DESIGN AND DEVELOPMENT OF IMPEDANCE MATCHING NETWORK FOR CLASS E ZVS INVERTER ACOUSTIC POWER TRANSMITTER

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A thesis submitted
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DEDICATION

To my loving parents, Allahyarham Tuan Haji Husin bin Haji Seleman, Puan Hajah Endon Binti Hj Pit, my husband Allahyarham Ismail Bin Rejab, my children Mardhiah, Muhammad Marwan, Nur Fatini and Muhammad Fatih

and

In memory, Allahyarham Abdul Hamid Bin Hamidon, your kindness and advice should never be forgotten.

ABSTRACT

Acoustic Power Transfer (APT) is known as one of the techniques used in wireless power transmission technology. APT uses sound waves or vibration as a tool to transmit power. APT can be applicable in air, metal, and water mediums and also pass through living tissue in the human body. APT systems consist of a transmitter, propagation medium, and receiver, allowing for efficient and non-contact energy transfer, even under challenging environments, especially where the electromagnetic (EMT) is not permissible. Even though APT has received considerable attention from researchers in recent years, however, APT is still experiencing the low performance efficiency. Most findings concluded that the efficiency of APT systems relies on the ultrasonic air transducer excitation circuit and power amplification circuit. Hence, the major objective of this thesis is to design a Class E ZVS inverter for driving an APT transmitter circuit useful for exciting ultrasonic transducer properly. However, the nature of Class E ZVS inverter is inherently unstable to parameter variations, which can lead to instability and a decrease in efficiency. The design starts with a Class E ZVS inverter for 47 Ω purely resistive component, which is the optimum load operation, R_s to produce 2.0 W output power. The experimental results show that the design capable to produce 85.42% of DC-to-AC power conversion efficiency. Then, the design of an APT transmitter unit that incorporated a π1a impedance matching circuit is proposed to aim for less sensitive network to load variation. The experimental results show that the design achieved an input power of 2.05 W and the output power of 1.74 W and produced 85.07% of DC-to-AC power conversion efficiency. The analysis regarding Zero Voltage Switching (ZVS) waveform, input power, P_i, output power, P_o, and efficiency, η for optimum load condition, load variation condition and frequency variation condition were conducted in this thesis, which developed the second objective of the thesis. Overall performance shown the designed inverter achieved the targeted objective in which the application of π1a impedance matching network able to lessen the sensitivity of Class E ZVS to not only the load variation, also the frequency variation. Both load and frequency variation efficiency can be observed. To justify the designed inverter in actual environment, the 40 kHz ultrasonic air transducer, as a vital component to convert an electrical energy to the sound wave is applied as a load to the inverter. Based on the experimental setup, this integration managed to preserve the ZVS condition, the input power, P_i, of 2.05 W, the output power, P_o, of 1.58 W and the DC-to-AC power conversion efficiency, η of 80.97%. This achievement is considered good due to that no alteration made to the ultrasonic air transducer parameters. Furthermore, this efficiency still more than 80% as suggested by more previous research dealing with Class E ZVS inverter. The developed APT transmitter unit is linked to the APT receiver unit to evaluate the performance of output voltage versus distance in the system. The highest performance that contributed in this thesis related to analysis output voltage versus distance is the efficiency of 4% at the distance of 10 mm.

REKA BENTUK DAN PEMODELAN RANGKAIAN PADANAN GALANGAN UNTUK PEMANCAR KUASA AKUSTIK PENYONGSANG KELAS E ZVS

ABSTRAK

Pemindahan Kuasa Akustik (APT) adalah salah satu teknik yang digunakan dalam teknologi penghantaran kuasa tanpa wayar. APT menggunakan gelombang bunyi atau getaran sebagai alat untuk menghantar kuasa. APT boleh digunakan dalam medium udara, logam dan air dan juga melalui tisu hidup dalam tubuh manusia. Sistem APT terdiri daripada penghantar, medium perambatan dan penerima, membolehkan pemindahan tenaga yang cekap dan tidak bersentuhan, walaupun dalam persekitaran yang mencabar, terutamanya di mana elektromagnet (EMT) tidak dibenarkan. Walaupun APT telah mendapat perhatian yang besar daripada penyelidik dalam beberapa tahun kebelakangan ini, namun, APT masih mengalami kecekapan prestasi yang rendah. Kebanyakan penemuan membuat kesimpulan bahawa kecekapan sistem APT bergantung pada litar pengujaan transduser udara ultrasonik dan litar penguatan kuasa. Oleh itu, tesis ini bertujuan, sebagai objektif utamanya, untuk menyediakan reka bentuk yang cekap bagi penyongsang ZVS Kelas E untuk menjanakan litar pemancar APT supaya transduser ultrasonik dapat diuja dengan betul. Walau bagaimanapun, penyongsang Kelas E ZVS dalam keadaan semula jadi, sensitif kepada variasi parameter, yang boleh membawa kepada ketidakstabilan dan penurunan kecekapan. Reka bentuk bermula dengan penyongsang Kelas E ZVS untuk 47 Ω komponen rintangan tulen, yang merupakan operasi beban optimum, R_s untuk menghasilkan kuasa keluaran 2.0 W. Keputusan eksperimen menunjukkan bahawa reka bentuk mampu menghasilkan 85.42% kecekapan penukaran kuasa DC-ke-AC. Kemudian, reka bentuk unit pemancar APT yang menggabungkan litar pemadanan impedans π1a dicadangkan untuk menyasarkan rangkaian yang kurang sensitif terhadap variasi beban. Keputusan eksperimen menunjukkan bahawa reka bentuk mencapai kuasa input 2.05 W dan kuasa output 1.74 W dan menghasilkan 85.07% kecekapan penukaran kuasa DC-ke-AC. Analisis mengenai bentuk gelombang Pensuisan Voltan Sifar (ZVS), kuasa input, P_i, kuasa output, P_o, dan kecekapan, η untuk keadaan beban optimum, keadaan variasi beban dan keadaan variasi frekuensi telah dijalankan dalam tesis ini. yang membangunkan objektif kedua tesis. Prestasi keseluruhan menunjukkan penyongsang yang direka telah mencapai objektif yang disasarkan di mana penggunaan rangkaian pemadanan impedans π1a dapat mengurangkan sensitiviti Kelas E ZVS kepada bukan sahaja variasi beban, juga variasi frekuensi. Kecekapan variasi beban dan frekuensi boleh diperhatikan. Untuk mewajarkan penyongsang yang direka dalam persekitaran sebenar, transduser udara ultrasonik 40 kHz, sebagai komponen penting untuk menukar tenaga elektrik kepada gelombang bunyi digunakan sebagai beban kepada penyongsang. Berdasarkan persediaan eksperimen, penyepaduan ini berjaya mengekalkan keadaan ZVS, kuasa input, P_i, sebanyak 2.05 W, kuasa output, P_o, dan kecekapan penukaran kuasa DC-ke-AC, η sebanyak 80.97%. Pencapaian ini dianggap baik kerana tiada perubahan dibuat pada parameter transduser udara ultrasonik. Tambahan pula, kecekapan ini masih lebih daripada 80% seperti yang dicadangkan oleh lebih banyak penyelidikan terdahulu yang berkaitan dengan penyongsang ZVS Kelas E. Unit pemancar APT yang dibangunkan dipautkan kepada unit penerima APT dalam konfigurasi SISO. Langkah ini adalah untuk menilai prestasi voltan keluaran berbanding jarak dalam sistem. Prestasi tertinggi yang disumbangkan dalam tesis ini berkaitan dengan analisis voltan keluaran berbanding jarak ialah kecekapan 4% pada jarak 10 mm.

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LIST OF SYMBOLS AND ABBREVIATIONS

WPT	-	Wireless Power Transfer
APT	-	Acoustic Power Transfer
CPT	-	Capacitive Power Transfer
IPT	-	Inductive Power Transfer
FEA	-	Finite Element Analysis
ZVS	-	Zero Voltage Switching
PIC	-	Programmable Intelligent Computer
PCB	-	Printed Circuit Board
AC	-	Alternating Current
DC	-	Direct Current
PWM	-	Pulse Width Modulation
IEEE	-	Institute of Electrical and Electronics Engineers
CCM	-	Continuous Current Mode
PM	-	Permanent Magnet
EV	-	Electric Vehicle
SS	-	Series-Series
SP	-	Series-Parallel
PS	-	Parallel-Series
PP	-	Parallel-Parallel
VFI	-	Voltage Fed Inverter
CFI	-	Current Fed Inverter
BJT	-	Bipolar Junction Transistor
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
IGBT	-	Insulated Gate Bipolar Transistor
PZT	-	Lead Zirconate Titanate
ESL	-	Equivalent Series Inductance
ESR	-	Equivalent Series Resistance
PV	-	Photovoltaic

LIST OF APPENDICES

LIST OF PUBLICATIONS

Indexed Journal

S. H. Husin, S. Saat, T. Zaid, S. K. Nguang., 2016. Development of Class D Inverter for Implantable Devices through Acoustics Energy Transfer Approach, *International Journal of Power Electronics and Drive System (IJPEDS)*, Vol.7, No. 1, Mac 2016, pp. 75~84 ISSN: 2088-8694.

H. Husin, S. Saat, Y. Yusmarnita, Z. Ghani, S. K. Nguang., 2016. Simulation of 416 kHz Piezoelectric Transducer Excitation using Class E ZVS Inverter, *Asian Journal of Scientific Research, 9(4)*, 176-187, 2016

Huzaimah Husin, Shakir Saat, Yusmarnita Yusop, Azmi Awang Md Isa, Saari Mohd Isa, Majid Darsono, Aziz Yahya, Sing Kiong Nguang., 2017. Class E ZVS Inverter Simulation for Series Resonance Mode Ultrasonic Transducer, *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, Vol. 9 (4), Dec 2017, pp. 91-96.

Conference Proceedings

H. Husin, H. Hamidon, S. Saat, and Y. Yusmarnita., 2016. "Simulation of Class D resonance inverter for Acoustics Energy Transfer applications," *7th Int. Conf. Inf. Technol.,* vol. 2015, pp. 527–532, 2015.
H. Husin, S. Saat, Y. Yusmarnita, S.K. Nguang, Development of 416 kHz PZT driver for Acoustic Energy Transfer applications, CSPA2016:12th *IEEE Colloquium on Signal Processing and its Applications.*

CHAPTER 1

INTRODUCTION

1.1 Background

In today's world of ever evolving technology, devices are continuously invented to the trend towards smaller, more mobile, and power-efficient devices highlights the importance of wireless power transfer (WPT) technologies. WPT is an evolving technology that can transfer electric power wirelessly over certain distances without any physical contact. For this main reason, WPT can be used in less accessible locations which cannot be operated by traditional wired technologies.

In general, WPT provides many advantages such as, (1) improves user-friendliness as the hassle from connecting cables is removed, (2) renders the design and fabrication of significantly smaller devices without the attachment of batteries, (3) provides better product durability (example, waterproof and dustproof) for contact-free devices, (4) it enhances flexibility, especially for the devices for which battery-replacement or connecting cables for charging is costly, hazardous, or infeasible (example, bodyimplanted sensors), (5) charging devices is based on-demand fashion and thus is more flexible and energy-efficient. WPT also able to deliver power wirelessly to an equipment or sensor used in antimplantable devices thus, becoming a limiting factor for miniaturization that mostly required in designing any implantable devices. WPT also able to deliver power wirelessly to an equipment or sensor used in any applications with metal barriers such as gas pipes, vacuum chambers, nuclear waste containers, submarines and spacecraft hulls. By means of its characteristics of flexibility, free-positioning capability as well as movability, the WPT technology is an ideal technical solution for energizing electric-driven devices within some specific regions in the near future, especially for smart home applications as shown in Figure 1.1.

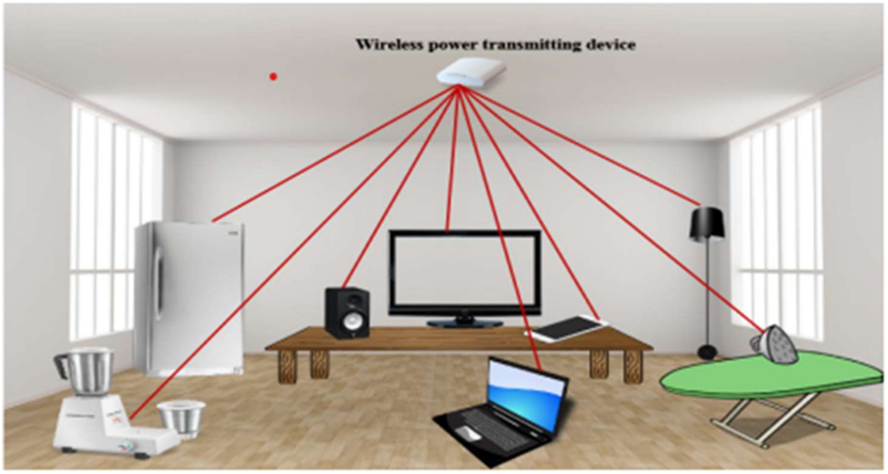

Figure 1.1 The smart home appliances (FH, S.,2018)

This thesis, however, only focus on the near field WPT technologies which power transferring is limited to few mm (Van Mulders et al., 2022). In this regard, there are three commont WPT types, 1) Inductive power Transfer (IPT), 2) Capacitive Power Transfer (CPT) and 3) Acoustic Power Transfer (APT). Each of this type employing different unique field as energy transfer medium, such as a magnetic field in IPT, the electric field in CPT, and sound wave in APT technology. This thesis looked into the development of efficient contactless power transfer based on APT technology. APT offers a promising solution for power delivery in situations where traditional electromagnetic methods face limitations, such as in underwater ewenvironments or through metal barriers. Nevertheless, the APT system still experiences low performance efficiency, and it remains the main issue of the APT system. Therefore, this thesis focus on proposing an efficienct method of contactless power transfer based on APT technology to improve the overall efficiency of the system. Specifically, the new power converter integration with impedance matching in power transmitter unit, thus enhancing the efficiency of the APT system.

1.2 Motivation

The low power applications are mostly human-related devices such as the charging devices, for example, the handphone and the implantable devices. Since it is a human-related application, it is a become an issue to offer the technology that does not bring harm to human beings. The current and most applicable IPT which implies an electric field as their energy carrier transmission. The World Health Organization (WHO), 2006 and Abdel-sattar (2019) states that an electric field have an adverse effect, such as illness and death, to the human in long run exposure. Cables and wires have long posed as physical and electrical hazards. Many injuries and fatalities have been reported in relation to these hazards. Medical implantable devices and electronics appliances should not bring any harm to its users,rather it should be a symbiotic relationship. These reasons have become a strong motivation to carry out further research on WPT, and its alternatives, which brings to the APT. The increasing trend of APT technology especially in biomedical field, has made a major contribution to scientific and medical advances (Basaeri et al., 2016),(Siddiqui and Khan, 2019) and (Jin et al., 2021).

APT offers a great advantage over its major counterpart, IPT and another technique namely as CPT. The CPT uses an electric field to transfer power, while APT uses ultrasound wave between the ultrasonic transducers making it the safest wireless transmission technique so far. Thus, it does not require a special shield mechanism in the system to prevent the harmful waves to the user and require simpler circuitry. Since APT propagates using ultrasound waves, it can penetrate any metal surrounding (Awal et. al., 2016), (V. F. G. Tseng et al., 2016) and (Freychet et al., 2020) which was a major limitatition encountered by the IPT and CPT technology. Additionally, due to the nature of the ultrasound waves, the transmission process does not generate eddy current heating effect to the application (Sarker et al., 2019) and (Yan et al., 2019). Also, in terms of power transmission efficiency over a distance, APT able to performs better than its major competitor, IPT as reported in (Basaeri et al., 2016), (Shadid and Noghanian, 2018) and (Cheah et al., 2019) whereas the acoustic power delivery outperforms the IPT at larger distances and for smaller devices.

1.3 Problem Statement

In the APT system, it is very important that the available energy from a source is transferred efficiently to the load through any possible medium such as solid, liquid and air. In other words, higher efficiency can be achieved by eliminating all the possibility of energy losses contributed by any elements during the transfer process. Based on the literature, the energy efficiency of the APT system is still considerably low, especially those involving energy propagation through air medium (Roes, 2011), (V.F. Tseng et al., 2018), (Ming Yuan et al., 2019), (V.F. Tseng et al., 2020) and (Liu and Abdulla, 2023). This air medium is considered the most difficult energy propagation substance among others (Md Rabiul Awal et al., 2016). The difficulty of air medium to propogate energy is due to its particles arrangement which is far apart from each others, resulting in difficulty to pass energy from one particle to the another thus, contributing to low energy transfer efficiency as mentioned by Patnaik, D. et al (2021). From this arrangement, air is considered as a low density medium that lacks the rigidity and consistency as compared to solid materials. In consequences, this means that sound waves encounter less resistance to move and are easily absorbed, reflected, or diffracted as they travel through the air medium (A. D. Pierce, 1994), (Rekha et al., 2017) and (Van Mulders et al., 2022). Apart from that, the losses of transmitting and receiving ultrasonic air transducers in terms of electrical and mechanical properties were identified as the contributing factors affecting the efficiency of the APT system (Roes, 2011) and (Ho Fai Leung et al., 2014).

A study claimed that the efficiency improvement of the APT system depends on the ultrasonic air transducer excitation circuit (DC-to-AC) which converts the energy to vibrational efficiently, reducing the transducer propagation loss (Shigeta et al., 2011) and (Bisschop and Serdijn, 2019). Furthermore, Yan et al., (2019) also has concluded that the transmitting unit generally utilises a power amplifying circuit (inverter) to supply energy to the transmitting air transducer. Hence, a high efficiency Class E ZVS inverter is utilized to generate the required power for the ultrasonic air transducer at the transmitter unit. However, the soft switching property of Class E ZVS inverter that is particularly dependent on variations in circuit parameters e.g., system loading and resonant elements could result in an unstable regime leading to a decrease efficiency once emergence off ZVS condition as discovered by Zhang, L., and Ngo, K.D (2019) and Komanaka et al. (2022). Based on these highlighted issues and problems, a further and enhanced air medium APT system must be deployed, hence, optimizing its efficiency. The proposed design involved the implementation of the Class E ZVS inverter at the APT transmitting side together with the impedance matching circuit.

1.4 Research Objective

Specifically, the objectives are as follows:

1. To design and optimize the efficiency of Class E ZVS inverter using π1a impedance matching that less sensitive to the load variations in APT transmitter unit.
2. To analyse the performance of the developed APT air through system based on ZVS conditions, input power, output power, efficiency and distance analysis.

1.5 Scope of Research

The scope of this research are as follows:

(i) The design of π1a impedance matching circuit at the acoustic power transmitter unit of APT system. The choice of π1a impedance matching circuit topology is due to its similarity of the ultrasonic air transducer equivalent circuit topology in its series mode resistance, which produced the highest mechanical vibration. Furthermore, through this circuit topology, the process of tuning for internal dynamic capacitor, C_0 of ultrasonic air transducer can be carried out.

(ii) The 40 kHz MCUSR18A40B12RS off-the-shelf ultrasonic air transducer used as the transmitting and receiving transducer respectively.

(iii) In considering the 50% transmission losses of APT system and application to low power sensors and biomedical implantable devices, this thesis proposed a 2.0 W air through APT system that used to demonstrate low power utilisation.

(iv) Regarding the implementation of the system for future consumption such as for biomedical implantable devices, the low operating frequency of 40 kHz was chosen due to mild effects to the users.

(v) The pulse width modulation (PWM) signal and tuning for Class E ZVS inverter circuit were generated by function generator.

(vi) The Mosfet driver circuit is operated at 39.8 kHz switching frequency. The selection of operating frequency is based on the series resonant frequency of the dedicated 40 kHz ultrasonic air transducers.

(vii) The propagation medium of this system is air at the room temperature between 20° to 26° degree celcius.

(viii) The verification of the design process was carried out through computer simulation using professional software programs.

(ix) Each developed circuit is implemented practically and experimental measurements were used to validate both the design process and the analysis.

1.6 Contribution of Research

Contributions of this thesis are made in the following related areas:

(i) Energy transfer capability using acoustic method for 2.0 W application through air as medium of propagation.

(ii) The π1a impedance matching circuit, as a major contribution in this thesis, was proposed to further enhance the efficiency of power conversion at the APT transmitter unit by providing the Class E ZVS inverter with capability of less sensitive to the load variations.

(iii) The characterization of off-the-shelf 40 kHz MCUSR18A40B12RS ultrasonic air transducer based on Butterworth Van Dyke (BVD) model for simple design execution.

(iv) The usage of high efficiency, the Class E ZVS inverter to excite an ultrasonic air transducer at the APT transmitter unit. In this thesis, the Class E ZVS inverter circuit was designed based on operation analysis at duty cycle, D = 0.5, with targeted 2.0 W as output power and more than 90% efficiency.

(v) Development of modeling a time domain transmitter APT system that contributes to usage of state-space approach.

1.7 Thesis Outline

Based on the objectives previously presented and, on the approach, proposed before, this thesis is made up of five (5) chapters,

Chapter 1 presents the background of this study, motivation, problem statement, objectives, scopes, contributions and significance of the research.

Chapter 2 starts with a brief overview of existing wireless power transfer (WPT) technologies, followed by the near field WPT category, which are Inductive Power Transfer (IPT), Capacitive Power Transfer (CPT), and Acoustic Power Transfer (APT). The explanation regarding advantages and disadvantages of each technology was included so that a clear comparison can be made. Meanwhile, the challenges in APT was also discussed in this section. In summary, this chapter also explained the APT system's current issues and how this thesis proposed a new solution to improve the current performance of the system.

Chapter 3 presents the methodology that has been used to design APT transmitter unit that integrating Class E ZVS inverter as a power converter to drive a 40 kHz ultrasonic air transducer. Also, the π1a impedance matching circuit that has been applied to further enhance the performance of the developed transmitter unit. In this chapter, besides an analytical approach in modeling the circuit, the state-space modeling approach is also discussed.

Chapter 4 discusses the results that were obtained whether through theoretical calculation, professional simulation and experimental works. In the first section, the design of Class E ZVS inverter with purely resistive component in the APT transmitter unit with single air transducer as transmission device is presented. This section showed the study that was carried out to understand the behavior of Class E ZVS inverter along specific load, load variation and frequency variation. Next, the design of Class E ZVS inverter integrated with π1a impedance matching circuit is proposed to further enhance the APT transmitter unit performance's efficiency with less sensitivity to load variations. The performance of developed Class E ZVS inverter with π1a impedance matching network in terms of ZVS, input power, output power were analyzed. The performance comparison of APT transmitter unit without and with π1a impedance matching is performed and the significant power conversion efficiency improvement is observed. At the end of this chapter, the performance analysis based on the voltage transfer efficiency versus distance is conducted between the developed APT transmitter unit with π1a impedance matching and APT receiver unit.

Chapter 5 summarizes the main conclusion as well as key achievements of the work undertaken in this thesis and recommendation areas for future work.