Senior Design Project Report

CSE/EEE/ETE 499

Wireless Power Transfer for Electric Vehicle

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ELECTRICAL AND COMPUTER ENGINEERING

NORTH SOUTH UNIVERSITY

[SUMMER 2021]

Declaration

This is to certify that this Project is our original work. No part of this work has been submitted elsewhere partially or fully for the award of any other degree or diploma. Any material reproduced in this project has been properly acknowledged.

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Agreement Form

We take great pleasure in submitting our senior design project report on **"Wireless Power Charging for Electrical Vehicle"**. This report is prepared as a requirement of the Capstone Design Project CSE/EEE/ETE 499 A & B which is a two semester long senior design course. This course involves multidisciplinary teams of students who build and test custom designed systems, components or engineering processes. We would like to request you to accept this report as a partial fulfillment of Bachelor of Science degree under Electrical and Computer Engineering Department of North South University.

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By the grace of almighty we have completed our senior design project named "**Wireless Power Transfer System for Electric Vehicles"**.

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Abstract

In the future transport area, electric vehicles are considered as replacement of oil powered internal combustion engine driven vehicle to achieve environmentally-friendly transportation. Even though electric vehicle (EV) usage is currently increasing, a technology breakthrough would be required to overcome battery related drawbacks. To address battery related limitations, the concept of Wireless Power Transfer (WPT) enabled EV has been proposed. Wireless Power Transfer system transfer electric energy from power source to load without wired connection conveniently. WPT is achieved through the affordable inductive coupling between two coils termed as transmitter and receiver coil. In EV charging applications, transmitter coils are buried in the road and receiver coils are placed in the vehicle. Wireless Power Transfer has the potential to overcome the drawbacks of wired chargers and eliminate some hurdles towards vehicle electrification and sustainable mobility. Even though inductive coupling has been applied in some applications of WPT, it is still not efficient enough to transfer high power at the kilowatts level due to weak coupling between the transmitter and the receiver. Using optimally-specified resonant circuits along with inductive coupling can enhance the coupling and make the system more efficient for practical applications. This research aims to design and analyze the performance of a WPT circuit. The optimal specification of a resonant circuit is studied and discussed. Theoretical calculations are performed to find the component values in the circuit to reach. The WPT system is verified by performing simulation tests in the MATLAB/SIMULINK environment. From the sustainability perspective, performance is defined in terms of energy, environmental, and economic metrics, and policy drivers and issues of health and safety are also examined.

Keywords: Wireless power transfer (WPT), electric vehicle (EV), induction power transfer (IPT), resonant circuit.

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CHAPTER 1
INTRODUCTION

1.1 Project Details:

Since global warming is increasing around the world, most of the industries are trying to lessen the emission of carbon through using electrical machine and device. Cars are one of the biggest reasons for air pollution or carbon emission. Today the automotive industry is trying to go full electric cause it causes almost zero carbon emission and is environment friendly. Almost every country in the world is working on the development of EVs. Since we rely too much on gasoline, it's a fact of fear that when there will be a shortage of gasoline, the world will face a huge price hike on gasoline and that will eventually affect the economy of the world. In future transport area, electric vehicles are considered as replacement of oil powered internal combustion engine driven vehicle to achieve environmental-friendly transportation. Electric vehicle has much less carbon emission, which prevent global warming to a considerable extent.

Even though electric vehicle (EV) usage is currently increasing, a technology breakthrough would be required to overcome battery related drawbacks. In an EV, the battery is not so easy to design because of the following requirements: high energy density, high power density, affordable cost, size, weight, fast charging, long cycle life time, good safety, and reliability, should be met simultaneously. Lithium-ion batteries are recognized as the most competitive solution to be used in electric vehicles. However, the energy density of the commercialized lithium-ion battery in EVs is only 90–100Wh/kg for a finished pack. This number is so poor compared with gasoline, which has an energy density about 12000Wh/kg.

To challenge the 300-mile range of an internal combustion engine power vehicle, a pure EV needs a large-amount of batteries which are too heavy and too expensive. The lithium-ion battery cost is about 500$/kWh at the present time. Considering the vehicle initial investment, maintenance, and energy cost, the owning of a battery electric vehicle will make the consumer spend an extra 1000$/year on average compared with a gasoline-powered vehicle. Besides the cost issue, the long charging time of EV batteries also makes the EV not acceptable to many drivers. For a single charge, it takes about one half-hour to several hours depending on the power level of the attached charger, which is many times longer than the gasoline refuelling process. The EVs cannot get ready immediately if they have run out of battery energy.

To overcome this, what the owners would most likely do is to find any possible opportunity to plug-in and charge the battery. It really brings some trouble as people may forget to plug-in and find themselves out of battery energy later on. The charging cables on the floor may bring tripping hazards. Leakage from cracked old cable, in particular in cold zones, can bring additional hazardous conditions to the owner. Also, people may have to brave the wind, rain, ice, or snow to plugin with the risk of an electric shock.

The wireless power transfer (WPT) technology, which can eliminate all the charging troublesome, is desirable by the EV owners. By wirelessly transferring energy to the EV, the charging becomes the easiest task. For a stationary WPT system, the drivers just need to park their car and leave. For a dynamic WPT system, which means the EV could be powered while driving; the EV is possible to run forever without a stop. Also, the battery capacity of EVs with wireless charging could be reduced to 20% or less compared to EVs with conductive charging. Because of all these disadvantages, EV owners are showing interest towards WPT vehicles. Wireless charging can make the task easier and reduce battery size

To address battery related limitations, wireless power transfer (WPT) enabled EV has been proposed. Wireless power transfer system transfers electric energy from power source to load without wired connection. WPT are attractive for many industrial applications because of their advantages compared to the wired counterpart, such as no exposed wire, ease of charging, fearless transmission of power in adverse environmental condition, and high efficiency. In this project the technologies for electric vehicle charging are reviewed using method of inductive coupling. The main focus of the design will be on studying and analyzing a resonant circuit topology to apply to the wireless inductive power transfer (IPT) design.

1.2 Background and Motivation:

A century ago, Nicola Tesla conducted experiments to transfer power wirelessly. In recent decades, wireless power transfer (WPT) has been an area of intensive research to facilitate the penetration of electric products into our lives. To carry the energy between the transmitter and receiver, air medium is used by WPT which is energized by charged particles. Depending on the applications, power ratings and the range of transmission, the energy can be transferred through an electric field, a magnetic field or electromagnetic waves. Depending on the distance the WPT techniques are divided into near field and far field as shown in Fig 1. When the energy is to be transferred through shorter distances, near field methods are used; when it is to be transmitted for longer distances far field techniques are used.

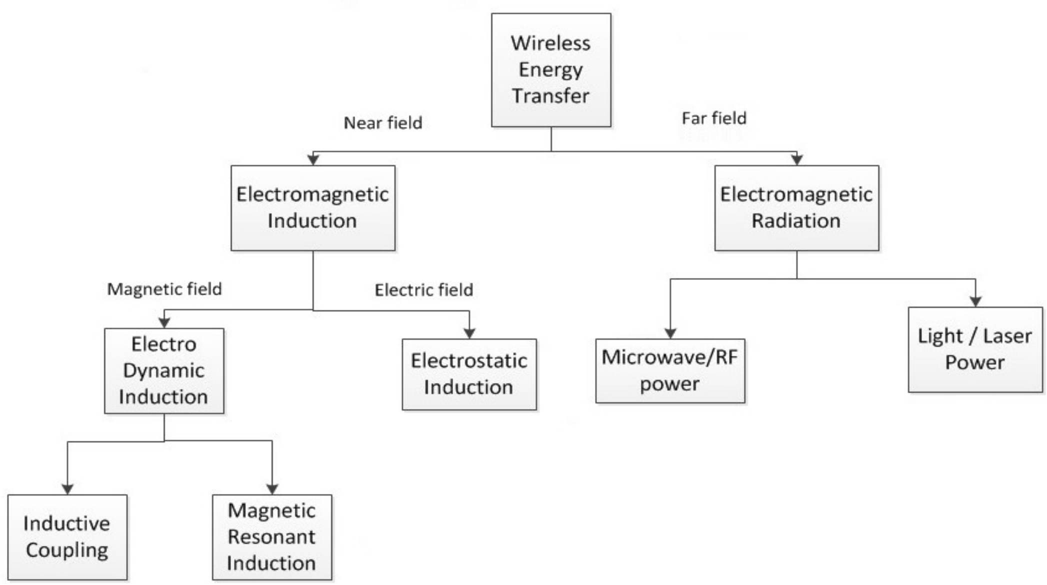


Fig 1: Examples of energy transfer in near field and far field

In the near field transmission, there are two primarily used techniques that are being applied in the present practical applications which can be categorized based on the coupling technology used in them. These coupling techniques are listed below.

1) Inductive coupling

2) Capacitive coupling.

Inductive coupling is one of the near field transmission techniques, in which the energy transfer is done between the two coils through magnetic fields. The coils will be placed in close proximity for transmission from transmitter to receiver. The mutual induction principle is used to transfer the energy between the two coils without using any physical medium. When a current is passed through the transmitter coil, it will produce a magnetic field in short range. When the receiver coil is brought and placed in this field, the current or voltage will be induced in the receiver coil. This induced voltage can be used for charging a device which is wireless or a storage system. In this way the electrical power is transferred from one coil to the other coil using the magnetic field. Because of mutual induction, the energy will be transferred between the coils in inductive coupling. A basic outline of inductive coupling is shown in Fig 2. A transformer can be a best example to explain how mutual induction works in which there will not be any contact between the primary and secondary coils.

Inductive power transfer can handle many kinds of power loads without major problems and with greater efficiency, and it is being used in a wide range of near field applications as it can retain greater efficiency within a meter. The mutual position and the distance of the transmitter and receiver plays a role in deciding the accuracy of transmission. However, this technique works well only for limited, short distances. When the distance is increased between the coils, or the secondary coil is placed apart from the primary coil, the amount of power transfer will be decreased. The application of inductive coupling for power transmission through longer distances is still under development. As in the case of inductive coupling, capacitive coupling is also primarily used for shorter distances, but the transfer of power is done through electric fields.

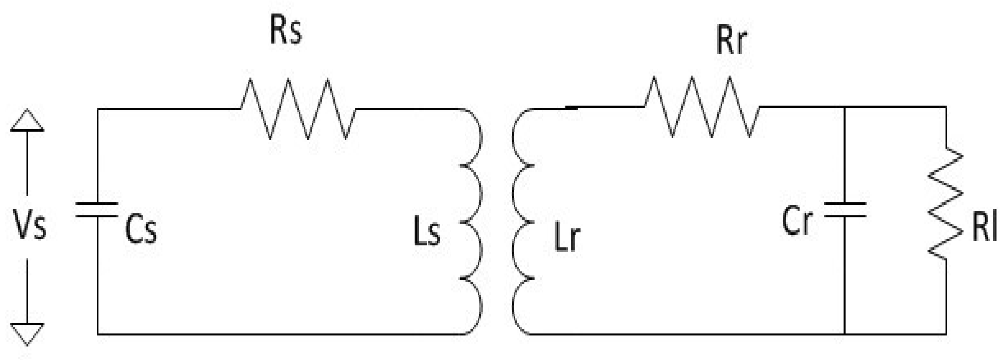


Fig 2: Transformer or Inductive coupling.

Even though both of these coupling techniques can be used for power transfer in EVs, this model uses inductive coupling due to its advantages compared to capacitive coupling. Some of the advantages of inductive coupling over capacitive coupling are:

1) CPT, although it is developing in small gap applications, is limited to low power level transmissions over short distances while IPT can be used for both low power to high power levels. CPT is suitable for gaps smaller than 1mm, while IPT is being applied in applications that require power transfer in centimeters, like in the case of EVs, factories, industrial automotive applications.
2) As IPT deals with magnetic fields in transferring the power, it is comparatively safer than CPT which uses electric fields.

3) IPT can use broad frequency ranges from 10 kHz to 10 MHz, while CPT can use smaller range of frequencies from 100 kHz to 10 MHz.

Although many advantages were mentioned related to IPT, there are few limitations in IPT. The power levels of these systems are not suitable for industrial applications. IPT cannot afford strong coupling between the transmitter and receiver. Due to this loose coupling, it is next to impossible for them to be applied in high power applications. Also, misalignment in the placement of the coils might affect the IPT system performance. I] it is stated that when the coils are placed in 25% of misalignment, efficiency decreases to 92%. Due to these drawbacks, IPT alone cannot be used for designing EV systems. In order to overcome the drawbacks of IPT, this system adopts resonant systems into the IPT system, which can help IPT in increasing the system performance. The features and advantages of implementation of these resonant circuits will be discussed in the following chapter.

Motivation:

This project is to decrease global warming and make transportation environment-friendly. With the present pace in the development of technology and urbanization, the number of personal vehicles is expected to increase. As most of the vehicles being used presently depend on fossil fuels, one can estimate the issues the usage of oil can bring to humanity. It can lead to global climate change, poor air quality and few political conflicts. Presently, the world is using nearly 85 million barrels of oil every day. 60% of the total oil is being used for transportation out of which 25% is consumed by the United States. It is proven that only 1300 billion barrels is available for further usage, which can lead to the scarcity of oil after 40 years. In preventing this, EVs can play a major role as they are clean and secure.

There are other important advantages that play a main role behind using the IPT technique in this system:

1) **Environmentally Friendly**: IPT can work in harsh environments as it has two independently enclosed parts. It is not much affected by dirt, dust or chemicals. It does not produce any kind of carbon residues that might have harmful effects on surroundings. One concern that was raised in IPT is regarding the magnetic effect on human beings. However, some research carried out at the medical school of the University of Auckland shows that there are no observable negative biological effects at low frequency ranges. These low frequencies usually do not have enough power density to heat the human body cells unlike the radio frequencies.

2) **Robustness and Reliability:** There is no electrical erosion or wear and tear in these systems as there is no direct friction. The electrical components of this system are closed completely; thus, it does not encourage any kind of chemical erosion in the conductor parts. Thus, there is less maintenance required.

This project will help me to learn more about how the wireless power transfer systems work and the most efficient wireless power transfer system for electric vehicle for our daily use. This project might help one to learn about the basic functionalities of a WPT in the easiest way.

1.3 Project Goal:

The aim of this thesis is to design, simulate and analyze a Resonant Inductive Wireless power transfer system for EVs, with advantages like improving system performance compared to conventional EV systems. The system designed in this thesis can fit commercial electric vehicle applications.

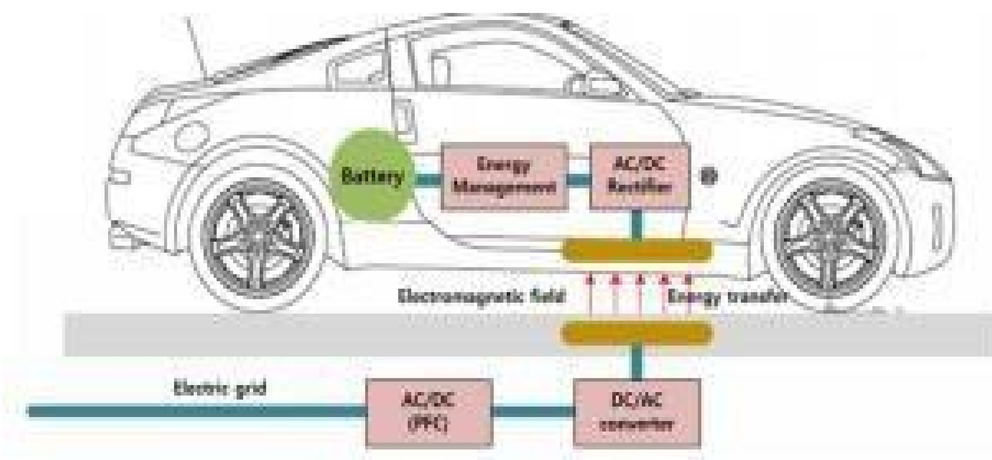


Fig 3: Wireless Power Transfer System for Electric Vehicle (Choi, 2014)

To overcome the disadvantages of IPT, resonant circuits can be integrated into the WPT systems with IPT. In resonant circuit, the supply frequency is made equal to the circuit resonant frequency and when the system is at resonance, it shows high performance. This model system makes use of this advantage and aims at developing a system with improved performance. The main circuit is tested in the simulation. The values of the components are calculated after deriving the equations for each component. These calculations are compared to the simulation results to verify the practicality of the designed model.

Although the goal of the project may change in the project development phases, here, list all the features/functionality/usefulness that this project will achieve by the timeline and we'll try to follow the standards provided by Qi.

Qi is the most widely used wireless standard. Qi was developed by the Wireless Power Consortium (WPC) as a standard for inductive charging across distances of up to 40mm. Many major smartphone manufacturers, including Samsung, Apple, Sony, LG, HTC, Huawei, Nokia (HMD), Motorola, and Blackberry, follow the Qi wireless charging standard. It operates at a frequency of 110-22 kHz and a power of less than 100W. This standard is mostly utilized in the in-vehicle charging, phone chargers, infrastructure chargers, domestic robots, laptop computers, and the speakers.

CHAPTER 2

TECHNICAL DESIGN

2.1 Existing Solution:

Transfer of power wirelessly was discovered and applied by Nikola Tesla. He invented the concept of WPT. This was further improved by other scientists and it was implemented in many applications. Applications like wireless mobile charging, electromagnetic toothbrush, electric vehicles etc., were invented. Electric vehicles were major breakthrough in the fields of Automobile and Transportation [1]. There are three essential requirements an effective and suitable electric vehicle charging structure has to meet: large air gap, high power and high efficiency (Beh, 2010). Electromagnetic waves serve as a means of propagating energy in an RF & Microwave system (Sample, 2011). This transfer of power takes place over air gaps within some km; however, it results in some drawbacks such as line of sight transmission, low power (less than 1 kW) transmission, a great loss in the air, low efficiency and an extensive effect on its environment (Wang, 2011). Inductive Power Transfer (IPT) (Xui, 2013) also referred to as non-resonant inductive method (Karalis, 2008) or electromagnetic induction or inductive coupling method (Sample, 2011) has low charging distance (about few centimeters) (Xui, 2013) because of its loose coupling between the receiving and transmitting coils respectively (Hasanzadeh, 2012).

2.1.1. Different Techniques for Wireless Electric Vehicle Charging

There are different techniques developed for charging electric vehicle battery, these include:

- Magnetic induction
- Microwave
- Capacitive coupling

Magnetic Induction Coupling

The magnetic induction coupling makes use of the principle of electromagnetic induction in which an electric vehicle is wirelessly charged. Its arrangement is composed of two coils. Current flows through the transmitting coil, which produces a varying magnetic field, thus inducing a current in the receiving coil, which in turn charges the electric vehicle.

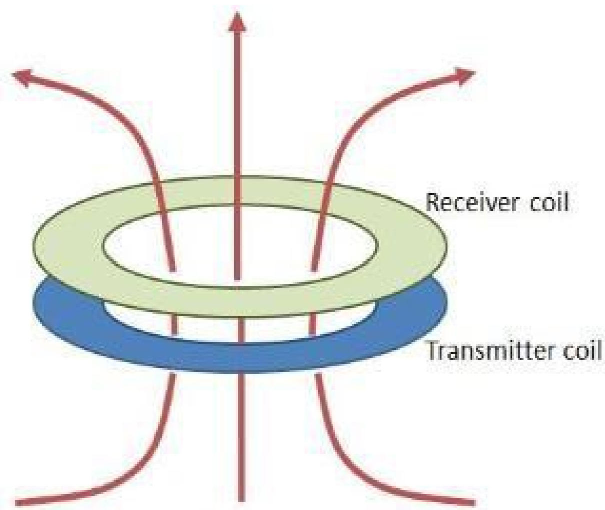


Fig 4: Operation of magnetic induction method

For inductive coupling to be efficient, the transmitting and the receiving coil must be near each other and well aligned. This method forms the foundation for the creation of the Wireless Power Consortium (WiTricity, 2014) (world's first international wireless charging standard-QI.) The standard started with low power (about 5W) at a 4 cm distance, published in 2009. The rule stretched to medium-power (about 120W) in 2011. IPT systems are resilient to environmental conditions and thereby very convenient for all flux guidance, which makes it operate at low frequencies; hence, the size reduces due to core losses (Covic, 2013; Haque, 2018).

Furthermore, in the magnetic induction method, there is a wireless power transfer through magnetic coupling from a fixed transmitter to the various moving secondary receiver (Wu, 2011). The transmitter and receiver coils have a large air gap, which causes the magnetic coupling effect between the coils to change. The change decreases the stability of the system due to the different charging cycles of the electrical properties (Siqi and Chunting,

2015). Based on the power specifications, it can only be a one-phase or three phase supply. A WPT system is usually composed of the battery, transmitting coil, receiving coil, electrical grid, microcontrollers, sensors, matching circuit (Vilathgamuwa, 2015). The topologies of the inductive power transfer are either distributed or lumped based on the coil's magnetic configuration (Mahbub, 2019). The magnetic field created
from the primary coil can be controlled and strong for wirelessly transferring power due to its constant frequency current. From the electrical grid, there is a generation of low-frequency alternating current created in the transmitting coil. The coupling of the transmitting coil and the series of receiving coils is via magnetic fields.

Advancement in power electronics technology has led to the discovery of a new application based on the IPT system like wireless EV charging over large air gaps, power wirelessly generated used by professional devices. These are examples of high-power applications (Swain, 2012). Lighting, medical implants, and mobile phones are examples of low power applications (Wang, 2005). In general, the mutual coupling in the IPT system is weak (Shital, 2016). Some of the advantages of IPT systems are as follows (Shital, 2016):

- The system is safe.
- The cost of maintenance is minimal
- It is durable.
- Conservation of energy.
- The system is reliable
- No magnetic field radiation.

Disadvantages include:

- Misalignment of transmitter and receiver coils
- Charging is only efficient on short distances (less than the coil diameter)

Microwave Power Transfer (MPT)

Radiative (far field) technique is another name for MPT. This type of wireless power transfer involves the use of radio waves to transmit power and the wavelength of the radio wave is lowered to that produced by microwave (Kawasaki, 2013). The components of MPT include a receiver, transmitter antenna, and generator (Kawasaki, 2013). It is important to note that there is no magnetic coupling between the transmitter and receiver antennas (Kawasaki, 2013). In this type of WPT system, transmitting and receiving antennas are magnetically separable therefore variation in the impedance of the transmitting and receiving antennas are not considered whereas, in the magnetic inductive and magnetic resonance coupling, there are considerations for variation in impedance (Shinohara, 2013). Microwave power transfer for the electric vehicle is a relatively new concept that works more efficiently than others. The transmitter of the microwave phased array generates a beam at frequencies of about 2.44 GHz and 5.79 GHz by direct current supply and discharges to rectenna of the EV underneath the vehicle.

The drawbacks of this system include: high power transmission in MPT (therefore detrimental to human health), minimal efficiency and its limitation to only straight-line propagation (Hossain, 2012).

Capacitive Wireless Power Transfer

The capacitive coupling method for transferring power wirelessly is newly applied in the EV battery charging. Its interface is composed of metallic sheets with an insulating coating at the secondary and primary side (Rozario, 2016). An inverter with a high frequency triggers the coupling interface, which in turn generates an electric field in between the primary and secondary side thereby allowing the flow of current; hence, power is transferred (Rozario, 2016; Haque, 2018). Figure below is the capacitive coupling system represented with a simple diagram by Young Soo. Here, a direct current voltage transformed to an alternating current voltage is with a high frequency, which in turn delivered to two primary metallic sheets by the inverter with high frequency (You, 2016).

The flow of displacement current generated by the electric field is because of the closeness between the primary and secondary metallic sheets. A rectifier then converts the AC to DC voltage (You, 2016).

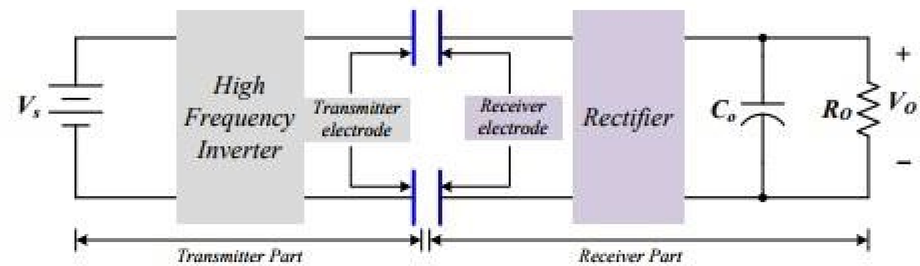


Fig 5: Operation of capacitive coupling method

One of the major advantages of the capacitive wireless power transfer is that the electric field passes through metal constraints with minimal power loss generated which makes it good for EV charging (Vincent, 2017). The metallic sheet can be Al, and this is cheap in comparison with litz Use section 1.2 and add detail of designs to that level at which proposed solution will be compared. inductive coupling (Vincent, 2017). By coating the surfaces of coupling plates with dielectric materials, the coupling capacitance can improve in providing electrical isolation. When an inductor is connected in series with the coupling plates and the equivalent coupling capacitor is tuned, enough power is achieved (Liu, 2011; Haque, 2018). There is no need for ferrites for flux guidance which makes it suitable to work at high frequencies and hence have higher efficiency and power transfer

densities than an inductive coupling technique (Lu, 2016). The system of capacitive coupling has a simple structure in comparison with other WPT techniques making it overcome misalignment problems greatly (Vincent, 2017).

Advantages by Murata include:

- The devices on the charging pad are positioned freely.
- Flat metal plates.
- There is a minimal rise in the electrode's temperature.

- Reduced power and frequency utilization because of the great potential difference across the metal plate

Disadvantages include:

- Efficiency is very low.
- Coupling capacitance is small.

Due to these drawbacks, IPT alone cannot be used for designing EV systems. In order to overcome the drawbacks of IPT, this system adopts resonant systems into the IPT system, which can help IPT in increasing the system performance. The features and advantages of implementation of these resonant circuits will be discussed in the following chapter.

2.2 Proposed Solution: Magnetic Resonant Wireless Power EV Charging

Methodology:

Magnetic induction operates on the principle of a transmitting coil that generates a magnetic field and a receiving coil inside the magnetic field, which induces the current in the coils (Hui, 2013). Generally, this leads to a short range because of the measure of energy needed to deliver a magnetic field. Therefore, the non-resonant method is incompetent for longer distances making it waste more energy when transmitting over longer distances. The resonance here improves efficiency drastically by channelling the electromagnetic field to the receiving coil resonating at a matching frequency (Hui, 2013), thereby increasing the charging distance as compared to other methods, which make it have the highest potential in the future. It is important to note that due to resonance characteristics, power transfer affects objects operating at a matching frequency and has no effect on objects with nearly matching frequencies. (Hadley, 2007.)

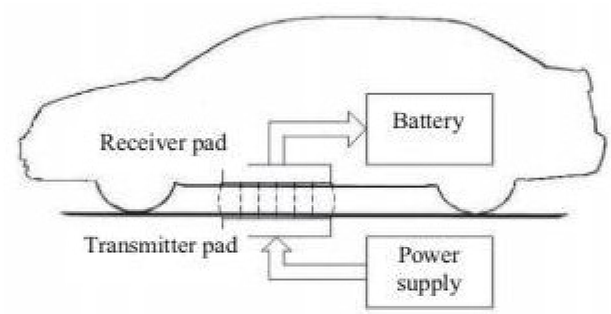


Fig 6: Wireless stationary vehicle charging (Hui, 2013)

The above figure shows a simple structure of the magnetic resonance coupling. The primary coils are used as a transmitting pad beneath the ground and the secondary coils are the receiver pad. There is an electric power transfer from the pad underneath the ground to the one mounted on the chassis of the vehicle without there being any contact with the two pads when the electric vehicle is parked at a fixed place (Bahareh, 2018). The resonant compensation helps to remove the great inductance leakage, and the small coupling to transfer power productively (Ching, 2017). The main compensation structures for magnetic resonant WPT method are PP, SS, PS-SP networks (Zhang, 2016).

Furthermore, the method is explained with the principle of a vibrating tuning fork, which is an application of the sound resonance. When a coil vibrates, the surrounding coil, having the same natural frequency, is excited thereby producing energy for charging the electric vehicle.

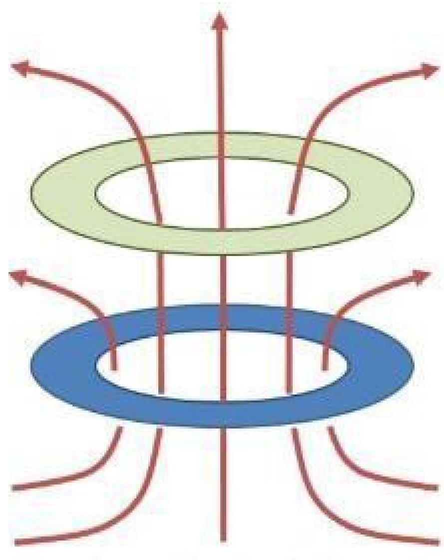


Fig 7: Magnetic Resonance Operation technique

Advantages:

- High frequency
- High power
- Longer charging distance

Disadvantages:

- Needs greater windings
- Is more costly

Resonant Inductive Power Transfer:

Early work on integrating WPT with resonance was started by Tesla, who explained the advantages of tuning the transmitting and receiving coils at resonance frequency, which is like the concept of an oscillation transformer. The oscillation transformer is the main principle behind the integration of resonance with WPT. As discussed in chapter 1, resonant circuits are implemented along with the IPT in order to increase the coupling and performance of the IPT system. Application of resonant circuits can increase the transmitting distance of the IPT systems. Resonant circuits are applied to get the resonance frequency, which can improve the rate of energy transfer. A resonator consists of a combination of an inductor and capacitor. This technique of combining inductive coupling and resonance is known as magnetic resonance coupling. Magnetic resonance coupling enables the interactions between two objects very strongly. In this technology, energy can be transferred from the source to the receiver very efficiently, with very little loss of energy. It is highly efficient, with negligible radiation losses and provides great range and directionality when compared to the conventional IPT.

Because of the resonance property, magnetic resonance coupling is immune to the neighboring environment. In an IPT system without resonance, the power transfer between the transmitter and receiver can decrease if there is a misalignment in the positions of primary and secondary coils, but inclusion of resonant circuits can give flexibility in the orientation between the source and load during the operation. One of the most advantageous features of magnetic resonance coupling is that it can also be applied between one transmitter and many receivers. It can transmit the power even if the multiple load devices have different power requirements. This technique is leading in the research field, and because of these advantages it is being applied in EVs, consumer electronics, biomedical implants, wireless sensor networks, and robotics power supplies.

In an electric circuit, electrical resonance is a phenomenon that occurs at a particular frequency known as resonant frequency when the imaginary parts of impedances or admittances of the elements of circuit cancel each other out. The response of a circuit is maximized at this particular resonant frequency. Resonance can occur in any circuit that has a combination of an inductor and a capacitor as both these elements can store the energy. In a resonant circuit, the energy will be oscillating between both the inductor and capacitor and the rate of transfer of the energy between these two elements depends on the values of L and C. Because of these energy transfer oscillations, we will see oscillations in the circuit. If this circuit is ideal, and if there is no presence of any kind of resistive elements, these oscillations will continue forever. In reality, though, all the circuits will have some resistance involved in them. Because of the presence of this resistance, there will be depreciation in these oscillations. To maintain these oscillations, we must provide supply from an external source with the same frequency to this LC circuit (which was addressed as resonant frequency). This way we can maintain the oscillations. Parallel and series RLC circuits are the two main basic resonance circuits. In resonance circuits, the sharpness of the resonance can be measured by a term called Quality factor. The Quality factor is given by the formula below.

$$Q = 2\pi \times \frac{Maximum\ Energy\ stored\ in\ the\ circuit}{Energy\ Dissipated\ by\ the\ circuit\ in\ period\ at\ resonance}$$

Another main advantage of resonant circuits that makes them suitable for IPT applications is that they can boost the voltage and current levels depending on their topology. For example, a series resonant circuit can act as a voltage amplifier and a parallel resonant circuit can act as a current amplifier. When the circuit applied acts as a voltage amplifier, the voltage produced at the resonant circuit will be very high compared to the input supply voltage.

2.3 Solution Assessment:

Inductive power transfer (IPT) is an emerging technology for transferring power without any physical contact based on electromagnetic induction. This technology has recently found many applications in commercial and residential sections such as material handling, biomedical implants, transportation systems and static and dynamic electric vehicle charging. This technology is employed to transfer power from one system to another across a relatively large air gap between two loosely coupled inductors which have a weak magnetic coupling. Since it is unaffected by dust or chemicals and eliminates sparking and the risk of electrical shock, it can be used in hazardous environments. This technology offers high reliability, robustness, high efficiency and provides a clean, safe, and robust way of transferring power. Also, it has rapidly gained an increased interest in the industrial and commercial sectors. In Figure 1, a typical IPT system is shown. This system is composed of power converters, loosely coupled magnetic structures and compensation components.

Contactless electric vehicle (EV) charging based on inductive power transfer (IPT) systems is a new technology that brings more convenience and safety to the use of EVs. It enables automated charging processes without the interaction of the driver by eliminating the charging cables. Contactless EV charging is divided into two main categories: static charging and dynamic (in-motion) contactless charging. In static charging, the goal is to charge the EV using a contactless charger when the EV is parked in a charging station. This is a solution that enables safe, efficient, and convenient overnight recharging of EVs. On the other hand, a dynamic contactless EV charging system enables contactless charging of the EVs while they are moving. This system is comprised of a power supply, primary and secondary converters, primary and secondary magnetic structures, and corresponding compensation circuits. The existing barriers in the deployment of IPT systems are their high cost, lower efficiency compared to conventional charging systems, vehicle misalignment sensitivity, and electromagnetic field (EMF) emissions. The aim of this research is to enhance the efficiency and reduce the cost and contribute to the development of IPT technology for EV charging applications.

2.4 Technical Design: Module Level

Block Diagram:

Figure below shows the block diagram model of the system. The input is from the AC mains and converts to a direct current with the help of the rectifier. Usually, the AC signal from the wall outlet is unsuitable for the coils because from the formula [Zc= 1/jwc= -jwc], the capacitance might be too small or too big. The voltage output, from the rectifier is converted to the required AC frequency by the inverter circuit switched at a frequency good enough to resonate the transmitting and receiving coils respectively. This is because the coils can only work when AC is applied. The high AC frequency is delivered to the transmitting coil, hence inducing a magnetic field, which is received by

the receiving coil through the electromagnetic induction principle. The coil, in turn generates an e.m.f. Next, it passes through the rectifier, and a DC-DC buck converter as the battery requires a DC voltage to operate. A three-level cascaded PI controller helps to control the variation of the voltage induced at the receiver to realize a steady voltage output to the battery.

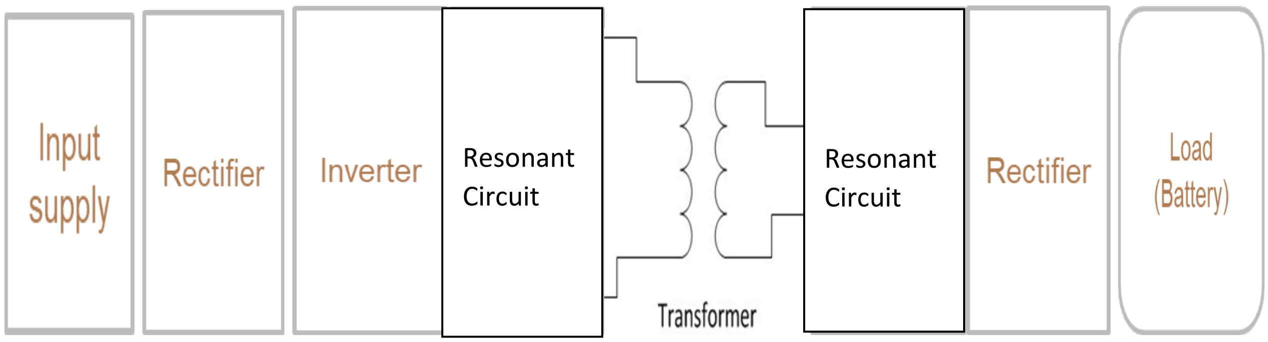


Fig 8: Block Diagram

2.5 Technical Design: System Level

The main circuit can be divided into two sides-transmitter side or the primary side and the receiver side or the secondary side. The circuit consists of two AC to DC full bridge rectifier circuits, an DC to AC converter and a mutual inductor for the wireless power transfer. We have taken a high frequency value of 40 kHz for the transmitter side for wireless power transmission the higher frequency will improve the rate of transfer of electrical energy from the primary side to the secondary side of the circuit.

$$f_{r(p,s)} = \frac{1}{2\pi\sqrt{L_{p,s} \cdot C_{p,s}}}$$

where fr is the primary and secondary coils' resonance frequency, and L and C are the transmitter and receiver coils' self-inductance and resonant capacitor values, respectively. When the primary and secondary coils' resonance frequencies are matched, efficient power transfer is feasible. In the wireless transformer design, magnetic ferrite cores are used in a variety of structures to increase the coupling coefficient.

In a series resonant circuit, this Quality factor is given by equation below.

$$Q = \frac{\omega o L}{R} = \frac{1}{\omega o C R} = \frac{1}{R}\sqrt{\frac{C}{L}}$$

Whereas in a parallel resonant circuit, it is given by following equation.

$$Q = \frac{\mathbf{R}}{\boldsymbol{\omega o L}} = \omega_o RC = R\sqrt{\frac{C}{L}}$$

Another main advantage of resonant circuits that makes them suitable for IPT applications is that they can boost the voltage and current levels depending on their topology. For example, a series resonant circuit can act as a voltage amplifier and a parallel resonant circuit can act as a current amplifier. When the circuit applied acts as a voltage amplifier, the voltage produced at the resonant circuit will be very high compared to the input supply voltage.

In a series circuit, at Resonance, the voltage across the inductor can be given by equation

$$V_L = \frac{Vm}{\mathbf{R}} \omega_o L$$

We know that, $\frac{\omega o L}{R}$ is the Quality factor Q, so in the above equation, if we replace that term with Q, we get equation

$$V_L = V_m Q$$

From the above equation, it is evident that the voltage across the inductor will be much larger than the input supply voltage; hence, this circuit can act as a voltage amplifier. The same concept can be applied for the voltage across the capacitor, so by properly designing the values of L and C in the resonant circuit, we can acquire higher voltages at higher frequencies.

Mathematical Modeling for WPT:

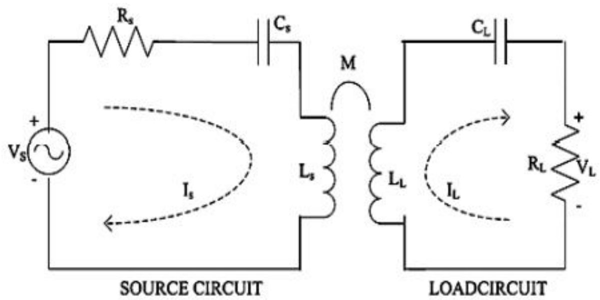


Fig 9: Basic WPT circuit.

Figure above shows a schematic of the WPT system's electric equivalent. The supply voltage excites a source coil (LS) with parasitic resistance (RS) and

a measure of capacitance (LS). The inductive link transmits power to the inductance-loaded load coil (LL). The load (RL) is the amount of work that must be linked to the parasitic capacitor (CL) via a rectifier coil to be loaded Zin is the input impedance of a load RL. It's possible to write linked in the load coil as,

$$Z_{in} = R_{SS} + j\omega L_S + \frac{\omega^2 M^2}{j\omega L_L R_{LS} + Z_L}$$

Here, Rss denotes the combination of source resistance RS and mutual inductance (M). It gives the relation of coupling factor

$$k = \frac{M}{\sqrt{L_S L_L}}.$$

Finding the value of capacitor using MATLAB Command:

Here we have taken LS=LL=1e-3 and angular frequency, W=1/40000 to find the value of the capacitor connecting to the mutual inductors.

PWM Module:

The system consists of a PWM module, which consists of two circuits that generate pulses to control the switches in the inverter. These two circuits are:

1) Controller IC

2) Driver circuit.

The controller controls the inverter switches by phase shifting the switching of one-half bridge with respect to the other, allowing constant frequency pulse width modulation. It provides the signals to the driver circuit, which is an interface between the controller and the switches.

Purpose of gate driver circuit

In general, MOSFETs have some parasitic capacitance because of their structure. This parasitic capacitance can limit the switching speed of MOSFET. Usually, the input parasitic capacitance which is the total of gate source capacitance and gate drain capacitance when seen from the input, must be charged in order for the MOSFET to turn ON, so this parameter is important in practical applications. This parasitic capacitance at the input must be charged at least to the minimum gate voltage required for the MOSFET to operate. To turn OFF the transistor, this capacitance should be discharged.

Also, when the MOSFET is switched on or off, it might not start conducting immediately and might conduct high current. The gate current that is applied to MOSFET to turn it ON, can produce a certain amount of heat which might even damage the MOSFET in a few cases, so in order to decrease the switching losses, decreasing the switching time might be necessary, but the decrease in switching time might requires more current to charge the gate. The control signal that is generated from the microcontroller is limited to current whose magnitude is in the range of a few milli amperes.

With this small amount of current, the MOSFET will turn ON very slowly producing considerable switching losses. Also, the parasitic capacitance mentioned before might draw current very fast, which might lead to excess current draw causing damage to the hardware involved. The usage of gate drivers might prevent all this damage from happening. The gate driver can produce a high current input for the MOSFET gate. This can reduce the switching time and the switching losses. In this way, the gate driver prevents the switches from damage and acts as an interface between the controller and power switches

Since the inductors have the same values the capacitor values for the primary and the secondary side of the circuit will be the same.

```
Command Window
>> w=1/40000

w =

   2.5000e-05

>> ws=w^2

ws =

   6.2500e-10

>> c=1/(ws*1e-3)

c =

   1.6000e+12

fx >>
```

Fig 10: Using MATLAB to find the capacitor value for the resonance frequency of 40kHz

Circuit Diagram of the Whole System:

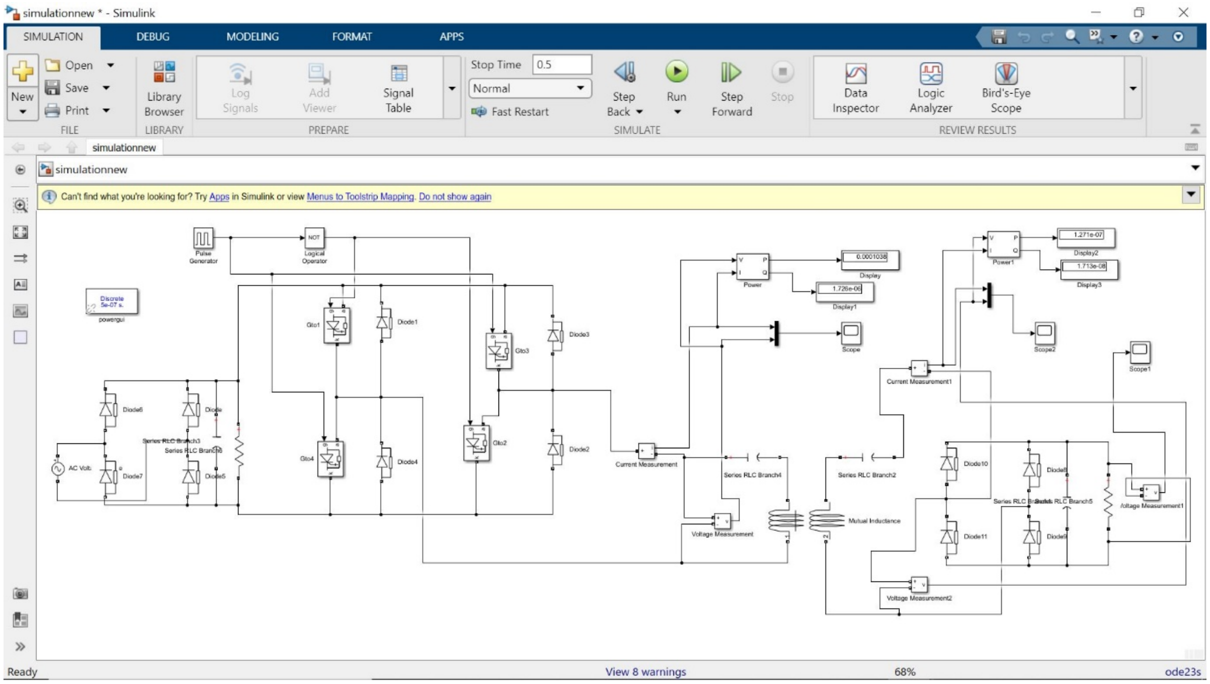


Fig 11: Simulink Schematic Diagram of the WPT System

Inverter circuit: The basic role of an inverter is to change DC power into AC power. The AC power can be supplied to homes, and industries using the public utility otherwise power grid, the alternating-power systems of the batteries can store only DC power. In addition, almost all the household appliances, as well as other electrical equipment can be functioned by depending on AC power. it converts DC to AC, and these devices never generate any kind of power because the power is generated by the DC source. The **full bridge inverter circuit** converts direct current to alternate current. It can be achieved by opening as well as closing the switches within the correct series. This type of inverter has dissimilar operating states which depend on closed switches. The output of the rectifier feeds into the inverter. The element making up the inverter is the MOSFET, and the pulse generation circuit. The Simulink model design of the inverter is in figure below. Note that the pulse generator of the inverter produces switching pulses, which feeds into the inverter input; hence, the inverter generates a square wave, which feeds into the transmitting end of the coil.

S1	S2	S3	S4	Vo (Inverter output voltage)
ON	ON	OFF	OFF	Vin
ON	OFF	ON	OFF	Zero
OFF	OFF	ON	ON	-Vin
OFF	ON	OFF	ON	Zero

Table 1: Different stages of full bridge inverter.

From the above table, one can understand the output of the inverter according to the different switching actions of the switches.

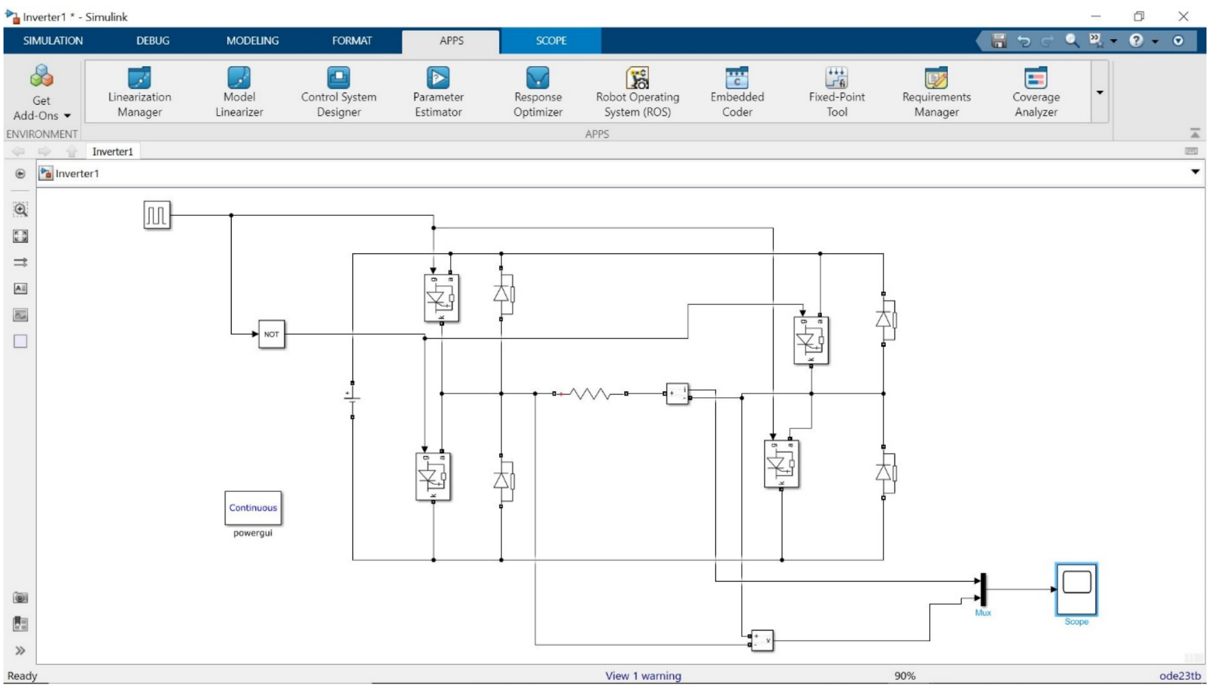


Fig 12: Schematic diagram of an inverter circuit.

Full Bridge Rectifier Circuit: A full bridge rectifier, or more simply, a bridge rectifier, is an arrangement of four or more diodes in a bridge circuit configuration, which provides the same output polarity for either input polarity. It is used for converting an alternating current (AC) input into a direct current (DC) output. This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop "bridge" configuration to produce the desired output.

The main advantage of this bridge circuit is that it does not require a special centre tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown below.

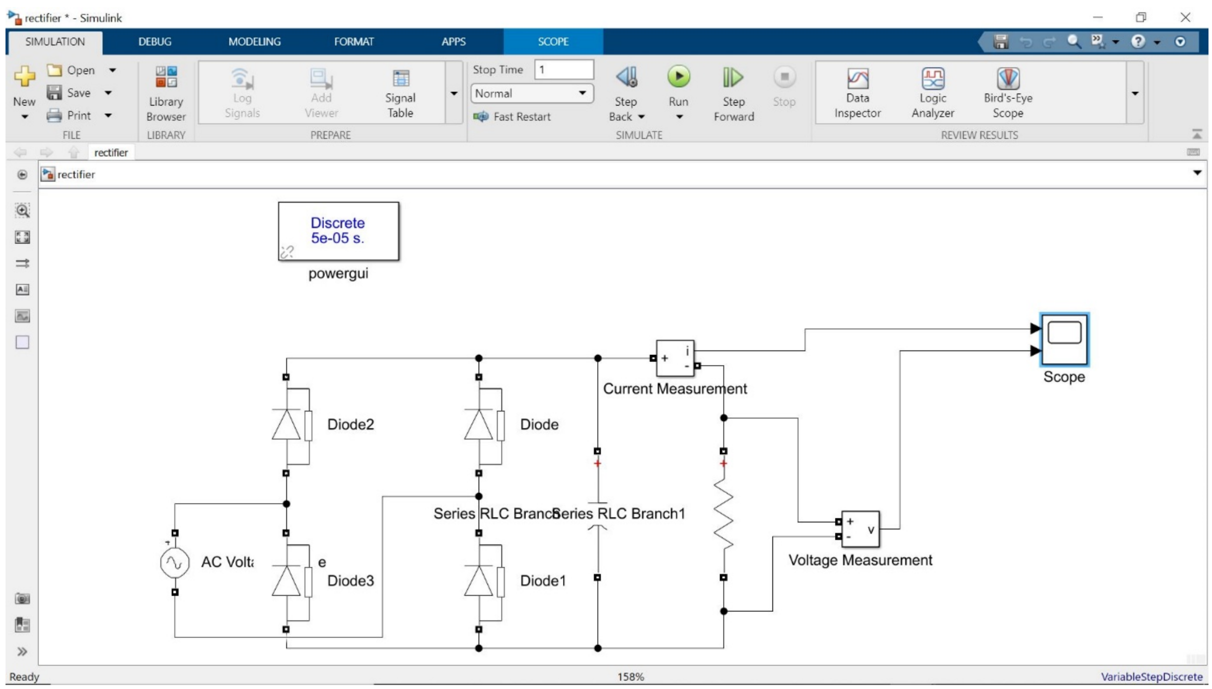


Fig 13: Schematic diagram of a full bridge rectifier circuit.

RC Filter: The RC filter is combined of two elements- a capacitor and a resistor connected parallel to the capacitor. The filter is used to make the output of the full bridge rectifier smoother so that we can get a fixed DC voltage for the stability of the whole wireless power transfer system otherwise we'd get a time varying DC output which may affect the longevity of the charging of the battery in the EV.

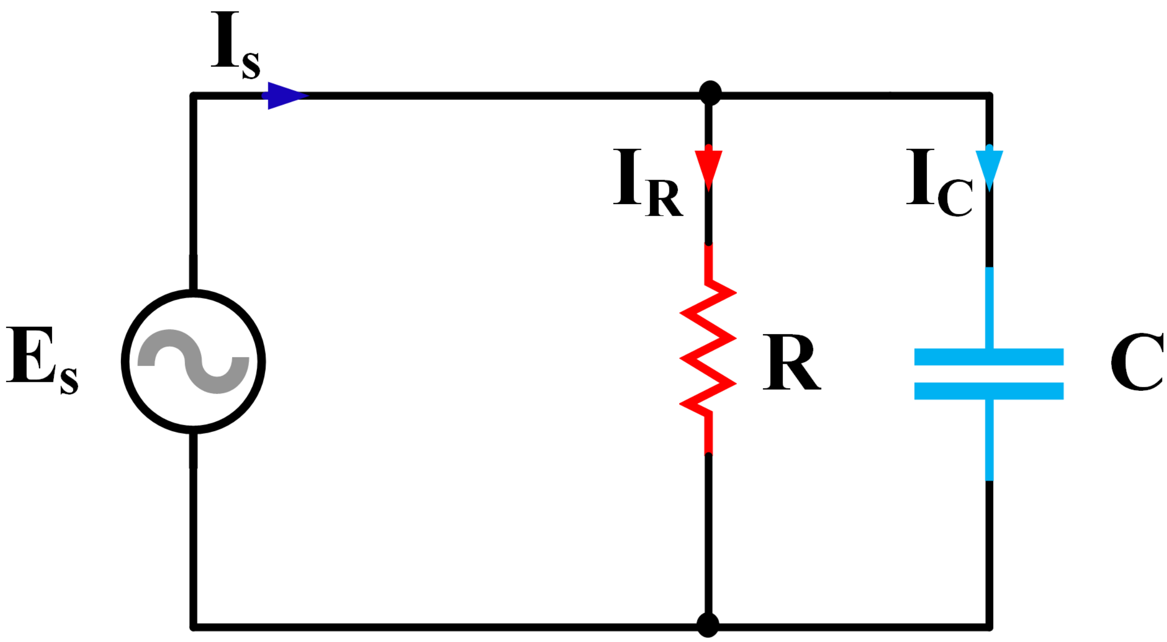


Fig 14: Circuit diagram of a basic RC filter.

2.6 Required Skills:

1. Operating in Simulink
2. The basic knowledge about EVs
3. The basic knowledge about rectifier circuit
4. The basic knowledge about power transfer systems
5. The basic knowledge about resonance circuit
6. The basic knowledge about Inverter
7. The basic knowledge about filter circuits

CHAPTER 3

ESSENTIAL PARTS AND DEVICES

3.1 Description of Components:

Component block type	No of component blocks used
1. Diodes	**12**
2. Gate Turn off Thyristor	**4**
3. AC source	**1**
4. Resistors	**2**
5. Capacitors	**4**
6. Pulse Generator	**1**
7. Logical Operator (NOT)	**1**
8. Mutual Inductance(2 winding)	**1**

Table 2: No and types of component blocks used in simulink

Diodes:

The diode is a semiconductor device that is controlled by its own voltage Vak and current Iak. When a diode is forward biased (Vak > 0), it starts to conduct with a small forward voltage Vf across it. It turns off when the current flow into the device becomes 0. When the diode is reverse biased (Vak < 0), it stays inthe off state.

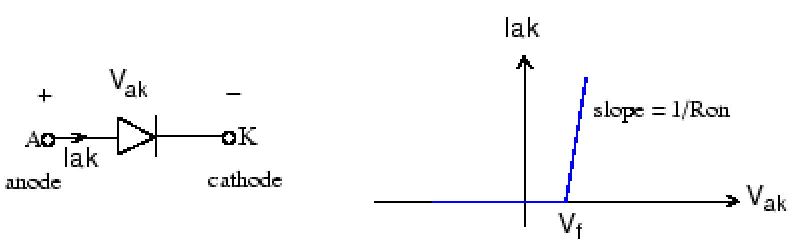


Fig 15: Diode schematic and V-I characteristics

The Diode block is simulated by a resistor, an inductor, and a DC voltage source connected in series with a switch. The switch operation is controlled by the voltage Vak and the current Iak.

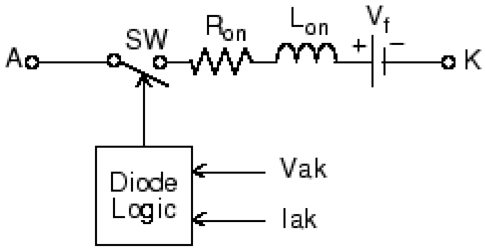


Fig 16: Diode working principle in logic level

Gate Turn-Off Thyristor:

The gate turnoff (GTO) thyristor is a semiconductor device that can be turned on and off via a gate signal. Like a conventional thyristor, the GTO thyristor can be turned on by a positive gate signal (g > 0). However, unlike the thyristor, which can be turned off only at a zero crossing of current, the GTO can be turned off at any time by the application of a gate signal equal to 0.

The GTO thyristor is simulated as a resistor Ron, an inductor Lon, and a DC voltage source Vf connected in series with a switch. The switch is controlled by a logical signal depending on the voltage Vak, the current Iak, and the gate signal g.

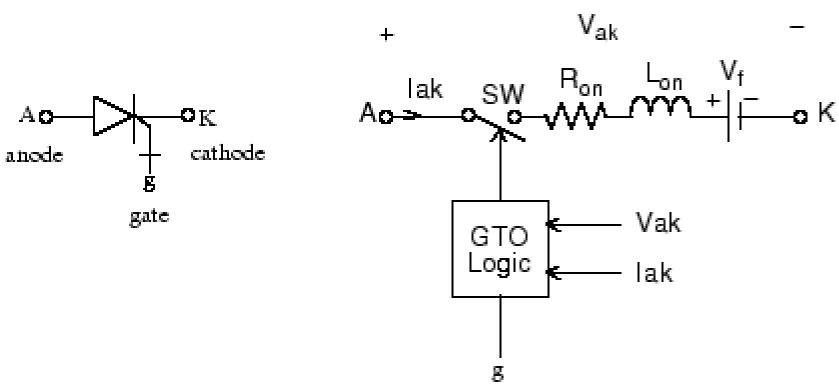


Fig 17: GTO thyristor schematic and working principle in logic level

Pulse Generator: The Pulse Generator block generates square wave pulses at regular intervals. The block waveform parameters, **Amplitude, Pulse Width, Period**, and **Phase delay**, determine the shape of the output waveform. The following diagram shows how each parameter affects the waveform.

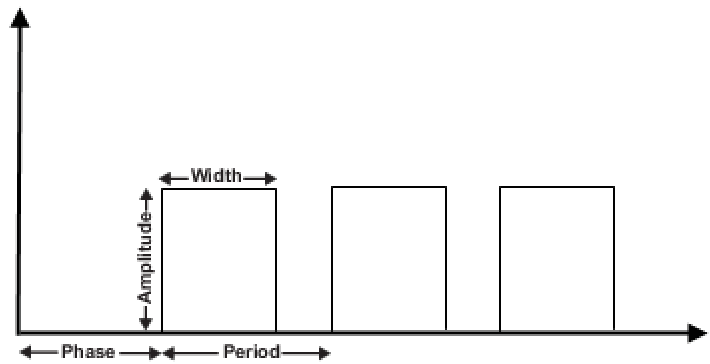


Fig 18: Pulse Generator output

The Pulse Generator block can emit scalar, vector, or matrix signals of any real data type. To emit a scalar signal, use scalars to specify the waveform parameters. To emit a vector or matrix signal, use vectors or matrices, respectively, to specify the waveform parameters. Each element of the waveform parameters affects the corresponding element of the output signal. For example, the first element of a vector amplitude parameter determines the amplitude of the first element of a vector output pulse. All the waveform parameters must have the same dimensions after scalar expansion. The data type of the output is the same as the data type of the **Amplitude** parameter.

The block output can be generated in time-based or sample-based modes, determined by the **Pulse type** parameter.

Logical Operator(NOT): The Logical Operator block performs the specified logical operation on its inputs. An input value is true (1) if it is nonzero and false (0) if it is zero.

You select the Boolean operation connecting the inputs with the Operator parameter list. If you select rectangular as the Icon shape property, the name of the selected operator displays on the block icon. If you select distinctive as the Icon shape property, the name of the selected operator does not display on the block icon. This table shows supported operations:

Operation	Description
AND	TRUE if all inputs are TRUE
OR	TRUE if at least one input is TRUE
NAND	TRUE if at least one input is FALSE
NOR	TRUE when no inputs are TRUE
XOR	TRUE if an odd number of inputs are TRUE
NXOR	TRUE if an even number of inputs are TRUE
NOT	TRUE if the input is FALSE

Table 3: Logical operands and their behaviors

Mutual Inductance: The Mutual Inductance block can be used to model two- or three-windings inductances with equal mutual coupling, or to model a generalized multi-windings mutual inductance with balanced or unbalanced mutual coupling.

If you choose to model two- or three-windings inductances with equal mutual coupling, you specify the self-resistance and inductance of each winding plus the mutual resistance and inductance. The electrical model for this block in this case is given below:

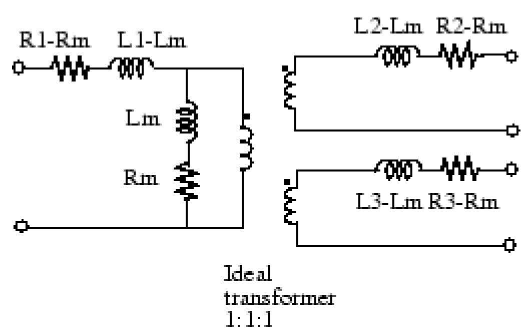


Fig 19: 3-phase mutual inductor

If you choose to model a general mutual inductance, specify the number of self-windings (not just limited to 2 or 3 windings) plus the resistance and inductance matrices that define the mutual coupling relationship between the windings (balanced or not).

3.2 Test Requirements:

A desktop or laptop computer which can run Matlab smoothly and has Matlab Simulink installed in the hard drive. The minimum system requirement to run this simulation in a desktop/laptop is given below:

Operating Systems: Windows 10 (version 1909 or higher) or Windows 7 Service Pack 1

Processors
Minimum: Any Intel or AMD x86-64 processor
Recommended: Any Intel or AMD x86-64 processor with four logical cores and AVX2 instruction set support
Disk
Minimum: 3.4 GB of disk space for MATLAB only, 5-8 GB for a typical installation
Recommended: An SSD is recommended
A full installation of all MathWorks products may take up to 30 GB of disk space
RAM
Minimum: 4 GB
Recommended: 8 GB
For Polyspace, 4 GB per core is recommended
Graphics
No specific graphics card is required.
Hardware accelerated graphics card supporting OpenGL 3.3 with 1GB GPU memory is recommended. GPU acceleration using Parallel Computing Toolbox requires a GPU that has a compute capability 3.0 or higher.

CHAPTER 4

WORKING SHEETS

4.1 Work Breakdown Structure:

The whole project was covered in 24 weeks by two parts.

Week	What have been covered
1	Project group created and discussed about our interests
2	Researched on our personal interests and enlisted them
3	Analyzing our personal interests and deciding to select this project
4	Read research papers which were relevant to our project
5	Worked on our methodology
6	Analyzed the total cost for our project
7	Checked the availability of resources for our project
8	Made two proposals based on our conflicts of interests
9	Selected one of the topic and reworked on our project proposal
10	Figuring out the most possible way to make our project practical
11	Working on the PowerPoint presentation
12	Presentation
13	Selection of simulation software that will be best for our project
14	Researching further about our topic
15	Making a mathematical model for our project
16	Trying to simulate each of the block differently : Inverter
17	Trying to simulate each of the block differently : Full Bridge Rectifier
18	Trying to simulate each of the block differently : RC filter
19	Trying to simulate the whole circuit
20	Finding out our errors and reworking on the project
21	Recalculation of our mathematical model to make the output more smooth
22	Successfully done simulating the circuit in Simulink
23	Final Presentation
24	Making poster and final report

Table 4: Working schedules

CHAPTER 5

PROJECT SUMMARY

5.1 Result and Discussion:

The simulation shows us the graphical representation of the voltages and the currents in both the primary side and the secondary side of the mutual inductors. The simulation took more than 10 mins to process the whole circuit. The simulation shows us a voltage of 5.9V supplied to the battery of the Electric Vehicle. In the primary side of the simulation the inverter circuit shows a square wave AC voltage output which has a high frequency about 40kHz. The higher frequency of the circuit transfers the power faster and the mutual inductance transmits and receives power more fast due to change of current according to time is higher. Since there are a small amount of power transferring into the secondary side through a mutual inductor, there are slight power loss due to the winding of the coils the efficiency of the circuit is given below:

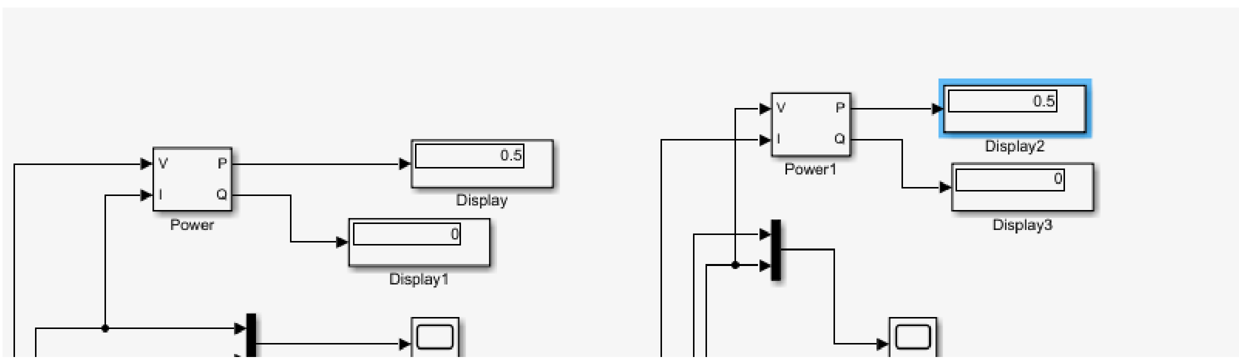


Fig 20: Output power in both primary and secondary side

Here the left one shows the real power on the primary side and the right display shows us the real power on the secondary side. So, it shows 99% efficiency ideally but which is not actually correct for all cases. The reactive power is shown zero for a while but when the circuit runs more than 0.3s of time the reactive power shows eventually some values while the real power draws down but it doesn't affect the supply of current or voltage to the battery since the full bridge rectifier actually makes it a pure DC voltage.

The resulting graphs of the simulation is given below:

DC to AC converter circuit Result:

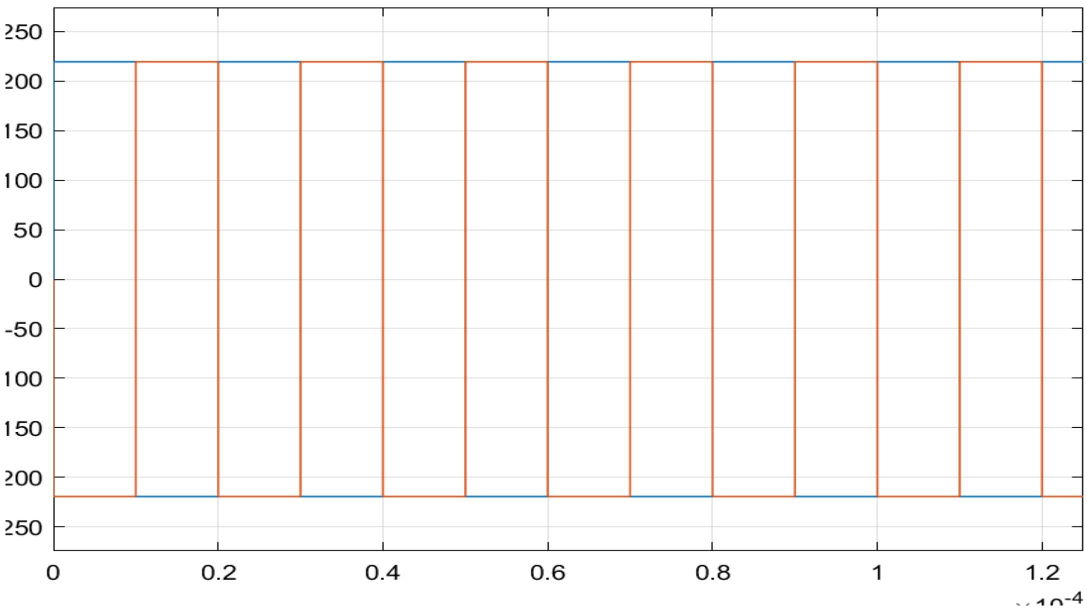


Fig 21: DC to AC converter output graph Current (Blue) Voltage (Red).

Output in Rectifier Circuit: The full bridge rectifier shows the following graphs-

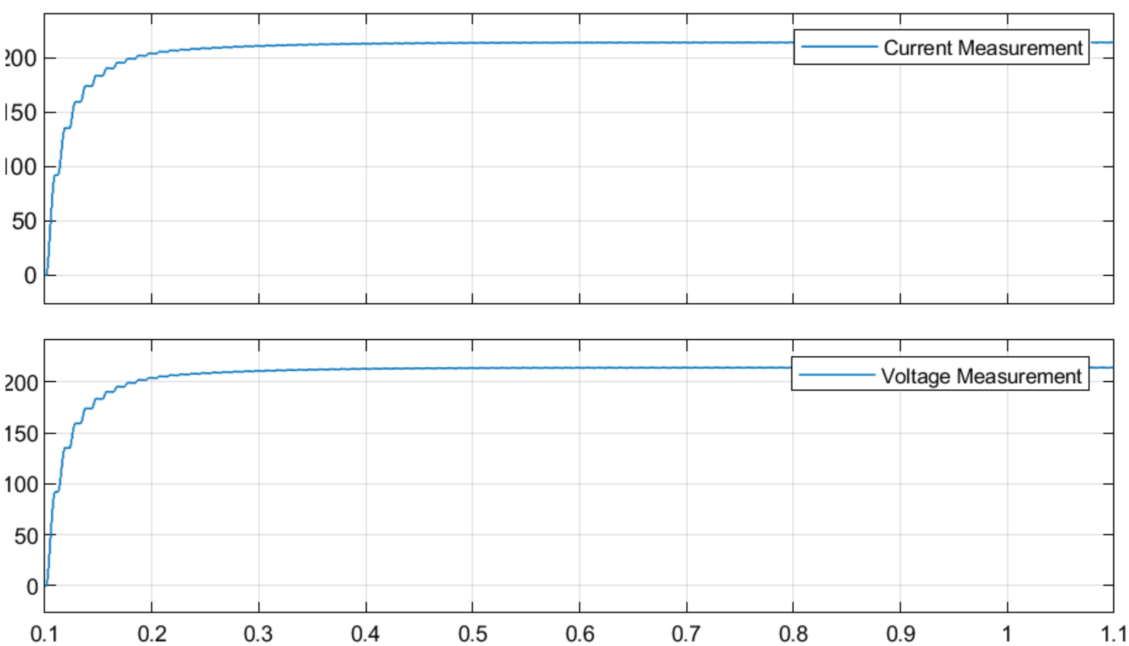


Fig 22: Primary side full bridge rectifier circuit output graph.

Voltage in the primary side of the Mutual inductance: The output voltage in the primary side of the mutual inductance shows a high frequency ac Voltage in a square shape.

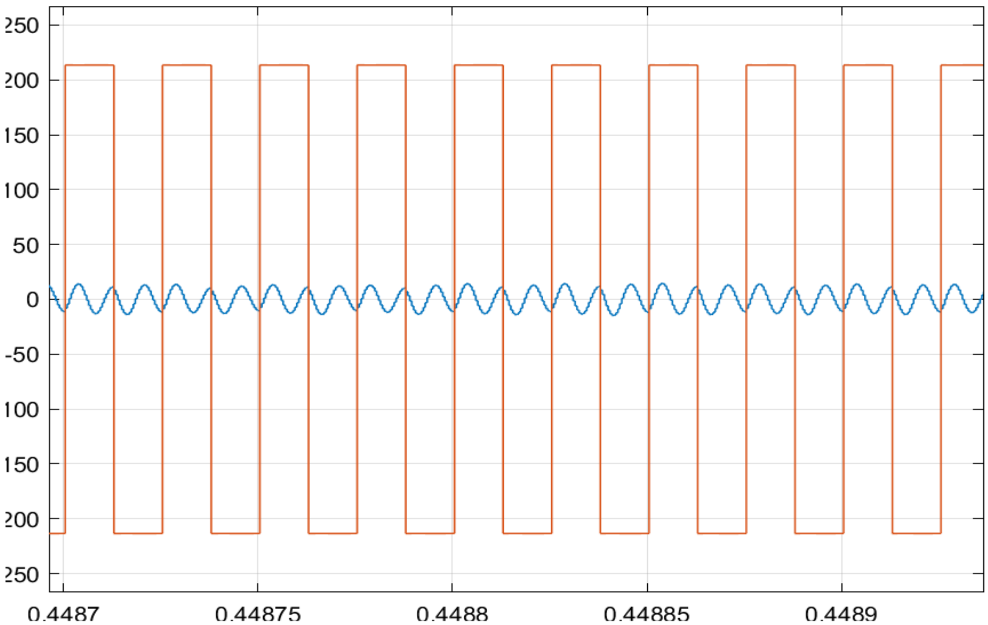


Fig 23: Primary coil output voltage(Red) and output current(Blue) graph

Output voltage supplied in the battery of EV: The output voltage of the charging system is connected to a load which is the battery and it will get a constant voltage of 5.9V while charging.

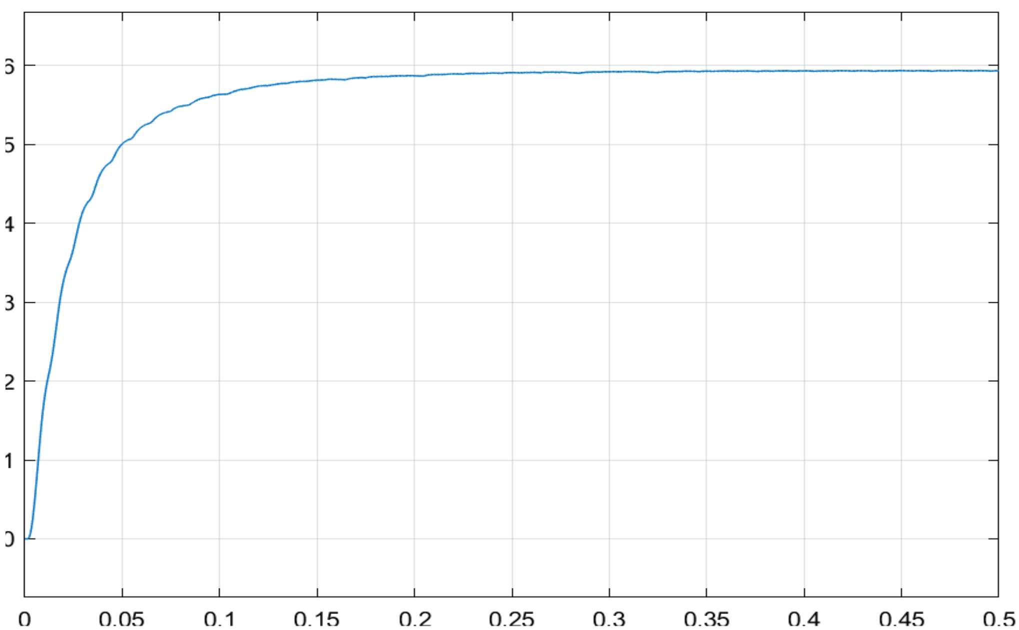


Fig 24: Final output voltage in the WPT system.

5.2 Feasibility Study:

Practically our project is not cost effective. It will cost a lot to build such infrastructure in a large scale. The components used to design this model aren't available at the values that are used in the simulation. Hence, the efficiency will not be as much as the simulation in real life. Since the electric vehicle industry is taking over the automobile industry the new feature of wireless charging system will be more user friendly and will have a great social value. The safety of the proposed solution depends on the coil conduction. When power is drawn from the mutual inductor, the coils must be insulated so that it is safe for the environment and the user. There must be a purchase system for the wireless charging system so that the consumer gets the energy he/she has paid for.

5.3 Problem Faced and Solutions:

Simulation time: While doing the simulation it took a long time to run the simulation and when there was an error we had to start it all over from the beginning. Then we reduced the simulation time from 10s to 0.5s and our simulation took lesser time to run.
RC filter: When we tried to design the simulation we didn't use RC filter firstly. Instead, we used smoothing capacitor to make the output in the primary side of our system to get a stable DC output from the full bridge rectifier. But it showed us a time varying DC voltage in the output.

5.4 Future Development:

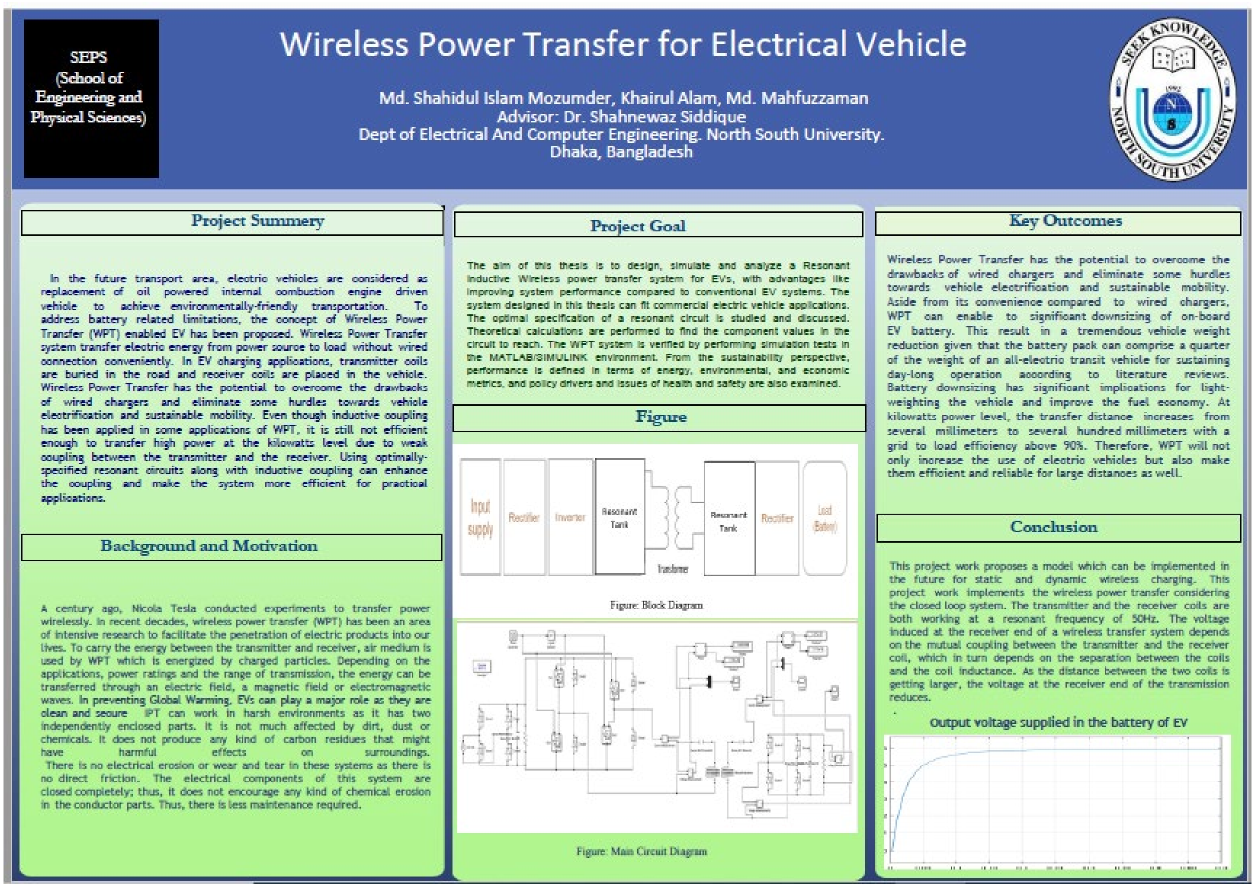
Since we have created a simulation project on the wireless power transfer system for electric vehicles, we are looking forward to work on it practically in future. The practical implementation of the project will be more cost effective as we'll use more frequency to reduce the turns of the coil in the mutual inductors. We'll construct an efficient power transfer system for electric vehicles. If we use compact version of each blocks in the practical implementation the project will be more cost effective and more power efficient. The compact version of the project can be implemented practically to charge small electronic devices such as mobile phones, laptops etc. If we use Power Factor Correction circuit the cost will rise but the system will be more efficient and stable. We'll work on static wireless charging system in future and this will help us to understand how a static wireless charging system behaves. Therefore, the project can be developed furthermore and can be taken to any competition.

5.5 Conclusion:

EVs have great potential of becoming the future of transport while saving this planet from imminent calamities caused by global warming. By using wireless charging system, we can charge EV anywhere at any time. Wireless power transfer systems will take over wired power transfer system in the future and the production of harmful substances for the environment like plastic insulators for wires will be decreased and there will be less pollution. The wireless power transfer system might take the power transfer and generation to a next extent. The technology could drastically improve the travelling range for electric cars as the EV battery can be charged while driving on roads and highways. In addition, wireless electric vehicle charging system eliminates the need for large energy storage, making vehicles more lightweight and compact. The wireless charging system eliminates the hassles associated with electric charging and allows you to charge your device sans wires. Because humans and pets can trip over cables, wireless power transfer is a safer option for smart homes. Furthermore, wireless charging is faster and provides a solution for damp and unclean settings where electric charging is not feasible. When it comes to the devices themselves, wireless charging allows for the universal charging of multiple devices over a long distance. In the future, home infrastructure will include built-in wireless charging pads, and all gadgets will be required to have wireless charging capabilities. Charging any device will be very easy in the near future and we'll be able to charge our devices even while walking. But there's a lot of harmful factors here too like- magnetic energy radiation.

5.6 Poster:

Our Project Poster is included here-



APPENDIX A

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