Faculty of Electronic and Computer Engineering

NEW POWER CONVERTER TOPOLOGY FOR LOW POWER ROTARY CAPACITIVE POWER TRANSFER SYSTEM

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NEW POWER CONVERTER TOPOLOGY FOR LOW POWER ROTARY CAPACITIVE POWER TRANSFER SYSTEM

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DECLARATION

I declare that this thesis entitled “New Power Converter Topology for Low Power Rotary Capacitive Power Transfer System” 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 : ……………………………………

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Date : 23 October 2018

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 the award of Doctor of Philosophy.

Signature	: …………………………………………….
Supervisor Name	: Assoc. Prof. Dr. Mohd Shakir Bin Md. Saat
Date	: 23 October 2018

DEDICATION

To my loving parents, Yusop Saat and Mariah Othman, my husband, Major Aziezi Ishak (Rtd), my son, Muhammad Farhan Aziezi, and my daughters, Anis Farhana Aziezi, Dhiya Alisha Aziezi and Alisha Safiya Aziezi

&

In memory of Abdul Hamid Hamidon, your kindness and advice should never be forgotten

ABSTRACT

Since the past decade, many researchers have taken interest to investigate the capacitive power transfer (CPT) as an alternative to achieve contactless power transfer. By employing the electric field as the energy transfer medium, CPT has the advantages of the confined electric field between coupling plates, power transfer capability through metal barriers, low eddy current power losses associated with metal surroundings, as well as the potential to minimise circuit size and cost. This thesis mainly concentrates on the development of a fundamental theory of CPT system and its application for low power contactless charging. Initially, the thesis begins by analysing the Class-E resonant inverter performance to generate high frequency AC power source to drive the CPT system. Due to the sensitivity of components variation, the investigation of Class-E resonant inverter with feedback frequency controller unit is proposed to enhance the efficiency of CPT system by preserving the zero voltage switching (ZVS) condition over a longer distance. Second, the utilization of compensation network to serve as an impedance converter in order to enable efficient power transfer between two stages with non-matching impedances had been investigated. Here, mathematical analysis of the sensitivity of the system output power in respect to the load variation was introduced. Third, a Class-E combined with LCCL compensation network topology for both transmitter and receiver is proposed to provide impedance matching and hence, keeping the ZVS condition for wider load-range changes. Next, based on the proposed Class-E LCCL topology, a single plate rotary CPT system was developed to realize power transfer to the rotating load. Finally, in enhancing the capacitive coupler embedded in the rotary CPT system, the rotating capacitive coupler was upgraded with multiple plate structure approach to generate a small and compact capacitive coupler plate without the need of increasing electric field emission. This was controlled by a novel power flow control topology called cascaded Boost-Class-E. With the application of these proposed control methods, the output power of rotary CPT system could be adjusted. Overall, this thesis presents a fundamental study on CPT technology carried out by employing mathematical analysis, computer simulations, and practical experiments for validation purpose. A 10W prototype was constructed to verify the proposed circuit. The best experiment prototype of this work has demonstrated more than 90% efficiency at 2 mm working distance, which 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, as well as the theory and the practical design methods that establish a solid foundation for future CPT research and development.

ABSTRAK

Sejak sedekad yang lalu, ramai penyelidik telah mengambil perhatian untuk mengkaji pemindahan kuasa kapasitif (CPT) sebagai alternatif untuk mencapai pemindahan kuasa tanpa sentuh. Dengan menggunakan medan elektrik sebagai medium pemindahan tenaga, CPT mempunyai kelebihan medan elektrik terkurung antara plat gandingan, keupayaan pemindahan kuasa melalui halangan logam, kehilangan kuasa arus pusar yang rendah apabila berkaitan dengan persekitaran logam, serta potensi untuk meminimumkan saiz litar dan kos. Tesis ini memberi tumpuan utama kepada perkembangan teori asas sistem CPT dan aplikasinya untuk pengecasan tanpa wayar berkuasa rendah. Pada peringkat awal, tesis ini dimulakan dengan menganalisis prestasi penyongsang resonans Class-E bagi menghasilkan sumber kuasa AC berfrekuensi tinggi untuk memacu sistem CPT. Disebabkan sensitiviti variasi komponen, penyiasatan keatas penyongsang resonans Kelas-E bersama unit suap balik pengawal frekuensi dicadangkan bagi meningkatkan kecekapan sistem CPT dengan memelihara keadaan penukaran voltan sifar (ZVS) pada jarak jauh. Kedua, penggunaan rangkaian impedans untuk berfungsi sebagai penukaran impedans bagi membolehkan pemindahan kuasa yang efisien antara dua peringkat yang impedansnya tidak sepadan telah disiasat. Di sini, analisis matematik berkaitan dengan kepekaan kuasa keluaran sistem terhadap perubahan beban diperkenalkan. Ketiga, gabungan Kelas-E dengan topologi rangkaian kompensasi LCCL untuk kedua-dua bahagian pemancar dan penerima dicadangkan bagi menyediakan padanan impedans dan oleh itu, keadaan ZVS untuk julat perubahan beban yang lebih luas dapat dikekalkan. Seterusnya, berdasarkan topologi Class-E LCCL yang dicadangkan, satu sistem CPT berputar plat tunggal telah dibangunkan untuk merealisasikan pemindahan kuasa kepada beban yang berputar. Akhir sekali, dalam meningkatkan plat gandingan kapasitif yang terdapat dalam sistem CPT berputar, pengganding kapasitif berputar ditambahbaik dengan menggunakan pendekatan struktur plat berganda bagi menghasilkan plat gandingan kapasitif yang kecil dan padat tanpa perlu meningkatkan pengeluaran medan elektrik. Ianya dikawal oleh topologi kawalan aliran kuasa baru yang dipanggil Cascaded Boost-Class E. Dengan penggunaan kaedah kawalan yang dicadangkan ini, kuasa keluaran sistem CPT berputar boleh diselaraskan. Keseluruhannya, tesis ini membentangkan satu kajian asas mengenai teknologi CPT yang dijalankan dengan menggunakan analisis matematik, simulasi komputer, dan eksperimen praktikal untuk tujuan pengesahan. Prototaip 10W telah dibina untuk mengesahkan litar yang dicadangkan. Prototaip eksperimen terbaik dalam kajian ini telah menunjukkan kecekapan 90% pada jarak 2mm, yang boleh dianggap sebagai sangat baik prestasinya, berbanding dengan pencapaian sistem CPT skala kuasa rendah sedia ada. Sebagai kesimpulan, hasil penyelidikan menggambarkan kemungkinan dan potensi CPT sebagai penyelesaian kepada pemindahan kuasa tanpa wayar, serta teori dan kaedah reka bentuk praktikal yang menubuhkan asas kukuh untuk penyelidikan dan pembangunan CPT masa hadapan.

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AC	-	Alternating Current
AET	-	Acoustic Energy Transfer
BJT	-	Bipolar Junction Transistor
CCM	-	Continuous Current Mode
CFI	-	Current Fed Inverter
CPT	-	Capacitive Power Transfer
DC	-	Direct Current
ESL	-	Equivalent Series Inductance
ESR	-	Equivalent Series Resistance
EV	-	Electric Vehicle
FCU	-	Frequency Controller Unit
FEA	-	Finite Element Analysis
IEEE	-	Institute of Electrical and Electronics Engineers
IGBT	-	Insulated Gate Bipolar Transistor
IPT	-	Inductive Power Transfer
KCL	-	Kirchhoff Current Law
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
PCB	-	Printed Circuit Board
PI	-	Proportional Integral
PIC	-	Programmable Intelligent Computer

PM	-	Permanent Magnet
PWM	-	Pulse Width Modulation
PP	-	Parallel-Parallel
PS	-	Parallel-Series
PV	-	Photovoltaic
PZT	-	Lead Zirconate Titanate
RF	-	Radio Frequency
SAR	-	Specific Absorption Rate
SP	-	Series-Parallel
SS	-	Series-Series
VCO	-	Voltage Control Oscillator
VFI	-	Voltage Fed Inverter
WFSM	-	Wound Field Synchronous Machine
WIFI	-	Wireless Fidelity
WPT	-	Wireless Power Transfer
ZVS	-	Zero Voltage Switching

LIST OF PUBLICATIONS

List of Journals:

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Cables and wires used to be the preferred choice during conventional times to connect a source to a load. This appears to be a simple and efficient method to transfer electrical energy and also suitable for most applications found to date since the loads are motionless. Nevertheless, with advancement of technology, products have taken smaller and portable shapes. Hence, relying on a cable connected to a power outlet to obtain energy may not be a practical solution any more. A direct cable connection limits one's freedom of movement and in some cases, may not be a safe option. For example, due to the increase in oil prices and to environmental concerns, electrical vehicles have a key impact for future research and development. These vehicles are installed with an on-board battery that provides power partially or entirely for the entire trip duration. Although a direct cable connection to a power outlet suits to a certain degree to provide power and recharge the batteries, more options would be made available if power is supplied without any cable and contact. As such, an electric vehicle can be charged 'on-the-go' while in motion. The risk of electric shock and sparks is highly reduced as no physical contact exists between the vehicle and the power supply. Furthermore, regular maintenance, such as changing the battery electrolytes and cleaning the contact parts can be minimised. Other instances of applications that demonstrate the need of contactless energy transfer to ease and to facilitate everyday life are illustrated in Figure 1.1.

Contactless energy transfer can be achieved through Wireless Power Transfer