Faculty of Electronic and Computer Engineering

DESIGN AND PERFORMANCE ANALYSIS OF CLASS-E DOUBLE-SIDED LC COMPENSATION TOPOLOGY FOR CPT SYSTEM EFFICIENCY IMPROVEMENT

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DECLARATION

I declare that this thesis entitled "Design and Performance Analysis of Class-E Double-sided LC Compensation Topologies for CPT System Efficiency Improvement" is the results 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.

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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	:	01.03.2023

DEDICATION

To my beloved mother and father, Tan Siew Wang and Cheok Ching Choon, my sister, Cheok Yan Han, Cheok Yan Ying, Cheok Yan Rou and my little brother, Cheok Yan Kai, your kindness and advice should never be forgotten.

ABSTRACT

Nowadays, Capacitive Power Transfer (CPT) is becoming an increasingly popular technology in the wireless charging field thus attracting the attention of many researchers. Although various research has been conducted with the aim of improving the performance of the system, there is still room for improvement to be made to further optimize the efficiency of the CPT system transmission. It is well known that the CPT system's efficiency and output power are limited when the transfer distance or gap distance between metal electrodes increases due to any misalignment of capacitive coupling plates or changes in load resistance. Therefore, this thesis proposed the development of a CPT system with high efficiency for low power contactless charging applications. Initially, the thesis begins by designing a Class-E resonant inverter that can provide high-frequency switching capability to increase the power of the system. The Class-E resonant inverter satisfies the soft-switching condition through parameter design thus improving the system's efficiency. Next, the output performance is analyzed by observing the zero-voltage switching (ZVS) condition, output power and efficiency of the system. Due to the characteristics of the Class-E resonant inverter which is sensitive to the circuit parameters variation, the π1b impedance matching circuit is included in the design to enable the power transfer efficiently between transmitter and receiver. In this part, the mathematical analysis of the sensitivity of the system's output power with respect to the load variation was introduced. In order to have a wider range of load variations, Class-E combined with double-sided LC matching circuits such as LCCL circuit and LCLC circuit were incorporated into the proposed approach. By switching the position of inductor and capacitor in LC matching at the receiver side of Class-E LCCL circuit, Class-E LCLC circuit was formed. The output performances of both circuits were analyzed and compared based on load variations, duty cycle variations and gap distance variations. MATLAB Simulink was used in this work to design and simulate all the aforementioned circuits. The design with the best output performance was selected to construct the CPT system. A 10W prototype was constructed which is operated at 1mm air gap with an efficiency of more than 84.6%. In conclusion, the research outcomes demonstrate the potential of CPT as an emerging wireless power transfer solution, as well as the theoretical and practical design methods to establish a solid foundation for future CPT research and development.

REKA BENTUK DAN ANALISIS PRESTASI TOPOLOGI PAMPASAN LC DUA SISI KELAS-E BAGI PENINGKATAN KECEKAPAN SISTEM CPT

ABSTRAK

Pada masa kini, Capacitive Power Transfer (CPT) menjadi teknologi yang semakin popular dalam bidang pengecasan tanpa wayar sekali gus menarik perhatian ramai penyelidik. Walaupun pelbagai kajian telah dijalankan dengan tujuan untuk meningkatkan prestasi sistem, masih terdapat ruang untuk penambahbaikan bagi mengoptimumkan lagi kecekapan penghantaran sistem CPT. Adalah diketahui umum bahawa kecekapan dan kuasa keluaran sistem CPT adalah terhad apabila jarak pemindahan atau jarak jurang antara elektrod logam meningkat disebabkan oleh sebarang salah jajaran plat gandingan kapasitif atau perubahan dalam rintangan beban. Oleh itu, tesis ini mencadangkan pembangunan sistem CPT dengan kecekapan tinggi untuk aplikasi pengecasan tanpa sentuh kuasa rendah. Pada mulanya, tesis dimulakan dengan mereka bentuk penyongsang resonan Kelas-E yang boleh menyediakan keupayaan pensuisan frekuensi tinggi untuk meningkatkan kuasa sistem. Penyongsang resonan Kelas-E memenuhi keadaan pensuisan lembut melalui reka bentuk parameter sekali gus meningkatkan kecekapan sistem. Seterusnya, prestasi keluaran tersebut dianalisis dengan memerhatikan keadaan pensuisan voltan sifar (ZVS), kuasa keluaran dan kecekapan sistem. Disebabkan oleh ciri-ciri penyongsang resonan Kelas-E yang sensitif kepada variasi parameter litar, litar padanan impedans π1b disertakan dalam reka bentuk untuk membolehkan pemindahan kuasa dengan cekap antara pemancar dan penerima. Dalam bahagian ini, analisis matematik sensitiviti kuasa keluaran sistem berkenaan dengan variasi beban telah diperkenalkan. Untuk mempunyai julat variasi beban yang lebih luas, Kelas-E digabungkan dengan litar padanan LC dua muka seperti litar LCCL dan litar LCLC telah dimasukkan ke dalam pendekatan yang dicadangkan. Dengan menukar kedudukan induktor dan kapasitor dalam padanan LC di bahagian penerima litar LCCL Kelas-E, litar LCLC Kelas-E telah terbentuk. Prestasi keluaran kedua-dua litar telah dianalisis dan dibandingkan berdasarkan variasi beban, variasi kitaran tugas dan variasi jarak jurang. MATLAB Simulink telah digunakan dalam kerja ini untuk mereka bentuk dan mensimulasikan semua litar yang disebutkan di atas. Reka bentuk dengan prestasi keluaran terbaik dipilih untuk membina sistem CPT. Sebuah prototaip 10W telah dibina dan dikendalikan pada celah udara 1mm dengan kecekapan lebih daripada 84.6%. Kesimpulannya, hasil penyelidikan menunjukkan potensi CPT sebagai penyelesaian pemindahan kuasa tanpa wayar yang muncul, serta kaedah reka bentuk teori dan praktikal untuk mewujudkan asas yang kukuh untuk penyelidikan dan pembangunan CPT masa hadapan.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

LIST OF ABBREVIATIONS

AC	-	Alternating Current
AET	-	Acoustic Power Transfer
CPT	-	Capacitive Power Transfer
DC	-	Direct Current
EMF	-	Electromotive Force
EV	-	Electric Vehicle
ICNIRP	-	International Commission on Non-Ionizing Radiation Protection
IEEE	-	Institute of Electrical and Electronic Engineers
IPT	-	Inductive Power Transfer
MOSFET	-	Metal-Oxide-Semiconductor Field-Effect Transistor
MPT	-	Microwave Power Transfer
NASA	-	National Aeronautics and Space Administration
NCRP	-	National Council on Radiation Protection and Measurements
OPT	-	Optical Power Transfer
PCB	-	Printed Circuit Board
PWM	-	Pulse Width Modulation/ Modulated
RF	-	Radio Wave
RMS	-	Root Mean Square
SAR	-	Specific Absorption Rate
WPT	-	Wireless Power Transfer
ZDS	-	Zero Derivative Switching
ZVS	-	Zero Voltage Switching

LIST OF PUBLICATIONS

List of Journals:

1. **Qi, C.Y.**, Yusop, Y., Saat, S., Husina, H., and Izadora, 2022. Modelling of Capacitive Power Transfer System Based on Class-E LCCL Topology. *Jurnal Teknologi*, 84(3), pp.69–79.

2. Yusmarnita Yusop, **Y.Q. Cheok**, K.C Wong, S.S. and K.K.H., 2022. Design And Analysis of Self-Charging Unmanned Aerial Vehicle (UAV) System Using Inductive Approach. *Journal of Advanced Manufacturing Technology (JAMT)*. (Paper waiting for publication)

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1. **Cheok Yan Qi**, Yusmarnita Yusop, Shakir Saat, Huzaimah Husin, K.K., 2022. Modelling of Capacitive Power Transfer System Based on Class-E LCLC Topology. *Proceedings of 4th International Conference on Telecommunication, Electronic and Computer Engineering (ICTEC'22)*, Melaka, Malaysia. (Paper Accepted)

CHAPTER 1

INTRODUCTION

1.1 Background of Thesis

Wireless Power Transfer (WPT) or wireless power transmission is a technology of transmitting electrical energy from the source to the load without any wires as physical connection. The WPT system consists of a transmitter, a medium for transferring power and a receiver. The transmitter receives the electrical power from the power supply and generates a time-varying electromagnetic field to carry power across the medium to the receiver which then supplies the power to the load. Several handheld devices can be considered for the load such as mobile phones and electric toothbrushes. Besides, WPT can be applied for induction cooking and charging implantable medical devices like artificial cardiac pacemakers. By having sufficient output voltage, WPT can even charge electric vehicles. Figure 1.1 illustrates the potential applications of WPT for daily usage in a domestic environment. Using the WPT method, the problem of wires tangling together when having a lot of home appliances can be solved. As a result, WPT increases mobility, convenience and safety for all electronic device users.

WPT mainly falls into two main categories which are the near field and far field. Two well-known techniques in the near field are Capacitive Power Transfer (CPT) and Inductive Power Transfer (IPT). This research focuses on the design of CPT due to negligible eddy-current loss, relatively low cost, low weight and excellent misalignment performance. The designed CPT system utilizes a Class-E resonant inverter and different types of impedance matching networks.

Figure 1.1: Application of WPT in House

1.2 Problem Statement

The Wireless Power Transfer (WPT) technology has been demonstrated since 1981 by Nikola Tesla with the illumination of phosphorescent lamps without using wire through CPT technology. Due to being more applicable to many power levels and various gap distances, IPT is the preferred choice when it comes to designing a WPT system. However, IPT has a significant shortcoming that concerns with the human safety regarding the field emission and overheating due to loss of eddy current when metal objects are close to the magnetic field (Huang et al., 2013). Therefore, most research in this field suggest CPT as the solution for this problem, as it is not sensitive to any metal presence and does not generate extra heat in metal due to eddy current losses (Li et al., 2015; Lu et al., 2015b).

In general, overall system efficiency is an important factor in designing and applying the CPT system. Although researchers have carried out a large amount of work to improve the performance of the system, there is still room for improvement to be made to further optimize the efficiency of the CPT system transmission. Based on the literature, system loss is mainly derived from power converter switching losses (Meade et al., 2008), coupling losses (Park, Thompson and Ferguson, 2005) and the parasitic resistance losses (Mohammad et al., 2013) from compensation components, including compensation inductors, capacitors, and switch devices. Most conventional CPT systems apply a full-bridge inverter for low-power CPT application. However, the use of the aforementioned approach to generate AC sinusoidal wave is complex due to the difficulty to drive the gating signal for power switches and will eventually lead to high switching losses (Bhardwaj, Borage and Tiwari, 2008). A full-bridge inverter consists of two pairs of switches which turn on and turn off simultaneously with a dead time. The dead time is necessary to avoid 'shoot through' or cross-conduction current through the same led of switches which resulting the failure of switching devices (Zammit, Apap and Staines, 2018). However, this dead time lead to switching loss. Therefore, CPT system using a Class-E resonant inverter is proposed because it could achieve 100% theoretical maximum efficiency by applying soft-switching condition via the use of one power electronic switching device.

An important aspect when designing the CPT system is the trade-off between the transfer distance, power and efficiency which implies that the current CPT system cannot achieve long distance, high power and efficiency at the same time. For low-power charging applications, the CPT system's efficiency and output power are limited when the transfer distance or gap distance between metal electrodes increases (Dai and Ludois, 2015a). Moreover, CPT is known to be sensitive to load and coupling variations (Mostafa, Muharam, et al., 2019). The system efficiency will decrease significantly due to any misalignment of capacitive coupling plates or changing in load resistance. Therefore, various impedance matching circuits based on L-type, T-type and π-type matching networks are designed and applied to the Class-E inverter to preserve the zero-voltage switching (ZVS) condition thus compensating for the power loss caused by load and coupling variation. The impedance matching circuits match the load impedance and the source impedance to minimize signal reflection, thus allowing the maximum power transfer from the source to load.

1.3 Research Objectives

The objectives of this research project are summarized as follows:

i. To design a Class-E resonant inverter that drives a CPT system.

ii. To investigate the performance of Class-E inverter with the presence of π1b, LCCL and LCLC impedance matching networks.

iii. To analyse the performance of the complete prototype of the CPT system in terms of ZVS, output power, and system efficiency.

1.4 Research Scope

This research aims to improve the efficiency of the CPT system. The details of the research scopes and the limitation of this work are as follows:

i. The proposed CPT is limited to the low-wattage charging application and small gap distance 1mm only. This is due to the fact that a large gap and high power causes the voltage across the gap from transmitter to receiver to exceed the permitted electric field for human exposure, which is 614V/m (IEEE standards, 2019) thus may not be safe for human contact (Asa et al., 2020). In order to demonstrate low power charging application, 10W output power is sufficiently for application in USB interface, LED driving and charging mobile devices such as mobile phones, laptops and tablets.

ii. Class-E resonant inverter is selected to build the CPT system because it can theoretically achieve 100% efficiency. It is designed at optimum operation with duty cycle, D = 0.5 to gain 10W output power and efficiency above 80% at an optimum load, $R_L = 50\Omega$.

iii. The pulse width modulation (PWM) signal and tuning for Class-E converter are operated at 1 MHz switching frequency. In order to protect human against adverse health effects when exposed to very high radio frequency, NCRP, IEEE and ICNIRP determined a threshold level of specific absorption rate (SAR) about 0.4 W/kg (IEEE, 2006). Therefore, a suitable frequency for maximum power transfer and within the permitted SAR is required and explored in this research.

iv. The size of the capacitive coupling plate with a parallel circular structure is equivalent to the capacitance value of the designed Class-E components. The circular plate is made from the single-sided FR4 printed circuit board (PCB) copper plate, which is easier and cheaper.

v. The verification of the proposed design and performance analysis is carried out through the simulation using MATLAB before the circuit was fabricated.

vi. Agilent Technologies DSO-X 2012A 100MHz oscilloscope was used to analyse the proposed design where several output parameters such as ZVS condition, input and output power, and efficiency were recorded.

1.5 Organization of Thesis

The thesis comprises five chapters. Chapter 1 presents the introduction of this project, consisting of background, problem statement, research objectives, limitation of the research, and the organization of the thesis.

Chapter 2 describes the literature review on wireless power transfer (WPT) technology. The history of Wireless Power Transfer (WPT) is introduced at the very beginning. Then, an overview of Wireless Power Transfer (WPT) is discussed. This chapter focuses mainly on Capacitive Power Transfer (CPT). Its working principle, applications and roles of each block that constitute the CPT system such as inverter, compensation circuit, rectifier, and capacitive coupler are presented. This chapter ends with several issues and challenges related to the present CPT system design.

Chapter 3 depicts the methodology for full development of CPT system. This chapter presents the derivation of related formulas for circuit parameters and output performances of CPT system. Firstly, a basic Class-E resonant inverter is designed. Then, π1b matching circuit is designed to change the optimum load to 50Ω. Then, an extra LC matching circuit is added to the receiver part of the Class-E with π1b matching circuit to form Class-E LCCL and LCLC circuits. Moreover, the Class-E DC-to-DC converter is formed by adding the full-wave rectifier and a capacitor filter to either of them. Lastly, the Class-E DC-DC converter is modified to CPT system.

Chapter 4 presents the results of the design specifications and output performances of the Class-E resonant inverter, Class-E with π1b impedance matching circuit, Class-E LCCL circuit, Class-E LCLC circuit, Class-E DC-to-DC converter and CPT system. The Class-E LCCL circuit and Class-E LCLC circuits are compared based on output performance at optimum load, load variations, duty cycle variations and gap distance variations to select one suitable to realize the CPT system.

Chapter 5 discusses the conclusion of this research, including research outcomes, contributions of this study and recommendations for future research based on this study.