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The design of auto-tuning capacitive power transfer for rotary applications using phased-locked-loop

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ABSTRACT

Wireless power transfer (WPT), through the transmission of contactless energy, is not only being used for charging batteries in smartphones, but it is also being increasingly used in the field of industrial applications. The capacitive based approach is utilized in this paper because of its ability to transmit power in a metal surrounding environment where the inductive-based approach failed to perform. This work focuses on the coupling study of a rotary CPT application where the power supply is stationary while the load rotates and therefore allows the load to rotate 360º free rotation. The Class E MOSFET power inverter is used here due to its ability to achieve high efficiency compared to other class of converters at high frequency. The prototype of the CPT for rotary application has also been successfully developed with disk plate thickness of 1mm-2mm. Overall, the developed CPT system for rotary application is able to deliver 5.5Watt with 83.33% efficiency. To enhance the power efficiency and ZVS conditions, a self-tuning circuit using phased-locked-loop has been proposed in this paper. The efficiency of the developed system with self-tuning circuit is increased to 97.%.

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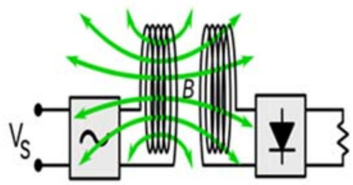
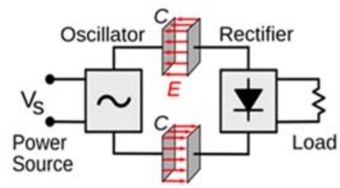
1. INTRODUCTION

Nowadays, wireless power transfer (WPT) technology has turned out to be one of the top research fields for its reliable applicability in low and high power applications such as phones charger, smart card system, high power electric vehicles (EV), and biomedical devices. In general, WPT is the transmission of electricity or energy from a power source to an electrical load without the connecting wire [1]. The advantages of WPT on cable elimination and maintenance-free operation are helpful especially for rotary applications to power up aside common electronic devices that we use every day [2].

The classification of WPT is divided into two categories that are near-field WPT and far-field WPT. Moreover, the near-field technique can be divided into three sections namely as inductive power transfer (IPT), acoustic power transfer (APT) and capacitive power transfer (CPT) [3]. In near-field power transfer, the IPT uses a coil that will produce the magnetic field to transfer power, see Figure 1(a), while CPT applies capacitive plate that will produce an electric field to transfer power, see Figure 1(b). Meanwhile, APT utilizes vibration to transmit energy. Among them, IPT is the most popular way to recognize wireless power transfer. However, the main disadvantage of IPT system is it is unable to efficienctly operate in metal surrouding enviromentas because magnetic field is not able to pentarate the metal barrier [4]. This work focuses on CPT system as shown in Figure 1(b). CPT system is a potentially convenient method based on the coupling capacitor approach, with the use of capacitor plate to come out with better EMI [5]. This CPT method is utilizing electric field rather than magnetic field used for the inductive approach which unable to penetrate metal shielding as it will induce the eddy current in metal [6]. Since capacitive power transfer used the electric field coupling, it has been the key part for the new improved method to achieve non-contact power transfer and gives greater effects onto the frequency, output power, and power efficiency of the system. This method can be the solution for drawback of the IPT system [3]-[6].



(a)



(b)

Figure 1. (a) Basic diagram of inductive power transfer, (b) Basic diagram of capacitive power transfer

The CPT system is very benefial in the rotary applications, such as robotic arm in automation industry to allow the actuator to achieve 360 degrees of free rotation. This type of WPT system will also allow a green technology for rotary machinery with high reliability to reduce the risk while handling rotary machine [7]. Currently, the rotary applications used brushed mechanical slip rings to transfer signals or power across rotating devices [8]. However, slip rings can cause failures due to the frictional rotation, physical connection problems and hence require the frequent maintenance. These problems can be solved by applying WPT technology disk plates concept. In this concept, the higher part is a rotating part and connected to the load, while the lower part is static and connected to the DC power supply [5].

However, by considering CPT system, the major challenge is to maintain the output efficiency during power transmission. Therefore, in this work, Class E power amplifier is proposed because it offers an improvised medium of high-frequency, which produces higher efficiency for the output, and has advantages in terms of simplicity [8]. This is true as the theoretical switching loss for Class E power amplifier is zero as the ZVS is perfectly achieved [8]. Also, to enhance the power efficiency, the self-tuning circuit is designed to obtain the desired output power at the high operating frequency. A self-tuning is potential to increase the efficiency of the system and make the power efficiency insensitive to the exact coupling capacitance. These self-tuning circuit can be implemented greatly in reducing noises in the analog and digital system [1].

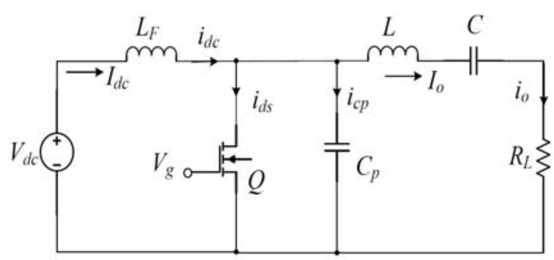


Figure 2. Class e zvs inverter circuit [1]

2. OVERVIEW

2.1. Development of transmitter plate

The structure of the common CPT system consists of a transmitter unit, two disk plates, and a receiver unit [9]; see Figure 4 for details. The transmitter unit acts as a high-frequency voltage source inverter, which converts DC signal to AC signal [1]. The specifications along with its description of this work are tabulated in Table 1.

Table 1: The specification of the work

Parameters		Description
1.Output Power	$P_o = 10W$	The power required to turn on the LED light
2.Operating Frequency	$f = 1\ MHz$	High frequency beneficial to small scale system design and power losses reduction.
3.Quality Factor	$Q_L = 10$	High quality factor in inverter design to achieve sinusoidal output signal.
4.Input Voltage	$V_{DC} = 12V$	The minimum input value required.

2.2. Materials

In this work, air has been used as dielectric materials. The relative permittivity of the dielectric material is εr = 1. The maximum coupling gap range in this work is 2 mm. The shape of the plate is disk plate that is suitable for rotary applications [10]. The assumption for the thickness of disk plate is 1mm-2mm [11].

2.3. Development of receiver plate

At the receiver unit, it consists a full bridge rectifier and the load as shown in Figure 3. This rectifier will convert AC source to DC source and deliver 10 W power to the load [12]. The C1 and C2 act as filter in this circuit and LM7809 is used to regulate the output voltage at 9V.

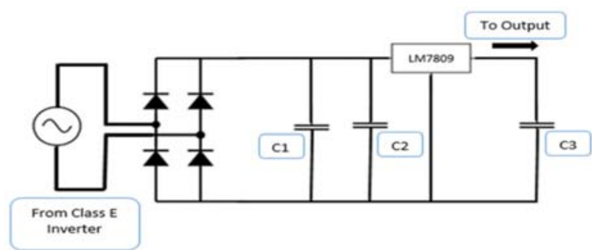


Figure 3. Rectifier circuit

2.3. Self-tuning capacitive power transfer

Based on Figure 4, a self-tuning CPT will be designed and constructed. The self-tuning CPT consists of a phase detector, low pass filter, and voltage control oscillator (VCO) [13]. The main purpose of this self-tuning is to maintain the ZVS of Class E circuit although there is a change in output load.

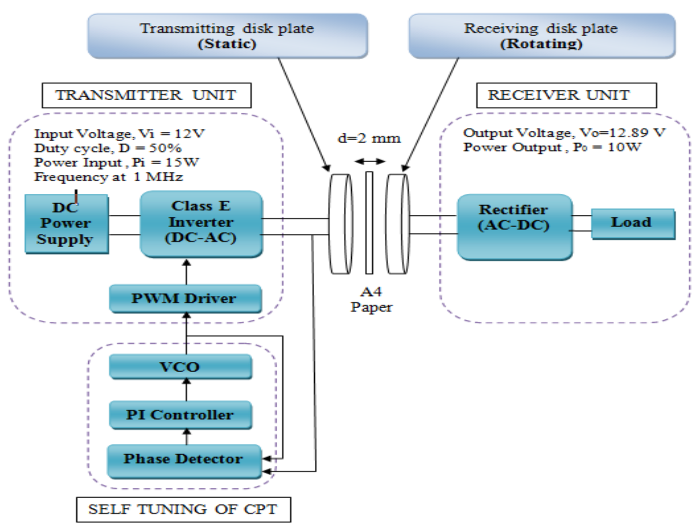


Figure 4. The block diagram of CPT system for rotary applications

3. METHODOLOGY

First of all, the class E inverter circuit will be designed by calculating components value based on requirements desired. Secondly, the class E inverter is designed and simulated using MATLAB/Simulink by considering input voltage, Vi = 12V and D = 50%. The simulation of the circuit is done before proceeding to experimental work so that the result can be compared accordingly. If the results are satisfied with the theory, the actual work will be done to achieve maximum efficiency. Next, the circuit will be connected to transmitter plate. In the experimental work, Class E inverter's MOSFET is triggered by MOSFET driver circuit that generates the frequency intended to be used for the circuit.

Next, the complete CPT System will be developed. The disk structure plate is used for this rotary applications. Furthermore, the design will be implemented practically to the typical CPT system. After completing CPT System, the self-tuning will be applied to overcome problems of uncertain variations of the inductor, capacitor, and resistor and get the optimum operations.

3.1. Class E inverter: derivation of equations

Firstly, to design the Class E ZVS inverter circuit, the full-load resistance can be determined by using (1) as the output power required is set to be 10W

$$R_i = \frac{8}{\pi^2+4}\frac{V_i^2}{P_{ri}} \qquad (1)$$

Next, the other parameters such as the amplitude of the output voltage and DC input current can be calculated using (2) and (3), respectively.

$$V_{rim} = \frac{4}{\sqrt{\pi^2+4}}V_i \qquad (2)$$

$$I = \frac{8}{\pi^2+4}\frac{V_i}{R_i} \qquad (3)$$

Due to capacitive plate width and length has been fixed for each plate, the distance between the pair of the plate is 2 mm and the material of the medium is plastic that has dielectric value, εr = 1, the capacitive value of the plate can be measured based on

$$C = \frac{A\varepsilon_0\varepsilon_r}{d} \qquad (4)$$

When the capacitance value is known, the new capacitance value is the actual value of Cseries while Q-factor, QL can be obtained using the following equations. Here, QL= 10

$$C_{series} = \frac{1}{\omega R_i\left[Q_L - \frac{\pi(\pi^2-4)}{16}\right]} \qquad (5)$$

The series inductor and shunt capacitor value can be obtained by (6) and (7) consequently. Then, the minimum value of choke inductor also can be calculated using (8). Lastly, the obtained and required parameters for this paper are tabulated in Table 2.

$$L_{series} = \frac{Q_L R_i}{\omega} \qquad (6)$$

$$C_{shunt} = \frac{8}{\pi(\pi^2+4)\omega R_i} \qquad (7)$$

$$L_{choke}\,(\text{min}) = 2\left(\frac{\pi^2}{4}+1\right)\frac{R_i}{f} \qquad (8)$$

Table 2: Comparison between calculation, simulation and practical values for the Class E

Parameter	Calculation	Simulation	Practical
Choke inductor, Lf	58.1µH	100µH	100µH
Shunt Capacitor, CS	3.52nF	3.85nF	3.9nF
Series Capacitor, C	2.17nF	2.17nF	2.2nF
Series Inductor, L	13.21µH	13.20µH	20µH
Load resistor, RL	8.31Ω	8.31Ω	10Ω
Output voltage, VRim	12.89V	13.50V	10.5V
Max switch voltage, VSM	42.74V	43.50V	43V
Input Current, Ii	0.83A	0.84A	0.55A
Max switch current, ISM	2.38A	1.80A	1.21A
Output Current, IM	1.55A	1.64A	1.05A
Input power, Pin	9.96W	9.76W	6.6W
Output power, Pout	9.99W	10.08W	5.5W
Efficiency, η	99.9 %	96.83%	83.33%

3.2. Circuit simulation : Class E inverter circuit

Class E power amplifier circuit that is built in MATLAB Simulink is illustrated in Figure 5. Next, ZVS condition of the simulation circuit is shown in Figure 6 and the maximum voltage for VSM = 43.50V is obtained. This is aligned with theory where the voltage will be at least 3 times greater than the input voltage. Therefore, the MOSFET selection must be made properly so that it will be able to handle this amount of voltage.

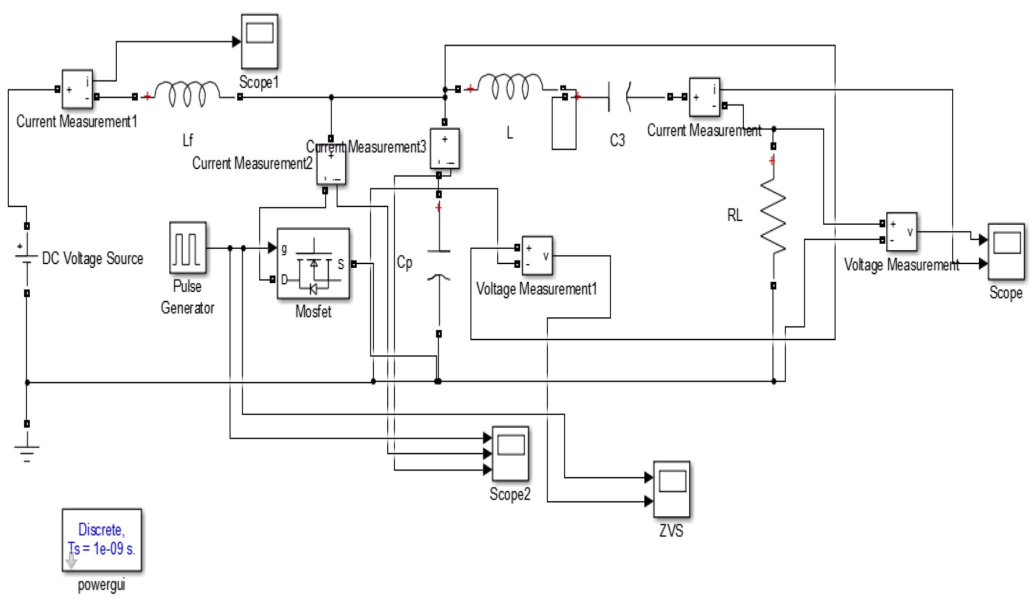


Figure 5. Full Class E power amplifier circuit built in MATLAB Simulink

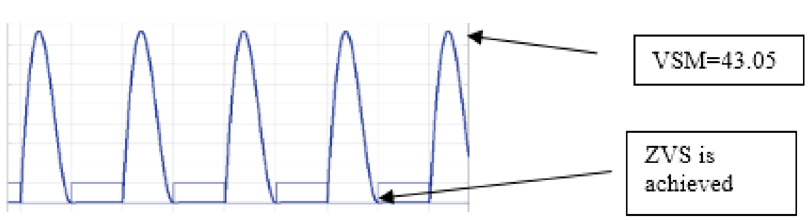


Figure 6. ZVS condition of the simulation circuit

3.3. Circuit simulation : Class E inverter circuit with PLL circuit

For some improvement, PLL circuit is introduced which is this circuit is connected to Class E inverter circuit. PLL is used in order to recover a signal from a noisy communication channel, for frequency synthesis/control and to distribute clock timing pulses in digital logic designs. Full Class E power amplifier circuit with PLL circuit built in MATLAB Simulink is illustrated in Figure 7. Besides that, ZVS condition of the simulation circuit with PLL circuit is shown in Figure 8 and the VSM = 43.53V is obtained.

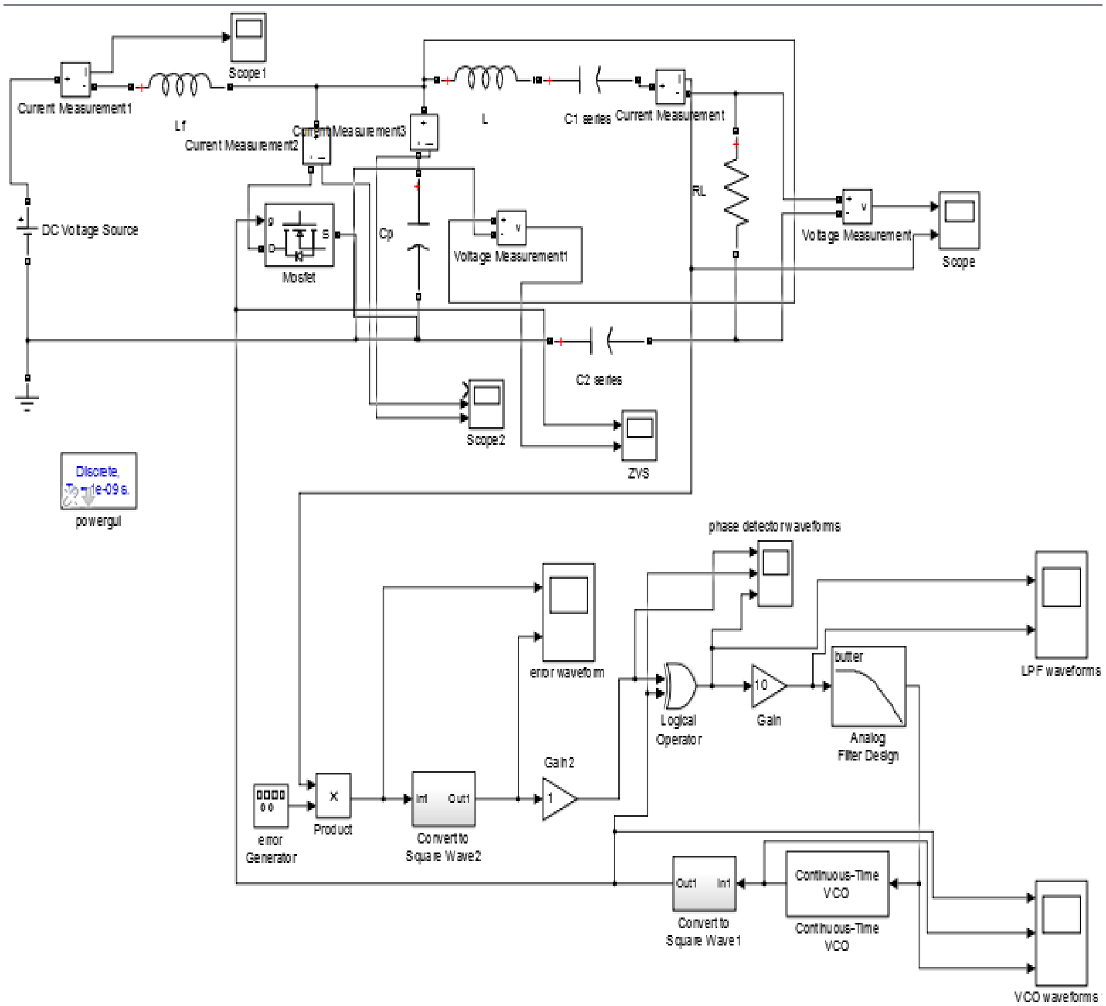


Figure 7. Class E inverter with PLL circuit built in MATLAB Simulink

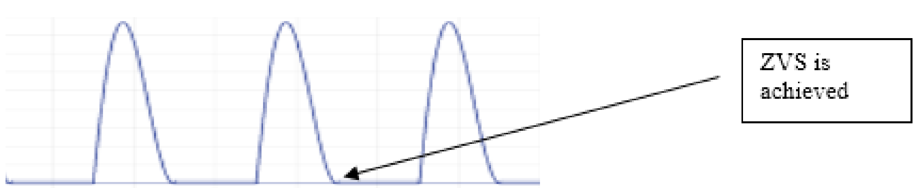
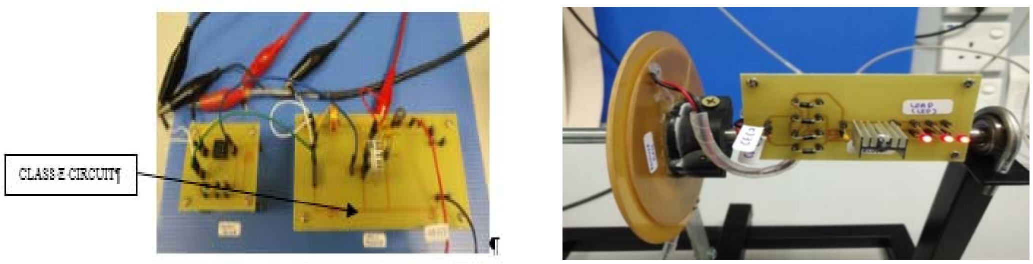


Figure 8. ZVS condition of the simulation circuit with the PLL circuit

3.2. Prototype construction

This project will consist of two disk coupling plate which is the static plate and rotating plate. This two-disk coupling plate size is 0.04904 m², with a combined interface capacitance of 2.17 nF. If the area is converted to cm² will get A = 490.4 cm². Using the formula area of circle $A = \pi r^2$, we get the radius, r = 12.5cm. The fabrication of MOSFET driver and Class E inverter circuit are connected as illustrated in Figure 9(a). MOSFET driver circuit will amplify pulse generated in order to turn on the MOSFET at Class E inverter. The AC waveform from the transmitter will be converted to DC waveform at receiver part so that the load such as LED can be powered up. Figure 9(b) shows the receiver circuit that installed at rotating plate part. Lastly, Figure 10 illustrated the complete setup of WPT system in rotary applications using capacitive approach.



(a) (b)

Figure 9. (a) MOSFET driver and Class E inverter circuit after fabricated, (b) Receiver circuit that installed at rotating plate part

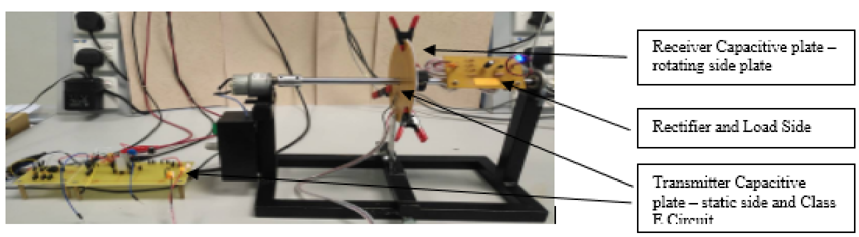
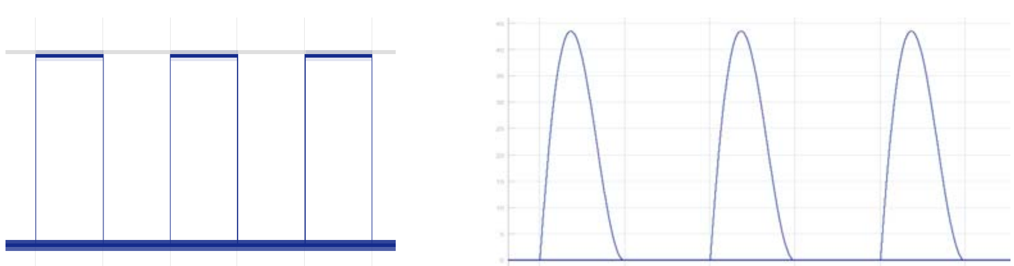


Figure 10. Complete setup of CPT system in rotary applications

4. RESULT

4.1. Simulation result: Class E inverter circuit

Figure 11(a) shows the waveform at gate MOSFET, Vg. This pulse proven that the gate is turned on due to the minimal voltage pulse needed to switch the MOSFET IRF510 is 10V. Next, the waveform in Figure 11(b) demonstrates the output at the drain of the MOSFET, Vds.



(a) (b)

Figure 11. a) Waveform at gate of MOSFET, b) Waveform at drain of MOSFET

By referring to Figure 11(b), the waveform at drain MOSFET indicates the nearly similar shape of the half-wave waveform. The highest amplitude achieved is 43.50V with a period of 1ns at 50% duty cycle. This value has really surpassed the theory where the drain amplitude expected to be the triple estimation of a gate voltage of MOSFET and proved the MOSFET switching works well. Combination of the waveform of gate MOSFET and drain MOSFET as shown in Figure 12.

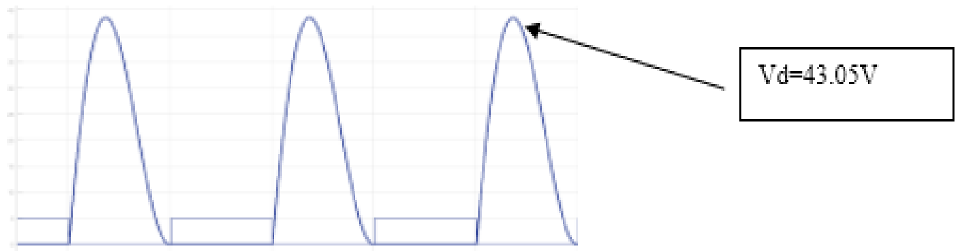
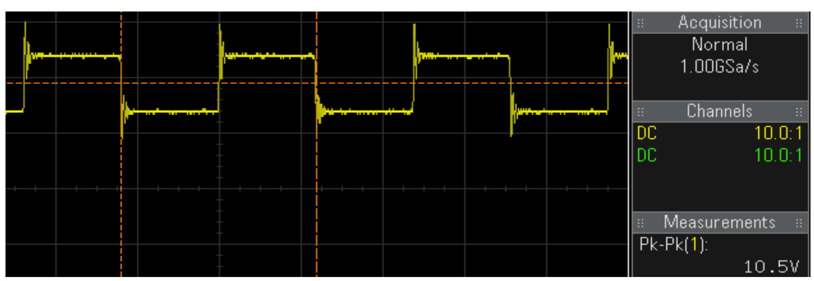


Figure 12. Waveform at drain and gate of MOSFET

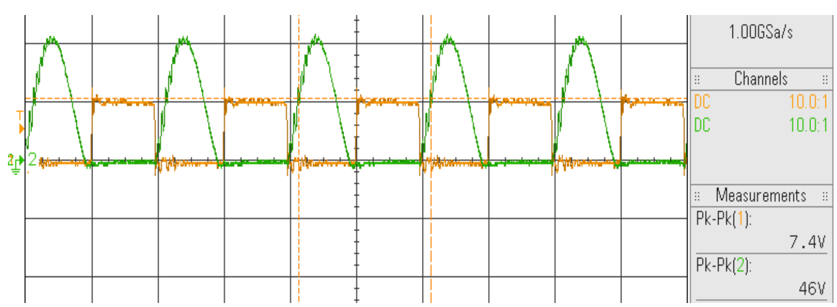
Based on Figure 12, the optimum condition for ZVS condition is achieved. This satisfies ZVS condition because of the absence of an overlap between the voltage waveform of the gate and drain MOSFET

4.2. Experimental result : Class E inverter circuit

Figure 13(a) indicates the pulse that has been produced using MOSFET driver and supplied into the gate of MOSFET in Class E inverter. Figure 13(a) shows the waveform at gate MOSFET that produces 10.5V amplitude at frequency 1MHz of 50% duty cycle. The larger value of capacitor can be used to filter the spikes and ripples present in each pulse. The waveform shows that the pulse is able to turn the MOSFET switching on. Next, Figure 13(b) shows the waveforms between MOSFET gate and MOSFET drain together in order to see whether the zero voltage switching is perfectly obtained



(a)



(b)

Figure 13. (a) Waveform at gate, V_g MOSFET, (b) Waveforms between MOSFET gate and MOSFET drain together

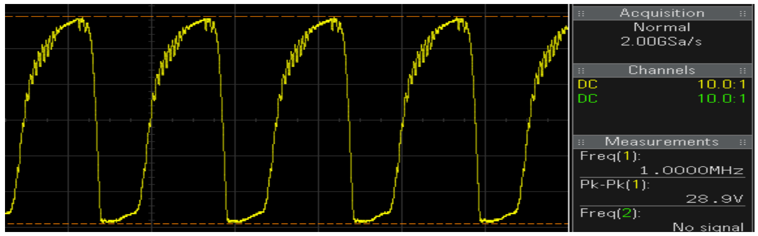


Figure 14: Waveform before rectified at the load

By referring to Figure 14, the waveform is in an AC form. The voltage peak of the waveform is 14.4V at 1MHz. We can see that the practical result only achieved half value compared than the simulation results one. This might be affected by the presence of two pairs of plates that act as the series capacitor when combining the circuit for wireless energy transfer system using capacitive approach.

4.2.1. Distance analysis for CPT system

The efficiency of transferred power will decrease if the distance between transmitter plate and receiver plate has increased. For distance and misalignment analysis, the input power is taken before placing the load into the system that is after voltage regulator. Calculation of efficiency can be done using (9)

$$\text{Efficiency (\%)} = \frac{Output\ Power\ (P_o)}{Input\ Power\ (P_i)} \times 100\% \qquad (9)$$

For this work, the distance in transferring the energy between one plate to another plate has been analyzed up to 10mm. The receiver plates are moved vertically away from the transmitter plate for this analysis. The result has been tabulated in Table 3 along with the efficiency of the system as distance increases. Based on Table 3, the graph of efficiency versus distance is plotted, see Figure 15.

Table 3. The distance in transferring the energy between one plate to another plate

Distance (mm)	Input Voltage (V)	Input Current (mA)	Input Power (W)	Output Voltage (V)	Output Power (W)	Efficiency (%)	LED Brightness level
0.1	12.00	550	6.6	10.5	5.5	83.33	Very High
1	12.00	380	4.56	9.4	2.6	57.00	Very High
2	12.00	185	2.22	8.8	1.25	56.31	High
3	12.00	109	1.308	7.2	0.61	46.64	High
4	12.00	95	1.14	7.0	0.45	39.47	High
5	12.00	58	0.70	5.4	0.24	34.29	Medium
6	12.00	45	0.54	4.3	0.16	29.63	Medium
7	12.00	30	0.36	4.0	0.98	27.22	Medium
8	12.00	24	0.26	3.5	0.05	19.23	Low
9	12.00	19	0.23	2.8	0.018	7.83	Low
10	12.00	17	0.204	1.8	0.98	0.98	Low

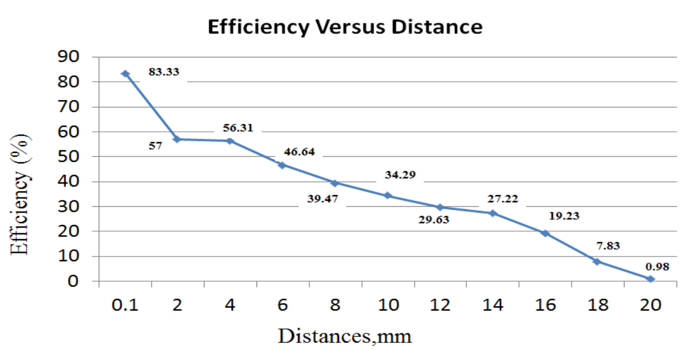


Figure 15. Graph of efficiency versus distance

In Figure 15, the highest efficiency that we can see through the graph is 83.33%. This situation is achieved when the distance between transmitter and receiver plate is 0.1mm which only separated by a thin A4 paper that is to prevent any contact. As for the lowest efficiency, the distance of 20mm recorded the lowest efficiency which is 0.98%. In this section, every distance is analyzed using LED light as the indicator or load. The brightest light of LED is obtained at 0.1mm distance while the dimmest light from LED strips is acquired at 20mm distance. From this graph, we can conclude that the efficiency decreases exponentially as the distance between plate increases. This is the main challenge of using CPT system.

4.3. Simulation result: Class E inverter circuit without PLL circuit

This section and the following intend to show the importance of having such kind of self-tuning circuit in order to overcome the previous stated problem in CPT system. The first section illustrates the results without any self-tuning circuit (PLL in this context). The change in Cseries means there is a change in the gap of between two plate that produced different impedence. Figure 16(a) shows the actual waveform of ZVS condition of Class E inverter. In this Figure 16(a), the value of CSeries and RLOAD is an actual value from the simulation of Class E circuit as described in previous section. Based on Figure 16(b), the value of CSeries is changed to 2.0nF but the value of RLOAD is constant. Then, the value of CSeries is changed to 3.0nF with a constant value of RLOAD that illustrated in Figure 16(c). We can see that there are changes of ZVS condition after we increase or decrease the capacitance value.

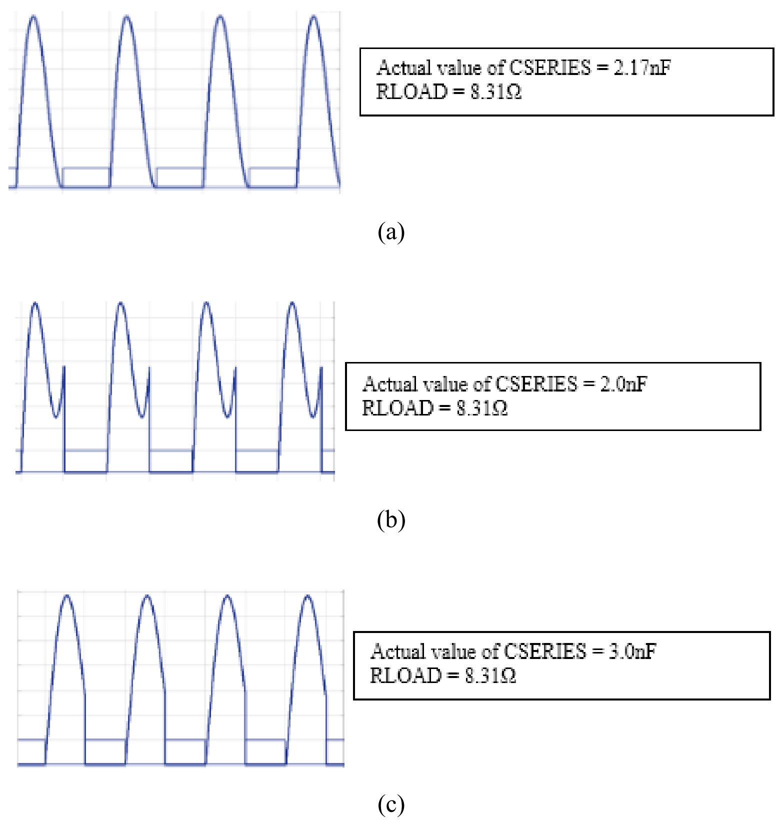


Figure 16. a) Actual ZVS condition for C=2.17nF b) ZVS condition for C= 2.0nF c) ZVS condition for C= 3.0nF

4.4. Simulation result: Class E inverter circuit with PLL circuit

Now, we will show the effectiveness of having PLL circuit that acts as a self-tuning circuit to the CPT system. The load is changed here in order to see the effectiveness of adding PLL in the circuit. The results are shown in Figure 17. Figure 17(a) illustrates the original specfications. Then, the load is changed to 8ohm and increased to 20ohm and 30ohm respectively. We can confirm that the ZVS can be guaranteed although there is a changed in load value but the results become worst when the Load is increased to 30ohm. This means that the proposed PLL can obly be effective at some change of load variation and not at all value.

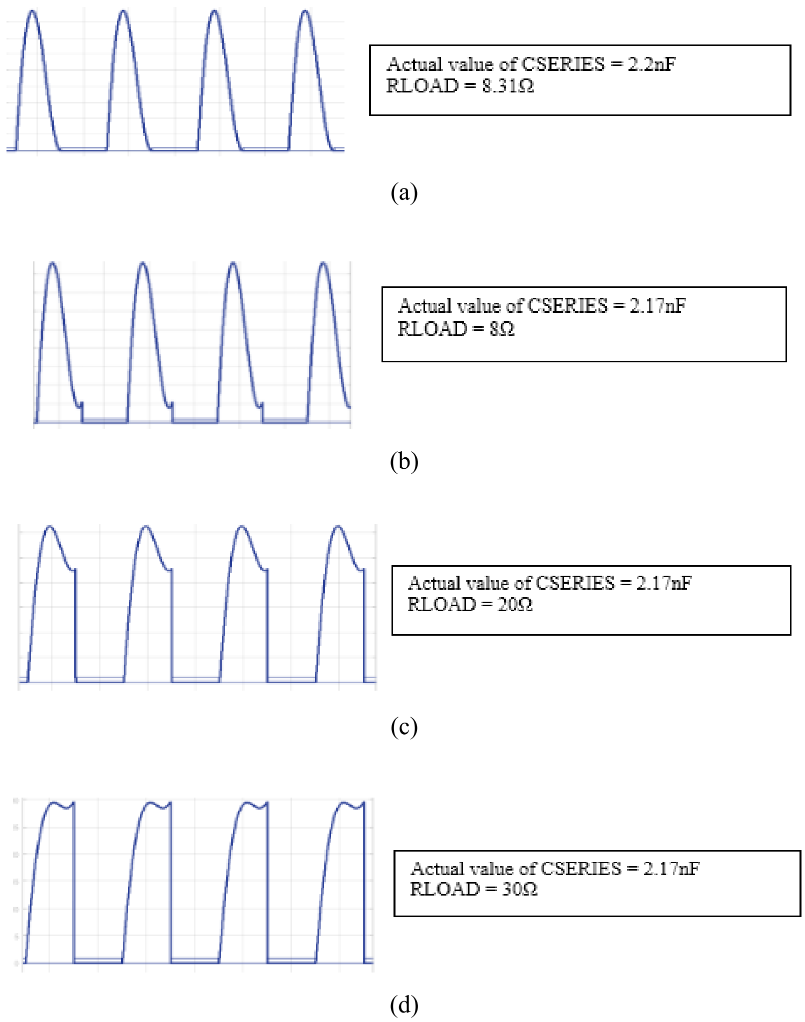


Figure 17. a) Actual ZVS condition for RL=8.31Ω, b) ZVS condition for RL=8Ω, c) ZVS condition for RL=20Ω, d) ZVS condition for RL=30Ω

5. DISCUSSIONS

Class E inverter result for both simulation and practical works have shown that ZVS condition was successfully accomplished and there are nearly 30% losses in the switching. This is due to the fact the voltage waveforms of the drain voltage as well as gate voltage overlap at each other. The overlapping may be reduced by controlling both shunt capacitor or series inductor. Moreover, resistances in every component used as a part of the project need to be considered as the resistances also influences the result produced for experimental. MOSFET IRF510 at Class E inverter circuit are considered to be ideal where heat loss as well as components resistance do not appear which is not realistic since the MOSFET IRF510 requires heat sink to help heat dissipated during the experiment.

In practical result, there are some ripples present especially in drain voltage waveforms. This is because the value of capacitance is not huge enough to filter the ripple. The ripple at waveforms can be eliminated by increasing the value of the capacitor. CPT system is known to have smaller range in transferring energy efficiently compared to the IPT system. In that case, the distance analysis for this project is taken up to 10mm. Furthermore, medium such as A4 paper has been used to prove that the energy transfer in capacitive approach. By using A4 paper or air gap, the power is proven can be transfered efficiently.

To overcome the parameter change issue, i. e load change in the CPT system that affect the overall efficiency of the system, PLL circuit is introduced and is added to transmitter part. Simulation with PLL circuit is developed to get a better efficiency. So, Class E inverter with PLL circuit is recommended to this work because ZVS condition is easily achieved if we made a change of capacitance or RLOAD value.

6. CONCLUSIONS

An analysis of rotary CPT systems using a Class-E inverter circuit is presented in this paper. Class E type of power amplifier which contains a choke and series of inductor and capacitor is presented through simulation using MATLAB Simulink. The basic equations and formula are also provided here. The result of simulation for the circuit built using MATLAB Simulink is explained and the efficiency of simulation is 96.83% while the efficiency of the experiment is 83.33%. The CPT system is unable to maintain such efficiency at a high level when the coupling gap distance is increased. Therefore, the existing CPT system is improved by adding a self-tuning circuit to help the CPT system in maximizing the power transfer efficiency by allowing variations in the coupling gap distance and load variations. Next, the design of the self-tuning circuit using phase-locked-loop had obtained through the simulation. The efficiency of the simulation for Class E with self-tuning circuit is 97.8%. Furthermore, the output power efficiency of different coupling gap distances is analyzed. The efficiency of the distance analysis for CPT system without PLL are within 83.33%–39.47% for the coupling gap range of 0.1–4 mm. Apart from that, the core purpose of designing the system is to come up with a rotary system that helps to be free of power cables so it can achieve 360 degrees of free rotation. For future works, authors may expand the circuit by adding matching circuit to increase the efficiency and to ensure the circuit will be able to conduct higher power while maintaining the zero-voltage switching (ZVS) condition and being able to conduct rotary motion applications.

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