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Simulation Study of Class E and Receiver Circuit for Inductive Power Transfer

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Abstract

This paper presents a circuit simulation of the transmitter and receiver side for an Inductive Power Transfer (IPT)--based application. A key issue of the IPT system is to produce a higher output power at the receiver side due to several losses such as switching losses, gap losses, and parasitic losses. To tackle the issue of switching losses at the transmitter side, a Class E circuit was proposed to energize the transmitter coil efficiently. Specifically, the IPT system's performance worked at 1MHz operating frequency and 9V DC supply voltage. In contrast, the rectifier and buck-boost circuit were used at the receiver side of the IPT system. The proposed circuit is validated through LTspice software. The results revealed that the Class E circuit could achieve an efficiency of 90% at the transmitter side, while the output voltage at the receiver is about 9 $V_{p\text{-}p}$, which is much lower than the voltage at the transmitter side. Thus, the proposed circuit is significant for portable IPT-based charging circuit applications without hassle wire.

1. Introduction

Inductive Power Transfer (IPT) is one of the Wireless Power Transfer (WPT) systems. Generally, it can be applied to portable devices such as smartphones and electronic devices [1]. Fig. 1 shows a general block diagram of the IPT system, which consists of the transmitter and receiver side. The inductive power transfer (IPT) method is an emerging charging technology that has some advantages over traditional plug-in systems. For example, it is safer, more convenient, and efficient, leading to its widespread acceptance [2]. However, the main drawback of the IPT system is suffering several losses such as switching losses, gap losses, and parasitic losses. After that, switching losses occur during the on-off cycles of power electronic switches in the IPT system. When a switch turns on or off, there's a brief overlap of voltage and current, which results in energy being dissipated as heat. This is particularly significant at higher frequencies, which are common in IPT systems to enable efficient power transfer [3]. Then, gap losses refer to the energy losses associated with the distance (or gap) between the transmitter and receiver coils. The efficiency of power transfer in IPT systems is highly dependent on the magnetic coupling between these coils. A larger gap can lead to a decrease in the coupling coefficient, which in turn increases the leakage inductance and reduces the system's efficiency. To combat this, IPT systems are designed with compensation networks and coil geometries that can tolerate some degree of gap variation without significant efficiency loss [4].

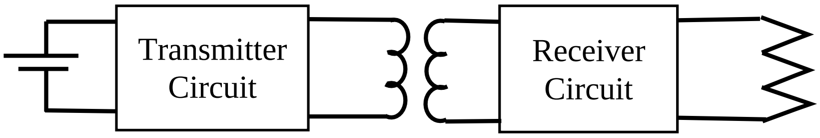


Fig. 1 *General Block Diagram of IPT System*

Previously, a few researchers proposed different transmitter circuits based on applications. For example, (Rahman & Saat, 2016) used the full circuit of a Class E power amplifier which has been built by using MATLAB Simulink [5]. Next, (Pellitteri, 2020) used a bridge circuit inverter to drive inductive links for electrical applications [6]. Lastly, (Wiesner, 2013) used a buck converter is utilized as a DC-DC converter for the charge controller [7].

On the other hand, on the receiver side, most researchers used adding series or parallel capacitors to coupled coils to increase the power [8]. Due to this, it motivated us to design and investigate Class E and receiver circuits for inductive power transfer.

The remainder of this paper is as follows: Section 2 describes project methodology as an overall system in brief. The third section presents results and discussion, which consists of project performance evaluation by doing functionality tests and discussing the results. Lastly, Section 5 concludes this work with the recommendation.

2. Methodology

Fig. 2 shows a block diagram of the IPT system. It illustrates an inductive power transfer system utilizing a Class E circuit for transmission and a rectifier circuit with a buck-boost converter for increasing the output power for the load.

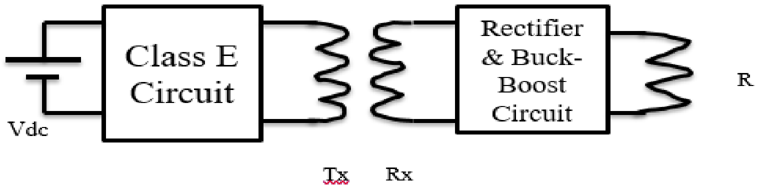


Fig. 2 *Block Diagram of the proposed IPT System*

The Class E circuit is a high-efficiency power amplifier, which converts DC voltage (Vdc) into a high-frequency AC signal [9]. It is primarily used to energize the transmitter coil (Tx). Then, this coil generates a magnetic field that transfers power wirelessly to the receiver coil (Rx), which captures the magnetic field and converts it back into an AC signal. The rectifier then converts this AC signal into a DC signal, as most electronic devices can operate on DC power. Following the rectifier, the buck-boost circuit regulates the DC voltage to the desired level, either stepping it up (boost) or down (buck) to suit the load. This ensures the load receives a stable and appropriate voltage, essential for its proper functioning.

2.1 Theoretical Calculation of Proposed Circuit

2.2.1 Class E circuit

Class E circuit is used at the transmitter side of the IPT system because the complexity is not high, it can adapt to low losses of switching and the benefits of WPT itself to deliver high power.

The current is drawn from the circuit power supply:

$$Ia = \frac{P\ load}{Vcc} \quad (1)$$

The R load is calculated by:

$$R = \frac{Vcc}{Io} \tag{2}$$

Hence, the shunt capacitance is:

$$C = \frac{0.197}{\omega RL} \tag{3}$$

While the series capacitance is:

$$C = \frac{0.1062}{\omega RL} \tag{4}$$

The inductor value is:

$$L = \frac{1.153Rload}{\omega} \tag{5}$$

Parallel inductor:

$$L = \frac{QRload}{\omega} \tag{6}$$

The formula for shunt capacitance and series capacitance, the inverse relationship between capacitance C and the product of angular frequency $\boldsymbol{\omega}$, resistance R, and inductive L. Here, $\boldsymbol{\omega}$ represents the angular frequency, measured in radians per second, and is related to the frequency f by ω=2πf. Resistance R, measured in ohms (Ω), quantifies how much a material opposes the flow of electric current, while inductance L, measured in henrys (H), indicates a conductor's tendency to oppose changes in the current flowing through it. Next, the inductor highlights the relationship between inductance L, quality factor Q, load resistance Rload, and angular frequency ω. Inductance, measured in Henry H, is the ability of a conductor to store energy in a magnetic field. The quality factor Q indicates the efficiency of the resonator, with higher Q values representing lower energy loss. Load resistance Rload is the resistance of the load connected to the circuit, measured in ohms (Ω). Angular frequency ω, related to the frequency by ω=2πf, measures the rate of change of the phase of a sinusoidal waveform.

2.2.2 Rectifier and Buck-boost circuit

A medium-voltage high-power dual single-phase buck-boost converter, which is an improved version of the single buck-boost converters discussed. It consists of two cascaded full-wave rectifier bridges and a series-commutable switch. A switch is used to control the output DC voltage by modulating the inductor current I_L. Turning on the switch boosts the energy stored in the DC inductor L_{dc}, and this stored energy supplies the load when the switch is off. The AC filter connected to the transformer's primary and secondary windings is turned to remove low-order harmonic currents not eliminated by the phase shift transformer and those associated with the switching frequency components and their sidebands.

The average output voltage of each bridge rectifier is:

$$-\frac{3\sqrt{3}}{\pi}V_{cm} \tag{7}$$

The average output DC voltage v_{dc} is:

$$v_{dc} = 2 \times \frac{\delta}{1-\delta} \times \frac{3\sqrt{3}}{\pi} v_{cm} \tag{8}$$

The parallel resonant frequency can be calculated as follows:

$$\omega_o = \frac{1}{2\pi(1M)\sqrt{LC}} \tag{9}$$

The output DC voltage for the buck-boost:

$$v_{dc} = 1 \times \frac{\delta}{1-\delta} \times \frac{2Vm}{\pi} \tag{10}$$

2.2 Simulation Circuit Design

In this section, the circuit was simulated based on two phases. The first phase is the Class E circuit design without inductive coupling and receiver circuit as illustrated in Fig. 3. To analyse the performance of Zero Voltage Switching (ZVS) and output voltage of Class E, the variation of the duty cycle were performed. For example, the Class E circuit was simulated from 10%, 50%, and 90% of the duty cycle. After receiving the coil from the transmitter side, the full bridge rectifier converts the AC supply receiver to DC before entering the buck-boost converter to enhance the voltage received as illustrated in Fig. 4. In this simulation, 1MHz utilizes the identical circuit to determine which is the simplest to use in the high-frequency method of operating frequency. The LTspice simulation model was initially built to validate the theoretical computation of Class E resonance transmitter circuit components. In general, achieving the appropriate Zero Voltage Switching (ZVS) waveform is challenging. However, it can be seen at this moment that there are several methods to optimise the design so that the ZVS is happy.

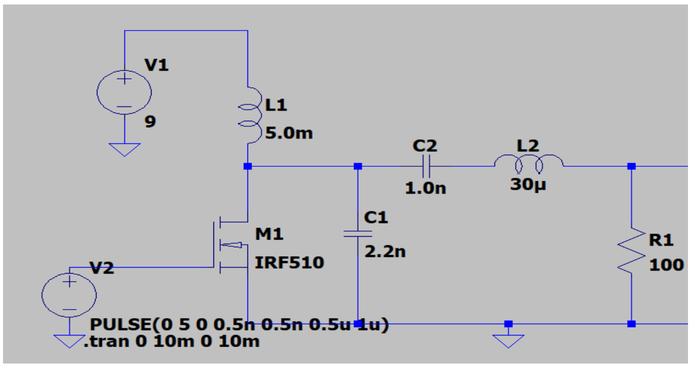


Fig. 3 *IPT system with Class E circuit without receiver circuit*

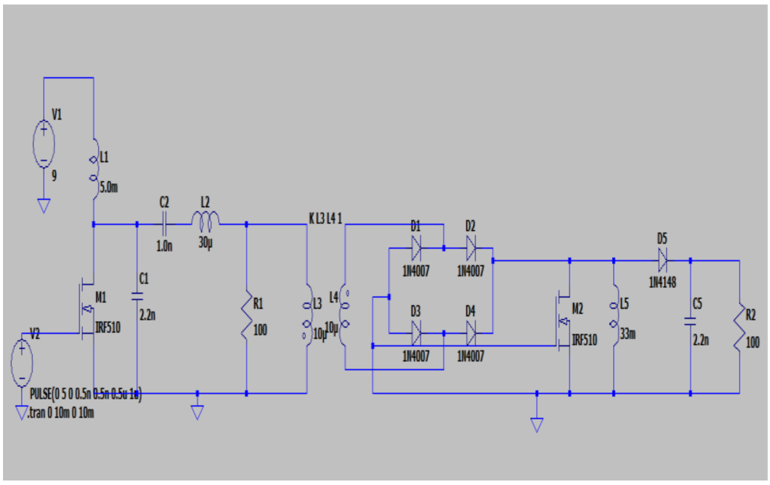


Fig. 4 *IPT system with Class E circuit and receiver circuit*

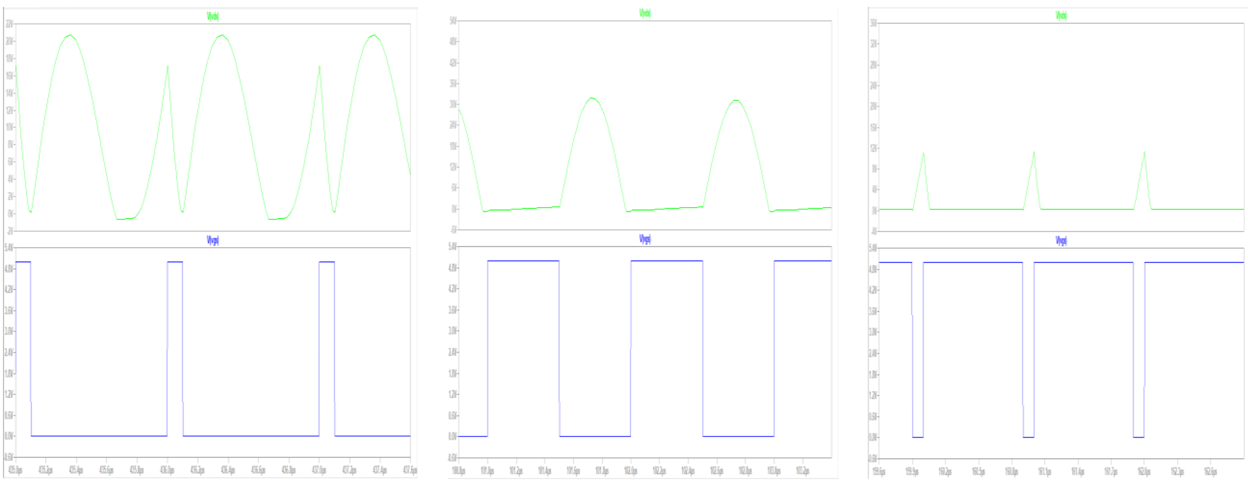
3. Results and Discussion

This section describes the results of circuit design based on simulation works. The class E converter circuit simulations are obtained first to determine the ZVS of the power converter. Next, simulation results using LTspice are delivered to confirm the theoretical results of Inductive Power Transfer. The received output power at load was also analysed.

3.1 Class E circuit as a transmitter circuit results

The duty cycles studied are 10%, 50%, and 90%. In the simulation, it show how effectively the duty cycle got a nice waveform. Therefore, a duty cycle of 50% is better than 10% and 90%.

To achieve the ZVS condition Fig. 5 and Fig. 6 will be compared and get the result of ZVS. For the 10% duty cycle, the Vds waveform, which is displayed on the graph, normally has a sinusoidal shape under ZVS circumstances. The Vgs waveform is displayed as a sequence of pulses on the graph. One way to control it is to change the duty cycle. The total effect of the switching actions is displayed in the output waveform. Because of the shorter on-time at 10% duty cycle, the waveform probably features smaller amplitude pulses. Then, for a 50% duty cycle, the Vds waveform, which corresponds to the switching intervals and usually varies sinusoidally under ZVS conditions, is displayed on the graph. The Vgs waveform pulses in the high and low states should be equivalent to a 50% duty cycle. Lastly, for 90%, the Vds waveform, which is typical of high-duty cycle operations, is displayed in the graph as a sawtooth-like pattern. The Vgs waveform pulses should be high for the majority of the time and low for a brief period of time for a 90% duty cycle.



(a) 10% (b)50% (c)90%

Fig. 5 *ZVS waveform at three different duty cycles (a) 10% (2) 50% (3) 90%*

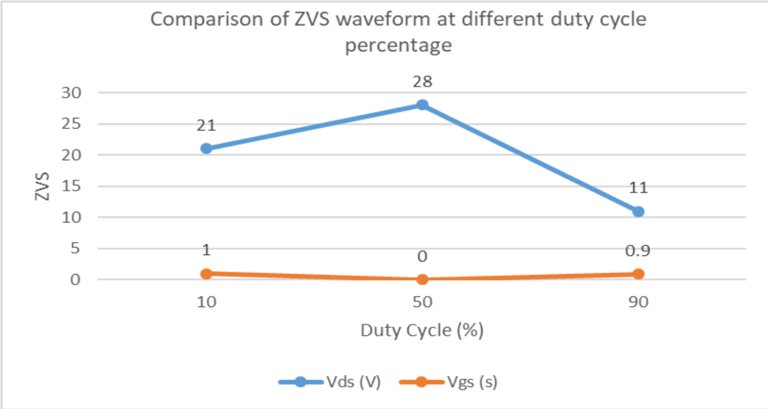
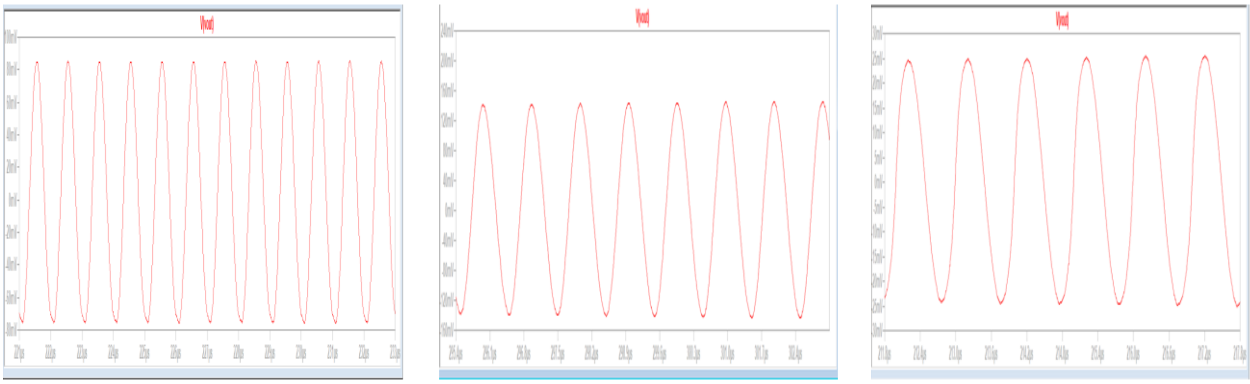


Fig. 6 *Graph analysis of the comparison of ZVS waveform at different duty cycle percentage*

Fig. 7 and Fig. 8 explain the voltage waveforms and graph of a transmitter coil at different duty cycles. At 10%, the transmitter voltage range is -80mV to 80mV, with a sine wave with a higher positive peak. At 50%, the voltage range increases from -160mV to 157mV, resulting in a sine wave with higher amplitude, indicating a substantial increase in power delivered to the coil. At 90%, the voltage range narrows to -30mV to 25mV, with the waveform remaining sine but with lower amplitude. The amplitude is highest at 50% duty cycle, indicating maximum power delivery, while 10% and 90% duty cycles have lower amplitudes. The waveforms are consistently sine-shaped across all duty cycles, with the 10% duty cycle showing slight asymmetry. The voltage range is broadest at 50% duty cycle and narrowest at 90% duty cycle. The 50% duty cycle is the most efficient power delivery to the transmitter coil, with the highest amplitude and symmetric waveform.



(a) 10% (b)50% (c) 90%

Fig. 7 *Output voltage waveform at three different duty cycles (a) 10% (2) 50% (3) 90%*

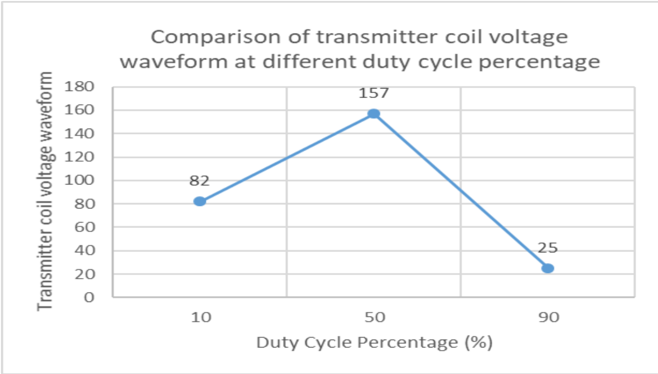
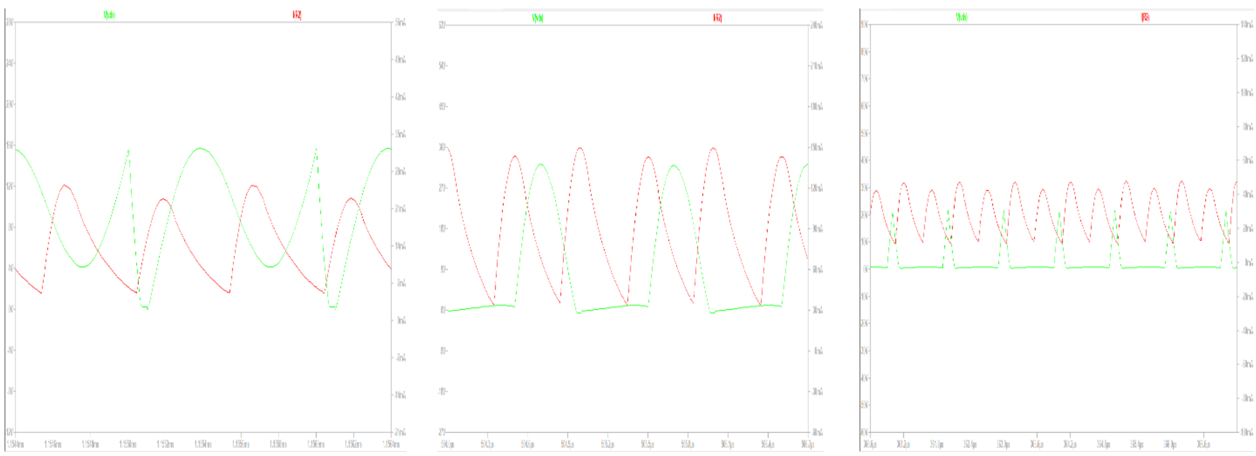


Fig. 8 *Graph analysis of the comparison of transmitter coil voltage waveform at different duty cycle percentage*

3.2 IPT system with Class E and receiver circuit results

Fig. 9 and Fig. 10 show the comparison of voltage and current waveform and graph at 10%, 50%, and 90% duty cycle percentages for an IPT system incorporating a Class E circuit and a receiver circuit revealing significant variations. At a 10% duty cycle, the output voltage is 15V and the current is 10mA, indicating lower power delivery. At a 50% duty cycle, the voltage increases to 36V and the current to 150mA, representing the highest power transfer efficiency. Conversely, at a 90% duty cycle, the voltage drops to 20V and the current to 50mA, similar to the 10% duty cycle, again reflecting reduced power delivery efficiency.



(a) 10% (b)50% (c)90%

Fig. 9 *Voltage and current waveform three different duty cycles (a) 10% (2) 50% (3) 90%*

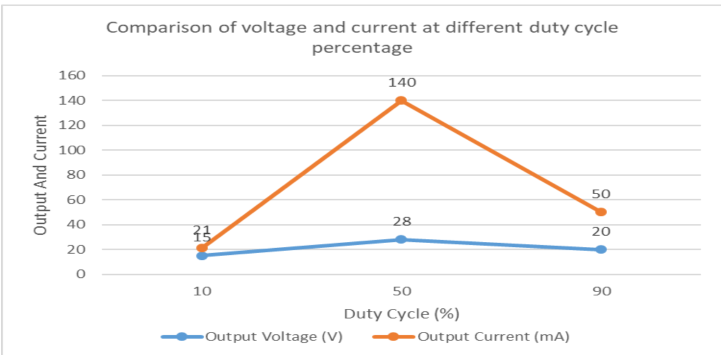
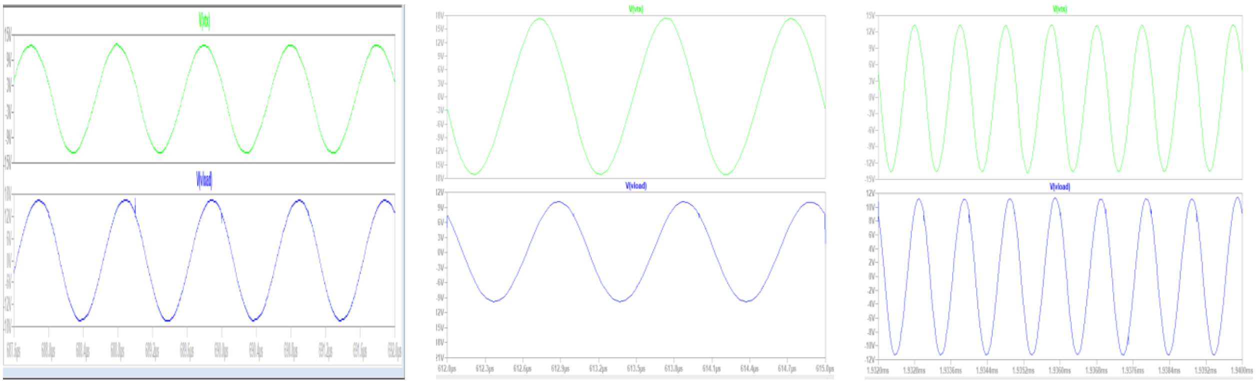


Fig. 10 *Graph analysis of the comparison of voltage and current waveform at different duty cycle* percentage

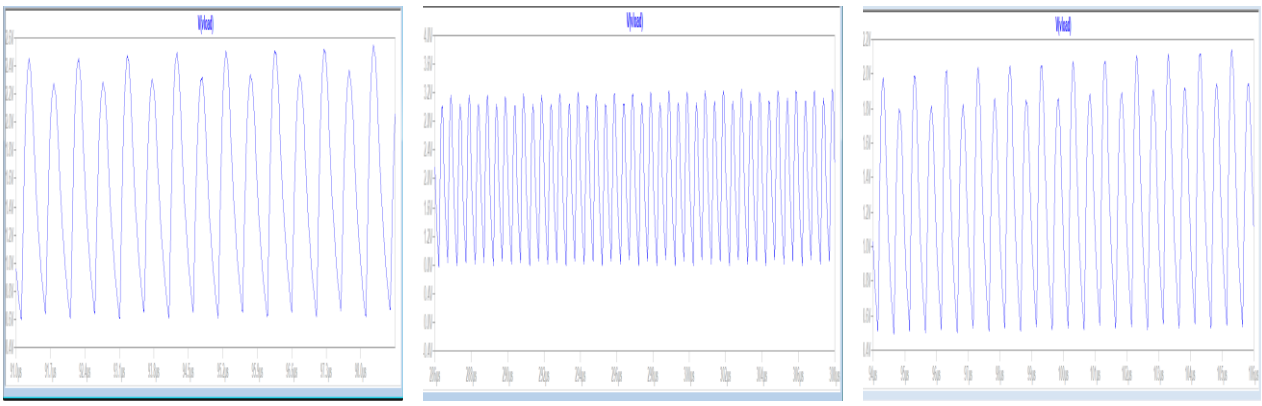
The provided Fig. 11 until Fig. 14, illustrate an IPT system incorporating a Class E and receiver circuit. It is demonstrated through three different configurations step up (10uH-24uH), identical (10uH-10uh), and step down

(24uH-24uH). In each configuration, the waveforms of the transmitter and receiver coils before the receiver circuit show a sinusoidal waveform, reflecting the AC nature of inductive coupling. Next, the step-up configuration, with lower inductance in the transmitter coil and higher in the receiver coil, highlights increased voltage levels in the receiver coil due to the step-up nature. Then, identical configurations present lower inductance values, resulting in different amplitude and frequency characteristics. Lastly, the step-down configuration shows the transmitter and receiver coil voltage with equal inductance values.



(a) Step up (10uH-24uH) *(b) Identical (10uH-10uH)* *(c) Step down (24uH-24uH)*

Fig. 11 *Transmitter and Receiver Coil Voltage Waveform before Conditioning Circuit*



(a) Step up (10uH-24uH) (b) *Identical (10uH-10uH)* (c) *Step down (24uH-24uH)*

Fig 12 *Output Voltage Waveform after Conditioning Circuit*

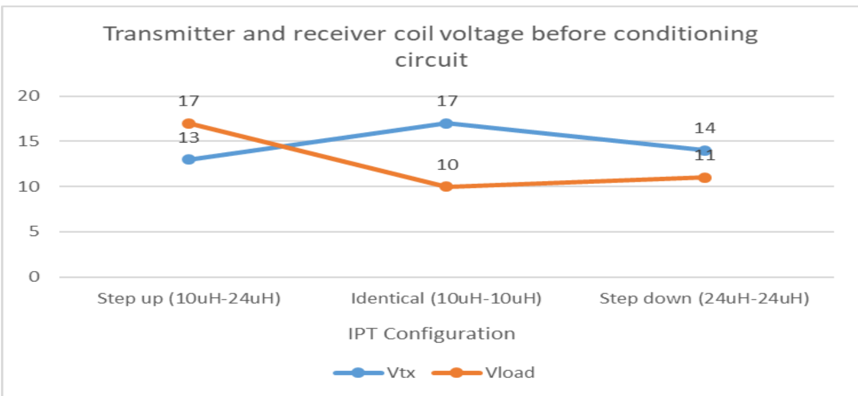


Fig. 13 *Graph analysis of the comparison Transmitter and Receiver Coil Voltage Waveform before Conditioning Circuit*

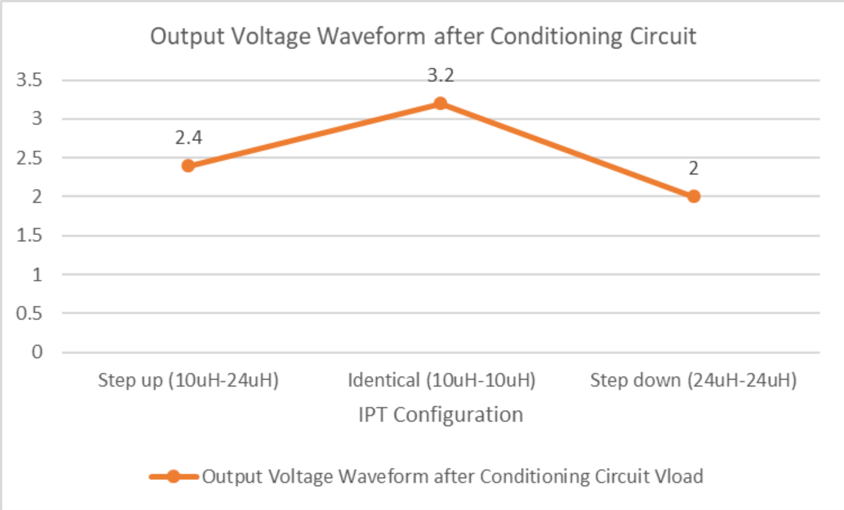


Fig. 14 *Graph analysis of the comparison Output Voltage Waveform after Conditioning Circuit*

After passing through the receiver circuit, the output voltage waveforms in all configurations demonstrate stabilized and consistent signals. This indicates the circuit's effectiveness in rectifying and filtering the AC signal to deliver a steady DC output. The receiver circuit's role is crucial in ensuring the IPT system provides a reliable output, regardless of inductance configuration. Overall, the IPT system, combined with a Class E and receiver circuit, successfully transfers power inductively while maintaining a stable output voltage suitable.

4. Conclusion

In conclusion, the simulation study on inductive power transfer has been analyzed in terms of duty cycle, and different inductive links. The result showed that the 50% duty cycle, produced higher voltage transferred at the transmitter side. Zero Voltage Switching (ZVS) situations have been successfully demonstrated using Class E inverters. The Class E converter circuit for inductive power transfer has been introduced at the primary circuit. In regard to the best compensation method that yields better efficiency, the parallel compensation seems to give a better result than the served one. Due to the leakage problem, the highest power that can be transmitted to the load. Therefore, future work that should be considered intends to design a self-tuning Class E converter circuit to resolve that problem.

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