Faculty of Electronic and Computer Engineering

THE CHARACTERIZATION OF CLASS E Pi1B CAPACITIVE POWER TRANSFER FOR BIOMEDICAL IMPLANTABLE DEVICE APPLICATION

Nurul Muslimah binti Meor Shaari

Master of Science in Electronic Engineering

2023

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NURUL MUSLIMAH BINTI MEOR SHAARI

A thesis submitted
in fulfilment of the requirements for the degree of
Master of Science in Electronic Engineering

Faculty of Electronic and Computer Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2023

DECLARATION

I declare thesis entitled "The Characterization of Class E Pi1b Capacitive Power Transfer for Biomedical Implantable Device Application" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	*Muslimah*
Name	:	Nurul Muslimah Binti Meor Shaari
Date	:	16 June 2023

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for award of Master of Science in Electronic Engineering.

Signature	:	…………………………………
Supervisor Name	:	Dr. Yusmarnita binti Yusop
Date	:	16 June 2023

DEDICATION

This thesis is wholeheartedly dedicated to my beloved parents, Mr. Meor Shaari bin Meor Chek and Mrs. Fatimah binti Abdullah, who have been my source of inspiration and gave my strength when I thought of giving up, who continually provide their moral, spiritual, emotional and financial support. I hope that this achievement will complete the dream that you had for me all those many years ago when you chose to give me the best education you could.

To my supportive siblings who shared their words of advice and encouragement to finish this research.

ABSTRACT

The use of Wireless Power Transfer (WPT) technology for recharging or providing a continuous supply of electricity to Biomedical Implantable Devices (BID) has become very useful recently. To date, Inductive Power Transfer (IPT) remains the most popular technique used to transmit power and data between the primary and secondary sides of the biomedical implanted system. However, designing a wireless transcutaneous system is complicated and the efficiency of existing system is still very low due to the variability of the environment and sensitivity to design parameter changes. Therefore, this research proposes the design of efficient WPT system based on capacitive approach for BID application. In this research, a Class E power amplifier with π impedance matching circuit is proposed to drive the Capacitive Power Transfer (CPT) system. An impedance matching is applied in order to optimize the system efficiency by making it less sensitive to the load variations. Two types of impedance matching, which are π1a and π1b matching resonant circuits are selected and compared in this research in order to understand the advantages and disadvantages of each in the framework of CPT system. MATLAB/Simulink software is used in this work to design and simulate the system. A 1W prototype operated at 6.78MHz frequency was constructed to verify the proposed circuit. The best experiment prototype of this work has demonstrated 89.4% efficiency with 0.636 cm x 0.636 cm area of capacitive coupling plates, which have a layer of meat in the range of 1mm to 10mm thickness in between. The results can be considered as an exceptional performance when compared to the existing low power scale CPT system achievements. In conclusion, the research outcomes portray the feasibility and the potential of CPT as an emerging contactless power transfer solution in BID applications, as well as the theory and the practical design methods that establish a solid foundation for future CPT research and development.

PENCIRIAN PEMINDAHAN KUASA KAPASITIF KELAS E Pi1B UNTUK APLIKASI PERANTI BIOPERUBATAN BOLEH IMPLAN

ABSTRAK

Penggunaan teknologi Pemindahan Kuasa Tanpa Wayar (WPT) untuk mengecas semula atau membekalkan bekalan elektrik berterusan kepada Peranti Bioperubatan Boleh Ditanam (BID) telah menjadi sangat berguna baru – baru ini. Sehingga kini, Pemindahan Kuasa Induktif (IPT) kekal sebagai teknik paling popular yang digunakan untuk menghantar kuasa dan data antara sisi primer dan sisi sekunder sistem bioperubatan implan. Walau bagaimanapun, mereka bentuk sistem transkutan tanpa wayar adalah rumit dan kecekapan sistem sedia ada masih sangat rendah disebabkan oleh kebolehubahan persekitaran dan kepekaan terhadap perubahan parameter reka bentuk. Oleh itu, penyelidikan ini mencadangkan reka bentuk sistem Pemindahan Kuasa Tanpa Wayar (WPT) yang cekap berdasarkan pendekatan kapasitif untuk aplikasi BID. Dalam penyelidikan ini, penguat kuasa Kelas E dengan litar padanan impedans π dicadangkan untuk memacu sistem Pemindahan Kuasa Kapasitif (CPT). Padanan impedans digunakan untuk mengoptimumkan kecekapan sistem dengan menjadikannya kurang sensitif terhadap variasi beban. Dua jenis padanan impedans, iaitu litar resonan padanan π1a dan π1b dipilih dan dibandingkan dalam penyelidikan ini untuk memahami kelebihan dan kekurangan setiap satu dalam rangka kerja sistem CPT. Perisian MATLAB/Simulink digunakan dalam kerja ini untuk mereka bentuk dan mensimulasikan sistem. Prototaip 1W yang dikendalikan pada frekuensi 6.78MHz telah dibina untuk mengesahkan litar yang dicadangkan. Prototaip eksperimen terbaik bagi kerja ini telah menunjukkan kecekapan 89.4% dengan keluasan 0.636cm x 0.636cm bagi plat gandingan kapasitif, yang mempunyai lapisan daging dalam julat ketebalan 1mm hingga 10mm di antara. Hasilnya boleh dianggap sebagai prestasi yang luar biasa jika dibandingkan dengan pencapaian sistem CPT skala kuasa rendah sedia ada. Kesimpulannya, hasil penyelidikan menggambarkan kebolehlaksanaan dan potensi CPT sebagai penyelesaian pemindahan kuasa tanpa sentuh yang muncul dalam aplikasi BID, serta teori dan kaedah reka bentuk praktikal yang mewujudkan asas kukuh untuk penyelidikan dan pembangunan CPT masa hadapan.

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious, the Most Merciful

First and foremost, I would like to thank and praise Allah the Almighty, my Creator, my Sustainer, for everything I received since the beginning of my life. I would like to extend my appreciation to the Universiti Teknikal Malaysia Melaka (UTeM) for providing the research platform. Thank you also to the Malaysian Ministry of Energy, Science, Technology, Environment and Climate Change (MESTECC) for the financial assistance.

My utmost appreciation goes to my main supervisor, Dr. Yusmarnita binti Yusop for all her support, advice and inspiration. Her constant patience for guiding and providing priceless insights will forever be remembered. Also, to my co-supervisor, Assoc. Prof. Dr. Mohd Shakir bin Md Saat who constantly supported my journey. Not forget to thank all my research teammates especially Puan Huzaimah binti Husin and Encik Khairul Kamarudin Hasan for all the kind help and support.

Last but not least, from the bottom of my heart a gratitude to my beloved parents, Mr. Meor Shaari bin Meor Chek and Mrs. Fatimah binti Abdullah, my siblings for their encouragements and who have been the pillar of strength in all my endeavors. Finally, thank you to all the individual(s) who had provided me the assistance, support and inspiration to embark on my study.

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LIST OF ABBREVIATIONS

AC	-	Alternating Current
AET	-	Acoustic Energy Transfer
APT	-	Acoustic Power Transfer
BID	-	Biomedical Implantable Device
CPT	-	Capacitive Power Transfer
DC	-	Direct Current
EMI	-	Electromagnetic Inteference
EV	-	Electric Vehicle
IMD	-	Implantable Medical Device
IPT	-	Inductive Power Transfer
MATLAB	-	Matrix Laboratory (Software)
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
PCB	-	Printed Circuit Board
WPT	-	Wireless Power Transfer
ZVS	-	Zero Voltage Switching

LIST OF SYMBOLS

ε_0	-	Vacuum permittivity / Electric constant / Permittivity of free space
A	-	Ampere
A	-	Area of plate
C	-	Capacitor
I	-	Current
d	-	Distance
D	-	Duty cycle
η	-	Efficiency
f	-	Frequency
F	-	Farad
H	-	Henry
Hz	-	Hertz
L	-	Inductor
P_i	-	Input power
V_i	-	Input voltage
R_L	-	Load resistor
M	-	Mega ($x10^6$)
µ	-	Micro ($x10^{-6}$)
Ω	-	Ohm
Po	-	Output power
Vo	-	Output voltage
π	-	Pi (3.14159)
Q_L	-	Quality factor
ε_r	-	Relative permittivity / Dielectric constant of a material
R	-	Resistor
V	-	Voltage / Volt
W	-	Watt

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LIST OF PUBLICATIONS

List of Journals:

1. **Meor, M.**, Saat, S., Yusop, Y., Husin, H., Mustapa, Z., and Hasan, K.K., 2020. Design and analysis capacitive power transfer (CPT) with π1a and π1b impedance matching circuit for 13.56MHz operating frequency. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, pp.1614-1624, vol 13, No 3. [SCOPUS]

2. Mustapa, M.Z. Bin, Saat, S., Yusof, Y., and Shaari, **M.M**., 2019. Capacitive power transfer in biomedical implantable device: a review. *International Journal of Power Electronics and Drive Systems (IJPEDS)*, 10(2), p.935. [SCOPUS]

3. Gnanasegaran, S., Saat, S., Rahman, F.K.A., Husin, S.H., Khafe, A., Isira, A.S.M., Darsono, A.M., Yahya, A., Yusop, Y., and Shaari, **N.M.M**., 2018. The development of wireless power transfer technologies for mobile charging in vehicles using inductive approach. *Journal of Telecommunication, Electronic and Computer Engineering*, 10(2), pp.143–149. [SCOPUS]

4. Hasan, K.K., Saat, S., Yusof, Y., H, M.A., Yusoff, Z.M., Shaari, **N.M.M**., and Mustapa, M.Z., 2018. Design of Capacitive Power Transfer (CPT) for Low Power Application using Power Converter Class E triggered by Arduino Uno Switching

Pulse Width Modulation (PWM). *International Journal of Engineering and Technology (UAE)*, 7, pp.77–81. [SCOPUS]

List of Conference Proceedings:

1. **Meor, M**., Saat, S., Yusop, Y., Husin, H., Mustapa, Z., and Hasan, K.K., 2019. Design and analysis capacitive power transfer (CPT) with and without π1a impedance matching circuit for 13.56MHz operating frequency. *Proceedings - 8th IEEE International Conference on Control System, Computing and Engineering, ICCSCE 2018*, pp.99–104.

2. **Meor, M**., Yusop, Y., Saat, S., 2021. Load and Coupling Variations Analysis of Capacitive Power Transfer at 6.78MHz Operating Frequency for Biomedical Implantable. *Proceedings – 2021 Asian Wireless Power Transfer Workshop, AWPT 2021*

CHAPTER 1

INTRODUCTION

1.1 Background

Previous era, wires and cables are utilised as a medium to connect a source to a load. They are chosen due to their simplicity and efficient method in order to transmit electrical energy. In addition, they become an ideal medium on the era since most of the loads are unmoving and stationary loads. Nowadays, with the demand of consumers and high technology development, devices and products become smaller in term of size, lightweight and portable shapes. One of the main disadvantages of a direct connection is freedom limitation for consumers in moving since it has to always connect directly by a cable or wires to obtain the energy transmission from a power source. Hence, in today's world, it's proven that cable or wires may not be a practical solution anymore since people keep moving from place to place so fast in a day.

To illustrate the real application of wires and cables usage from a "compulsory needed" to "do not depend anymore" is telephone. In previous century, telephone has a bulky size, heavy weight and need a lot of wires and cables to make sure it is well working. Decade by decade, the size of telephone is become smaller, the weight is become lighter and less usage of wires and cables due to the growth of technology and demand of consumers. Today, smartphone has a huge gap and many developments compare to the original telephone on decades ago especially in wires and cables usage. The smartphone does not need a single wire and cable in order to make it works. It is not depend on the wires and cables to make a connection or communication to others. Practically, the limitation freedom in moving for consumers is solved. According to t.com, the evolution of the telephone since the 1880s until today is as shown in Figure 1.1.

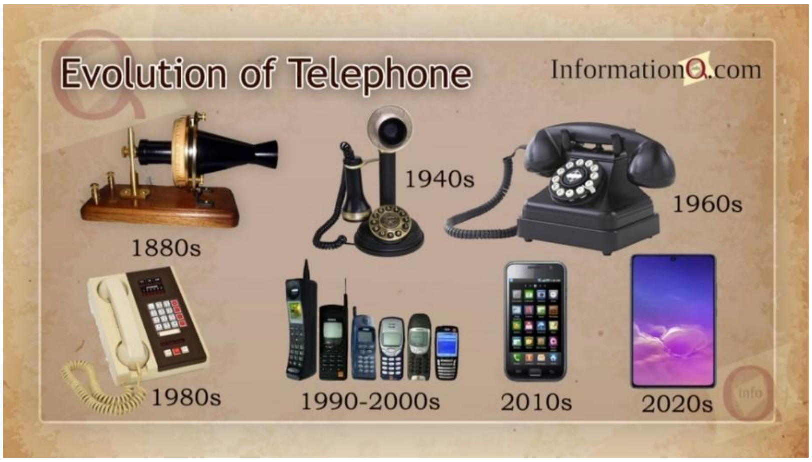

Figure 1.1: The Telephone Evolution (InformationQ.com, 2020)

Basically, near-field techniques are applied for short distance applications, which the gap between transmitter and receiver parts is in the range of a few millimeters and centimeters (Nguyen et al., 2020). The applications that suit these techniques are induction cooking, charging handheld devices, radio frequency identification (RFID) tag technology and wireless charging or continuous WPT in implantable medical devices (IMD). As opposed to near-field, far-field methods are capable to reach longer distance, where the distance between transmitter and receiver parts is around several kilometers (Nguyen et al., 2020). To illustrate one of the application from these methods is geostationary satellite transmits the power to ground devices.

To date, WPT becomes more popular since it develops great quantities of new technology applications. The most recent WPT applications are Wireless Mobile Charging, Electric Vehicles (EV) Charging and Wireless Biomedical Implantable Devices (BID). The demanding of WPT is getting higher day by day since it simplifies the wired devices, tools, equipment and applications.

1.2 Motivation

The most ubiquitous methods of Wireless Power Transfer (WPT) technology are Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT). Up to now, both of these methods have enormous development process and widely used in industry and daily life due to their tremendous performance. These methods have high demands since they are applicable to generate a wide range in term of output power, distance and power transmission.

Inductive Power Transfer (IPT) is in common used staring 1990s in various applications. Previously, it has accomplished great performance as first technology of Wireless Power Transfer (WPT) in industry. However, there are some limitations in this method since IPT used magnetic field as transfer interface. First, magnetic field is unable to penetrate through metal shielding environment, thus it is inapplicable to utilise in condition which metal exists between power source and load. Besides, since the magnetic field is functioning as transfer interface, it may cause electromagnetic interference (EMI) problems. Electromagnetic interference (EMI) surfeit amount may interfere with peripheral circuits and cause health concerns (Liu, Hu and N. K. C. Nair, 2009). Hence, to overcome the disabilities of Inductive Power Transfer (IPT), the Capacitive Power Transfer (CPT) method is introduced. On the other hand, Capacitive Power Transfer (CPT) used electric field as energy carrying medium (Liu, Hu and N. K. C. Nair, 2009), (Silva and Petry, 2015) and has potential in minimizing the electromagnetic interference (EMI) (Silva and Petry, 2015), (Liu, Hu and Nair, 2011). This method which based on capacitive coupling overcomes the drawback of any interference with other devices since it is based on Electrostatic Coupling (S et al., 2016). In addition, it has a few advantages which are small power density due to low coupling capacitance, simpler coupling structure, light weight and lower cost (Silva and Petry, 2015). It is really applicable for biomedical implantable devices which put health and human safety as main priority.

Biomedical implantable device, such as pacemaker required low power which about 10 to 30µW (Yang et al., 2021) and it is powering by small lithium ion batteries, which has limited lifetime. Due to the limited battery lifetime which about every 5 – 8 years (Bocan and Sejdić, 2016) and in other research is 8 – 12 years (Yang et al., 2021), the patient or user require a battery replacement or maintenance which lead to periodic surgery to replace the non-chargeable batteries (Bocan and Sejdić, 2016), (Yang et al., 2021). In other research, these batteries have a long life of 7 years normally (Ahmad et al., 2015). Thus, the patient's operation time can be deferred to each 7 to 12 years after for replacement of the battery as the charging can be done for 7 to 12 years externally. There are a few effects that may happen when having the surgery for the purpose of replacing battery. Firstly, patient is easily get infection from the surgery and may affect the health condition besides considering the patient traumatized due to periodic surgery. Secondly, high cost or expense for the battery replacement surgery that should be paid by the patient (Yang et al., 2021). Therefore, to overcome the problems, the power will be transferred wirelessly to charge the battery based on capacitive approach. In a nutshell, this is the purpose and importance of Wireless Power Transfer for Biomedical Implantable Devices application.

1.3 Problem Statement

Nowadays, technology for low watt scale applications has high demanding in industrial including BID applications. However, until today most of the systems exhibit limited output power and efficiency (Roes et al., 2011), (T. Zaid et al., 2014). This is due to high losses in the power converter which resulting low efficiency achievement (Shigeta et al., 2011), (Yan et al., 2019). Therefore, to overcome this problem, Class E power converter is proposed in CPT system in order to attain high efficiency and ZVS condition during power conversion process. Besides it can produce higher efficiency of the output, it also has the advantage in terms of simplicity which is the simplest topology compared to other class inverters and also has a low noise rectification system. The circuit of Class E power converter obtains high efficiency by only operating the switching element at points of zero current (off to on switching) or zero voltage (off to on switching) which minimizes power lost in the switch, even when the switching time of the devices is long compared to the frequency of operation (Zammit, Apap and Stainess, 2018), (Meade et al., 2008).

Other than that, even though the current technology reached at the top, every system that has created will have the tolerance such as tolerance in load resistances. The problem is the Class E power converter is sensitive to the load variations (Sokal, 2001), (Marian and Darius, 2011). Thus, the impedance matching network is proposed in this system in order to achieve the best circuit performance. There are a few categories of matching network. However, $\pi 1$ matching is selected due to the ability to provide voltage transformation and to increase the level of power transfer in CPT system. The $\pi 1a$ and $\pi 1b$ matching resonant circuits are selected and compared in this work in order to analyse the best performance of complete system.

1.4 Research Objective

The objectives of this research project are summarised as follows:

a) To investigate the electrical impedance of different capacitive coupling plates with different meat properties.

b) To design WPT system using capacitive approach specifically for Biomedical Implantable Device application.

c) To optimize the CPT system efficiency by using Class E resonant inverter with the presence of impedance matching.