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A new design of capacitive power transfer based on hybrid approach for biomedical implantable device

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ABSTRACT

This paper presents the development of a new design method of capacitive power transfer (CPT) which is based on hybrid concept for Biomedical Implants. This method is able to improve various issues found in the widely used CPT system that is bipolar CPT method. Based on the ability of this purposed, the simulation of the CPT system has been designed to prove an amount of power transferred through a layer of tissue. The design used to validate the suggested model which to powering implanted device, and it was performed with 3cm square plates, which have a layer of beef with the 5mm thickness in between 2 coupling plate. Power signal was generated by Class E zero voltage switching. The Class E zero voltage switching has been designed to generating alternate current with the 1MHz frequency appropriate to the hybrid CPT system specification.

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1. INTRODUCTION

Wireless power transfers have been broadly explored for various applications such as electric car charging, smartphone charger, RFID devices, powering implantable devices and much more [1]. Wireless power transfers approach generally can be classified into near field and far field power transfer applications [2]. The near-field approach can be divided into several types which are an inductive resonance frequency coupling (IRFC), ultrasonic energy transfer, and near-field capacitive coupling (NCC). Previously, the comparison of characteristics of each type of wireless power transfers has been made by other researchers and based on the comparison made, every type of wireless power transfers has the advantage over other types [3-4]. This reason reinforces that each type of WPT can be applied according to suitability and requirement of the applications.

Advancement of biomedical implants has been very successful in the creation of several types of implantable devices such as cardiovascular implantable devices, Cochlear, neural, retinal and more others to meet medical needs [5]. Each type of implantable device has its own specifications especially in term of power characteristics to allow then to safely operated. Some implantable device types require a biosafety source of electrical power to operate properly. The sealed battery as the power source of implantable devices can only supply the energy for a limited time [6]. The patient will experience trauma with repeated surgery for replacing the battery. Because of constant dependence on electrical power sources, a wireless power transfer method is required to overcome the limited lack of battery power source capability and this could able to avoid repeated surgery to replace the battery of implants [7].

At present, biomedical technology has been already established with both type of wireless power transfer, which is inductive and ultrasound power transfer, and already used for wireless power delivery for several implantable devices such as neural implants [8]. However, both methods have weaknesses in terms of signal interference [9]. Also, since the inductive power transfer propagating power by inducing electromagnetic field, it is risky to interfere with other surrounding devices that sensitive to the electromagnetic field. Thus, reducing this kind of interference is one of the main challenges to design an inductive power transfer system [10].

The capacitive wireless power transfer, on the other hand, has been used in several applications and has been proposed for biomedical implantable device since 2009 by Amir M. Sodagar et. al [2-11]. This approach was also recently used for sensing the biomedical signal as given in [12]. However, up to date, to the authors' knowledge, the achievement in capacitive linkage studies is not as successful as the inductive link. This is because of the limited range factor of the capacitive link. NCC approaches is different to the inductive power transfer, in which the electromagnetic as a mechanism for transferring energy [13-14]. But In CPT, the electric field between both parallel transmitters and receiver plates is used as the mechanism for transferring energy in term of power and data. It was the solution to the IPT problem which the CPT approaches eliminated the relatively large electromagnetic interference from the sensitive electronic implantable device [15]. However, the size of bipolar CPT system are the weaknesses that need to be addressed in the design. In addition, the bipolar CPT system experiencing the high power loss due to low capacitive value at both forwarding and return path coupling plate in the power transmitting circuit. Further description will be discussed in the next section [16]. Therefore, this paper provides a study on the Hybrid CPT system to solve the size and efficiency problems of existing CPT bipolar systems.

In general, the main objective of this paper is to present the development of a new method of hybrid capacitive power transfer (CPT) for Biomedical Implants. Contents of this paper are organized as follows: In section 2, the basic theory of the capacitive coupling power transfer in biomedical device is explained, and it continues to coupling plate with tissue analysis in subsection 3. The hybrid capacitive link is explained in section 4 and it continues to Power Management which consists the simulation on designing class E power amplifier with CPT applied. The drawbacks and solution of the system are discussed in section 6, the remaining section is the conclusion and the future development of this study. The paper summarizes the research needs of capacitive wireless power transfer in biomedical implantable device's technology. In order to improve the system, the study remains open to discover the best solution. Thus, the author prepares plans future work for these research and development of CPT in the biomedical implantable device.

2. CAPACITIVE COUPLING POWER TRANSFER IN BIOMEDICAL DEVICE

CPT approaches is a wireless power transfer scheme using a pair of coupling plate to transfer electrical field through a dielectric barrier. This scheme is performed by the displacement of current without a conductor as a medium for the transfer of charges.

The powering system consists of pairs of conductor plate located on either side of the skin of certain tissue thickness, and its form a capacitive coupling which to enable the wireless power transfer [17]. The principle of CPT wireless power transfer is about the displacement current to transfer the power between two contactless conductor plates. Together with that, conduction current also induced between both plates. Both displacement and conduction equations are given in (1) and (2), respectively [18-19].

$$I_{disp} = \epsilon_0 \epsilon_r(\omega) A \frac{\partial \vec{E}}{\partial t} \quad (1)$$

$$I_{cond} = \frac{V(t)\sigma(\omega)A}{D} \quad (2)$$

For a complete circuit of power delivery to load in bipolar CPT system, two such capacitances are required. In order to improve the effective power delivery, displacement current should be increased while the conduction current needs to minimize as low as possible to reduce the power loss with considering the parameter of area (A), electric field €, distance (D), and relative permittivity (ϵr) in optimum values [20]. From the displacement current equation in (1), there are several parameters that are possible to be manipulated in order to increase the displacement current and at the same time to improve the power transfer efficiency. Among them, the parameter of electric field strength, E is the most affected one to the displacement current value. These parameters can improve the efficiency by increasing the transmitter excitation voltage and reducing the separation distance between the coupling plates. The displacement current value is also affected by the rate of change of the electric field. Thus the efficiency can be improved by increasing the operating frequency [21]. Besides that, increasing the magnitude of the electric field also can improve the transferring power efficiency, whereby it can be done by expanding the conductor of the coupling plate area [22-23]. However, all the parameters were limited by the biomedical implantable device specification.

Since the pairs of conductor plate (limited Biohazard dimension) separated D by a few millimeter tissues (<5mm) as the dielectric medium ϵr, σ, the power transfer strength is limited due to the weak capacitance values[24]. Thus, a few millimeters deep of tissues which possible to attach the receiver plate is under the layer of skin as illustrated in Figure 1 [25]. Besides that, the surface area of the coupling plate that needs to be minimized will be a challenge to obtain high power transfer values. Thus, the specific on designing capacitive wireless power transfer should be proposed to overcome the constraints and to fulfill the biomedical implantable device requirement. In designing capacitive wireless power transfer for the biomedical purpose, there are several particular aspects needs to be concerned, such as the element of Biosafety, the performance of the power delivery efficiency, range for misaligning, effective range of system and others [26].

Figure 1 illustrates the pair of coupling plate used in bipolar CPT system for biomedical implant devices. Bipolar CPT system requires a bigger space to accommodate the 2 receivers implanted plate. This matter will lead to the risk of skin tissue damage. Thus, the authors would like to propose the new CPT system which is a hybrid CPT system. These new design will able to reduce the size of the implanted receiver plate, and at the same time able to improve power delivery efficiency. Before discussing on hybrid CPT system, first, one needs to understand the capacitive Coupling Plate with Tissue specification. Hence the discussion on Coupling Plate with Tissue Analysis is given in the next section.

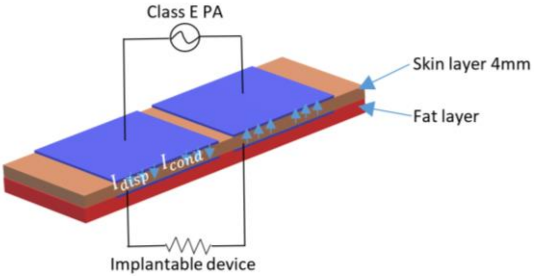


Figure 1. Pair coupling plate bipolar CPT system for implantable devices Effects of selecting

3. COUPLING PLATE WITH TISSUE ANALYSIS

To design the capacitive power transfer for the biomedical purpose, it is important to investigate the characteristic of the coupling plate where this will be used as a medium for power transfer. From this analysis, several parameters of coupling plate such as capacitance, impedance, and constant permittivity of tissue can be found and will be used for the development of bipolar capacitance power transfer (CPT) for Biomedical Implants.

The value of dielectric thickness, t, operating frequency, f and plate size to be used, A (A) is a fixed parameter in measuring and calculating parameters of coupling plate. In this work, the value of dielectric thickness is 0.005m, while the operating frequency is 1Mhz and size of the plate to be used is 9cm2. To carry the proper permittivity measurement, 20Hz-10Mhz impedance analyzer and dielectric fixture test have been used, see Figure 2. Capacitance measurement from 1kHz to 10MHz as shown in Figure 3.

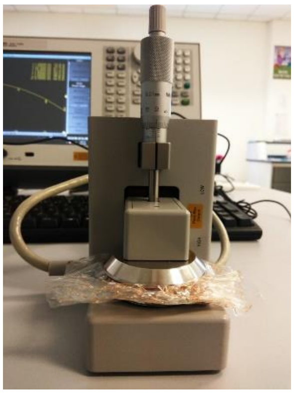
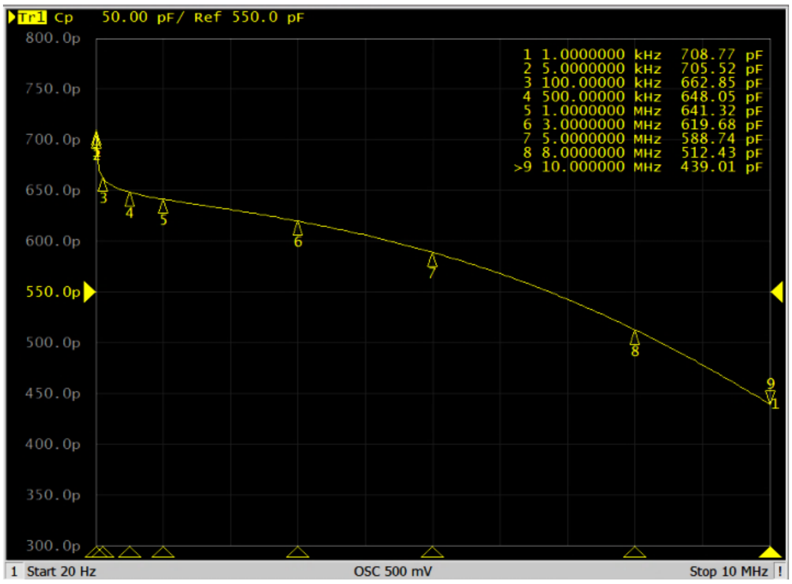


Figure 2. Dielectric fixture test

The dielectric constant can be obtained using the following (3-4):

$$\epsilon = \epsilon_0 \epsilon_r = \frac{t}{A} C_p \tag{3}$$

$$\epsilon_r = \frac{t \times C_p}{A \times \epsilon_0} \tag{4}$$



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 1  1.0000000 kHz   708.77 pF
 2  5.0000000 kHz   705.52 pF
 3  100.00000 kHz   662.85 pF
 4  500.00000 kHz   648.05 pF
 5  1.0000000 MHz   641.32 pF
 6  3.0000000 MHz   619.68 pF
 7  5.0000000 MHz   588.74 pF
 8  8.0000000 MHz   512.43 pF
>9  10.000000 MHz   439.01 pF
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Figure 3. Capacitance measurement from 1kHz to 10MHz

where ,

ε = Dielectric constant (permittivity) $[F/m]$

ε_0= Space permittivity = 8.854x10^{-12} $[F/m]$

ε_r = (Relative permittivity) of test material

C_t = Equivalent parallel capacitance value for dielectric test [F] = 641.32pF

t = Thickness of test material [m] = 0.005m

d = diameter of dielectric fixture test [m] = 0.038m

Then, the following parameters can be calculated (5-6);

$$A = \pi \times \left(\frac{d}{2}\right)^2 = 1.1341 \times 10^{-3} m^2 \tag{5}$$

$$\epsilon_r = \frac{0.005 \times 641.32 \times 10^{-12}}{1.1341 \times 10^{-3} \times 8.854 \times 10^{-12}} \tag{6}$$

$$\epsilon_r = 319.34\, {}^{F}/_{m} \qquad \epsilon = 2.82744 \times 10^{-9}$$

Hence, the capacitance for single coupling plate with 9cm^2 size and separated by 5mm tissue can be written as (7):

$$C_p = \frac{A \epsilon_0 \epsilon_r}{t} C_p = 5.09 \times 10^{-10} F = 509 pF \tag{7}$$

4. HYBRID CAPACITIVE LINK

This newly proposed capacitive power transfer system has only applied one active coupling capacitor, and use the tissue to serve as the return path for the current. This method applied both type of current which is the displacement current for forward biasing and conduction current for the return path. This method will reduce the size of the implant device and at the same time increase the efficiency of power transfer which the return coupling capacitive plate as in bipolar system has been remove. Figure 4 illustrates the hybrid CPT system for biomedical implantable devices.

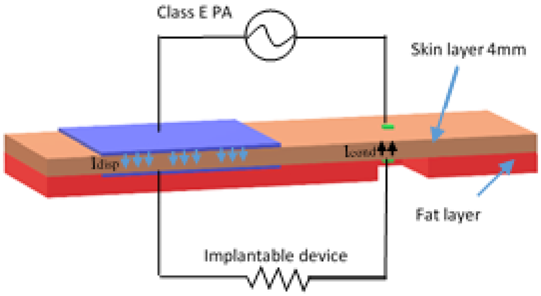

Figure 4. Class E zero voltage switching circuit [27]

Based on Figure 4, exterior part of the system contains transmitter forwarding plate and transmitter conductor terminal and Class E power amplifier, while receiver forwarding plate, receiver conductor terminal, and implantable device are implanted part of the system. Figure 5 illustrates the general schematic of the hybrid CPT system.

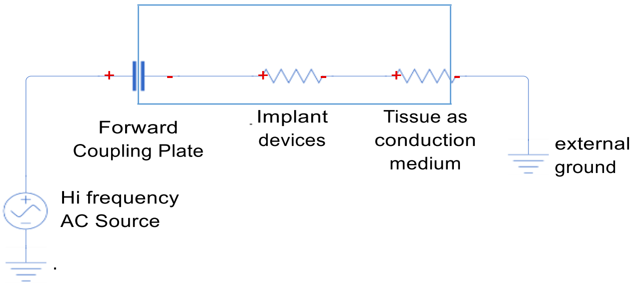

Figure 5. The general schematic of the hybrid CPT system

Thus, value of reactance if f=1Mhz is (8)

$$X_c = \frac{1}{2\pi fC} = \frac{1}{2\pi\times 1M\times 509p} = 312.682\Omega \quad (8)$$

By assuming the resistance of the implant device is 50Ω, the impedance value of the circuit is equal to 316.65Ω Hence, the current (I) in series RC circuit value is (9)

$$\mathrm{I} = \frac{\mathrm{V}}{\mathrm{Z}} = \frac{12}{316.65} = 37.896\mathrm{mA} \quad (9)$$

Thus, voltages across the implant devices in the circuit is 1.8948V. Then, the simulation of the coupling CPT circuit is executed based on the parameters set. Figure 6 shows the simple simulation to observe the output voltage and current of a coupling capacitive system. The simulation used to prove that an amount of displacement current flow through the coupling capacitive plate to the load.

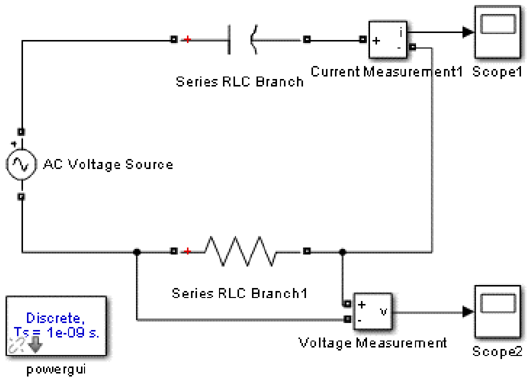

Figure 6. Displacement current flow simulation

Figure 7 presents the waveform according to the current flow in the circuit. Maximum value captured in the simulation is 0.038A which is close to the theoretical calculation as given in (6). Figure 8 shows the waveform according to the voltage across the load. Maximum value captured in the simulation is 1.9V which is close to the theoretical calculation, V_L=1.8948V.

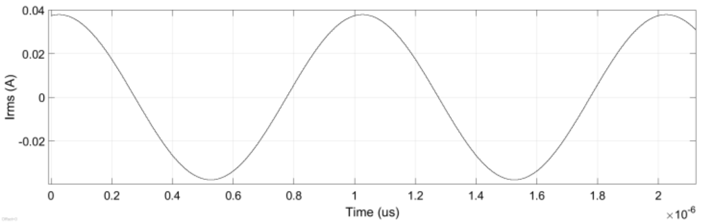

Figure 7. Current flow in the circuit

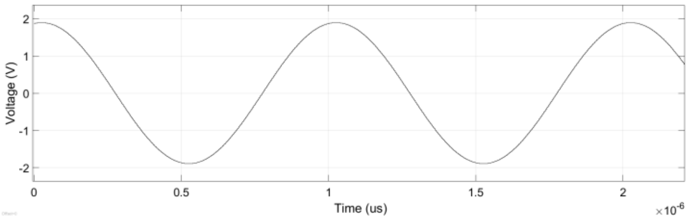

Figure 8. The voltage across the load

5. POWER MANAGEMENT

The previous section, the characteristic on the hybrid CPT design based on the biomedical implantable device constraint has been discussed. The specification will be a part of modeling and experimental validation CPT as a developing wireless power transfer to powering biomedical implantable devices. Determining the size of the capacitance plate at the receiver part is very important before the power management design is proposed. Since the receiving plate will be placed inside after the skin layer, the size of the plate should minimize as small as possible while small capacitance plate will cause the reduction of the power transmission efficiency [26]. However, it can be solved by choosing the optimum operating frequency and apply the appropriate impedance matching network of the power amplifier system will be increasing the power transmission efficiency while ensuring high frequency generated in perfect zero voltage switching [27].

The study of optimization for capacitive wireless power transfers system has been covered by many researchers [28]. The optimization power transfers study focuses on increasing the efficiency of power transfers and to manage system due to misalignment of coupling plate. The power transmission efficiency rate for CPT depends on power signal frequency generated by the inverter. An Inverter or known as Power amplifier topologies has been classified by its design named A, B, AB and C for analog designs and class D and E for switching design. Xiong [29] has recommended class E amplifier as its proof ability to give the highest efficiency with a simple switching circuit required. The class E power amplifier has two different types which are a Class E zero current switching and Class E zero voltage switching where both belong to the family of soft-switching inverters. Class E ZVS inverters known as the most efficient inverter which the switch closed at zero voltage conditions occurred if all components values of properly designed. General Class E zero voltage switching an amplifier with hybrid CPT links schematic diagram as shown in Figure 9 [30]. For notation simplicity and values are as shown in the Table 1.

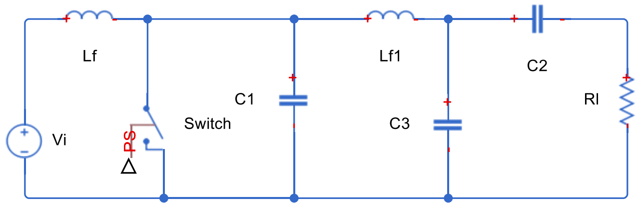

Figure 9. Class E ZVS with Hybrid CPT links schematic

Table 1. Parameters for Class E inverter with π1b impedance matching

Parameter	Value
Frequency (f)	1.00 MHz
Duty Cycle (D)	50.00%
Input voltage DC (V_i)	12.00V
Input current (I_i)	0.37A
Load Resistance (R_L)	50.00 Ω
Choke inductor (L_f)	300.00 µH
Shunt capacitor (C_1)	4.5 nF
Series inductor (L)	21 µF
Matching capacitor (C_3)	860 pF
Fixed coupling capacitor (C_2)	509 pF
Maximum switch current (I_{SM})	1.4 A

The optimum value power of output was evaluated in which the circuit generates the zero voltage switching condition. The circuit was simulated using Simulink as shown in Figure 10. In Figures 11 and 12 is the voltage across an output load and current across an output load. The result of the simulation as shown in Table 2.

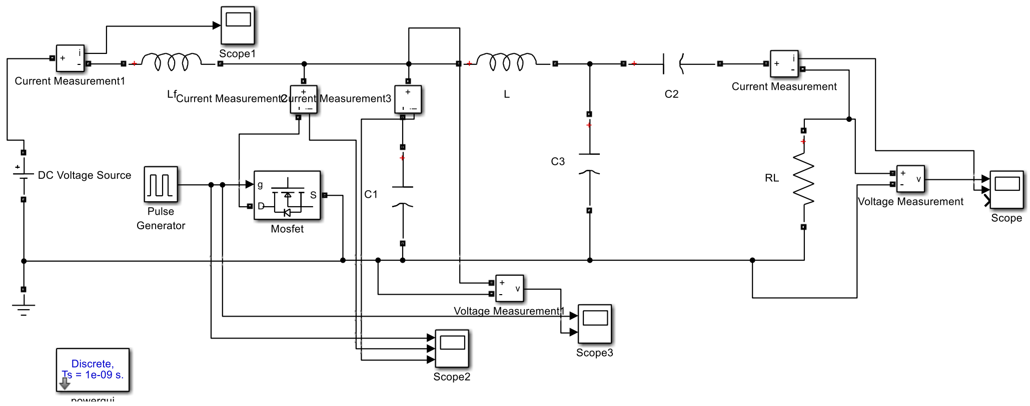

Figure 10. Class E ZVS with Hybrid CPT links simulation

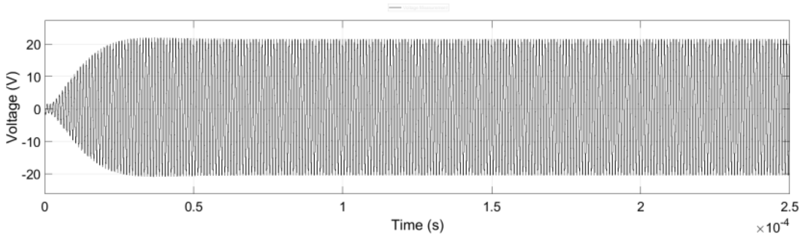

Figure 11. The voltage across an output load

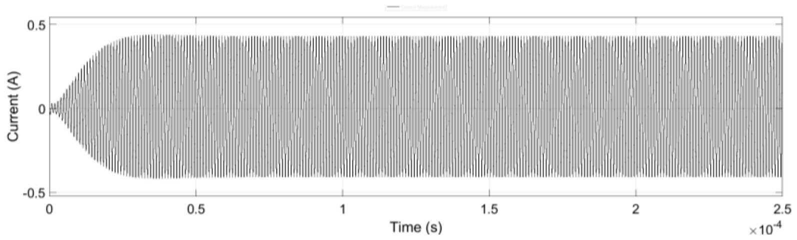

Figure 12. Current across an output load

Table 2. The result of the simulation

Result	Value
Output Voltage (V_{RL})	$21.39V_p$
Current Output (I_{out})	$0.4278A_p$

6. DRAWBACKS AND SOLUTION

Power transfer efficiency PTE is an important value which to ensuring the final load receives enough power for their circuit operation. Since the CPT efficiency very sensitive to changes in the alignment of coupling capacitive plates, the power delivery on the receiver will be inconsistency value [31]. This is a challenge for researchers to find solutions to the inconsistency problems of power output. Furthermore, this system should be designed following the requirement of devices and the biosafety specification standard [32]. In order to analyze limitation of biosafety in the system, specific absorption rate (SAR) analysis need to be done to see the maximum limit of this design [33].

In order to complete the proposed method of hybrid capacitive power transfer in the biomedical implantable device, the study remains open to discover the best solution. The improvement can be studied through several parts of the system, such as the feedback and regulating the operating frequency, design of impedance matching, and design of coupling capacitive plate [34]. Thus, an efficient and reliable way of capacitive wireless power transfer for implantable biomedical devices is expected as a successful outcome.

7. CONCLUSION

This paper is to prepare a new method of hybrid capacitive power transfer in the biomedical implantable device. Based on this study, hybrid capacitive power transfer systems are a new method that has the potential to apply to biomedical implantable devices. It was the solution to the bipolar CPT problem which the hybrid CPT approaches eliminated the return path active coupling plate to form the complete current flow in the circuit. The investigation proved that the hybrid CPT system able to deliver more efficient rather than the bipolar system where the total of output reactance value has been reduced significantly. However, all the parameters especially size and biosafety were limited by the biomedical implantable device specification.

Class E ZVS inverters known as the most efficient inverter which the switch closed at zero voltage conditions occurred if all components values was properly designed. However, there is also an element of input impedance and load impedance equilibrium that needs to be ascertained to produce the maximum power at the output of the class e power amplifier. Since the CPT efficiency very sensitive to changes in the alignment of coupling capacitive plates, the power delivery on the receiver will be inconsistency value. In order to improve the efficiency of changing power transferred, the study remains open to discover the best solution.

The improvement can be studied through several parts of the system, such as the feedback and regulating the operating frequency, design of impedance matching, and design of coupling capacitive plate. However, there are so many things has to master in, especially on the standard of procedure of the designing capacitive wireless power transfer for biomedical practice. Thus, the author prepares several plans for future work for these research and development.

8. FUTURE DEVELOPMENTS

The development of Hybrid Capacitive Power Transfer in Biomedical Implantable Device should have their specific modeling which is to considering every parameter which affecting the whole operating system. The modeling included the power management circuit, coupling capacitor with tissue, and the receiver part with the implant device as their load. To design the system, all the limitation in term of biosafety and the device requirement should be followed. To ensure the vision of bioelectronic medicine technology yet to come, the path for the inventor advancements in capacitive wireless power transfer is becoming clearer.

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REFERENCES

[1] K. Agarwal, R. Jegadeesan, Y. X. Guo, and N. V. Thakor, “Wireless Power Transfer Strategies for Implantable Bioelectronics,” *IEEE Reviews in Biomedical Engineering*, vol. 10. pp. 136-161, 2017.

[2] A. M. Sodagar and P. Amiri, “*Capacitive coupling for power and data telemetry to implantable biomedical microsystems*,” in 2009 4th International IEEE/EMBS Conference on Neural Engineering, NER ’09, pp. 411-414, 2009.

[3] D. Rozario, N. A. Azeez, and S. S. Williamson, “*Analysis and design of coupling capacitors for contactless capacitive power transfer systems*,” in 2016 IEEE Transportation Electrification Conference and Expo, ITEC 2016, 2016.

[4] A. I. Al-Kalbani, M. R. Yuce, and J. M. Redoute, “A biosafety comparison between capacitive and inductive coupling in biomedical implants,” *IEEE Antennas Wirel. Propag. Lett.*, vol. 13, pp. 1168-1171, 2014.

[5] A. M. Sodagar and K. Najafi, “*Wireless interfaces for implantable biomedical microsystems*,” in Midwest Symposium on Circuits and Systems, vol. 2, pp. 265-269, 2006.

[6] M. Takhti, F. Asgarian, and A. M. Sodagar, “*Modeling of a capacitive link for data telemetry to biomedical implants*,” in 2011 IEEE Biomedical Circuits and Systems Conference, BioCAS 2011, pp. 181-184, 2011.

[7] R. Jegadeesan, K. Agarwal, Y.-X. Guo, S.-C. Yen, and N. V. Thakor, “Wireless Power Delivery to Flexible Subcutaneous Implants Using Capacitive Coupling,” *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 1, 2017.

[8] M. Kline, “Capacitive Power Transfer,” Report, pp. 1-35, 2010.

[9] R. Jegadeesan, K. Agarwal, Y.-X. Guo, S.-C. Yen, and N. V. Thakor, “Wireless Power Delivery to Flexible Subcutaneous Implants Using Capacitive Coupling,” *IEEE Trans. Microw. Theory Tech.*, pp. 1-13, 2016.

[10] a K. Ramrakhyani, S. Mirabbasi, Mu Chiao, and C. M, “Design and optimization of resonance-based efficient wireless power delivery systems for biomedical implants.,” *IEEE Trans. Biomed. Circuits Syst.*, vol. 5, no. 1, pp. 48-63, 2011.

[11] J. Dai and D. C. Ludois, “A Survey of Wireless Power Transfer and a Critical Comparison of Inductive and Capacitive Coupling for Small Gap Applications,” *IEEE Trans. Power Electron.*, vol. 30, no. 11, pp. 6017-6029, 2015.

[12] M. Kline, I. Izyumin, B. Boser, and S. Sanders, “*Capacitive power transfer for contactless charging*,” in Conference Proceedings-IEEE Applied Power Electronics Conference and Exposition-APEC, pp. 1398-1404, 2011.

[13] R. Jegadeesan, Y. X. Guo, and M. Je, “*Electric near-field coupling for wireless power transfer in biomedical applications*,” in 2013 IEEE MTT-S International Microwave Workshop Series on RF and Wireless Technologies for Biomedical and Healthcare Applications, IMWS-BIO 2013-Proceedings, 2013.

[14] R. Jegadeesan, K. Agarwal, Y.-X. Guo, S.-C. Yen, and N. V. Thakor, “Wireless Power Delivery to Flexible Subcutaneous Implants Using Capacitive Coupling,” *IEEE Trans. Microw. Theory Tech.*, vol. 65, no. 1, pp. 280-292, 2017.

[15] M. P. Theodoridis, “Effective capacitive power transfer,” *IEEE Trans. Power Electron.*, vol. 27, no. 12, pp. 4906-4913, 2012.

[16] T. M. Mostafa, A. Muharam, and R. Hattori, “Wireless battery charging system for drones via capacitive power transfer,” in 2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer, WoW 2017, 2017.

[17] J. Kim, D. H. Kim, and Y. J. Park, “Analysis of Capacitive Impedance Matching Networks for Simultaneous Wireless Power Transfer to Multiple Devices,” *IEEE Trans. Ind. Electron.*, vol. 62, no. 5, pp. 2807-2813, 2015.

[18] J. J. Casanova, Z. N. Low, and J. Lin, “Design and optimization of a class-E amplifier for a loosely coupled planar wireless power system,” *IEEE Trans. Circuits Syst. II Express Briefs*, vol. 56, no. 11, pp. 830-834, 2009.

[19] Y. Yusop, S. Saat, Z. Ghani, H. Husin, and S. K. Nguang, “Capacitive power transfer with impedance matching network,” in *2016 IEEE 12th International Colloquium on Signal Processing & Its Applications (CSPA)*, pp. 124-129, 2016.

[20] H. Zhang, F. Lu, H. Hofmann, W. Liu, and C. C. Mi, “A Four-Plate Compact Capacitive Coupler Design and LCL-Compensated Topology for Capacitive Power Transfer in Electric Vehicle Charging Application,” *IEEE Trans. Power Electron.*, vol. 31, no. 12, pp. 8541-8551, 2016.

[21] D. C. Ludois, J. K. Reed, and K. Hanson, “Capacitive power transfer for rotor field current in synchronous machines,” *IEEE Trans. Power Electron.*, vol. 27, no. 11, pp. 4638-4645, 2012.

[22] W. Zhang and C. C. Mi, “Compensation topologies of high-power wireless power transfer systems,” *IEEE Trans. Veh. Technol.*, vol. 65, no. 6, pp. 4768-4778, 2016.

[23] K. Lu and S. K. Nguang, “LQG control of capacitive power transfer system,” in *2017 IEEE PELS Workshop on Emerging Technologies: Wireless Power Transfer*, WoW 2017, pp. 128-132, 2017.

[24] R. Erfani, F. Marefat, A. M. Sodagar, and P. Mohseni, “Transcutaneous capacitive wireless power transfer (C-WPT) for biomedical implants,” in *Proceedings-IEEE International Symposium on Circuits and Systems*, 2017.

[25] Y. Yusop, S. Saat, S. K. Nguang, H. Husin, and Z. Ghani, “Design of Capacitive Power Transfer Using a Class-E Resonant Inverter,” *J. Power Electron.*, vol. 16, no. 5, pp. 1678-1688, 2016.

[26] R. Erfani, F. Marefat, A. M. Sodagar, P. Mohseni, “Modeling and experimental validation of a capacitive link for wireless power transfer to biomedical implants,” *IEEE Transactions on Circuits and Systems II: Express Briefs*, 2017.

[27] Vrushali B. Gore, Dhanashri H. Gawali, “Wireless Power Transfer Technology for Medical Applications,” In *IEEE Conference on Advances in Signal Processing (CASP)*, pp. 455-460, 2016.

[28] Vladimir Vulfin, Shai Sayfan-Altman & Reuven Ianconescu, “Wireless power transfer for a pacemaker application,” *Journal of Medical Engineering & Technology*, 2017.

[29] Quan Xiong, “Wireless Charging Device for Artificial Cardiac Pacemaker,” *International Conference on Information Technology and Management Innovation (ICITMI)*, Atlantis Press, pp. 765-768, 2015.

[30] “Summary of blood brain barrier (BBB) permeability,” in *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields*, 3 kHz to 300 GHz, IEEE Std C95.1-2005.pp. 57

[31] Chao Liu; Aiguo Patrick Hu; Nirmal-Kumar C. Nair, “Coupling study of a rotary Capacitive Power Transfer system,” in *IEEE International Conference on Industrial Technology*, pp. 1-6, 2009.

[32] Fariborz Musavi; Murray Edington; Wilson Eberle, “Wireless power transfer: A survey of EV battery charging technologies,” in *IEEE Energy Conversion Congress and Exposition (ECCE)*, pp. 1804-1810, 2012.

[33] L. Huang; A. P. Hu, “Defining the mutual coupling of capacitive power transfer for wireless power transfer,” in *IET Journals & Magazines, Electronics Letters* 22nd, Vol. 51 No. 22 pp. 1806-1807, October 2015.

[34] Hua Zhang; Fei Lu; Heath Hofmann; Weiguo Liu; Chris Mi, “A Large Air-Gap Capacitive Power Transfer System with a 4-Plate Capacitive Coupler Structure for Electric Vehicle Charging Applications,” in *IEEE Applied Power Electronics Conference and Exposition (APEC)*, pp. 1726-1730, 2016.