CLASS E INVERTER-IMPEDANCE MATCHING NETWORK INTEGRATION FOR 40KHZ ULTRASONIC AIR TRANSDUCER

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This report is submitted in partial fulfilment of the requirements for the degree of Bachelor of Electronic Engineering with Honours

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DECLARATION

I declare that this report entitled "Class E Inverter-Impedance Matching Network Integration for 40kHz Ultrasonic Air Transducer" is the result of my own work except for quotes as cited in the references.

Signature :

Author : Nur Raihan binti Mat Aziz

Date : 15 Jun 2021

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 Bachelor of Electronic Engineering with Honours.

Signature :

Supervisor Name : Siti Huzaimah Binti Husin

Date : 15 Jun 2021

DEDICATION

This study is lovingly dedicated to my respective parents, Mat Aziz and Rokiah and my siblings who have been my constant source of inspiration.

ABSTRACT

The new engineering concepts involved in wireless power transfer systems were discussed in this study Wireless Power Transfer (WPT). In contrast to the existing WPT systems of inductive power transfer (IPT) and capacitive power transfer (CPT), a new alternative methodology called acoustic energy transfer (AET) is offered. In order to transfer electricity from the transmitter unit to the reception unit, the AET system uses vibration or sound waves propagation. This project focuses on power conversion performance in a Class E ZVS inverter at the transmitter unit, as well as the appropriate circuit developed for impedance matching to overcome impedance variance. Furthermore, this work also includes on previous study proven that the AET system had several advantages compare to IPT and CPT. Moreover, there are further explanation on WPT techniques and theory related to circuit design. Next, the methodology that being used in the process will give an explanation on the overall simulation results regarding to the simulation. Lastly, the conclusion and recommendation for further development is suggested.

ABSTRAK

Konsep kejuruteraan baru yang terlibat dalam sistem pemindahan kuasa tanpa wayar telah dibincangkan dalam kajian ini (WPT). Berbeza dengan sistem WPT yang ada iaitu pemindahan kuasa induktif (IPT) dan pemindahan daya kapasitif (CPT), metodologi alternatif baru yang disebut pemindahan tenaga akustik ditawarkan (AET). Untuk memindahkan elektrik dari unit pemancar ke unit penerimaan, sistem AET menggunakan perambatan getaran atau gelombang bunyi. Projek ini memfokuskan pada prestasi penukaran kuasa dalam penyongsang Kelas E ZVS di unit pemancar, serta litar yang sesuai yang dikembangkan untuk pemadanan galangan untuk mengatasi varians galangan. Selanjutnya, projek lebih baik makalah ini juga merangkumi kajian sebelumnya yang membuktikan bahawa sistem AET mempunyai beberapa kelebihan berbanding IPT dan CPT. Selain itu, terdapat penjelasan lebih lanjut mengenai teknik dan teori WPT yang berkaitan dengan reka bentuk litar. Seterusnya, metodologi yang digunakan dalam proses tersebut akan memberikan penjelasan mengenai hasil simulasi secara keseluruhan berkenaan dengan simulasi. Akhir sekali, kesimpulan dan cadangan untuk pengembangan selanjutnya disarankan.

ACKNOWLEDGEMENTS

There is a race of existence in the present world of competition in which these having to succeed. In the name of Allah, the most merciful and with help of Him. All spiritual inspirations, devotions, good words and prayers are for Him whose grace and encouragement helped me throughout this whole venture.

I would like to express my deepest gratitude to all people who, throughout this venture, directly or indirectly contribute their contributions and useful ideas. My special thanks go to my supervisor, Mrs. Siti Huzaimah binti Husin for her guidance, comments and ideas from the initial stage to the completion of this project on this project. Supervision and support really helped with the progress of project and smoothness during the Final Year Project program. Your kindness, leadership, and wisdom will always be close to my heart. There is a lot of appreciation for the cooperation. My gratitude also goes to my beloved parents and family, who gave tremendous support and great encouragement to my progress of project. Special thanks to my colleagues and friends who give support and cooperation at all times. Last but not least, I would like to take this opportunity to express my appreciation to all people for the courage, perseverance and advice they gave me during this progress of project.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS AND ABBREVIATIONS

WPT	:	Wireless power transfer
AET	:	Acoustic energy transfer
CPT	:	Capacitive power transfer
IPT	:	Inductive power transfer
PZT	:	Piezoelectric device
ZVS	:	Zero voltage switching
ZCS	:	Zero current switching
AC	:	Alternating current
DC	:	Direct current
RFID	:	Radio frequency identification
CET	:	Capacitive energy transfer
L_f	:	Choke inductance
C_p	:	Shunt capacitor
Ω	:	Ohm
ω	:	Omega
BVD	:	Butterworth-Van-Dyke
PWM	:	Pulse width modulation

CHAPTER 1

INTRODUCTION

In this chapter, a brief introduction about this project was explained in depth. This includes the goals to be achieved, some problems during the project and also the project limitation that needs to be focused.

1.1 Introduction

In the beginning of the technology [1], every machine, electrical equipment and many other devices such as implantable devices, mobile phone needs power to activate them. The power transfer has proven that it plays a major part in powering the devices. However, there are limitation of these old methods which one of limit is they are bounded to transfer the power using cable or wire. It is undeniable that power transfer via wire or cable are much more direct and the possibility of power loss is very low. Unfortunately, not every application usage of wire can be guarantee as convenient and safe. Thus, the industry came out with different approach to replace wired power transfer with wireless power transfer (WPT) as the alternative way to be explored. The technology of wireless power transfer (WPT) systems [2] is the technique to transfer the power source in transmitter to the load in receiver by eliminates wires or cables. Therefore, the development and study of wireless power transfer of which involve Acoustic Energy Transfer (AET) which uses sound waves to propagate energy without relying on electrical contact, Inductive Power Transfer (IPT) that utilizes magnetic coupling and Capacitive Power Transfer system that use electrical field coupling in capacitive plate become flexible [13]. Because of that idea, wireless power transfer (WPT) is more portable and convenient in order to run the system. Although Acoustic Energy Transfer is still new under a research, the results from in the past have already proven that AET can exceed the limit of IPT and CPT [14].

AET is a technology that uses sound waves or vibrations to transfer energy wirelessly instead use of electromagnetic fields like CPT and IPT [4]. Hence, energy can be transmitted through metal wall which overcoming the major drawback of IPT, in open air as well as in living human tissue.

However, each of the types of power transfer has advantage and limitation in the system. For example, CPT has the limitation on the size, distance and plate to transfer the power based on the medium [5]. IPT has the limitation on the transfer the energy in metal and water. For the IPT system, metal unsuitable uses as medium to transfer the energy for the IPT system. In addition, AET is electromagnetic-free, in along the distance of power transmission with high consistency, and is better option compared to others. This study aims to analysis the efficient power transfer using the AET system through metal propagation medium. Thus, the efficiently method to transmit energy from transmitter to the receiver in terms of gap distance and propagation medium is an AET system method. In order to achieve this, a high frequency power amplifier was proposed to be used at the transmitter side of AET system.

In Figure 1.1, an AET system consists of a primary/transmitter unit that generates a high voltage sinusoidal waveform to drive the primary ultrasonic transducer as described by Zaid et al [15]. The primary ultrasonic transducer will convert the electrical energy into a mechanical acoustic wave known as sound wave for the power propagation. Then, the generated sound wave propagates through a small gap medium. Next, at secondary/receiver unit the ultrasonic transducer converts back the mechanical energy into electrical energy. Lastly, the DC power at the receiver unit can be supplied to power up the load.

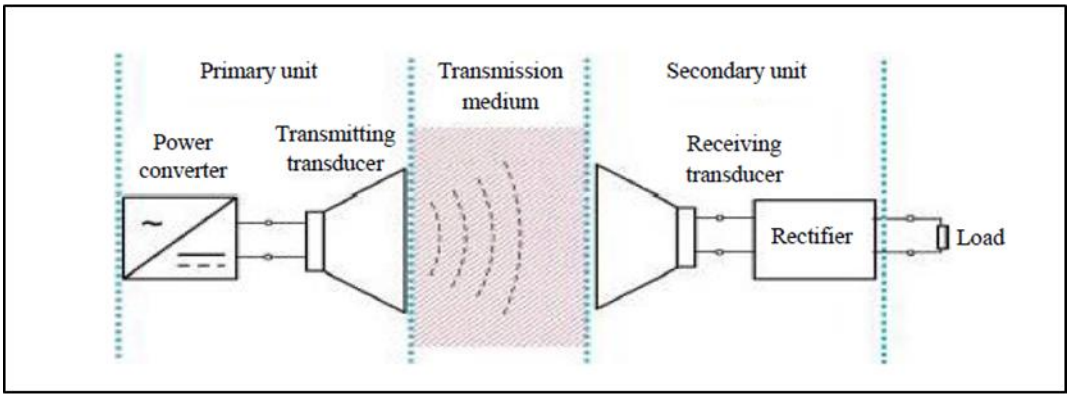


Figure 1.1: Basic ideal diagram of AET system by Zaid et al

The innovative technology of wireless power transfer (WPT) systems is to supply the any device with electrical energy to the load by reduce number of cables. However, there are few problems that may face by an AET system network design that will cause downside in AET system. Firstly, an imprecise circuit design for Class E ZVS inverter in the transmitter unit which lead to low efficiency of energy conversion. This is due during the conversion of electrical energy from DC to AC, there is switching loss happened along the way of conversion. If this issue is not prevented, it will affect the entire of AET system performance. At the end of this, the output power will not meet the expected value, where the condition of zero voltage switching (ZVS) is fail to achieve. Secondly, the integration between Class E ZVS inverter and ultrasonic transducer in the transmitter unit will cause impedance variation in circuit design. This is because the Class E ZVS inverter work ideally in purely resistive, but when Class E ZVS is combined with ultrasonic transducer, the impedance will be no longer in a simple network. In other word, an impedance variation (complex impedance) can resulting in power loss and cause low efficiency of power conversion in transmitter unit.

1.2 Objectives

1. To design an efficient Acoustic Energy Transfer system using Class E ZVS inverter at the transmitter unit in order to reduce or eliminate switching amplifier losses.

2. To design impedance matching circuit to overcome the impedance mismatch between the purely resistive load and ultrasonic transducer, thus high efficiency of Class E ZVS can be maintained.

3. To design the power efficiency of Acoustic Energy Transfer system at the receiver unit for power transmitter efficiency.

1.3 Scope of Project

1. The design of power amplifier to drive 40 kHz ultrasonic transducer that using Class E ZVS inverter due to its ability to achieve high performance based on the switching condition.

2. The analyzation will be covered on the compensation networks to determine the most suitable impedance matching design to stabilize the impedance variations.

3. The Class E ZVS inverter model for power conversion will be design and evaluated.

4. Evaluation mainly cover on the zero-voltage switching (ZVS), power input, power output and the efficiency of the system.

5. All the schematic design and simulation will be used MATLAB software via Simulink.

1.4 Thesis Outline

This project report consists of five chapters that briefly discuss on the concept of the project and all the activities in achieving the objectives of this project.

Chapter 2 describes about WPT systems and detail of the background study and previous project. The review of the working principles and previous works on AET system are discussed in this chapter. Furthermore, this chapter discusses the application, operation and factor affect the performance of AET systems.

Chapter 3 explains a flow process method use of the project from the transmitter to receiver. Next, this chapter presents the Class E Zero Voltage Switching (ZVS) in the AET system as a power amplifier. In general, the Class E Zero Voltage Switching (ZVS) is also known as a driver circuit converter direct current (DC) to alternating current (AC). So, this chapter is discussed the method to design the circuit Class E Voltage Switching (ZVS) that consists of MOSFET, series capacitor and inductor circuit and also shunt capacitor. The data of the calculation and simulation of the circuit design is analyzed.

Chapter 4 describes the analysis performance of the AET system in Class E ZVS, piezoelectric transducer and adding impedance matching to achieve the maximum power transfer. The performance results of the proposal approach were given and discussed by using the simulation study.

Chapter 5 concludes overall of thesis. A few future works can be improved related to this analysis is discussed in this chapter. Basically, its summary of the research about and the element related to it.

CHAPTER 2

BACKGROUND STUDY

This chapter explains the review of the literature that was done for the development of project purposes from various developed projects. It will discuss the information details extracted from a specific elements and topics.

2.1 Background Study

As the wireless power transfer transmission (WPT) move forward, it has covered a wide range of current devices in many field and become a highly active research area for student, researchers, and many other due to their potential to provide significant impact to our daily lives [4]. The WPT will have brighter future since the transmission of electrical energy from a power source to an electrical load is implemented to an electrical load across an air gap without any wires or cable. This chapter is to create understanding of the workings of acoustic energy transfer based on the propagation medium into three kinds such as living tissue, through metal and air [5]. The background of Wireless Power Transmission technologies and its applications is briefly explained [1]. However, at the present moment, the subject is starting to gain some attention and the number of publications on the topic slowly but steadily increases [6]. AET can be advantageous, especially if it uses sound or vibration to transmit energy. AET is also not limited by frequency band or energy propagation direction. For that reason, the following sections will provide a review on different techniques of wireless power transfer and their recent application. The detailed descriptions of the elements in wireless power transfer are also discussed.

2.2 Wireless Power Transmission Technologies

Several types of wireless power transmission (WPT) systems have recently piqued the interest of researchers. Other examples of technological issues that involved sensors or transducers incorporated in a human body or charging a moving vehicle on the road, not only because of their ability to charge consumer household products. WPT invented the energy migration in a cordless way and change our traditional utilization patterns of the energy by implementing modern technology in various applications [1]. The WPT can be categorized into two techniques, which consists far-field and near-field transmission [2]. WPT can be implemented in the distant field by using energy carriers such as acoustic, optical, and microwave. In near-field techniques, the inductive coupling affected nonradiative electromagnetic fields by comprising their inductive and capacitive mechanisms. For instance, inductive coupling of wireless technology is widely used for electric vehicles, phones, RFID tags and chargers for implantable medical devices [4]. By utilizing the WPT techniques, it is an ideal technical solution for energizing electric-driven devices. Therefore, it reduces the over-dependence on the battery within some specific regions in the near future.

2.3 Applications of Wireless Power Transmission Technologies

In the field of wireless power transmission, WPT techniques provide the ability to harness the energy in the air. The energy access flexibility of electric-driven devices is unrestricted by the limitations of traditional wires [2]. WPT can be used in moving targets like fuel-free electric vehicles, medical purposes such as biomedical implants and portable electronics.

There are two distinct and effective implementation mechanisms for wireless electric vehicles include the resonant CPT for dynamic wireless charging and the resonant IPT for both static wireless charging and dynamic wireless charging. Figure 2.2 illustrates the wireless charging of electronic vehicle [2]. This means that what the driver needs to do is just parking the car at specific position. Besides, the battery can be charged automatically via coupled magnetic field between the transmitting and the receiving coils. However, for the dynamic wireless charging, the vehicle can continuously acquire the energy when driving on a road.

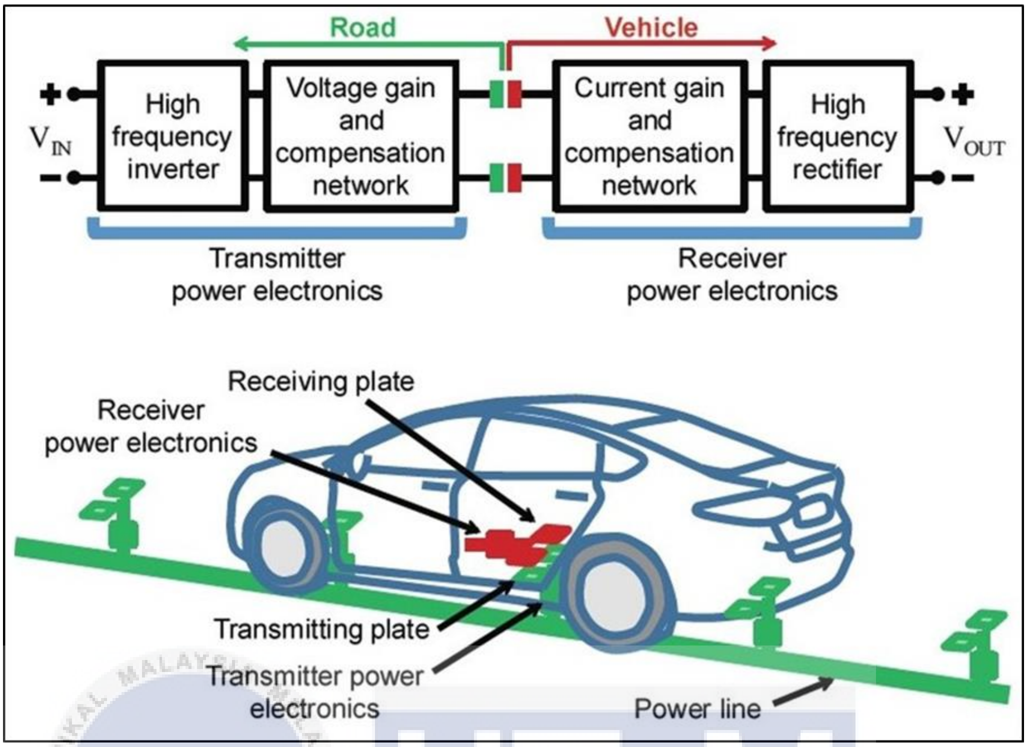


Figure 2.1: Wireless Charging of Electronic Vehicle by Sumi et al

The WPT shows promising future for portable electronics because of their weakness in having inconvenient power cords. Based on Figure 2.3, wireless charging of portable device used inductive coupling. The overall system is made using charger pad and the battery [2]. Each part must have planar coils to transfer energy from charging pad to the battery. In this way, the electrical energy is modulated due to communication between the charging pad and battery with each other. However, the charging pad will verify that a valid battery is in place or not before transmits full power to the battery. Thus, this communication continues throughout the entire charging process to confirm the battery is still in place.

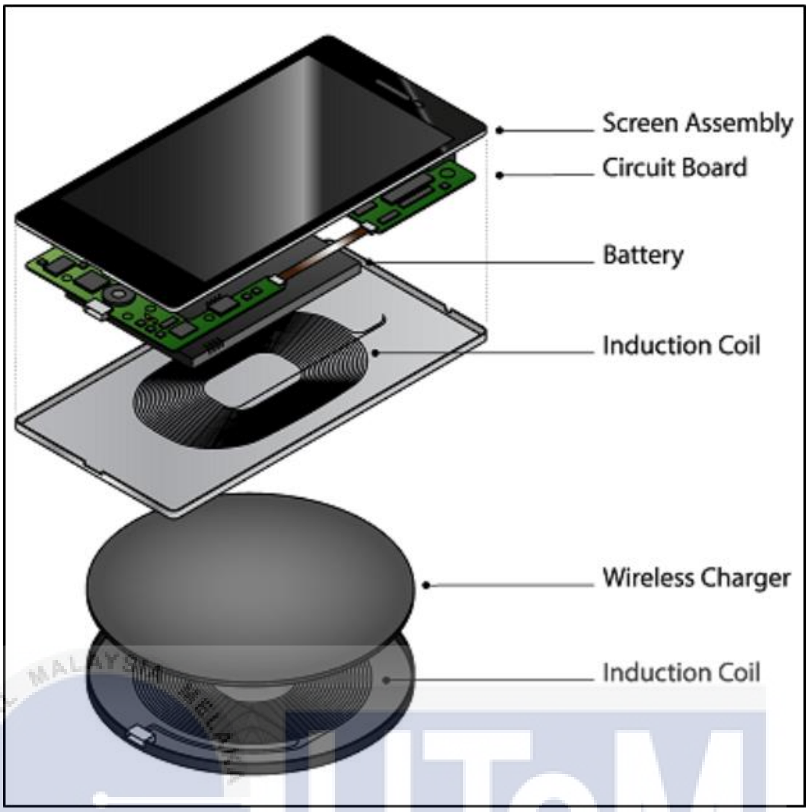


Figure 2.2: Wireless Charging of Portable Device using Inductive Coupling by Sumi et al[3]

2.4 Acoustic Energy Transfer (AET)

Methods rely on the electromagnetic field for the transfer energy can be divided into energy transfer based on radiative (microwave and optical CET) and nonradiative fields (inductive and capacitive CET). The transport of energy by sound waves instead of electromagnetic waves lies at the basis of AET. Acoustic Energy Transfer (AET) is a relatively new alternative method of transferring energy that relies on sound waves or vibrations rather than an electrical connection between the transmitter and receiver equipment [12]. Figure 2.4 depicts the fundamental structure of an AET system, which consists of a primary (transmitter) unit and a secondary (receiver) unit separated by any material capable of transmitting sound or pressure waves as a transmission medium. The power converter or inverter in the transmitter unit will convert a dc supply to an ac supply that will be pumped into a piezoelectric transducer. The energy will be converted to a pressure wave by the transducer, which will then be transferred wirelessly. Another transducer on the receiver side collects the pressure and turns it back into electrical energy, which is amplified dependent on the load requirements. Ultrasonic cleaning, medical ultrasonography, ultrasonic welding, and a variety of other applications use AET.

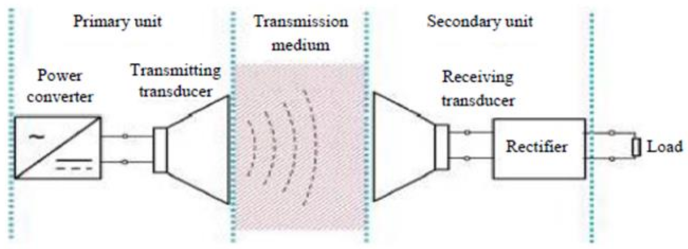


Figure 2.3: Basic AET system

2.5 Three groups on the basis of the propagation medium in AET

2.5.1 Living tissue

Many papers on acoustic energy transfer deal with biomedical applications, where the energy of ultrasonic waves is used directly for the intended purpose without being converted to electrical energy beforehand [20]. At the moment, batteries account for the majority of volume of an implant. Wireless energy transfer is presented as a way to improve the implants by reducing the battery capacity. Because there are no electromagnetic fields and a tiny receiver may be used, AET is a good alternative to inductive contactless energy transfer in this instance. Through vivo research, a number of writers have already demonstrated the possibility of biomedical AET. Furthermore, one of the reasons why the AET was chosen for biomedical use because of the operating frequency for the AET system was satisfactory enough to tradeoff with diffraction losses, attenuation losses and receiving thickness of transducers. For that reason, AET manage to surpass the IPT in the overall performance.

2.5.2 Through metal wall and enclosure area

There are times when transferring electricity wirelessly across a metal wall is desirable. For instance, the applications that use of sensors in nuclear waste containers, gas cylinders, vacuum chambers, pipelines. Any system qualifies if direct wire feed through would significantly complicate system design and hinder system performance. Therefore, any kind of WPT based on electromagnetic was plainly impossible due to shielding effect [16] that it would be possible to transfer power through metal element. Shielding effect would inhibit the coupling of an electromagnetic field system and induced eddy current in the wall which lead to high losses. Hence, the best option multiple authors have therefore proposed to use acoustic transfer energy as an alternative. AET achieves high power output and efficiencies through wall than an air or tissue medium. This is because the similarity in acoustic impedance between the wall and piezoelectric material (approximately 45 Mrayl for steel and 30 Mrayl for lead zirconate titanate) which a good match impedance implies optimal power throughput. In through-wall, AET system is describe that delivers 50W at 51% efficiency [17].

2.5.3 Air

The publication of AET technique in gaseous medium is far less trendy than others. This is due to air as transmission medium which is highly can cause reflection, diffraction and attenuation of sound waves. This aspect would change the characteristics of sound wave which could contributed to low performance of the system. Nevertheless, there are some publication that prove WPT using air medium is possible to achieve. The maximum efficiency that was measured was 17% and the transferred power was very low (4uW) [19]. It should be noted that the authors indicated that the measurements were performed with a non-optimized system and are meant to be nothing more than indicative.

2.6 Power Amplifier Class E Inverter

In electronics courses, the power amplifier is one of the common knowledges that student must know in engineering. However, not all of amplifier have the same characteristics, in fact they have their own operating characteristics which is the linearity, signal gain, efficiency and power output. Thus, the term of class is used to distinguish between the amplifier type. The amplifier classes are categorized based on the amount of output signal over one cycle operation when excited by the input signal. The amplifier classes are divided in two group, first group which is Class A, Class B, Class AB and Class AC. These classes are the standard amplifier that commonly used for linearity of the system which the output stage transistor whether fully ON or fully OFF. Besides that, the second group known as switching amplifier; Class D, Class E, Class F and Class G. These amplifiers use digital circuit and pulse width modulation (PWM) to switch the signal between fully ON and fully OFF.

Class E power amplifiers, also known as Class E dc-ac inverters, are classified into two types. First and foremost, we have class E zero-current-switching (ZCS) power amplifiers where the transistor usually operates as a switch in Class E amplifiers. On the other hand, Class E zero-voltage-switching (ZVS) power amplifiers is relatively recent amplifier format and known as the most efficient amplifiers so far. So, the power conversion from DC to AC can be evaluated by measuring either ZVS or ZCS. In this paper, only ZVS is consider to analyze measurement. Additionally, this device is operated as a switch as well. The current and voltage waveforms of the switch are displaced with respect to time, yielding a very low power dissipation in the transistor. If the component values of the resonant circuit are properly chosen, the switch will turn on at zero voltage. If the switch current and voltage waveforms do not overlap during the switching time intervals, the switching losses can be assumed at very low or zero. In other word, there is very little power dissipation in the device. To sum up, the total efficiency is high.

Class E ZVS inverter are theoretically capable of delivering any power to a load and achieve 100% efficiency [9]. It is the most efficient and excellent switch inverters circuit, which capable in reducing the voltage stress and switch conduction loss in the resonant circuit. On top of that, class E still manage to operate at the high efficiency. The Class E Inverter described has the high efficiency, low input voltage, low component count and produces good performance and stability by adjusting the duty cycle and optimizing circuit parameters.

2.6.1 Class E Circuit Description

The basic circuit of the Class E ZVS power amplifier can be described [9] by Figure 2.5. The circuit consists of power MOSFET that operates as a switch, inductor (L), capacitor (C), resistor (R) series circuit, shunt capacitor, C_1 and choke inductor, L_f.

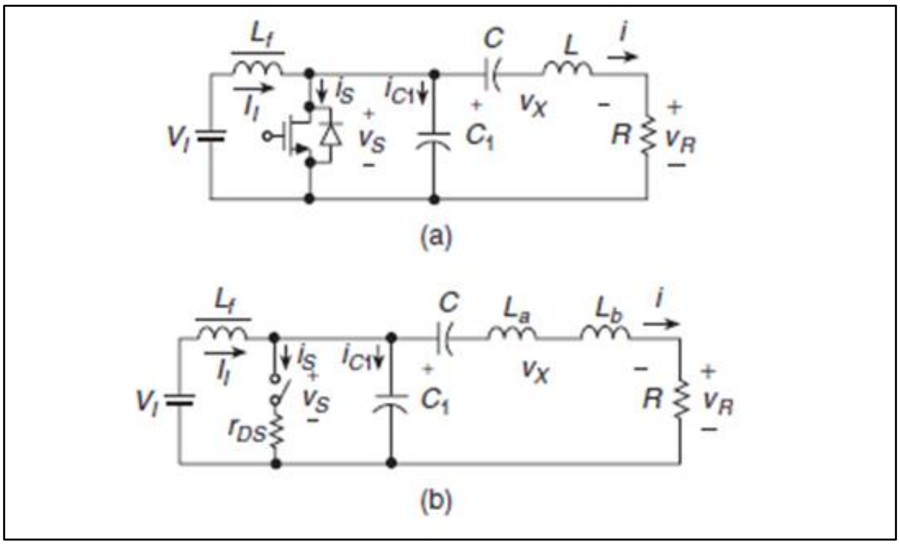


Figure 2.4: Class E zero-voltage-switching inverter. (a) The basic circuit. (b) Equivalent circuit for operation above resonance.

The basic operation of the circuit is at the frequency 40 kHz, the switch will turn on and off depending by the input driver as described by Marian et al [9]. When the switch is ON, the L, C, R in series circuit become short circuit because there is shunt capacitance, C_1.

The choke inductance, L_f, function as a filter to reduce the AC current ripple on DC supply current. Next, the shunt capacitor and series inductor, these components used to improve the power factor in the circuit. Moreover, it can improve the voltage stability and network losses. Meanwhile, the resistor, R is an AC load.

2.7 Impedance Matching Technique

The primary goal of an impedance matching network is to find a conjugate match between a source and a load. Thus, when the load impedance is same with source impedance, the power transfer can be achieved at the maximum level. In AET system, the Class E circuit combined with purely resistive 470 Ohm is an ideal design.

However, when the circuit is integrated with an ultrasonic transducer, there is impedance variation between source and the load.

Therefore, integration of Class E circuit with impedance matching is necessary at the end of project because the AET system can produce the desire output power, high in total efficiency and low in losses. The impedance matching network only apply at the transmitter unit which is in order to cancel out the capacitance value that already build in the ultrasonic transducer, so that there will be only single resistance in the transmitter unit. In this project, the impedance matching π1a will be investigated. Figure 2.6 illustrate the block diagram of impedance matching being apply at Class E power amplifier circuit [9].

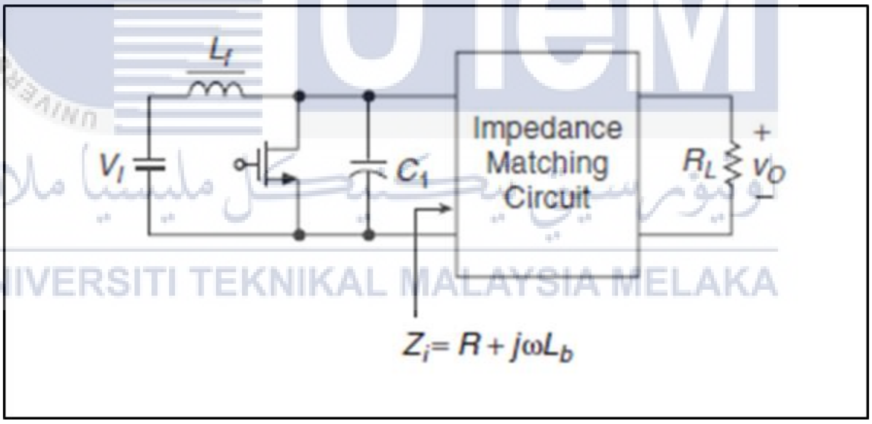


Figure 2.5: Block diagram of the Class E inverter with impedance matching circuit

2.7.1 Impedance Matching Circuit π1a

In Figure 2.7(a) shows the impedance matching circuit π1a and its equivalent circuit in Figure 2.7(b)

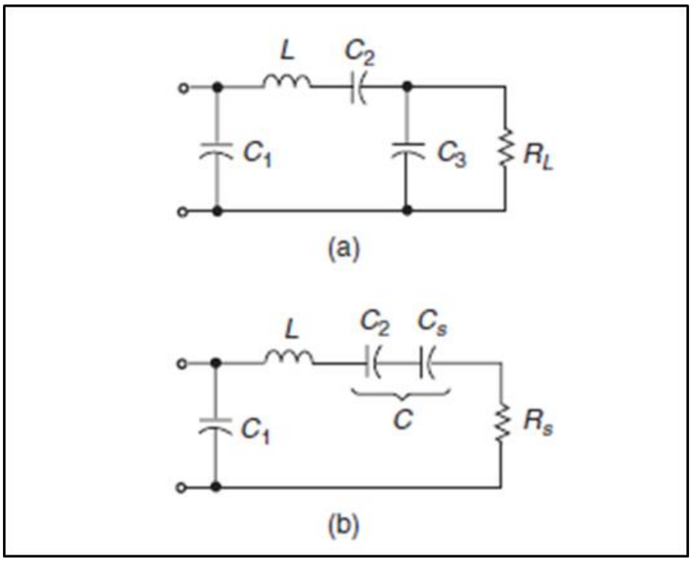


Figure 2.6: (a) Matching resonant circuit π1a. (b) Equivalent circuit of matching π1a as described by Marian et al

Resistances R_S can be calculated as

$$R_S = R = \frac{8}{\pi^2 + 4}\,\frac{V_I 2}{P_o} \approx 0.5768\,\frac{VI^2}{Po} \qquad (1)$$

The value of Xc_1 can be obtain

$$X_{C1} = \frac{1}{\omega C1} = \frac{\pi(\pi^2+4)R}{8} \approx 5.4466R \qquad (2)$$

and

$$X_L = \omega L = Q_L R \qquad (3)$$

Then, the reactance factor of the R_L -C_3 and R_S -Cs equivalent circuit is

$$q = \frac{Rl}{Xc3} = \frac{Xcs}{Rs} \qquad (4)$$

Resistances R_S, R_L and the reactance Xcs and Xc_3 can be derive as

$$R_S = R = \frac{RL}{1+q^2} = \frac{RL}{1+(\frac{RL}{XCS})^2} \qquad (5)$$

and $X_{cs} = \frac{Xcs}{1+\frac{1}{q^2}} = \frac{XC3}{1+(\frac{XC3}{RL})^2}$ (6)

Thus, $C_S = C_3(1+\frac{1}{q^2}) = C_3[1+(\frac{XC3}{RL})^2$ (7)

Rearrangement of (5) define

$$q = \sqrt{\frac{RL}{RS} - 1} \tag{8}$$

From (4) and (8),

$$X_{C3} = \frac{1}{\omega C3} = \frac{RL}{1} = \frac{RL}{\sqrt{\frac{RL}{RS}-1}} \tag{9}$$

Substitution of (8) into (4) define as

$$X_{CS} = qR_S = R_S\sqrt{\frac{RL}{RS} - 1} \tag{10}$$

Then,

$$X_C = \frac{1}{\omega C} = \left[QL\ \frac{\pi(\pi^2-4)}{16}\right]R \approx (Q_L - 1.1525)R \tag{11}$$

Refer to (11) and (10)

$$X_{C2} = \frac{1}{\omega C2} = XC - XS = \left[QL\ \frac{\pi(\pi^2-4)}{16}\right]Rs - qRs$$

$$= R_S\,[Q_L - \frac{\pi(\pi^2-4)}{16} - \sqrt{\frac{RL}{RS} - 1} \tag{12}$$

2.8 Previous Research Study on Class E ZVS Inverter Impedance Matching

2.8.1 Wireless Power Transfer Using Class E Inverter with Saturable DC-Feed Inductor

This paper investigates a method to adapt to variations in range for a Class E inverter used as coil driver in a wireless power transfer (WPT). In order to facilitate a strong magnetic field for the weak coils of coupling to deliver high power levels over long distances necessitates the use of coil drivers in the kilohertz (kHz) and megahertz

(MHz) ranges. The Class E inverter was proposed by [6] in this research as a suitable type of DC-AC converters to meet such requirements since it is easy to construct because it consists of a single switching element and has a large power handling capability compared to other inverters. The completion of the Class E inverter demonstrated that the displacement of the coils from their optimum position causes the Class E inverter to operate in a non-optimum switching condition. Hence, the overall level of efficiency of the wireless power transfer system and the power delivered to the load is reduced. Class E inverter undergoes tuning method to prevent the switching element from damaged, reduce large voltages and overcome current spikes. This tuning method allow inverter to operates optimally by replacing a capacitor and adjusting the switching frequency. The circuit analysis of the Class E inverter along with an inductive link was verified by implementing the proposed tuning. A function generator is connected to the MOSFET driver to vary the duty cycle of the switching signal for MOSFET. The control of the DC-feed inductance is achieved by using a saturable reactor. It consists of two windings, a primary winding which represents the DC-feed inductance to be controlled and a control winding which is connected to a variable DC current source. If the control direct current is zero, then the DC-feed inductance will be at maximum. Hence, the control DC current is increased. Consequently, the proposed project has been successfully demonstrated. This allows Class E inverter to operate safely and efficiently.

2.8.2 Low Cost Matching Network for Ultrasonic Transducers

In this article [10], a low-cost matching network for high impedance ultrasonic transducers was investigated as provision for maximize power transfer. Besides, it helps to improve the efficiency of the transducers transmission in resulting a superior signal-to-ratio. A tuned inductor was introduced into ultrasonic applications based on piezoelectric transducers (PZT), which was generally installed in an experimental method.

This research proposes utilizing a simple L-C matching network with only one inductor and one capacitor to analyze the improvement in transducer performance using computer simulation. The matching network proposed by [10] has been also experimentally tested with two different types of transducers. Firstly, a piezoelectric air coupled ultrasonic transducer with an active surface area of 15mm2 and the resonance frequency at 800kHz that it is used for Lamb wave generation 0. In addition, a shear wave transducer (100kHz, Panametrics) was used in the ultrasound rheology of some food products. Thus, the power emitted by a matched transducer at the intended frequency (marked by a point) is more than 9 times higher than that observed for a transducer without a matching network, as shown in the Figure 2.8, Figure 2.9, Figure 2.10 and Figure 2.11 below. Furthermore, the amplitude signal of the matched transducer improved by over 300 percent when compared to the signal obtained with the unmatched transducer is shown in Figure 2.12 and Figure 2.13. As a result, the experimental and modeling results are consistent.

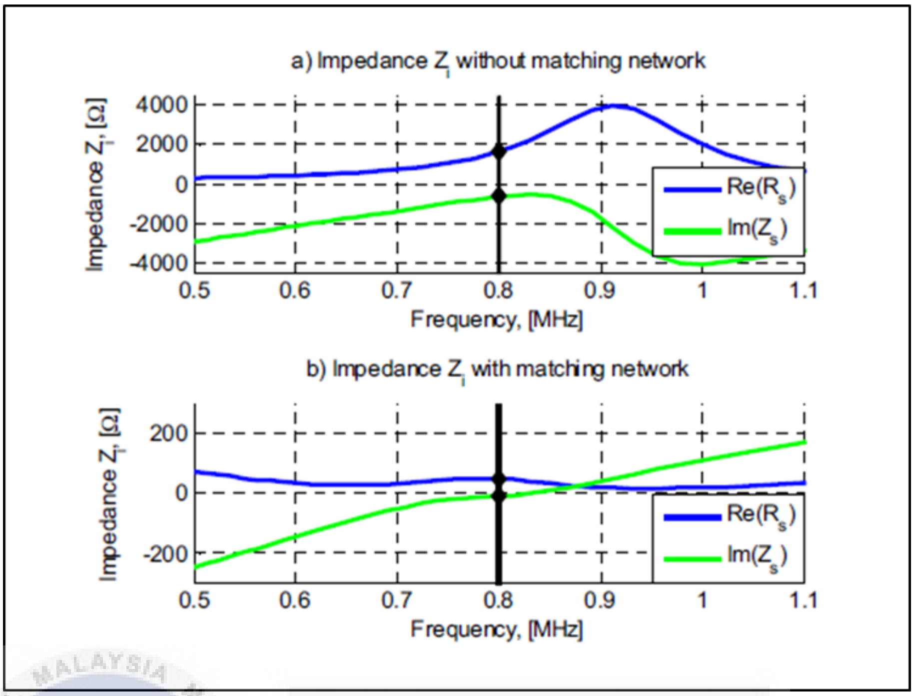


Figure 2.7: Simulated impedance Zi for air coupled transducer

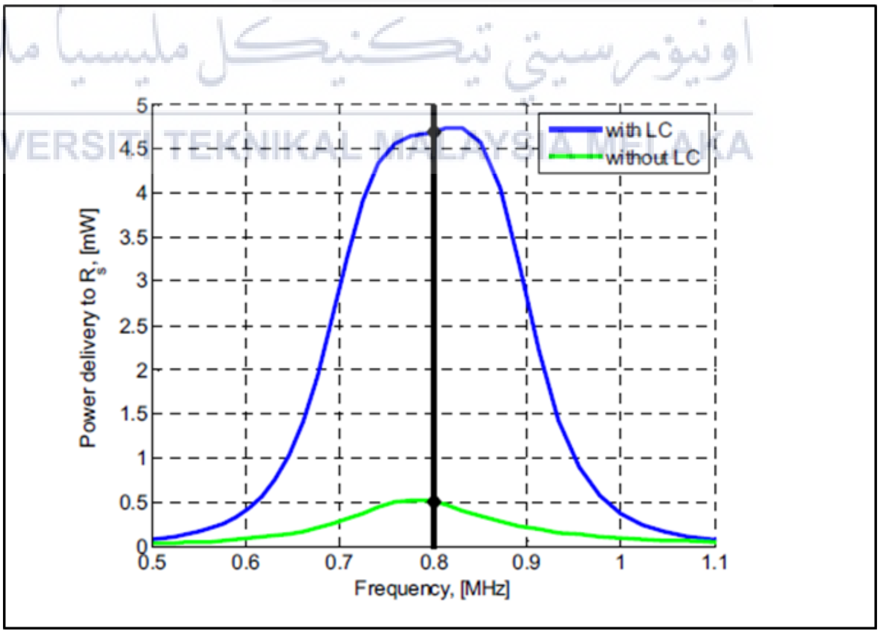


Figure 2.8: Simulation acoustic power emitted for circuit with LC matching network and without matching for air coupled transducer

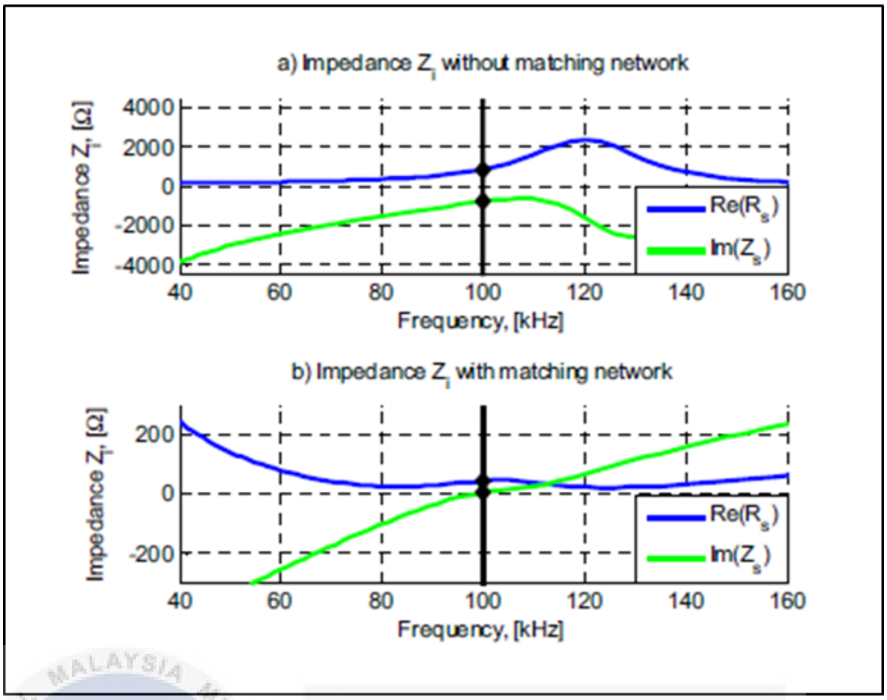


Figure 2.9: Simulation impedance Zi for shear wave transducer

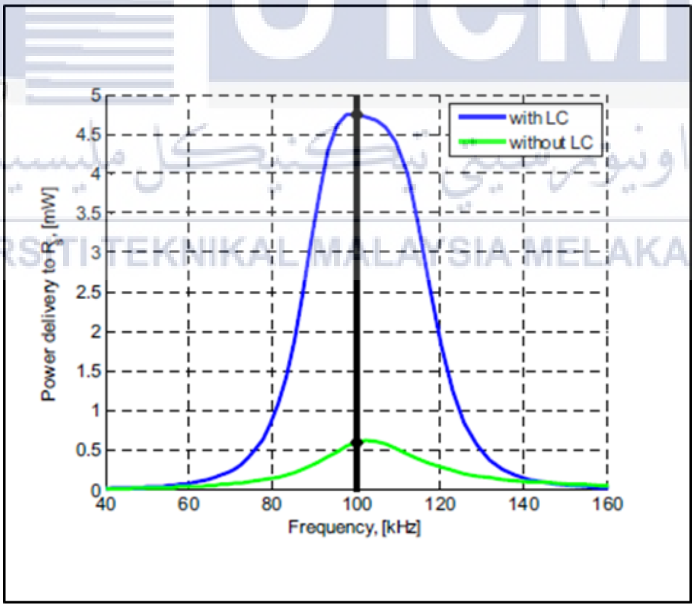


Figure 2.10: Simulation acoustic power emitted for circuit with LC matching network and without matching for shear wave transducer

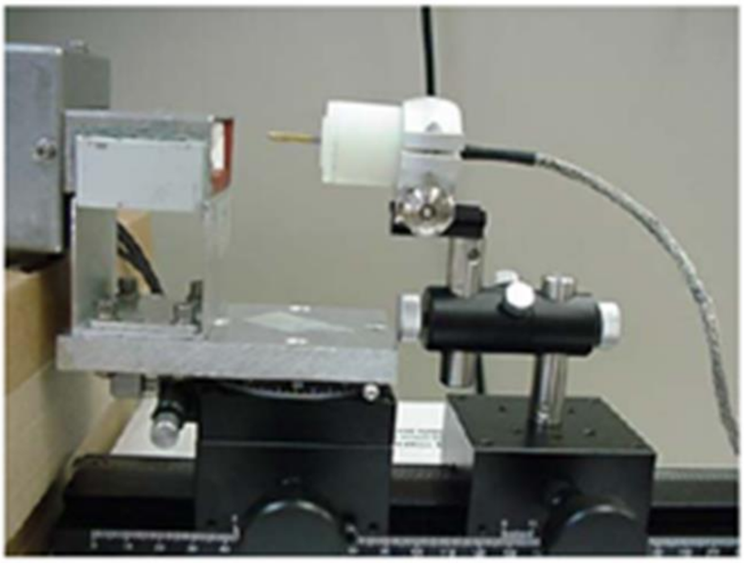


Figure 2.11: The setup used for measuring the signal generated by the piezoelectric transducer

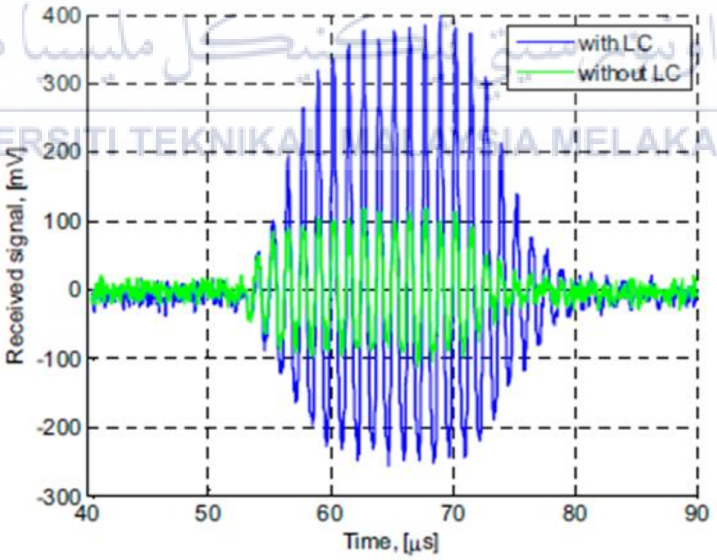


Figure 2.12: Signals received by hydrophone with matching network and without matching

2.8.3 Evaluation of the Ultrasonic Transducer Electrical Matching Performance

This article indicates and analyze the matching techniques performance based on the measured transducer impedance instead of BVD model. The ultrasonic transducer was predicted approximately using Butterworth-Van-Dyke (BVD) model [17]. BVD model is derived by simplifying the Mason equivalent circuit [18] and made of piezoelectric impedance. Besides, it was considered the best lumped parameter equivalent circuit suitable as piezoelectric transducer are fitted and able to represent transduction. The transducer electrical impedance affects an ultrasonic transducer noise performance, driving response, bandwidth and sensitivity. These parameters can be modified by applying the electrical circuit in between the ultrasonic transducer and the excitation generator. [11] suggested to use matching performance evaluation based on the measured ultrasonic transducer impedance. Six matching performance evaluation criteria offered are power delivered to a load at the operation frequency, -3dB bandwidth, effective bandwidth, power delivery to load efficiency, power factor and total efficiency.

The power delivered to a load is maximized when the load impedance is equal to the generator intrinsic resistance, Rg. At the serial resonance the complex impedance of Lm, Cm series connection is zero and the equivalent transducer circuit is simplified to parallel connection of Rm, and Co as shown in Figure 2.14. The power supplied to transducer is intruded by the capacitance of the piezoelectric transducer, Co. This capacitance is loading the excitation generator output and is reducing the generator efficiency.

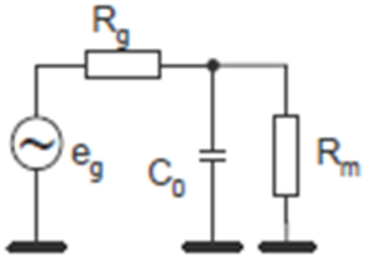


Figure 2.13: Equivalent circuit and mechanical resonance

2.8.4 A Simple Class E Inverter Design for Driving Ultrasonic Welding System

Wen Chun Chang (2009) [12] centered on the construction of a basic Class E inverter circuit that used matching technology to operate a zero voltage switching ultrasonic welding device. This inverter has been tuned for great efficiency and has the benefits of a simple architecture, such as low switch voltage and a zero-voltage switch, making it ideal for high-power ultrasound systems. Because the resonance quality factor of an ultrasound transducer is so high, the useable bandwidth will be limited. The ultrasound of welding system of the operating frequency must be inductance characteristic range of piezoelectric transducer. Figure 2.15 depicts he equivalent circuit of a Class E resonant inverter that consists of a FGPA chip with current detect circuit, OPA-RMS circuit, 8051 A/D converting circuit, driver circuit (power amplifying circuit), multiplexer circuit, voltage detector, oscillating circuit and signal fetching. In order to provide operation frequency around 40 kHz, the FGPA chip is used to control multiplexer circuit. The end study of this research showed the high efficiency with zero voltage switching of Class E inverter succeed to drive the ultrasonic welding system. The characteristic model of simple inverter and a feedback self-adjust model are proven to make the system state became more stable.

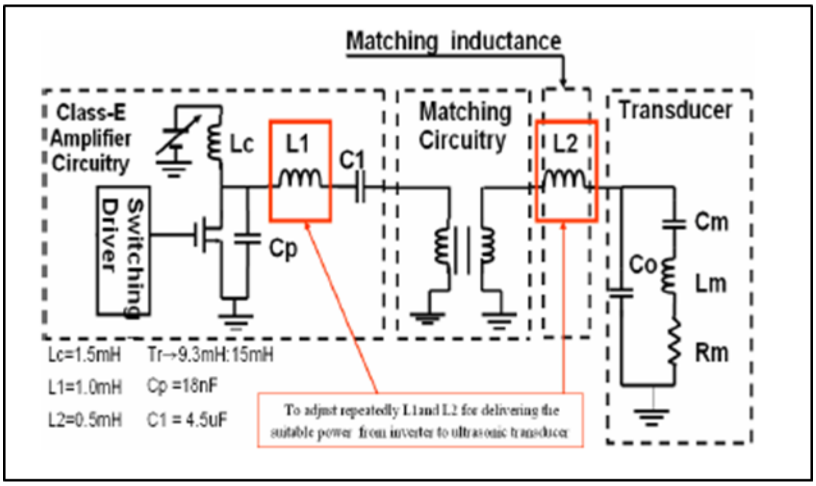


Figure 2.14: The matching technology of ultrasonic welding system

2.8.5 Driving an Inductive Piezoelectric Transducer with Class E Inverter

The research paper [8] proposed an innovative driving scheme of a Langevin piezoelectric transducer under its inductive frequency range. It has advantages in maximum efficiency frequency between the resonance and anti-resonance. Through this approach, a constant vibration velocity measurement system is used to find the optimum driving frequency. In addition, the equivalent circuit of the transducer based on Butterworth-Van Dyke (BVD) model is established to drive the transducer at the resonance frequency (resistive) and transducer at the optimum frequency (inductive) parameters. A Langevin transducer is put to the test with a constant vibration velocity. Then, to achieve optimal efficiency, a class E inverter circuit is built to drive this transducer at resonance and anti-resonance. Another similar transducer circuit is also designed based on the BVD model for creating drive circuits. They conducted comparison studies to prove that driving a Langevin transducer between its resonance and anti-resonance frequencies achieves better results than driving it between its resonance and anti-resonance frequencies. However, the design of BVD model does not exhibit the maximum efficiency between resonance and anti-resonance. As a result, the voltage, current, and vibration velocity waveforms in these two driving methods, as well as the sinusoidal waveforms we obtained in this experiment, are reported as shown in Figure 2.16.

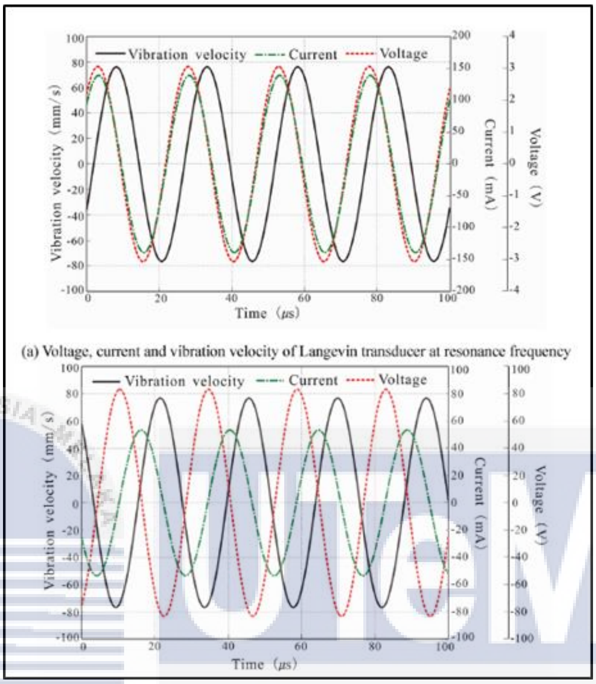


Figure 2.15: The voltage, current and vibration velocity of Langevin transducer at the optimum frequency

CHAPTER 3

METHODOLOGY

In this chapter, the methodology of this project is explained in detail. The project implementation by the circuit design, circuit operation and circuit testing. In this research, will descript the detail in simulation that is designed the using the MATLAB software. From this method, the performance result is analyzed. This chapter focuses on the calculation and design process of AET system in Class E converter, ultrasonic transducer and impedance matching in simulation at MATLAB software. The detail about the circuit is designed and show the equation used for the design in this chapter.

3.1 Project Methodology

The methodology explains the process that needs to be done to establish an acoustic energy transfer system which involved the research study, simulation, hardware design and troubleshooting process. Besides, the performance of the system is measure and compare with others to verify overall performance. It explains the steps were involved in producing the desired result.

3.2 Project Flowchart

The simulation flowchart in Figure 3.1 describe the working process and steps that need to be followed in order to produce an ideal simulation of an acoustic energy transfer (AET) system. The steps were divided into several parts; research and study, design, integrate circuit, simulate, troubleshoot and lastly performance analyze. After the title selection for the project, research and background study on previous work regarding to AET was conducted in order to get an idea and prepared for the draft proposal project.

Apart from that, the AET circuit was designed and simulated along with the right value for each component by using MATLAB via Simulink. The designing and simulation would be in three parts which were the first one was to design basic construction of standard class E circuit. The most importantly, each of part would consists on evaluation regarding to ZVS condition whether it was achieved and overlapping. If the result showed overlapping, there would be troubleshooting process. Secondly, the class E circuit would be combined with ultrasonic transducer, which would cause impedance variation because the impedance value in ultrasonic transducer made the circuit no longer purely resistive. Because of that, the next step would be on impedance matching process that can be overcome the impedance variation problem. During the evaluation, beside zero voltage switching observation, there would be several measurements that need to be taken to analyze the performance of AET system which were the power input, power output and total efficiency that achieved by the system.

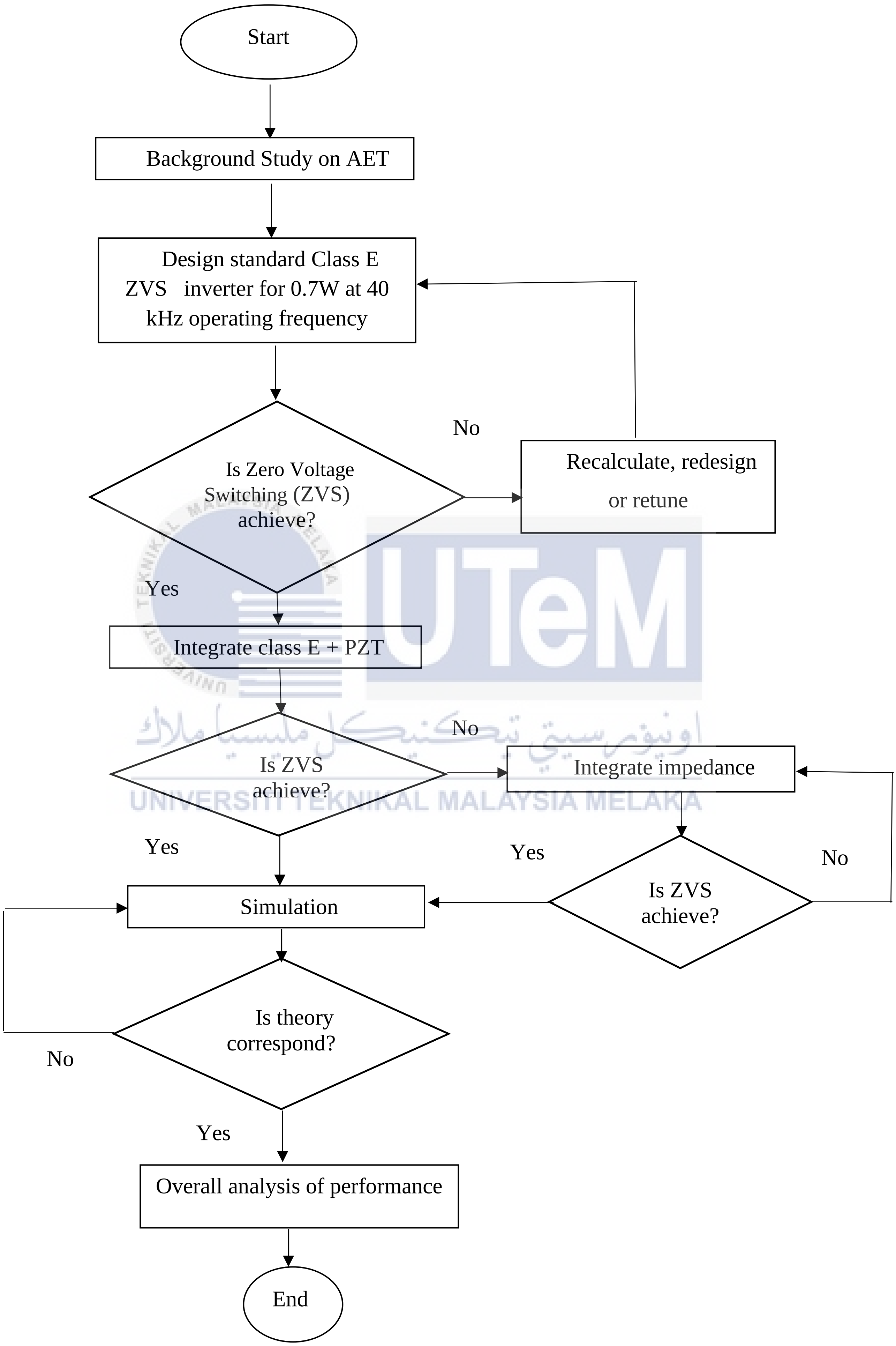


Figure 3.1: Simulation of flowchart diagram

3.3 Simulation of Class E ZVS Inverter

The Simulink program in MATLAB could provide the designed process where the circuit was constructed and determined the exact value of component that needed to build the ideal circuit. Next, the simulation of the circuit could be done set up the correct setting of Simulink such as runtime of the simulation, power supply, frequency, duty cycle and others. Then, the measurement of performance obtained through scopes.

The Acoustic Energy Transfer (AET) system of the project is designed by Class E ZVS has been chosen at the transmitter circuit which is the design as an amplifier for the maximum power. In addition, Class E ZVS is proposed to drive the Acoustic Energy Transfer (AET) system caused to its low switching capability. According to Figure 3.3, the Class E circuit design in MATLAB software act as a converter circuit which consists of choke inductor (L_f) and shunt capacitor (C_p). Choke inductor (L_f) is to reduce current ripple through the circuit while shunt capacitor (C_p) is to shape and modify the drain current and voltage waveform [9]. Class E circuit also consists of a series capacitor (C_{series}) and a series inductor (L_{series}) which the components used as a filter to reduce the effects of harmonic in waveform. The class E have many advantages from the other converter because it is simple passive purely and working operation has no overlap between current and voltage.

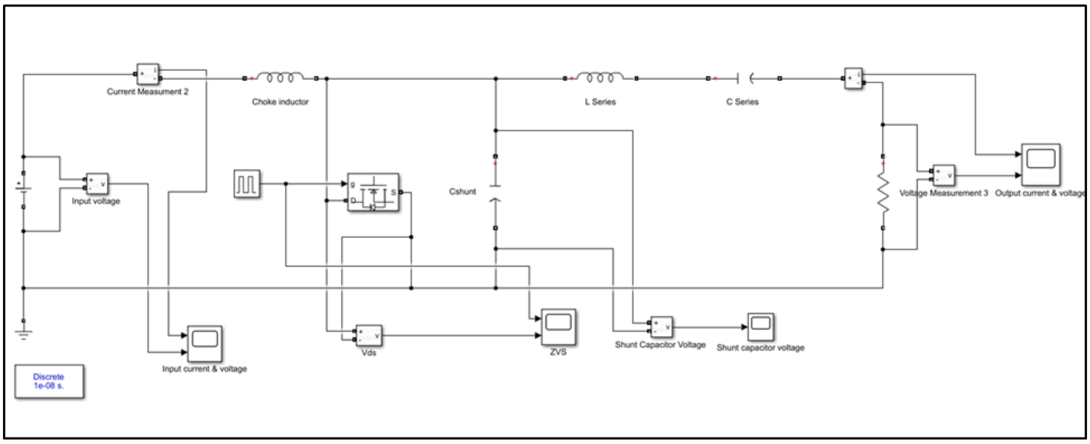


Figure 3.3: Design of Class E ZVS Inverter in MATLAB software

Table 3.1 shows the specification value of AET system in Class E ZVS has been designed by the value to analyze.

Table 3.1: The specification value of AET system in Class E ZVS

Data	Value
Power (P_o)	0.7 W
Voltage (V_{CC})	23.88 V
Frequency (f_s)	39.8 kHz
rDS	0.54
Q	10

By using the purely resistance is 470 Ω inserted to the formula:

Full-load resistance, $R_L = \frac{8}{\pi^2 + 4}\,\frac{V_I{}^2}{P_o}$ (13)

Shunt capacitor, $C_p = \frac{8}{\pi(\pi^2+4)\omega R}$ (14)

Series capacitor, $C = \frac{1}{\omega R\left(Q - \frac{\pi(\pi^2-4)}{16}\right)}$ (15)

Choke inductor, $L_f = 2\left(\frac{\pi^2}{4} + 1\right)\frac{R}{f}$ (16)

Series inductor, $L_{series} = \frac{QR}{\omega}$ (17)

Voltage across load R, $V_{RL(max)} = V_{CC}\frac{4}{\sqrt{\pi^2+4}}$ (18)

Voltage switch maximum, $V_{S(max)} = 3.562\ V_{CC}$ (19)

The method is to achieve the ZVS in the condition of the tuning process and redesign that the system of class E able to work in purely resistive.

By using (13), we obtain

$$R_L = \frac{8Vcc^2}{(\pi^2+4)P}$$

$$= 470\ \Omega$$

By using (14), we obtain

$$C_p = \frac{I_o}{\omega\pi Vcc^2} = \frac{1}{\omega R\left(\frac{\pi^2}{4}+1\right)\frac{\pi}{2}}$$

$$= 1.56\ \text{nF}$$

By using (15), we obtain

$$C = \frac{1}{\omega R\left(Q-\frac{\pi(\pi^2-4)}{16}\right)}$$

$$= 0.96\ \text{nF}$$

By using (16), we obtain

$$L_f = 2\left(\frac{\pi^2}{4}+1\right)\frac{R}{f}$$

$$= 82\ \text{mH}$$

The operating frequency in the datasheet is indeed 40 kHz. But this ultrasonic transducer only works at the minimum impedance which will produce the highest vibration when at series resonance. However, if we use the series frequency equation, we will get a value of 39.8 kHz.

The transistor output capacitance, Co, becomes greater than the shunt capacitance, C_p, necessary for ZVS functioning at high frequencies. Class E ZVS functioning is calculated using the maximum operating frequency *fmax*.

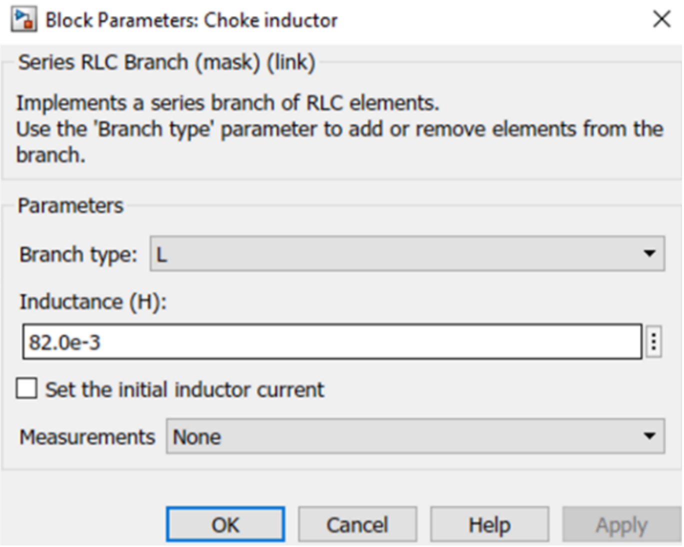
$$fmax = \frac{4}{\pi^2(\pi^2+4)CoR} = \frac{0.02922}{CpR}$$

$$= \frac{0.02922}{(1.56nF)(470\Omega)}$$

$$= 39.8 \text{ kHz}$$

Table 3.2 shows the value is calculated based on the equations of circuit design for Class E ZVS inverter for AET system in simulation.

Table 3.2: Class E ZVS parameter by calculation in MATLAB simulation

Parameters	Value
Operating frequency, *fmax*	39.8 kHz
Quality factor, *Q*	10
Choke inductor, *Lf*	

<table>
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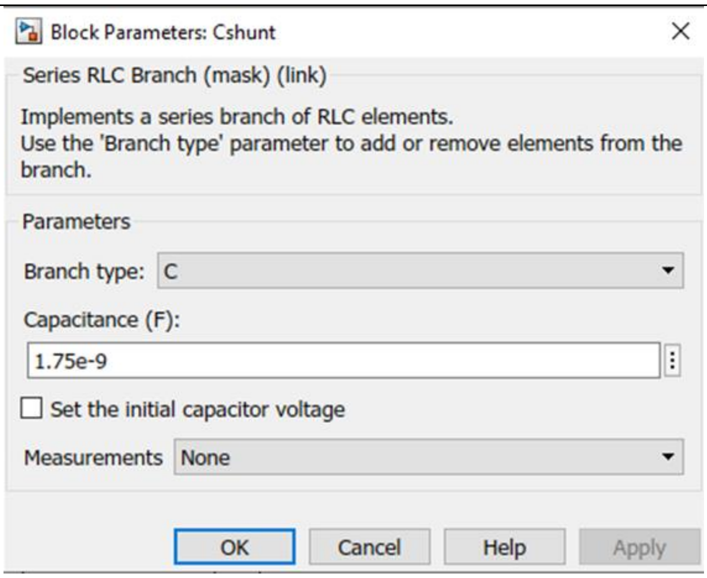
<td>Shunt capacitor, C1</td>
<td>


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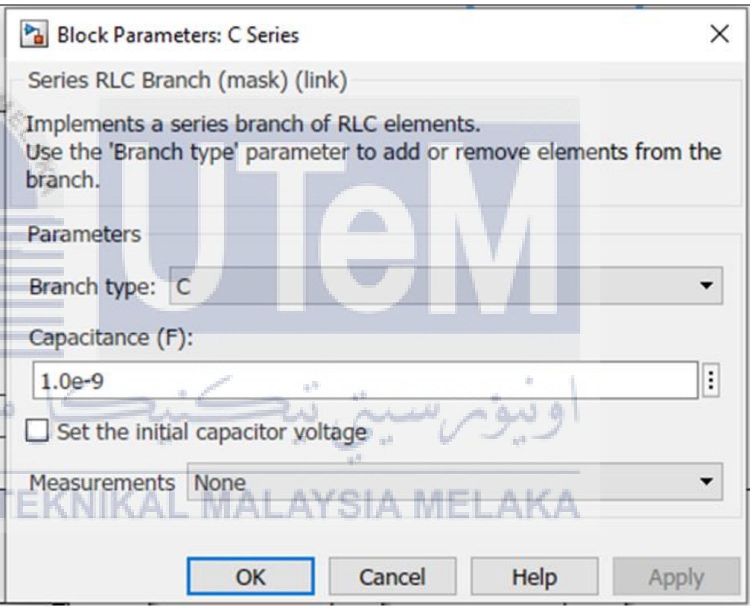
<tr>
<td>Series capacitor,
Cseries</td>
<td>


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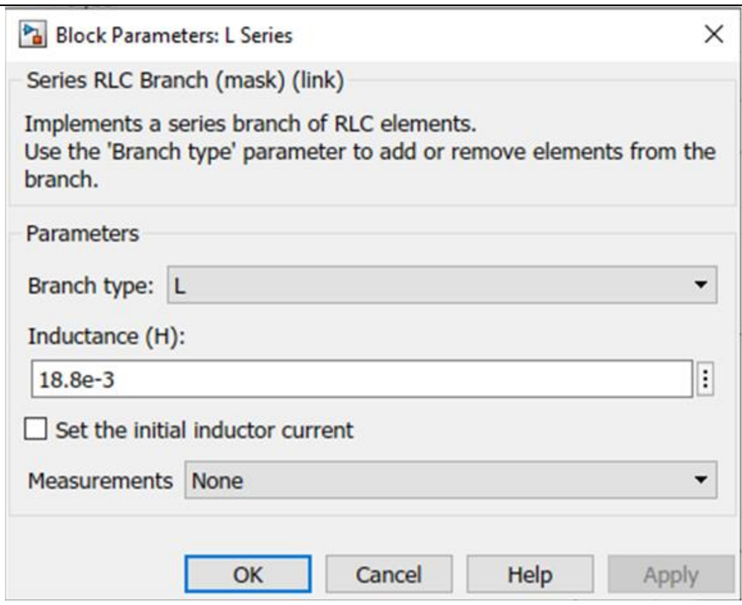
<tr>
<td>Series inductance,

Lseries</td>
<td>
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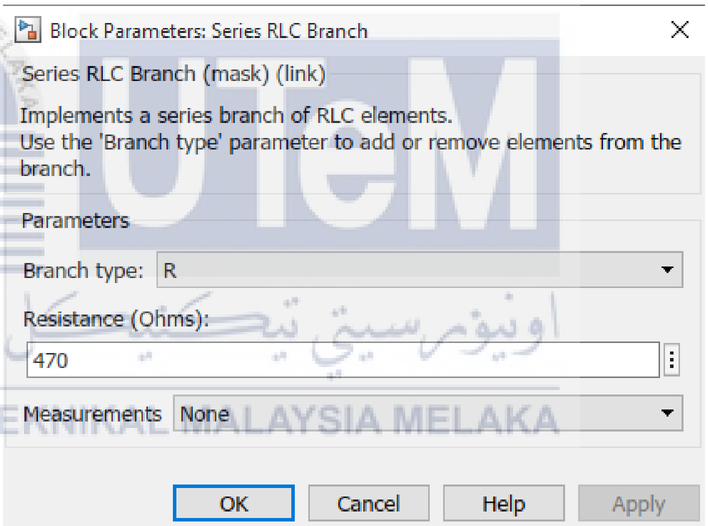
<tr>
<td>Load resistance, R_L</td>
<td>
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3.4 Integrate the Class E and Ultrasonic Transducer

The ultrasonic transducer is the transducer sensor used to transfer the energy and reflect signal into electrical signal form transmitter and receiver by wave. Table 3.3 shows internal specification of the ultrasonic transducer and the value to build the ultrasonic transducer. The capacitance of the ultrasonic transducer material is represented by Co.

Table 3.3: Value of ultrasonic transducer

R_1 (Ω)	482.36
Co(F)	1.94n

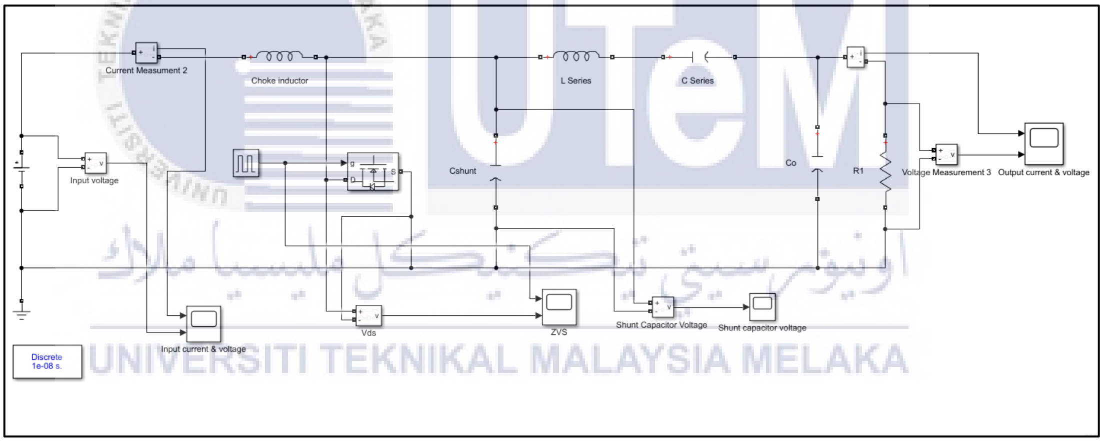

Figure 3.4: Design Class E ZVS with the ultrasonic transducer in MATLAB software

3.5 Integrate with the Impedance Matching

Based on the theory [9], the impedance matching used to improve the ZVS when transducer inserted in the Class E ZVS. In the project, π1a impedance matching circuits is designed to achieve dynamic tuning match because the Zero Voltage Source (ZVS) and efficiency drop after integrate the ultrasonic transducer in the transmitter. Manual tuning match of transducer is achieved in different types of load and the transducer can result in good resonance condition tuning match where it is one of the effective ways.

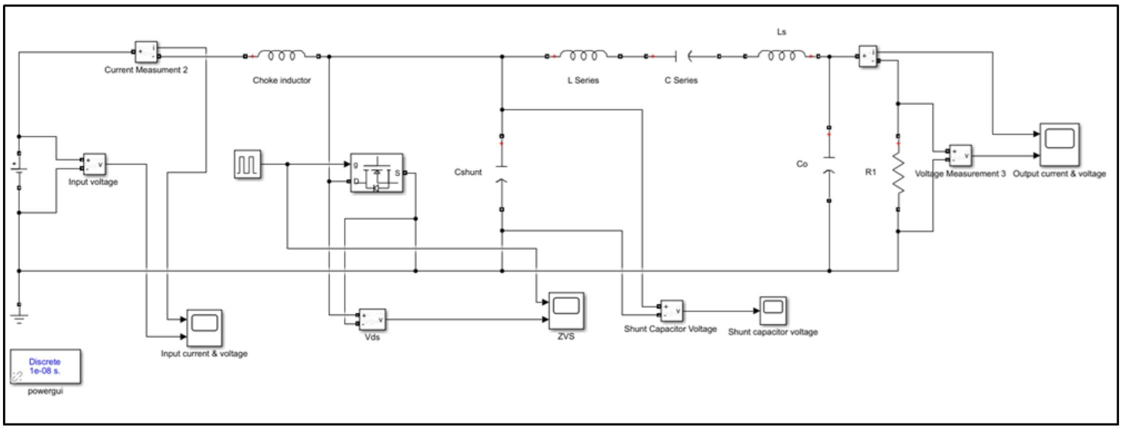

Figure 3.5: Design Class E with π1a impedance matching in MATLAB software

3.6 Tuning Process

In the circuit to achieve the ZVS condition at the operating frequency must adjusting the three components C1, C2 and L2. The following step is the conditions of tuning process to obtain the waveform as guided in [9] by changing value that can be affect the waveform.

1. To obtain the waveform upwards and the right side is increasing value of C_1.

2. To obtain the waveform downwards and the right side is increasing value of C_2.

3. To obtain the waveform downwards and the right side is increasing value of L_2.

4. To obtain the waveform upwards is increasing value of R.

CHAPTER 4

RESULTS AND DISCUSSION

This chapter present the result of the circuit operation. Ultimately, the data is obtained through the implementation of established equations, then followed by verification processes through simulation steps. The measured and recorded results then analyzed for the system performance indicators.

4.1 Impedance Matching π1a Calculation

Impedance matching π1a is basically the capacitor is placed in series in the Class E ZVS inverter. The π1a capacitor value, C3 can be calculated as follows:

The given value:

- Frequency = 40 kHz
- Load resistance = Rs = R = 470 Ω
- Ultrasonic transducer built-in internal value = C_o = 1.94 nF, R_L = 482.36 Ω
- Q_L = 10

First, find the reactance factor of the circuit, q using equation

$$q = \sqrt{\frac{RL}{RS} - 1}$$

$$= \sqrt{\frac{482.36}{470}} - 1 = 0.1622$$

Then, by using (9), the impedance of the π1a circuit, X_{C3} can be calculated as

$$X_{C3} = \frac{1}{\omega C3} = \frac{RL}{q} = \frac{482.36}{0.162} = 2.977x10^3\ \Omega$$

By using (20), the value of C_3

$$C_3 = \frac{1}{2\pi(39.8k)(2.977x10^3\Omega)} = 1.34nF$$

Hence, to obtain the capacitance value, C_s, we can calculate

$$X_{CS} = \frac{XC3}{1+\frac{1}{q^2}}$$

$$= \frac{2.977x103}{1+\frac{1}{0.1622^2}} = 76.14\Omega$$

Thus, the value of C_S

$$C_S = C_3\,(1+\frac{1}{q^2})$$

$$= 1.34x10^9\,(1+\frac{1}{0.01622^2}) = 52.40\text{ nF}$$

Referring to equation Xc_2, the value of Xc_2 can be calculate as

$$X_{C2} = \frac{1}{\omega c2} = Rs\left[QL - \frac{\pi(\pi^2-4)}{16} - \sqrt{\frac{RL}{RS}} - 1\right] = 4082.15\Omega$$

4.2 Simulation

The simulation part is conduct using MATLAB software via Simulink software. The Figure 4.1 depicts the basic simulation circuit of Class E ZVS inverter which mainly consist of input power, function generator, choke inductor, series inductor, shunt capacitor and series capacitor.

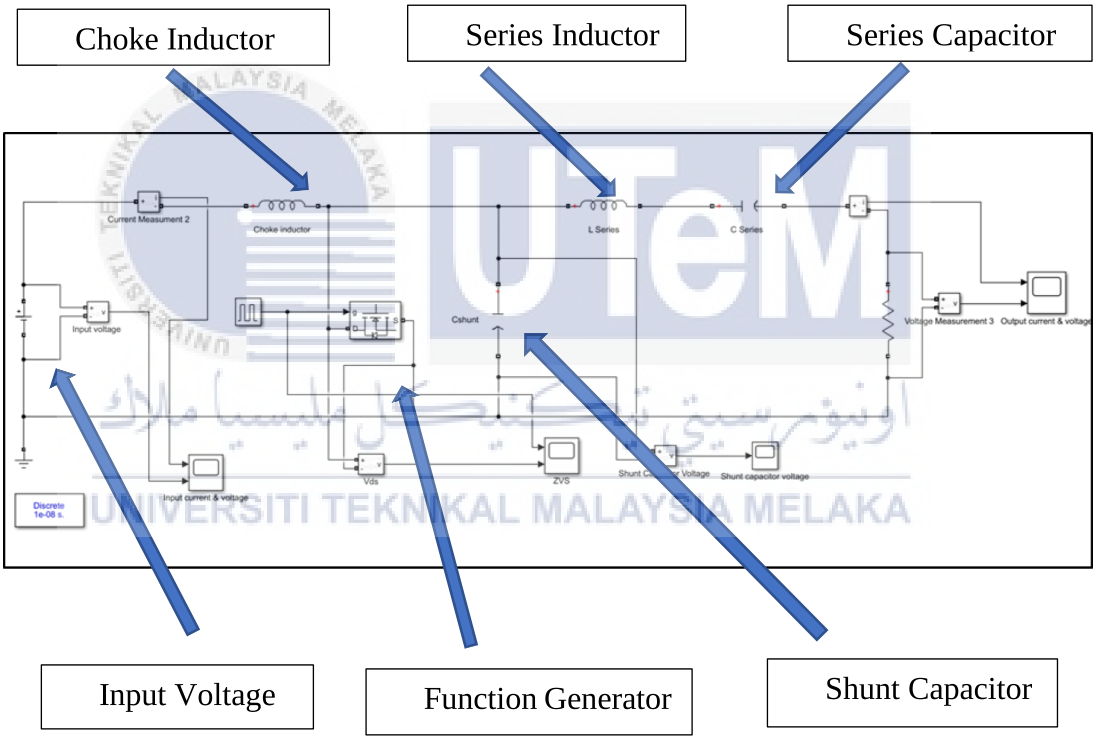

Figure 4.1: Basic simulation circuit using Simulink

For the evaluation of system performance, the values that can be analyze are:

(1) **Zero voltage switching, ZVS**
(2) **Power input, Pi**
(3) **Power output, Po**
(4) **Efficiency**

4.2.1 Class E ZVS + 470 Ohm

As Figure 4.2 shown below, a 470 Ohm resistor is added to Class E ZVS inverter as a load.

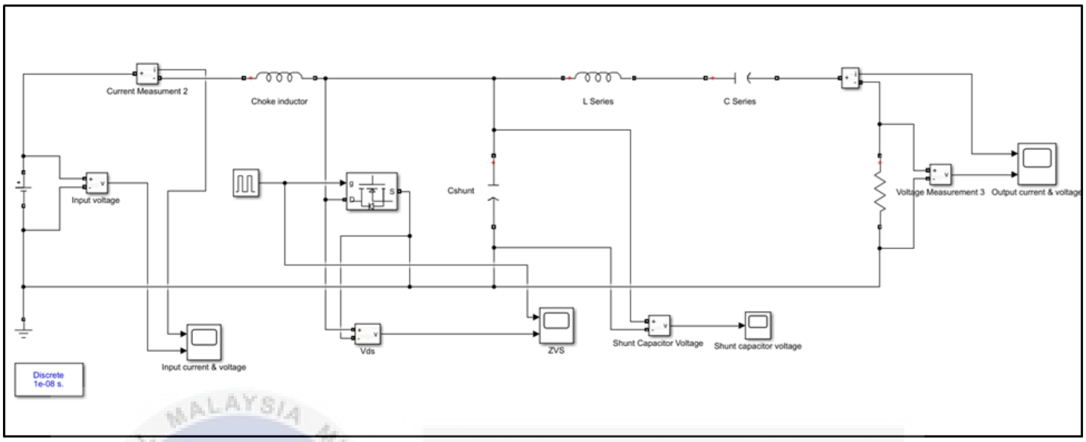

Figure 4.2: Simulation circuit of Class E ZVS + 470 Ohm

The following values in Table 4.1 are represent the values of each component and equipment being set during simulation of Class E + 470 Ohm.

Table 4.1: Class E ZVS + 470 Ohm simulation values

Parameter	Value
Frequency, f	39.8 kHz
Input voltage, Vin	23.88 V
Choke inductor, Lf	82 mH
Series inductor, L	18.2 mH
Shunt capacitor, Cp	1.75 nF
Series capacitor, C	1.0 nF
Resistor, R	470 Ohm

The Figure 4.3 shows the ZVS waveform which is generate by MATLAB simulation. Based on Figure 4.3, the zero-voltage-switching does not overlap to each other, which mean that almost zero switching losses.

- ZVS

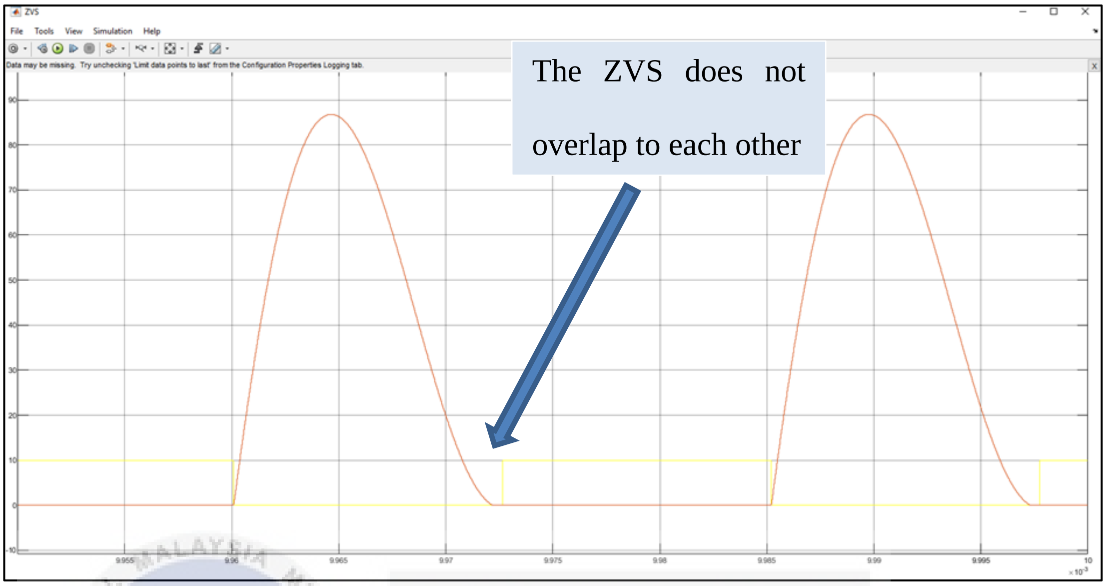

Figure 4.3: ZVS for Class E ZVS + 470 Ohm

- **Power input, Pi**

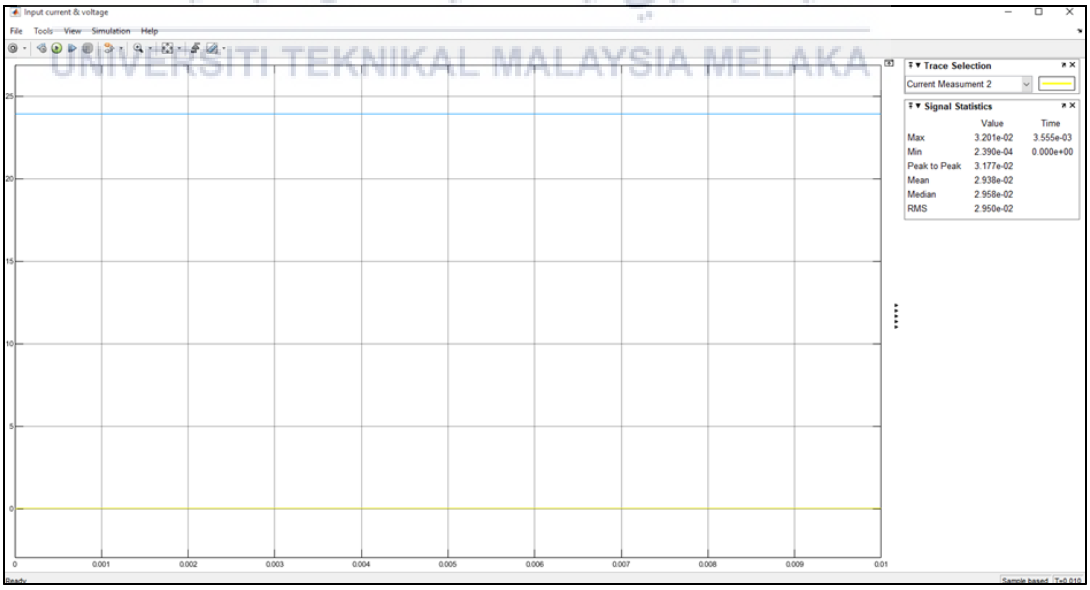

Figure 4.4: Input of current and voltage for Class E ZVS + 470 Ohm

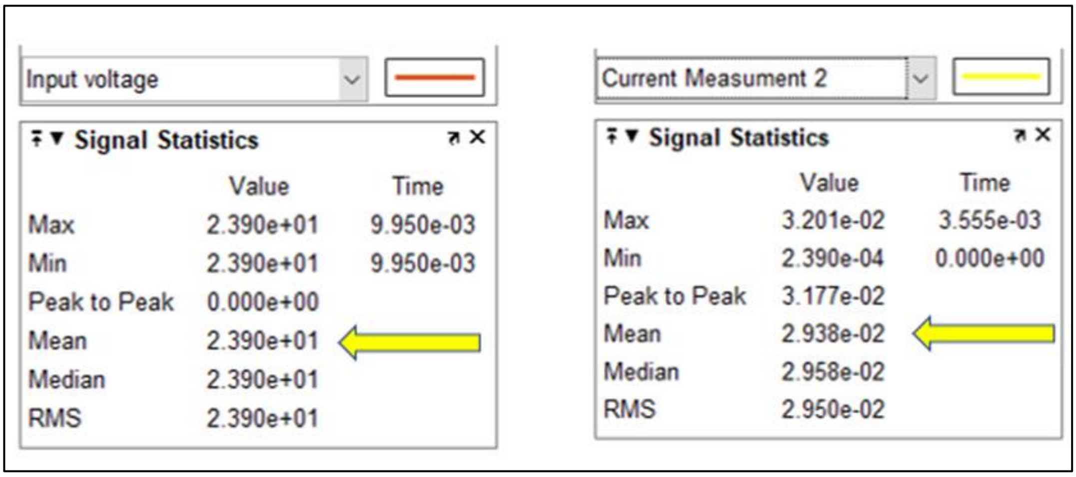

Figure 4.5: Mean input current and voltage for Class E ZVS + 470 Ohm

Power input can be calculated as:

Power input, Pi = current, I x voltage, V (W)

By using above equation and mean value from the figure 4.6:

Power input, Pi = 23.9 V x 0.02938 A= 0.70 W

- **Power output, Po**

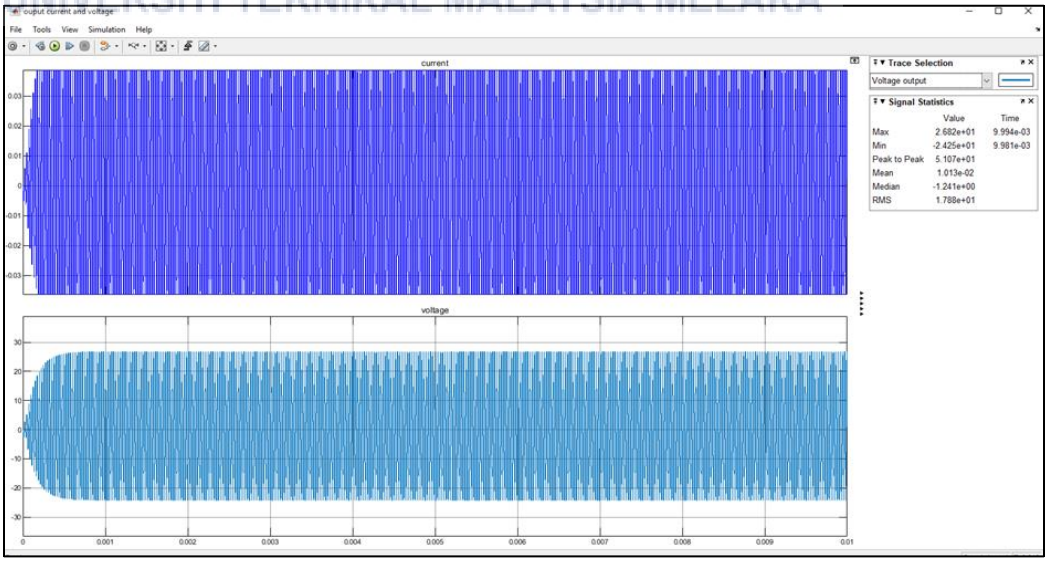

Figure 4.6: Output of current and voltage for Class E ZVS + 470 Ohm

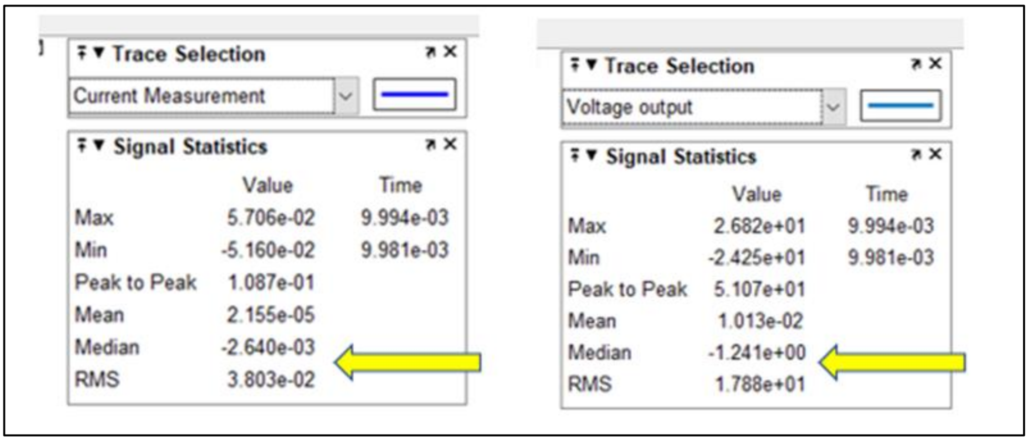

Figure 4.7: RMS output current and voltage for Class E ZVS + 470 Ohm

Power input, Po = $\frac{Vrms^2}{R}$

By using (22) and RMS value from the figure:

Power output, Po = $\frac{18.05^2 V}{470\Omega} = 0.69\ W$

- Efficiency

The efficiency of the system can be calculated as:

Efficiency = $\frac{Power\ output, Po}{Power\ input, Pi}\ x\ 100\%$

$= \frac{0.69W}{0.70W}\ x\ 100\% = 98.57\%$

4.2.2 Class E + Ultrasonic transducer

As Figure 4.8 depicts below, Class E ZVS inverter is combined with an ultrasonic transducer. The ultrasonic transducer is placed at the end of the circuit in parallel position replaced the 470 Ohm resistor.

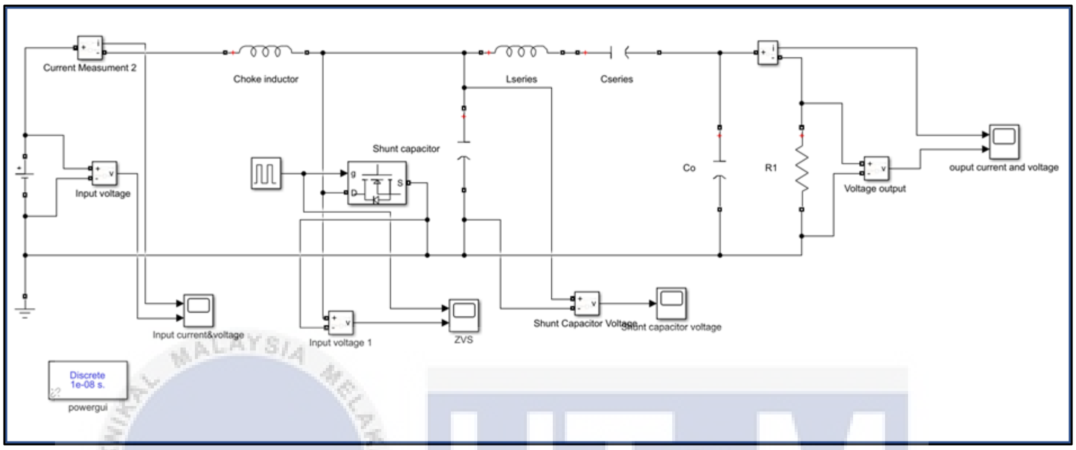

Figure 4.8: Simulation circuit of Class E + Ultrasonic transducer

The following values in Table 4.2 are represent the values of each component and equipment being set during simulation of Class E + Ultrasonic transducer. The 470 Ohm resistor is replaced by the built-in internal values of the ultrasonic transducer.

Table 4.2: Class E + Ultrasonic transducer simulation values

Parameter	Value
Frequency, f	39.8 kHz
Choke inductor, Lf	18.2 mH
Series inductor, L	82 mH
Shunt capacitor, Cp	1.75 nF
Series capacitor, C	1.0 nF
PZT capacitor, C0	1.94 nF
PZT resistor, R1	482.36 Ohm

- ZVS

The Figure 4.9 shows the waveform of Class E + ultrasonic transducer. This waveform is different with Class E + 470 Ohm as shown in Figure 4.9 because it fails to achieve the condition ZVS when merge with ultrasonic transducer. There is overlapping between VGS and VDS waveform where it causes the losses. It is predicted as in theory [7] ZVS will fail to achieve when involve with complex load circuit.

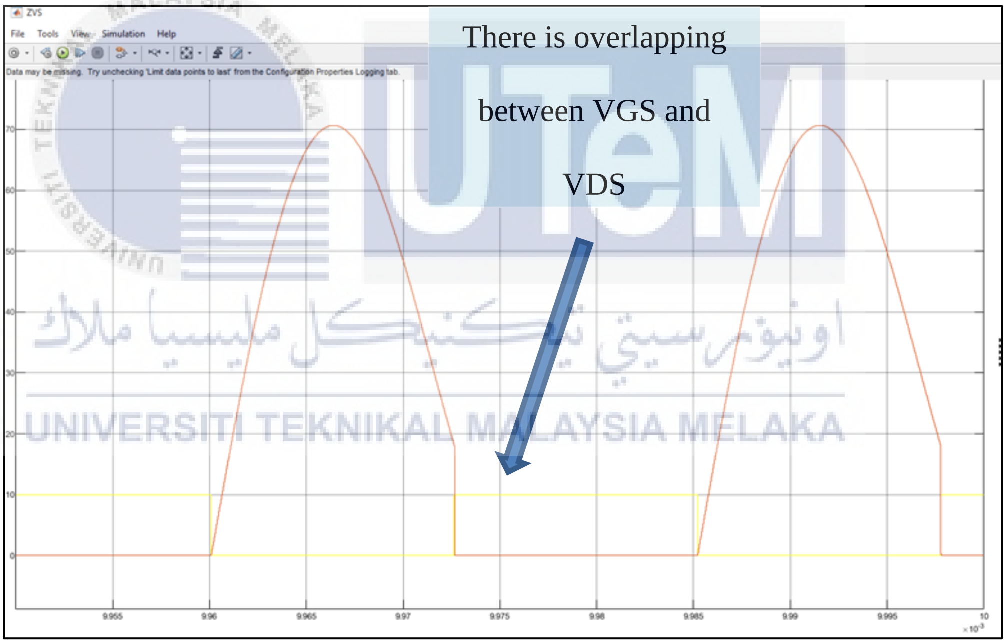

Figure 4.9: ZVS for Class E + Ultrasonic transducer

- **Power input, Pi.**

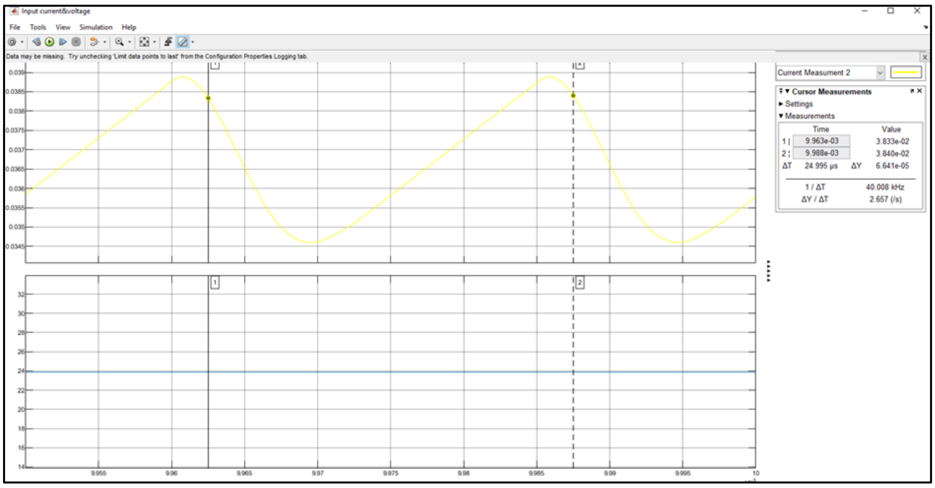

Figure 4.10: Input of current and voltage

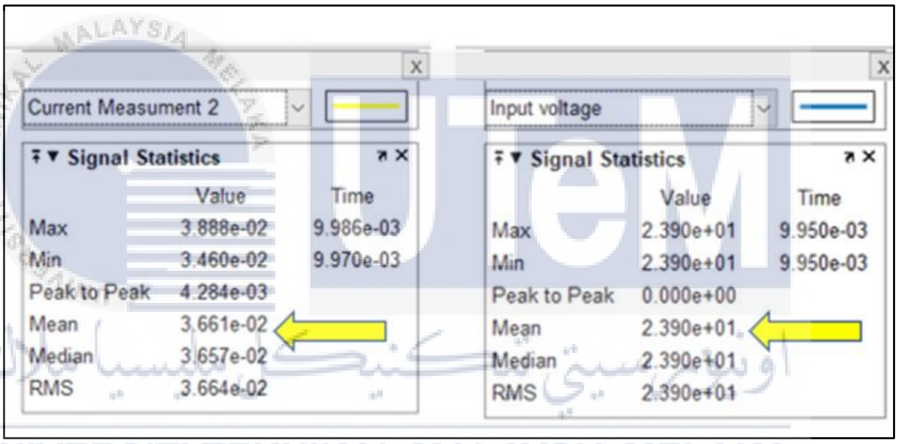

Figure 4.11: Mean input current and voltage for Class E ZVS + Ultrasonic transducer

By using (22) and the mean value:

Power input, Pi = 0.3661A X 23.9V = 0.874 W

- Power output, Po

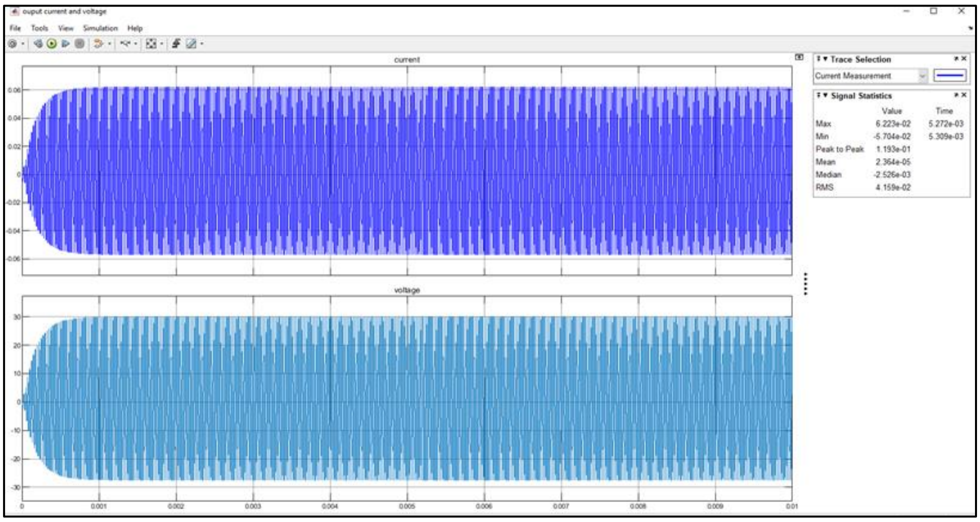

Figure 4.12: Output of current and voltage for Class E ZVS + Ultrasonic transducer

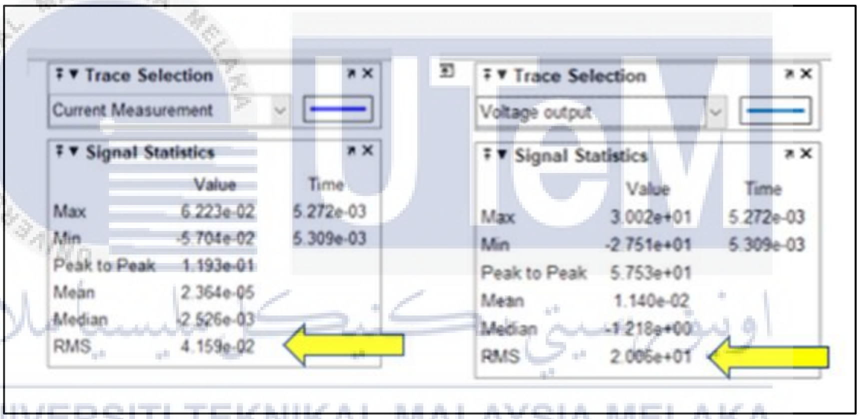

Figure 4.13: RMS output current and voltage for Class E ZVS + Ultrasonic transducer

By using (22) and the RMS value:

Power output, Po = 0.04159A X 20.16V = 0.83 W

- Efficiency

By using (23) the efficiency is

Efficiency = $\frac{Po}{Pi} = \frac{0.83W}{0.874W}$ X 100% = 95 %

Hence, when the impedance variation of the Class E ZVS combined with ultrasonic transducer, the performance of efficiency of the system such as ZVS, power output and the efficiency of the system are degraded. Therefore, this circuit design needs impedance matching which is important to achieve ZVS and increase the performance of the system.

4.2.3 Class E + Ultrasonic transducer + Impedance matching π1a

As Figure 4.1.1 depicts, an impedance matching π1a is added in the circuit. The π1a capacitor is placed in series in the circuit. Basically, the series capacitor, C is replaced with π1a capacitor, C1 to balance the network design.

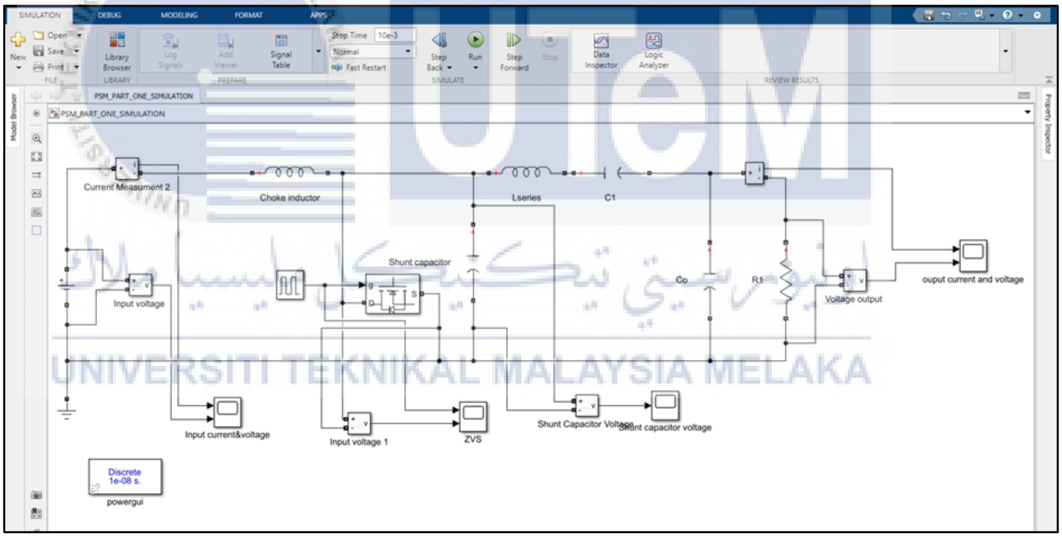

Figure 4.14: Simulation circuit of Class E + Ultrasonic Transducer + impedance matching π1a

The following values in Table 3 are represent the values of each component and equipment being set during simulation of Class E + Ultrasonic Transducer + impedance matching π1a. The series π1a capacitor, C1 is added to simulation network design.

Table 4.3: Class E ZVS + Ultrasonic transducer + π1a simulation values

Parameter	Value
Frequency, f	39.8 kHz
Input voltage, Vin	23.9 V
Choke inductor, Lf	82 mH
Series inductor, L	18.2 mH
Shunt capacitor, Cp	1.75 nF
PZT capacitor, C0	1.94 nF
PZT resistor, R1	482.36 Ohm
Series π1a capacitor, C1	52.40 nF

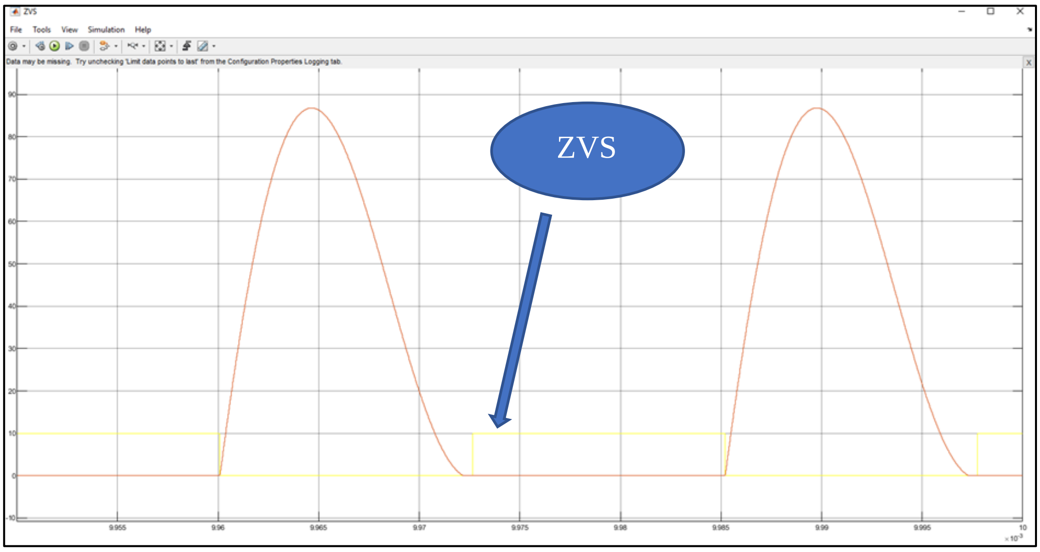

Figure 4.15: ZVS for Class E + Ultrasonic transducer + impedance matching $\pi 1a$

- Power input, Pi

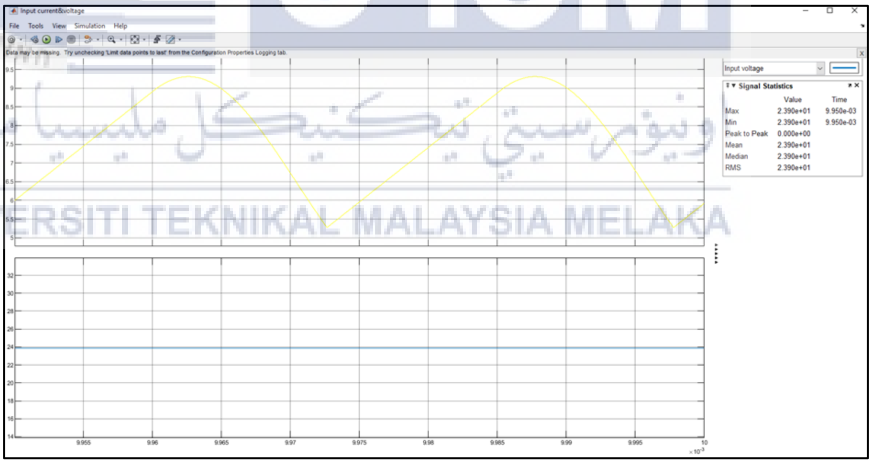

Figure 4.16: Input of current and voltage for Class E + Ultrasonic transducer + impedance matching π1a

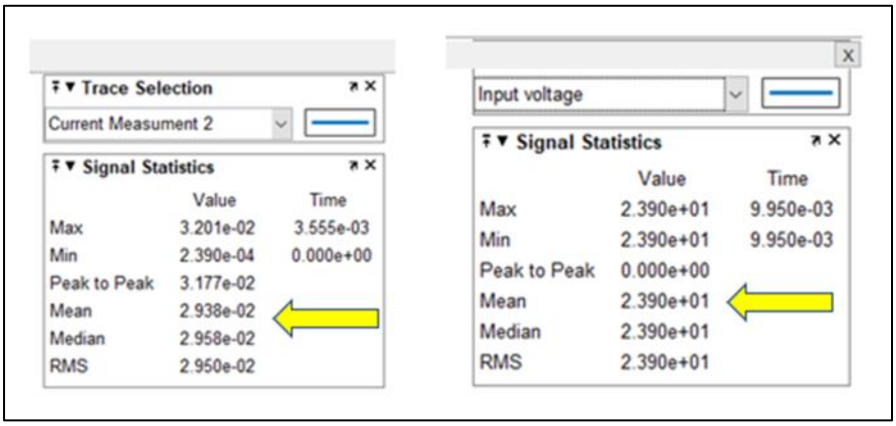

Figure 4.17: Mean input current and voltage for Class E ZVS + Ultrasonic transducer + impedance matching π1a

Power input can be calculated as:

Power input, Pi = current, I x voltage, V (W)

Power input, Pi = 0.02938A X 23.9V = 0.702 W

- **Power output, Po**

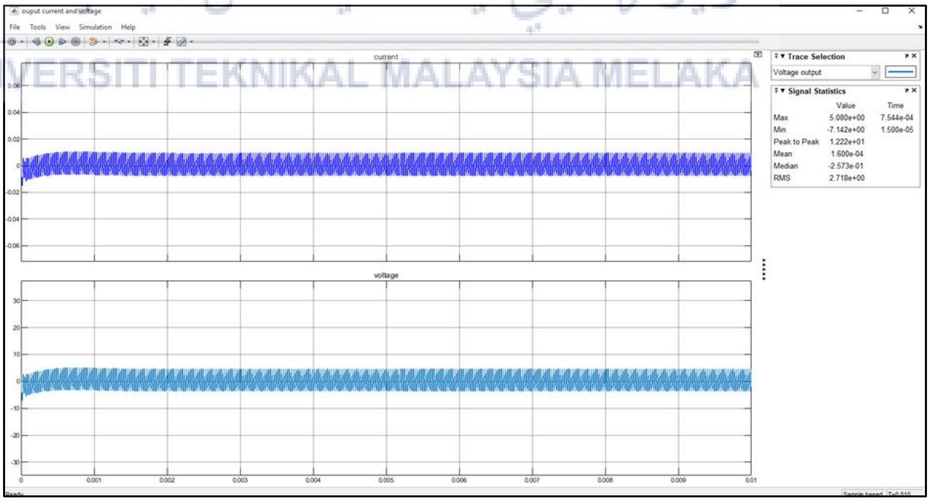

Figure 4.18: Output of current and voltage for Class E ZVS + Ultrasonic transducer + impedance matching π1a

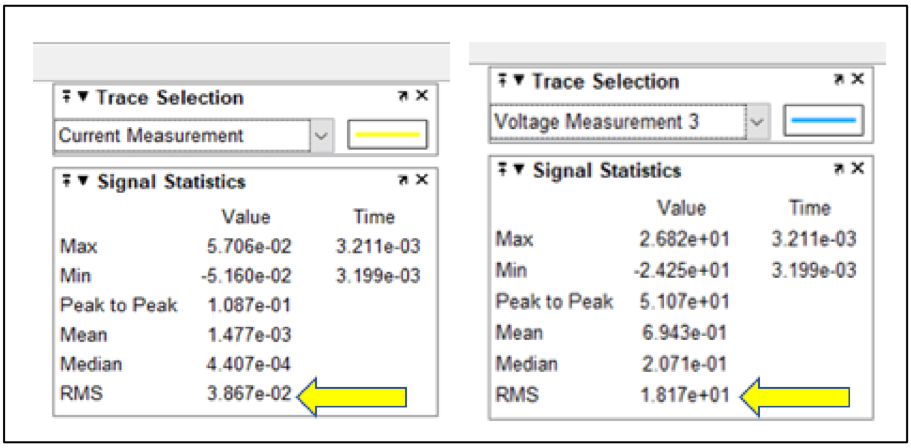

Figure 4.19: RMS output current and voltage for Class E ZVS+ Ultrasonic transducer + impedance matching π1a

By using (22) and the RMS value,

Power output, Po = 0.03867A X 18.17V = 0.70W

- Efficiency

By using (23), the efficiency is

Efficiency = $\frac{Po}{Pi} = \frac{0.702W}{0.70W}\ X\ 100\% = 100\%$

4.3 Comparison in simulation result

According Table 4.4 below, the integration between Class E ZVS and Ultrasonic transducer has lowered the total efficiency of the system to 95%. Therefore, the most suitable impedance matching π1a was chosen to overcome this issue. This integration of Class E ZVS inverter was designed so that the performance of efficiency of the system will increase. Based on their simulation, the power input and power output obtained almost the same value which result in high percentage of total efficiency, which is 100%.

Table 4.4: Overall result in simulation

	Class E + 470 Ω	Class E + Ultrasonic transducer	Class E + Ultrasonic transducer + impedance matching π1a
Parameter	Values		
Frequency, f	39.8 kHz	39.8 kHz	39.8 kHz
Input voltage, Vi	23.9 V	23.9 V	23.9 V
Input current, Ii	29.38 mA	36.61 mA	29.38 mA
Output voltage, Vo	17.88 V	20.06 V	18.17 V
Output current, Io	38.03 mA	41.59 mA	38.67 A
Power input, Pi	0.7 W	0.874 W	0.702 W
Power output, Po	0.69 W	0.83 W	0.70 W
Total efficiency (%)	98.57 %	95 %	100%

4.4 Analysis of Frequency Variations and Load Variations versus Power

To design Class E ZVS for the use of ultrasonic transducers, the standard procedure is to use the real value of impedance which is 470 Ohm, which single resistor component is applied. The need for this real value of impedance is to qualify to use Class E which requires a purely resistive load. Class E requires purely resistive load to produce maximum efficiency of dc to ac conversion. In addition, this is to facilitate the work of calculations and simulations.

However, to see the practical effect, an actual ultrasonic air transducer which contains a complex impedance value (482.36+jX Ohm) is used. So, for R = 470 Ohm it can be known as purely resistive load. For R = 482.36 Ohm is an actual ultrasonic air transducer, with complex impedance load.

According Figure 4.20 shown below, the graph simulation of class E with a real value impedance R = 470 Ohm was obtained using Microsoft Excel. The value of frequency is varied so that the power can be determined. From the graph, the zero-voltage switching condition is achieved during frequency at 39.8kHz and generates a 0.50 W of power.

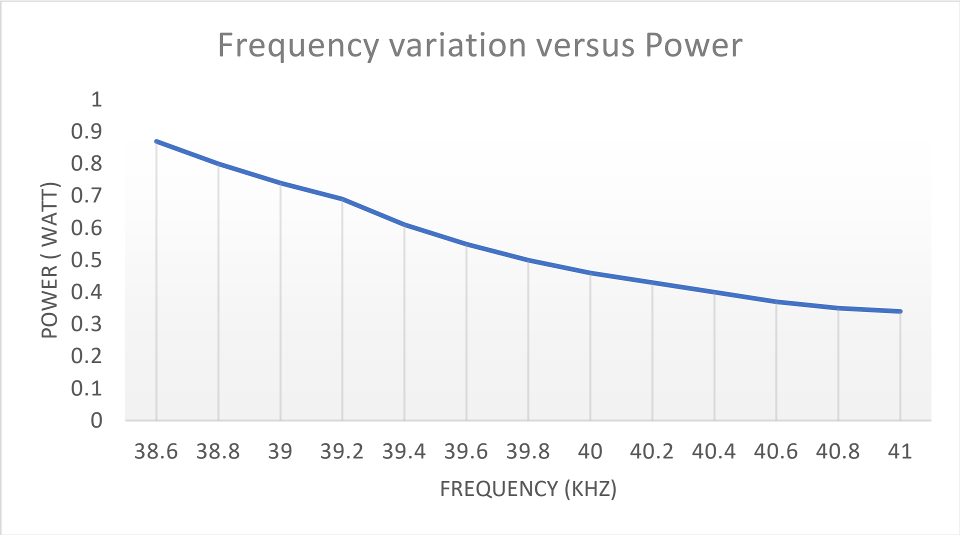

Figure 4.20: Graph simulation of frequency variation versus power

Table 4.5 illustrates the value of frequency and power after simulation.

Table 4.5: Value of frequency and power for R = 470 Ω

Frequency (Hz)	Power (Watt)
38.6k	0.87
38.8k	0.80
39.0k	0.74
39.2k	0.69
39.4k	0.61
39.6k	0.55
39.8k	0.50
40.0k	0.46
40.2k	0.43
40.4k	0.40
40.6k	0.37

40.8k	0.35
41.0k	0.34

According to Figure 4.21, the graph simulation of load variation versus power was obtained using Microsoft Excel. The value of load is varied to determine its power. Therefore, the zero-voltage switching condition is achieved during R = 470 Ohm and generates a 0.69 W of power.

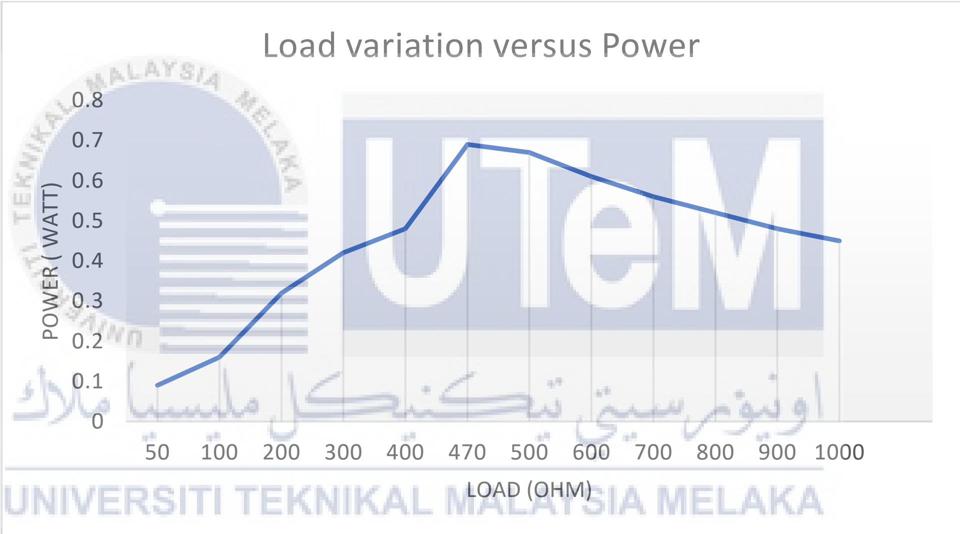

Figure 4.21: Graph simulation of load variation versus power

Table 4.6 illustrates the value of load and power after simulation.

Table 4.6: Value of load and power for frequency = 39.8 kHz

Load (Ω)	Power (Watt)
50	0.09
100	0.16
200	0.32

300	0.42
400	0.48
470	0.69
500	0.67
600	0.61
700	0.56
800	0.52
900	0.48
1000	0.45

According to Figure 4.22 below, the graph simulation of class E ZVS with a real value impedance R = 482.36 Ohm was obtained using Microsoft Excel. The value of frequency is varied and contains a complex impedance value of R = 482.36 Ohm so that the power can be determined. Therefore, the zero-voltage switching condition is achieved at frequency 39.8 kHz and generates a 0.70 W of power. The value of frequency is varied and contains a complex impedance value of R = 482.36 Ohm so that the power can be determined.

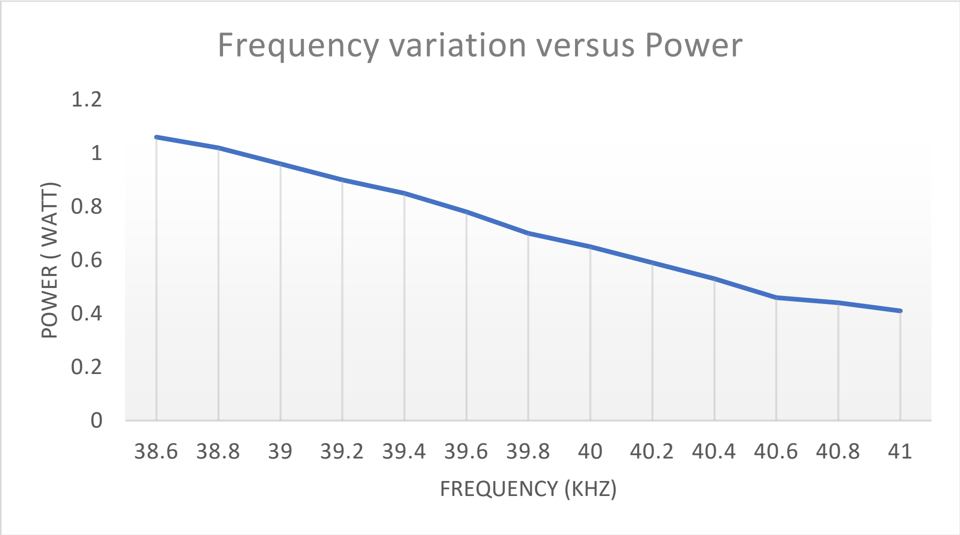

Figure 4.22: Graph simulation of frequency variation versus power

Table 4.7 illustrates the value of frequency and power after simulation.

Table 4.7: Value of frequency and power after simulation for R = 482.36 Ω

Frequency (Hz)	Power (Watt)
38.6k	1.06
38.8k	1.02
39.0k	0.96
39.2k	0.90
39.4k	0.84
39.6k	0.78
39.8k	0.70
40.0k	0.65
40.2k	0.59
40.4k	0.53
40.6k	0.44

40.8k	0.445
41.0k	0.410

According to Figure 4.23, the graph simulation of load variation versus power was obtained using Microsoft Excel. The value of load is varied to determine its power. Therefore, the zero-voltage switching condition is achieved during R = 482.36 Ohm and generates a 0.71 W of power.

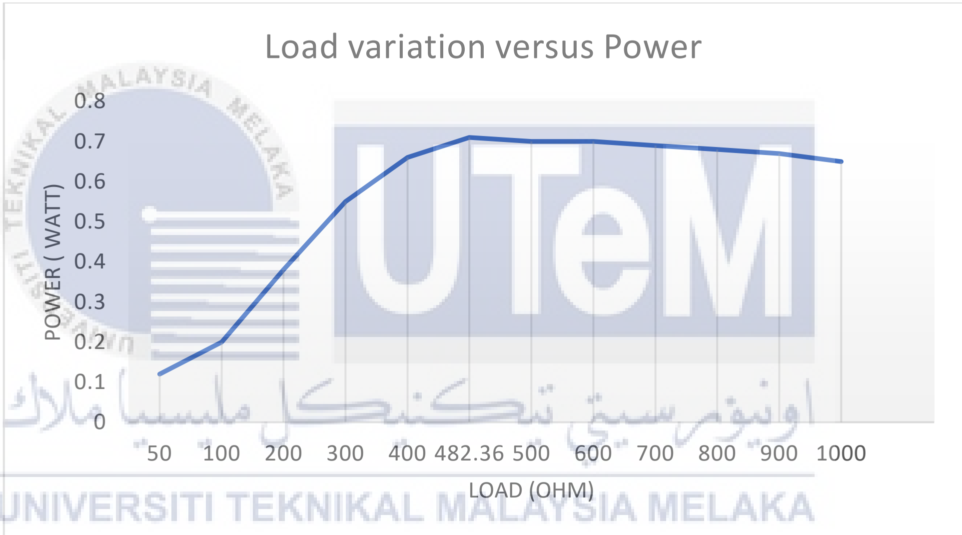

Figure 4.23: Graph simulation of load variation versus power

Table 4.8 illustrates the value of load and power after simulation.

Table 4.8: Value of load and power after simulation for f = 39.8 kHz

Load (Ω)	Power (Watt)
50	0.12
100	0.20
200	0.38

300	0.55
400	0.66
482.36	0.71
500	0.70
600	0.70
700	0.69
800	0.68
900	0.67
1000	0.65

Based on the simulations that has been done, it can be concluded that the circuit operation designed have to meet the needs of zero-voltage switching for the purpose of high efficiency inverter although the value of output is higher.

4.5 Project Sustainability

The word sustainability gives the meaning of the ability of future generations to meet their own needs by maintaining or improving life quality. Frequently, the sustainability can be categorized into environmental, social and economic. As for acoustic energy transfer system (AET), this project can be categorized into environmental and economic sustain section. This project is relevant to environmental sustain because it intends to utilize noise through the use of piezoelectric materials as a method of conversion to produce green sustainable electric energy that may be useful to reduce the non-renewable energy. As a kind of mechanical energy, sound can be transformed to electric energy in a various way, such as heating, diaphragm use, and the use of piezoelectric materials. Because of the technology available, the researchers decided to perform a study to aid in recycling and develop a gadget that can assist people in their daily lives as long as noise or sound energy exists. Previous research has demonstrated that sound waves of various types of acoustics, sound pressure levels, and frequencies have an effect on growth for a certain exposure time.

Since AET is a new form of contactless energy transmission that uses sound waves to wirelessly convey energy, there are no cable or wire needed for the energy system. Hence, this is economic sustain because less material is used to build the system. The metal that made of copper which are used to make electric wire will extinct in future since it is limited natural resources. Hence, everyone can get clean and green wireless power. It would be beneficial if in future, wireless power transfer technology to transfer power from power station to everywhere without the need of wire can be implemented. Moreover, the AET frequencies employed are low, reduce loses and simplifying the circuit.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1 Conclusion

To conclude, the technology of wireless power system had brought the innovation to world technology. Most likely, some of the people may prefer to stick with the old method of WPT. However, soon enough they will realize that this innovation is beneficial for society as a whole. Elimination of wire and cable can reduce hazard and help to get green environment in present and in future. As a prove, this project managed to achieve three of our objectives which are to design an efficient Acoustic Energy Transfer system using Class E ZVS inverter at the transmitter unit in order to reduce or eliminate switching amplifier losses. Due to this action, the efficiency of the system is 95.87% which prove that AET system met the requirement benchmark 80% of total efficiency. In addition, the second objective is to design impedance matching circuit to overcome the impedance mismatch between the purely resistive load and ultrasonic transducer, thus high efficiency of Class E ZVS can be maintained. As the investigation and evaluation done in MATLAB/Simulink, the most suitable impedance matching chosen is π1a. Moreover, last objective is to design the power efficiency of Acoustic Energy Transfer system at the receiver unit for power transmitter efficiency. Consequently, the efficiency of the system is 100%.

5.2 Recommendation for future work

The AET system is one of the emerging technologies which many different research, test and experiments that has been left for future due to lack of funding and time. Although this project is able to describe the power conversion and power transfer, there are still have limitation and the weakness of this project which prove that the following part needs a recommendation in next future work.

First and foremost, the design for AET circuit can develop the circuit design by using another type of MOSFET model, which to use IC power driver to power up MOSFET. Instead, replace with TC4422A IC driver with pulse width modulation, PWM. Besides, it is recommended to develop the AET system with different values of input voltage and frequency.

Next, by define the compatible and closes values of the assembly component in the circuit, it may increase the performance of the system much better. Reducing the stack of component can prevent efficiency losses.

Lastly, the scope of analysis can be extended by considering different types of variable that can be used to achieve an excellent ZVS and high efficiency.

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