DESIGN AND SIMULATION OF WIRELESS POWER TRANSFER USING CAPACITIVE TECHNIQUE

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FACULTY OF ENGINEERING
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DESIGN AND SIMULATION OF CAPACITIVE POWER TRANSFER USING CAPACITIVE TECHNIQUE

ABSTRACT

The development of wireless power transfer technology in various applications has getting widely nowadays. Wireless energy can be transferred by inductive power transfer (IPT) through electric field and capacitive power transfer (CPT) through magnetic field. Most of the applications has been utilized the technology of IPT for transfering power wirelessly, but in this project, a new method of CPT will be used for the purposed of biomedical implantable application which is implantable pulse generator (IPG). In terms of biomedical implantable application, CPT has some extra advantages compared to the traditional method of IPT such as the circuit structured will be more simple and convenient as the receiver circuit for this application will be implanted inside of the human body. Besides, the main reasons to use CPT technique are CPT has low electromagnetic interference (EMI), power losses is low and the ability of CPT to transfer power across metal barriers. In this project, the CPT technique has been applied through class E inverter circuit. A 12V DC source has been supplied to the inverter circuit that will operate at 1 MHz frequency to deliver 2 Watt of power to the load. The effects of higher load resistance values will be analyzed through the class E circuit system and the improvement of class E circuit by impedance matching will be applied. Overall, class E circuit is able to achieve ZVS waveform and efficiency of 95.38% by Matlab simulation for the resistance load value that have been designed theoretically. As the resistance value is set to some higher random values, class E circuit could only achieve ZVS and efficiency of more than 90% with the improvement by impedance matching circuit.

Keywords: capacitive power transfer, class E circuit, impedance matching.

REKA BENTUK DAN SIMULASI PERALIHAN TENAGA KAPASITIF MENGGUNAKAN TEKNIK KAPASITIF

ABSTRAK

Perkembangan teknologi pemindahan kuasa tanpa wayar dalam pelbagai aplikasi kini semakin meluas. Tenaga tanpa wayar dapat dipindahkan melalui pemindahan kuasa induktif (IPT) melalui medan elektrik dan pemindahan kuasa kapasitif (CPT) melalui medan magnet. Sebilangan besar aplikasi telah menggunakan teknologi IPT untuk memindahkan tenaga tanpa wayar, tetapi dalam projek ini, kaedah CPT yang baru akan digunakan untuk aplikasi implan bioperubatan iaitu generator nadi implan (IPG). Dari sudut aplikasi implan bioperubatan, CPT mempunyai beberapa kelebihan tambahan berbanding kaedah tradisional IPT seperti struktur litar yang lebih mudah dan sesuai kerana litar penerima untuk aplikasi ini akan ditanamkan di dalam tubuh manusia. Selain itu, alasan utama untuk menggunakan teknik CPT adalah CPT mempunyai gangguan elektromagnetik yang rendah (EMI), kehilangan tenaga rendah dan kemampuan CPT untuk memindahkan daya melintasi halangan logam. Dalam projek ini, teknik CPT telah diaplikasikan melalui litar penyongsang kelas E. Sumber 12V DC telah dibekalkan ke litar penyongsang yang akan beroperasi pada frekuensi 1 MHz untuk menyalurkan 2 Watt kuasa kepada beban. Kesan nilai rintangan beban yang lebih tinggi akan dianalisis melalui sistem litar kelas E dan penambahbaikan litar kelas E melalui litar impedans akan dilaksanakan. Secara keseluruhan, litar kelas E dapat mencapai bentuk gelombang ZVS dan kecekapan 95.38% melalui simulasi Matlab untuk nilai beban rintangan yang telah dikira secara teori. Apabila nilai rintangan ditetapkan ke beberapa nilai yang lebih tinggi secara rawak, litar kelas E hanya dapat mencapai ZVS dan kecekapan lebih dari 90% melalui penambahbaikan litar impedans.

Kata kunci: peralihan tenaga kapasitif, litar kelas E, litar impedans

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LIST OF SYMBOLS AND ABBREVIATIONS

WPT : Wireless power transfer

CPT : Capacitive power transfer

IPT : Inductive power transfer

IPG : Implantable pulse generator

APT : Acoustic Power Transfer

LPT : Light Power Transfer

MPT : Microwave Power Transfer

SAR : Specific Absorption Rate

CHAPTER 1: INTRODUCTION

1.1 Project background

Wireless power transfer (WPT) can be created through electric, electromagnetic pairing or magnetic by the power transmission without any wires being connected (Mohammed, Ramasamy, & Shanmuganantham, 2010). Electrical gadgets are mostly connected by wires and these could lead to impractical, troublesome and unsafe issues. The innovation of WPT somehow can overcome issues involved in connecting wires. The basic concept of WPT system are shown in Figure 1.1 in which the transmitter side will convert DC to AC energy and the receiver side will convert AC to DC energy. The primary and the secondary side is not connected by any wires and will be separated by an energy transmission medium. The secondary side will then supplied a DC energy by rectifier according to the requirement parameters of the load (Yusop, Saat, Nguang, Husin, & Ghani, 2016).

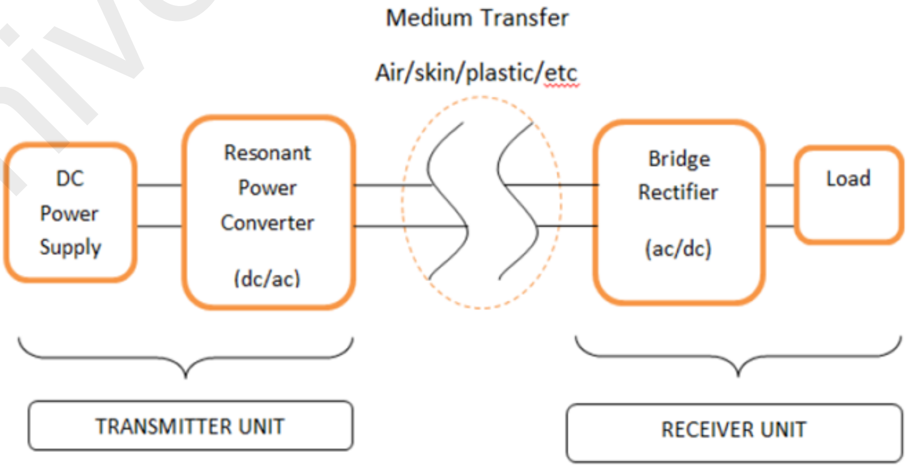


Figure 1.1: Basic block diagram of WPT system

Near-field and far-field were two major techniques of transferring power wirelessly. Radiative or far-field method transfer power using beams by electromagnetic radiation in corresponds towards laser beams or microwaves (Roes, Duarte, Hendrix, & Lomonova, 2013). Longer range of transmitted power can be achieved by this far-field method but the receiver must be targeted. Some of the applications that were using this method are wireless aircraft drone and satellites power by solar energy (Roes et al., 2013).

In near field methods, power can be transferred by coils of wires in inductive coupler through magnetic fields or via capacitive plates coupling that transfer power through electric fields. As for IPT (inductive power transfer), these two sides of coils which are transmitter and receiver will operates like a transformer. Magnetic field (B) that is oscillating will be produced by the alternating current (AC) from the transmitter coil. Alternating current will then be generated at the receiver side as the magnetic field flows over the receiver coil and an alternating EMF (voltage) will be prompted according to the Faraday's law of induction. The load may be powered up directly by the AC current or need to be rectified by the rectifier if the load need a DC supply.

On the other hand, capacitive coupling is the conjugate of inductive coupling where the energy transmission occurred through the electrodes like metal plates by the electric fields. The couple plates; transmitter and receiver plates will act like a capacitor where there is a dielectric space between them. The transmitter plate will generate an alternating voltage and induces an alternating potential by electrostatic induction on the receiver plate. The alternating current will flow into the rectifier circuit which will supply the load with the DC current.

The uses of wireless technology have been developing in many applications and gave a lot of benefits towards human nowadays. One of the application that is developing widely by WPT is in biomedical implantable device. In this project, the design of WPT by class E inverter will be applied for implantable pulse generator (IPG) part in spinal cord stimulator (SCS) device as illustrated in Figure 1.2. One of the most growing advances in the treatment of chronic pain is the spinal cord stimulator (SCS). Over four decades it has been used to treat persistent neuropathic symptoms that have failed to respond to other therapies (Jeon, 2012). Spinal cord stimulators consist of thin wires (the electrodes) and a small, pacemaker-like battery pack (the implantable pulse generator). The electrodes are placed between the spinal cord and the generator is placed under the skin, usually near the buttocks or abdomen. Wireless power transfer using CPT (capacitive power transfer) technique will be design for the rechargeable implantable pulse generator (IPG) part of this device with 2 Watt of power requirement to operate (Agarwal, Jegadeesan, Guo, & Thakor, 2017).

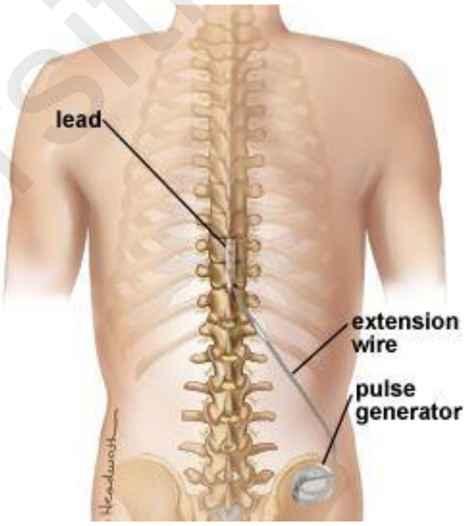


Figure 1.2 : Implantable pulse generator device

In CPT, the complexity of implanted electronics can be reduces as the development of CPT system will retain compensation and tuning circuitry at the transmitting side which is outside of the body. In addition, CPT are using electric fields that are well bounded with the capacitor plates so it has better EMI performance and minimal effects when surrounded by metal objects compared to IPT that are using magnetic fields (Takhti, Asgarian, & Sodagar, 2011). Even though IPT is the oldest and most widely used wireless power technology in commercial products, CPT have more benefits than IPT for the implantable biomedical devices. Hence in this project, the rechargeable implantable pulse generator will be designed using CPT technique.

As the development of the CPT system for the implanted device as shown in Figure 1.3, two parallel conductive plate will act like a capacitor and the gap between the plates will be separated by skin and tissue that act like a dielectric material of the capacitor. D is the distance separation between the gap. RX receiver plate will be implanted inside of the patient's body with the biomedical device while TX transmitter plate will be placed outside of the body on the skin surface with the power source when the charging process occurred. The conductive plates are aligned so that the power is transferred at optimal condition.

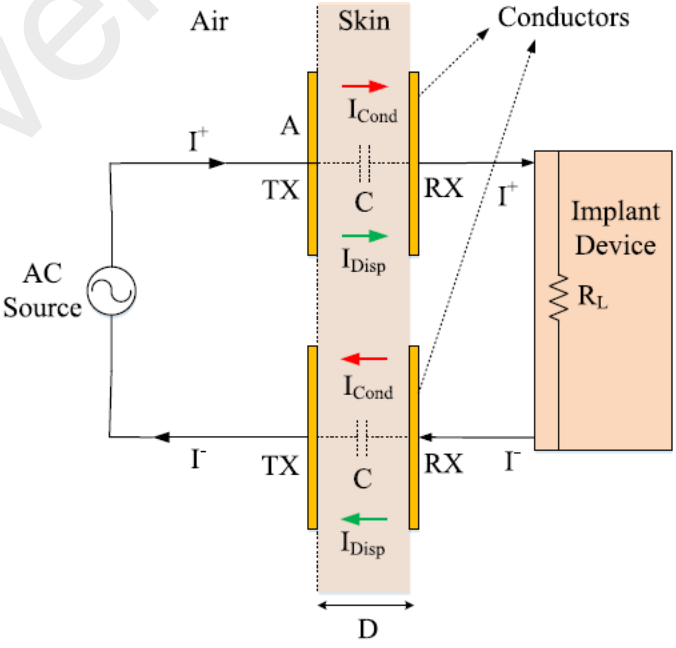


Figure 1.3: CPT system for biomedical implanted device

1.2 Problem statement

1.2.1 Limited battery life

A fully implantable pulse generator (IPG) with a battery inside and an IPG with a rechargeable battery that can be powered up by external supplied are two forms of IPG that are currently available. Non-rechargeable of fully implantable pulse generators can last up between 2 and 5 years of battery life with a regular use. An improved IPG device with a rechargeable power supply, on the other hand, could last 10 to 25 years (Jeon, 2012). As a result of its small size and ease of maintenance, the rechargeable IPG is gaining popularity.

Limited battery life can cause impracticality, health concerns, and expense of performing surgery on patients in order to replace the battery. Patients may have trauma as a result of the procedure. Charging of the implantable device’s battery can be done without any wire connecting the internal and external circuitry on the patient’s body through the wireless technologies being developed. Therefore, the wireless power transfer (WPT) is proposed in this work to accommodate the issue.

1.2.2 Reduces EMI and power losses

The most popular and commonly used WPT is inductive power transfer (IPT) system. However, because magnetic field in inductive coupling is unable to penetrate through metal objects and can cause large eddy current losses, IPT is not suitable for transferring power across metal barriers or in metal surrounding environments. Capacitive power (CPT) technology, on the other hand, offers a new method which employs electric field rather than magnetic field to achieve contactless power transfer so that metal barriers and surroundings become less a concern. CPT also has the potential to reduce power losses and EMI (Electromagnetic

Interference) since the power is transferred by electric field (Hu & Liu, 2009). Electromagnetic interference (EMI) is still one of the most important problems associated with inductive links (Takhti et al., 2011). The capacitive coupling have found to have lower sensitivity of interference compared to inductive coupling (Erfani, Marefat, Sodagar, & Mohseni, 2017). Thus we can reduce these kinds of interferences by using capacitive coupling.

1.2.3 The design of Class E inverter and impedance matching circuit to improve power efficiency

A power amplifier is an electronic device to boost the electrical signal to adequate power levels suitable for wire or wireless transmission from the transmitter to the receiver. Typically, they work at relatively high power levels and hence are a major power consumer in the overall transmitter system. Important considerations in power amplification is power efficiency, power efficiency is one of the crucial factor in CPT system.

The type of class E is chosen because it offers an improvised medium of high-frequency, can produce higher efficiency for the output, has advantages in terms of simplicity, and it is a low-noise rectification system (Rahman & Saat, 2016). The most vital lead of class E power amplifier is its potential to provide high efficiency which is approaching 100% efficiency at 180 degree conduction angle other than conventional class B or class C. The class E amplifier is basically a magnification of class D, contributing more complex and better output filtering. Class E circuit will also have nearly 100% efficiency theoretically as the circuit satisfies zero voltage switching (ZVS) condition and have fixed load thus making them the most suitable inverter for WPT (Yusop, Saat, et al., 2016).

In addition, impedance matching has been implement in the Class E circuit in order to improve the maximum power transfer between the source and its load (Rahman, Saat, Yusop, Husin, & Aziz, 2017). The objective of the impedance matching network is to convert the load resistance or impedance into the impedance required to produce the desired output power Po at the specified supply voltage Vi and the operating frequency f (Kazimierczuk & Czarkowski, 2011).

1.3 Project objectives

There are three objectives of this project which are :

1) To design capacitive power transfer by implementing class E inverter circuit
2) To improve output power efficiency by designing impedance matching network in class E inverter circuit
3) To analyze the capacitive power transfer system performance by output power efficiency

1.4 Scope of project

The capacitive power transfer system will be designed using class E inverter circuit for the rechargeable implantable pulse generator (IPG) device that has been used in spinal cord stimulator (SCS). The output power that need to be delivered by the circuit designed is according to the IPG which is 2Watt. The design of the circuit will be started with theoretical calculation and then simulation of the circuit design in Matlab software. Practical part of the circuit design will not be covered in this project. 12V of DC power source will be supplied to the class E circuit at 1Mhz operating frequency. The system performance of class E inverter circuit simulation will be analyzed first, then the effects of variable load resistance will be investigated. The need of improvement by implement impedance matching circuit into the class E circuit in order to achieve high efficiency will be approached. The whole system performance of the circuit will then be analyzed by measuring the voltage, current, input power, output power and efficiency.

CHAPTER 2: LITERATURE REVIEW

2.1 Wireless Power Transfer (WPT)

The discussion about wireless power transmission as a contrasting option to transmission line power dissemination has been explored in the late of 19th century (Brown, 1996). The possibility of wireless power transmission has been theorized both by Heinrich Hertz and Nicola Tesla. In 1899, Tesla has revealed the powering of fluorescent lamps 25 miles away from the power source without utilizing wires (Brown, 1996). It was the first of public WPT showing to power a "typical" load between large capacitive plates (Dai & Ludois, 2015). Again, Tesla demonstrated electromagnetic induction through a separation and turned out to be more flexible for wireless power usage. The advancement of few far-field radiative procedures occurred and the inductive power transfer (IPT) methods by Tesla evolved in the era of 1900s (Nikola, 1897).

The cutting edge improvement of microwave power transmission which for some reasons overwhelms innovative work of wireless transmission today are much contributed by William C. Brown (Brown, 1996). In the mid-1960s, Brown created the rectenna which straight forwardly changes over microwaves the exclusively through microwaves. Notwithstanding these developments wireless power transmission has not been received for commercial utilize aside from the sole to DC current. He showed its capacity in 1964 by running a helicopter from exemption of pacemakers and electric toothbrush rechargers. Due to many promising applications appropriate for wireless power transmission, the study is still continuing.

A huge improvement have passed Wireless Power Transfer (WPT) technologies recently.Power source that transmit electrical energy without the presence of man-made conductors is called WPT. This technology expands the dependability and maintenance free process of frameworks in critical applications, for example multisensors, biomedicine, aviation, and robotics. There are various techniques being categorized depending on the medium utilized for power transfer such as capacitive-based WPT, light-based WPT, acoustic-based WPT and the commonly used method which is inductive-based WPT (Jegadeesan, Guo, & Je, 2013).

Figure 2.1 shows the basic concept of WPT block diagram. The transmitter unit consists of DC to AC resonant power converter that will receive DC power supply from the power source and then convert it into AC energy. This will allow the AC energy to be transferred from the primary medium of transmitter to the secondary medium of receiver. The primary side of the medium is not linked electrically to the secondary side of the medium. Rectifier will convert the AC energy into DC energy at the receiver unit to transmit power to the load at the specified requirements.

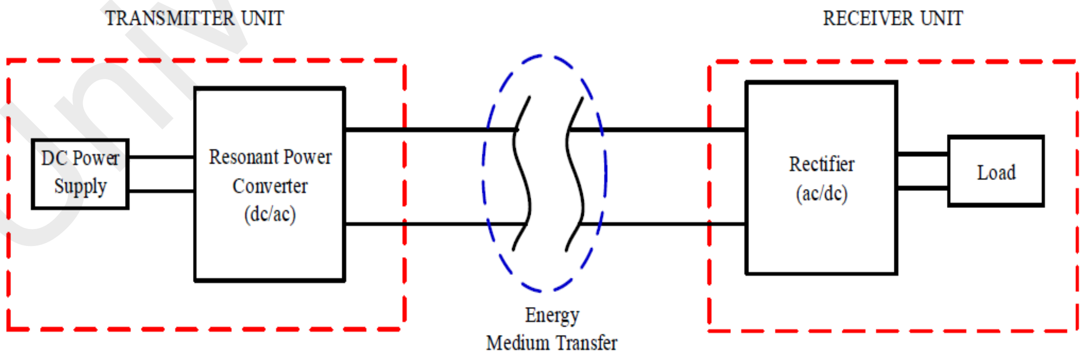


Figure 2.1: WPT basic block diagram

In general, WPT techniques can be categorized into two categories which are near-field and far-field. These categories are based on three important factors; the transmission distance from the transmitter to the receiver, the characteristics in the change of electromagnetic field and techniques in achieving WPT. In this chapter, the two classification will be disclosed thoroughly to be clearly understand about the variety of WPT techniques.

2.2 Near Field WPT

Near field WPT is defined as power transfer that is only capable to transfer power between medium in a closed range distance. These fields are non radiative, which means the energy remains within a short separation of the transmitter. In the event that there is no receiving device or absorbing material within their restricted range to "couple" to, no power leaves the transmitter. The range of these fields is short, and relies upon the size and shape of the "antenna" devices, which are normally coils of wire (Erfani et al., 2017). The word "antenna" is utilized freely here; it might b a coil of wire which produces a magnetic field or a metal plate which creates an electric field, or piezoelectric to generate vibration.

The fields, and consequently the power transmitted, decrease exponentially with distance, so if the separation between the two "antennas" Drange is substantially bigger than the diameter of the "antennas" Dant, inadequate power will be delivered (Haerinia, 2020). Thus, these methods cannot be utilized for long range power transmission. In near field methods, there are three sorts of wireless power transfer that we are going to discuss in this chapter which are Acoustic Power Transfer (APT), Inductive Power Transfer (IPT) and Capacitive Power Transfer (CPT).

2.2.1 Acoustic Power Transfer (APT)

A new rising technique for transferring power wirelessly is acoustic power transfer (APT) which abuses vibration or ultrasound waves (Zaid & Saat, 2014). APT is a new strategy of contactless energy transfer that uses acoustic coupling through ultrasonic propagation wave rather than electromagnetic fields to transfer energy. However, APT is still in its initial stages and has seen only bit advancement when contrasted with IPT (Zaid & Saat, 2014). APT system works based on sound waves or vibration and applied essentially by utilizing ultrasonic transducer. A usual acoustic energy system mainly comprises of essential and auxiliary unit where the two sides include ultrasonic piezoelectric transducer and isolated by a transmission medium as appeared in Figure 2.2.

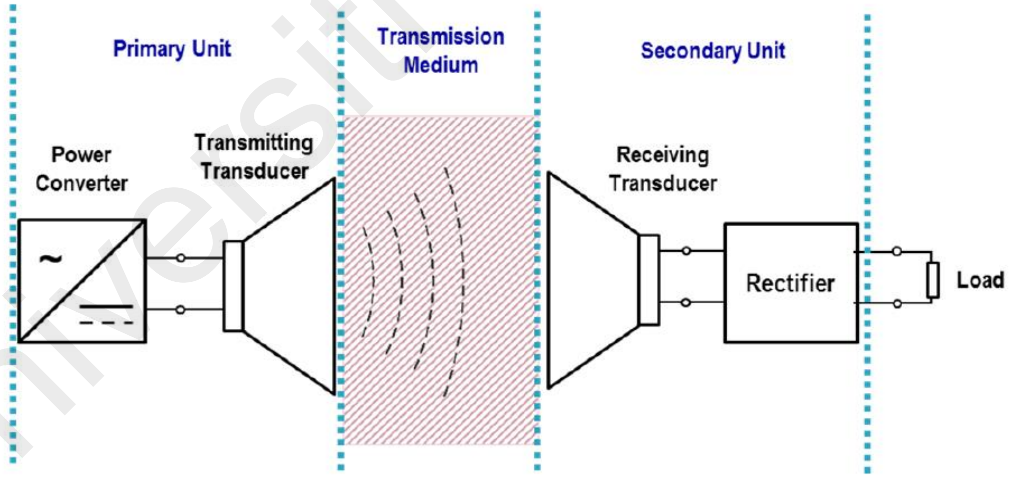


Figure 2.2: Basic diagram of APT system

The quantity of power required by the primary transducer is drive through the power converter at the primary unit. The primary transducer will change electrical energy into a pressure or acoustic wave. It creates wave as mechanical energy and transmits through a medium. The secondary transducer is set at a point along the way of the sound wave for the reverse procedure of changing over once again into electrical energy. As such, a secondary transducer will pick up the acoustic wave at a particular frequency and transforms the mechanical energy into the electrical energy so that it can be used for driving up an electrical load.

The primary transducer ought to be driven at a particular frequency and regularly denoted in a sinusoidal waveform to acquire the best execution that match with transmission medium. The secondary transducer likewise produces a sinusoidal waveform. A DC-AC converter should be comprised in the circuit at the primary unit and an AC-DC rectifier at the receiving unit.

There are numerous benefits that could be accomplished through APT system. As it delivers power through vibration, it can transmit energy through a metal medium where IPT and CPT fail to achieve. The sheltering effect in metal that restricts the electromagnetic fields and entices eddy currents in the IPT system is not arising in APT (Imoru et al., 2013). Besides that, APT is reasonable in many applications that include driving and connecting with electronic devices inside or outside sealed metal compartment.

However, the major constriction in low power biomedical application is to design APT in a biocompatible device so that it can be used effectually. Besides, it is relatively hard to attain higher current in energy transfer instead of higher amplitude voltage (Zaid & Saat, 2014). As for high power applications, an APT system would become a concern since it will built up of heat. The high acoustic energy that uses from acoustic wave transmission would resemble to violent vibrations. This could lead to extreme heat and performance of the system might be interrupted (Zaid & Saat, 2014).

In comparison with IPT and CPT, the inductive power transmission in a bigger space is extremely wasteful and not functional because of high conduction misfortunes (Waffenschmidt & Staring, 2009). In addition, these systems cannot deliver power effectually through a conductive medium. In contrast, CPT systems transfer power by high frequency resonant power electronic converter that is associated to two essential metal plates. The CPT method has been effectively executed in some small devices though, they share an indistinguishable issue from experienced in IPT which is low productivity over a substantial separation (Zheng, Tnay, Alami, & Hu, 2010). Since APT system practice ultrasonic wave as a technique, it is an elective way that can resolve the drawbacks arise from IPT and CPT because of the contactless energy transfer that is based on the electromagnetic field principle.

2.2.2 Inductive Power Transfer (IPT)

Inductive power transfer is by far the most prominent method used today to transmit power wirelessly over short distances (few tens of mm). IPT utilizes the mutual inductance (inductive coupling) between two inductors to transmit power from one to another. Inductive coupling is a well-studied phenomenon and was first proposed by Tesla and has consequently discovered use in modern, automated and biomedical applications. A significant achievement has been accomplished by IPT after several years of research; and the ability of the coupled magnetic resonances power transfer (CMRPT) technology that can transmit a high power wirelessly for few meters up to tens of meters made the IPT in numerous considerations (Xia, Zhou, Zhang, & Li, 2012).

The most familiar energy transfer system that has been used nowadays is IPT system where it utilizes coupled of the electromagnetic field coil. This system is very comparable with capacitive idea of energy transfer, however the capacitive idea utilizes capacitance coupling. The accomplishment of this IPT framework has been demonstrated in numerous applications, for example, assembled in electric vehicles, cell phones, and different sorts of the battery charging framework (Kim & Bien, 2013).

However, there is a major drawback of this electromagnetic coupling technique where the transmission separation is moderately restricted and affecting the proficiency decrease quickly as the separation increase. This will lead the transmission quality in electromagnetic fields to be decreased.

In the IPT system, the input voltage Vs passes through the oscillator and then it works as the input voltage of the primary resonance coil, then the power will be supplied to the load by the magnetic field coupling between L1 and L2 coils as shown in Figure 2.3.

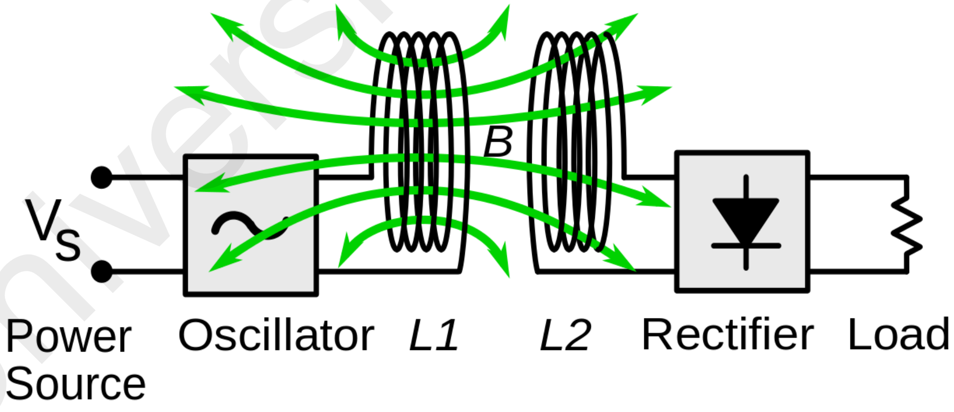


Figure 2.3: Basic diagram of IPT system

At the moment, in some system need to embrace WPT innovation, it typically utilizes IPT technology, however the IPT system needs a high frequency to create a magnetic field, typically 10k-10MHz, thus a huge electromagnetic interference will be created. The technology is dependent on the coupling magnetic field which it can be easily shielded by metal conductor with small resistance rate and higher losses of eddy current losses will be produced. Therefore, transferring power in a metal environment by IPT through magnetic field is an advantage of the technology (Xia et al., 2012).

Besides, other advantages include long life of the system, with virtually no components prone to wear and tear, the service life of the system is greatly increased. There is no friction in the system, hence no limit to the acceleration possible, plus with no galvanic contact, there is no corrosion. In safety aspect, IPT had the advantages to the environments in terms of safety as power sources using wired are hazardous and troublesome that can have risk of sparks from static electricity or friction. The technology also will not involve in pollution and the maintenance is low since no batteries is needed to be replaced. However, its limitation comprises of the medium of transfer can get heated up at high frequency and conductive medium with high magnetic permeability will limit the power transfer (Imoru et al., 2013).

2.2.3 Capacitive Power Transfer (CPT)

Wireless transfer by capacitive is the first form of wireless power transfer that had been achieved (Dai & Ludois, 2015). In 1891, Tesla conducted the experiment at Columbia College , New York. In the following months, Tesla utilized inductors to transfer power wirelessly. After the innovation of inductive system take place, capacitive coupled system was forgotten. The capacitive coupled system was overlooked until the year 2008. Several experiments have been conducted since 2008 in the wireless capacitive area and this have made a prompt development (Theodoridis, 2012).

Figure 2.4 shows the basic block diagram of the CPT system. A DC power source voltage is changed over to a high frequency AC voltage through the resonant power converter circuit which is then connected to two transmitting metal plates. When two receiving plates are put near them, alternating electric field is created between the plates thus a displacement current can ‘flow’ through. Consequently, this will allows power to be transmitted to the load without direct electrical contacts through the medium between the plates that can be air, plastic, paper, skin etc. In order to drive the load, the receiver unit will convert AC to DC energy through the rectifier circuit (Hu & Liu, 2009).

In contrast of IPT, there are certain advantages of the electric field coupling; the CPT technology can overwhelmed the disadvantage that the magnetic energy could not be transmitted in the metal shielding environment. The CPT technology can transmit through the metal body, reduce energy loss, and also has good anti-interference ability of the magnetic field. Strong anti-interference makes the device able to work in saturated or intense magnetic fields environment, and can reduce energy loss and electromagnetic interference. Therefore, the CPT technology has a number of advantages that IPT technology unparalleled (Xia et al., 2012).

In addition, due to the absence of eddy currents, CPT system can be highly efficient. In an inductively coupled system, the transmitter and receiver coil are nothing but a loosely coupled transformer. There are always eddy current losses in a transformer. Eddy current losses are inherent in transformers. The coils used can get heated due to the current in them. A CPT system would be a better choice as eddy current losses are absent and the system has low standing power losses. Due to its low standing power losses, the CPT system can be used in biomedical implants (Zheng et al., 2010). Besides that, we know that the design of magnetics is a complete area by itself. For an IPT system to perform at its best efficiency, the design of the magnetic components is very critical. With introduction in various configuration of coils and cores, the design gets more complicated along the way. On the other hand of a CPT system, the design of the system is quite straight forward compared to the IPT system and easily integral with other circuits.

Wireless power transmission using capacitive coupling is the simplest method to transfer power wirelessly. It needs fewer components than an IPT system due to the fact that same currents flow through the transmitting and receiving side, thereby eliminating the need for separating tuning circuits at the transmitting side and receiving side. However, wireless power transfer using CPT finds its use in very few applications due its very short range (<10 mm). It is used in very few applications for harnessing specific benefits such as wireless power transfer through metallic interfaces (Jegadeesan et al., 2013).

In biomedical application, the utilization of CPT technique is preferred than IPT since the relation efficiency of capacitive coupling declines slower as a function of the separation between plates, compared to inductive coupling (Al-Kalbani, Yuce, & Redoute, 2014). Additionally, it have been proved that capacitive coupling system yields smaller 10g SAR values compared to inductive coupling. SAR or known as specific absorption rate is the rate of absorption of electromagnetic energy by body tissue. The body’s thermoregulatory mechanism can be defeated and causes tissue damage if the SAR averaged across 10g of tissue is higher than 2 W/kg (Al-Kalbani et al., 2014).

2.3 Far Field WPT

Regions that have distances greater than two wavelengths of the electromagnetic wave are called far field regions as shown in Figure 2.4. As it drops with square of the distance, the strength of the field is lower in this area. Along these lines, an ordinary electromagnetic wave is incapable for exchanging high measure of energy over this relatively substantial separation (Nalos & Lund, n.d.). There are some techniques and applications for wireless power transfer in far field , which will be discussed in the accompanying content.

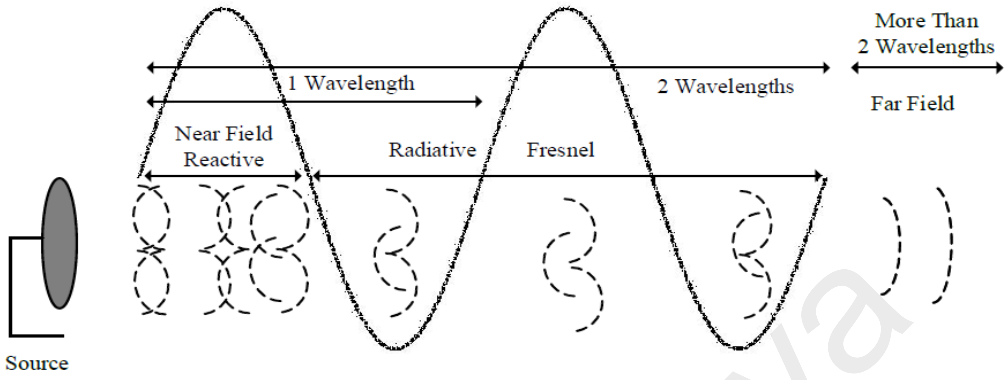


Figure 2.4: Representation of near and far field wave

2.3.1 Microwave Power Transfer (MPT) and Light Power Transfer (LPT)

In the earliest communication antenna, the energy does not achieve the load because of the small directivity of the framework. Thus, the higher frequency signals in microwave array is used to enhance the directivity of the electromagnetic wave so that signicant amount of power transfer is possible. This phenomena was introduced in seventies and later demonstrated experimentally (Nalos & Lund, n.d.). Specifically outlined coherent sources can enhance the electromagnetic radiation and deliver it accurately to long separations. The power transfer technique is called Laser Power Transfer (LPT) and the technology is called LASER (Light Amplication by Stimulated Emission of Radiation) (Hasan, 2015).

Be that as it may, both MPT and LPT can be lethal to human wellbeing, because of substantial measure of energy kept in dense electromagnetic waves, in this manner these advancements are constrained to applications with least human disclosure. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered. Laser 'powerbeaming' technology was explored in military weapons and aerospace applications. Also, it is applied for powering of various kinds of sensors in industrial environment.

2.4 Class E zero voltage switching (ZVS) Inverter

There are two types of Class E DC-AC inverters which are Class E zero voltage switching (ZVS) inverters and Class E zero current switching (ZCS) inverters. The inverters belong to soft-switching family inverters and both types used transistor as switch. In this section, Class E ZVS inverter is focused in this project since the inverter is known to be the most efficient inverters (Kazimierczuk & Czarkowski, 2011).

The basic circuit of the Class E ZVS inverter is shown in Figure 2.5. It consists of a power MOSFET operating as a switch, a L-C-Ri series-resonant circuit, a shunt capacitor C1, and a choke inductor Lf. The switch turns on and off at the operating frequency = $\omega/(2\pi)$ determined by a driver. The resistor Ri is an AC load. The choke inductance Lf is assumed to be high enough so that the AC ripple on the DC supply current Ii can be neglected. A small inductance with a large current ripple is also possible, but the consideration of this case is beyond the scope of this text. When the switch is ON, the resonant circuit consists of L, C, and Ri because the capacitance C1 is short circuited by the switch. However, when the switch is OFF, the resonant circuit consists of C1, L, C, and Ri connected in series.

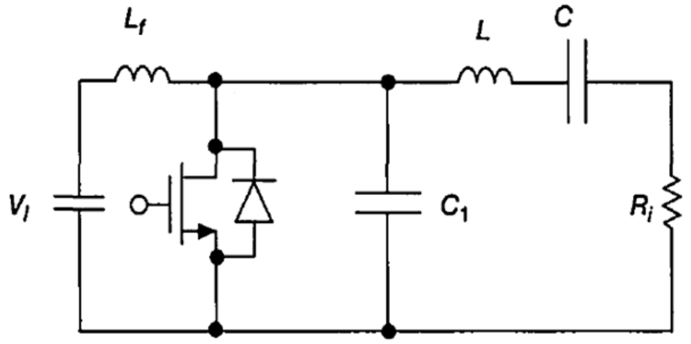


Figure 2.5 : Class E zero voltage switching inverter

Class E inverter can operates in ZVS operation with matching resonant circuit from full load to open circuit along the output voltage is near to fixed value.Besides that, a fixed frequency can be operated on the inverter using resonant gate drive that reduce the losses at gate drive significantly which makes the circuit able to operate a higher frequency without damage from thermal effects.

Lastly, compared to Class D, Class E has higher efficiency and the frequency range of reliability is in between 3MHz and 10MHz. In order to achieve optimum condition of Class E, components values that are being calculated need to be as exact value as for practical in order to obtain ZVS and ZCS, otherwise losses will occur at switching severely.

2.4.1 Zero Voltage Switching (ZVS)

For optimum operation of Class E ZVS inverter, zero voltage switching condition is needed to be achieved (Kazimierczuk & Czarkowski, 2011). This condition is an ideal operation of Class E inverter where no switching losses occur. The ZVS condition is illustrated on Figure 2.6.

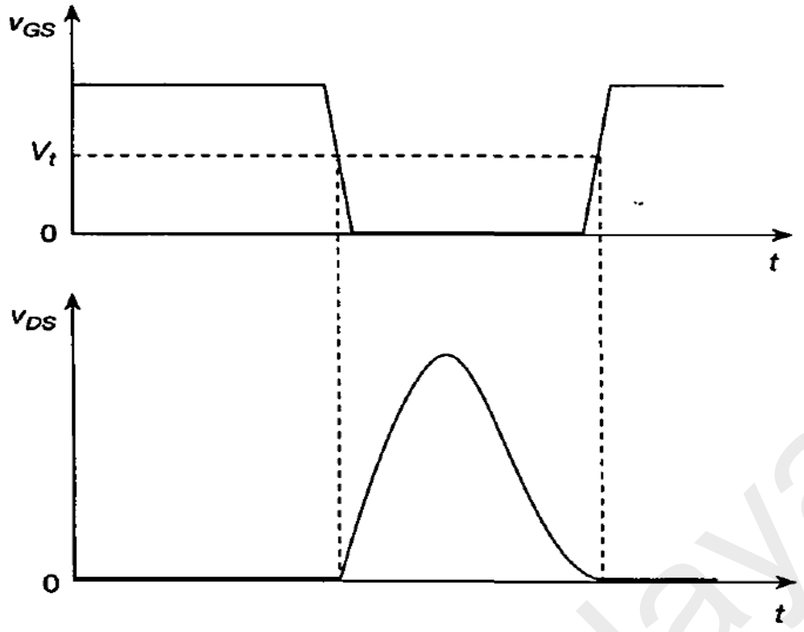


Figure 2.6: ZVS waveform condition

The zero voltage switching condition is defined when the maximum drain efficiency is obtained where the drain voltage is turned on as the gate voltage is off without any overlapped occurs. This achievement of optimum operation are heavily sole on the relationships of shunt capacitor, switching frequency, choke inductor, duty cycle and load resistances. If the load resistances of real component is not as exact value of designed, the optimum condition obviously could not be obtained (Kazimierczuk & Czarkowski, 2011). Therefore, series diode can be added to the transistor so that ZVS operation can be obtained at a wider load range and the switch will turn on at zero voltage for less value for load resistances that has been designed. Achieving ZVS condition will lead to high efficiency of the Class E circuit system performance.

2.4.2 Impedance matching resonant circuit

The purpose of the impedance matching network is to convert the load resistance or impedance into the impedance required to produce the desired output power Po at the specified supply voltage Vi and the operating frequency f (Kazimierczuk &

Czarkowski, 2011). Figure 2.8 shows the block diagram with the implementation of impedance matching in class E amplifier circuit. The basic resonant class E circuit does not have matching capability. In order to transfer a specified amount of output power Po at a specified dc voltage Vdc, the load resistance R must be of the value determined by Eq. (1). Therefore, impedance matching circuit is needed to match any impedance to the desired load resistance.

The full load resistance is:

$$R = R_s = \frac{8V_{dc}^2}{(\pi^2+4)P_o} = 0.5768\,\frac{V_{dc}^2}{P_o} \qquad (1)$$

Based on Eq. 1, Vdc, Po and R are dependent quantities. In many applications, the load resistance is given and is different from that given in Eq. (1). Hence, there is a need for a matching circuit that provides impedance transformation downward or upwards. A diagram of the Class-E amplifier with an impedance matching circuit is shown in Fig. 2.9. This impedance matching type is selected because there is a capacitor that is connected in series with a load, which will be then modified to capacitor coupling plate to fit to actual CPT system. It can be seen in Figure 2.7 where the impedance matching circuit is applied into the basic Class E circuit and the complete circuit of Class E after implement of impedance matching circuit in Figure 2.8.

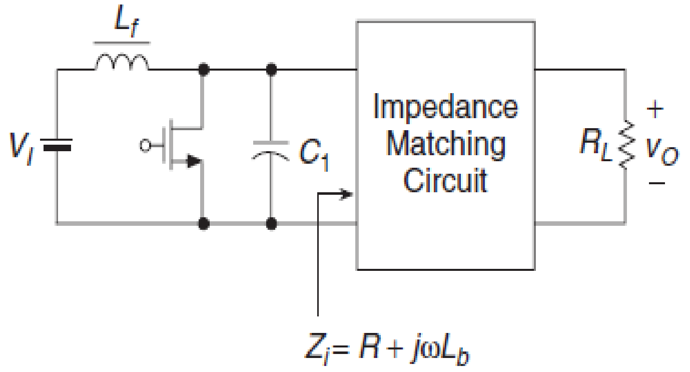


Figure 2.7: Block diagram of the Class E amplifier with impedance matching resonant circuit

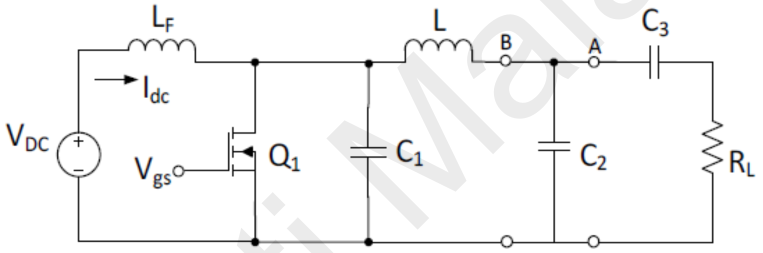
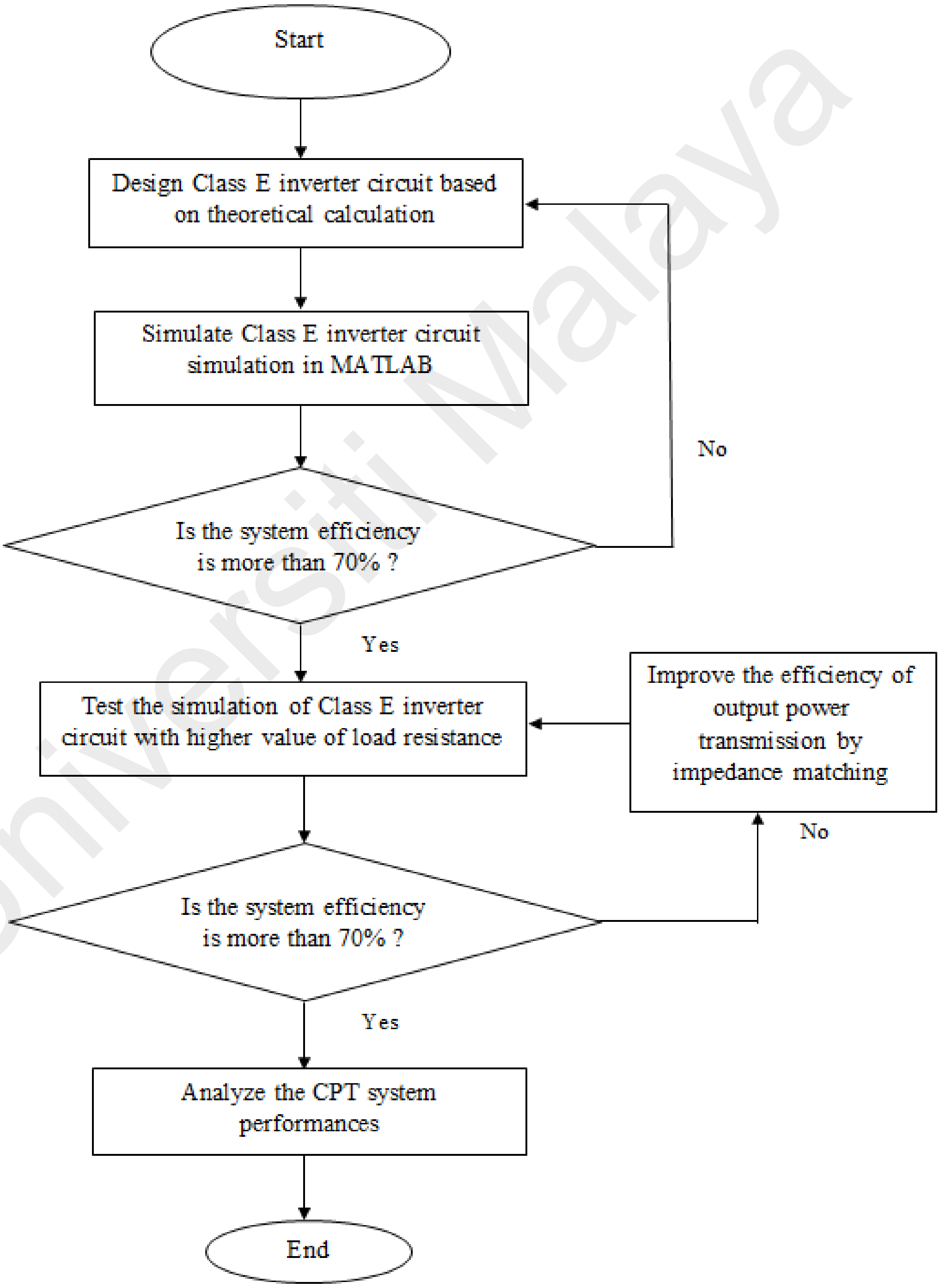


Figure 2.8: Class E with impedance matching circuit

CHAPTER 3: METHODOLOGY

3.1 Process flow of the project



3.2 Class E inverter circuit design

The component's value in the circuit Figure 3.1 that will be calculated are choke inductor (Lf), shunt capacitor (C1), LC series and load resistor (Ri). The operating frequency, DC power supply and power output to the load have been stated in the project scope of the first chapter. Using these conditions, the value of parameters in Class E inverter can be determined using some related equations. First, the value of load resistance can be obtained by using equation (3.1).

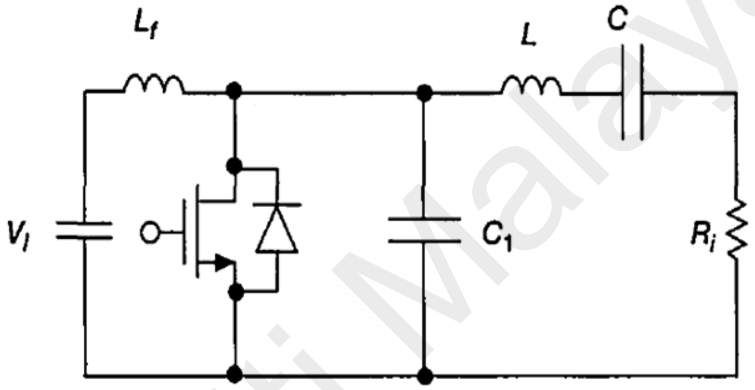


Figure 3.1: Class E inverter circuit

$$Ri = \frac{8}{\pi^2 + 4}\frac{V_I^2}{P_{Ri}} \tag{3.1}$$

Then, the amplitude of the output voltage can be calculated by

$$V_{Rim} = \frac{4}{\sqrt{\pi^2 + 4}}V_I \tag{3.2}$$

The maximum voltage across the switch and shunt capacitor is then determined by

$$V_{SM} = 3.562V_I \tag{3.3}$$

The DC input current then can be calculatedp by

$$I_I = \frac{8}{\pi^2 + 4}\frac{V_I}{R_i} \tag{3.4}$$

The maximum switch current is then given by

$$I_{SM} = \left(\frac{\sqrt{\pi^2 + 4}}{2} + 1\right) I_I \tag{3.5}$$

The output current amplitude is calculated as

$$I_m = \frac{I_I\sqrt{\pi^2 + 4}}{2} \tag{3.6}$$

Assuming $Q_L = 7$, so that the current I through the resonant circuit is sinusoidal. Using equation (3.7), (3.8) and (3.9) respectively, the component values of the load network can be determined as follows

$$L = \frac{Q_L R_i}{\omega} \tag{3.7}$$

$$C_1 = \frac{8}{\pi(\pi^2 + 4)\omega R_i} \tag{3.8}$$

$$C = \frac{1}{\omega R_i \left[Q_L - \frac{\pi(\pi^2 - 4)}{16}\right]} \tag{3.9}$$

Finally, using the listed formula equations, all the required parameters for Class E inverter are tabulated in Table 3.1.

Table 3.1 : Calculated parameters for Class E inverter

Parameters	**Symbol**	**Value**	**Unit**
Frequency	f	1	MHz
Duty cycle	D	50	%
Input voltage	Vi	12.00	V
Input current	Ii	0.167	A
Resistance of load	R_L	41.53	A
Choke inductor	Lf	288	uH
Shunt capacitor	C_1	0.704	nF
Series inductor	L	46.3	uF
Series capacitor	C	0.655	nF
Maximum switch current	I_{SM}	0.48	A
Maximum switch voltage	V_{SM}	42.74	V
Output current	I_M	0.31	A
Output voltage	V_{Rim}	12.89	V
Power input	Pi	2.04	W
Power output	Pout	2.00	W
Efficiency	η	98.04	%

3.3 Class E with impedance matching circuit design

In order to improve the output power efficiency when the load resistance is changing, impedance matching circuit has been designed to be implemented with the Class E circuit as illustrated in Figure 3.2. Hence, the complete inverter circuit after the implementation of impedance matching circuit on the Class E circuit is shown in Figure 3.3. The values of V_{DC}, L_F, C1 and L remains the same as in the previous Class E circuit, only the values of C2, C3 and R_L will be changed. On the further step of developing a complete system of CPT, C3 capacitor will be replace with metal plate for the biomedical implant application prototype which will not be covered in this project.

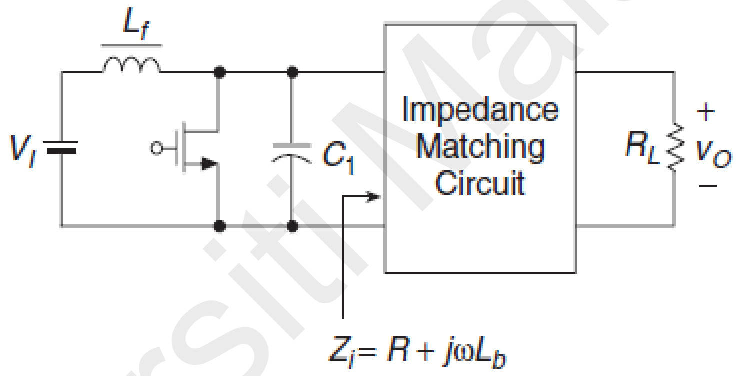


Figure 3.2: Implementation of impedance matching circuit on the Class E circuit

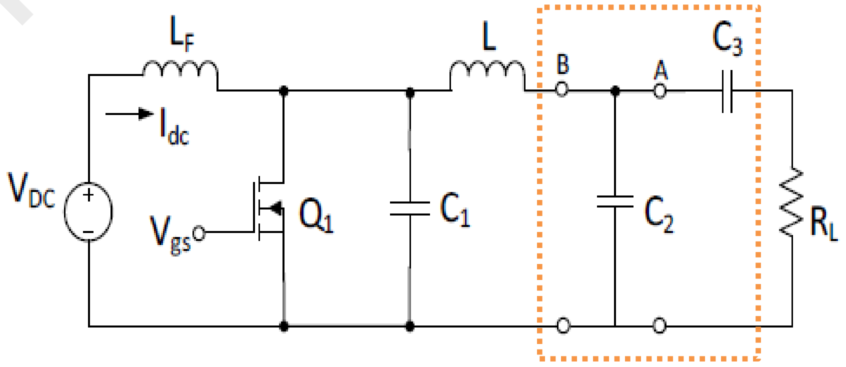


Figure 3.3: Class E with impedance matching circuit

By using $Q_L = 7$, R_L is chosen as 270 ohm and R is the value of R_L in the previous Class E circuit design, the reactance of the capacitor C3 is calculated as

$$X_{C3} = \frac{1}{\omega C_3} = R_L \sqrt{\frac{R[(Q_L - 1.1525)^2 + 1]}{R_L} - 1} \tag{3.10}$$

resulting in

$$C_3 = \frac{1}{\omega X_{C3}} \tag{3.11}$$

R_L is chosen as 270 ohm since the larger value of R_L will give smaller value of C3 thus resulting smaller size of capacitive plate to be used in the device application.

The reactance of the capacitor C2 is given by

$$X_{C2} = \frac{1}{\omega C_2} = \frac{R[(Q_L - 1.1525)^2 + 1]}{Q_L - 1.1525 - \sqrt{\frac{R[(Q_L - 1.1525)^2 + 1]}{R_L} - 1}} \tag{3.12}$$

yielding

$$C_2 = \frac{1}{\omega X_{C2}} \tag{3.13}$$

Thus, resulting the parameters in Table 3.2

Table 3.2: Impedance matching circuit calculated parameter

Parameters	Values
C2	0.408nF
C3	0.2805nF
RL	270Ω

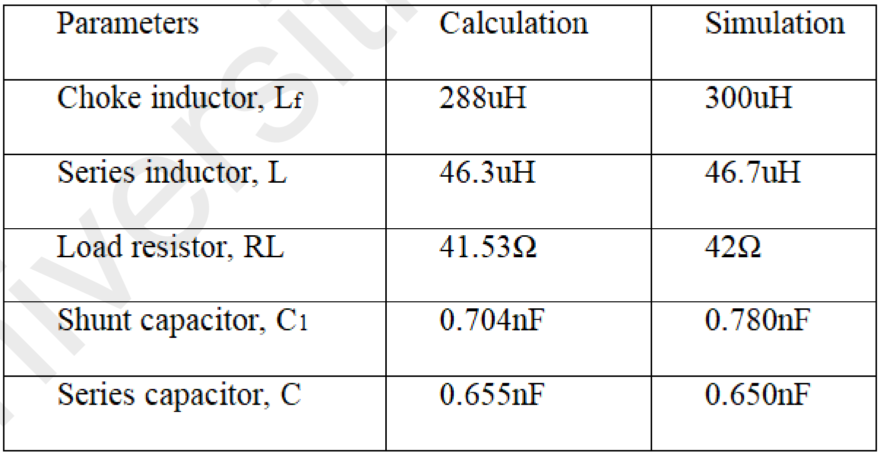
The design step is repeating for difference value of R_L which are 310 ohm and 350 ohm to get the new value of C2 and C3.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Class E circuit simulation

The result of Class E inverter circuit simulation after the design process that was constructed in Chapter 3 was recorded. Table 4.1 shows the components value for design calculation and the components value used in the simulation. There were slightly differences between the components value as the value of some components in the circuit need to be tuned or manipulated so that the best ZVS waveform will be achieved in order to ensure the circuit is running at its optimum condition. Figure 4.1 shows theoretical ZVS waveform that should be achieved (Kazimierczuk & Czarkowski, 2011)

Table 4.1: Components value



Parameters	Calculation	Simulation
Choke inductor, L_f	288uH	300uH
Series inductor, L	46.3uH	46.7uH
Load resistor, RL	41.53Ω	42Ω
Shunt capacitor, C_1	0.704nF	0.780nF
Series capacitor, C	0.655nF	0.650nF

Figure 4.2 shows the simulation result of the ZVS waveform recorded from oscilloscope in Matlab Class E circuit simulation. The ZVS simulation waveform obtained is nearly to the theoretical waveform after the tuning of the components value have been done. In this circuit simulation, L series, C series and C_1 shunt value have been varying slightly from the calculated values.

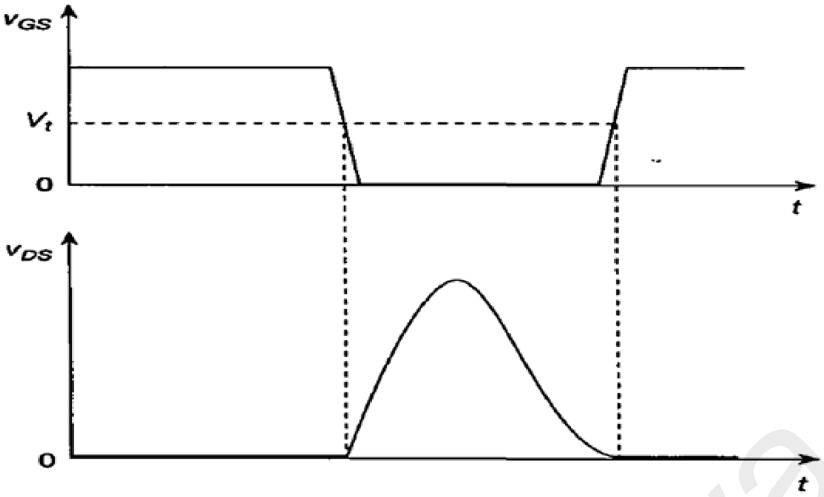
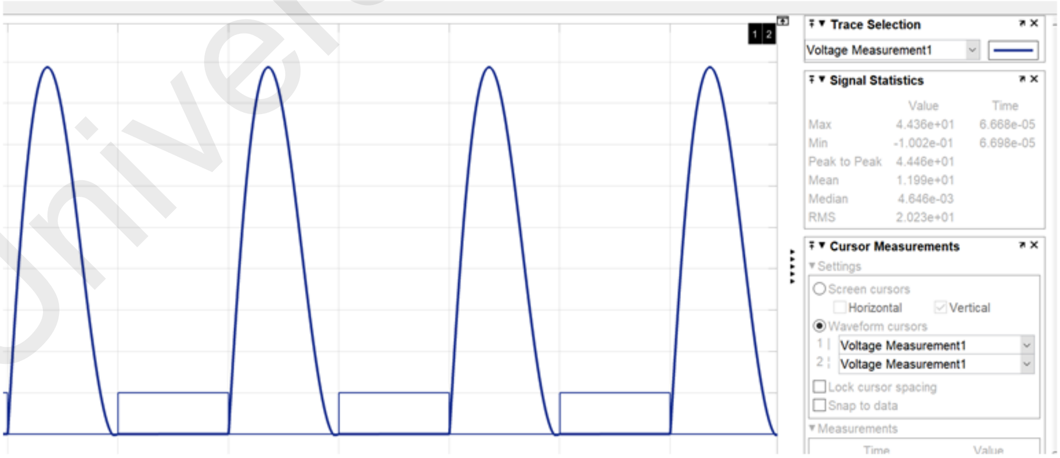


Figure 4.1 : Theoretical ZVS waveform

Table 4.2 shows the comparison between calculation and simulation values of system performance in the Class E circuit that have been designed. Based on Figure 4.2, V_{DS} Max measurement is 44.36V which is recorded as V_{SM} which is 42.74V in Table 4.2. There are no significant difference between the calculated and simulation value of the V_{DS} mosfet.



Trace Selection

Voltage Measurement1

Signal Statistics

	Value	Time
Max	4.436e+01	6.668e-05
Min	-1.002e-01	6.698e-05
Peak to Peak	4.446e+01	
Mean	1.199e+01	
Median	4.646e-03	
RMS	2.023e+01	

Cursor Measurements

Settings

○ Screen cursors

☐ Horizontal ☑ Vertical

● Waveform cursors

1 Voltage Measurement1

2 Voltage Measurement1

☐ Lock cursor spacing

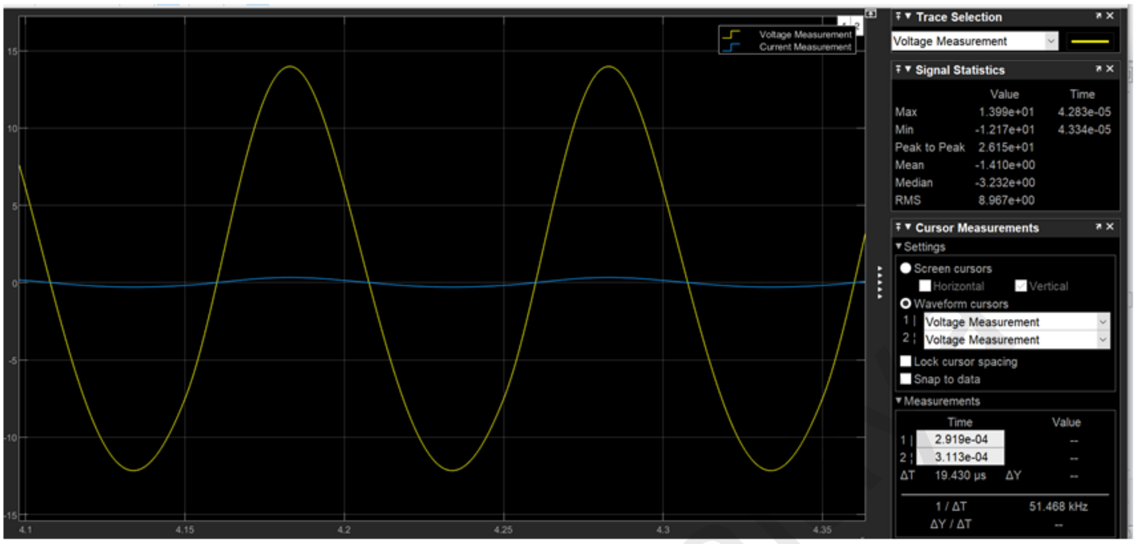
☐ Snap to data

Measurements

Time	Value

Figure 4.2 : Simulation ZVS waveform

Figure 4.3 shows the output simulation waveform of the circuit. Based on Figure 4.3, smooth AC output waveform is obtained and the maximum output voltage reading is 14V that was recorded as VRim which is 12.88V in Table 4.2. These two values were also not having a big difference from theoretical calculation with the simulation. Hence, the overall of Class E system performance comparison is recorded in Table 4.2.



```
Trace Selection
Voltage Measurement

Signal Statistics
              Value        Time
Max           1.399e+01    4.283e-05
Min           -1.217e+01   4.334e-05
Peak to Peak  2.615e+01
Mean          -1.410e+00
Median        -3.232e+00
RMS           8.967e+00

Cursor Measurements
Settings
○ Screen cursors
   ☐ Horizontal   ☑ Vertical
● Waveform cursors
   1 | Voltage Measurement
   2 ¦ Voltage Measurement
☐ Lock cursor spacing
☐ Snap to data
Measurements
      Time                 Value
1 |   2.919e-04            --
2 ¦   3.113e-04            --
ΔT    19.430 μs       ΔY   --
      1 / ΔT               51.468 kHz
      ΔY / ΔT              --
```

Figure 4.3: Output waveform from simulation

Table 4.2: Comparison of system performance in Class-E circuit

Parameters	Calculation	Simulation
Maximum switch current, I_{SM}	0.48A	0.46A
Input current, Ii	0.17A	0.18A
Gate to source voltage, V_{GS}	5.00V	5.00V
Output current, I_{M}	0.31A	0.33A
Maximum switch voltage, V_{SM}	42.74V	44.36V
Output voltage, VRim	12.88V	14.00V
Power output, Po	2.00W	1.91W
Power input, Pi	2.04W	2.004W
Efficiency, η	98.04%	95.38%

4.2 Class E circuit improvement by impedance matching

Figure 4.4 shows the implementation of impedance matching by the additional components of C2 and C3 in the previous class E inverter circuit. In order to improve the maximum power transfer efficiency when the load is change, the implementation of an impedance matching in the Class E circuit has been designed. The main objective behind the impedance matching circuit is to change over the load resistance or impedance to the impedance required to deliver the desired output power, Po at the specified supply voltage Vdc and at the operating frequency f (Yusop, Ghani, Saat, Husin,&Nguang, 2016).The performance of the system and the effect of higher load resistor value, RL on the Class E inverter circuit with or without the implementation of impedance matching will be analyzed. RL value is varying at 270, 310 and 350 ohm since the larger value of RL will give smaller value of C3 thus resulting smaller size of capacitive plate to be used in biomedical device application.

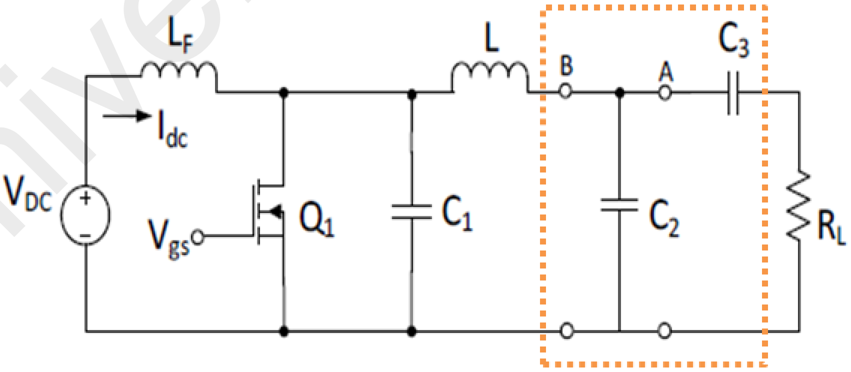
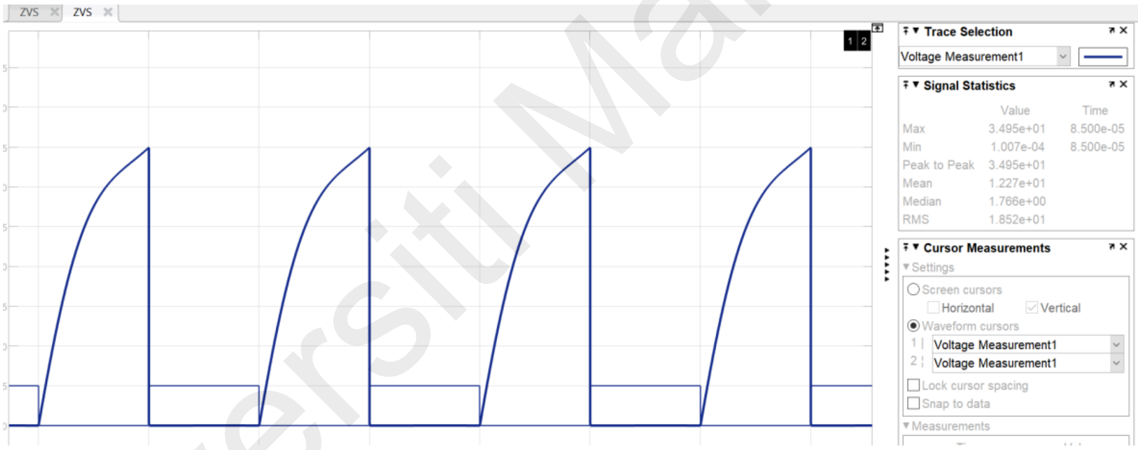


Figure 4.4: Impedance matching circuit

a) At RL = 270 ohm

Table 4.3: Parameter of impedance matching circuit

Parameters	Calculation	Simulation
L_f	288uH	300uH
C2	0.408nF	0.398nF
C3	0.2805nF	0.2780nF
R_L	270Ω	270Ω
L	46.3uF	47uF
C_1	0.704nF	0.780nF



Trace Selection: Voltage Measurement1

	Value	Time
Max	3.495e+01	8.500e-05
Min	1.007e-04	8.500e-05
Peak to Peak	3.495e+01	
Mean	1.227e+01	
Median	1.766e+00	
RMS	1.852e+01	

○ Screen cursors
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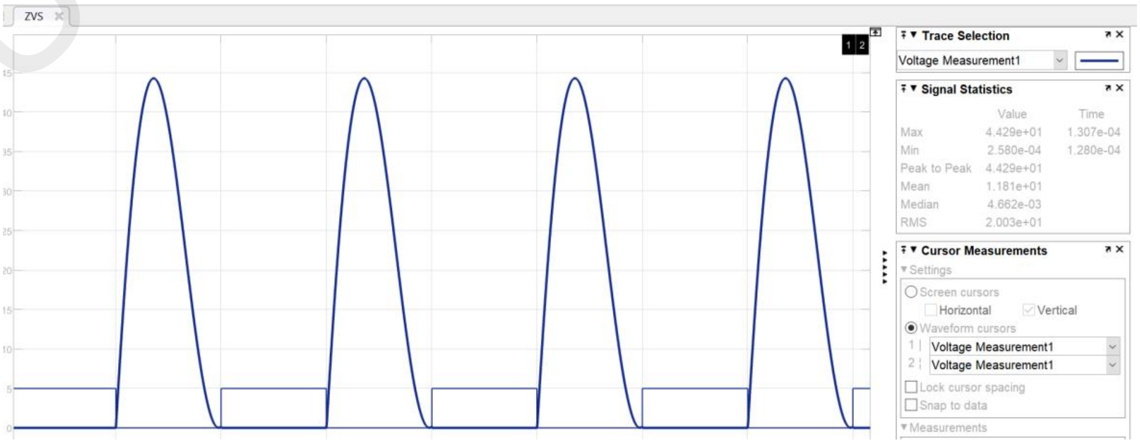
● Waveform cursors
1 Voltage Measurement1
2 Voltage Measurement1
☐ Lock cursor spacing
☐ Snap to data

Figure 4.5: ZVS waveform without impedance matching



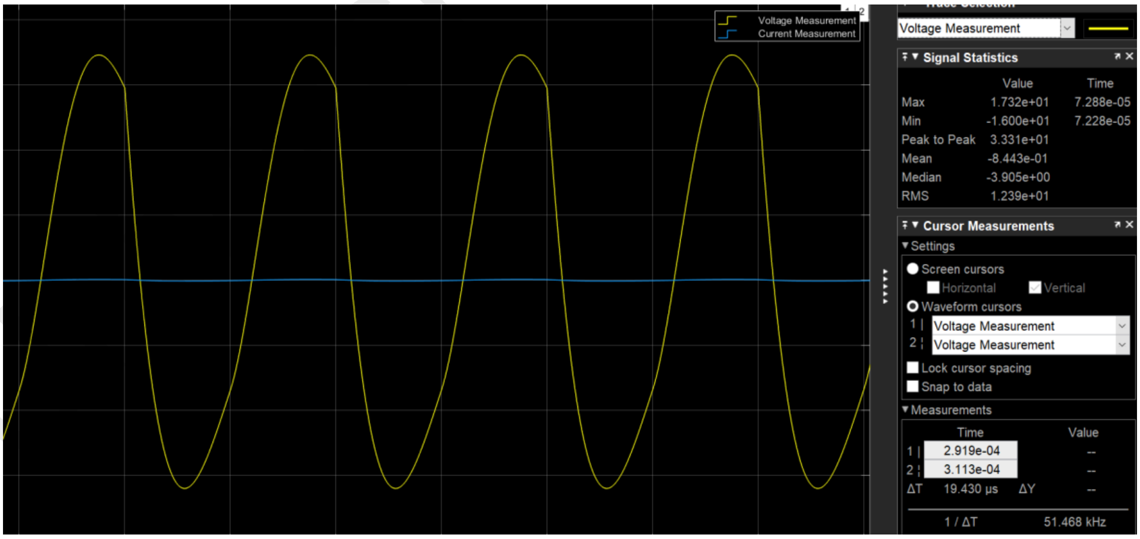
Trace Selection: Voltage Measurement1

	Value	Time
Max	4.429e+01	1.307e-04
Min	2.580e-04	1.280e-04
Peak to Peak	4.429e+01	
Mean	1.181e+01	
Median	4.662e-03	
RMS	2.003e+01	

○ Screen cursors
☐ Horizontal ☑ Vertical
● Waveform cursors
1 Voltage Measurement1
2 Voltage Measurement1
☐ Lock cursor spacing
☐ Snap to data

Figure 4.6: ZVS waveform with impedance matching circuit

Table 4.3 shows the parameter of impedance matching circuit by calculation and simulation at RL=270 ohm. The components value for simulation have been slightly tuned from the calculation values until the best ZVS waveform is achieved. ZVS waveform is clearly could not be achieved in Figure 4.5 as no impedance matching being applied on the circuit and as the improvement of impedance is being applied, ZVS waveform can be obtained in Figure 4.6. Output voltage waveform also has been observed as the AC output voltage without impedance matching is distorted in Figure 4.7 while the circuit with impedance matching can get a smooth AC output voltage in Figure 4.8. The output voltage value is also different as 12.39V without the impedance and higher output voltage value which is 23.31V with the impedance. The efficiency without impedance circuit in Class E is very low which is 49.14% while impedance matching circuit could achieve up to 91.14% in Table 4.4.



Signal Statistics

	Value	Time
Max	1.732e+01	7.288e-05
Min	-1.600e+01	7.228e-05
Peak to Peak	3.331e+01	
Mean	-8.443e-01	
Median	-3.905e+00	
RMS	1.239e+01	

Cursor Measurements

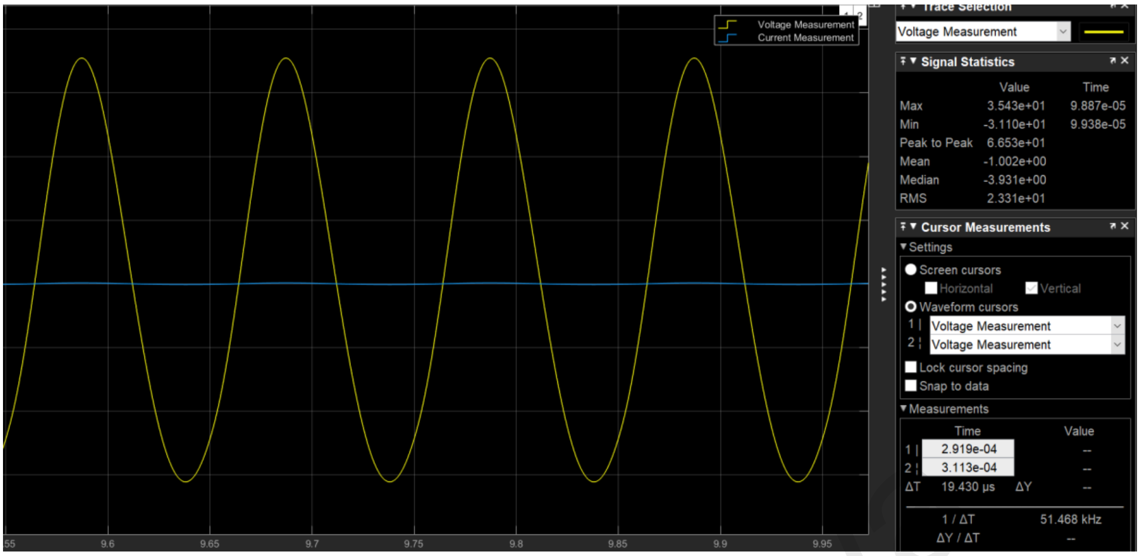
Settings

○ Screen cursors
☐ Horizontal ☑ Vertical
● Waveform cursors
1 Voltage Measurement
2 Voltage Measurement
☐ Lock cursor spacing
☐ Snap to data

Measurements

	Time		Value
1	2.919e-04		--
2	3.113e-04		--
ΔT	19.430 μs	ΔY	--
	1 / ΔT		51.468 kHz

Figure 4.7: Output voltage waveform without impedance matching circuit



Signal Statistics

	Value	Time
Max	3.543e+01	9.887e-05
Min	-3.110e+01	9.938e-05
Peak to Peak	6.653e+01	
Mean	-1.002e+00	
Median	-3.931e+00	
RMS	2.331e+01	

Cursor Measurements

Settings

○ Screen cursors
☐ Horizontal ☑ Vertical
● Waveform cursors
1 Voltage Measurement
2 Voltage Measurement
☐ Lock cursor spacing
☐ Snap to data

Measurements

	Time		Value
1	2.919e-04		--
2	3.113e-04		--
ΔT	19.430 µs	ΔY	--
	1 / ΔT		51.468 kHz
	ΔY / ΔT		--

Figure 4.8: Output voltage waveform with impedance matching circuit

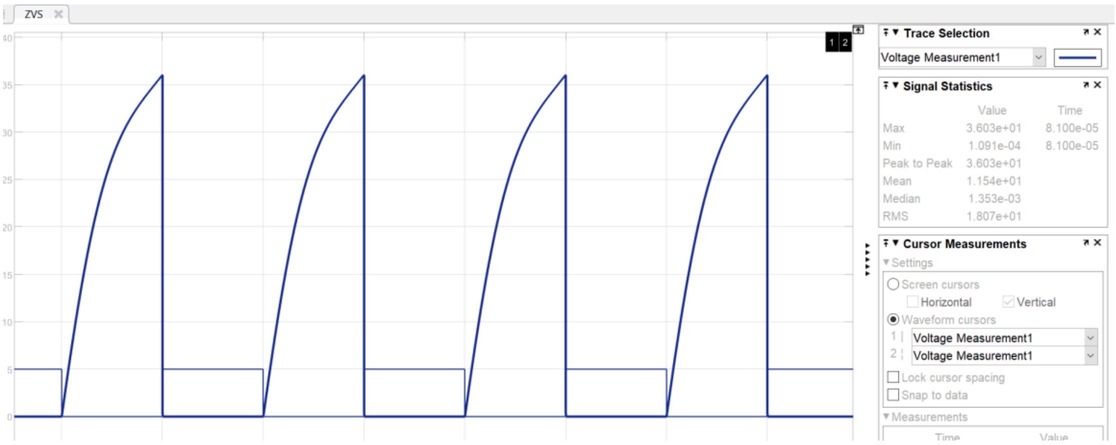
Table 4.4: Comparison of efficiency

Condition	Vi (V)	Ii (mA)	Pi (W)	Vo (V)	Po (W)	Efficiency (%)
Without impedance	12	96.3	1.160	12.39	0.57	49.14
With impedance	12	184	2.208	23.31	2.01	91.14

b) At RL = 310 ohm

Table 4.5: Parameter of impedance matching circuit

Parameters	Calculation	Simulation
L_f	288uH	300uH
C2	0.427nF	0.417nF
C3	0.266nF	0.258nF
R_L	310Ω	310Ω
L	46.3uF	47uF
C_1	0.704nF	0.780nF



	Value	Time
Max	3.603e+01	8.100e-05
Min	1.091e-04	8.100e-05
Peak to Peak	3.603e+01	
Mean	1.154e+01	
Median	1.353e-03	
RMS	1.807e+01	

○ Screen cursors
☐ Horizontal ☑ Vertical
● Waveform cursors
1 Voltage Measurement1
2 Voltage Measurement1
☐ Lock cursor spacing
☐ Snap to data

Time	Value

Figure 4.9: ZVS waveform without impedance matching

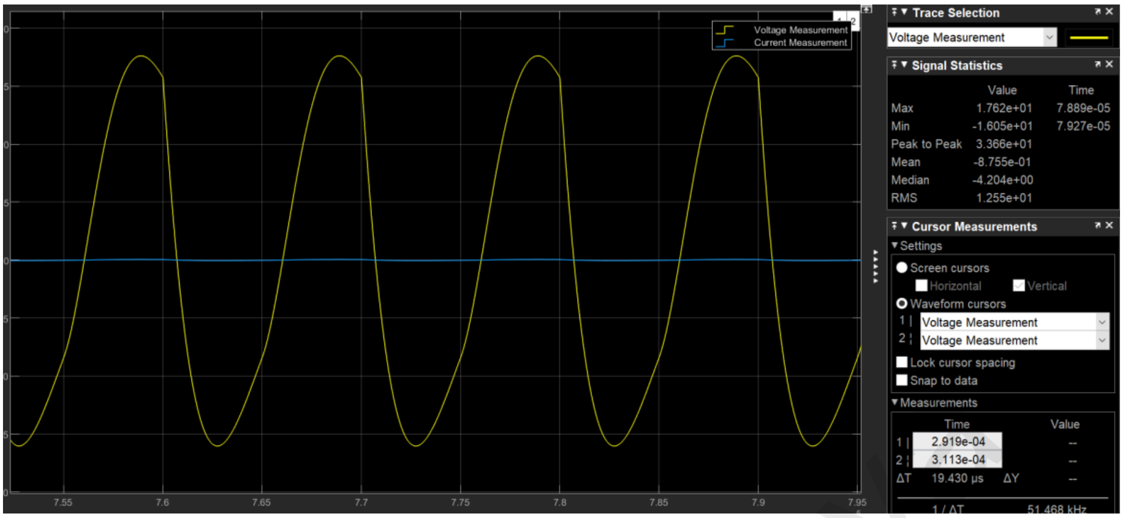
	Value	Time
Max	4.481e+01	8.668e-05
Min	-1.003e-01	8.697e-05
Peak to Peak	4.491e+01	
Mean	1.172e+01	
Median	4.817e-03	
RMS	2.009e+01	

○ Screen cursors
☐ Horizontal ☑ Vertical
● Waveform cursors
1 Voltage Measurement1
2 Voltage Measurement1
☐ Lock cursor spacing
☐ Snap to data

Time	Value

Figure 4.10: ZVS waveform with impedance matching

As RL value is change to 310 ohm, the ZVS waveform also could not be obtained without the impedance circuit as shown in Figure 4.9 and can only be obtained with the impedance circuit being applied as shown in Figure 4.10. The observation of output waveform are also the same in which smooth AC output voltage can only be achieved with impedance circuit in Figure 4.12 compared to the AC output voltage without the impedance in Figure 4.11. Higher value of output voltage with higher efficiency is recorded in Table 4.6 for impedance circuit which is 25.87V with 94.32% efficiency compared to the circuit without the impedance matching that can only reach 12.55V output voltage with only 45.54% efficiency.



Signal Statistics

	Value	Time
Max	1.762e+01	7.889e-05
Min	-1.605e+01	7.927e-05
Peak to Peak	3.366e+01	
Mean	-8.755e-01	
Median	-4.204e+00	
RMS	1.255e+01	

Cursor Measurements

Settings

● Screen cursors

☐ Horizontal ☑ Vertical

○ Waveform cursors

1 Voltage Measurement

2 Voltage Measurement

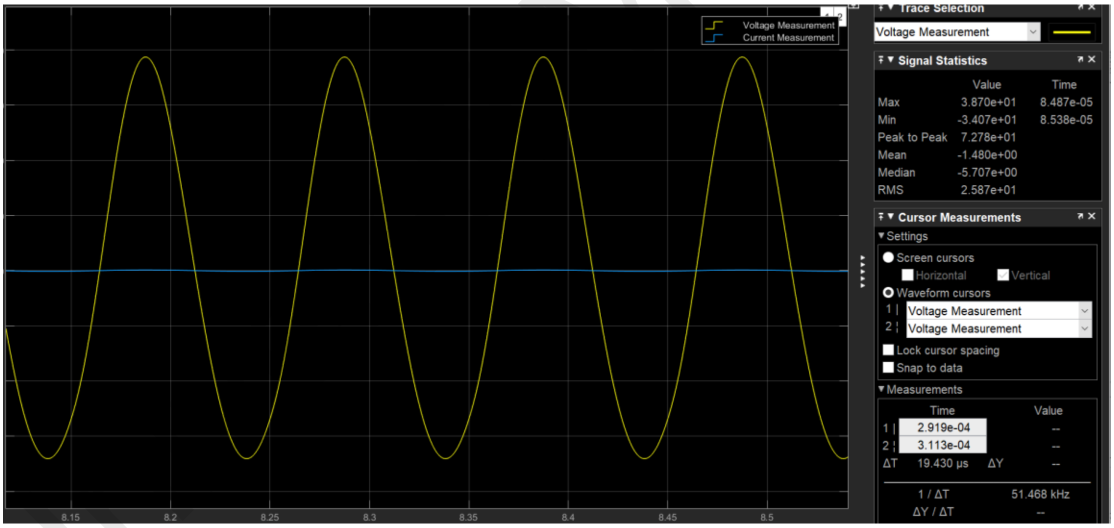
☐ Lock cursor spacing

☐ Snap to data

Measurements

	Time		Value
1	2.919e-04		--
2	3.113e-04		--
ΔT	19.430 μs	ΔY	--
1 / ΔT			51.468 kHz

Figure 4.11: Output voltage waveform without impedance matching circuit



Signal Statistics

	Value	Time
Max	3.870e+01	8.487e-05
Min	-3.407e+01	8.538e-05
Peak to Peak	7.278e+01	
Mean	-1.480e+00	
Median	-5.707e+00	
RMS	2.587e+01	

Cursor Measurements

Settings

● Screen cursors

☐ Horizontal ☑ Vertical

○ Waveform cursors

1 Voltage Measurement

2 Voltage Measurement

☐ Lock cursor spacing

☐ Snap to data

Measurements

	Time		Value
1	2.919e-04		--
2	3.113e-04		--
ΔT	19.430 μs	ΔY	--
1 / ΔT			51.468 kHz
ΔY / ΔT			--

Figure 4.12: Output voltage waveform with impedance matching circuit

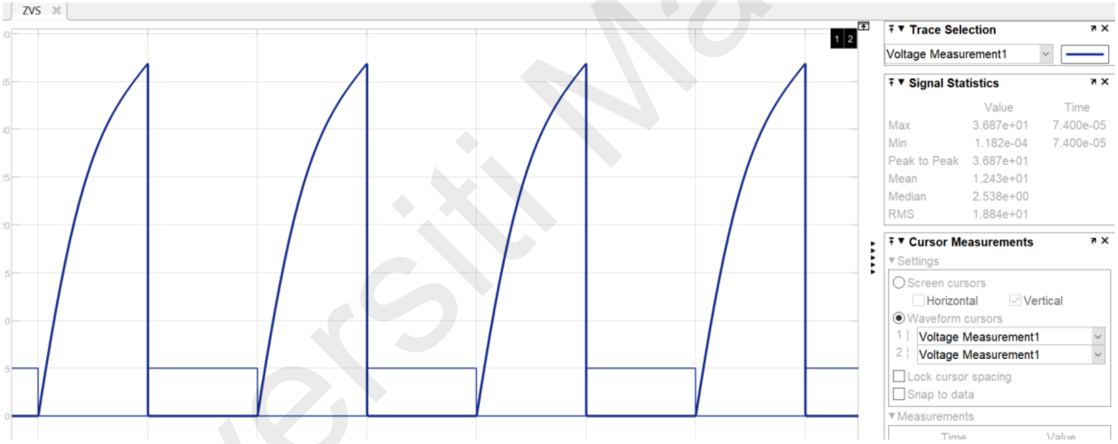
Table 4.6: Comparison of efficiency

Condition	Vi (V)	Ii (mA)	Pi (W)	Vo (V)	Po (W)	Efficiency (%)
Without impedance	12	93.7	1.12	12.55	0.51	45.54
With impedance	12	191.4	2.29	25.87	2.16	94.32

c) At RL= 350 ohm

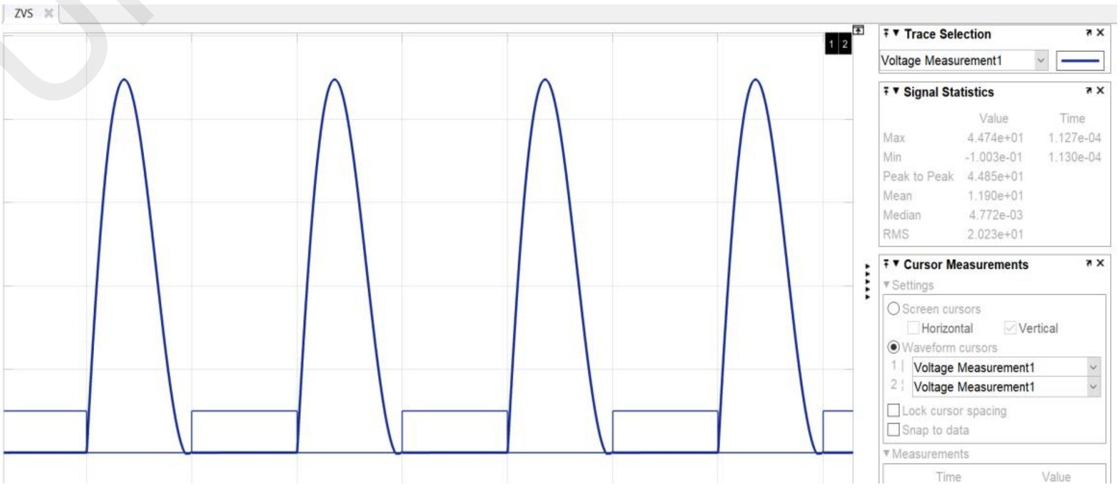
Table 4.7: Parameter of impedance matching circuit

Parameters	Calculation	Simulation
L_f	288uH	300uH
C2	0.443nF	0.433nF
C3	0.255nF	0.248nF
R_L	350Ω	350Ω
L	46.3uF	47uF
C_1	0.704nF	0.780nF



	Value	Time
Max	3.687e+01	7.400e-05
Min	1.182e-04	7.400e-05
Peak to Peak	3.687e+01	
Mean	1.243e+01	
Median	2.538e+00	
RMS	1.884e+01	

Figure 4.13: ZVS waveform without impedance matching

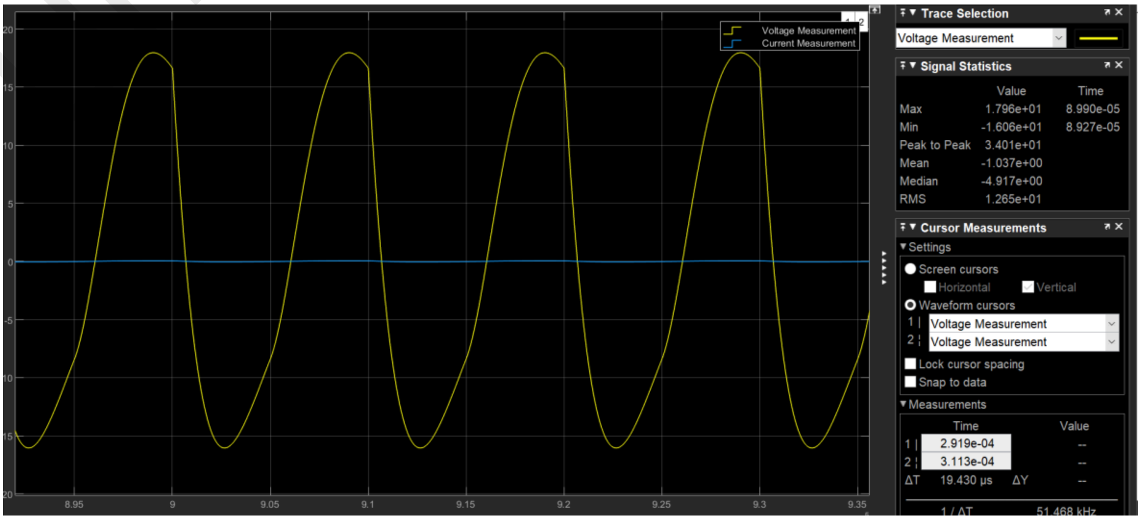


	Value	Time
Max	4.474e+01	1.127e-04
Min	-1.003e-01	1.130e-04
Peak to Peak	4.485e+01	
Mean	1.190e+01	
Median	4.772e-03	
RMS	2.023e+01	

Figure 4.14: ZVS waveform with impedance matching

As the value of RL is changing to the higher value which is 350 ohm, the ZVS waveform is still can be observed only where the impedance matching circuit is being applied as shown in Figure 4.14 compared to the ZVS waveform that could never be achieved without the impedance circuit as seen in Figure 4.13. The comparison of output voltage waveform shows that the smooth AC output voltage can only be obtained with the impedance circuit as recorded in Figure 4.16 compared to Figure 4.15. The output voltage with impedance circuit are able to achieve higher value which is 27.56V with a very high system efficiency of 95.6% compared to only 12.65V output voltage without the impedance matching with a very low efficiency of 39.41% as recorded Table 4.8.

Hence, the comparison of efficiency prove that the higher resistance of the load being applied to the Class E inverter circuit will give lower output power efficiency compared to the efficiency of Class E circuit that have been improvised with impedance matching circuit that can achieve up to 90% and above for all the three resistance values being varied.



Signal Statistics

	Value	Time
Max	1.796e+01	8.990e-05
Min	-1.606e+01	8.927e-05
Peak to Peak	3.401e+01	
Mean	-1.037e+00	
Median	-4.917e+00	
RMS	1.265e+01	

Cursor Measurements

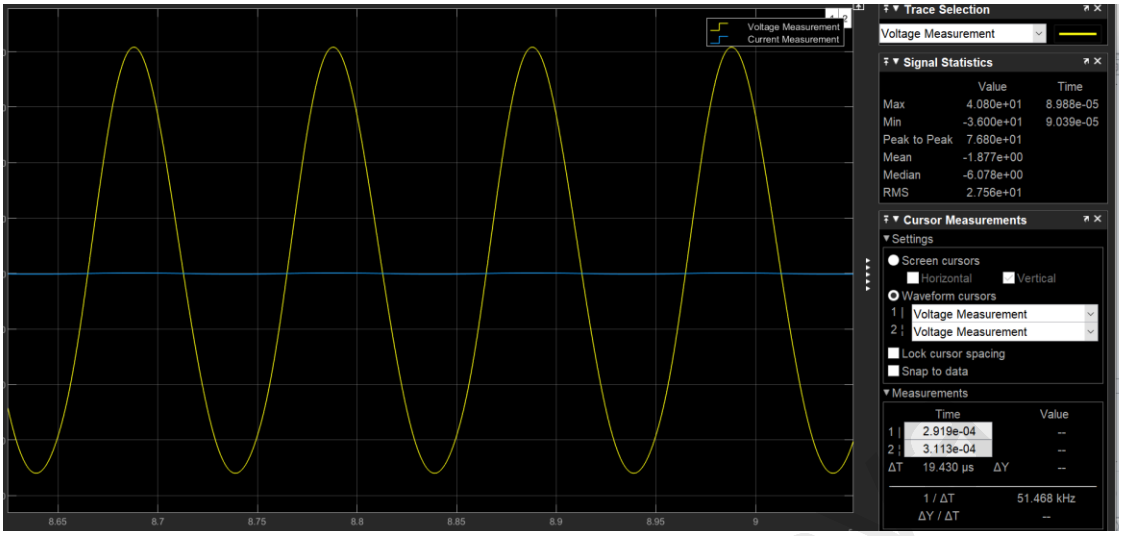
Settings

● Screen cursors
☐ Horizontal ☑ Vertical
○ Waveform cursors
1 Voltage Measurement
2 Voltage Measurement
☐ Lock cursor spacing
☐ Snap to data

Measurements

	Time	Value
1	2.919e-04	--
2	3.113e-04	--
ΔT	19.430 μs	ΔY --
1 / ΔT	51.468 kHz	

Figure 4.15: Output voltage waveform without impedance matching circuit



Trace Selection

Voltage Measurement

Signal Statistics

	Value	Time
Max	4.080e+01	8.988e-05
Min	-3.600e+01	9.039e-05
Peak to Peak	7.680e+01	
Mean	-1.877e+00	
Median	-6.078e+00	
RMS	2.756e+01	

Cursor Measurements

Settings

○ Screen cursors

☐ Horizontal ☑ Vertical

● Waveform cursors

1 Voltage Measurement

2 Voltage Measurement

☐ Lock cursor spacing

☐ Snap to data

Measurements

	Time		Value
1	2.919e-04		--
2	3.113e-04		--
ΔT	19.430 μs	ΔY	--
1 / ΔT			51.468 kHz
ΔY / ΔT			--

Figure 4.16: Output voltage waveform with impedance matching circuit

Table 4.8: Comparison of efficiency

Condition	Vi (V)	Ii (mA)	Pi (W)	Vo (V)	Po (W)	Efficiency (%)
Without impedance	12	91.73	1.160	12.65	0.46	39.41
With impedance	12	189	2.27	27.56	2.17	95.6

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

As a conclusion, the design of capacitive power transfer by Class E inverter circuit is able to be completed via theory calculation and Matlab Simulink circuit simulation. ZVS waveform in the simulation circuit are able to be achieved after the components value have been slightly tuned from the calculated design value in order to get the best ZVS waveform. The ZVS waveform that has been achieved indicates that the Class E inverter circuit is operating at its optimum condition where no switching losses occur. This have been proved by the output power efficiency of the circuit that can reach up to 95.38% and able to deliver 1.91W output power which satisfied the requirement of the implantable pulse generator device in this project design that need 2W of power. Hence, the first objective of this project which is to design capacitive power transfer by implementing class E inverter circuit is achieved.

In addition, the class E inverter circuit has been improved with the implementation of impedance matching circuit in order to maintain high output power efficiency of the circuit system for variable load resistance. Higher RL (R load) values which are 270, 310 and 350 ohm have been analyzed to design the impedance matching circuit. The performance of the class E circuit simulation with and without the impedance matching circuit for all of the resistance value have been observed. The ZVS waveform could only be achieved with the impedance matching circuit for all of the resistance values. All of the three resistance values also gave a very high output power efficiency which are more than 90% efficiency with high output power being delivered while the class E circuit without impedance matching could only produce low output power efficiency which are less than 50% efficiency with a very low output power delivered. This indicates that the second objective to improve output power efficiency by designing impedance matching network in class E inverter circuit has been achieved.

Lastly, the capacitive power transfer system performance have been analyzed for the whole project including theoretical design and simulation design. The simulation circuit system performance are not giving a big difference from the calculation circuit system performance parameter when the calculated values were used in the simulation. Several components value in the simulation circuit need to be tuned slightly from the calculated one in order to achieve the best ZVS waveform to produce high efficiency system performance. The design of class E circuit system performance and the effects of variable load resistance with the improvement by impedance matching in order to maintain high efficiency have been analyzed in this project. Thus, the third objective which is to analyze the capacitive power transfer system performance by output power efficiency also has been achieved.

5.2 Recommendation for future works

In this project, the impedance matching circuit that has been designed in order to maintain high efficiency when higher load resistance is applied is π1b circuit topology. The effects of different types of impedance matching network towards the efficiency and performance of the CPT system can be investigated by applying other types of circuit topology. This will give the best choice of circuit topology to be designed for the CPT system in terms of circuit simplicity, efficiency and power delivered to the load.

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