International Journal of Engineering & Technology, 7 (4.22) (2018) 77-81

International Journal of Engineering & Technology

Website: www.sciencepubco.com/index.php/IJET

Research paper

Design of Capacitive Power Transfer (CPT) for Low Power Application using Power Converter Class E triggered by Arduino Uno Switching Pulse Width Modulation (PWM)

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Abstract

This paper presents Capacitive Power Transfer (CPT) design for low power application using Arduino Uno Switching Pulse Width Modulation (PWM). Generally, the CPT system consists of primary side direct current to alternate current (DC-to-AC) resonant converter that converts DC to high frequency AC energy to the secondary side receiver via energy medium transfer. The secondary side is not connected electrically with the primary side, which is movable (linearly or/and rotating) to offer flexibility, mobility, and safety for supplied loads. The CPT that is examined in this study used TC 4422 and Class E MOSFETs as the main components to power the circuit, which is supported by Arduino Uno technologies to produce PWM signal. One advantage of this circuit is that the Class E MOSFETs yields low switching losses. In technical terms, the performance of CPT is determined by applying 250 kHz frequency and 12 V DC voltage (Adapter) via TC44422 and Class E MOSFETs circuits. Lastly, a CPT prototype has been successfully developed with 0.1 cm air gap between the two plates and generated sufficient power from the transmitter to the receiver plate to power up the devices. Based on the experimental outputs, the prototype exerted 85.49% of efficiency to transmit power, wherein the secondary plate received power at 5.85 V peak and 250 kHz. This research is beneficial for electrical hazardous environment, moveable applications, consumer electronics, and medical implants.

Keywords: *Capacitive Power Transfer, Wireless Power Transfer, Power Converter*

1. Introduction

In this globalization era, most of the modern charging devices, such as mobile phones and electric vehicles, do without the hassle of wire connection in charging batteries. Hence, Wireless Power Transfer (WPT) technology is preferable in substituting the conventional method of wired charger, as illustrated in Figure 1. In fact, three types of recent WPT techniques involve non-radiation power transmission, hence suitable to be used for near field applications such as Inductive Power transfer (IPT), Capacitive Power Transfer (CPT), and Acoustic Energy Transfer (AET)[1], [2]. Since IPT and AET systems possess several shortcomings, in which the IPT system is sensitive to metal barrier, while AET is very sensitive to variation in frequency[1], [3]. As such, this research proposes a CPT system due to its advantage in minimising power loss and electromagnetic interference (EMI)[4]–[6]. This technique employs an electric field to transfer power without any wire contact at the near field[7], [8]. As depicted earlier, the main drawback of contactless power transfer methods using magnetic coupling is that the power cannot be transmitted through metal barriers. Nevertheless, this is not the case for electric field coupling. Figure 1(a) illustrates a capacitive coupling with a metal slab that serves as a barrier between them. Upon insertion of the metal slab, charges of opposite polarity accumulate on the top and bottom surfaces. Since metals are good conductors, electric field does not exist within the metal slab. Hence, an imaginary wire, as portrayed in the equivalent diagram, substitutes the metal slab.

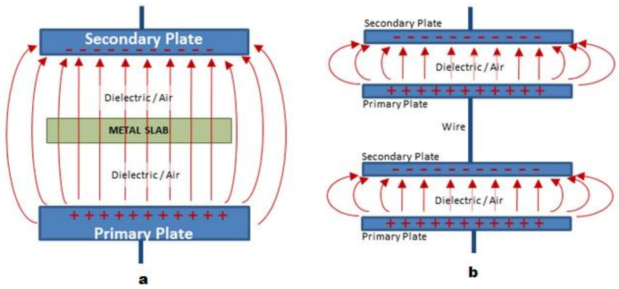

Fig 1: Capacitive Coupling

This means; a capacitive coupling with metal barriers embedded between them can be considered as two capacitors in series connection, wherein the total equivalent capacitance becomes larger due to reduction in effective air gap distance. Due to this unique feature, electric field coupling functions as a perfect contactless power transfer solution to transmit power through metal barriers, as portrayed in[9], whereby the charging is not hampered by the metal slab. Nonetheless, if a metal slab is inserted between inductive coupling, as displayed in Figure 1(b), the metal is deemed to block the magnetic flux, hence disabling power transfer to occur. In fact, since loosely coupled magnetic flux is emanative to form a loop, metals placed closer to the inductive coupling would be able to attract magnetic flux for a shorter reluctance path, thus causing power losses due to the generation of eddy currents[10]. The IPT has emerged to be the cutting-edge and predominant technique of implementing WPT systems. Nevertheless, when powering small devices under low power level, especially when compact physical spot are required, the IPT systems become impractical. Since IPT systems are more efficient at lower frequencies, they demand large circuit components[11]. With increasing frequency, CPT may compete with IPT, as the former can offer equally good galvanic isolation, cheaper to construct, and dismisses costly and high-frequency magnetic core. Moreover, a recent study has proven the efficacy of CPT in vehicle application after upgrading the coupling capacitive between every two plates to six-plate coupler, which substantially decreased electric field emissions[12]. Another experimental work generated 9.5 W output power by using a combined interface (Printed Circuit Board, PCB plate) capacitance of 2.82 nF at an operating frequency of 1 MHz, which resulted in 95.44% efficiency. The experimental work applied impedance matching to select the right frequency operating of CPT to minimise error of zero voltage switching (ZVS)[13].

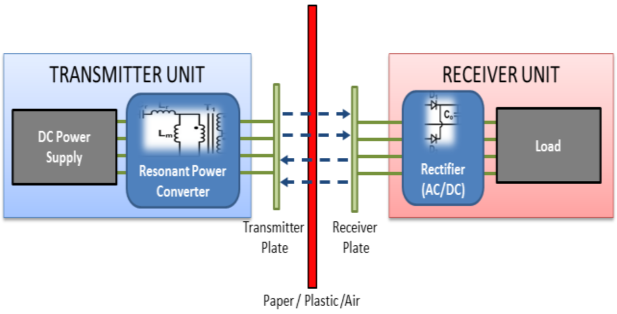

Fig 2: Block Diagram of CPT System

In precise, the CPT system works based on capacitive coupling that consists of two metal plates separated by an air gap, as illustrated in Figure 2. A primary converter circuit is attached at the transmitter side to transform direct current (DC) source into alternate current (AC) source, as presented in Figure 3.

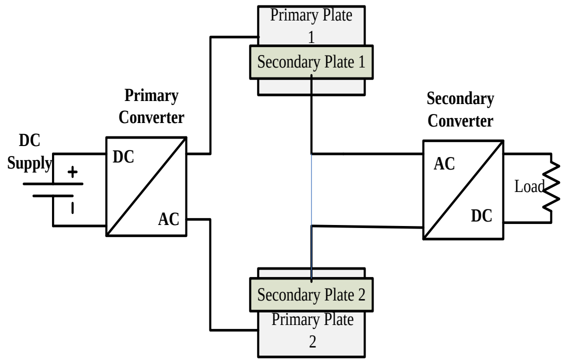

Fig 3: Typical converter power supply in CPT system

Since power is transmitted from the transmitter side to the receiver side via an air gap, high frequency current is required to drive two capacitor plates[8]. Therefore, a Class E resonant converter circuit is proposed in this paper due to its low switching losses[4], [5], [13]–[16] The AC on the primary capacitor plate, Plate 1, generates an oscillate electric field to induce AC on the secondary capacitor plate, Plate 2, through electrostatic induction. Hence, the secondary converter circuit or also known as the rectifier circuit is required to rectify the AC signal to change a DC, in powering the load. Nonetheless, in the CPT system, the major constraint is to generate high power transfer, which is caused by switching losses at the primary converter circuit. To date, various primary converter circuits have been designed and introduced to drive capacitive coupling to cater to the requirements of the modern power electronic devices. Additionally, Arduino Uno was applied in this research as a microcontroller to generate PWM at 250 kHz. The output from the Arduino Uno was injected into the circuit high driver, MOSFETs (TC4422), so as to generate 10 V output by using 5 V input (output voltage from Arduino Uno). After that, the output derived from the high driver MOSFETs circuit was injected into the Class E circuit to convert the 250 kHz PWM to 250 kHz Sine Wave. Next, the output from Class E circuit (Sine Wave 250 kHz) was injected into the transmitter capacitive plate, wherein the power was transferred to the receiver capacitive plate.

2. Power Inverter Class E in Capacitor Power Transfer (CPT)

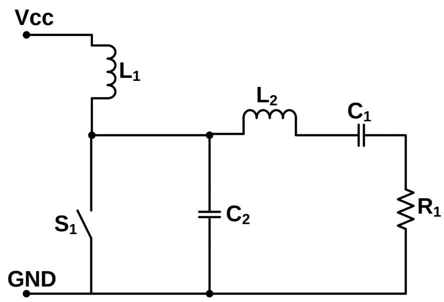

Fig 4: The basic circuit of Class E MOSFETs Inverter

Figure 4 illustrates the fundamental circuit of Class E MOSFETs Inverter, whereby the inverter can be technically used to fix output voltage. The amplifier consists of a load network that refers to a series of resonant circuit (RLC) and a shunt capacitor with power MOSFETs that operates as a switch at the input frequency to power the MOSFETs. The L choke, L_1, is usually applied to generate adequate DC in order to achieve ZVS condition. When a MOSFET is turned on, the current may overlap and some current discharged from the capacitor may be lost. The ZVS condition recycles and clamps all energy stored in the power transformer leakage inductance by softly turning on the power of MOSFETs. The condition enhances efficiency and discards the need of primary snubbers. It is importance to highlight that the ZVS can operate only during turn-on losses, switching losses in turn-off, and both overlapping. The Class E MOSFET has been reckoned to be the most productive and efficient inverter that generates ZVS condition.

3. ARDUINO UNO As Switching Device PWM

Figure 5 portrays a microcontroller board called Arduino Uno that functioned in this study to generate 250 kHz frequency and to supply 5 V directly to the MOSFET driver. The 5 V charged the MOSFETs to serve as a power amplifier that accepted input power and produced high output power, while simultaneously powering IRF510 with a minimal voltage of 12 V, and finally, driving the Circuit Class E MOSFETs.

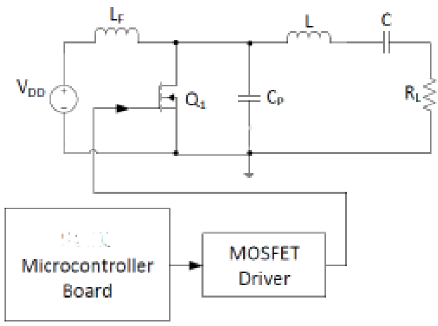

Fig 5: Class E Controller by Microcontroller

IRF510 was selected in this study due to its exceptional amplification that eases differentiation amongst multiple classes in amplification. For example, this component directly gives rise at power dissipation from switching losses. Besides, it offers a perfect sinusoidal waveform by blocking harmonics components prior to reaching the load. Hence, the IC drive, which is TC4422, had been employed to implement a charge that allowed Class MOSFET to function with sufficient voltage injection at the gate. High voltage was required to activate IRF510 and to convert PWM to Sine Wave AC. The output was injected from TC4422 circuit (250 kHz frequency, 5 V, and PWM DC) to drain and 12 V DC was connected to the inductor (34.7 micro farad) before connection was secured to the source. The gate was connected to the ground (GND).

4. Simulation Work of the CPT system

In circuit analysis, the equivalent circuit of capacitive coupling was modelled, as displayed in Figure 6. In order to simplify the analysis, the CPT system was segregated into transmitter and receiver sides. The transmitter side was attached to the Class E converter, whereas the receiver side used a circuit with low application to light up LEDs at ON condition.

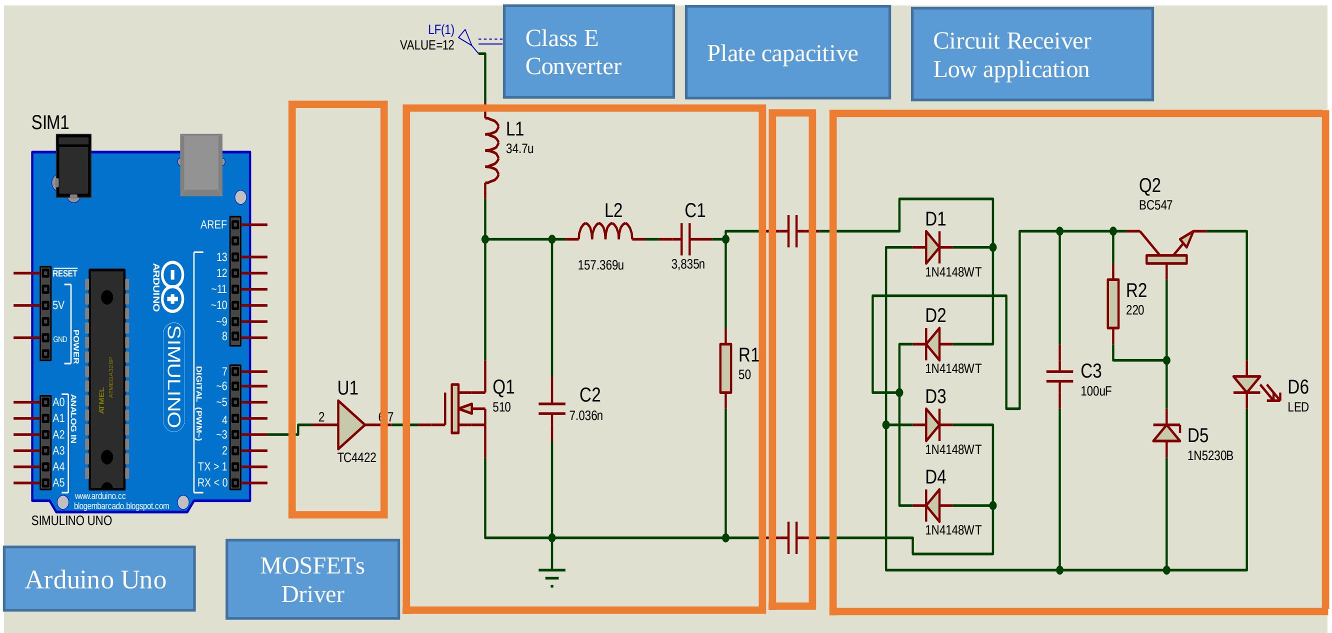

Fig 6: Overall Circuit of the CPT System using Controller PWM Arduino Uno

Figure 6 illustrates the overall circuit of the CPT System by using Controller PWM Arduino Uno for test by turning on the LED, while Figure 10 portrays the experimental outcomes of Class E Circuit Converter that generated 250 kHz frequency retrieved from the laboratory circuit experiment. The circuit of class E MOSFETs converter was designed after weighing in several practical aspects. A suitable value of inductor choke biased amplifier was identified as 34.7 uH. In analysing the amplifier, the values for shunt and resonant capacitors were 7.036 nF and 3.835 uF, respectively. After considering the selection of critical components, the analysis generated 250 kHz at a duty cycle of 50% with 12 V peak voltage. The performance analysis for Class E circuit had taken into account selection of viable critical components, such as choke inductor, shunt capacitance, and resonant circuit parameter. Figure 8 displays the outcomes with a smooth sine wave waveform at 250 kHz and a 50% duty cycle for a maximum of 18 voltage peak-peak. When all the values echoed the theoretical calculation presented in Table 1, it is ascertain that the right circuit and components do generate better results.

Table 1: Specification of Class E Circuit

Parameter	Theoretical/ Calculation
Voltage Input, Vcc	12 V
Power Output, Po	5 Watt
Frequency, f	250 kHz
Quality Factor, Q	10
Choke Inductor,L_1	34.7uH
Load Resistor,R_1	50 Ohm
Shunt capacitor,C_2	7.036 uF
Series Capacitor, C_1	3.835 uF
Inductance,L_2	157.369 uH

The passive component values for Class E converter circuit had been determined first. The required load resistance obtained from the switch was computed as follows:

$$R = \frac{8V_{CC}^2}{(\pi^2+4)P_O} \tag{1}$$

Next, the shunt capacitor value,

$$C_2 = \frac{P_O/V_{CC}}{\omega\pi V_{CC}} \tag{2}$$

The series capacitor,

$$C_1 = \frac{1}{QR\omega} \tag{3}$$

Then, the inductance, L, can be defined as

$$L_2 = \frac{1.153R}{\omega} + \frac{QR}{\omega} + \frac{RR_1\sqrt{R/R_1 - 1}}{\omega}$$

$$L_2 = \frac{R\left(1.153+Q+R_1\sqrt{R/R_1 - 1}\right)}{\omega} \tag{4}$$

Based on the calculated values, as described in equations (1) until (4), the simulation of Class E was designed and was analysed by using protues simulation, as illustrated in Figure 7.

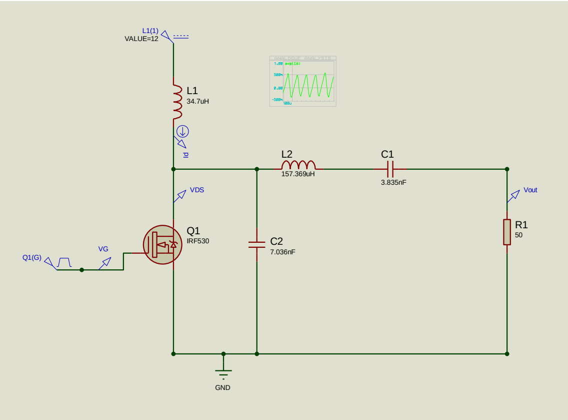

Fig 7: Measurement Points of Gate Voltage, VG, Drain Source Voltage, VDS, and Output Voltage, Vout

Figure 8 presents that the Voltage Output is 11.7 V peak. The efficiency of the proposed Class E MOSFET based on simulation was approximately 98.6% from the following calculation:

$$\text{Efficiency}, n = \frac{Vorms * IOrms}{VccIdc} * 100\% = 98.6\% \quad (5)$$

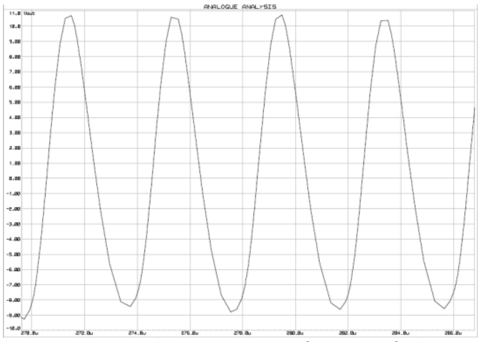

Fig 8: The Simulation Outcomes for Vout of Class E

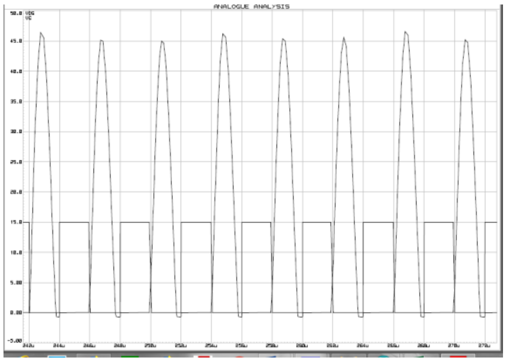

Fig 9: The Outputs of ZVS for VGS and VDS

Theoretically, the result should be 100% for efficiency of Class E MOSFET. Figure 9 displays the outcomes of ZVS upon trigger voltage at the MOSFETs gate. In theory, the value of VD must exceed that of VCC by 2- to 3-fold. Based on the simulation outputs, the value of VD was 45 V peak with minimal overlap in the waveform.

5. Experimental Work of the CPT system

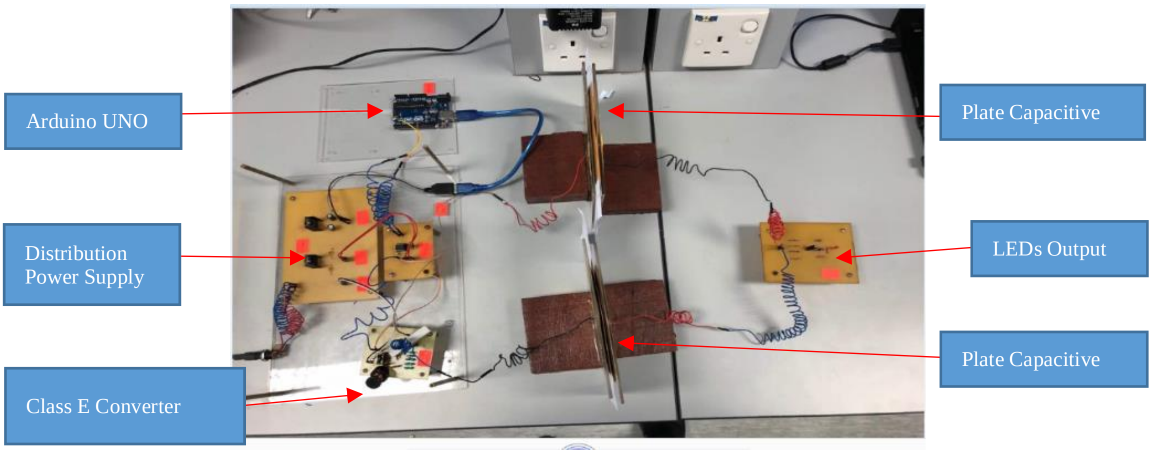

Fig 10: Experimental Setup Circuit to Test LED

Figure 10 presents the design steps adopted for experimental setup in relation to the proposed CPT system. The initial step in analysing the CPT system is to understand the capacitive, thus requiring some basic analyses of capacitive coupling. Nevertheless, since the capacitive coupling was treated as wholesome when designing the CPT system, the analysis turned challenging especially when the system order appeared to be high. Furthermore, based on the projection of the whole system, convictive conclusion was disregarded to determine the efficacy of the coupling itself.

Fig 11: The Outcomes of ZVS for Class E Converter

Figure 11 presents the practical experimental outcomes. As such, Vds recorded 47 V peak-peak, while Vgs resulted in 19.2 V peak-peak. The ZVS occurred when the switch was ON for the voltage gate at MOSFETs and the drain voltage was approximately zero. Nonetheless, when the switch was OFF, the voltage gate was zero and the VD was at its maximum point.

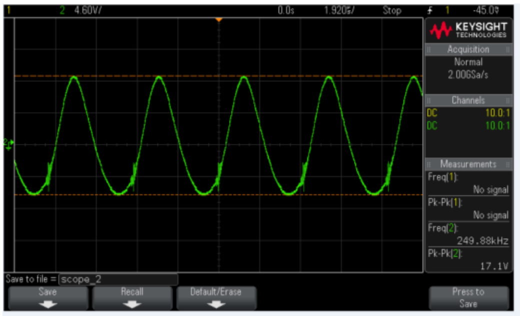

Fig 12: Output of Class E Converter

Figure 12 illustrates the output at the primary plate after the Voltage Output in Class E showed 8.55 Voltage Peak. The efficiency of the experiment was 85.49%. Theoretically, a 12 V peak should be attained, thus indicating power loss during switching. Another cause of power loss refers to the parasitic resistance in inductors and capacitors, which is also known as Equivalent Series Resistance (ESR). The following section focuses on the construction of CPT hardware for transmission of 5 W power to the load. Figure 13 portrays that the maximum output power received by the secondary plate was 5.85 V peak at 0.1 cm of air gap, which happened to be the closest distance between the capacitive coupling. This appeared to be the highest electric field that had been achieved. Additionally, it is indeed challenging to record a higher amount of power at the secondary plate of capacitive interface, mainly because the current generated by the secondary plate is relatively low due to high impedance load. Hence, this output can only be used for low power applications, such as that portrayed in Figure 10 to turn ON the LEDs.

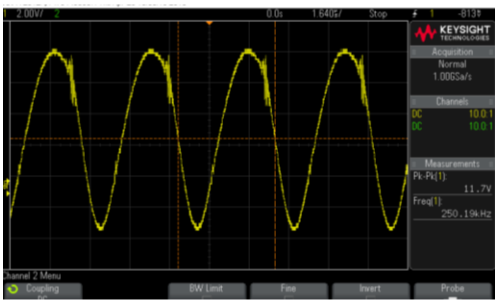

Fig 13: The results of CPT secondary plate

6. Conclusion and Recommendations

The WPT based on capacitive method using Arduino Uno had been successfully analysed in this study. This study proves that small air gap capacitors enable high efficiency contactless power transfer. In Class E MOSFETs converter, the analysis looked into performance switching and system efficiency. The Class E converter has been substantially applied in power transfer applications because it exerts exceptional performance and efficiency, particularly for high frequency applications. However, one challenge stumbled upon when designing the CPT refers to the small delivery power at the secondary plate. Therefore, the implementation of CPT is recommended for use of small applications, such as panel to charge the Unmanned aerial vehicle, UAV system, which is mostly used to monitor a large area in long distance. The CPT is based on pairing electric field between two capacitive plates and it dismisses the use of expensive ferrite core or intricate protection. These features of the CPT address the drawbacks of the IPT, which is a common method used to achieve WPT in operating system materials, wireless battery charge, and power supply to electric vehicle, to name a few. Some shortcomings of the IPT that is based on magnetic coupling between the loops are that it does not only demand the use of costly ferrite core, but also requires a shield to hinder from EMI occurrences. In future work in this direction research will focusing on CPT in analysis of performance differences distance between gap of CPT. That's will solve problem in losses power at secondary plate when to give a bit far distance between plates by method tuning parameters selected will discuss and new design on next research.

Acknowledgement

The authors would like to take this opportunity to express their gratitude and appreciation to Universiti Teknologi MARA (UiTM) and Universiti Teknikal Malaysia Melaka for professional support.

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