The Development of Capacitive Power Transfer for Biomedical Implantable Devices

F.A. Ahmad, S. Saat, N.M. Shaari , M.Z. Mustapa , A.A. Basari

Abstract*: Wireless power transfer using electric and magnetic near-fields has been used in many applications widely, and biomedical implants being one of them. The most commonly used method for powering power wirelessly to biomedical implantable device is using inductive coupling between two mutually-coupled coils. In this paper, a consider new method will be proposed in transferring power for biomedical device which is based on capacitive coupling and known as capacitive power transfer (CPT) system. The main reasons of using this method are the low electromagnetic interference (EMI), can reduce power losses and the abilities to transfer power across metal barriers compared to inductive power transfer. To be specific, in this work, we have designed Class E circuit as an inverter to convert the 12VDC to AC with 1 MHz frequency. The prototype of the capacitive power transfer for implantable application has also been successfully developed with capacitive plate dimensions of 3cmx3cm width per length for receiver plate and 4cmx4cm for transmitter plate, respectively. 5mm thickness of beef separation between the plates is used in this paper. The design specification of this work is accordance to stimulator for peripheral nerve implantable device which only needs 100 mW of power to operate in the CPT system. Overall, the developed CPT system for the biomedical device is able to deliver 76mWatt with 41.43% efficiency. To enhance the efficiency, the impedance matching circuit has been proposed in this work and the prototype is now able to deliver 140mWatt power to the DC load, achieving zero voltage switching (ZVS) waveform and efficiency of 77.5%.

***Keywords* : Capacitive Power Transfer, Impedance Matching, Biomedical Impnatable Devices, Class E Mosfet.**

I. INTRODUCTION

In the late of 19th century, the discussion about wireless power transmission as a contrasting option to transmission line power dissemination has been explored [1]. The possibility of wireless power transmission has been theorized both by Heinrich Hertz and Nicola Tesla. In 1899, Tesla has revealed the powering of fluorescent lamps 25 miles away from the power source without utilizing wires [1]. It was the first of public WPT showing to power a “typical” load between large capacitive plates [2]. Again, Tesla demonstrated electromagnetic induction through a separation and turned out to be more flexible for wireless power usage. In the era of 1900s, the inductive power transfer (IPT) methods by Tesla evolved and a few far-field radiative procedures were likewise advanced [3].

The transmission of electrical energy without wires is called wireless power transfer (WPT). WPT can be accomplished by creating electric, magnetic or electromagnetic coupling between a device and its counterpart [4]. This innovation can be another option to control electrical gadgets while interconnecting wires are troublesome, unsafe, or are impractical. WPT framework is utilizing the fundamental idea as appeared in Figure 1. The essential side includes DC-to-AC resonant converter that will convert DC control supply to high frequency AC energy. An energy transfer medium will then transferred the AC energy to the auxiliary side of receiver. The auxiliary side is not associated electrically to the essential side. High frequency AC energy is then changed by an AC-to-DC converter to meet the requirements indicated by the load parameters [5].

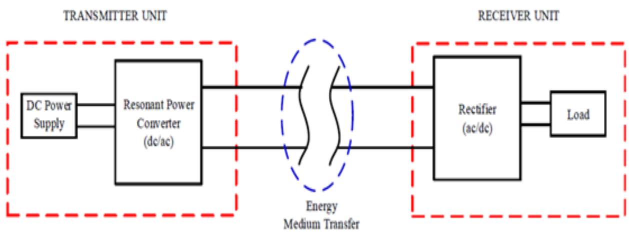

Figure 1: General Diagram of WPT

Wireless power techniques have two categories which are near-field and far-field. As for far-field or radiative techniques, which is also called power beaming, power is transmitted by beams of electromagnetic radiation, corresponding to microwaves or laser beams. As for near field techniques as shown in **Error! Reference source not found.**, power is transferred by magnetic fields using inductive coupling between coils of wire, or by electric fields using capacitive coupling between coupling plates. The power transferred in inductive coupling (electromagnetic induction or inductive power transfer, IPT), is occurring between coils of wire by a magnetic field. The transmitter and receiver coils together will act like a transformer. In capacitive coupling (electrostatic induction, CPT), the conjugate of inductive coupling, energy is transmitted between electrodes such as metal plates by electric fields. The transmitter and receiver plates will act like a capacitor, with

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the intervening space as the dielectric

IPT system is the most familiar energy transfer system nowadays where it utilizes coupled of the electromagnetic field coil. This system is very comparable with capacitive idea of energy transfer, however the capacitive idea utilizes capacitance coupling. The accomplishment of this IPT framework has been demonstrated in numerous applications, for example, assembled in electric vehicles, cell phones, and different sorts of the battery charging framework [7][8][9].

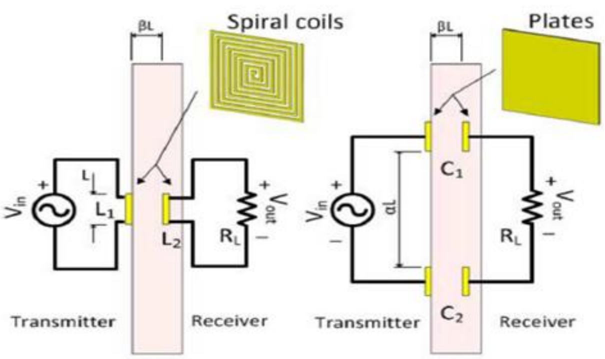

Figure 2: Comparison of IPT and CPT Techniques

However, in contrast of IPT, there are certain advantages of the electric field coupling; the CPT technology can overwhelmed the disadvantage that the magnetic energy could not be transmitted in the metal shielding environment. The CPT technology can transmit through the metal body, reduce energy loss, and also has good anti-interference ability of the magnetic field. Strong anti-interference makes the device able to work in saturated or intense magnetic fields environment, and can reduce energy loss and electromagnetic interference. Therefore, the CPT technology has a number of advantages that IPT technology unparalleled [10].

Transfer power across metal barriers is not possible when it comes to IPT systems as the magnetic field finds the path of least reluctance. Therefore, when the IPT system is placed in an environment, the system has extremely low efficiency. If a metal plate is placed between the primary and secondary coil of the power transfer system, eddy currents are induced in the metal plates and the magnetic field completes the pole to pole completion through the metal plates. Therefore, it will not allow power to be transferred. In the case of CPT systems, the presence of metal barriers does not affect the performance of the wireless system. If a metal plate is introduced between the transmitter and receiver, the metal plate behaves as another plate of a capacitor forming two series capacitors between the transmitter and receiver. The transfer of power remains unaffected and the metal plate introduced also acts as a range extender. Based on this characteristic, the technology is suitable for applications where there are metal objects present between the antenna. Therefore, the systems could be used in charging platforms of mobiles, laptops, electric vehicles etc [11].

Furthermore, the CPT system can be highly efficient due to the absence of eddy currents. In an inductively coupled system, the transmitter and receiver coil are nothing but a loosely coupled transformer. There are always eddy current losses in a transformer. Eddy current losses are inherent in transformers. The coils used can get heated due to the current in them. A CPT system would be a better choice as eddy current losses are absent and the system has low standing power losses. Due to its low standing power losses, the CPT system can be used in biomedical implants [11]. Besides that, we know that the design of magnetics is a complete area by itself. For an IPT system to perform at its best efficiency, the design of the magnetic components is very critical. With introduction in various configuration of coils and cores, the design gets more complicated along the way. However, in case of a CPT system, the design of the system is quite straight forward compared to the IPT system, which makes the CPT system stand out and easily integrable with other circuits.

II. CAPACITIVE POWER TRANSFER CONCEPT IN BIOMEDICAL DEVICE

One of the applications of the wireless power transfer system is biomedical implantable devices. Biomedical implants are being used for diagnostic as well as therapeutic purposes. Diagnostic implants are inserted into the patient’s body for recording physiological signals such as body temperature, blood pressure, and blood glucose level. Therapeutic implants are used for neuromuscular microstimulation, for instance to control limbs and bowel and bladder muscles, restore vision and hearing, or as miniature drug delivery systems [6]. Biomedical implants such as cochlear, retinal, neural and artificial hearts are mostly powered using transcutaneous transformers which use the principle of inductive coupling. Powering neural implants wirelessly eliminates the need for batteries: this can be achieved inductively and capacitively [4].

By using capacitive power transfer (CPT), compensation and tuning circuitry needed for proper operation can be retained at the transmitting side, hence reduces the complexity of implanted electronics. Moreover, the electric fields in capacitive link are well bounded by the capacitor plates unlike the magnetic fields in an inductive and hence have a better EMI performance and the effects of surrounding metallic elements are minimal [16]. Therefore in this work, the capacitive wireless power technology for biomedical implantable devices will be design as it has more advantages compared to IPT for the purposed of biomedical applications.

Capacitive coupling uses two parallel plate-pairs, separated by tissue. The energy that is fed to the implant is dependent on the electric field in both plate pairs as shown in Figure 3. The skin and tissue act as dielectric material for each capacitor, consisting of two plates: one of these plates is implanted, while the other one is applied to the surface of the skin. The plates are aligned so as to overlap maximally. We will be using small size of receiver plate so it will be more convenient to be implanted inside of the body. The overall development of the CPT system prototype is shown in Figure 3 and the specification of the power operated for the biomedical device application to be designed is according to peripheral nerve stimulator implant which only needs 100mWatt of power to operate [12]. The Class E circuit will be supply by 12V DC source and then convert it into AC power. The AC energy will then be transmitted to 4cm x 4cm transmitting plate and the powering transfer in AC energy is occurring between 5mm beef separation to the 3cm x 3cm receiver plate. In order to supply DC power to the load, the rectifier circuit that receives power from the receiver plate will convert

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AC to DC energy. The transmitter plate will be larger than receiver plate size since it will be placed outside of the body and to avoid misalignment.

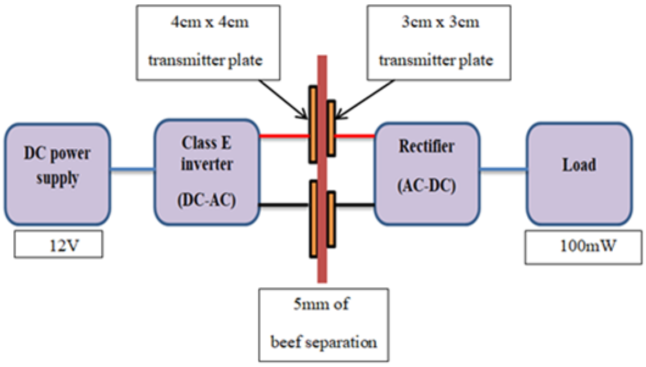


Figure 3: Overall block diagram of the proposed CPT system for biomedical implantable devices.

III. CLASS E INVERTER CIRCUIT DESIGN

A. Basic Class E Inverter Circuit Design

Class E inverter circuit is part of the design of capacitive power transfer system. The series capacitor, C component of the Class E inverter circuit as shown in the Figure 4 will later be replaced by the capacitive plate. The class E circuit is chosen here because it offers an improvised medium of high-frequency, can produce higher efficiency for the output, has advantages in terms of simplicity, and it is a low-noise rectification system [13].

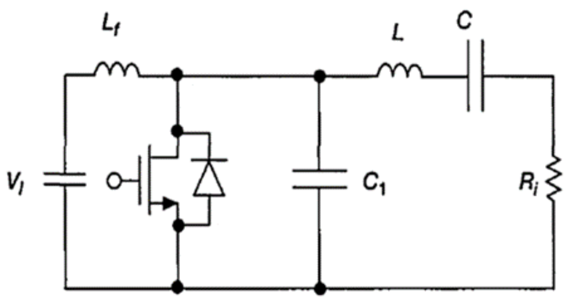


Figure 4: Basic Class E Circuit.

The operating frequency, DC power supply and power output to the load has been described earlier. By using those values, the value of parameters in Class E inverter can be determined using some related equations. Firstly, the resistance value of load can be calculated by using equation (3.1).

$$Ri = \frac{8}{\pi^2+4}\frac{V_I^2}{P_{Ri}} \tag{3.1}$$

After that, we can calculate the amplitude of the output voltage by

$$V_{Rim} = \frac{4}{\sqrt{\pi^2+4}}V_I \tag{3.2}$$

The maximum voltage across the switch and shunt capacitor is then determined by

$$V_{SM} = 3.562V_I \tag{3.3}$$

The DC input current then can be calculated by

$$I_I = \frac{8}{\pi^2+4}\frac{V_I}{R_i} \tag{3.4}$$

The maximum switch current is then given by

$$I_{SM} = \left(\frac{\sqrt{\pi^2+4}}{2}+1\right)I_I \tag{3.5}$$

The amplitude of output current is calculated as

$$I_m = \frac{I_I\sqrt{\pi^2+4}}{2} \tag{3.6}$$

Assuming $QL = 7$, so that the current I through the resonant circuit is sinusoidal. Then, using equation (3.7), (3.8) and (3.9), respectively, the component values of the load network can be determined as follows

$$L = \frac{Q_L R_i}{\omega} \tag{3.7}$$

$$C_1 = \frac{8}{\pi(\pi^2+4)\omega R_i} \tag{3.8}$$

$$C = \frac{1}{\omega R_i\left[Q_L - \frac{\pi(\pi^2-4)}{16}\right]} \tag{3.9}$$

Therefore, the efficiency of the output power can be calculated as

$$\text{Efficiency}(\%) = \frac{Power\,Output}{Power\,Input} \times 100\%$$

(3.10)

B. The Implementation of Impedance Matching in Class E Circuit Design

In order to improve the maximum power transfer between the source and its load as stated by the author in [14], the implementation of an impedance matching in the Class E circuit has been proposed in this work. The motivation behind the introduction of impedance matching system is to change over the load resistance or impedance to the impedance required to deliver the desired output power, *Po* at the specified supply voltage, *Vdc* and the operating frequency, *f* [15]. The chosen circuit composition of impedance matching network is π1b circuit as shown in the red dotted line of Figure 5.

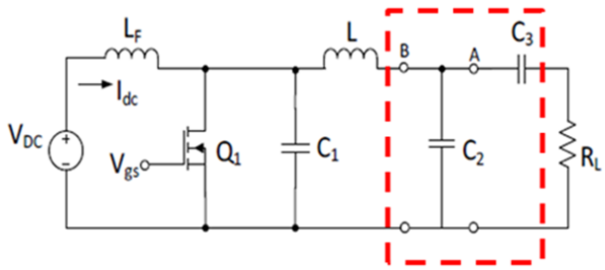


Figure 5: π1b impedance matching circuit.

The different values of parameters used are denoted as C_2, C_3 and R_L in comparison from the Class E circuit provided in Figure 4. Later, in building the complete CPT system, C_3 capacitor will be replaced by metal plate for the biomedical implantable application prototype.

Next, again by using $QL = 7$, R_L is chosen as 300 ohm and R is the value of RL in the previous Class E circuit design, hence, reactance of the capacitor C_3 can be calculated as

$$X_{C3} = \frac{1}{\omega C_3} = R_L \sqrt{\frac{R[(Q_L - 1.1525)^2 + 1]}{R_L} - 1} \quad (3.11)$$

Therefore,

$$C_3 = \frac{1}{\omega X_{C3}} \quad (3.12)$$

In this case, R_L is chosen as 300 ohm since the larger value of R_L will give smaller value of C_3 and thus resulting in smaller size of capacitive plate to be used in biomedical device application.

Furthermore, the reactance of the capacitor $C2$ is given by

$$X_{C2} = \frac{1}{\omega C_2} \quad (3.13)$$

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

producing

$$C_2 = \frac{1}{\omega X_{C2}} \quad (3.14)$$

IV. IMPLEMENTATION OF CPT SYSTEM

A. Simulation Results and Analysis for Class E Inverter Circuit

Through the calculation based on Class-E design formula as shown in Section 3.1, the Class E circuit parameters can now be obtained and they are shown in Table 1.

Table 1: Class E Components value

Parameters	Calculation	Simulation	Percentage difference (%)
Choke inductor, Lf	115uH	200uH	73.91
Shunt capacitor, C1	1.76nF	1.9nF	7.95
Series inductor, L	18.5uH	19uH	2.7
Series capacitor, C	1.64nF	1.60nF	2.43
Load resistor, RL	16.61Ω	17Ω	2.35

Values of the components in simulation are different from the calculation one because we need to tune or manipulate the components value to get the best result of ZVS waveform. The simulation work is done using Matlab/Simulink and shown in Figure 6.

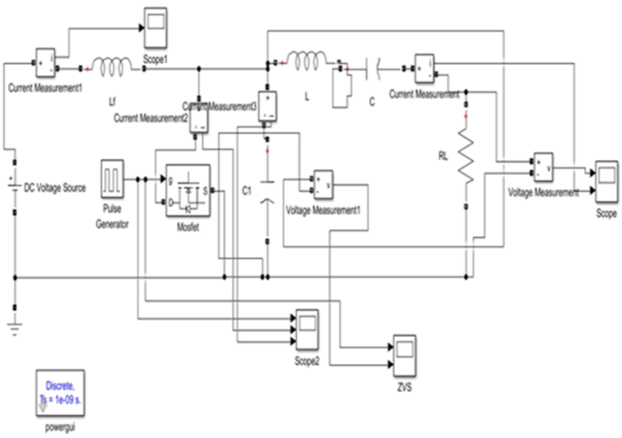
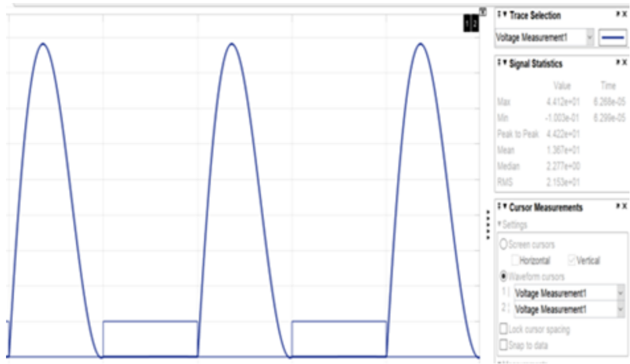


Figure 6: Simulation circuit using Matlab/Simulink

The ZVS simulation result is given in Figure 7(a). From the result, we can see that the VDS Max is 44.12V which is recorded in the Class-E system performance in Table 2 as VSM. This value is very close to the calculated one which is 42.74V. Next, based on Figure 7(b), the output maximum voltage reading is 13.84V that was recorded as VRim in the **Error! Reference source not found.** and the value is near to the theoretical one, 13.0V. The overall performance comparison between theoretical and simulation is then tabulated in **Error! Reference source not found.**.



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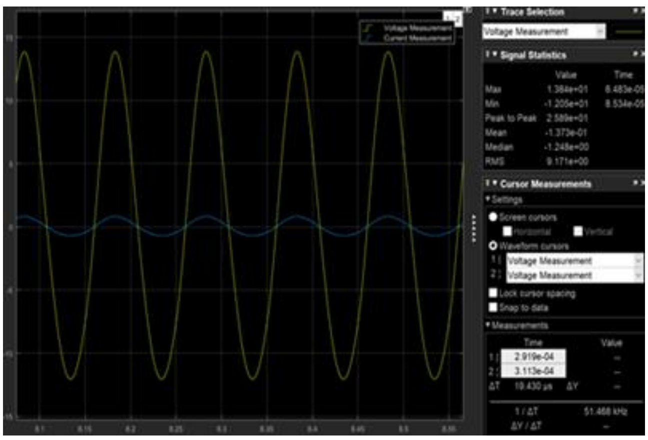

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Figure 7(a): ZVS Performance of the simulation work of Class E circuit

Figure 7(b): Output performance of Class E Circuit

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Table 2: Comparison of system performance in Class E circuit

Parameters	Calculation	Simulation	Percentage difference (%)
Input current, Ii	0.42A	0.41A	2.38
Gate to source voltage, VGS	5.00V	5.00V	0
Maximum switch current, ISM	1.19A	0.90A	24.37
Maximum switch voltage, VSM	42.74V	44.12V	3.23
Output current, IM	0.78A	0.80A	2.56
Output voltage, VRim	13.0V	13.84V	6.46
Power input, Pi	5.04W	4.92W	2.38
Power output,Po	5.00W	4.76W	4.8
Efficiency, %	99.20%	96.70%	2.52

B. Practical Result and Analysis for The Development of CPT System

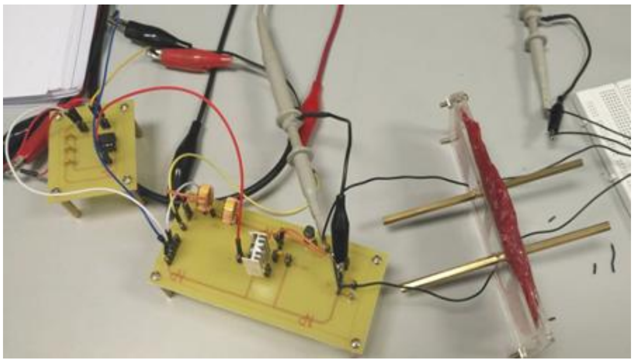
In this part, the series capacitor, *C* of Class-E circuit has been replaced by 2 pairs of copper plate representing forward path of current flow on the left side and reverse path on the right side. Beef is used to replace human tissue in this work and the depth of the beef is 5mm. Table 3 shows the comparison of the components value used in this work in terms of calculation, simulation and experimental. The values somehow have slightly difference due to the standard value that available in the market and the optimum value for each of the component in order to get the best ZVS waveform.

Table 3: Comparison of Component Value Used

Parameters	Calculation	Simulation	Experiment
Choke inductor, Lf	115uH	200uH	195uH
Shunt capacitor, C1	1.76nF	1.9nF	2.1nF
Series inductor, L	18.5uH	19uH	23.1uH
Series capacitor, C	1.64nF	1.60nF	3.3nF
Load resistor, RL	16.61Ω	17Ω	22Ω

(i) Misalignment Analysis

In this part, some analysis of misalignment for the CPT system will be analyzed and discussed. The experimental setup of this experiment is shown in Figure 8(a).



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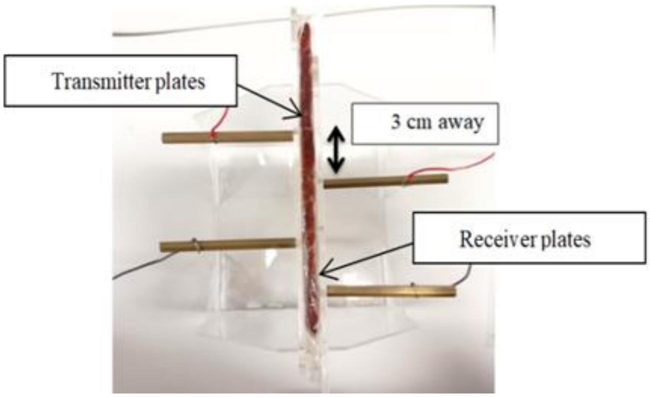


(b)

Figure 8(a): ZVS Performance of the simulation work of Class E circuit
Figure 8(b): Output performance of Class E Circuit

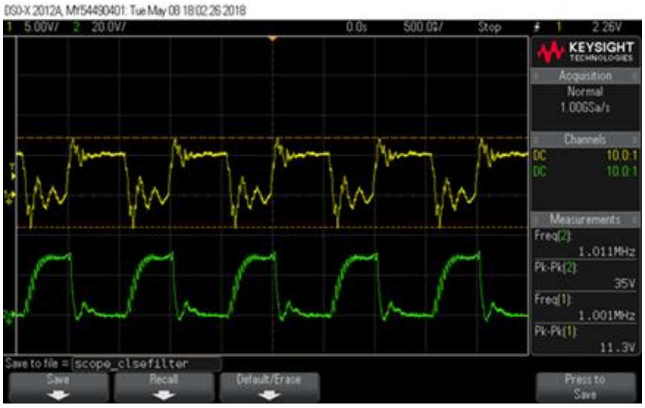
Both of the transmitter and receiver plate with the size of 3cmx3cm width per length have been used in this experiment. For the analysis of misalignment, the initial condition of the transmitter and receiver plates are in aligned position. After that, the transmitter plates are moved by horizontally away from the receiver plate up to 3cm from the original aligned position of the capacitive coupling plates as shown in Figure 8(b). The analysis of misalignment work is shown in Table 4.

Table 4: Misalignment analysis

Distance (cm)	Vi (V)	Ii (mA)	Pi (W)	Vo (V)	Io (mA)	Po (W)	Efficiency (%)
1	12	362	4.34	5.23	193	1.01	23.27
2	12	297	3.56	4.34	161	0.70	19.66
3	12	197	2.36	2.01	68	0.14	5.93

The recorded data shows that the input power, Pi and output power, Po are inversely proportional towards the distance of misalignment. This proves that misalignment affects the efficiency of power transfer of the system. Based on Table 4, one can observe that the higher the distance of misalignment, the lower the efficiency of the CPT system. This is actually an important problem to be encountered since the receiver plate will be implanted inside of the body, thus making it hard to be aligned with the transmitter plate when transferring power from outside of the body. Hence, one possible solution to avoid this problem is, the transmitter plates must been made bigger in size compared to the receiver plate. This work chooses 4cm x 4cm width per length.

Next, ZVS performance and output power of the CPT system are studied and the corresponding results are given in Figure 9. From Figure 9(a), the Vds peak to peak value is 35V while the Vgs peak to peak value is 11.3V which is high enough to drive the MOSFET. Meanwhile, from Figure 9(b), the obtained output power is 5.7V. Based on the results, efficiency of the system can be calculated and it gives 41.43% only. This is not good enough and therefore the impedance matching approach will be proposed next in order to improve the overall performance of such system.



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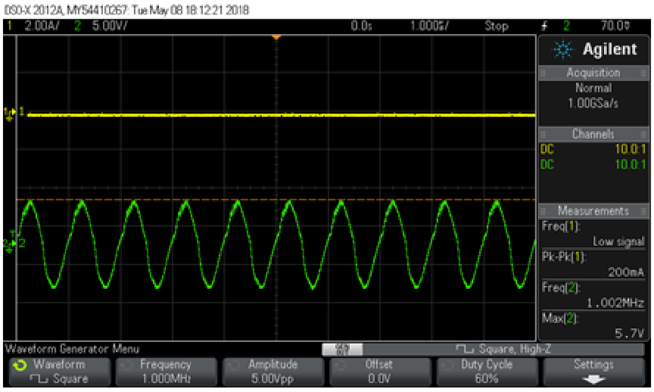


(b)

Figure 9(a): ZVS Performance of the experimental work of Class E circuit
Figure 9(b): Output performance of Class E Circuit

(ii) The Improvement of Class-e Circuit by Impedance Matching Technique

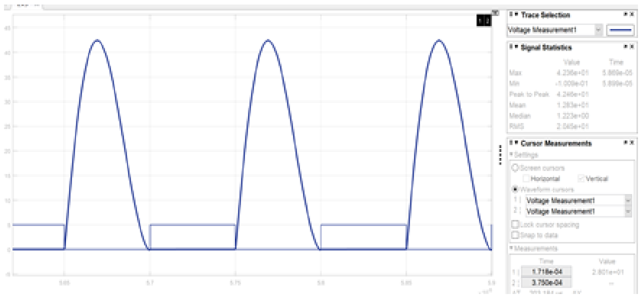
The implementation of impedance matching circuit on the Class E circuit is been approached in order to improve the power efficiency of the CPT system up to 70%. Analysis of the performance of the system and the effect of the higher load resistor value, RL which is 300ohm on the Class-E circuit will be investigated throughout the impedance matching implementation. Table 5 shows the comparison of components value used in theoretical calculation, simulation and practical work.

Table 5: Comparison on Component Value Used

Parameters	Calculation	Simulation	Practical
Lf	115uH	200uH	195uH
C1	1.76nF	1.9nF	2.1nF
L	19uH	20uH	17.75uH
C2	1.3267nF	1.25nF	1.5nF
C3	0.545nF	0.545nF	1.2nF
RL	300Ω	300Ω	300Ω

(a) Simulation Results

In this part, the performance comparison between the circuit with and without impedance matching will be discussed. To note here that the RL used is 300 ohm.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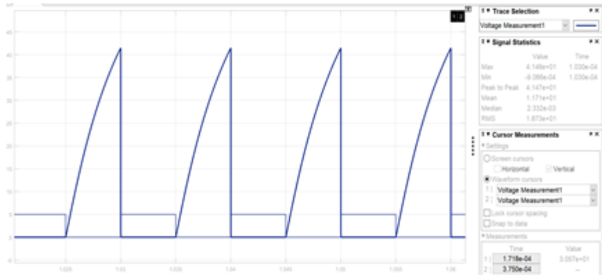
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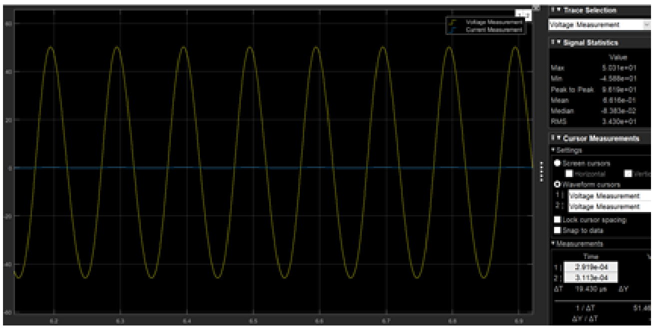
Figure 10(a): ZVS Performance of the experimental work of Class E circuit
Figure 10(b): Output performance of Class E Circuit

According to Figure 10(a) and Figure 10(b), we can clearly observe that the ZVS performance for the circuit with impedance matching is much better than the one without the matching. Through this we can guarantee that the switching losses of the CPT circuit with impedance matching will be lower than the other one. This will lead to improvement in the overall efficiency later.

In regards to output power, it can be clearly observed that the smooth AC output voltage waveform at R_L can be obtained in Figure 11(a) compared to Figure 11(b) that has not implemented impedance matching. The maximum voltage output readings are also having a big difference as Vmax of Figure 11(a) is 50.31 V and Vmax in Figure 10(b) is 22.52 V. Next, the comparison of efficiency between the Class E circuit with impedance and without impedance is recorded in Table 6.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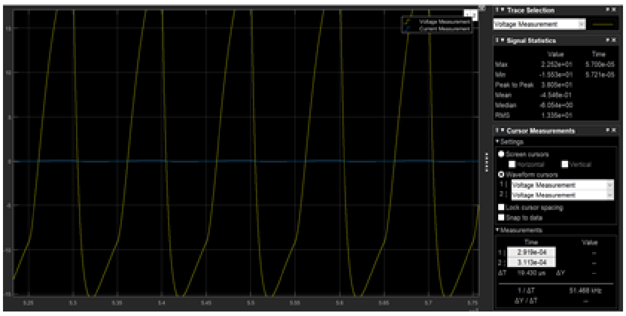


(b)

Figure 11(a): Output voltage with impedance matching
Figure 11(b): Output voltage without impedance matching

Table 6: Comparison on Component Value Used

Condition	Vi (V)	Ii (mA)	Pi W)	Vo (V)	Po (W)	Efficiency (%)
With impedance	12	350	4.2	50.31	4.08	97.1
Without impedance	12	200	2.4	22.52	0.85	35.41

(b) Practical Results

In this section, the comparison between the Class-E circuit with implementation of impedance matching and without the implementation of impedance matching for 300 ohm RL will be analyzed experimentally. The overall prototype of the CPT system for biomedical application that has been developed for the practical part analysis is shown in Figure 12.

ZVS waveform is able to achieve with impedance matching in Figure 13(a) even though there are some ripples in Vgs. As for Figure 13(b), ZVS waveform could not be achieved in this practical part just like in the simulation part without the impedance matching implementation.

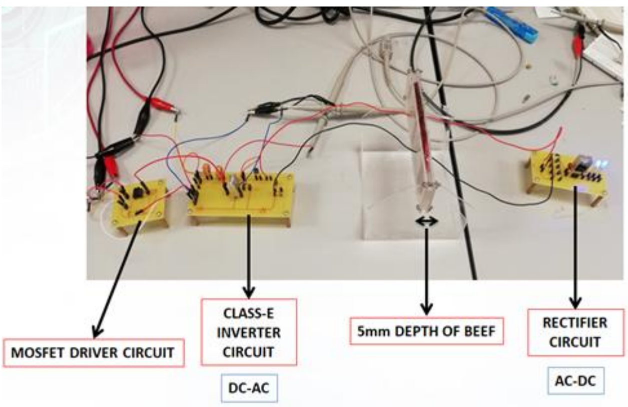
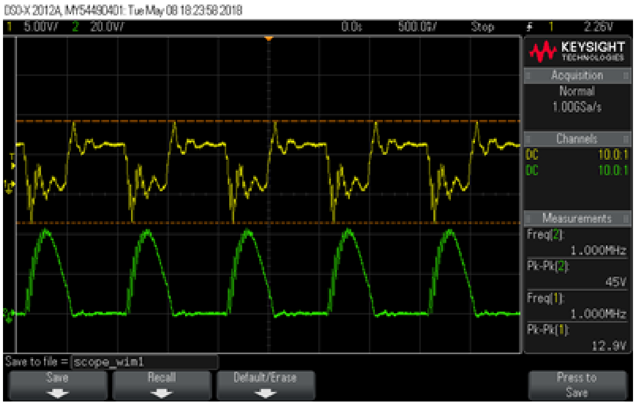
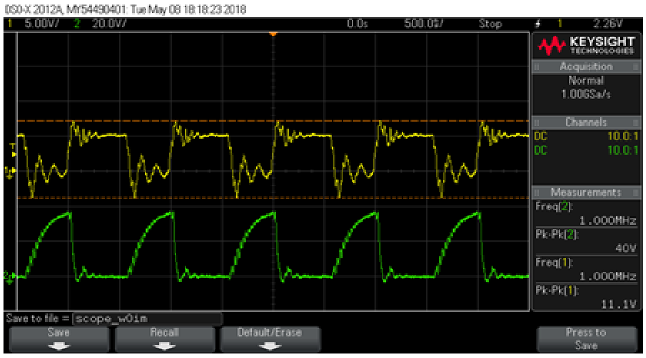


Figure 12: Output voltage with impedance matching



(a)



(b)

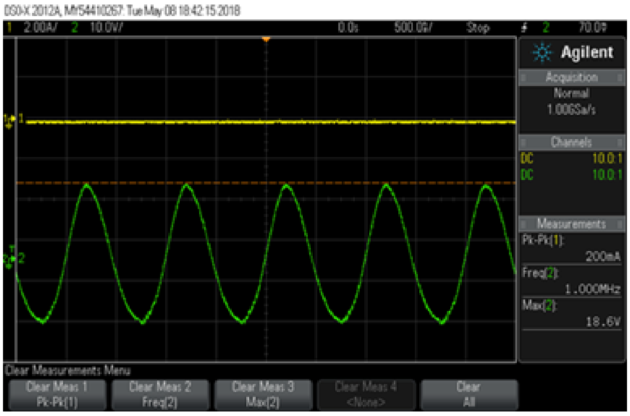
Figure 13(a): ZVS with impedance matching
Figure 13(b): ZVS without impedance matching

The AC output voltage waveform without impedance matching in Figure 14(b) is also not as smooth as the output voltage waveform with impedance matching in Figure 14(a) and Voutput with impedance matching is higher which is 18.6V compared to 17.0V without impedance matching. The comparison of efficiency is recorded in Table 7.

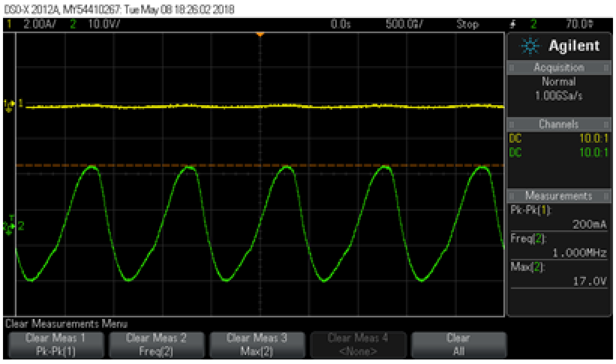
Table 7: Comparison on Component Value Used

Condition	Vi (V)	Ii (mA)	Pi (W)	Vo (V)	Io (mA)	Po (W)	Efficiency (%)
With impedance	12	400	4.8	18.6	200	3.72	77.5
Without impedance	12	180	2.16	17.0	58	0.98	45.6

As a conclusion, the impedance matching network implementation on Class-E circuit could improve the efficiency up to 77.5% of the CPT system even when higher RL is used as the load. This improvement overall can achieve ZVS waveform nearly to the theoretical and produced higher output voltage.



(a)



(b)

Figure 14(a): Output voltage with impedance matching Figure 14(b): Output voltage without impedance matching

V. CONCLUSION

In conclusion, the overall CPT system that has been designed for the biomedical implantable device is able to deliver 140mWatt power to the DC load at rectifier circuit by using impedance matching and 76mWatt power when no impedance matching network available. The specification taken for the biomedical device application in this work is peripheral nerve implantable biomedical device that only needs 100mWatt power to operate [12]. Hence, the improvement of the Class-E circuit by impedance matching is able to transfer power to the peripheral nerve implantable device wirelessly by the CPT system up to 140mWatt. The main recommendation for this work is to build a CPT system for powering biomedical device wirelessly with smaller receiver capacitor plate. This is due to most of the biomedical devices are small and only need low power in the range of microWatt to miliWatt to operate [17] plus it is easier to implant smaller size of receiver plate inside of the patient's body. Another problem that needs to be considered is the power efficiency of the system. When using smaller capacitor plate size, it is difficult to get a high efficiency so the other type of impedance matching circuit topology can be implemented to investigate the effect of different types of impedance matching network towards the efficiency and performance of the CPT system.

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