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Case Report
A Study of Capacitive Power Transfer Using Class-E Resonant Inverter

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Abstract
Capacitive Power Transfer (CPT) system has been introduced recently as an attractive alternative to the traditional inductive power transfer method. This is due to the CPT benefits of simple topology, fewer components, better EMI performance and robustness to surrounding metallic elements. This study proposed a CPT system consists of an efficient class-E resonant inverter and capacitive coupling formed by two flat rectangular transmitter and receiver plates. In CPT system, the capacitive coupling is used to transmit power between the transmitter and receiver units, in which efficient resonant high frequency ac power source is very much needed to ensure the best transmission rates and low power losses. Therefore, a class-E resonant inverter has been utilized as a high frequency AC power source because of its ability to perform the DC-AC inversion efficiently with significant reduction in switching losses even when operating at high frequencies. The validity of the proposed concept has been verified by conducting a laboratory experimental CPT system. The effect on output performance at an operating frequency 1 MHz for different capacitive plate sizes and distances are studied. The simulation and experimental results agree well with theoretical results.

Key words: Wireless power transfer, resonant inverter, capacitive coupling, DC-AC inversion, CPT system, ZVS

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INTRODUCTION

Recently, Wireless Power Transfer (WPT) systems have become more widely developed and investigated by Kline *et al.*[1], Liu *et al.*[2], Si *et al.*[3], Nair and Choi[4] and Duong and Lee[5]. The WPT is the transmission of electrical energy from a power source to an electrical load without man-made conductors. Innovative technology brings about new possibilities of supplying mobile devices with electrical energy by allowing elimination of cables, connectors and/or slip rings. This increases reliability and maintenancefree operation of such systems in critical applications such as aerospace, biomedicine, multisensors and robotics. Various techniques are divided according to the medium used for energy transfer such as acoustics based WPTs, light based WPTs, capacitive based WPTs and the largest group, inductively coupled WPTs.

The most popular WPT method is based on magnetic induction, known as Inductive Power Transfer (IPT). The IPT technique has achieved great success in theoretical development and industrial applications to deliver power in certain areas of applications. However, IPT has some limitations, (1) Magnetic field cannot penetrate through metals. This means that IPT cannot be used in situations where metal barrier exist between power sources and loads and (2) Electromagnetic field is used as the 'energy carrying medium'. This can cause electromagnetic interference (EMI). Therefore, to overcome these limitations, CPT is used since an electric field can penetrate through any metal shielding environment. The CPT not only can transmit through metal and shielded body, but also has good anti-interference ability of magnetic field proposed by Liu *et al.*[6], Theodoridis[7], Liu and Hu[8] and Kamarudin *et al.*[9].

In CPT system, the power converter circuit is the most important element because it determines the performance of the overall system. The power converter operates not only as the power converter, but also as the control circuit. According to previous studies, the current-fed push-pull inverter is very suitable for CPT system due to its simplicity and attainment of Zero Voltage Switching (ZVS) without extra control circuits[10]. But this topology is vulnerable to the variation of circuit parameters, so other types of high frequency resonant inverters need to be further investigated. Therefore, this study proposes a high efficiency class-E resonant inverter for the CPT application to obtain an excellent characteristic. Typically, switching power amplifiers such as class-d or class-E are the most suitable amplifier for the WPT systems because of their high efficiency, achieving near 100% theoretically switching losses[10-17]. Moreover, compared to other types of switching power amplifiers, the class-E has fewer components, yielding high reliability.

This study focuses on designing a CPT system using class-E resonant inverter. The contribution of this study can be summarized as follows:

- Design and analysis of efficient resonant power converter of the transmitter unit in the CPT systems are presented. The proposed class-E resonant inverter efficiency is 98.44% powered with 12 V DC and operated at frequency 1 MHz to produce a stable sinusoidal signal to drive the capacitive coupling based on flat rectangular copper plates
- The effect on output power performance at different capacitive plate sizes and coupling distances are systematically analysed, being proof through experimental results

CPT system overview: The basic structure of CPT system is shown in Fig. 1. This system consists of a transmitter unit, electric field coupler plates and a receiver unit. The transmitter unit is acting as a high frequency voltage source inverter that converts standard DC power supply to a high frequency AC voltage. There are several types of inverter which can be used at the transmitting side, such as push-pull resonant inverter[2]

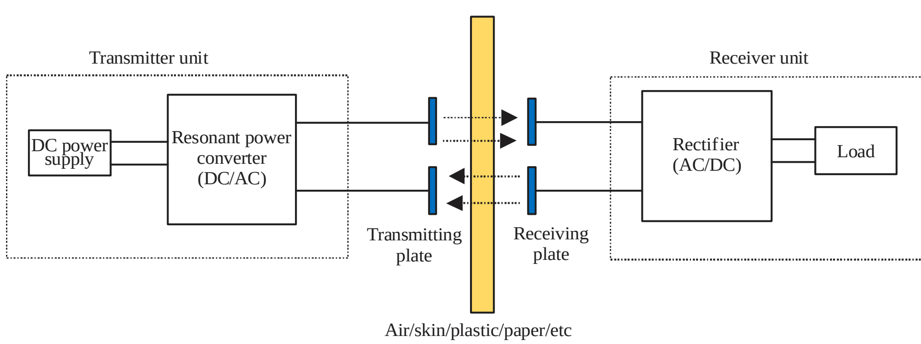

Fig. 1: Block diagram of CPT systems

Class-D inverter, class-E, class-F and other types of resonant converter topologies by Hannan *et al.*[18] and Huang *et al.*[19].

The electric field coupling part is the key element of the complete WPT system. During the operation of CPT, the electric field coupler functions as two capacitor plates connected in series. The operation of CPT system requires a high frequency voltage to drive the two primary plates. When two secondary plates are placed close to them, an alternating electric field is formed between the plates resulting in displacement current that will flow through it. As a result, power can be transferred to the load without direct electrical contact and meanwhile, certain freedom of movement between the primary and secondary plates is allowed. The capacitive coupling structure can be of various configurations according to different applications such as rectangular, cylinder, disk and matrix[6,20].

For the receiver unit, it will regulate the collected power and drive the load as demanded. In most cases, the power collected by the receiver side cannot be used directly by the load. As can be seen in Fig. 1, the rectifier circuit in the receiver unit usually comes with the power flow controls to regulate the collected power. In the case of powering or charging moveable load, any position change at the receiver side can cause mismatch between the coupling plates. This can cause significant voltage drop and degrade the power transfer capacity. Therefore, power flow control circuits are usually necessary to maintain the output power at constant level.

Class-E resonant inverter: The basic circuit of the class-E ZVS resonant inverter that is considered in this study (Fig. 2). In Fig. 2a, the circuit operation can be divided into two modes:

Mode 1 and mode 2. During mode 1, the transistor Q is turned on. The equivalent circuit is shown in Fig. 2b. The switch current i_{ds} consist of source current i_{dc} and load current i_o. To obtain an almost sinusoidal output current, the values of L and C are chosen to have a high quality factor and low damping ratio. The switch is turned off at zero voltage. When the switch is turned off, its current is immediately diverted through capacitor.

During mode 2, transistor Q is turned off. The equivalent circuit is shown in Fig. 2c. The capacitor currents i_{cp} becomes the sum of i_{dc} and i_o. The switch voltage rises from zero to maximum value and fall to zero again. When the switch voltage falls to zero, i_{cp} normally is negative. Thus, the switch voltage would tend to be negative. To limit the negative voltage, an antiparallel diode is connected across the switch. If the switch is a MOSFET, its negative voltage is limited by its built-in diode to a diode drop.

To achieve ZVS condition, the operating frequency should be between the resonant frequencies f_{o1} and f_{o2} which are given in Eq. 1 and 2, where total equivalent capacitance $C_T = {}_{Ccp}/(C+C_p)$.

$$f_{o1} = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

$$f_{o1} = \frac{1}{2\pi\sqrt{LC_T}} \tag{2}$$

Many factors should be considered in order to design optimum class-E resonant inverter. The components such as L_F, C_p, L, C and the switch transistor should be chosen to

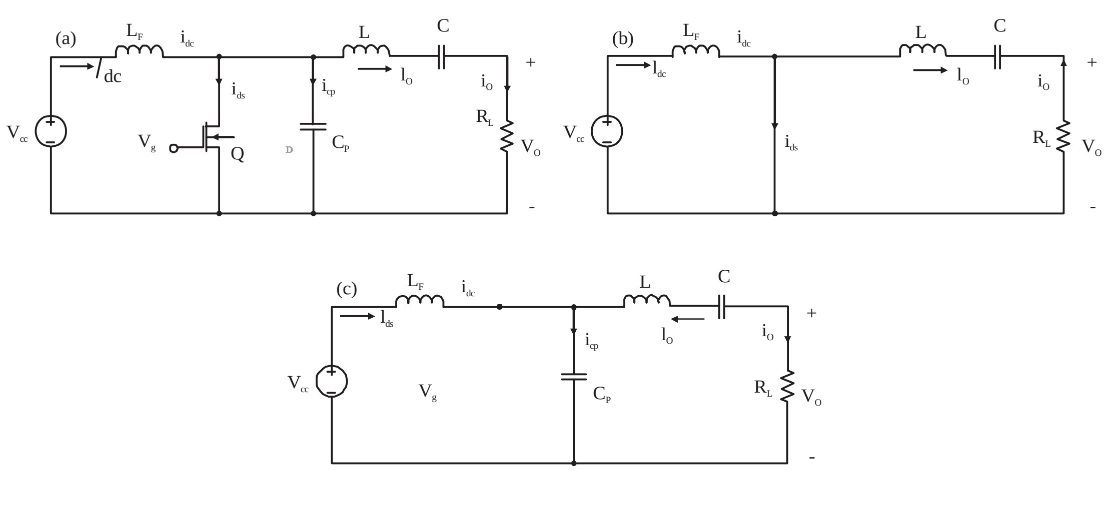

Fig. 2(a-c): (a) Typical class-E circuit, (b) Equivalent circuit: Mode 1 and (c) Equivalent circuit: Mode 2 achieve high speed of switching at the predetermined output power. The values of the components shown in Fig. 2 are calculated as follows.

The full load resistance is:

$$R_L = \frac{8V_{CC}^2}{(\pi^2 + 4)\ P} \tag{3}$$

The current drawn from the DC power supply is:

$$I_o = \frac{P}{V_{cc}} \tag{4}$$

The component values for the load network are as follows:

$$C_P = \frac{I_o}{\omega\pi V_{cc}} = \frac{1}{\omega R_L\left(\frac{\pi^2}{4}+1\right)\frac{\pi}{2}} \tag{5}$$

$$C = \frac{1}{\omega R_L\left(Q - \frac{\pi\,(\pi^2-4)}{16}\right)} \tag{6}$$

$$L = \frac{QR_L}{\omega} \tag{7}$$

where, Q is quality factor. In order to keep the current ripple in the choke inductor stays at below 10% of the full-load DC input current I_{dc}, the value of the choke inductance must be greater than:

$$L_{f\ (min)} = 2\left(\frac{\pi^2}{4}+1\right)\frac{R_L}{f} \tag{8}$$

In practical terms, the choke inductance value is not all that critical, as long as its impedance is atleast an order of magnitude higher than the load resistance and it is not selfresonant at the first three or four harmonics. It needs to look like an open circuit to these harmonics, if possible.

MATERIALS AND METHODS

Figure 3 and 4 shows a block diagram and complete experimental set-up for the proposed CPT system, respectively. In this application a DC power source is used. Since high system frequency and low standing power losses are preferred, a class-E resonant inverter as shown in previous section is designed. The design specifications used here are as follows; DC power supply, V_{cc} = 12 V, operating frequency, f = 1 MHz, duty cycle, D = 0.5, Q = 10 and output power, P_o = 10 W. Based on the design specifications, all the circuit parameters are calculated and tabulated as in Table 1. Then simulations are carried out using Proteus before the real circuit is implemented. In order to validate the simulation results, the experimental study is carried out.

The CPT system proposed in this research can be divided into three parts, a transmitter unit, capacitive coupling plates and a receiver unit. For the power converter of the transmitter unit, a class-E resonant inverter has been utilized as a high frequency ac power source because of its ability to perform the dc-to-ac inversion efficiently with significant reduction in switching losses even when operating at high frequencies. IRF510 MOSFET is used as a switching device in the design. The SK40C microcontroller board with PIC16F887A is used to generate a 1MHz switching control signal at 50% duty cycle for the MOSFET gate. However, the microcontroller output voltage, typically 5V is not sufficient to turn on the IRF510 MOSFET that requires at least 10V to operate in safe operating area. Therefore, an IC gate drive TC4422 is used to provide sufficient gate voltage or charge to drive the IRF510 MOSFET.

For the capacitive coupling structure, the capacitive interface is implemented with copper plate capacitors

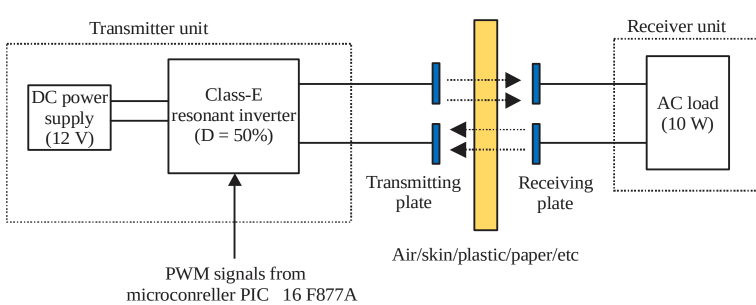

Fig. 3: Proposed CPT system block diagram

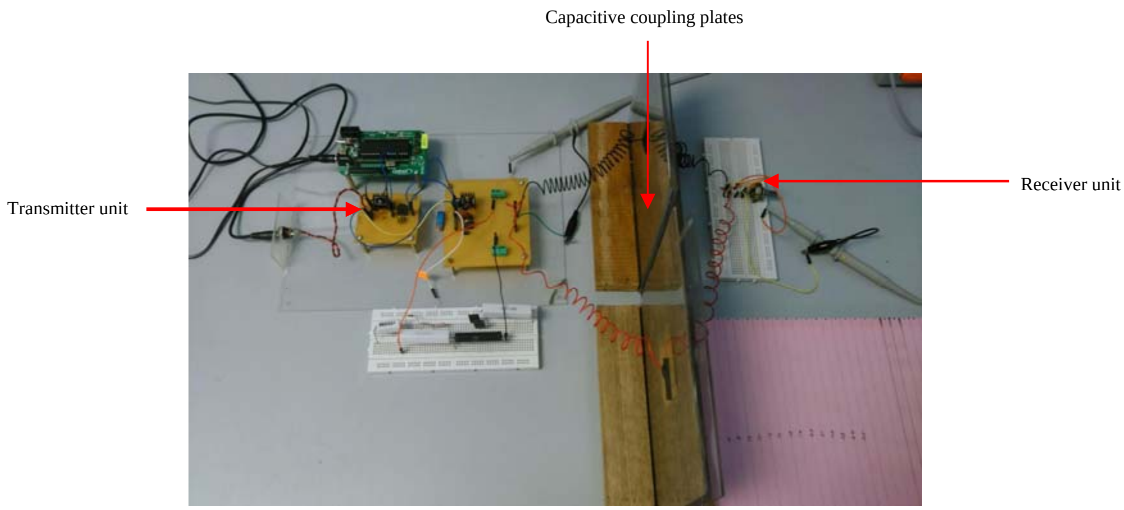

Fig. 4: Proposed CPT system experimental set-up

Table 1: Class-E design parameter

		Design values		
Parameters		Calculation	Simulation	Experiment
R_L	Ω	8.31	8.31	8.4
Cp	F	3.52	3.52	3.60
C	nF	2.17	2.17	2.20
Lf	uH	57.60	57.60	100.00
L	uH	13.22	13.22	13.30

Table 2: Class-E resonant inverter results

		Results		
Performance Parameter		Calculations	Simulation	Experiment
VRL(peak)	V	12.89	12.00	12.50
Vds(peak)	V	42.74	41.00	39.00
Idc	A	0.83	0.82	0.80
IRL(peak)	A	1.55	1.44	1.50
Vc(peak)	V	114.03	112.00	108.50
VL(peak)	V	128.89	122.00	125.50
Is(peak)	A	2.39	2.10	2.30
Is(rms)	A	1.28	1.26	1.20
Po(ac)	W	10.01	8.62	9.45
Pi(dc)	W	10.00	9.84	9.60
h	%	100.12	87.56	98.44

separated by a piece of white A4 paper. The copper plates are clamped together to minimize capacitance variation due to flatness imperfection. The initial gap is about 1 mm with a dielectric constant of 2.5. In this study, the impact of changes in plate size and distance on the output voltage performance is investigated. The investigation is done by using two different plate sizes and the distance is limited from 1-150 mm.

The experimental set-up for the design presented in Figure 4 was implemented with discrete components on a Printed Circuit Board (PCB). The components were chosen to match the above design as closely as possible. All the voltage and current of the designed CPT system are measured by using a Sanwa CD771 digital multimeter and agilent technologies DSO-X 2012A oscilloscope was used to obtain the waveforms data of the output voltage. The analysis of the results obtained is discussed in the following section.

RESULTS AND DISCUSSION

Figure 5 shows the waveforms obtained from Proteus simulation and circuit experiment for the class-E resonant inverter at operating frequency 1 MHz. It can be seen in Fig. 5a and Table 2, the simulation value for the maximum voltage across MOSFET during turn OFF is $V_{ds(peak)}$ = 4 1V, almost three times larger than V_{cc}. Meanwhile, during turn ON, $V_{ds(peak)}$ = 4.5 V, nearly 11% of the peak switch voltage. In an optimum design yielding the maximum drain efficiency, the switch voltage V_{ds} at the switch turn ON time is usually 10% to 50% of the peak switch voltage, which is a nonzero voltage switching condition. From Fig. 5b, the experiment value of maximum voltage across the MOSFET during turn OFF is $V_{ds(peak)}$ = 37.8 and 8.75% lower than the simulation value. Meanwhile, during turn ON, $V_{ds(peak)}$ = 4 V, nearly 10% of the switch peak voltage. The experiment value of the peak output voltage, $V_{RL(peak)}$ is 12.50 V, 2.9% higher than the simulation value.

All the simulation and experiment results are consistent with the theoretical predictions for the first circuit design. Therefore, it can be concluded that the optimum operation can be achieved only at an optimum load resistance, $R_L = R_{opt}$. When $R_L = R_{opt}$, the sinusoidal output voltage will reach nearly

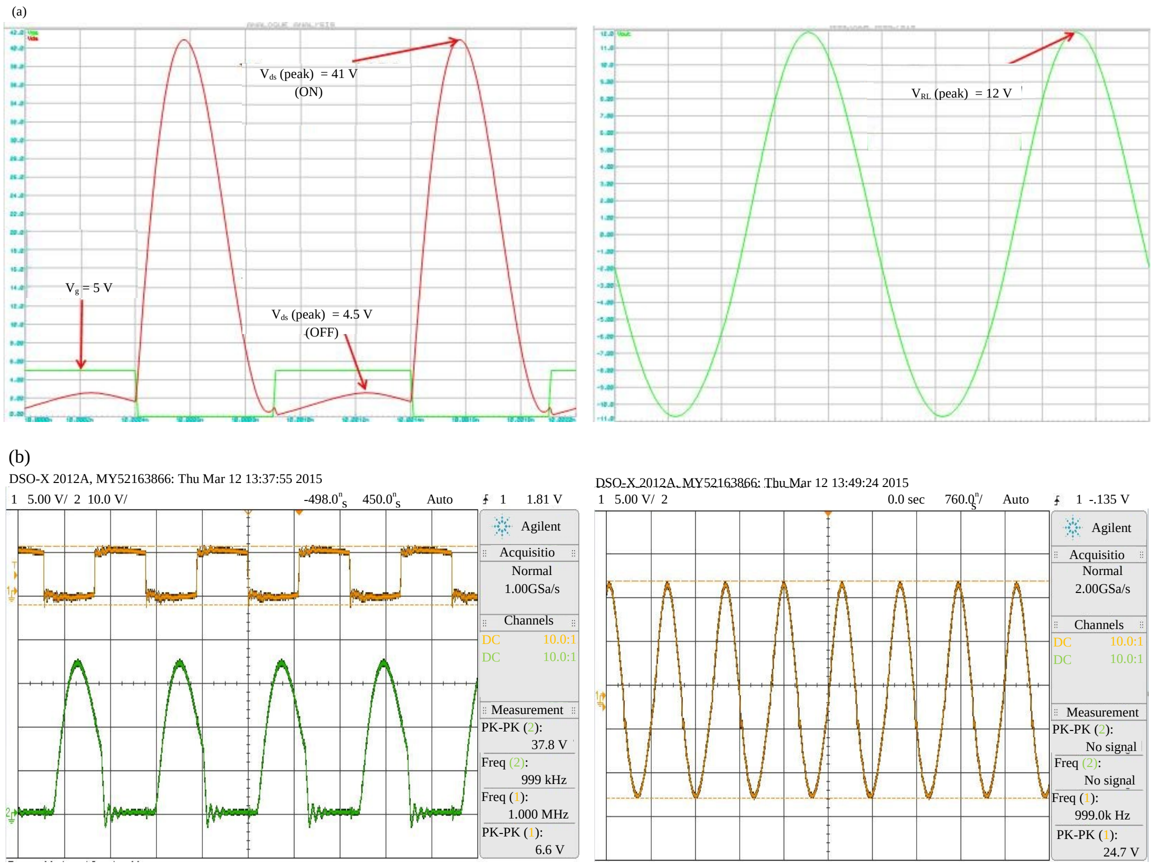

Fig. 5(a-b): Input, switching voltage and output voltage waveforms for the class-E resonant inverter at 1 MHz frequency, (a) Proteus simulation and (b) Circuit experiment

to maximum for all tested operating frequencies. Furthermore, the experiment switching voltage waveform proved that the class-E power amplifier circuit using PIC16F877A satisfy the ZVS conditions since there is no overlap between voltage over the MOSFET channel and current through the channel. In terms of the efficiency, it can be seen that the experiment circuit produces 98.4% efficiency, 11.05% higher than the simulated value. This is due to switching losses, non-pure resistive load, Equivalent Series Resistance (ESR), parasitic resistance of each components and dissimilarities in component selections for experimental circuit.

Analysis of CPT systems: An experimental set-up for a complete CPT system with a rectangular coupling structure has been developed in order to verify the proposed concept. From Fig. 6a, the experimental of initial voltage indicated at the transmitter plate is 11.45 V and the voltage at the receiver is 11.05 V. Meanwhile, from Fig. 6b, the experimental of initial voltage indicated at the transmitter plate is 11.25 V and the voltage at the receiver is 8.3 V. They are measured when the two plates are clamped together with the gap distance less than 1 mm. From Fig. 7a, the initial output power for the plate size equal to 0.0144 m^2 is 0.7 mW with the combined interface capacitance of 3186 pF and at an operating frequency of 1 MHz. Meanwhile, from Fig. 7b, the initial output power for the plate size equal to 0.0025 m^2 is 0.4 mW with the combined interface capacitance of 550 pF, at the same operating frequency of 1 MHz. From the results obtained, this behavior can be correlated to the equivalent capacitance equation of each pair of the coupling plates as expressed below:

$$C = \frac{A\varepsilon_0\varepsilon_r}{d} \quad (9)$$

where A, d, ε_0 and ε_r denote the effective coupling area, the coupling distance, the permittivity in vacuum and the relative permittivity of the dielectric material between the coupling plates, respectively.

From Eq. 9, theoretically, capacitance is directly proportional to the dielectric constant and physical size of the plates as determined by the plate area. Meanwhile,

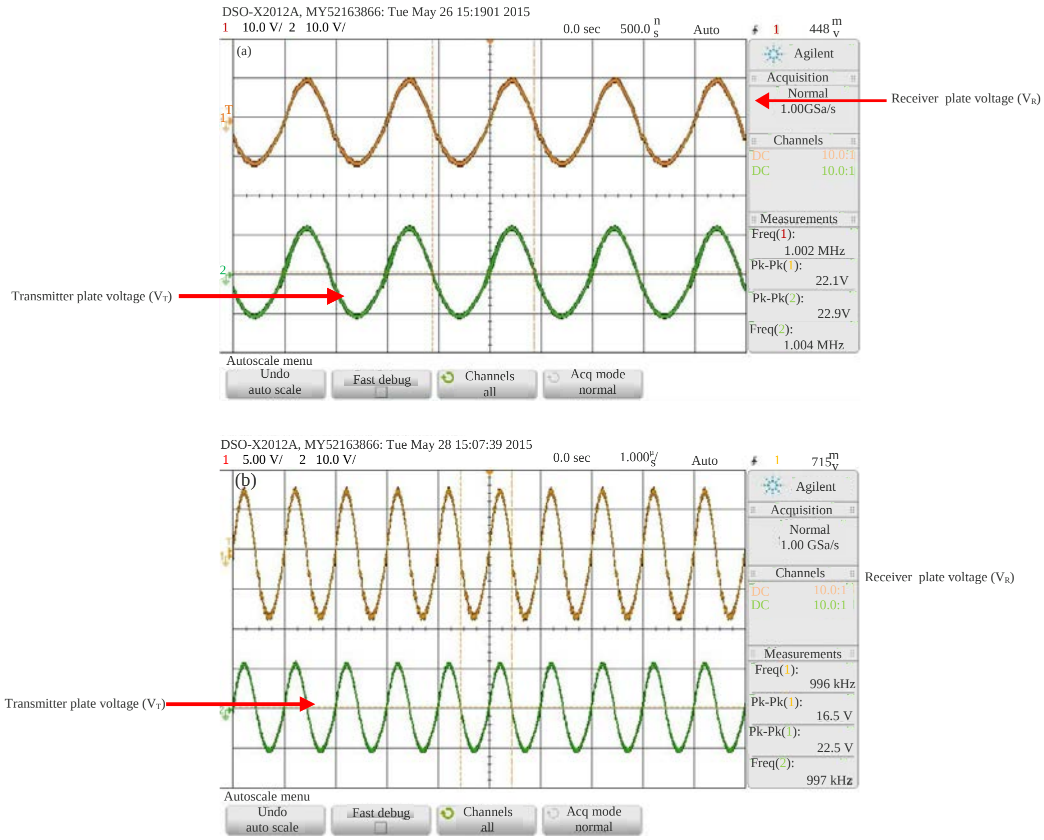

Fig. 6(a-b): Waveforms of V_T and V_R for the CPT system at d <1 mm, (a) Plate size: 0.0144 m^2 and (b) Plate size 0.0025 m^2

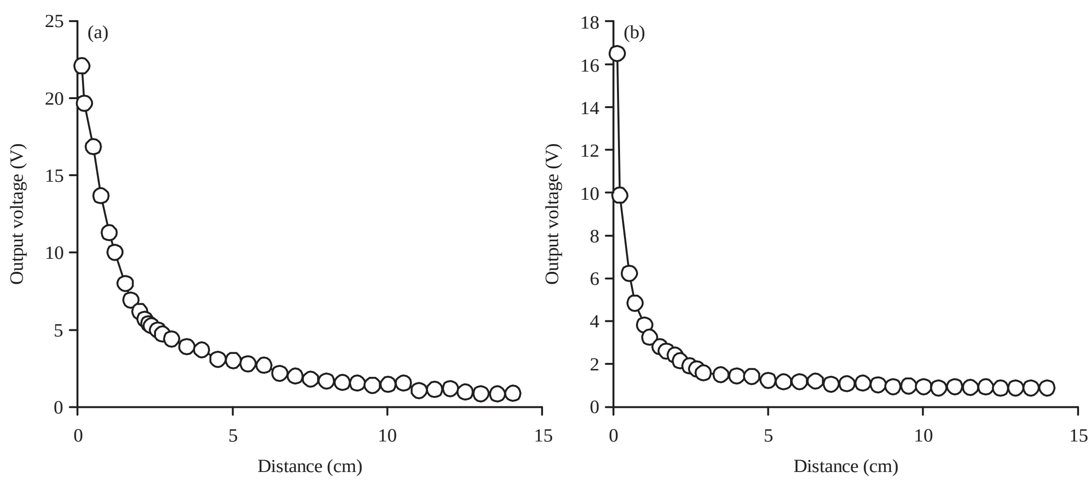

Fig. 7(a-b): Analysis of output voltage for different plate sizes and distances, (a) Plate size 12×12 cm and (b) 5×5 cm

capacitance is inversely proportional to the distance between the plates. A larger plate area produces more capacitance and a smaller plate area produces less capacitance. This relationship behavior of the CPT system can be proven by the graphical analysis plotted in Fig. 7. Starting at a gap distance of 1 cm, the plotted graph shows that the receiver voltage is decreasing exponentially towards 0 V. The most obvious finding to emerge from this study is that small air gap capacitive coupling enables high efficiency contactless power transfer.

CONCLUSION

An analysis of the CPT system using class-E resonant inverter has been presented. The requirement of power converter for the CPT system at the transmitter side is analyzed. The switch control signal for IRF510 MOSFET using microcontroller PIC16877A has been proposed and the experiment results indicate that ZVS condition can be achieved successfully. In the experiment result, the class-E resonant inverter efficiency is 98.44% powered with 12 V dc and operated at frequency 1 MHz to produce a stable sinusoidal signal to drive the capacitive coupling based on flat rectangular copper plates. Furthermore, the analysis of the output power efficiency for different coupling gap has been investigated. The agreement between experiment performance and theoretical performance can still be considered excellent. For future development, CPT system with self-tuning feedback controller will be investigated in order to solve the mismatch between coupling plates problems and increase the power transfer efficiency.

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