WiTricity Wireless Power Transfer

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WiTricity: Wirelesss Power Transfer

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Abstract

The idea of WiTricity technology is based on the foundation of strongly coupled magnetic resonance. This developing technology transfer power wirelessly over mid-range distance without any physical connection of wire. In Witricity, power exchange happen between two conductive coil with same resonant frequency. With the help of this technology no need of messy wires which is widely spread all over due to that costly batteries also eliminated. WiTricity also help to improve environmental impact because millions of tons of plastic is used to insulate copper wire every year.

The main focus of this project is to understand core concept behind WiTricity. I will also focus on power loss of wireless power transfer on multiple ranges and what are the important factor to reduce it. Secondly, also work on international standard of WiTricity for different applications. Compensation topology are the back bone of wireless power transfer, the most common series to series compensation network is discuss mathematically and theoretically and analyze what is the effect on power efficiency. In my dissertation, I work on wireless power transfer for mobile devices by developing a prototype model of electric buss charging. Work on mathematically calculation of different parameter of wireless power involve in power transfer and analyze what is the difference in practical observation.

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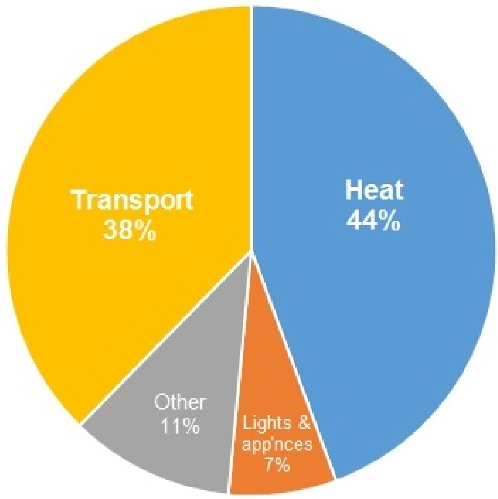
CHAPTER 1

Introduction

In the United Kingdom (UK) transportation industry consumed around 38 % of total amount of energy as shown in figure . Whereas, oil is considered the most used energy which contains 39.7 % for transportation purposes as recorded in the 2019 detail can be found in a pie chart. Due to extensive use of gasoline develop a lousy impact on the environment and these dangerous gases impact the environment which is already polluted by greenhouse gases. Scientists and engineers are working to find an alternative to gasoline. Therefore, In order to overcome energy consumption in the transportation section concept of electric vehicles arrive which consider a major solution in the field of transportation.[39].Secondly, plug-in hybrid electric vehicles (PHEV) also play crucial roles in preventing environment. From 1999 to 2015 approximately 2.1 million EV sold and it is predicted that to have a growth of 20.6 million at the end of 2025.[[30],[40]].

The main issue for Battery Electric Vehicle (BEV) is that how we can store such a large amount of energy and make it sufficient for different ranges of velocities. Basically, batteries are large and heavy in nature. EV batteries consist of Lithium-ion circuit which is most expensive material in the world. One the other hand, batteries take long time to charge around 6 to 7 hours.However,the complete power and the cost of performing fast charging consider to be higher if the energy store in with the help of advance charging system is used. That's why charging time consider to be longer as compare to refueling the car with petrol. Tesla launch another solution which is known as hot swapping in which vehicle need to be replace their batteries in charging station but later Tesla drop that idea.[31].



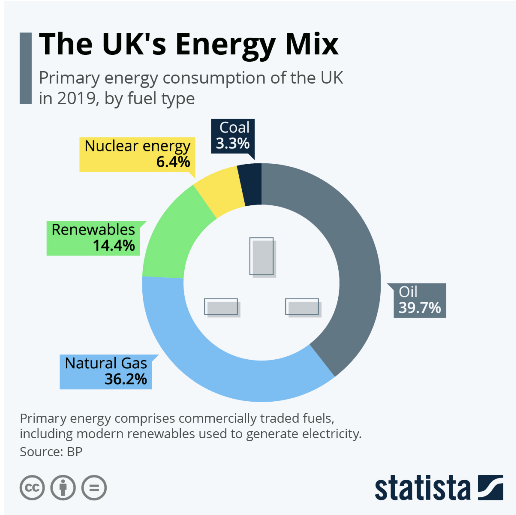


Figure 1.1: (a) Energy usage in UK for transportation (b) Percentage of fuel consume in different sectors

Currently in order to charge EV we are using electrical power cable to plug in to the car which will charge our battery this technique is know as onboard charger (OBC) [48]. The basic issue with conductive charging for electrical vehicle is to carry heavy and long electrical cables to connect EV for charging purpose secondly it can make tripping hazards.[[12] [48]].Therefore, Scientist research on charging of electrical vehicle with the help pf electro magnetic coupling also know as Wireless power transfer. With WPT EV charging consider to be very convenient,safe for electrical hazards and it will be fully automatic charging without any physical connection.[18].WPT consist of three types stationary, quasi stationary and dynamic charging system. stationary charging is used in workplace, home car parking or in public charging stations.

With the help of strong electromagnetic resonance, research tool place at MIT which powered 60 W bulb wireless with 40 percent of efficiency from 2m distance. Intel company work on 1894 implementation of electrodynamics induction using wireless power on a close light bulb having 75 percentage of efficiency. Sony created a wireless TV using electron dynamic induction from the distance of 50cm with 60V of power voltage. An LCD TV was invented by Haier company which transfer power wireless using home digital interface.

Quasi stationary charging system is the advance version of static wireless charging but the primary coil pad installed in traffic light ,highways rest area. The battery charging problem for battery electrical vehicle (BEV) [[12], [27] [46]] can be solved by dynamic wireless charging. In dynamic wireless charging not battery is used on EV, an ultra capacitor is used, the power

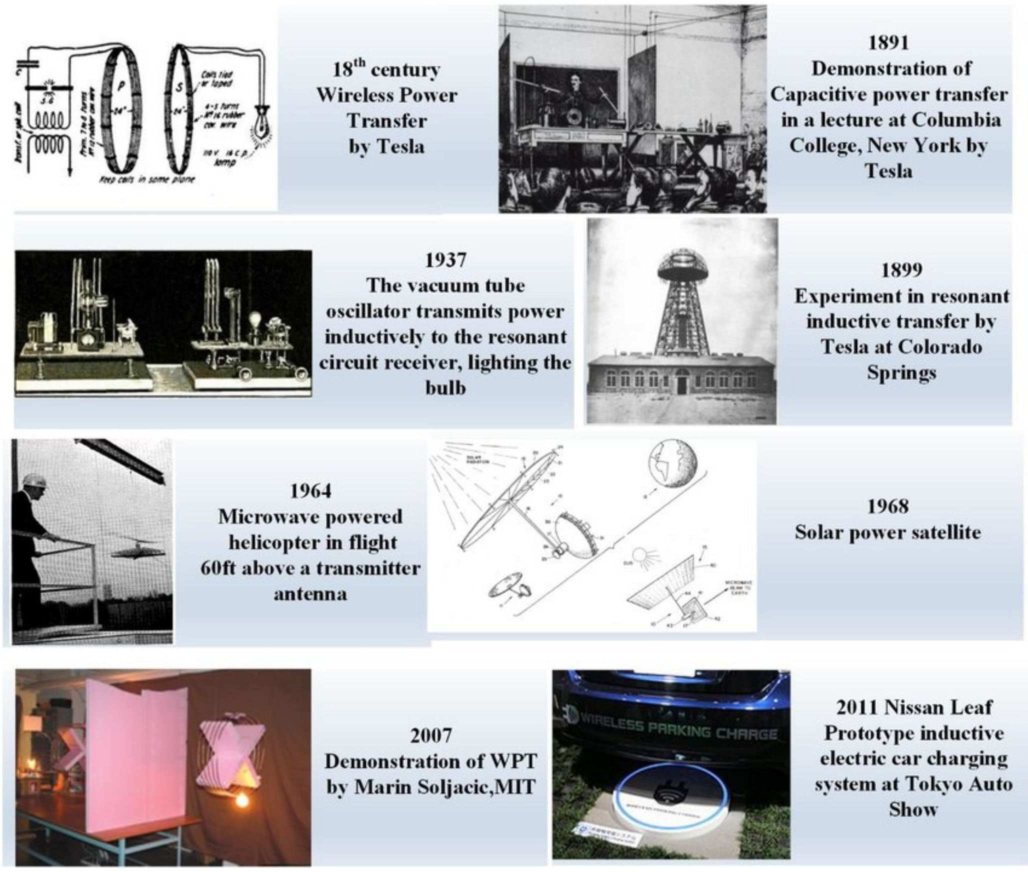


Figure 1.2: Timeline for the development of Wireless Power transfer

required for EV is transfer from the power rail in the road. [17] [43].

1.1 History

In 19th century Wireless power transmission was first predicted by Maxwell in his research that power can be transfer from one place to another place in free medium. Hertz perform experimental implementation of Maxwell equation which is consider to be initial step. However, Tesla implementation on wireless power transfer consider to be major role, however he fail to transfer power wireless to the space [50]

The idea of wireless vehicle charging has drawn more attention from the electric vehicle sector in recent years. Car parks with wireless charging stations might guarantee that your car gets fully charged when it's time to leave. Wireless charging stations can be designed to be positioned at intersections or along large range of road network to increase the operational range of electric vehicles. Other applications may profit by improvements in wireless energy transfer, such as the continuous operation of electric vehicles in a warehouse thanks to the installation of wireless charging tracks in the floor. The achievement of a wireless energy transfer system with simultaneous efficiency and high-power transfer over a range of airborne distances considered to be difficult task.

1.2 Classification of WPT

Wireless power transfer divided into different types depend on distance between primary and secondary coil due to which electromagnetic characteristics will be change depend on changing the field and so different method for achieving wireless power transfer is used.Following are three categorized.

1. Near Field
   (a) Induction Coupling
   (b) Resonant Induction Coupling
   (c) Air Ionization
2. Far Field
   (a) Microwave Power Transmission (MPT)
   (b) Laser Power Transmission

1. **Induction Coupling**
   When an ac current passes through a transmitter coil it will generate magnetic field so when the receiver coil come closer within the range of magnetic field the voltage will be induce power from primary coil to secondary coil and power will be transfer. The power can be used to energize a mobile device in which rechargeable battery is used. The efficiency ratio of the wireless power transfer depend on coupling factor(K).The coupling factor can be calculated by distance between inductors and the ratio of D_2 /D further more it can also be determine by the shape and angle of induction

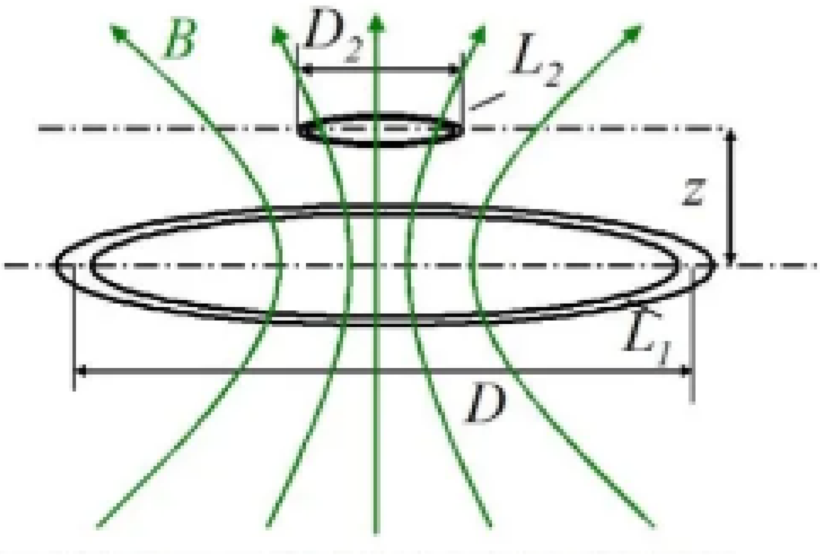


Figure 1.3: Induction Coupling System

2. **Resonant Inductive Coupling** This method uses both inductance and resonance of the coil for generating electromagnetic induction in the circuit. Resonance work with the improvement between two coil of the circuit. On the other hand, inductance induce current.

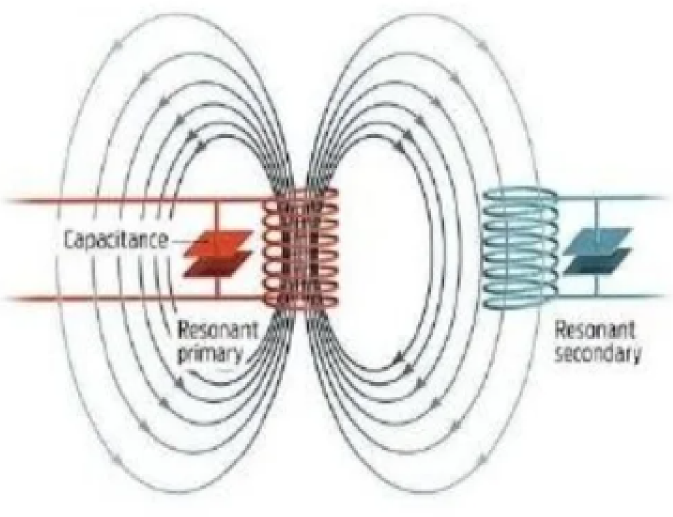


Figure 1.4: Induction Coupling System

3. **Air Ionization** We know that ionized gas is the good conductor of electrical and conductivity of gas is directly proportional to ionization. This technique consider to be difficult because air ionization occurs when high magnetic field

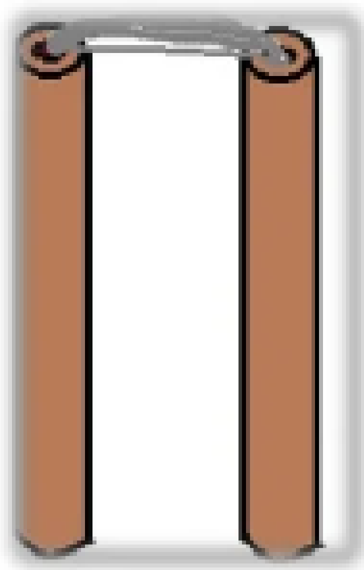


Figure 1.5: Induction Coupling System

Far field technology consist of two radiative transfer. Power can be transmitted in the form of magnetic or light. The following two technique are used in the far field

1. **Microwave power transmission** In this transmission energy will be converted into microwave and can transfer through rectenna (rectifier and antenna) from transmitting side and convert into productive electrical form on the receiver side.

2. **Laser Power transmission** In laser power transmission power doesn't dispersed during the power transmission from one point to another point but attenuation develop when pass through atmosphere. A photovoltaic cell is used as a receiver circuit which make the cost efficient as compare to microwave power transmission. Laser power transmission is used in powering up satellite station in the space with the help of photovoltaic cell.

For near field radiation, wavelength is restricted to one within one region. In mid field, the boundary region for electromagnetic radiation contain one to two wavelength. For far field, radiating source and receiver distance is double the wavelength of radiation.[35]

Wireless power transfer classified into three major techniques with respect to mode of coupling.

1. Electromagnetic Induction
2. Far Field Transfer
3. Electrostatic Induction

WPT Technology Category	Advantages	Disadvantages
Inductive Coupling	Safe, Simple, high efficiency for short measuring distance	Accurate alignment needs for short transmission distance
Magnetic Resonant Coupling	Provide long transmission distance, no radiation	Adjust of resonant frequency for different devices is difficult
Electromagnetic Radiation	Very high transmission efficiency for far distance	High Radiation, need line of sight

Table 1.1: Advantages and Disadvantage of WPT Technology [40]

1.2.1 Different Types of Wireless Power Transfer:

The ability of transferring power wireless with safely, effectively, good efficiency and with range of distance will improve the reliability of the consume and make the product more environmental friendly. There are two major types of wireless power transfer

1. **Automatic Wireless Power Charging:** Without a power cable or new batteries, a gadget with rechargeable batteries can power up the device while using it or when it is inactive. When a mobile device is within reach of its power source, this mode allows for wireless charging without the need for any cable connection.

2. **Direct Wireless Power Charging:** Device need to be energized by wirelessly without any battery connection required. This mode power up the electronic devices which come under the range of power supply.

1.3 Application for WPT

Wireless power transfer can be using where we need to charge electronic component with the help of cable wire. [41]

1. **Commercial Electronic Product:**
   Wireless power charging is used in portable electronics equipment like mobile phone, personal laptop, online gaming console, electrical vehicle. This wireless charging technique is more effective on static position where we do not need to change the position of device like Tv, wireless keyboard, speaker, mobile printer etc

2. **Automobile Application:**
   The future of automobile industry is directly proportional to the advancement of wireless power transfer. As we can see electrical vehicle manufacturing due to which different concept of wireless battery charging is develop. We can also develop car parking for electrical vehicle where car charge wireless or make it on car garage so it will not need any power cable to charge a battery

3. **Manufacturing Industry Application:** In the manufacturing industry different assemble line control by multiple robots which make difficult to move the robot due to size of the cable with the help of wireless power transfer their is no need for physical electrical connection.

4. **Military Equipment:** Wireless power transfer can also be useful in powering up military components in which delicate sensor are used. Secondly, vehicle seat at the back of the solder can transfer wireless power for charge the battery while driving the vehicle.

5. **Medical Instrument:** With the help of wireless power transfer we do not need to connect physical battery with implantable medical devices wireless power transfer which will energize the circuit. On the other hand, for implantable device which need 10s of power for therapy become practical with help of WPT.

CHAPTER 2

Background

2.1 Literature Review

The development of Wireless Power Transfer started dates back to Hertz's groundbreaking work and continues today. Figure.2.1 depicts the historical progression of WPT. Professor. Heinrich Hertz showed the propagation of electromagnetic waves in free space having a considerable amount of gap to generate power at high frequency in order to find receiving end of the circuit which was develop in late 18 century[21].Nikola Tesla began testing the use of radio waves to transmit power in the year 1890. In 1899, he made his first try for the transmission power in the area of Colorado[39]. In his laboratory, he constructed a huge coil with a copper ball perched on a tower. When powered by 300 kW, the Tesla's coil with the resonating frequency of around 150 kHz [9]. However, there is no proof that its demonstration was successful. William Brown works on the technology which we use in far field in 1960[3].The demonstration of microwave technology was made possible by the creation of magnetron tubes and parabolic antennas [22]. Additionally, the Rectenna, a 1964 device that could effectively convert microwaves radiation into DC power with the representation of microwave beaning, a moving helicopter energize wirelessly from ground.[15][3].Peter Glaser proposed the idea of a solar-powered satellite in the 1970s. The spacecraft would gather energy from sunlight using solar cells in orbit before beaming it to the earth via a microwave antenna.[20].In 1975, Brown experiment small range microwave transmission of 475 W with a DC to DC efficiency of 54 %. Then, with 80 percent efficiency, 5 Brown with his friend Robert

Dickinson at NASA's laboratory transmitted power of around with the frequency of about 2.38 GHz with the distance of 26 meter dish to 7.3x3.5m rectenna array[15][3].Having 30 cm of radius With coupling coils, a team of MIT researchers successfully implemented coupled mode theory which provide better result in Tesla experiment in 2007. Their efficiency was 40 percent with the total distance of 2m.[4]. As Concluded, there are many applications for WPT, and with number of ways to operate frequency of the wireless power transfer. Depending on the operating frequency, Figure 2.1 provides an overview of various wireless power transfer methods.

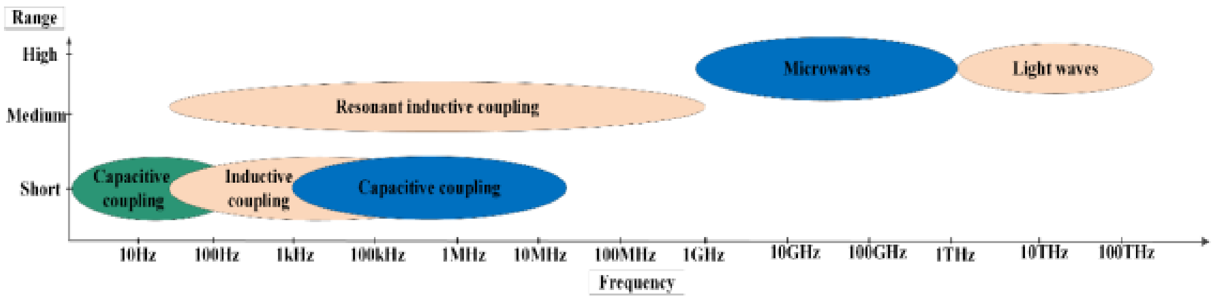


Figure 2.1: Fundamental Principle of Wireless Power Transfer [21]

2.2 WPT for Electrical Vehicle

Due to the advancement in the technology use of wireless power charging make it simple and feasible to implement. In late 1997/1998 the development of the stationary charging was started, when inductive power transfer (IPT) charging technique newly develop which was then demonstrated in New Zealand at Rotorua Geothermal Park when for the first time a bus was charge wirelessly on a bus stop in Genoa and Turin in the 2002 [17][8][7]

Company	Frequency	Airgap	Power	Efficiency
Witricity [28]	145 kHz	180 mm	3.3 KW	90%
Conductix Wampflex [45]	20 kHz	40 mm	60 - 180 kW	>90 %
Momentum Dynamics [17]	-	610 mm	3.3 - 10 KW	92 %
HEVO power[17]	85kHz	304.8mm	1 - 10KHz	> 85 %

Table 2.1: Stationary charging available commercially [17]

The prominent companies working on the Witricity project are named as WiTricity, Qualcomm, Momentum Dynamics, Conductix-Wampfler[17][8][7]. Massachusetts Institute of Technology (MIT) initiated Witricity project by developing a transmitter and receiver coil with strong coupled magnetic resonance. After experimental result WiTricity project provide 90% of efficiency for 3.3kW power rating with the operational frequency of around 145 kHz consist of ±20cm to ± 10cm of lateral misalignment [46][28]. Qualcomm's Halo company work on the Double D polarized magnetic pads which can transfer double power from one coil to another coil with high efficiency compare to circular coil pad with operational frequency of 20 KHZ with the collaboration of University of Auckland [**?**][7] Conductix-Wampfle's develop static charging system for an electrical bus by adjusting the resonant frequency in order to achieve the efficiency of 90% with the coil separation of 40 mm at 60 KW power transfer[45]

An stationary WPT system is develop by momentum dynamics having air gap of 24 inches with power rating of about 3.3kW with the efficiency of 92%. More development has been made on charge by increasing power from 7.2 kW to 10 KW could fully charge chevy volt with around 1 hour. This also working on the develop of coil design for FedEx truck from switch electric vehicle [6] On the other hand, HEVO Power also working on stationary power charging system which is mention in table 2.1 which provide central idea of the availability of the commercial static charging system. [17]

Parameters	KAIST				ORNL	Bombardier	Conductix - Wampfler AG	WAVE
Application	Car (2009)	Bus (2009)	Train (2010)	Bus (2016)	Car(2016)	Trams (2010)	Bus (2002)	Bus (2011)
Air gap	10mm	170mm	120mm	200mm	162mm	60mm	40mm	~152mm - 254mm
Efficiency	~88%	~72%	~74%	~80%	~93%	~90%	~90%	~90%
Pickup	E-type	Flat -type	DD coil	DD coil	Rectangular with ferrite bar	-	F- type	-
Power rail or primary transmitter	E-type	U-type	W-type	I- type	Rectangular with ferrite core	-	E –type	-
Power level	3kW	6kW	15kW	27kW	~20kW	200kW	120kW	50kW
Misalign-ment	~3mm	~230 mm	-	240mm	150mm	Low few mm	-	~254mm
Frequency	20kHz	20kHz	60kHz		~22kHz	20kHz	15-20kHz	20kHz

Figure 2.2: Different Wireless Power Technology [34][9] [3]

In 2009, a further research group from KAIST a Korea's school developed a 3 kW electric grid for an online electric vehicle (OLEV) having mechanically controlled system, an air gap of roughly 10mm, and an efficiency of 80 % when working at a frequency of 20 kHz. A 60 KW OLEV system was develp for an electric bus charging on the same year. The design struction capable of handling coil to coil air gap of 10mm with the maximum efficiency of 72% without any physical movement of pickup.[34][25]

Utah state university initiated WAVE to develop a 50 KW wireless charging system for electric buss. This technology capable transmitting power of 50 kW with air gap of around 15 to 30cm with the operational frequency of 20 KHz and reported to be 90% efficiency. An IPT system for static and dynamic application which is develop by bombardier primov.[38]. A 250 kW system was created for Primov Trams in Augsburg, Germany. For the dynamic charging application. He use F-type pickup along with an E-type power rail in their system. Approximately, 60mm air gap between the primary and secondary that allows for a little amount of lateral misalignment. Momentum dynamics successful design a WPT system capable of generating power 200 KW with a huge gap of 610 mm and efficiency of 92%. The WPT system for delivery vehicles has been effectively applied using dock or roadside embedded static charging stations. Utah State University already accomplished 25 kW DWPT for Bus in 2016 with a circular primary coil. This WPT system could generate about 25 KW with the lateral misalignment sidtance should be around $\pm$ 15cm.[5] Finally, a comparison between different technology of IPT is completely describe in the figure 2.2.

CHAPTER 3

Theory

In this chapter we will discuses about the fundamental concepts and principal use in wireless power transfer. In previous chapter we review different parts of WPT and background work done on the research side.

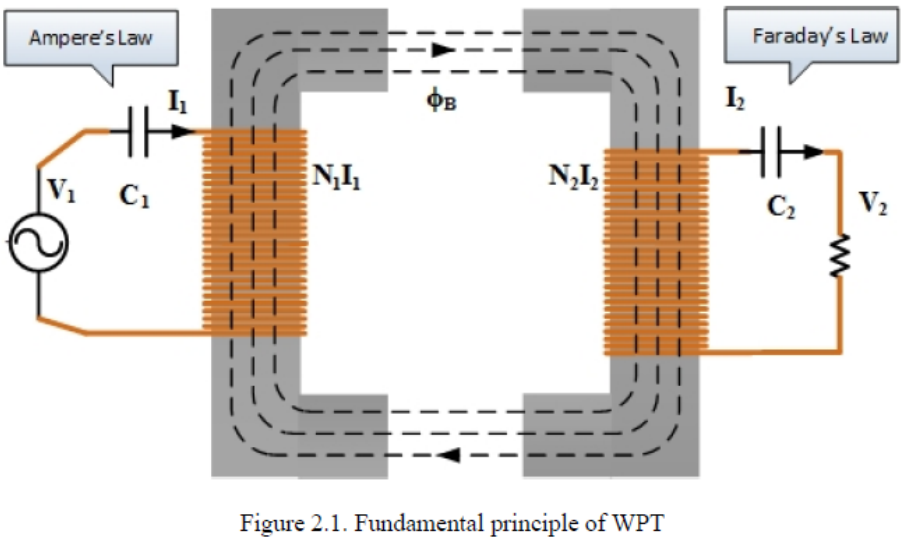


Figure 3.1: Comparison between different technique in Wireless power transfer [24]

3.1 Fundamental

Wireless power transfer operates on two fundamental laws Ampere's Law and Faraday's Laws. Laws are explain briefly below.

1. **Ampere's Law**:
   A magnetic field is produced when an electric current passes through a conductor. Electric current and the permeability of empty space determine how strong the magnetic field will be as a result. [24]
   $$\Sigma B_T \Delta l = \omega_o I N_1 \tag{3.1.1}$$

2. **Faraday's Law**:
   When a conductor is exposed to a time-varying magnetic field, a voltage is induced. The value is proportional to the conductor's number of turns and the pace at which the magnetic flux changes..[24]
   $$e = -N_2 \frac{d\phi_B}{dt} \tag{3.1.2}$$

Where magnetic flux density represented by B_T unit is Tesla. Δ l is the length (in meter)of the conductor in which current passes through,N_2 is total number of secondary turns, N_1 is total number of primary coil turns wind together, electronic current flow through primary coil is represented by I measured in amperes and magnetic flux generated between two coil is denoted by ϕ .

According to Figure 3.1,WPT features two coils that are spaced far apart by an air gap. To enhance coupling and reduce proximity losses, the coils are positioned around a magnetic substance. Ac current with high frequency energize the primary coil, generating a magnetic field that changes over time[11].In order to induce voltage in secondary coil. By Faraday's law, Due to the coupling coefficient k, a small quantity of the time varying magnetic field is coupled with a secondary coil in order to induce voltage in secondary coil.

Because of the big air gap, the circuit is inductive. As a result, to generate a powerful enough magnetic field to connect secondary coils, a significant current (or magneto motive force) is needed.[14] In real-world WPT systems, it is required to reduce the inverter's VA rating by erasing the inductive component of the electronic circuit using a capacitor due to which it resonates with the primary inductance. To erase secondary leakage inductance and increase efficiency of power transfer, the secondary side of the circuit should be turn with respect to the primary coil so that resonant frequency will generate.[34]

Ac current will be generated with the help of high frequency mosfet which provide oscillation rapidly and due to high level of oscillation magnetic field produce so with the help of this electromagnetic induction when secondary coil come closer to the primary coil power will be transfer without any physical connection due.

Wireless power system work on the resonance frequency which means when the inductive reactance and capacitive reactance of both the primary and secondary circuit become equal so at that point the frequency is called resonance frequency. Generally, when power transfer from one coil to another coil consider to be very small then potential difference drop at the leakage inductance of the coil consider to be small even when the== large amount of current flow through the coil[13].Large amounts of power must be forced while maintaining a constant input current because greater power causes a bigger voltage drop across leaky inductance at higher frequencies. The system will experience significant conduction losses as the input current rises. Additionally, the inverter's VA rating will rise due to the higher reactive power needed.[13]

3.2 Resonance

According to physics concept theory, resonance is the propensity of any system, often a linear system, to oscillate at particularly higher amplitude at specified frequencies as opposed to other frequencies. These specific frequencies are known as resonance frequencies, and even weak periodic driving forces can result in oscillations with significant amplitudes at these frequencies.Resonance results from a system's ability to shift energy between two or more storage modes. Resonance occurs when a pendulum's kinetic and potential energy combine together[33]. Each physical system has a natural frequency where its oscillations are at their strongest. When the system is configured to oscillate, the losses in each cycle known as damping cause the amplitude to decrease. When the damping is at its lowest, the system's resonant frequency is about equal to its natural frequency.

When magnetic field applied to inductor and capacitor circuit LC circuit then due to electromagnetic induction current induced into winding which will energize the capacitor of the circuit. So after the capacitor fully charge then it will start discharging the electronic current which will generates magnetic field within the inductor. Basically, resonance occurs when the inductance and capacitance resistance of both the component basic equal in same magnitude and at that point the frequency will be consider as resonance frequency. With the help of this result in frequency electric energy between capacitor and inductor will be consider electric and magnetic field respectively. In resonance, the series and parallel impedance's of the inductor and capacitor are minimum and maximum, respectively, whereas the magnitudes of the inductive and capacitive reactance are equal. According to the theory: When inductive and capacitive reactance be equal

$$X_L = X_c \tag{3.2.1}$$

After evaluating the equation we get.

$$2\pi f L = \frac{1}{2\pi f C} \tag{3.2.2}$$

where ω is the resonant frequency of the circuit can be define as. $\omega = 2\pi f$
So we can rewrite the equation as

$$\omega L = \frac{1}{\omega C} \tag{3.2.3}$$

$$\omega = \frac{1}{\sqrt{LC}} \tag{3.2.4}$$

3.3 Resonator

Each physical system possesses a unique level of freedom. The physical system vibrates as a harmonic oscillator with several resonance frequencies should be equal to the number of degrees of freedom with which it is endowed. Simple pendulums, LC tuned circuits, systems with a mass on a spring, etc., all have a single degree of freedom and a single resonance frequency.Some of the systems with two resonant frequencies include coupled pendulums and resonant transformers. The number of connected harmonic oscillators has a substantial impact on how long it takes energy to go from one oscillator to another.[29] Through the connected harmonic oscillators, the vibrations travel through a wave propagation process. Resonators are items like vibrating strings, quartz crystals, and organ pipes that experience resonance because of internal vibrations.These resonators have a large number of connected moving elements and a wide range of resonance frequencies. At a constant speed, the waves generated by the resonator's vibrations bounce back and forth frequently between its surfaces. The wave travels a distance of 2d in a single round trip when the distance between the resonator's sides is taken into account[42].

After one full cycle, when the wave's starting phase is similar to the sinusoidal wave's phase, the waves reinforce one another, creating resonance. The distance taken by the wave in a roundtrip must therefore equal the wave's numerical integer wavelength λ as the consequent criterion for resonance. Where N= 1,2,3,4,...

$$2d = N\lambda \tag{3.3.1}$$

Assuming the wave velocity is represented by ν and the frequency can be calculated by $f = \nu/\lambda$. So by considering above equation we can rewrite the formula for frequency,

$$f = \frac{N\nu}{2d} \tag{3.3.2}$$

As a result, with equal spacing, the resonance frequencies of the resonators are multiples of the fundamental frequency, which is the lowest frequency. Overtones are the name given to these multiples. A system can have many series of resonance frequencies depending on different vibrational modes.

3.4 Resonant Energy Transfer

For the short distance of energy transfer we use WiTricity which use magnetic field for the transfer of energy from one coil to another coil, with the help of resonant energy transfer theory. According to science it is prove that the magnetic field develop during the power transfer not makes any problem related to medical issues in human body as compare to electrical field.

In order to develop a wireless power system we need two coil which consist of same resonant frequency which means their inductive and capacitive reactance become same. On the other hand, the system should have less losses and good efficiency which makes the quality factor Q higher. Energy transfer from one coil to another coil when both the coil circuit have same resonant frequency. These system also called resonant transformer which take air core in order to decrease iron losses. These coil covered into similar equipment for better transmission rate or sometime separate core is used.

When the alternating current passes through a coil with resonant frequency it will generate a strong magnetic field. Due to the phenomenon of resonant coupling so with the help of this theory we can say that if another coil place within the resonant coupling area having same frequency and within the required range then the energy will transfer from one coil to another coil.

3.5 Resonant Coupling

In transformer non resonant coupling technique is use to transfer power without any use of a physical wire. But, In WiTricity primary coil consume power first which generate strong magnetic field so that the secondary coil which is near to primary coil try to take as much power as it can which is possible within the magnetic field range. In order to transfer power from primary coil to secondary coil it is necessary to have magnetic core in between two coils. When there is a significant distance between the two coils, this approach is very inefficient and causes energy loss in the primary coil via resistive losses. With the help of resonance efficiency of the circuit will improve dramatically. In order to refine the performance of the circuit we attached LC circuit with the coils to transfer power efficiently. We can transfer power with mid range of distance if the frequency of both coil are same.

3.6 Energy Transfer and Efficiency

According to the theory, when a current pass through a primary coil with full capacity it will generate an oscillation magnetic field. Energy will be transfer between inductor magnetic field and capacitor electrical field when inductive and capacitive reactance become same at resonant frequency. Quality factor Q of the coil base on the decrement of frequency oscillation due to which resistive and radiative loss. If the secondary coil is able to penetrate the field and receive energy before it is lost in each cycle, the majority of the energy can still be transferred. A series RLC circuit is form at primary coil side and quality factor Q can be written as

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}} \tag{3.6.1}$$

Quality factor play a significant role in wireless power transfer higher the Q factor is more efficiency of power transfer at secondary coil output.

3.7 Coupled Mode Theory

In coupled mode theory, upon which resonant energy exchange is based, is well known. This theory states that the field of the system of two resonant coils 1 and 2 is roughly described by [49]

$$F(r,t) \approx a_1(t)F_1(r) + a_2(t)F_2(t) \tag{3.7.1}$$

Where $F_{1,2}(r)$ are donated as eigen modes of resonant coil 1 and 2 and $a_{1,2}(t)$ are field ampliude of the system.Where as field of two resonant coil 1 and 2 can be find as [49]

$$\tfrac{da_1(t)}{dt} = (i\omega_1 - T_1)a_1(t) + ik_{11}a_1(t) + a_2(t)F_2(t)$$

$$\frac{da_2(t)}{dt} = (i\omega_2 - T_2)a_2(t) + ik_{22}a_2(t) + a_2(t)F_2(t) \tag{3.7.2}$$

Where $\omega_{1,2} = 2\pi f_{1,2}$ is the separate angular frequency of the circuit. $T_{1,2}$ is the delay rate due to intrinsic loss created by coil radiation in free space and the material absorption from inside, where K_{11} and K_{21} consider to be the coupling coefficients of resonant coil and non resonant object, where as K_{12} and K_{21} are coupling coefficient between primary and secondary coil.

The resonant coil and non resonant object contain coupling coefficient much less than the primary coil 1 and secondary coil 2, (K_{11},K_{22} $<<$ K_{12}, K_{21}), we can rewrite equation 3.6.2 as [49]

$$\tfrac{da_1(t)}{dt} = (i\omega_1 - T_1)a_1(t) + a_2(t)F_2(t)$$

$$\frac{da_2(t)}{dt} = (i\omega_2 - T_2)a_2(t) + a_2(t)F_2(t) \tag{3.7.3}$$

Applying Laplace transformation o equation 3.6.3, we get

$$sL(a_1(t)) - a_1(0) = i(\omega_1 - T_1)L(a_1(t)) + ik_{12}(L(a_2(t)))$$

$$sL(a_2(t)) - a_2(0) = i(\omega_2 - T_2)L(a_2(t)) + ik_{21}(L(a_1(t))) \tag{3.7.4}$$

After laplace transformation, we have[49]

$$L(a_1(t)) = \frac{iK_{12}a_2(0)+a_1(0)(s+T_2-i\omega_2)}{(s+T_1-i\omega_1)(s+T_2-i\omega_1)(s+T_2-i\omega_2)+K_{12}K_{21}}$$

$$L(a_1(t)) = \frac{ik_{12}a_2(0) + a_1(0)(s+T_2-i\omega_2)}{(s+T_1-i\omega_1)(s+T_2-i\omega_1)(s+T_2-i\omega_2)+K_{12}K_{21}} \tag{3.7.5}$$

Suppose that resonant coils 1 and 2 have perfect characteristics and that resonant coil 1 initially contains all of the system's energy.

$$\omega = \omega_1 = \omega_2, T = T_1 = T_2 \text{ , } K = k_{12} = k_{21}, a_1(0) = 1 \text{ , } a_2(0) = 1$$

Applying condition on equation 3.6.5

$$L(a_1(t)) = \frac{s+T-i\omega}{(s+T-i\omega)^2+k^2}$$

$$L(a_2(t)) = \frac{iK}{(s+T-i\omega)^2+k^2} \tag{3.7.6}$$

Taking inverse laplace transformation we get

$$a_1(t) = e^{(i\omega-r)t}cos(kt)$$

$$a_2(t) = e^{(i\omega-r)t}cos(kt) \tag{3.7.7}$$

Finally total power can be calculated by.

$$p(t) = p_1(t) + p_2(t) = |a_1(t)|^2 + |a_2(t)|^2 = e^-2Tt \tag{3.7.8}$$

Where p(t) is represented by total energy transfer and $p_1(t)$ and p_2 are the energy for primary and secondary coil

CHAPTER 4

Implementation and Results

For the implementation of wireless power transfer, we need copper coil. In order to transfer power wirelessly through a short distance so it is compulsory to have an AC power supply so when the current passes into the coil it will produce alternating magnetic field at high frequency. Circular copper coil made with the help of water bottle so that the shape of every turn should be same and overlap with each other. In my project, I used 12 turns for primary coil winding with a centre tap at turn 6 means during the winding of the primary coil on the 6 turn an additional new point is develop which is called centre tap point. So practically we centre tap the winding and made in such a way the both the winding generates magnetic field when an electronic current flow through a coil.

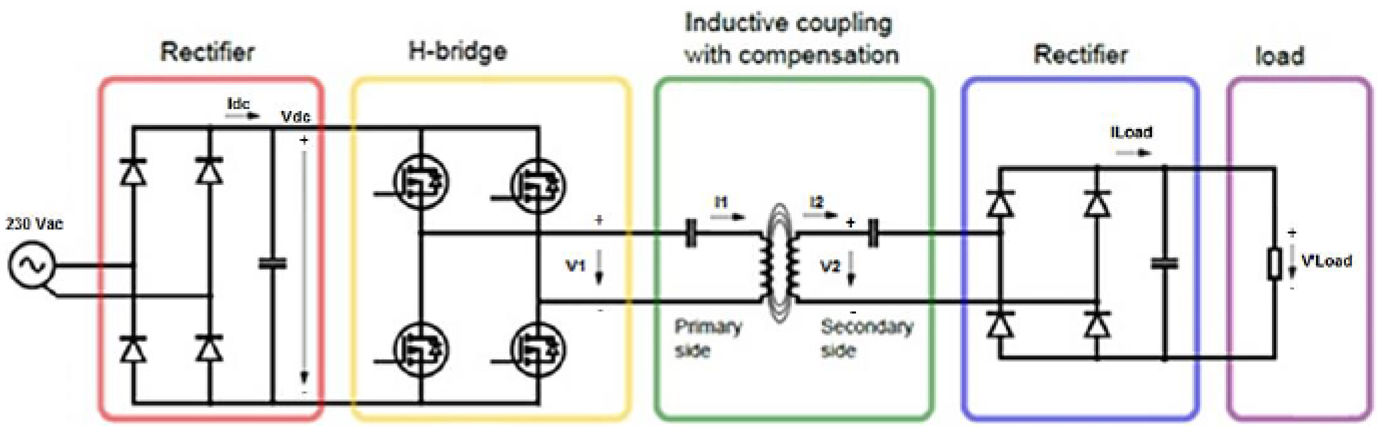


Figure 4.1: Different WPT section [12]

So, when the first coil winding gets energize then the second coil will get no supply and when the second coil get power supply the first one gets zero supply. As a result of this process magnetic field generate due to centre tap configuration. On the secondary side we donât need to generate magnetic field basically secondary coil is develop as a receiving coil which receive the voltage transmitter from the primary coil with the help of electromagnetic induction.

There are a lot of technique available for the develop an effective wireless power transfer system. In the above block diagram complete wireless power transfer step by step modelling is done. In my practical implementation I use power supply which will provide constant dc supply to the circuit and the rectification part on the input side of the circuit is not implemented. After getting smooth dc current then it will pass through the BJT (Bipolar junction transistor) transistor which will work as an oscillating circuit and convert dc power into fluctuating Ac supply due to that oscillation magnetic field will be generated around the copper coil and what ever conducting material come within the range of magnetic field power transfer from primary coil to secondary coil respectively.

4.1 Experimental Issues

During the implementation of the circuit, I face alot of problem related to the efficiency of the power transfer because the power I want to get on the output terminal is not achieving. I have change multiple things related to circuit like change the value of resistance and capacitance but unfortunately, none of these tricks got success. After research on internet and reading some good research paper from IEEE I got to know that transistor can only be used effectively for low voltage application with low frequency. In order to get better efficiency, high frequency switching required low power consumption mosfet (Metal-Oxide-Semiconductor-Field-Effect-Transistor) should be used. Mosfet is a very delicate electronic component it consists of three terminals namely drain, gate and source. Initially, during the implementation circuit around 7 of my mosfet got damage due to the reason which initially I donât know but after multiple experimental result, I got to know the if I donât give power supply to the gate terminal of the mosfet then it this tiny electronic component destroy within second. That happen because I want to measure current and voltage across all the components the circuit, so I took out connection from gate terminal in order to get experimental reading so due to that multiple mosfet got wasted. Secondly, I also realized that when I increase the voltage to order to achieve maximum voltage at secondary side of the coil the temperature of the mosfet start rising due to which after some time mosfet stop working which can be easily identify with the help of multimeter by putting on continuity test if all the terminal of the mosfet are short the mosfet is damage.

4.2 MOSFET IRFZ44N

A popular MOSFET transistor with a wide range of general-purpose applications is the IRFZ44N. The transistor has high-speed switching capabilities, making it the perfect choice for applications where high-speed switching is essential. The transistor has a maximum load voltage of 55V and can drive loads of up to 49A. However, the maximum pulse current is 160A. This transistor requires a minimum threshold voltage of 2V to 4V to operate in a fully open state. This transistor has a major audio output of 94W and can also be used as an audio amplifier or in audio amplifier stages.[32] IRFZ44N can be utilised in a multiple range of applications, such as if we need high speed switching between two input , such as in a UPS, and you want to instantly switch the input power to battery backup power. Additionally, it can be utilised in a variety of power supply and power saving applications. Moreover, this transistor can be used to manage a load of up to 49A at the output of integrated circuits, micro-controllers, and electronics platforms like Arduino and Raspberry Pi, among others. However, it can also be utilised to create a variety of high-power audio amplifiers. Please click here to find datasheet.

4.2.1 Application

. Battery Chargers

. Solar Battery Chargers Applications

. Fast Switching Applications

. Stable Power Supplies

4.3 Schematic Circuit Diagrams

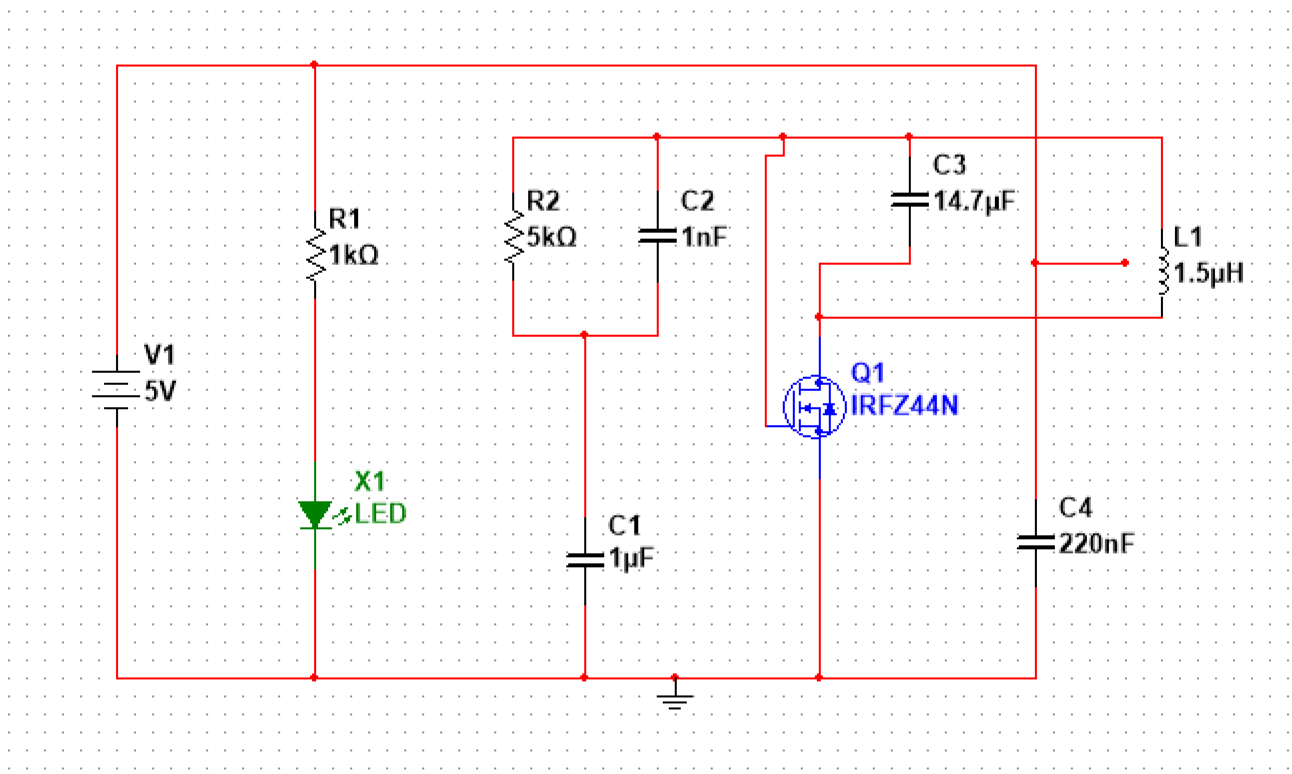


Figure 4.2: Transmitter Circuit

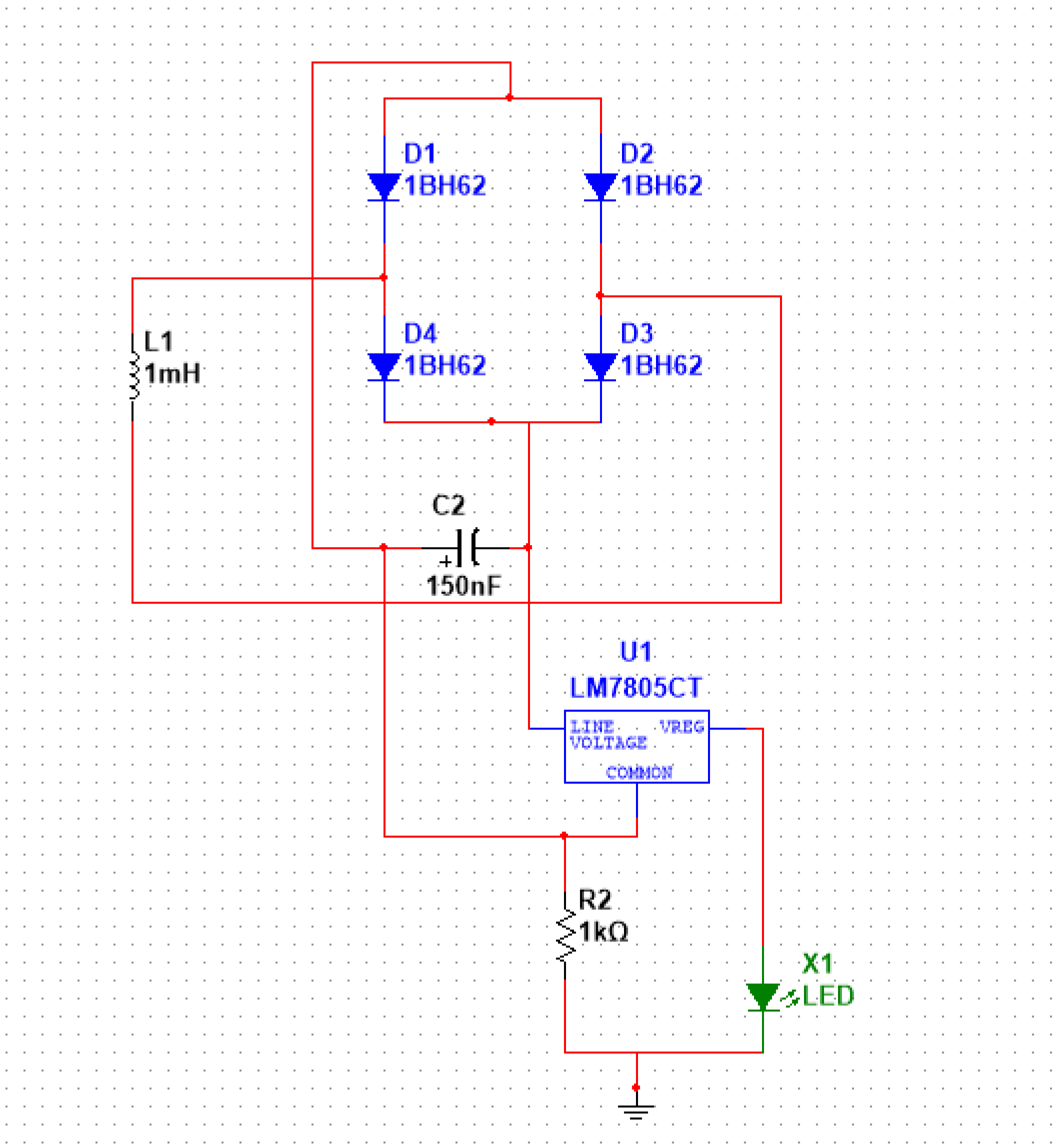


Figure 4.3: Receiver Circuit

4.4 Working of Transmitter Circuit

Transmitter circuit consist of a DC source with 5 V and around 1 A because I am working with low voltage application so 5V is enough and current should be limited with 1A so that no over current will be flow across the mosfet which is expensive and delicate electronic equipment. Capacitor is used to store electrical charges. Two capacitor is used to make a combine capacitance and connected to the gate terminal of the mosfet IRFZ44N which will provide pulse to the mosfet. On drain terminal of the mosfet a capacitor and coil three terminal is connected. Where as first point of the coil directly connect to the 5v power supply of the circuit and the center tape of the coil terminal join with 1 nF capacitance and then connected with a ground. The source terminal is directly connected with the ground.

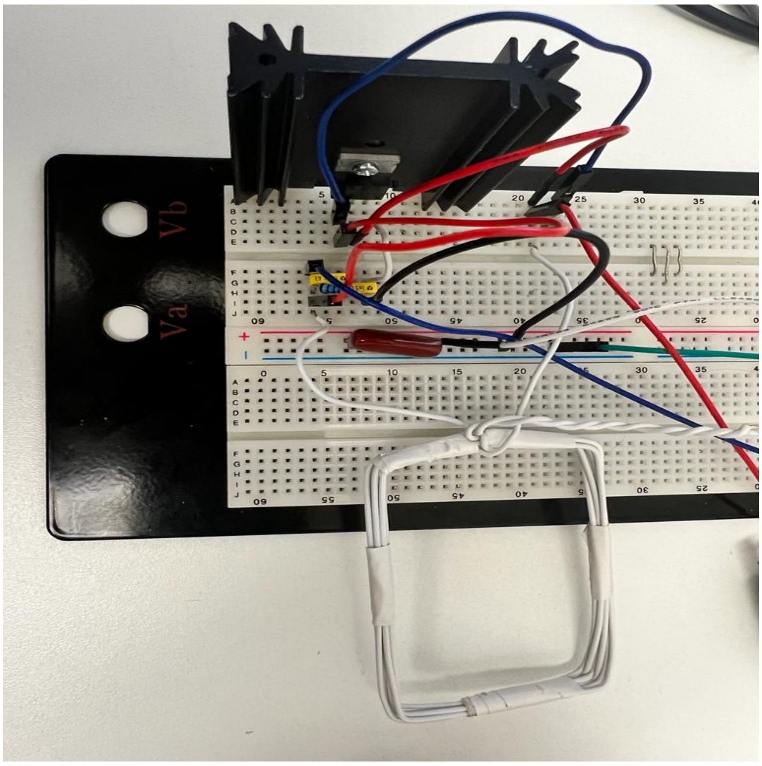


Figure 4.4: Bread Board implementation of transmitter circuit

The primary coil used in this project consist of rectangular shape with the diameter of 0.5 mm and 12 turns overlapping each other to product magnetic field around the coil when electronic current flow through the cable. Capacitor is attached with the coil in series which will store electrical charge. We can assume that the resonance frequency will be in the range of 200 to 400 KHZ depend on the capacitance of the circuit with the help of LCR meter we can measure the resistance and inductance of the circuit which is 5K ohm resistance and 1 mH inductance of the coil. In order to find the value of capacitance of the circuit we can calculate by the condition of resonant frequency $X_L = X_C$ so calculated capacitance is 1nF.

4.5 Working of Receiver circuit

The receiver circuit primary function is to deliver the system's or battery's electricity generated by the transmitter magnetic field. The first stage of this circuit's operation is the rectifier's conversion of the AC input voltage to a stable DC voltage, and the second stage is

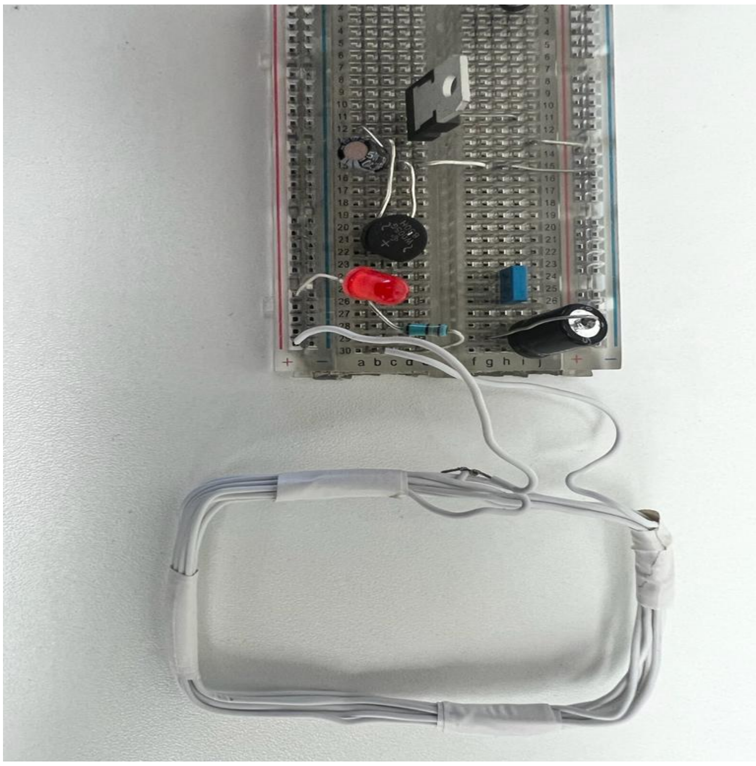


Figure 4.5: Bread board implementation of receiver circuit

the system or battery storage of the energy gathered from the transfer side. Receiver circuit consist of a coil with o.5mm diameter having 12 turns a full wave bridge rectifier is connect with secondary coil of the circuit which will convert DC into AC power source. The output of the bridge rectifier is connected to bipolar capacitor which is used to smooth the voltage. LM7805CT is a voltage regulator which will provide stable voltage at output so that it will control the fluctuation of the voltage which is harmful for the devices. In order to observe output response of the circuit led will be connected with resistor.

The secondary coil is made with the help of cut piece of a wood in a rectangular form then rap the copper coil on to the wood so that the copper coil will take the shape of the wood. Secondary coil with the diameter of 3mm contain 12 turns with the resonant frequency within the range of 200kHz to 400 kHz. The resistance and inductance of the circuit can be measured by LCR meter and with the help of resistance and capacitance value we can compute the value of capacitance.

4.6 Experimental results

In this experiment two coil are used. Primary coil consist of 6 turns and Secondary coil consist of 16 turns with the air gap of around of 0.03 meters respectively. As with the help of experimental value we can say that when the frequency of the increase the voltage on the secondary side across the led decrease. Furthermore, we can also analyze the capacitance of the circuit in inversely proportional to the frequency means if we increase the capacitance value frequency will decrease and vice versa.

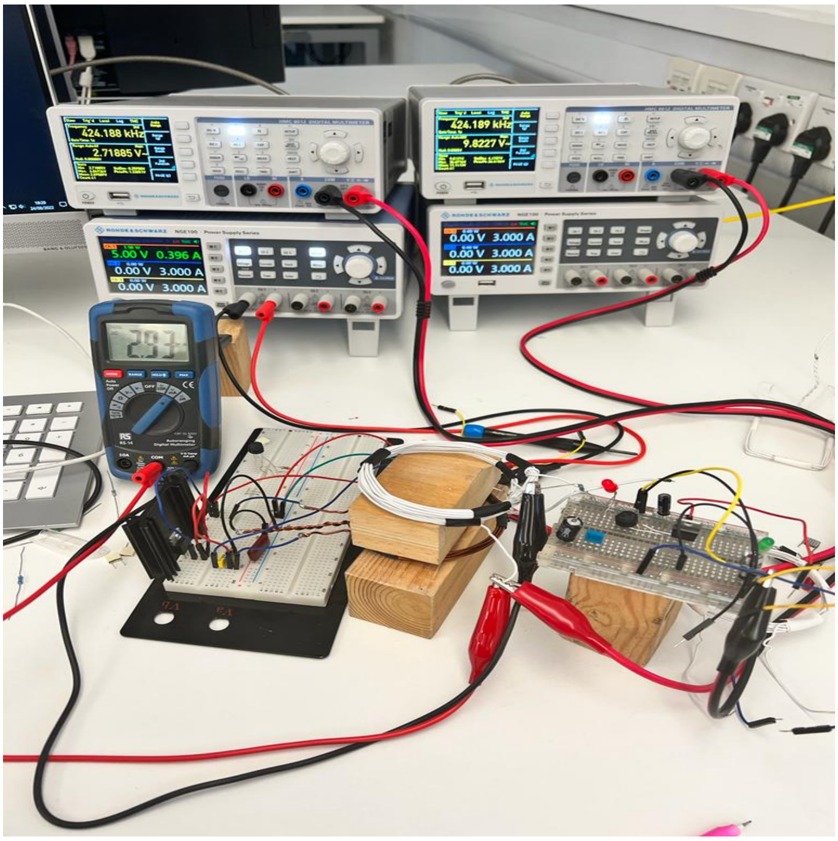


Figure 4.6: Experimental wireless power transfer system setup

Input Voltage	Capacitor	Frequency	Current	Output Voltage
5V	2nF	904.9 KHZ	2.39 mA	2.3V
5V	10nF	424.87K HZ	2.83mA	2.65V
5V	15nF	365.87KHz	3.6 mA	3.9V
5V	22nF	317.6KHz	3.94mA	4.2V
5V	33nF	276.9KHZ	4.76mA	5.9V

Table 4.1: Observational Result 1

Below table 4.3 show practical reading for a circular coil with primary turn 10 and secondary coil turns of around 10 which provide less output voltage as compare to the previous reading because of large number of turn on the secondary side of the circuit which boost the output voltage and current rating. So with the help of these reading we can say that when capacitance of the circuit increase then the frequency of the circuit decrease due to which voltage increase.

Input Voltage	Capacitor	Frequency	Current	Output Voltage
5V	2nF	260 KHz	1.3 mA	2.19V
5 V	10 nF	420.87 KHz	1 mA	2.08 V
5 V	15 nF	331.8 KHz	0.95 mA	2 V
5 V	22 nF	270 KHz	0.82 mA	1.88 V
5 V	33 nF	226.9 KHz	0.84 mA	1.91 V

Table 4.2: Observational Result 2

For this experiment primary coil consist of 10 turns and the secondary coil circuit have 10 turns as well. The shape of the coil is different from previous reading now coil shape is rectangular which provide better result with less number of turns as compare to previous reading.

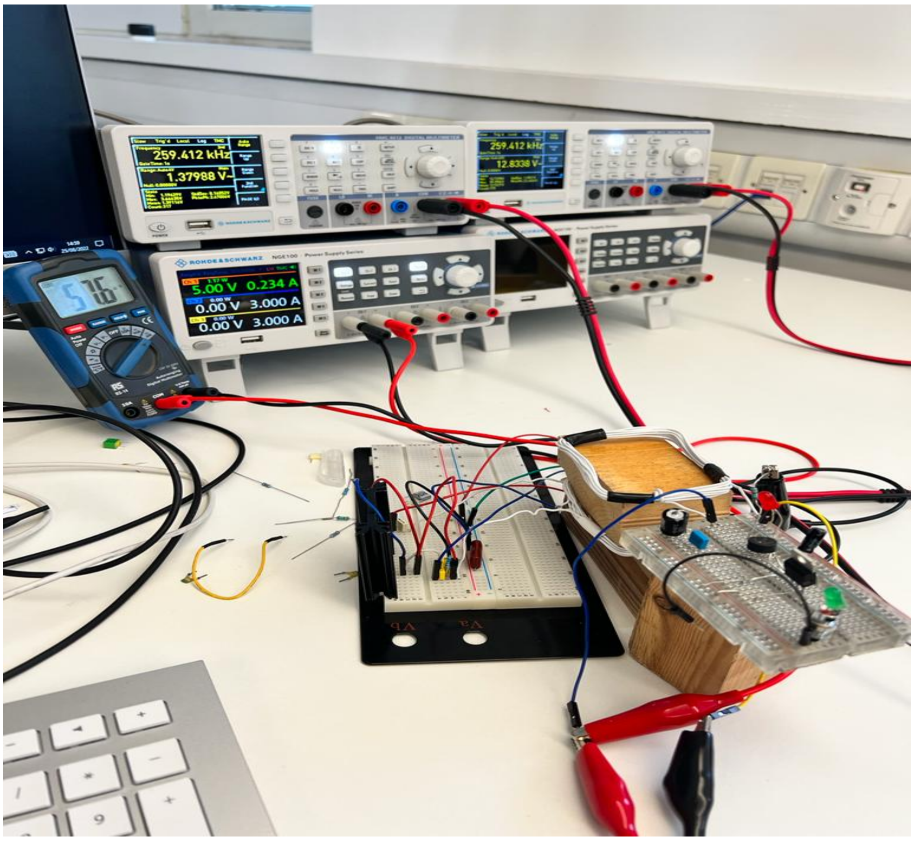


Figure 4.7: Experimental result on rectangular coil

Input Voltage	Capacitor	Frequency	Current	Output Voltage
5V	2nF	260.55 KHz	105 μ A	1.4V
5 V	10 nF	233.32 KHz	103 μA	1.35 V
5 V	22 nF	197.43 KHz	96.4 μA	1.25 V
5 V	33 nF	188.64 KHz	43.6 μA	1.091 V
5 V	49 nF	174.18 KHz	15μA	1 V

Table 4.3: Observational Result 3

4.7 Vero Board Implementation

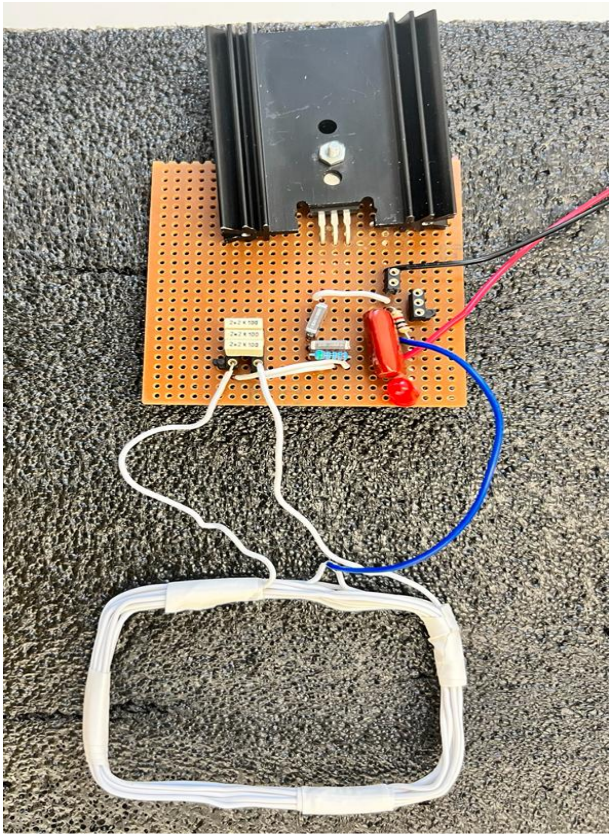


Figure 4.8: Vero board transmiter circuit implementation

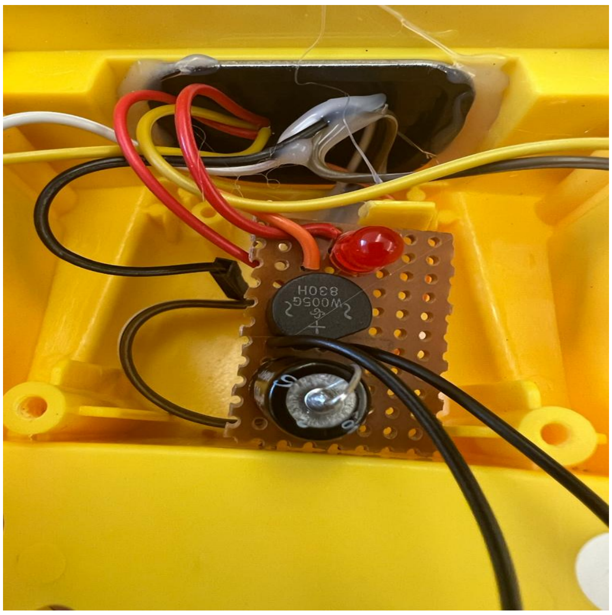


Figure 4.9: Vero board receiver circuit implementation

4.8 Rectifier Circuit

A rectifier is an electrical device which convert AC current into DC current, which means when an alternating current passes through the circuit it consist of two level one is positive level other is negative level but in Dc supply we have only one constant level. So in order to convert AC to Dc source different types of rectifier is used namely semi conductor switching, silicon based semiconductor and solid state diode. In my project, I am using full wave bridge rectifier which convert sinusoidal AC wave form into constant Dc supply. Working of bridge rectifier explain below

An electrical device called a rectifier changes alternating current (AC), which occasionally flips direction, into direct current (DC), which only flows in one direction. The action is referred to as correction. Reciters come in a variety of physical configurations, such as solid-state diodes, silicon-controlled rectifiers, and other silicon-based semiconductor switches.Four diodes arranged in a bridge circuit layout to produce a desired output is known as a full-wave bridge rectifier. The fact that the output's polarity is constant independent of the input's polarity is a full-wave bridge rectifier's defining characteristic. The bridge rectifier functions as follows.[19]

1. Initially D1 and D2 should be forward bias and pass current on the positive cycle only after the positive cycle finish D3 and D4 are in forward bias and D1 and D2 will consider to be in reverse bias respectively.

2. For the negative half cycle, the direction of the diode D1 and D2 will be reverse.

$$C = \frac{It}{\Delta V} \tag{4.8.1}$$

4.9 Prototype implementation

In this project, I work on wireless power transfer based on electric vehicle due to that reason I have design buss or car charging system in which two coils are used transmiter and receiver coil. The primary coil should be aligned with the ground level and the secondary coil is fitted inside the buss so that when buss come under the primary coil then led glow but when their is a misalignment between transmiter and receiver coil the led will not glow. For the video demonstration youtube link `https://youtu.be/RLHV4AoMm9g` is attached.

Figure 4.10: Wireless Buss Charging Prototype

CHAPTER 5

Overview of Wireless Power Transfer

Due to the mutual inductance of the two coils in the Wireless Power transfer system, power is transmitted inductively from one coil to the other. The general idea is the same as it is with a transformer. The primary distinction is that whereas in a transformer there is a significant coupling between the two sides, with a Wireless power transfer system there is a low coupling because of the big air gap between two coils or magnetic material. Most WPT devices use air to conduct the flux because they don't use ferrite or other magnetic materials. Although there is less coupling in these systems, there should be no core losses. Low coupling results in lower magnetization flux and relatively large leakage inductance on both sides of the transformer. To enhance the flux, a larger magnetization current is required for better performance.

5.1 Standard WPT System

A basic wireless power transfer circuit consist of different block for Ac power source to charging a Dc battery. The inverter connected to a primary resonant tank circuit consist of primary coil and compensation circuit with high frequency square wave voltage. The secondary circuit coil and compensation circuit energize with the help of electromagnetic induction this effect is called mutual induction. The secondary resonant tank product output square wave voltage with rectifier attached with a load battery.FHA (first harmonic approximation) is used to convert square wave voltage signal into sinusoidal voltage and also convert battery rectified load into resistive load. In order to model wireless power transfer compensation circuit play significant role to transfer power from one coil to another coil effectively.[10]

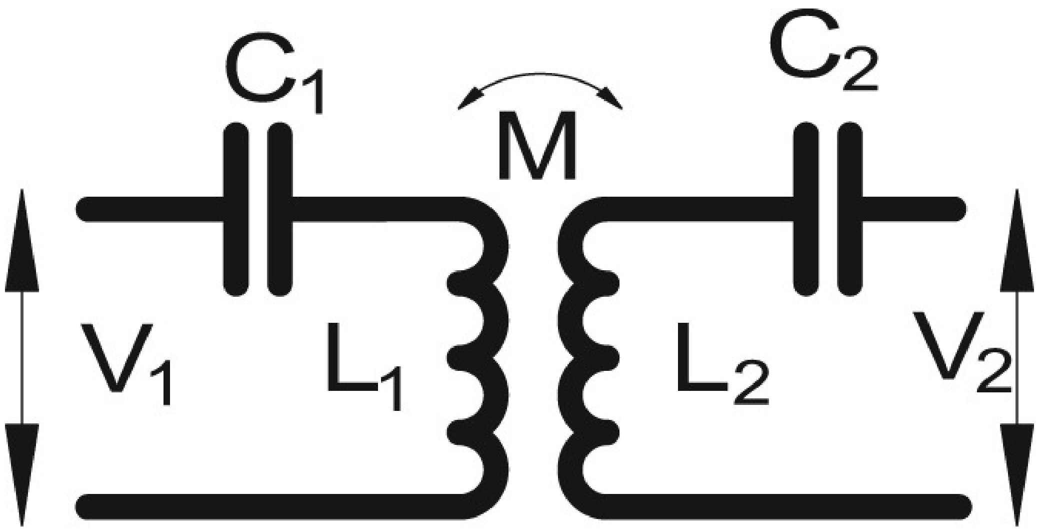


Figure 5.1: Wireless Power Transfer Circuit [47]

5.2 Compensation Network

In order to select topology we need to consider different factor. There are four different types of compensation network which are as follows

1. Series-Series (SS)
2. Series-Parallel (SP)
3. Parallel-Parallel (PP)
4. Parallel-Series (PS)

We can see in the figure 5.2, L1 and L2 are equivalent to primary and secondary coil respectively. C1 is consider to be equivalent to primary compensation circuit and C2 is equal to secondary compensation circuit.Whereas, M is the mutual induction between two coil of the circuit. We can use any kindly of compensation topology depend on the application and requirement of the circuit.

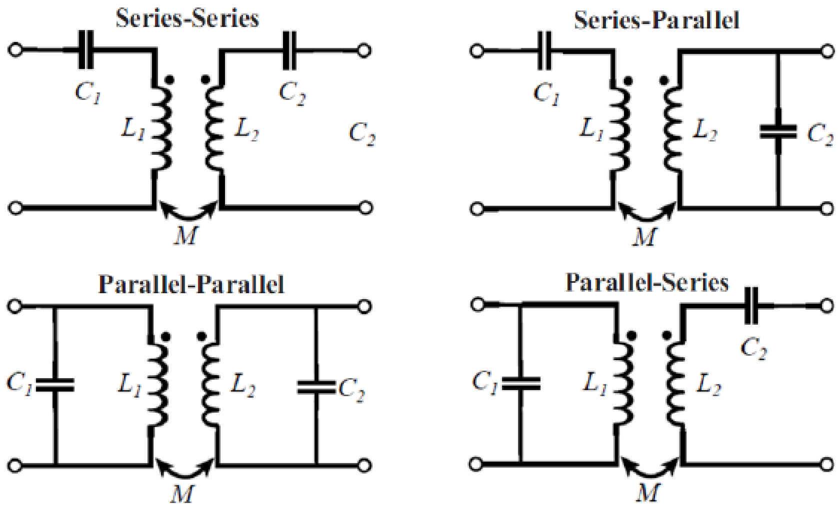


Figure 5.2: Different compensation topology [23]

	Series-Series	Series-Parallel	Parallel-Parallel	Parallel-Series
Depend on Load R_L and coupling factor	Both primary and Secondary compensation capacitor independent of load and K	Compensation capacitor of secondary is depend on Load and K	Primary Compensation capacitor dependent on load and K	Both Primary and Secondary compensation capacitor are dependent of load and coupling factor
Voltage rating of inverter device	Required lower dc link voltage (Higher than S P)	Lower DC link voltage	Higher voltage require as compare to S-S and S-P	High voltage needed as compared to S-s and S-P
Current rating of inverter device	Primary coil current	Primary coil current	Active component of primary coil current	Active component of primary coil current

Table 5.1: Comparison between four different compensation topology [4]

Compensation topology	Primary capacitance	Theoretical efficiency	Transferred impedance
Series-Series	$\frac{C_2 L_2}{L_1}$	$\frac{\omega^2 M^2 R_L}{((R_2 + R_L)^2)R_1 + (\omega^2 M^2)(R_2 +}$	$(R_1 + j(\omega L_1 - \frac{1}{\omega C_1})) + \frac{\omega^2 M^2}{R_2 + R_L + j\left(L_2\omega - \frac{1}{C_2\omega}\right)}$
Series-Parallel	$\frac{C_2 L_2^2}{L_1 L_2 - M^2}$	$\frac{\omega^2 L^2 R_L}{R_L\omega^2 + R_2\omega^2 L_2^2 + R_2 R_L^2 + \frac{R_1 R_2^2 L^2}{M^2}}$	$(R_1 + j(\omega L_1 - \frac{1}{\omega C_1})) + \frac{\omega^2 M^2}{R_2 + \frac{R_L}{1 + jR_L C_2\omega} + jL_2\omega)}$
Parallel – Series	$\frac{C_2 L_2}{\frac{M^4}{L_1 C_2 L_2 R_L} + L_1}$	$\frac{\omega^2 M_{12}^2 R_L}{((R_2 + R_L)^2)R_1 + (\omega^2 M_{12}^2)(R_2 +}$	$\frac{1}{R_1 + jL_1\omega + \frac{\omega^2 M^2}{\left(R_2 + R_L + j\left(L_2\omega - \frac{1}{C_2\omega}\right)\right)}}$
Parallel-Parallel	$\frac{(L_1 L_2 - M^2)C_2 L}{\frac{M^4 C_2 R_L}{L_2} + (L_1 L_2 -}$	$\frac{\omega^2 L^2 R_L}{R_L\omega^2 + R_2\omega^2 L_2^2 + R_2 R_L^2 + \frac{R_1 R_2^2 L^2}{M^2}}$	$\frac{1}{\frac{1}{R_1 + jL_1\omega + \frac{\omega^2 M^2(1 + jR_L C_2\omega)}{(R_L + (R_2 + jL_2\omega)(1 + jR_L}}}$

Figure 5.3: Formula for different compensation network [4]

5.2.1 Selection between Series-Series and Series-Parallel topology

In order to choice for their compensation capacitance's is independent of the load, which is a desired quality in particular when the loading profile is changing, is a very significant trait that the primary series compensation topologies possess. Different criteria, including efficiency and its tolerance to different frequencies, the intended power levels of operation, power factor and its tolerance to varied frequencies, and cost, will determine which of the two basic series compensation schemes is used. Generally when high power voltage is transfer on series parallel compensation will get high power with low voltage and high current. However, as compare to series series compensation network due to large amount of input impedance at resonant frequency with that factor current flow at a very low voltage is not that very high. Therefore, In order to transfer high power only high voltage will be used.Series-series topology is preferable for variable frequency operations because it has a larger tolerance for power factor when frequency varies. It is also observed that Series-series topology has a substantially greater maximum efficiency than Series-parallel topology as a result for fix frequency network it is consider better to use series series compensation. Secondly, series-series topology provide better efficiency for frequency tolerance as compare to series-parallel specially at super resonant frequency.[2]

There are two major criteria to select the primary and secondary compensation capacitance given below.

1. First we have to select secondary capacitance of the network. This is due to compensate the leakage inductance in secondary coil and mutual inductance. With the help of this compensation network power transfer to the load efficiency will increase.

2. Secondly, In order to select the primary capacitance which is consider to be the inductance of whole circuit. In theory primary capacitance is use to compensate the entire circuit network plus the self inductance of the circuit. However, it is good option to select compensation network for complete circuit so that source power factor (pf) will become one.

5.2.2 Series-Series Compensation Network

For this dissertation series series network is used because primary component C_1 will act like a current and provide stable output current.[51] which will provide induce voltage into the secondary coil with the fix voltage amplitude. On the other hand second capacitor C_2 will act like a voltage source that provide constant voltage and is used to provide constant resonant frequency which is not depending on load and coupling factor. Due to that multiple factor I decided to go with series-series compensation network

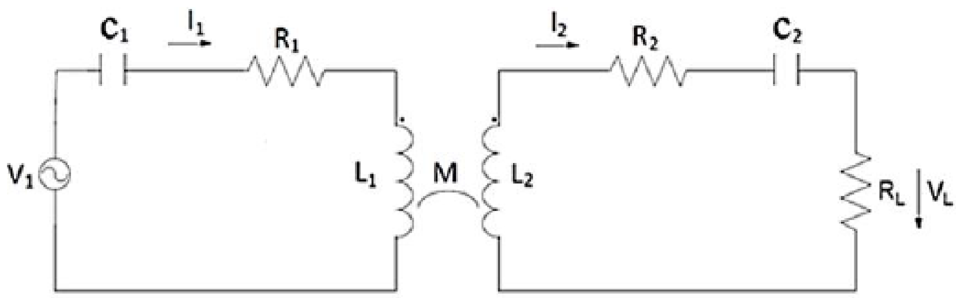


Figure 5.4: Basic Wireless Power Transfer Designing

5.2.3 Modes of Operation

There are two methods to improve the power transfer efficiency of the system.

1. Soft Switching technique: In order to decrease the resonant inverter's switching loss, use the soft switching technique of zero voltage switching (ZVS) or zero current switching (ZCS).

2. Compensation network and impedance matching: Series and parallel capacitor should be added across the primary and secondary coil in order to improve coupling between two winding. The purpose of designing compensation circuit is to achieve zero phase angele (ZPA) on primary coil side to get resonant frequency. So , to achieve higher output power with minimum input voltage current. ZPA is used when we want maximum power transfer with minimum VA rating.

The below plot 5.2.3 is between switching frequency and a resonant tank gain K on different values of quality factor Q and value of m is consider to be 6. The zero current switching (ZCS) is label in red colour whereas zero voltage switching (ZVS) is label in white colour.

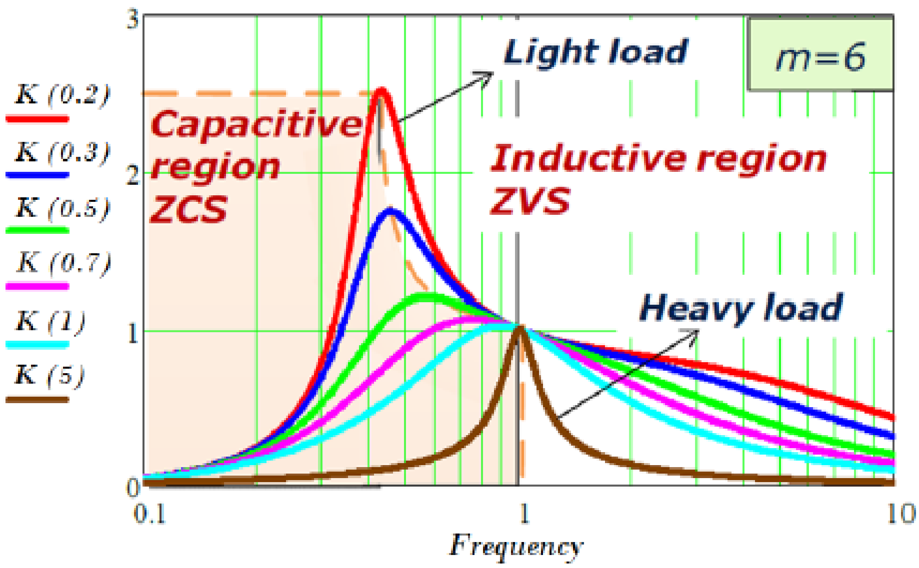


Figure 5.5: Working region between ZCS and ZVS [22]

Below figure tell there are three mode of operation [1] which is depend on supplied voltage and load current.

1. Above resonant frequency operation fs>fr

2. At resonant frequency fs=fr

3. Below resonant frequency fs<fr

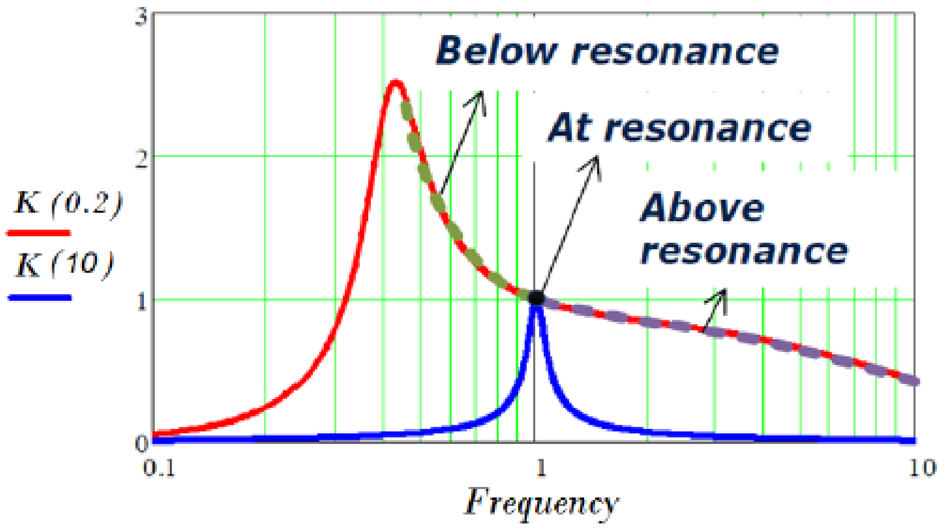


Figure 5.6: Modes of Operation[47]

5.3 Coil Design

There are two main design configuration for Wireless power transfer circular and rectangular. In my project rectangular coil has been used which offer good coupling results without any misalignment consideration. The transmitter coil is place under the table and the receiver coil should be place under the buss so that when the buss come under the range of primary coil it start charging the buss battery.[26]

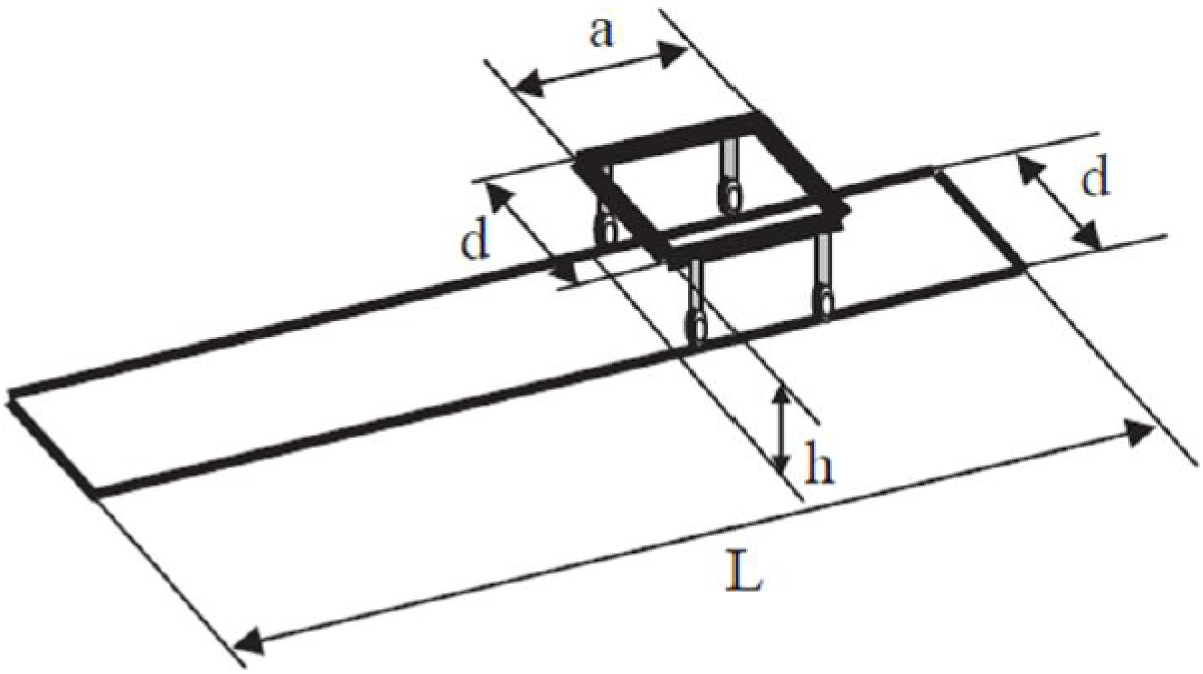


Figure 5.7: Coil shape and different parameter [26]

5.3.1 Important Parameter for Coil designing

In order to compute the size and shape for primary and secondary coil multiple parameter we need to follow.

- Mutual induction between two coil (M)
- Efficiency of power transfer η
- Real power transfer P_2
- Coupling Coefficient K

5.3.2 Coil size and shape

For the development of wireless power transfer two major design technique is used one is circular and other is know as rectangular [26]. For my thesis, I selected rectangular coil which provide good coupling performance and high misalignment.

Applying condition on equation 3.6.5 $L(a_1(t)) = \frac{s+T-i\omega}{(s+T-i\omega)^2+k^2}$

$$L(a_2(t)) = \frac{iK}{(s+T-i\omega)^2+k^2} \tag{5.3.1}$$

Taking inverse laplace transformation

$$a_1(t) = e^{(i\omega - r)t}cos(kt) \tag{5.3.2}$$

5.4 Prototype Circuit Modeling

5.4.1 Equivalent circuit equation for Wireless Power transfer

Figure 3.7 show the combine version of series-series compensation network. where Z_2 is combine impedance of secondary coil.

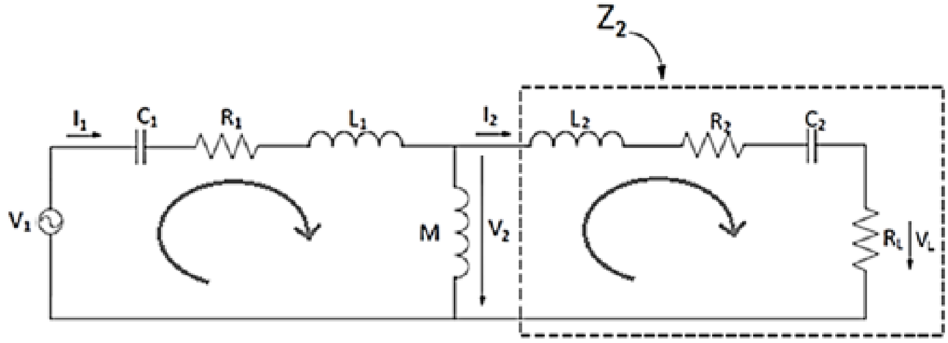


Figure 5.8: Series to series compensation WPT system [15]

Applying Kirchhoff's second law to compute the mash equation on both the loops of the circuit

$$v_1 = I_1(\frac{1}{j\omega C_1} + j\omega L_1) + j\omega M(I_1 - I_2) \tag{5.4.1}$$

$$0 = I_2(j\omega L_2 + R_2 + \frac{1}{j\omega C_2} + R_L) + j\omega M(I_2 - I_1) \tag{5.4.2}$$

where n is consider to be the turns ratio between primary and secondary coil of the circuit

$$n = \frac{N_1}{N_2} \tag{5.4.3}$$

In order to find total resistance from the circuit

$$R_L = \frac{8n^2}{\pi^2} R_load \tag{5.4.4}$$

The terminal load of a DC circuit is given by

$$R_{Load}=\frac{V_load}{I_Load} \tag{5.4.5}$$

The Figure 3.8 is the equivalent circuit design for the primary components with equivalent impedance of secondary coil Z_2

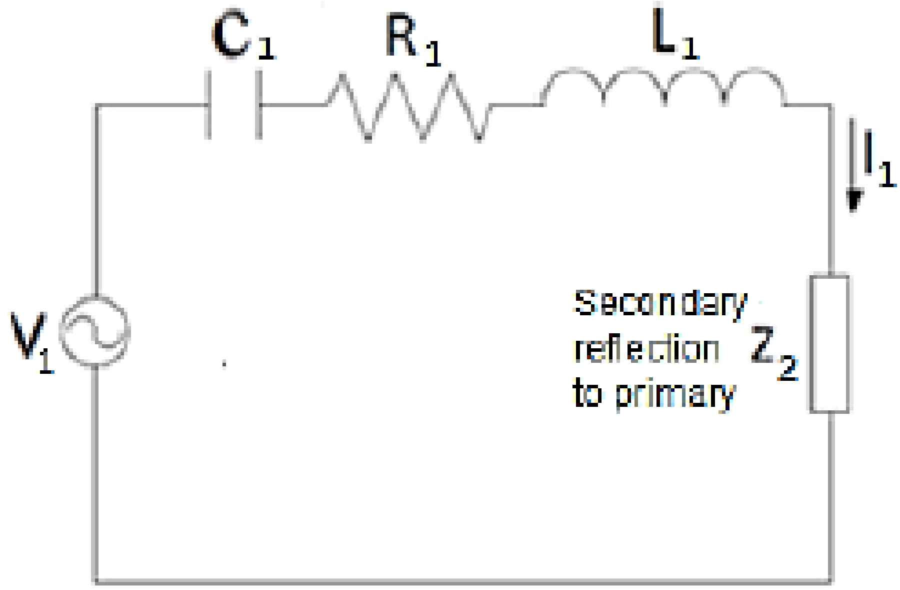


Figure 5.9: WPT RLC circuit from primary side[37]

As we can see in the above series circuit current will be the same through all the components of the circuit so we can easily calculated the current flow through the circuit with the help of ohms law which is V=IR.[26]

$$I_1\frac{V_1}{Z_Total} \tag{5.4.6}$$

Z_total is the equivalent impedance of the circuit including resistance of primary and secondary coil

$$Z_{Total} = R_1 + j\omega L_1 + \frac{1}{j\omega C_1} + \frac{\omega^2 M}{Z_2} \tag{5.4.7}$$

On the order hand Z_2 is consider to be the total impedance of secondary reflecting primary side of the circuit.

$$Z_2 = R_2 + \frac{1}{j\omega C_2} + j\omega L_2 + R_L \tag{5.4.8}$$

Putting equation (3.5.8) in equation 3.5.7 so we can rewrite the equation 3.5.6 as

$$I_1 = \frac{V_1}{R_1 + j\omega L_1 + \frac{1}{j\omega C_1} + \frac{\omega^2 M^2}{R_2+j\omega C_2+j\omega L_2+R_L}} \tag{5.4.9}$$

We can cancel out the LC components in the equation when the circuit is working at resonant frequency so the updated equation is given by

$$I_1 = \frac{V_1}{R_1 + \frac{\omega^2 M}{R_2 + R_L}} \tag{5.4.10}$$

The current flow through the secondary side of the circuit can be measured by the induced voltage divided by the total impedance of the secondary coil

$$I_2 = \frac{j\omega M I_1}{Z_2} \tag{5.4.11}$$

I_2 can also be written as

$$I_2 = \frac{j\omega M I_1}{R_2 + \frac{1}{j\omega C_2} + j\omega L_2 + R_2} \tag{5.4.12}$$

The voltage V_2 applied to the secondary coil is directly proportional to the current induce in the primary coil

$$V_2 = j\omega M(I_1 - I_2) \tag{5.4.13}$$

5.4.2 Power and Efficiency Calculation

The parameters used in this section are RL, which represent total load resistance of the rectifier circuit and battery load, R1, which stands for resistance of the coil L1, and R2, which stands for resistance of the coil L2. P1, which stands for power generated at the primary side, P2, which stands for power transferred to the secondary side, and M, which stands for mass, are also used. V1 is the voltage source, I1 is the current flowing through the primary side, and f is the mutual inductance.

Efficiency of the system can be computed by

$$\eta = \frac{P_2}{P_1} \tag{5.4.14}$$

Power calculation of primary side can be given by the formula

$$P_1 = \frac{V_1^2}{R_1 + \frac{\omega^2 M^2}{R_2 + R_L}} \tag{5.4.15}$$

Secondary side power formula is obtained by

$$P_2 = \frac{\omega^2 M^2 I_1^2}{R_L} \tag{5.4.16}$$

ω represent as resonant frequency which operation between primary and secondary coil, which can be calculated by

$$\omega = \frac{1}{\sqrt{L_1 C_1}} \tag{5.4.17}$$

$$\omega = \frac{1}{\sqrt{L_2 C_2}} \tag{5.4.18}$$

ω can be calculated by

$$\omega = 2\pi f \tag{5.4.19}$$

5.5 Parameter Calculation of Wireless Power Transfer

In order to find the inductance of the circuit L_1 and L_2 can be represented as [44]
L_1 is represented as

$$\begin{aligned} L_1 = \frac{\mu_0}{\pi} N_1^2 (d.ln \frac{2.L.d}{R_1(d+\sqrt{L^2+d^2})} + \frac{\mu_0}{\pi} N_1^2 (d.ln \frac{2.L.d}{R_1(d+\sqrt{L^2+d^2})} \\ - 2(d+L-\sqrt{(d^2+L^2)} + + \frac{\mu^0}{4\pi} N_1^2 (L+d) \end{aligned} \tag{5.5.1}$$

L_2 is represented as

$$\begin{aligned} L_2 = \frac{\mu_0}{\pi} N_2^2 (d.ln \frac{2.a.d}{R_2(d+\sqrt{a^2+d^2})}) + \frac{\mu_0}{\pi} N_2^2 (a.ln \frac{2.a.d}{a+R_2(\sqrt{a^2+d^2})} \\ - 2(d+a-\sqrt{d^2+a^2})) + \frac{\mu^0}{4\pi} N_2^2 (a+d) \end{aligned} \tag{5.5.2}$$

R_1 and R_2 consider to be internal radius of primary and secondary winding respectively

$$R_1 = \sqrt{\frac{N_1 S_1}{\pi}} \tag{5.5.3}$$

$$R_2 = \sqrt{\frac{N_2 S_2}{\pi}} \tag{5.5.4}$$

S_1 and S_2 consider to be section radius of the winding.

M is represented as Mutual inductance between two coil with same dimension can be represented by:

$$M = \frac{\mu_0}{\pi} N_1 N_2 (d.ln \frac{d + (\sqrt{h^2+d^2})(\sqrt{h^2+a^2})}{d + h\sqrt{h^2+d^2+a^2}})$$

$$+\frac{\mu_0}{\pi}N_1N_2(a.ln\frac{a+(\sqrt{h^2+d^2})(\sqrt{h^2+a^2})}{a+h\sqrt{h^2+d^2+a^2}})$$
$$+\frac{\mu_0}{\pi}N_1N_2(2(h-\sqrt{h^2+d^2}-\sqrt{h^2+a^2}+\sqrt{h^2+d^2+a^2})) \tag{5.5.5}$$

For this thesis we assume that primary track consider to be longer than secondary so a « L [44] so the updated formula for mutual inductance can be define as:

$$M=\frac{\mu_0}{\pi}N_1N_2aln(\frac{\sqrt{h^2+d^2}}{h}) \tag{5.5.6}$$

μ_0 is the permeability constant in the air with the constant value of $4\pi \times 10^{-7}$ H.m^{-1}

Winding resistance value can be calculated by the formula

$$Rwp_1=\frac{1}{57}N_1\frac{2(L+d)}{S_1} \tag{5.5.7}$$

Above equation 5.5.7 define primary winding resistance and below equation 5.5.8 is use to calculate secondary winding resistance.

$$Rws_2=\frac{1}{57}N_2\frac{2(a+d)}{S_2} \tag{5.5.8}$$

5.6 Operational Frequency

In order to find the frequency of the circuit below formula is used

$$f=\frac{1}{2\pi\sqrt{LC}} \tag{5.6.1}$$

C_1 and C_2 are the capacitors value which will be tune at resonant secondary frequency to achieve maximum wireless power transfer[44]

The compensation resonant capacitor can be calculated by the formula

$$C_1=\frac{1}{\omega^2L_1} \tag{5.6.2}$$

Electromagnetic induction work on resonant frequency which means when inductive and capacitive reactance of the circuit be come equal then at that particular time period the frequency is know as resonance frequency. In the figure 5.10 one complete cycle take 2 μ sec so the frequency will become 500K KHz

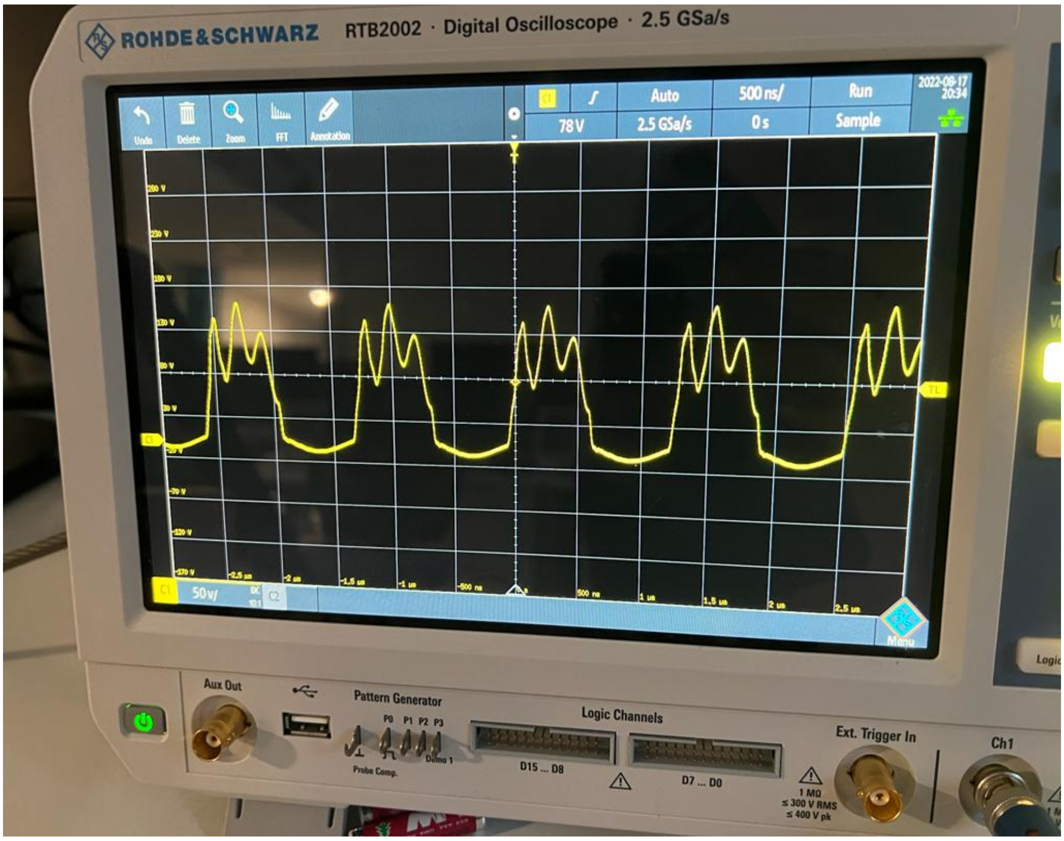


Figure 5.10: Frequency and time period analyzer

5.7 Capability of Power transfer

5.7.1 Coupling Coefficient

The potential of wireless power transfer to transmit energy wirelessly depend on the coupling coefficient which in represented by K[44] and can be calculated by the following formula.

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{5.7.1}$$

5.7.2 Comparison between frequency and coupling coefficient in WPT

In order to find the coupling coefficient develop between secondary and primary coil can be illustrated by 5.7.1. If no magnetic field exist between primary and seconding winding then mutual induction M=0. Ideally transformer with core and no air gap consider to have maximum coupling coefficient. The coupling coefficient with K value greater then 0.5 (K>0.5) consider to be highly coupled. On the other side if the value of K less then 0.5 (K<0.5) then we called loose coupling. The value of mutual induction M and the distance between two coil, number of coil turn on each winding are the factor for depend on the value of K.[26]. To increase the coupling between primary and secondary winding we need to add the turns for both primary and secondary coil with the help of laminated copper wire. With stronger coupling between coil, the lower is the design frequency.

5.7.3 Quality factor

Quality factor measure how much of the coil is inductive only. It identify how much a coil can produce a huge magnetic field. Wireless power transfer system generally have same frequency but it can change due to fluctuation in circuit parameter like load, capacitance, the free space medium. Therefore transfer efficiency decrease and the system lose it zero phase angle frequency.[25] Quality factor represent how idea an inductor is for wireless power transfer.

$$\mathbf{Q_1}=\frac{\omega \mathbf{L_1}}{\mathbf{Rwp_1}} \tag{5.7.2}$$

$$\mathbf{Q_2}=\frac{\omega \mathbf{L_2}}{\mathbf{Rws_2}} \tag{5.7.3}$$

Where

1. $\omega = \mathbf{2}\pi\mathbf{f}$
2. $L_1 L_2$ are inductance for primary and secondary
3. f is frequency
4. Rwp_1 and Rws_2 are wire resistance for primary and secondary respectively.

Generally a good inductor contain no resistive loss which result as an infinite quality factor however ideally inductor have wire resistance. With low frequency resistive value for copper wire will be low. On the other hand, with high frequency the value of copper resistive wire will also be high.This effect is called skin effect. In order to counter this effect litz wire is used for high frequency and low resistive.

5.8 Matlab Code Calculation

In order to transfer power wirelessly circuit designing play a crucial role. So, In order to transfer power effective mathematically calculation for each electronic component with respect to the coil size, shape, length of coil, distance between two coil, etc play significant role.

Parameter	Input
L primary coil length	0.0635 m
A secondary coil length	0.0635 m
D width of primary and secondary coils	0.0381m
H height between primary and secondary coil	0.03
N1 total number of turns for primary coil	10
N2 total number of turns of secondary coil	10
S1 area cross section of litz wire winding	$0.96x10^-6$
S2 area cross section of litz wire winding	$0.96x10^-6$
ω_0 Permeability of the air	$4\pi\ x10^-7\ H/m$
F frequency	400 KHZ

Table 5.2: Input parameter value

Parameter	Calculated Value
L1 Primary coil inductance	1.7982x10$^-4$ m
L2 Secondary coil inductance	8.97x10 $-$ 5 m
C1 Primary coil capacitance	8.8x10$^-$10m
C2 Secondary coil capacitance	1.76x10$^-9$
R1 resistance of primary coil	0.0031
R2 resistance of secondary coil	0.0031
M Mutual Inductance	1.2198x10$^-5$
K coupling coefficient	0.0960

Table 5.3: Calculated value generated by matlab code

5.9 Power Losses

The majority of inductive coupling-based high-power wireless charging solutions contai system efficiencies between 80 and 90%. These efficiencies translate to a heat loss of roughly 750W in a 5kW system. Due to increase in the temperature of the circuit efficiency of the power transfer also decrease. The factor depending on power losses are Joule heating, skin effect, proximity effect, switching losses in the power stage, and rectifier losses at the receiver.[47]

5.9.1 Joule heating

Joule heating is a phenomenon that happens whenever a wire or component has current flowing through it. A certain amount of resistance exists in each cable, connection, path, etc., and when combined with the current, this resistance results in a power loss, P = RI2.[47]

5.9.2 Skin Effect

when conductors are subjected to an alternating current. The "skin" of the conductor experiences current flow as a result of this phenomena. The skin depth decreases with increasing frequency, increasing resistance. As a result, the cable will heat up and experience additional joule losses. Consequently, a snowball effect may happen: hotter cable wrapping may increase cable resistance, causing additional heating, etc. One can figure out the skin depth by:[22]

$$d = \sqrt{\frac{2}{\omega.\mu.\gamma}} \tag{5.9.1}$$

Where angular frequency of alternating current is donated by ω and equal to 2π f (rad/s), μ is the magnetic permeability between two conductor coil (H/m), and γ consider to be the resistance of the circuit. (S/m)

5.9.3 Switching Losses

The switching loss is generated by MOSFET which required a particular time to switch the circuit on and off which create loss in power transfer. Due to very fast switching produce heat in the circuit which cost high internal impedance or sometime may increase the temperature of the circuit.

5.9.4 Proximity Effect

A phenomenon known as the proximity effect happens when two conductors through which an AC current runs are close to one another. Eddy currents will form as a result, altering the current density. When the direction of adjacent conductor currents is the same then the conductor's outside will receive the majority of the current. In the same way, if the two the currents are in opposite direction, the current will focus inside the conductor.[22] Due to the fluctuating magnetic field of the object, eddy currents are generate in proximity effects. Current in the surrounding winding layer, which causes an increase in the amplitude of the Eddy currents due to the quantity of coil windings or layers, exponentially.

5.9.5 Rectifier loss

High frequency current is used to transmit power but this is not follow in every real application so depending on the device we have to convert from ac to dc vice versa at the receiving end. Normally we use passive rectifier is used for rectification so when the diode perform it rectification so a forward voltage applied over it. This increase in voltage create high current flow which cause high power losses.[47]

CHAPTER 6

Wireless Power Transfer for Electric Vehicle

The basic structure of wireless power transfer for electrical vehicle consist of front AC-DC converter which will correct the power factor of the system and convert alternating current power source from consuming to an adjustable DC level. I have discuss about varies standard of wireless charging in section 5.10. There are many published standards for electric vehicle charging wirelessly, including the SAE J2954/1 standard for charging light-duty automobiles, which classifies charging into five smallÂ categories based on power levels.[16]. WPT1 system is develop for the household equipment provide maximum load capacity of around 3.7 KVA with single phase output of 120V AC power supply. WPT2 is the advance version of WPT1 with the increase in the power capacity of about 7.7 KW with two phase power supply of 240V ac from main system. After that WPT3 develop which improve to 11 KW. WPT4 system capable to provide 22KW input power with three phase voltage source 240V. For wireless power transfer charging of heavy-duty electric vehicles, such as buses, where the power rating should be larger than 22kW to 150kW and higher from different ranges of voltage supply like 208 Vac three-phase, 480 V for three-phase, or medium voltage supply, SAE J2954/2 is currently being developed. Power efficiency of the system must be better than 85% for a balanced system at power rating and greater then 80% for compatible systems at either level of charging. [5]. In the table 6.1 which provide central idea of the standard requirement of J2595 in wireless power system. In the second portion of the figure 6.1 full wave bridge rectifier is used to convert Dc voltage in Ac voltage with high frequency[23]. High frequency AC power transmitted through the compensating network to make up for the coupler coils’ need for reactive power.

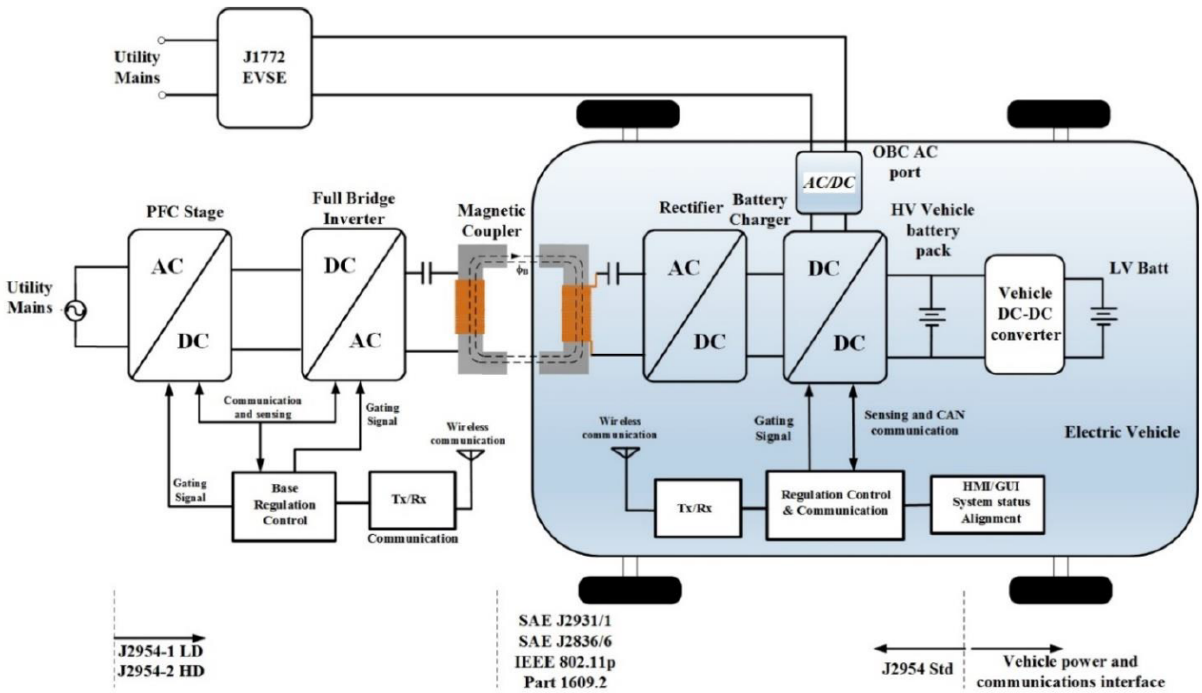


Figure 6.1: Block diagram of Electrical Vehicle[25]

Coupler secondary coil voltage rectified when the current passes through the secondary rectifier circuit then passing through the compensation network. To increase the efficiency of power transfer, the compensation network is configured to resonate within the limited bandwidth frequency range (81 kHz to 90 kHz). Additionally, it has adjustments to the loading variability and coupling coefficient. Primary or secondary side controller is used to control the output of the circuit.

	WPT1	WPT2	WPT3	WPT4
Maximum input Volt Amp	3.7 KVA	7.7KVA	11.1KVA	22KVA
Minimum Target Efficiency	> 85%	7.7KVA	11.1 KVA	22KVA
Minimum target efficiency at offset	>80%	80%	>80%	TBD
Frequency	85kHz within international frequency band (81.38-90)kHz	85kHz within international frequency band (81.38-90)kHz	85kHz within international frequency band (81.38-90)kHz	85kHz within international frequency band (81.38-90)kHz

Table 6.1: Proposed WPT Power Class for J2954/1 [37],[39]

6.1 Design Consideration of WPT

In the recent research SAE J2951/1 different standard of WPT has been introduce for electric car. In the figure 6.1 which is take from an research article related to witricity show different components required for an electrical vehicle and its corresponding standard for each category. THD total harmonic distortion of a WPT system should be less then 5 percent and power factor must be above the range the 0.95 mean (pf > 0.95)[48]. These technical level are define in SAE J2894/1 power quality requirement for electric vehicle plug in charger but later transfer to J2954/1 with the agreement of SAE for wireless power transfer chargers. Battery charge should match with the wpt charger due to the requirement of different electrical vehicle such as pick-ups. The electronic sensor should be compatible with the different variety of wireless power charging with respect to transmitter and receiver coil. The air gap between primary and secondary coil and the electromagnetic gap between two coil can be categorized into three class which is reported in table 6.2 and the definition of coil ground clearance is shown in figure 6.2.

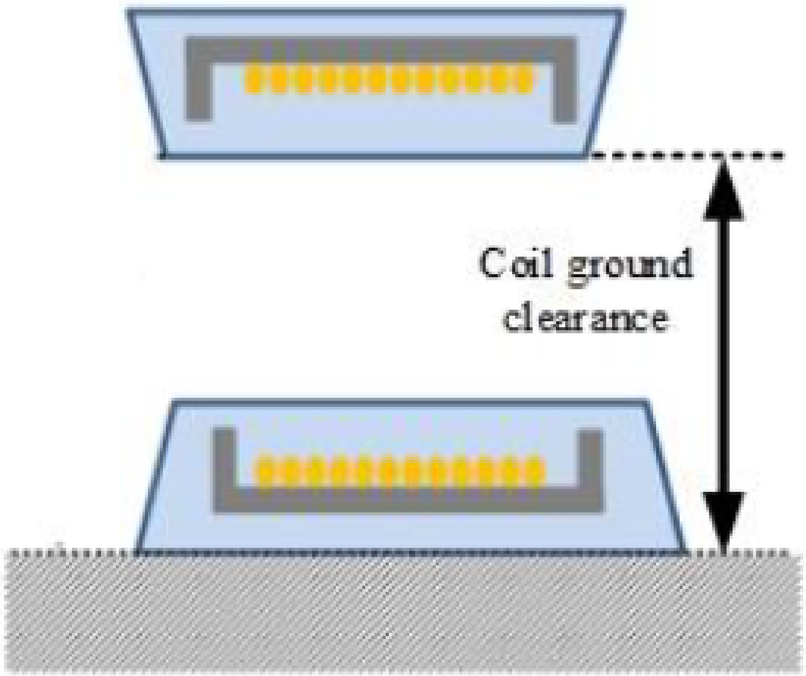


Figure 6.2: Definition Ground clearance specified as in [3]

Misalignment tolerance has detected in different direction and position in SAE J2954/1 has been reported which is describe in table 6.2. Ground clearance varies depending on load and is typically 16 cm for small passenger cars and greater then 20 cm for SUVs. In order to prevent accidental coil damage from obstacles or other road debris, it is crucial that the WPT receiver coil mounted on the vehicle does not diminish the vehicle's ground clearance.[36] The ground assembly and primary coil sometime mounted on the garages but should be attached for the people spaces or on highways. The nominal frequency for the SAE J2954/1 system is 85 kHz. On the other hand system turns the frequency within the range of 81 KHz to 90 KHz, the accessible spectrum location should be one and recognized internationally and share problems with each others.

Z-class	Ground clearance range(mm) between primary and secondary coil
Z1	100-150
Z2	140-210
Z3	170-250

Table 6.2: J2954 Specification of the Z- classes[7]

6.2 Wireless Power Consortium

The Wireless Power Consortium (WPC) is a free, open, and cooperative standards development organisation with aroundÂ 400 global members. There are many different power transmission technologies available. They differentiate between four standards: Qi light electric vehicle (LEV) standard, Ki Cordless Kitchen standard, LEV standard and Industry standard.

1. Qi Standard: relies on tightly coupled coils for inductive coupling, there is less spatial freedom when recharging devices. Over 70 % of charging efficiency is achieved. Load modulation and frequency-shift keying (FSK) are used to develop a bidirectional communication link, reducing the need for an additional radio system. This standard is made for portable electronic and smart phone devices use to transfer power around 30W. After the advancement into specification of the circuit we can transfer 60W wirelessly which is used in Laptop charging. It also includes stopping the WPT when efficiency declines owing to, for example, misalignment and when foreign objects, like, metals, are discovered that may pose a risk to safety.

2. KI Cordless Kitchen standard: is now under development face for the electrical kitchen equipment having power approximately 2200W. Kitchen equipment like rice cooker, blender, coffee maker, air fryers, toaster and many more appliances which required power cord in order to power device will not need to do that in future. A initial draft available for the member companies of wireless power consortium.

3. LEV Standard: In addition to the existing standards created for electric vehicles, such as automobiles, the LEV standard under construction outlines the criteria to charge electric bikes and scooters. Currently, proprietary implementations are used to implement LEV charging. A WPC wants to collaborate with industries to create the LEV standard to assure every manufacturing industry works with same standard.

4. Industry Standard: Future commercial battery-powered vehicles should be able to safely charge wirelessly according to industry standards. UGVs that are wirelessly recharged by companies currently exist. There is currently no interoperability across the existing systems because an industrial WPT standard is lacking. Working with partners in the industry to create its Industry standard, WPC hopes to change this.

6.3 International Standard

There are several existing standard related to wireless power transfer. The standard SAE J2954/1/2 deal with the problem related to power level, operational frequency, lateral misalignment and interoperability Different features like obstacle detection, contact current, electric shock, temperature range, safety issues are being discussed in the research paper

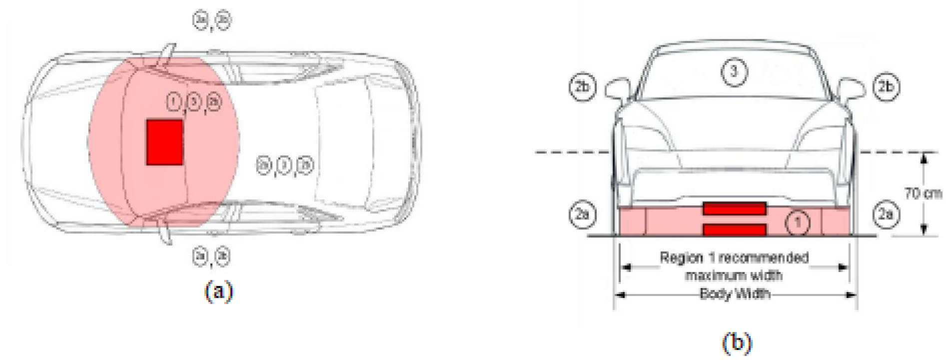


Figure 6.3: J2954 EMF exposure region[36]

In the figure 6.3 describe the car misalignment define in the standard protocol in SAE J2954/1/2. Moreover two standard of misalignment method is report

1. The ground assembly coil produces a minor magnetic field. Vehicle assembly coils are used to identifyÂ magnetic fields. However, this technique has a 1-meter maximum range approximately.

2. Auxiliary coil is used to transmit magnetic signal from vehicle assembly. The ground assembly coil received magnetic signal and with the help of communication interface position of vehicle assembly will be identify.[36]

	RMS	Peak
Magnetic field	27 μ T or 21.4 A/m	38.2 μ T or 30.4 A/m
Electric field	83 V/m	117 V/m
Contact current	0.2Xf(kHz)=17mA @85kHz	0.283xf(kHz)=24mA @ 85KHz

Table 6.3: EMF exposure standard level [36]

Standard	Title
J2954/1,/2	WPT for Low Power Plug-In Electric Vehicles with misalignment methods
ICNIRP2010	Provide term and condition for minimising exposure to magnetic and electric fields that change over time (1 Hz to 100 kHz)
IEEE C95-1234	IEEE Standard which make sure to provide health safety with respect to electromagnetic radio frequency, 3 kHz to 300 GHz
ISO 19363	Electrically propelled road vehicles - Magnetic field wireless power transfer – Safety and interoperability requirements
ISO 15118-1	Road vehicles Vehicle to grid communication interface Part 1: General information and use-case definition
ISO 15118-2	Road vehicles Vehicle to Grid Communication Interface Part 2: Network and application protocol requirements
ISO 15118-8	Road vehicles: Vehicle to grid communication interface Part 8: Physical layer and data link layer requirements for wireless communication

Table 6.4: Fundamental Standard of Wireless Power transfer [37],[39]

CHAPTER 7

Conclusions

During the experimental result, we analyzed wireless power transfer with the help of WiTricity. I found that choosing a suitable compensation topology before beginning the design is crucial. The series-series compensation topology was selected and studied for this purpose to get good efficiency within the electrical boundary related to current and voltage. After comparing the results and examining the efficiency of the power transfer, it is not feasible to utilize WiTricity on electrical devices but it is efficient for charging up various mobile electrical gadgets with pricey batteries. The major use of WiTricity will be in implantable medical devices because it does not transmit radio frequencies that will affect human body biological tissues and also interfere with different electronic equipment placed within the range. WiTricity is a simple and economical technology that will reduce the amount of plastic and copper used in electrical equipment.

APPENDIX A

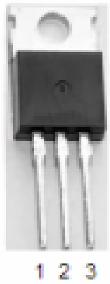
A Long Proof

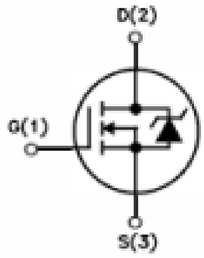
Datasheet of mosfet IRFZ44N

isc N-Channel MOSFET Transistor　　IRFZ44N

FEATURES

- Drain Current –I_D=49A@ T_C=25℃
- Drain Source Voltage-
  : V_{DSS}= 55V(Min)
- Static Drain-Source On-Resistance
  : $R_{DS(on)}$ = 0.032Ω (Max)
- Fast Switching





PIN 1.Gate
2.Drain
3.Source
TO-220C package

DESCRIPTION

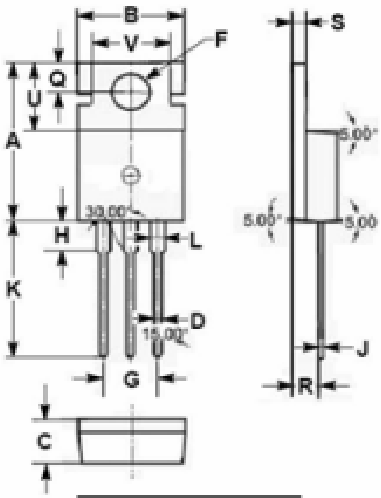
- Designed for low voltage, high speed switching applications in power supplies, converters and power motor controls, these devices are particularly well suited for bridge circuits where diode speed and commutating safe operating areas are critical and offer additional safety margin against unexpected voltage transients.

ABSOLUTE MAXIMUM RATINGS(T_a=25℃)

SYMBOL	PARAMETER	VALUE	UNIT
V_{DSS}	Drain-Source Voltage	55	V
V_{GS}	Gate-Source Voltage-Continuous	±20	V
I_D	Drain Current-Continuous	49	A
I_{DM}	Drain Current-Single Pluse (t_p≤10μs)	160	A
P_D	Total Dissipation @T_C=25℃	94	W
T_J	Max. Operating Junction Temperature	175	℃
T_{stg}	Storage Temperature	-55~175	℃

THERMAL CHARACTERISTICS

SYMBOL	PARAMETER	MAX	UNIT
$R_{th\ j\text{-}c}$	Thermal Resistance, Junction to Case	1.5	℃/W
$R_{th\ j\text{-}a}$	Thermal Resistance, Junction to Ambient	62	℃/W



	mm	
DIM	MIN	MAX
A	15.70	15.90
B	9.90	10.10
C	4.20	4.40
D	0.70	0.90
F	3.40	3.60
G	4.98	5.18
H	2.70	2.90
J	0.44	0.46
K	13.20	13.40
L	1.10	1.30
Q	2.70	2.90
R	2.50	2.70
S	1.29	1.31
U	6.45	6.65
V	8.66	8.86

isc N-Channel MOSFET Transistor IRFZ44N

ELECTRICAL CHARACTERISTICS

T_C=25℃ unless otherwise specified

SYMBOL	PARAMETER	CONDITIONS	MIN	MAX	UNIT
$V_{(BR)DSS}$	Drain-Source Breakdown Voltage	V_{GS}= 0; I_D= 0.25mA	55		V
$V_{GS(th)}$	Gate Threshold Voltage	V_{DS}= V_{GS}; I_D= 0.25mA	2	4	V
$R_{DS(on)}$	Drain-Source On-Resistance	V_{GS}= 10V; I_D= 25A		0.032	Ω
I_{GSS}	Gate-Body Leakage Current	V_{GS}= ±20V;V_{DS}= 0		±100	nA
I_{DSS}	Zero Gate Voltage Drain Current	V_{DS}= 55V; V_{GS}= 0 V_{DS}= 55V; V_{GS}= 0; T_j= 150℃		25 250	μA
V_{SD}	Forward On-Voltage	I_S= 25A; V_{GS}= 0		1.3	V

•

APPENDIX B

Another Appendix

Matlab code implementation in order to calculate the different parameter use in wireless power transfer.[39]

Matlab Code for Parameters Calculations [42]

```
f=18000; % frequency Hz

u0=4*pi*1e-7; % mu permeability of the air

w0=2*pi*f; % resonance frequency

L=0.0635; % m Length of the primary coil

d=0.0381; % m width of the coils

h=0.03; % m Height

a=0.0634; % m length of the primary coil

N1=6; % number of turns for primary coil

N2=16; % number of turns for secondary coil

S1=0.196e-6; % mm2 Area cross sections for primary winding

S2=0.196e-6; % mm2 Area cross sections for secondary winding

S1=1; % for the calculation of Res1

S2=3; % for the calculation of Res2

Find the equivalent radius of the windings

R1=sqrt(N1*S1/pi);

R2=sqrt(N2*S2/pi);

% In order to find Inductance L1 and L2

L1=u0/pi*N1^2*d*log(2*L*d/(R1*(d+sqrt(L^2+d^2))))+u0/pi*N1^2*(L*log(2*L*d/(R1
*(L+sqrt(L^2+d^2))))-2*(d+L-sqrt(d^2+L^2)))+u0*N1^2*(L+d)/(4*pi);

L2=u0/pi*N2^2*d*log(2*a*d/(R2*(d+sqrt(a^2+d^2))))+u0/pi*N2^2*(a*log(2*a*d/(R2
*(a+sqrt(a^2+d^2))))-2*(d+a-sqrt(d^2+a^2)))+u0*N2^2*(a+d)/(4*pi);

% For the calculation of mutual inductance

M=((((u0/pi)*(N1*N2))*(d*log((d+(sqrt(h^2+d^2))*sqrt((h^2)+(a^2)))/(d+h*sqrt(
(h^2)+(d^2)+(a^2))))))+(((u0/pi)*(N1*N2))*(a*log((a+sqrt((h^2)+(d^2))*sqrt((h
^2)+(a^2)))/(a+h*sqrt((h^2)+(d^2)+(a^2))))))+(((u0/pi)*(N1*N2))*(2*(hsqrt((h^2)+(d^2))-
sqrt((h^2)+(a^2))+sqrt((h^2)+(d^2)+(a^2))))));

% Mutual inductance considering a case where the primary track is longer than
the secondary pick up, L >> a

M1=((u0/pi)*N1*N2*a*log(sqrt((h^2)+(d^2))/h));

% To find the resistance of Res1 and
```

```
Res1=((1/57)*N1*((2*(L+d))/S1)); % resistive value of the windings

Res2=((1/57)*N2*((2*(a+d))/S2)); % resistive value of the windings

% Find C1 and C2

C1=1/((2*pi*f)^2*L1); % Capacitor 1

C2=1/((2*pi*f)^2*L2); % Capacitor 2

% Find coupling coefficient K

K=(M1/(sqrt(L1*L2)));

% Resonant frequency can be find by

wo=(1/sqrt(L1*C1));
```

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