A Modified Class-E π1b for Capacitive Power Transfer System

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***Abstract*—This paper exhibits the advancement of another power transfer method utilizing electric field as energy medium transfer, namely capacitive power transfer. Capacitive power transfer system has been introduced as an attractive alternative to the traditional inductive coupling method due to better electromagnetic interference performance and robustness to surrounding metallic elements. In this work, a Class-E inverter has been utilized to drive the proposed CPT system. However, the Class-E inverter is highly sensitive to its circuit parameters under the scenario of having small capacitance at the coupling plate. As a solution, a π1b matching type has been integrated with Class-E inverter to provide impedance transformation and increase coupling capacitance for a better performance. The validity of the proposed idea has been approved through a 10W experimental work. The performance of the proposed topology is broke down in term of zero voltage switching and DC-DC effectiveness. Experimental work has successfully demonstrated that the proposed system able to transfer 8.82W of power across the 1.82nF capacitive interface, operating frequency of 1MHz, with 91.2% efficiency at 0.25mm working distance.**

***Index Terms*— Capacitive Power Transfer, Class-E Inverter, Wireless Power Transfer, Zero Voltage Switching.**

I. INTRODUCTION

In the recent decade, abundant resources and research has been dedicated in the area of wireless power transfer (WPT). WPT is extremely relevant to power electrical devices in situations where interconnecting wires are inconvenient or risky. The theory of transferring power without wires was first formulated and demonstrated by Nikola Tesla in the year 1891 at Columbia College, New York [1]. In the following months, Tesla utilized inductors to transfer power wirelessly [2]. The capacitive coupled system was forgotten after the invention of an inductive system. The capacitive coupled system was overlooked until the year 2008. However, since 2008 up to date, the CPT technology has attracted much attention as an alternative solution to WPT [3][4][5][6][7][8][9]. Compared with the conventional inductive power transfer (IPT) which uses inductive magnetic field coupling, it transfers power through capacitive electric field coupling. Therefore, it has the ability to transfer power through metal objects, which is a desirable feature in many wireless power transfer applications with metallic obstacles. Apart from that, the development of coupling structure is simple and does not require high costs. When comes to high frequency, the CPT may compete IPT because it does not require high frequency rated magnetic core which makes the system bulky and costly. Due to these advantages, CPT became more attractive method in contactless power transfer applications.

Figure 1 shows a block diagram of a CPT system. It consists of transmitter unit, capacitive coupling unit, and receiver unit. The resonant power converter is acting as a high frequency inverter that converts standard frequency DC supply to high frequency AC voltage. This AC voltage is then supplied to the transmitting plates. When the receiving plates are placed close to the transmitter plate, an alternating electric field is formed and resulting displacement current that can flow through it. Receiver unit will regulate the captured power and drive the load as demanded. The electric field coupler functions as two capacitors connected in series during the CPT operation. As a result, power can be transferred to the load in receiver unit without direct electrical contact.

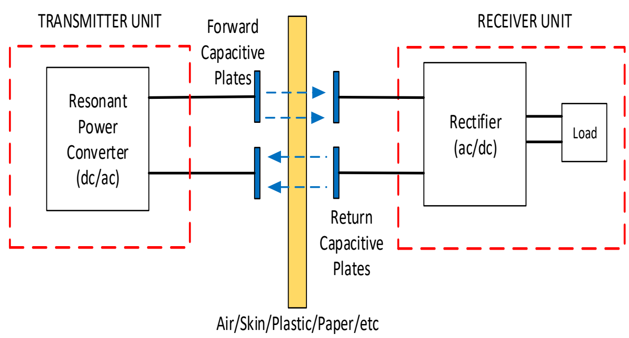


Figure 1: Block Diagram of Typical CPT System

In CPT system, the power converter circuit of the transmitter unit is one of the most important element because it determines the performance of the overall system. According to [13], [14], [15] and [16], Class-E is the most suitable amplifier for the WPT systems because of their high efficiency, achieving near 100% theoretically. Therefore, this paper proposed CPT system with a single-ended switch Class-E inverter that. other types of high frequency resonant. The contribution of this paper can be summarized as follows:

1) Development of efficient CPT system based on the Class-E inverter with a π1b matching network. The experimental efficiency is 91.2% powered by 12V DC, and operated at frequency 1MHz to produce a stable 8.82W to the load.

2) The operating principle, design procedures of the proposed CPT system are briefly discussed, and their performances are compared in term of ZVS condition and DC-DC efficiency.

The rest of the paper is organized as follows: Section 2 presents the design idea of the proposed CPT system. Section 3 presents the design procedure and both simulation and experimental results are shown in Section 4. Final conclusion are drawn in Section 5.

II. Proposed Block Diagram

The block diagram of the proposed CPT system is shown in Figure 2. A Class-E inverter converts the input DC voltage to high frequency AC voltage. Then followed by the LC network that boosts the voltage at the transmitter side and to increase power transfer. To transfer high power through the coupler, it requires generating high voltage between the capacitive plates to build up electric fields. The capacitive interface consist of two set of parallel plates, separated by air as a dielectric medium. The receiver side of the capacitive interface is connected to the full–bridge rectifier that supplies DC voltage to the load. This type of single phase full-bridge rectifier uses four individual rectifying diodes connected in a closed loop "bridge" configuration to produce the desired output. The main advantage of this bridge circuit is that it does not require a special center tapped transformer, thereby reducing its size and cost. The single secondary coupling plate is connected to one side of the diode bridge network and the load on the other side as shown below. In the CPT operation, the load is actually connected in series with diode rectifier and both forward and return capacitive plates.

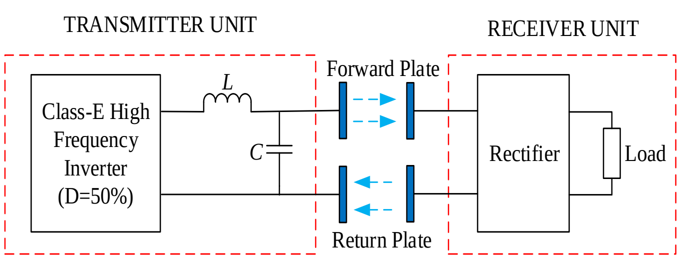


Figure 2: Block Diagram of the Proposed CPT System

Another purpose of the LC matching network is to convert the load resistance or impedance into the impedance required to produce the desired output power P_o at the specified supply voltage, V_{dc} and the operating frequency, f. According to (1), V_{dc}, P_o and R are dependent quantities. In many applications, the load resistance is given and is different from that given in (1). Therefore, there is a need for a matching circuit that provides impedance transformation. A diagram of the Class-E inverter with an impedance matching circuit πlb is shown in Figure 3. This impedance matching type is selected because there is a capacitor that is connected in series with a load, which will be then modified to capacitor coupling plate to fit actual CPT system. In addition, π1b matching type able to match the load resistor, R_L that is lower than series resistance, R_S while offering constant-current output through the load.

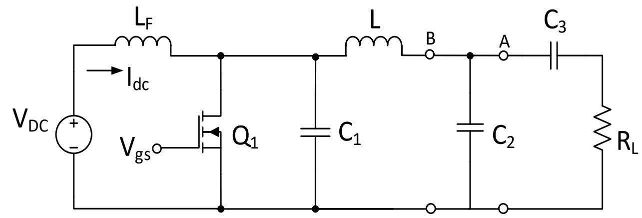


Figure 3: Class-E with π1b Matching Circuit.

The design parameters of the circuit shown in Figure 3 are defined as follows.

The full-load resistance is:

$$R = Rs = \frac{8V_{dc}^2}{(\pi^2+4)P_o} = 0.5768\frac{V_{dc}^2}{P_o} \quad (1)$$

The reactance of shunt capacitor is:

$$X_{C1} = \frac{1}{\varpi C_1} \approx 5.4466R \quad (2)$$

The reactance of the resonance inductor is:

$$X_L = \omega L = Q_L R \quad (3)$$

The minimum of choke inductance, $L_{f(min)}$ is:

$$L_{f(\min)} = 2\left(\frac{\pi^2}{4}+1\right)\frac{R}{f}. \quad (4)$$

The coupling capacitance, C_3 is:

$$C_3 = \frac{1}{\omega R_L\sqrt{\frac{R[(Q_L-1.1525)^2+1]}{R_L}-1}} \quad (5)$$

The transmitter matching capacitance, C_2 is:

$$C_2 = \frac{Q_L - 1.1525 - \sqrt{\frac{R[(Q_L-1.1525)^2+1]}{R_L}-1}}{\omega R[(Q_L-1.1525)^2+1]} \quad (6)$$

The power efficiency, η can be calculated from the input power, P_{in} and output power, P_o, that is:

$$\eta = \frac{P_o}{P_{in}} = \frac{V_o^2}{RV_{CC}I_{dc}} \quad (7)$$

Where Q_L is loaded quality factor.

III. Design and Implementation

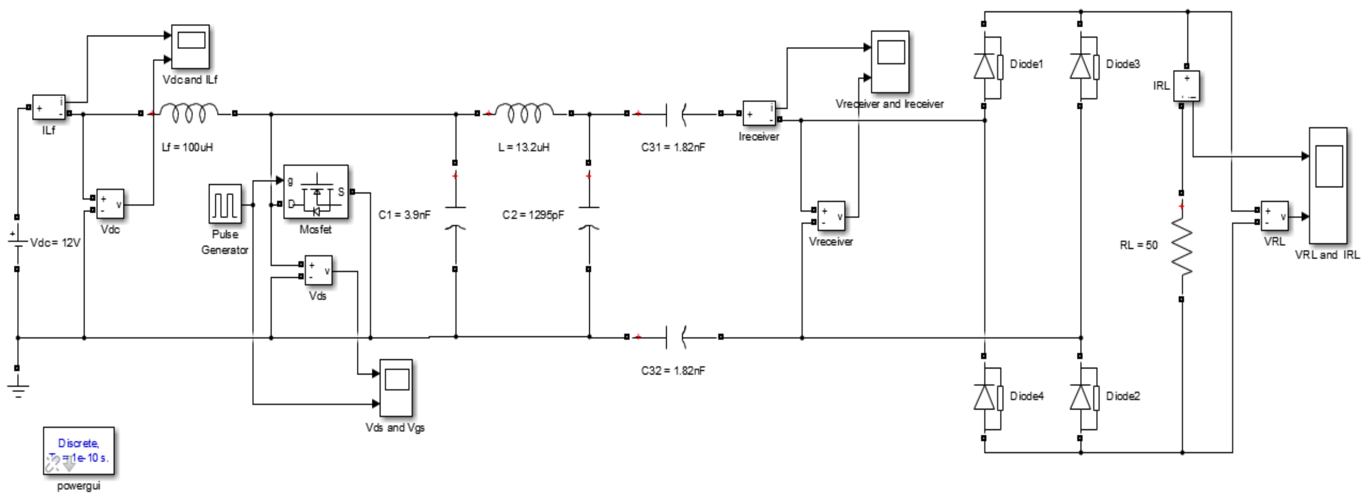


Figure 4: Circuit Simulation using MATLAB Software

Based on the equations provided in Section 2 and system design specifications, all the circuit parameters for the proposed CPT system are calculated and tabulated as in Table I. To validate the performance of the proposed topology, computer simulations of the CPT system in Figure 4 are carried out using MATLAB Professional Software before the real circuit is implemented. The components of the simulation circuit were chosen to match the design as closely as possible. All the voltage and current of the designed CPT system are measured in order to analyze the performance of the developed CPT system in term of ZVS condition, input power, output power and DC-DC efficiency.

Table 1
Design Specification and Circuit Parameter

Design Specification		**Circuit Parameter**	
Parameter	Design Value	Parameter	Design Value
Vin	12V	*Lf*	57.6uH
Pin	10W	L_1	13.2uH
Po	10W	C_1	3.52nF
f	1MHz	C_2	1295.3pF
R_L	50Ω	C_{31}=C_{32}	1820pF
D	50%	C_3	912.5pF

In this work, a 10W CPT system is designed, aiming to power a consumer electronic device through a capacitive coupling interface of 1.82nF with a working distance of 0.25mm. The design of coupling structure is very important since it directly impacts the maximum power transferred, output power, frequency and efficiency of the CPT system. As depicted in Figure 5, the coupling structure constitutes a pair of coupling plates, which in the rectangular form. The capacitance value can be calculated by applying (8), where *d* is the distance between plates, *A* is the area of the plate, ε_0 is the permittivity in vacuum, and ε_r is the relative permittivity of the dielectric material between the two conductive coupling plates.

$$C = \frac{A\varepsilon_0\varepsilon_r}{d} \tag{8}$$

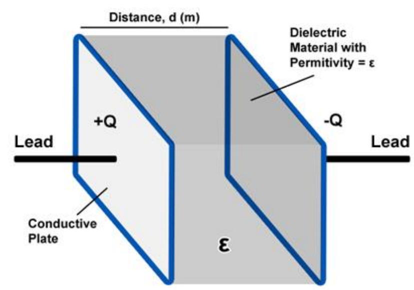


Figure 5. Coupling Structure

One of the factors that limit capacitive power transfer to be applied to long distance applications is the voltage across the capacitor given by equation (9). As the distance increases the capacitance of the coupling interface decreases. Thereby, increasing the voltage across the plates. This was one of the factors that limited CPT system from being used in the large air gap and high power applications.

$$V_C = \frac{1}{C}\int I(t)d(t) \tag{9}$$

In term of the operating frequency selection, it is determined by the value of coupling capacitance. It is worth to note that the voltage developed across the capacitor depends on the frequency of operation. Hence, the capacitive coupling plates can be reduced by increasing the operating frequency. Theoretically, the impedance of the coupling plates is inversely proportional to the capacitance and operating frequency. This fact implies that the capacitance and operating frequency should be large to minimize the coupling plate impedance, resulting in smaller coupling plate size. Also, the selection of operating frequency should not inference with the existing communication frequencies such as radio, cellular network, medical device communication, WIFI etc. Apart from that, operating frequency range affects a number of performance criteria. But the main consideration from a design perspective is system power efficiency and safety, particularly human exposure to radio frequency (RF). Human RF exposure is measured by the specific absorption rate (SAR) and the induced current density, or J field. Therefore, we as a designer must decide on a frequency that allows the best power transfer level within the permissible SAR and J field limits. Hence, 1 MHz operating frequency has been selected due to above mention reason.

IV. RESULTS

The analysis of the results obtained from both simulation and experiment is discussed in this section. A lab prototype of the proposed system has been developed as shown in Figure 6. The system performance parameter tabulated in Table II was analyzed and compared between theoretical, simulation and experiment. In this part, the system performance in terms of ZVS condition and DC-DC efficiency is studied.

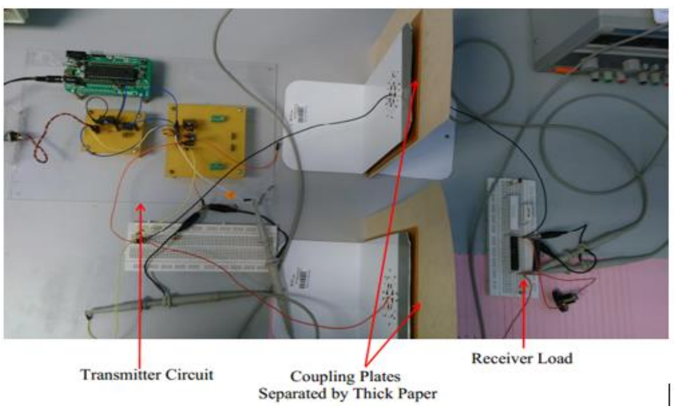


Figure 6: Experimental setup for CPT system with impedance matching circuit

Table2
System Performance Parameter

Parameter		Theoretical	Simulation	Experiment
Vdc	V	12	12	12
Idc	A	0.83	0.83	0.8
Vreceiver(peak)	V	31.6	31.6	30
Ireceiver(peak)	A	0.64	0.64	0.6
$V_{RL(avg)}$	V	22.36	21.72	21
$I_{RL(avg)}$	A	0.45	0.43	0.42
Pin	W	10	10	9.6
Po	W	10	9.34	8.82
η	%	100	93.4	91.9

A. Zero Voltage Switching

Based on the result in Figure 7, the maximum voltage across the MOSFET and the shunt capacitor during turn off is; $V_{ds(peak)}$ = 43.27V for simulation and $V_{ds(peak)}$ = 41.8V for an experiment. Meanwhile, during turn on, $V_{ds(peak)}$ = 0V for both simulation and experiment. Therefore, both waveforms proved that the ZVS condition has been satisfied since there is no overlapping in time between the MOSFET drain voltage and gate voltage.

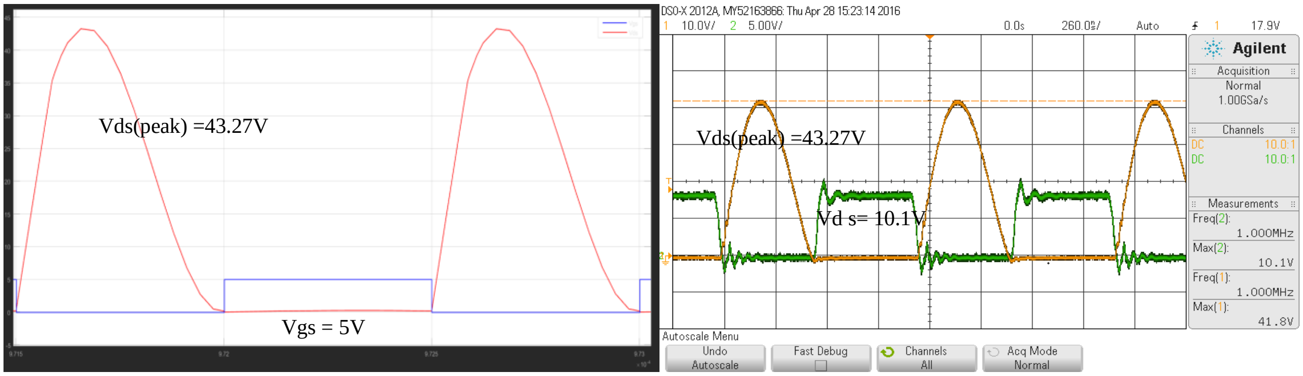
B. DC-DC Efficiency

The DC-DC efficiency is calculated by using (7). Figure 8(a) shows the measurement results for the input power and output power in the case of without a smoothing capacitor respectively. Firstly for the simulation results, the DC input power, P_{in} can be calculated using $P_{in} = V_{cc} \times I_{dc}$ = 12 x 0.83 = 10W. Meanwhile, for the DC output power of Figure 8(a)(i), P_o can be calculated using $P_o = V_{(avg)} \times I_{(avg)}$ = 0.636 x 31.6 x 0.4 = 8.08W. This will gives 80.8% simulation efficiency. Secondly for the experimental results as shown in Figure 8(a)(ii), Pi and P_o equals to 9.6W and 7.28W respectively. Therefore, in terms of efficiency, it can be seen that the CPT system circuit without a smoothing capacitor only can produce 81% efficiency.

Theoretically, the maximum efficiency of full-wave rectifier is 81.2%. This is due to non-filtered DC output voltage. As can be seen in Figure 8(b), the full-bridge rectifier produces an output wave every cycle, gives us an average DC value (0.637x$V_{receiver}$) with less superimposed ripple while the output waveform is twice that of the frequency of the input supply frequency. We can, therefore, increase its average DC output level even higher by connecting a suitable smoothing capacitor across the output of the bridge. In this case, a 0.1uF smoothing capacitor has been chosen. From Figure 8(b), the simulation output power has been increased from 8.08W to 9.34W. Meanwhile, for the experiment output power has been increased from 8.1W to 8.82W. Therefore, the practical work indicates the proposed system is able to transfer 8.82W to the 50Ω load with 91.9% efficiency. With the results tabulated in Table II, all the simulation and experimental results are consistent with the theoretical ones.

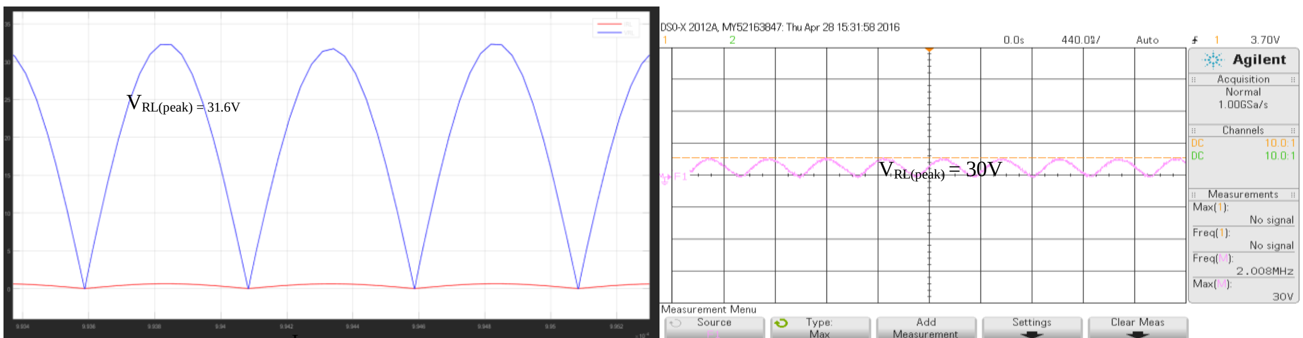
V. CONCLUSION

An analysis of the CPT system based on Class-E topology has been presented. The purpose of Class-E with π1b matching network is to help the CPT system maximize the power transfer by increasing voltage at the transmitter side and. Consequently, by utilizing the proposed method, the ZVS condition is still can be achieved even if the load is different from the optimum one.



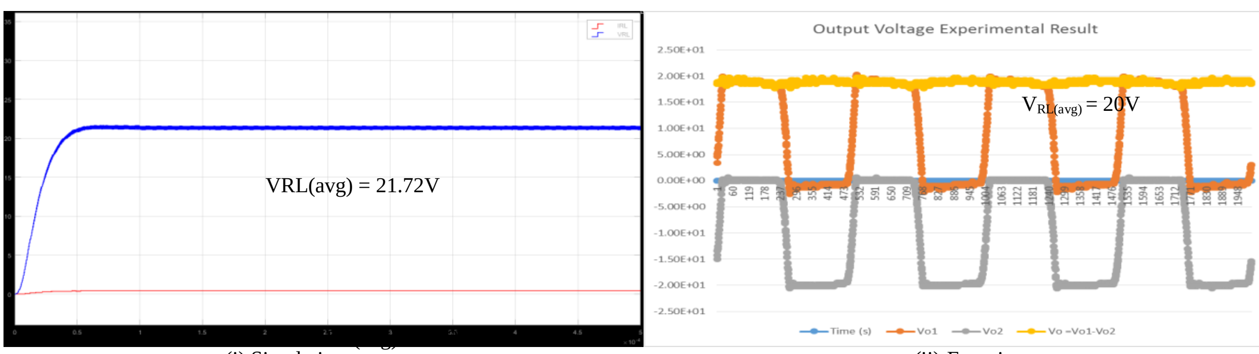
(i) Simulation (ii) Experiment

Figure 7: Zero Voltage Switching Waveforms



(i) Simulation (ii) Experiment

(a) Without SmoothingFilter



(i) Simulation (ii) Experiment

(b) With Smoothing Capacitor

Figure 8. Waveforms of Output Current and Voltage

Experimental work has shown that the efficiency is 91.9% powered with 12V DC, and operated at frequency 1MHz with only 1.82nF capacitive coupling plates. The agreement between experiment performance and theoretical performance can still be considered excellent.

For future development, the proposed system will be implemented practically and CPT system with self-tuning feedback controller will be investigated in order to increase the power transfer efficiency over a longer distance.

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