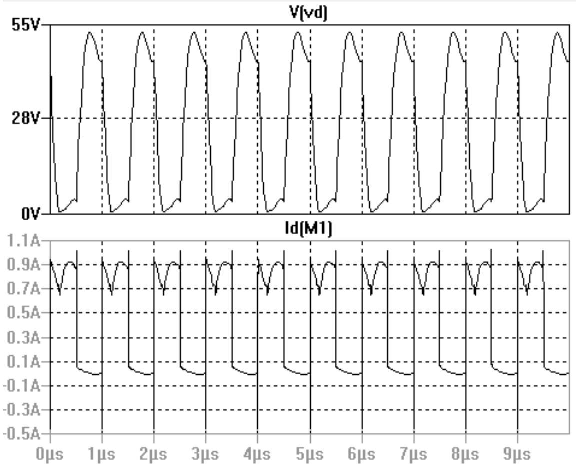


Fig. 8. Output Waveform of Class E Amplifier

Based on Fig. 8, the rated power, *P* for Class E Amplifier when the load resistance, R_L is 50Ω is 26W has been produced from Class E Amplifier at a frequency of 1MHz and acting as a power source for the loosely coupled IPT system. Furthermore, Fig. 9 shows the waveform of output voltage and the current at 50Ω load resistance, R_L for SS topology of the loosely coupled IPT system. It can be observed that the maximum output voltage is 24V and maximum output current is 520mA. Therefore, the output power, P_o is 6.24W.

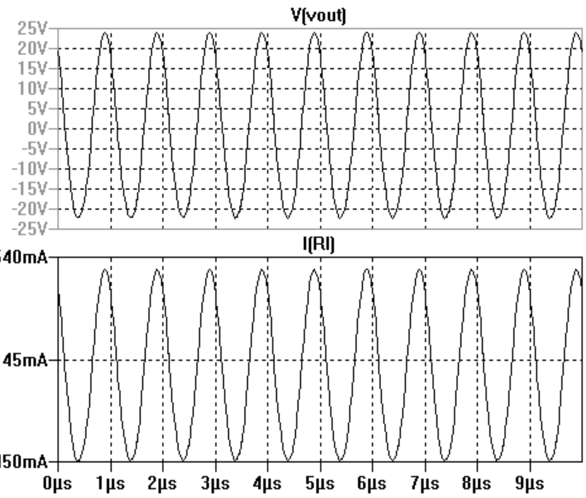


Fig. 9. Output Waveform of SS Topology of Loosely Coupled IPT System

Fig.10 depicts the output waveform of the SP topology of the loosely coupled IPT system, where the upper waveform shows the output voltage with 180mV and the current at 50Ω load resistance is 3.3mA at lower graph. Therefore, the output power, P_o is 0.30mW. The PS and PP topology of the loosely coupled IPT system are respectively illustrated in Fig. 11 and Fig. 12. For PS topology, the output voltage at 50Ω load resistance is 149mV and the load current is 2.8mA. This significantly provides an output power, P_o is 0.21mW. Meanwhile, for PP topology, the output at 50Ω load resistance is 1.6mV and the load current is 34µA. This produces an output power, P_o is 27.20nW.

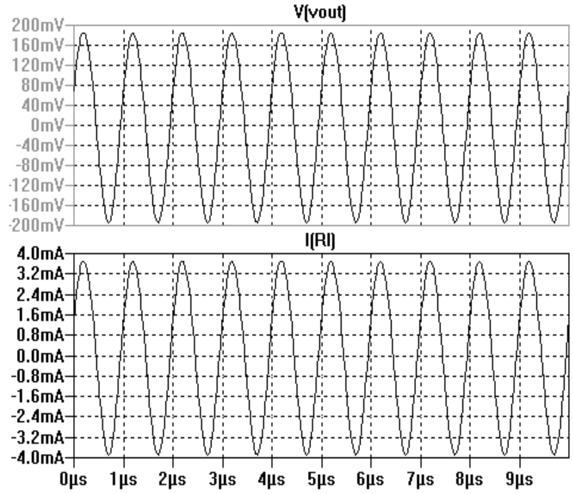


Fig.10. Output Waveform of SP Topology of Loosely Coupled IPT System

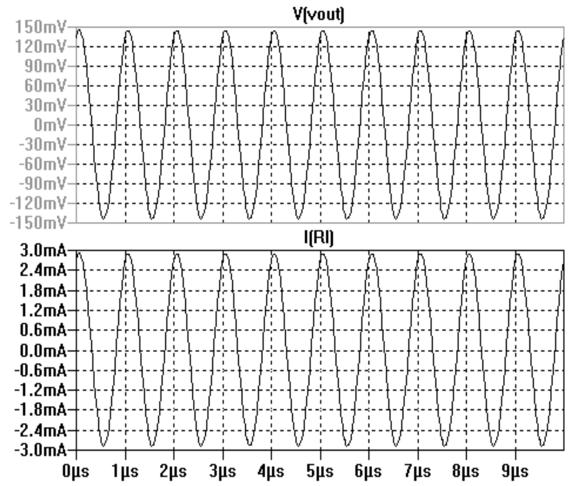


Fig. 11. Output Waveform of PS Topology of Loosely Coupled IPT System

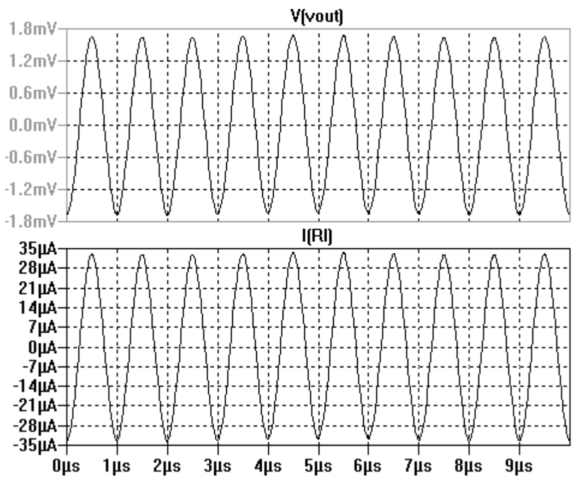


Fig. 12. Output Waveform of PP Topology of Loosely Coupled IPT System

From previous analysis we can summarize that for a different topology, the different output voltage and the current flow through the 50Ω load resistance is obtained. Moreover, we provide a more analysis on the circuit efficiency and it is provided in Table IV.

TABLE IV. SIMULATION RESULTS OF DIFFERENT TOPOLOGIES

TOPOLOGIES	SS	SP	PS	PP
Output Power at 50Ω, P_o (W)	6.24	0.30m	0.21m	27.20n
Input Power, P_{in} (W)	8.88	3.63	13.9	13.9
Efficiency, η (%)	70.27	8.26 x 10^{-3}	1.51 x 10^{-3}	12.08 x 10^{-6}

From Table IV, we can conclude that the SS topology of the loosely coupled IPT system has the highest maximum output power compared to other topologies with 6.24W. Then, the efficiency for SP, PS, and PP topologies is lowest except the SS topology is better with 70.27%. Therefore, the different topologies have been shown their own performance base on the simulation results.

CONCLUSION

The SS, SP, PS and PP topology of capacitor compensation techniques for loosely coupled IPT systems with Class E Amplifier at 1 MHz have been analyzed in this paper. The comparison among different topologies has been provided and it has been shown that the SS topology of the loosely coupled IPT system provides the best efficiency at 1 MHz frequency. Therefore, it is recommended to use this topology when IPT systems are driven at a 1MHz frequency from a Class E Amplifier. The future direction of the research is to implement the compensation topologies in IPT system practically in order to see the effect of the frequency variation. Also, the controller method should be investigated to maximize the output power when the load is varied.

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