Faculty of Electronic and Computer Engineering

SELF-FREQUENCY TRACKING HIGH-FREQUENCY CLASS E RESONANT INDUCTIVE LINKS FOR WIRELESS POWER TRANSFER APPLICATION

Norezmi binti Md Jamal

Master of Science in Electronic Engineering

2016

SELF-FREQUENCY TRACKING HIGH-FREQUENCY CLASS E RESONANT INDUCTIVE LINKS FOR WIRELESS POWER TRANSFER APPLICATION

NOREZMI BINTI MD JAMAL

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

2016

DECLARATION

I declare that this entitled "Self-frequency Tracking High-frequency Class E Resonant Inductive Links for Wireless Power Transfer 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 :..

Name :..

Date :..

APPROVAL

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

Signature :..

Supervisor Name :..

Date :..

DEDICATION

To my beloved husband, mother and father.

ABSTRACT

Nowadays, Wireless Power Transfer (WPT), specifically based on Inductive Power Transfer (IPT) technology is widely used in mobile applications such as mobile phone, pacemaker, and other applications. It is capable to transfer an electrical power from a power source (transmitter) to an electronic device (receiver) via an air gap, make it flexible and portable to be used for mobile device charger. Therefore, the IPT charger must be compact and small in size. In order to realize it, the coil size should be reduced. So, the operating frequency of the IPT system must be increased significantly to ensure the strongest magnetic field can be generated for a better power transmission. However, as the frequency increases, the switching losses in resonance power converter circuit increase at the same time. Thus, a Class E resonant power converter circuit that yields low switching loss is proposed and designed to drive inductive links with high frequency at transmitter side. In this research, the used operating frequency is 1MHz. To guarantee the maximum power transfer and improvement in efficiency, some studies and experiments on the type of compensated capacitor connection in IPT system were conducted. The simulation and experimental results showed that the external capacitor in series with the transmitter coil improved the result of the induced voltage. Further investigation on capability of larger inductance of inductive links to receive more power with a secondary series compensated capacitor is also conducted. On top of that, since the power transmission is based on the induced voltage concept of two inductive resonance coupling coils, the frequency of the driver circuit may dynamically drift away from the designed circuit. This is because the reflected load impedance exists in transmitter side. In order to rectify the aforementioned problem, a self-frequency tracking approach with feedback loop, which is Phased Lock Loop is proposed to ensure the frequency of the IPT system is operated at 1MHz stably. The analysis of the IPT system with self-frequency tracking performance is validated through LTspice simulations and experimental works. The results revealed that the proposed self-frequency tracking approach improved the power transfer efficiency as compared to without using frequency tracking. Therefore, the total power transfer efficiency of IPT system for simulated results is equal to 84.3% with frequency tracking and 80.6% of without tracking results, respectively. Otherwise, the experimental result of self-frequency tracking is 85.0% and the efficiency of without tracking is 80.4% at 10 mm of air gap distance. Thus, the power transfer efficiency has increased about 4.6% for experimental results.

ABSTRAK

Pada masa ini, Aplikasi Pemindahan Kuasa Tanpa Wayar (WPT), khususnya yang berasaskan Pemindahan Kuasa Beraruhan (IPT) digunakan secara meluas dalam aplikasi mudah alih seperti telefon bimbit, perentak jantung dan aplikasi-aplikasi lain. Ia mampu untuk memindahkan kuasa elektrik daripada bekalan kuasa (penghantar) kepada alat elektronik (penerima) melalui sela udara, yang menjadikannya fleksibel dan mudah dibawa untuk digunakan bagi pengecasan alat peranti mudah alih. Oleh itu, pengecas IPT haruslah padat dan bersaiz kecil. Justeru, saiz gegelung perlu dikecilkan. Maka, frekuensi operasi sistem IPT mestilah ditinggikan dengan banyak untuk memastikan medan magnet yang terkuat dapat dihasilkan untuk pemindahan kuasa yang lebih baik. Walaubagaimanapun, dengan peningkatan frekuensi, kehilangan kuasa ketika proses pensuisan dalam litar salunan kuasa penukar juga meningkat pada masa yang sama. Oleh itu, litar bersalunan kuasa penukar kelas E yang mempunyai kehilangan kuasa pensuisan yang rendah adalah dicadangkan dan direka bentuk untuk memacu pautan beraruhan dengan frekuensi yang tinggi di bahagian penghantar. Dalam penyelidikan ini, frekuensi operasi yang dipilih ialah 1MHz. Untuk menjamin pemindahan kuasa maksimum dan penambahbaikan dalam kecekapan sistem, beberapa kajian dan eksperimen terhadap jenis sambungan kapasitor pengimbang dalam sistem IPT telah dijalankan. Keputusan simulasi dan eksperimen menunjukkan bahawa kapasitor pengimbang luar yang disambung secara sesiri dengan gegelung penghantar dapat meningkatkan penghasilan voltan teraruh. Penyiasatan lanjut terhadap keupayaan kearuhan pautan gegelung yang beraruhan untuk menerima lebih banyak kuasa dengan kapasitor pengimbang sesiri sekunder juga dijalankan. Selain itu, memandangkan pemindahan kuasa adalah bergantung kepada konsep voltan teraruh pada dua aruhan pautan gegelung , frekuensi litar pemacu boleh tersasar daripada litar yang direka bentuk. Hal ini adalah disebabkan beban galangan yang terpantul wujud di bahagian penghantar. Untuk memperbaiki permasalahan yang dinyatakan, pendekatan pengesanan frekuensi tersendiri dengan gelung maklum balas iaitu Fasa Pengunci Gelungan (PLL) adalah dicadangkan untuk memastikan frekuensi sistem IPT beroperasi pada 1MHz dengan stabil. Analisis sistem IPT dengan pengesanan frekuensi tersendiri disahkan melalui simulasi-simulasi LTspice dan kerja eksperimen. Keputusan mendedahkan bahawa cadangan pendekatan pengesanan frekuensi tersendiri memperbaiki kecekapan pindahan kuasa berbanding dengan tanpa menggunakan pengesanan frekuensi. Justeru, jumlah kecekapan untuk keputusan simulasi ialah 80.6% dengan pengesanan frekuensi tersendiri dan 84.3% tanpa pengesanan frekuensi tersendiri, masing-masing. Sebaliknya, keputusan eksperimen pengesanan frekuensi tersendiri ialah 85.0% dan kecekapan tanpa pengesanan frekuensi ialah 80.4%. Maka, kecekapan pindahan kuasa telah bertambah lebih kurang 4.6% untuk keputusan eksperimen.

ACKNOWLEDGEMENTS

In the name of Allah, the Most Gracious and the Most Merciful. All praises and thanks to Allah, as all the hard work and other helps have been prized by completing this thesis.

First and foremost, I would like to take this opportunity to express my appreciation to my honourable supervisor, Dr. Mohd Shakir bin Md Saat for his kindness in treating my manners, possessing high level of enthusiasm in his supervision, and guiding me on track throughout my master research journey. His willingness to supervise me has enormously contributed to my progress such as sharing opinions on what need to do and what need not to do, reviewing my publications and many more.

I would also like to acknowledge my co-supervisors, PuanYusmarnita binti Mohd Yusop and Dr. Zamre bin Abd Ghani who have involved in this research. Besides, I would like to thank the Faculty of Electronics and Computer Engineering (FKEKK) for providing me equipment facilities and financial support for this project under Short Term Research Grant (PJP).

Moreover, many thanks to my family, especially my beloved husband, Mohd Nurul Al-Hafiz bin Sha'abani, my dear dad, Md Jamal bin Md Yusof, my lovely mom, Leli binti Mohd Dewa and my siblings for their prayers, love, high motivation, strong support and understanding that significantly led to my success.

Last but not least ,not to forget my technicians and colleagues in the laboratory, especially Puan Hafizah binti Adnan, Encik Azmi bin Hussin, Encik Imran bin Mohamed Ali, , Puan Siti Huzaimah binti Husin, Muhammad Thoriq bin Mohamad Zaid, Muhammad Zaki bin Mustafa, Muhammad Khairul Kamarudin bin Hasan and others for their kind help and supports. Also, thanks to everyone who has helped me directly or indirectly in completing this research.

Thank you very much.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	-	Alternating Current
AET	-	Acoustic Energy Transfer
CPT	-	Capacitive Power Transfer
DC	-	Direct Current
IPT	-	Inductive Power Transfer
KCL	-	Kirchhoff's Current Law
KVL	-	Kirchhoff's Voltage Law
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
NMOS	-	N-Channel Metal Oxide Semiconductor
PLL	-	Phased Lock Loop
PWM	-	Pulse Width Modulation
SP	-	Series-Parallel
SS	-	Series-Series
UHF	-	Ultra High Frequency
VCO	-	Voltage Control Oscillator
WPT	-	Wireless Power Transfer
ZCS	-	Zero Current Switching
ZDS	-	Zero Derivative Switching
ZVS	-	Zero Voltage Switching

LIST OF PUBLICATIONS

1. Jamal, N., Saat, S., Yusmarnita, Y., and Zaid, T. 2015. "**Simulation Study on Self-Frequency Tracking Control Strategy for Inductive Power Transfer System**". *Journal of Telecommunication, Electronic and Computer Engineering (JTEC).* Accepted: May, 2015.
2. Jamal, N., Saat, S., Yusmarnita, Y., Zaid, T., and Isa, A. A. M. 2015. "**Investigations on Capacitor Compensation Topologies Effects of Different Inductive Coupling Links Configurations**". *International Journal of Power Electronics and Drive Systems (IJPEDS)*, Vol. *6*(2).
3. Jamal, N., Saat, S., and Yusmarnita. 2014. "**A Development of Class E Converter Circuit for Loosely Coupled Inductive Power Transfer System**". *WSEAS Transactions on Circuits and Systems,* Vol.13, pp.422-428.
4. Jamal, N., Saat, S., Yusmarnita, Y., and Zaid, T. 2014, "**Design of Series-Parallel Compensation for Loosely Coupled Inductive Power Transfer System**". 3rd IET International Conference on Clean Energy and Technology (CEAT 2014), Sarawak, 23-24 Nov. 2014.
5. Jamal, N., Saat, S., Azman, N., and Zaid, T. 2014. "**The Experimental Analysis of Class E Converter Circuit for Inductive Power Transfer Applications**". In *International Symposium on Technology Management and Emerging Technologies (ISTMET),* Bandung, 27-29 May 2014, pp. 516-520.
6. Jamal, N., Saat, S., and Shukor, A. Z. 2013. "**A Study on Performances of Different Compensation Topologies for Loosely Coupled Inductive Power Transfer System**". In *IEEE International Conference on Control System, Computing and Engineering (ICCSCE),* Mindeb, Nov. 29 2013- Dec. 1 2013, pp. 173-178.

CHAPTER 1

INTRODUCTION

1.1 Introduction

The development of Wireless Power Transfer (WPT) systems based on loosely coupled Inductive Power Transfer (IPT) systems has been significantly improved over the past few years. A loosely coupled IPT system works based on separable inductive coupling, which is responsible for the transfer of electrical energy from the transmitter coil to the receiver coil without any wire contact over a small air gap distance. Its principle operation is based on induced voltage, which is similar to the closely coupled IPT system. Meanwhile, a closely coupled system is a conventional method used by an IPT system with a physical contact like a transformer. Due to the nature of the targeted applications, i.e., mobile applications, closely coupled IPT systems are deemed unsuitable to be adopted. Thus, loosely coupled IPT systems are more suitable to be used for WPT systems.

This study aims to design a low power loosely coupled IPT system. In order to develop a compact low power IPT technology, the coil size was reduced. Thus, the only method to efficiently transmit the magnetic field from the transmitter coil to the receiver coil is using a high operating frequency without increasing the coil size. In order to achieve this, a high frequency power converter was proposed to be used at the transmitter side of the IPT system. The reason for this is to generate the strongest possible magnetic field which is able to transfer the induced voltage of the transmitter coil to the receiver coil of the IPT system. However, the power transfer is relatively low due to the resonance inductive coupling is not fulfilled between two separate coils. On top of that, other constraint of a loosely coupled IPT system with a high operating frequency is switching losses in the power converter circuit. This problem occurs due to the frequency drifting, or variation caused by the reflected load impedance that exists in the transmitter side of the IPT system, i.e., mutual coupling, reactive components and load. Hence, the mismatch frequency occurred between the drifted frequency and designed frequency will cause the efficiency of IPT system affected.

Due to the aforementioned problems, the transmitter side of the IPT system is the main focus of this research. Hence, this research utilized a Class E resonant power converter circuit to drive the inductive links. The inductive links refer to the coupling between the transmitting and receiving coil. The Class E resonant power converter circuit was chosen due to its simplicity, as well as its 100% theoretical efficiency. In addition, an external capacitor, known as capacitor compensation, is connected to the transmitting and receiving coil, in order to ensure that a resonance inductive coupling can be achieved. Besides that, a self-frequency tracking control approach at the transmitter side of the IPT system is a possible solution to rectify the identified problems. This is to maintain the frequency of the resonant power converter circuit when driving the inductive links. The proposed self-frequency tracking control uses a Phased Lock Loop (PLL) circuit to act as a feedback loop for the Class E resonant power converter circuit. Therefore, any variation in frequency can be corrected by the proposed self - frequency tracking control approach.

1.2 Motivation

All electronic devices such as implantable devices, mobile phones, among others, need a power supply to activate them. To make it more portable, flexible and convenient in order to charge the battery, a WPT system is more preferable compared to a wired charger. For example, the use of a smart phone causes fast discharging due to the use of many applications. Consequently, a wired power bank needs to be plugged in to charge the smartphone's battery. In order to eliminate the hassle of a wired connection, a WPT system based on a loosely coupled IPT system was proposed. This is because other WPT systems, like Capacitive Power Transfer (CPT) systems and Acoustic Energy Transfer (AET) systems have their own limitations. A CPT system can only obtain low output power at the smallest air gap. Meanwhile, an AET system is very sensitive to the variation of operating frequency propagation. Therefore, an IPT system was chosen in this research, mainly because of its higher output power transfer and produces better efficiency. In an IPT system, a loosely coupled system is a non-contact power transfer with a small gap between the primary and secondary side that is suitable to be used for moving objects, especially for charging systems. Therefore, a contactless power transfer solution, i.e., loosely coupled IPT system for power delivery or battery charging without direct electrical contact is preferred for these mobile devices.

1.3 Problem statement

Currently, a major challenge of loosely coupled IPT system is to produce an efficient power transfer from transmitter coil to receiver coil. This power transfer is normally produced in the form of magnetic field at the transmitter coil. The transmitter coil has been energized by primary converter circuit to couple with the receiver coil. So, the design and development of primary converter circuit is a key factor in loosely coupled IPT system to generate high frequency of alternate current (AC). Since this research work operates at a high operating frequency, the primary converter circuit of loosely coupled IPT system experiences the switching losses. In order to overcome this problem, a good primary converter circuit needs to be designed to ensure switching losses can be eliminated or reduced. Moreover, in order to perform the transmitter and receiver coil are resonance with the frequency of primary converter circuit, capacitor compensation is required at this stage. So, the maximum power transfer can be guaranteed when the coil and capacitor connected together, which is known as resonant circuit. On top of that, when two resonant circuits are tightly coupled at smallest air gap distance, variation in frequency occurs. It is caused by the reflected load impedance that exists in the transmitter side of the IPT system, i.e., mutual coupling, reactive components and load at difference air gaps. Therefore, a feedback circuit is required to have in order to detect and correct the variation in frequency.

1.4 Objectives

The main objective of this research is to design and develop a self-frequency tracking of Class E resonant power converter circuit for a loosely coupled IPT system. More specifically, the objectives of this research are as follows:

i. To design a Class E resonant power converter circuit as a driver for inductive links.
ii. To analyze the performance of compensation technique for resonance inductive coupling.
iii. To propose a self-frequency tracking control for frequency stabilization.

iv. To analyze the performance of the developed IPT system with the proposed self-frequency tracking approach in terms of power transfer efficiency.

1.5 Scope of works

The main focus of this research is to utilize a Class E resonant power converter circuit at the transmitter side of the IPT system. The detailed scope of this works is as follows:

i. The output power of the loosely coupled inductive power transfer system is less than 3W for low power applications. It can be noticed that for low power applications, only small size of coil is enough to be used at small air gap distance.

ii. Pancake spiral coils for transmitter and receiver coil are used, i.e., the sizes of wireless coil devices that are used are 37.0mm x 37.0mm x 1.8mm for 10µH, and 53.3mm x 53.3mm x 6.0mm for 24µH. These pancake spiral coils are chosen because of the coil losses can be reduced at high frequency (Hui *et. al.*, 2014).

iii. Focuses on switching losses. Coil losses (i.e. eddy current and hysteresis losses) and magnetic flux leakage are omitted.

iv. The air gap distance between the two separation coils is varied between 5 millimetres (mm) and 45 millimetres (mm) to fulfil near field applications.

v. Since the output power is low due to the small coil size and air gap distance, so, high frequency is chosen (Pérez, 2014). The operating frequency is set to 1 MHz.

vi. The validation process is through simulation using LTpsice software and experimentation.

vii. DSO-X-2012A Digital Agilent Technologies oscilloscope with two channels is used.

1.6 Significance of study

This research is predicted to be of benefit for improvement in high efficiency power transfer of loosely coupled IPT systems. It is believed that the high efficiency of resonance inductive coupling can be achieved by controlling the operating frequency of the resonant power converter circuit. This will ensure that switching losses can be minimized.

1.7 Contribution of the research

The contributions of this research can be summarized as follows:

i. A Class E resonant power converter circuit has been designed for 1MHz of frequency to drive inductive links.

ii. Capacitor compensation has been studied to identify which topologies are the best for the IPT system.

iii. A self-frequency tracking control for single switch of Class E resonant power converter has been proposed with a feedback loop to detect and correct the frequency of IPT system.