The design of an efficient class E-LCCL capacitive power transfer system through frequency tuning method

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Article Info

ABSTRACT

In this work, the optimum zero voltage switching (ZVS) of Class E-LCCL capacitive power transfer (CPT) was determined via frequency tuning method. Through this an efficient system can be guanranteed although there is a change in the capacitive plates distance. This study used a Class-E LCCL inverter, as it can operate at a high alternate current frequency, besides producing low switching losses and minimal power losses. Specifically, this study conducted simulations and experiments to analyse the performance of an LCCL CPT System at 1 MHz operating frequency and 24 V DC supply voltage. Using an air gap distance of 0.1 cm, the designed CPT system prototype successfully achieved an output power of 10W and an efficiency of 95.45%. This study also found that by tuning the resonant frequency of the Class E-LCCL system, the optimum ZVS can be obtained although capacitive plate distance was varied from 1-3 cm via experimental. The results of this study could benefit medical implant and portable device development, consumer electronics, and environments that involve electrical hazards.

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1. INTRODUCTION

In this hyper-connected age, consumers demand less hassle when charging portable technology such as electric vehicles and mobile phones, and consider wires a major hindrance. Therefore, conventional methods involving wired charging are fast being replaced with wireless power transfer (WPT) technology, as illustrated in Figure 1. Currently, wireless power transfer (WPT) relies on power transmission that is not based on radiation, and mainly falls under three categories: acoustic energy transfer (AET), capacitive power transfer (CPT), and inductive power transfer (IPT), all of which are suitable for near-field applications [1-6]. These technologies have certain limitations such as sensitivity to frequency variations (e.g., AET) and sensitivity to metal barriers (e.g., IPT) [7-9]. Because of the weaknesses of AET and IPT; CPT, which transfers power via an electric field (i.e. without a wire contact at near field) [10, 11], was chosen as the current subject of study, with the main aim of reducing electromagnetic interference (EMI) and power losses [7, 8]. The primary disadvantage of using magnetic coupling in contactless power transfer methods is that it does not allow power to transmit through metal barriers. A CPT system containing a DC power supply, a resonant power converter, a rectifier, and a load is shown in Figure 2.
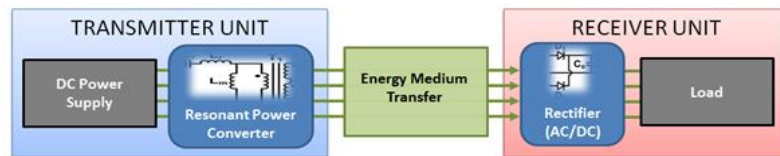
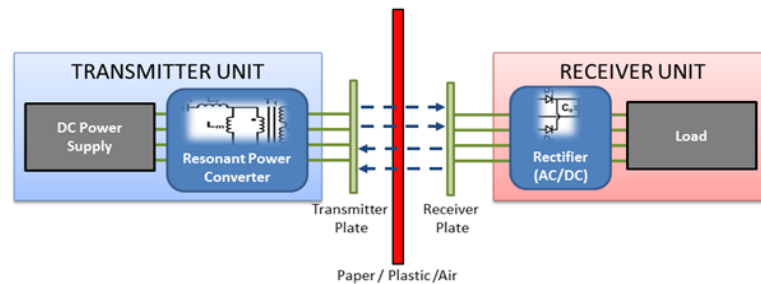Figure 1. Wireless power transfer block diagram

Figure 2. Capacitive power transfer block diagram

The CPT system uses capacitance coupling to transfer energy from other capacitor plates via an electrical insulator known as a dielectric. The dielectric is based on two capacitance concepts: i) mutual capacitance and ii) capacitive coupling. In the first, the capacitor plates are separated via electricity, usually by a material such as ceramic, plastic, waxed paper, or mica or a liquid gel. These plates are made of metal (conductive) and are connected in parallel [12, 13]. In the second, energy is transferred within an electrical network (one plate to another plate) using a displacement current between circuits by inducing an electric field [8, 14, 15]. In the current CPT system, capacitive coupling was applied to transfer energy from one circuit to another circuit.

A CPT system normally transfers power wirelessly i.e. via an electric field [10, 11, 14-17]. Past studies have widely investigated the application of CPT in WPT such as in biomedical implants [18-21]. In one study, the dielectric material used successfully transferred 59-290 mW of energy through a beef shoulder that was 5 mm thick to the secondary implant side. The study used a capacitive link comprising two pairs of coated parallel plates aligned around the (beef) tissue to replace a series resonant converter in tank capacitors [19]. CPT technology was also applied for charging drone batteries [22], where one study successfully charged a drone with 3 battery cells at 50% efficiency and delivered 12 W of power. Elsewhere, CPT technology has also been used in industrial applications, eliminating the need for a mechanical slip ring and thus the traditional rotor power coupling technique in wound-field synchronous machines by replacing it with a capacitive non-contact power transfer technique [23]. Other successful works were done using multiple rotary plates for a CPT prototype with the results revealing more than 76% power transfer efficiency at 1 MHz operating frequency, albeit at a 1 mm plate distance [24].

By considering all aspects significant to the CPT system, this research focuses more on analysing, optimising the functionality, and designing an effective CPT system with efficient wireless power transfer capabilities. Capacitance coupling is the transfer of energy within an electrical network (one plate to another plate) via the displacement current between circuits by inducing an electric field [8, 14, 15]. A Class E-LCCL inverter was used for the current circuit to produce the desired output power [25]. Two circuits-a Class E-LC topology circuit and an LC match circuit-are combined in this inverter. The main advantage of this circuit is that it can match the power requirement by converting the current impedance to the desired impedance [26].

All the studies mentioned above struggled to define the maximum power transfer in the capacitive plates based on the plate distance, for example, biomedical implants have a maximum transfer distance limited to around 5mm between plates. In other applications, some researchers selected a maximum distance of around 1mm to achieve maximum efficiency, by matching the impedance at the transfer unit to that of the receiver unit. In this study, a Class E-LCCL inverter was implemented for the capacitive power transfer (CPT) system to achieve high efficiency, to reduce the plate size, and to reduce the electric field emission during the transfer of energy from the transmitter to the receiver [25, 24]. In specific, in this paper, the distance of the capacitive plates was analysed by investigating the result of ZVS using a Class E-LCCL system by tuning the resonant frequency in real-time and by adjusting the distance of the capacitive plates from 1-7 cm.

There are four main sections in this paper. The analysis and design of the Class E-LCCL capacitive power transfer system are presented in section 2 together with the design specifications of the system and the simulation and experimental results. Section 3 presents the selected resonant frequency for the Class E-LCCL CPT system together with the simulation and experimental works to get the best ZVS. This section also discusses and analyses related ZVS and the output power of the circuit system designed. Finally, a summary of the findings is presented in section 4.

2. CLASS E-LCCL CPT SYSTEM

Section 1 discussed the background of wireless power transfer (WPT) with an emphasis on CPT. In this section, an overview of the Class E-LCCL CPT System designed in this study is presented together with its design specifications and the results of simulation and experimental works. A Class E-LCCL inverter was used in the proposed circuit to produce the desired output power [25]. Two circuits-a Class E-LC topology circuit and an LC match circuit-were combined in this inverter. The main advantage of this circuit is that it can match the power requirement by converting the current impedance to the desired impedance. Figure 3 illustrates the Class E-LCCL system.
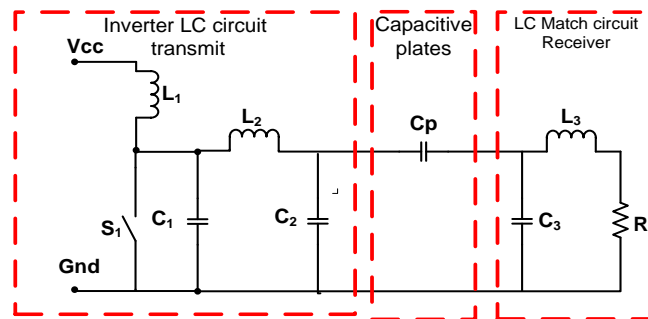

Figure 3. The class E-LCCL CPT system

It is assumed that all conditions for the Class-E inverter are satisfied and that the switch is perfect. Also, the power dissipated in the load resistor is assumed to be equivalent to the DC power provided by the bias DC source. Therefore, 10 W was chosen as the power delivered to the load while 24 V was selected as the input voltage, Vcc. All circuit component values were obtained using (1) and (2) [25].

The value of the capacitors:

$$C_1 = \frac{1}{33.22\omega\left(\frac{\pi^2}{4}+1\right)\frac{\pi}{2}}, \; C_P = \frac{1}{2\pi f\left[\frac{2633.62}{8.85-\sqrt{\frac{2633.62}{R_L}-1}}\right]}, \; C_2 = \frac{1}{2\pi f\left[R_L\sqrt{\frac{2633.62}{R_L}-1}\right]}, \; C_3 = \frac{1}{2f\omega\left[\frac{1316R_L}{2\pi f L_3}\right]} \quad (1)$$

The value of the inductors:

$$L_1 = 66.33\left(\frac{\pi^2}{4}-1\right)\frac{1}{f}, \; L_2 = \frac{33.22Q}{\omega}, \; L_3 = \frac{\sqrt{1316R_L-R_L^2}}{2\pi f} \quad (2)$$

The system efficiency was calculated as 100%. This result was then checked against the simulation results and the experimental findings. Power input, Power output, and zero voltage switching (ZVS) were measured in MATLAB. Finally, the results of varying the capacitance plate distance from 1-7 cm were obtained. The variables that were calculated are listed in Table 1.

The experimental setup of the Class E-LCCL CPT system is shown in Figure 4. To ensure precise results are obtained (i.e. system efficiency, power output, power input, and ZVS measurements), the components used in this study used exactly matched or were similar to that of the simulation circuit. The simulation result and the experiment result were discussed in detail while considering a coupling capacitance plate distance, Cp, of 0.1 cm. Zero voltage switching (ZVS) is an important variable, as it ensures minimal power losses during switching in MOSFET [27].

Table 1. The variables of the study

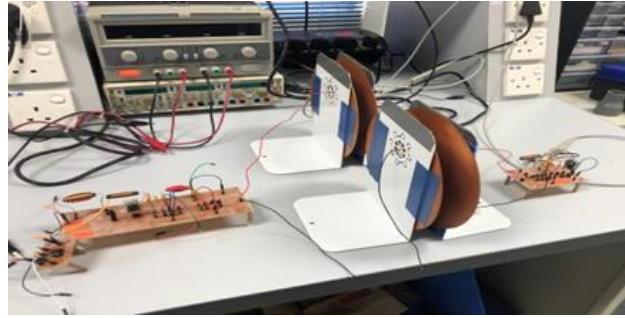| Name of variable	Unit	Value
Load resistance	R_L	50 Ω
DC supply voltage	V_{cc}	24 V
Reactance capacitor value	C_1	880 pF
Transmit resonant capacitor	C_2	475 pF
Receiver impedance capacitor	C_3	609 pF
Coupling capacitor value	C_P	120.9 pF
Choke inductor	L_1	230 μH
Reactance inductor value	L_2	53 μH
Receiver impedance inductor	L_3	40 μH

Figure 4. The CPT LCCL system experimental setup

Figure 5 shows the simulation results of ZVS, depicting a VDS=87 V and smooth, efficient switching while Figure 6 shows the ZVS experimental results with a VDS=107 V, which is still considered acceptable. Theoretically, both values of VDS (experimental and simulation) are good because both are higher than Vcc by 3- to 4-fold. Figure 7 to Figure 10 show the result of the experimental and simulated power input and output as well as the system efficiency.
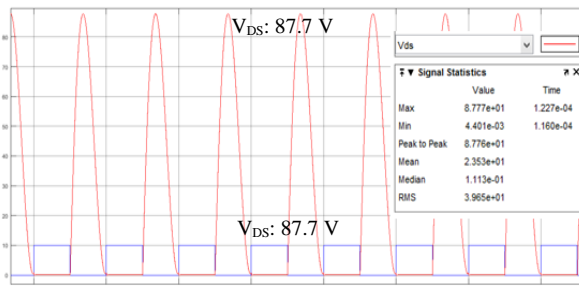

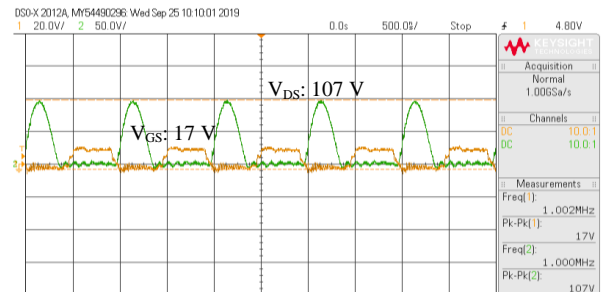Figure 5. ZVS simulation result of the Class E-LCCL CPT SYSTEM

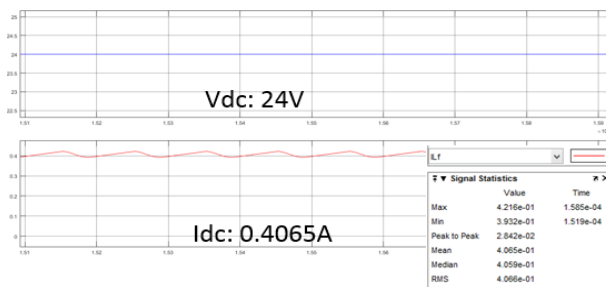Figure 6. ZVS experimental result of the Class E-LCCL CPT system

Figure 7. Class E-LCCL CPT system input voltage and input current simulation result
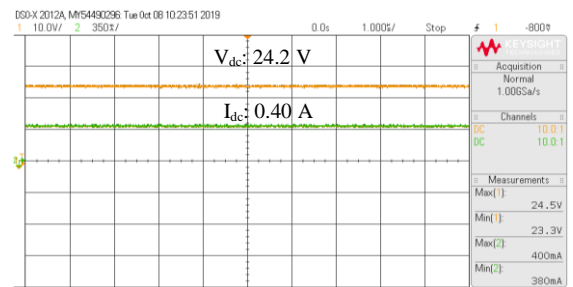

Figure 8. Class E-LCCL CPT system output voltage and output current simulation result
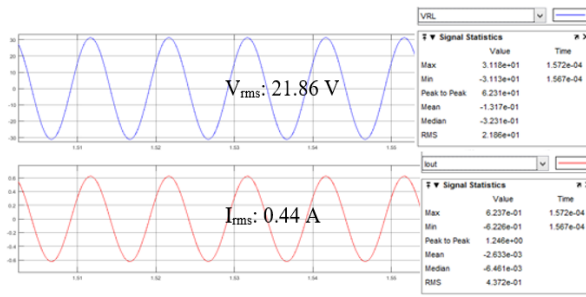
Figure 9. Class E-LCCL CPT system input voltage and input current experimental result
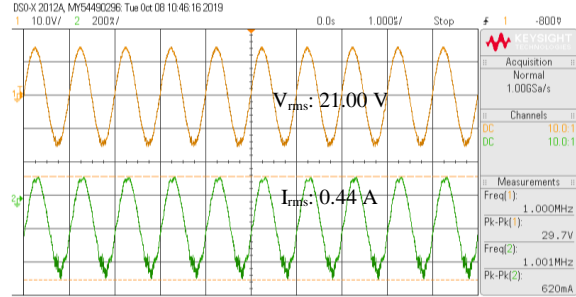

Figure 10. Class E-LCCL CPT system output voltage and output current experimental result

As shown in (3) presents an equation to calculate the system efficiency based on the power input and output obtained and as presented in Figures 6 to 9:

$$\%n = \frac{Vo(rms)*Io(rms)}{Vin(dc)*Iin(dc)} \qquad (3)$$

Table 2 lists the LCCL CPT system simulated and experimental efficiency, which are 97.96% and 95.45%, respectively. This result is based on the following conditions: the coupling capacitance plate distance was set to 1mm and the load was 50 Ω, while the power was 10 W; both results indicate the system's high efficiency in transferring power.

Table 2. System efficiency results

Variable	Variable Unit	Simulation Result	Experimental Result
Input Current (dc)	I_{in} (dc)	0.41 A	0.40 A
Output Current (rms)	I_o (rms)	0.44 A	0.44 A
Input Voltage (dc)	V_{in} (dc)	24.00 V	24.20 V
Output Voltage (rms)	V_o (rms)	21.86 V	21.00 V
Efficiency	%n	97.77%	95.45%

Next section of this paper is to investigate the performance of CPT system when the distance of cpacitive plate is no longer 0.1 cm. In this case, we investigate the condition of ZVS when the coupling plates distance are varied from 1-7 cm. Then the frequency tunung approach is proposed to get the optimum ZVS condition despite of the coupling capacitance plate's distance.

3. OPTIMUM ZVS DESIGN

In Section 2, the Class E-LCCL CPT system at resonant frequency, operating at a 1 MHz frequency with 97.96% and 95.45% efficiency, based on the results of the simulation and experimental works, respectively, was analysed at 1mm coupling gap distance. This section focuses on analysing the adjustment in the operating resonant frequency to select the best ZVS via calculation when the coupling plate's distance change. Table 3 shows the values of the variables when the distance between the coupling capacitance plates was varied from 1-7 cm.

Table 3. Variable values of the class E-LCCL CPT system when the plate distance was varied from 1 cm to 7 cm

Distance	1 cm	2 cm	3 cm	4 cm	5 cm	6 cm	7 cm
V_{in}	24.2	24	24	24.2	24.1	24.1	24.1
I_{in}	0.45	0.55	0.64	0.7	0.71	0.73	0.75
V_o	21.21	15.06	13.65	9.26	5.65	5.23	4.6
I_o	0.37	0.26	0.23	0.2	0.12	0.11	0.1
P_{in}	10.89	13.2	15.36	16.94	17.111	17.593	18.075
P_{out}	7.8477	3.9156	3.1395	1.852	0.678	0.5753	0.46
%n	72.06	29.66	20.44	10.93	3.96	3.27	2.54

The result shows that the change in capacitive plate distance could reduce emission field energy, as it is affected by total impedance, which will decrease, with an especially drastic reduction in efficiency when the plate distance was varied from 1-3 cm. Figure 11 shows the system efficiency when the coupling capacitive plates were varied from 1-7 cm.
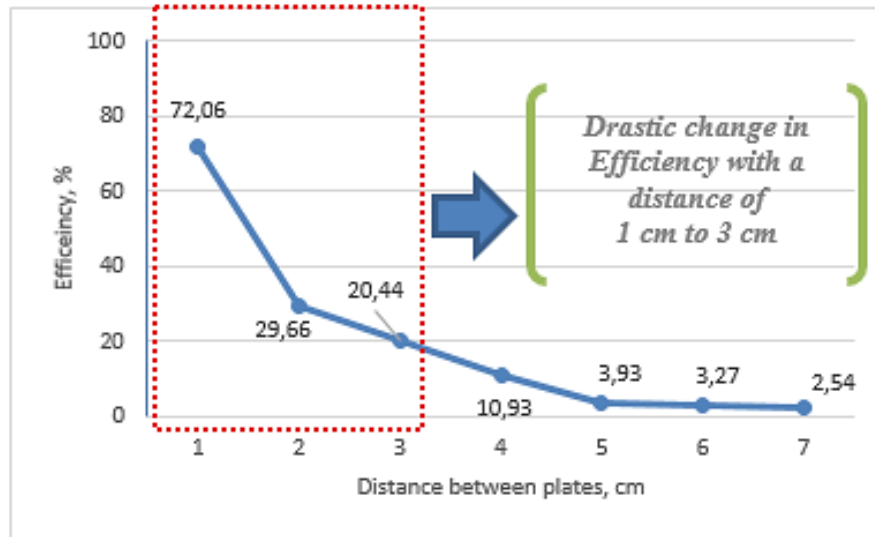

Figure 11. Graph of system efficiency vs. varying the distance of the capacitive plates from 1 cm to 7 cm

The result above does not exactly represent the switching of ZVS, as ZVS is affected by the change in the resonant frequency of the operating system.

The resonant frequency must, therefore, be selected from (4):

$$C_{eq} = \frac{C_1 C_S}{C_1 + C_S}, \ f_{01} = \frac{1}{2\pi\sqrt{LC_S}}, f_{02} = \frac{1}{2\pi\sqrt{LC_{eq}}}, f_0 = \frac{f_{02} - f_{01}}{2} \qquad (4)$$

Table 4 shows the result of the calculations for the new resonant frequencies of the system while varying the capacitive plate distance from 1-3 cm. The total capacitor series value and total equivalent capacitor value had to be changed due to the change in the capacitive plate value, which is 34.39 pF at 1 cm, 18.4 pF at 2 cm, and 14 pF at cm.

Table 4. Difference in variables as the plate distance was varied from 1cm to 3cm

Variable	Unit	1 cm	2 cm	3 cm
Reactance inductor value	L	53 uH	53 uH	53 uH
Reactance capacitor value	C_1	880 pF	880 pF	880 pF
Total capacitor series value	C_S	**509.55 pF**	**493.42 pF**	**489.01 pF**
Total equivalent capacitor value	C_{eq}	**322.7 pF**	**316.15 pF**	**314.33 pF**
Low resonant frequency	f_{01}	0.968 MHz	0.984 MHz	0.989 MHz
High resonant frequency	f_{02}	1.217 MHz	1.230 MHz	1.233 MHz
Resonant Frequency of the system	f_0	1.093 MHz	1.107 MHz	1.110 MHz

Thus, the measurement values are relevant for the calculation of the Class E-LCCL CPT system resonant frequency when the distance plates were varied. The ZVS, output voltage, and output current were measured using a digital storage oscilloscope (Agilent Technologies). Figure 12 shows the result of ZVS, and the change in the output voltage and the output current when the distance between the capacitive plates, fixed at 1 MHz resonant frequency, was set to 1 cm, 2 cm, and 3cm. The result shows the ZVS showing a gap during switching and the output voltage and the output current dropping with this change in distance. Figure 13 shows the result of the ZVS, the output voltage, and the output current when the resonant frequency was varied, as per Table 4.
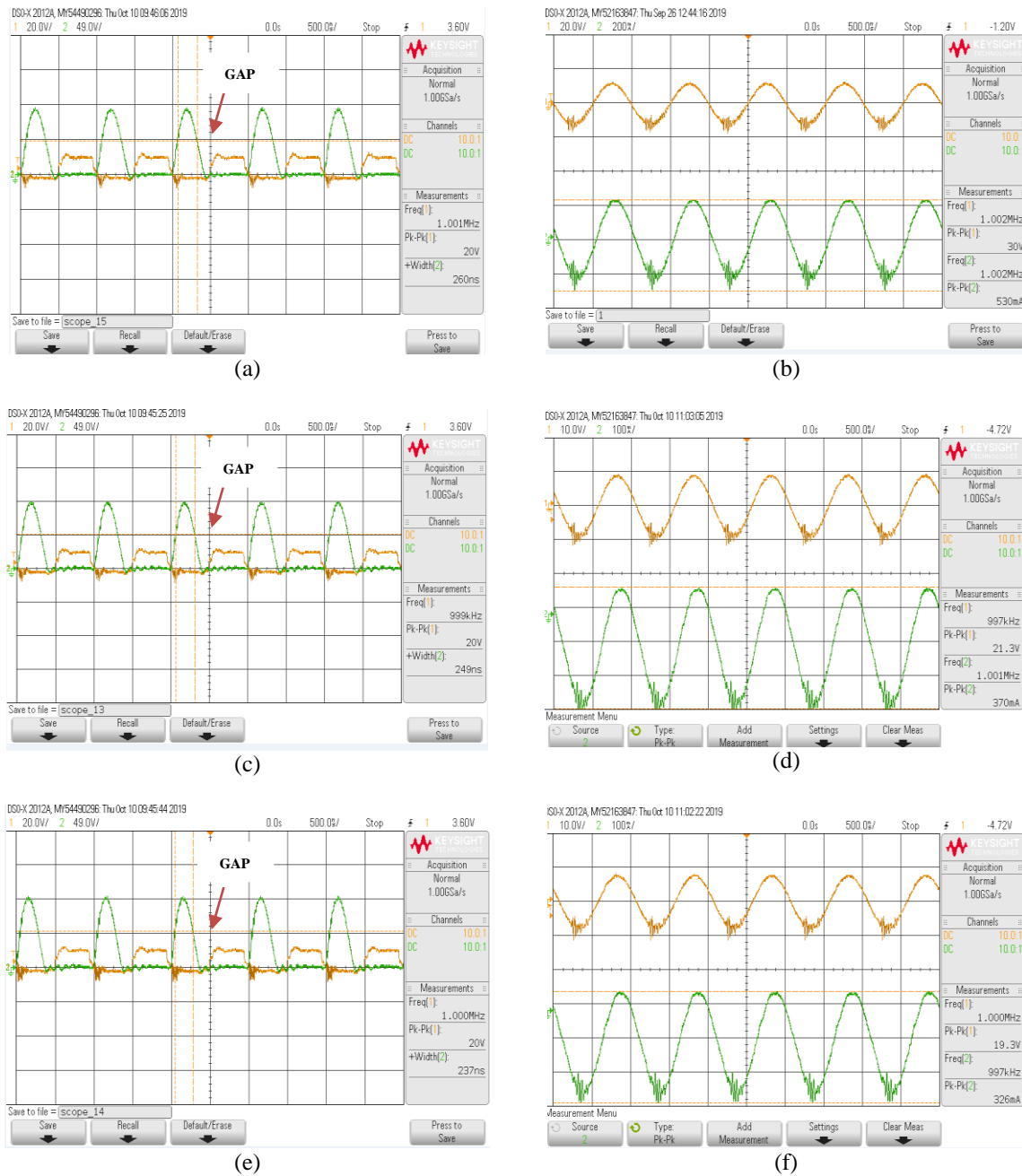
Figure 12. ZVS, ouput voltage, and output current at a fixed 1 MHz resonant frequency; (a) ZVS at 1cm, (b) output at 1 cm, (c) ZVS at 2 cm, (d) output at 2 cm, (e) ZVS at 3 cm, (f) output at 3 cm

The above result shows that the best ZVS condition was achieved with no gap during switching, with an operating resonant frequency between the bandwidth frequencies of f01 and f02. Otherwise, the results of the output voltage and output current would reduce drastically when the frequency was increased. Increasing the resonant frequency of the Class E-LCCL CPT affected the output voltage and the output current. Both parameters are related to the delivery of power to the load. Based on the analysis conducted, a change in the power output was obtained when the resonant frequency was changed because the total impedance of the Class E-LCCL CPT system also changed. After the calculation was done manually for a plate distance of 1 mm, the total impedance was found to be 57.94+j198.42 Ohm prefers of inductance impedance, XL. When the resonant frequency was increased, the total inductance impedance increased and caused the power output to drop. The power output is inversely proportional to the overall impedance of the Class E-LCCl CPT system.
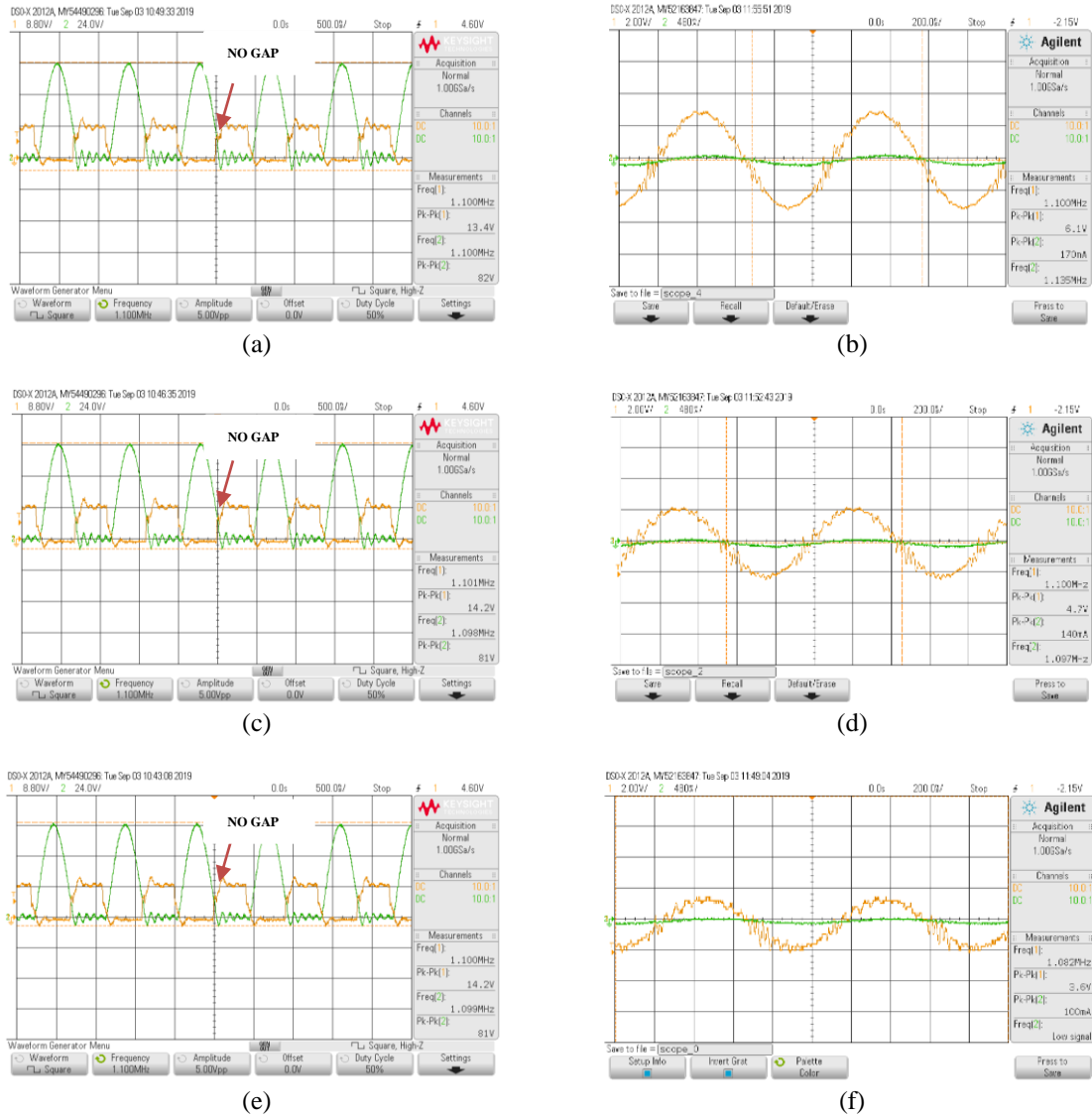
Figure 13. ZVS, ouput voltage, and output current at varying resonant frequencies; (a) ZVS at 1 cm,
(b) output at 1 cm, (c) ZVS at 2 cm, (d) output at 2 cm, (e) ZVS at 3 cm, (f) output at 3 cm

4.   CONCLUSION AND FUTURE WORK

In this study, a Class E-LCCL CPT System was successfully designed, operating at 1 MHz resonant frequency, and achieving 97.96% and 95.45% simulated and experimental efficiencies, respectively at 0.1 cm coupling gap distance. It was found that the efficiency of the overall CPT system was affected by power losses in the rectifier, the transmitter unit and the variation in the capacitive coupling distance. This study also identified the optimum ZVS can be achieved when the resonant frequency of the system is varied accordingly based on the distance changed. This study primarily aimed to reduce the power loss in the transmitter to enhance the CPT system efficiencyand it has been successfully delivered. It is recommended that future works focus on designing the mechanism to control thr frequency automatically when there is a change in distance. The findings of this study will greatly benefit wireless technology applications, especially in the medical field.

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