UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DESIGN OF A SELF-TUNING WIRELESS POWER TRANSFER SYSTEM FOR LOW POWER APPLICATION USING CAPACITIVE APPROACH

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A thesis submitted
in fulfillment of the requirements for the degree of
Doctor of Philosophy

Faculty of Electronics and Computer Engineering

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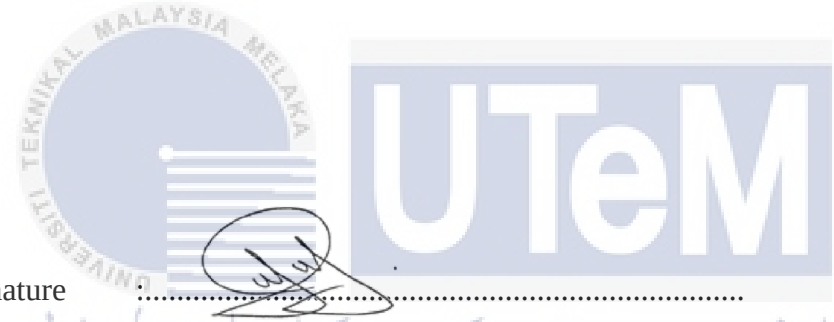
2021

DECLARATION

I declare that this thesis entitled " Design of a Self–Tuning Wireless Power Transfer System for Low Power Applications Using Capacitive Approach" 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.



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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 the award of Doctor of Philosophy.

Signature :.....

Supervisor Name : Associate Prof. Dr. Mohd Shakir B. Md. Saat

Date : 09 NOVEMBER 2021

DEDICATION

To my loving parents, Hasan Hamid and Che'Wa Said, to for all the support and understanding

ABSTRACT

Since a decade ago, the Wireless Power Transfer Techonology has gain significant attention from researchers around the world. The popularity mainly due to the ability of tranferring power without physical connection especially in short distance power transfer applications. This short distance power transfer is normally from a few milimetre (mm) to a few metre (m) and this is commonly known as near field application. The main research interest is in the area of Capacitive Power Transfer (CPT) as a potential contactless power transfer option. The use of an electric field as an energy transfer medium provides CPT the advantages of confining the electric field between coupling plates, therein allowing power transfer through metal barriers. CPT also reduces eddy current power losses from metal surroundings including the potential to minimize circuit size and cost. Certain studies selected a maximum transfer distance of other applications at about 1 mm with similar impedance at both transfer unit and receiver unit in order to attain maximum efficiency. However tha main issue of CPT system is the variation in the plate transfer distance, its affects most of the applications in terms of their system efficiency and power of receiving at load. To overcome the mentioned problem, this thesis proposes a self-tuning frequency resonant technique for Class E-LCCL CPT system with impedance matching circuit topology to improve efficiency to address varying distances between capacitive coupling plates. The thesis begins by analysing the Class-E resonant inverter performance to generate a high frequency AC power source to drive the CPT system. Second, by utilizing a compensation network as an impedance converter to enable power transfer efficiently between two stages with a Class-E combined with LCCL compensation network topology for both transmitter and receiver is proposed as a method to provide impedance matching and hence, keeping the Zero Voltage Switching (ZVS) in good condition for wider distance range. Finally, the optimum efficiency of the Class-E LCCL CPT system was determined by employing the frequency tuning method during changes in the capacitive plates distance. Specifically, simulation and experimental works were done to analyse the developed Class-E LCCL CPT system with a 24 V DC supply voltage and 1 MHz operating frequency. With an air gap distance of 0.1 cm, the designed CPT system prototype successfully achieved a power output of 10 W and 95.45% efficiency. When the distance of the coupling plates was changed in the range of 1mm to 10mm, the original efficiency decreased from 95.45% to 72.06%. To overcome this efficiency-drop, the frequency tuning approach is proposed as a method to maintain the output efficiency despite the change in distance. In this study, an Arduino Uno pulse-width modulation (PWM) controller was used to tune the resonant frequency accordingly. By using this method, the original efficiency decreased only from 95.45% to 80.08% with varied frequency. These findings could be beneficial for household apparatus, medical implants, and charging consumer electronics.

REKA BENTUK SISTEM PEMINDAHAN KUASA WAYARLES PENALAAN-DIRI BAGI APLIKASI KUASA RENDAH MENGGUNAKAN PENDEKATAN KAPASITIF

ABSTRAK

Sejak sedekad yang lalu, teknologi Pemindahan Kuasa Tanpa Wayar (WPT) telah mendapat perhatian yang besar dari para penyelidik di seluruh dunia. Populariti ini terutama disebabkan oleh kemampuan memindahkan kuasa tanpa sambungan fizikal terutamanya dalam aplikasi pemindahan kuasa jarak dekat. Pemindahan kuasa jarak dekat ini biasanya dari beberapa milimeter (mm) hingga beberapa meter (m) dan ini biasanya dikenali sebagai aplikasi medan dekat. Minat penyelidikan utama adalah dalam bidang Pemindahan Kuasa Kapasitif (CPT) sebagai pilihan pemindahan kuasa tanpa sentuh yang berpotensi. Penggunaan medan elektrik sebagai medium pemindahan tenaga memberikan CPT kelebihan membendung medan elektrik antara plat gandingan, di dalamnya memungkinkan pemindahan daya melalui penghalang logam. CPT juga mengurangkan kehilangan kuasa arus eddy dari persekitaran logam termasuk berpotensi untuk meminimumkan saiz dan kos litar. Kajian tertentu memilih jarak pemindahan maksimum aplikasi lain pada jarak sekitar 1 mm dengan impedans serupa pada kedua unit pemindahan dan unit penerima untuk mencapai kecekapan maksimum. Masalah utama dalam research ini adalah Variasi jarak pemindahan plat, ia akan mempengaruhi sebahagian besar aplikasi dari segi kecekapan sistem dan kekuatan penerimaan pada beban. Untuk mengatasi masalah yang disebutkan, tesis ini mencadangkan teknik baru resonan frekuensi penyesuaian diri sistem CPT Kelas-E dengan litar pegabungan impedans untuk meningkatkan kecekapan untuk menangani jarak yang berbeza antara plat gandingan kapasitif. Tesis dimulakan dengan menganalisis prestasi penyongsang resonan Kelas-E untuk menghasilkan sumber kuasa AC frekuensi tinggi untuk menggerakkan sistem CPT. Kedua, dengan menggunakan rangkaian pampasan sebagai penukar impedans untuk memungkinkan pemindahan daya secara efisien antara dua tahap dengan Kelas-E yang digabungkan dengan topologi rangkaian pampasan LCCL untuk pemancar dan penerima diusulkan sebagai kaedah untuk memberikan padanan impedansi dan dengan itu, menjaga Penukaran Voltan Sifar (ZVS) dalam keadaan baik untuk jarak jarak yang lebih luas. Akhirnya, kecekapan optimum sistem CPT Kelas-E LCCL ditentukan dengan menggunakan kaedah penalaan frekuensi semasa perubahan pada jarak plat kapasitif. Khususnya, simulasi dan eksperimen dilakukan untuk menganalisis sistem CPT Kelas-E LCCL dengan voltan bekalan 24 V DC dan frekuensi operasi pada 1 MHz. Dengan jarak jurang udara 0.1 cm, prototaip sistem CPT yang dirancang berjaya mencapai keluaran kuasa 10 W dan kecekapan 95.45%. Apabila jarak plat gandingan diubah dalam julat 1mm hingga 10mm, kecekapan asal menurun dari 95.45% menjadi 72.06%. Untuk mengatasi penurunan kecekapan ini, pendekatan penalaan frekuensi diusulkan sebagai kaedah untuk mempertahankan kecekapan output walaupun terdapat perubahan jarak. Dalam kajian ini, pengawal Arduino Uno 'pulse-width modulation (PWM)' digunakan untuk menyesuaikan frekuensi resonan dengan sewajarnya. Dengan menggunakan kaedah ini, kecekapan asal hanya menurun dari 95.45% hingga 80.08% dengan frekuensi yang berbeza-beza. Penemuan ini boleh bermanfaat untuk peralatan elctronic perkakasan di rumah,implan perubatan dan pengisian elektronik pengguna.

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AET	-	Acoustic Energy Transfer
AC	-	Alternating Current
AVR	-	Audio/Video Receiver
ARM	-	Advanced RISC Machines
API	-	Application Programming Interface
BJT	-	Bipolar Junction Transistor
CFI	-	Current Fed Inverter
CPT	-	Capacitive Power Transfer
CCM	-	Continuous Current Mode
CPAP	-	Continuous Positive Airway Pressure
DC	-	Direct Current
DUT	-	Device Under Test
ESL	-	Equivalent Series Inductance
ESR	-	Equivalent Series Resistance
EV	-	Electric Vehicle
EMI	-	Electromagnetic Interference
EEPROM	-	Electrically Erasable Programmable Read-Only Memory
FEA	-	Finite Element Analysis

FCU	-	Frequency Controller Unit
GPIO	-	General-Purpose Input/Output
GND	-	Ground
GaN	-	Gallium Nitride
HCC	-	Harmonics Control Circuit
IPT	-	Inductive Power Transfer
IGBT	-	Insulated Gate Bipolar Transistor
IEEE	-	Institute of Electrical and Electronics Engineers
I/O	-	Input / Output
KCL	-	Kirchhoff Current Law
KB	-	Kilo Byte
LCCL	-	Inductor-Capacitor Capacitor-Inductor
LC	-	Inductor-Capacitor
LPT	-	Low-Earth Orbit
LCD	-	Liquid Crystal Display
LED	-	Light Emitting Diode
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
MTP	-	Microwave Power Transfer
OPT	-	Optical Power Transfer
PZT	-	Lead Zirconate Titanate
PV	-	Photovoltaic
PS	-	Parallel-Series
PP	-	Parallel-Parallel
PIC	-	Peripheral Interface Controller

PCB	-	Printed Circuit Board
PWM	-	Pulse Width Modulation
PM	-	Permanent Magnet
PI	-	Proportional Integral
PAE	-	Power Added Efficiency
RF	-	Radio Frequency
RAM	-	Random Access Memory
SS	-	Series-Series
SP	-	Series-Parallel
SPI	-	Serial Peripheral Interface
SAR	-	Specific Absorption Rat
SMLCMRC	-	Symmetrical Meandered Lines Compact Microstrip Resonant Cell
UAV	-	Unmanned Aerial Vehicle
VFI	-	Voltage Fed Inverter
USB	-	Universal Serial Bus
VCO	-	Voltage Control Oscillator
VA	-	Volt-Ampere
VCO	-	Voltage Controlled Oscillator
WPT	-	Wireless Power Transfer
WFSM	-	Wound Field Synchronous Machine
WIFI	-	Wireless Fidelity
ZVS	-	Zero Voltage Switching
ZCS	-	Zero Correlation Spread

LIST OF PUBLICATIONS

The research papers produced and published during the course of this research are as follows:

1. Khairul Kamarudin Hasan, Shakir Saat, Yusmarnita Yusop, Masmaria Abdul Majid, Mohd Sufian Ramli, "Analysis and Design of Class E-LCCL Compensation Circuit Topology Circuit Topology for Capacitive Power Transfer (CPT) System" *International Journal of Power Electronics and Drive Systems*,12(2), pp.1265–1274, 2021.

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