DESIGN OF A 1 kW WIRELESS CHARGING SYSTEM FOR ELECTRIC VEHICLE IN LINE WITH BHARATH EV STANDARDS

A PROJECT REPORT

Submitted in Partial fulfillment of the requirements for the award of the degree of

MASTER OF TECHNOLOGY
IN
POWER AND ENERGY ENGINEERING

by

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CERTIFICATE

This is to certify that the thesis entitled, "**Design of a 1 kW Wireless Charging System for Electric Vehicle in line with Bharath EV Standards"** being submitted by **Mr. Shivanand M N** for the award of the degree of Master of Technology in Power and Energy Engineering is a record of bonafide project work carried out by him in the Department of Electrical Engineering of Central University of Karnataka, Kalaburagi.

Mr. Shivanand M N has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained here in have not been submitted to any other University or Institute for the award of any degree.

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DATE

ABSTRACT

Emerging technologies in an electric vehicle had greater advancement in the control, battery and electric motor. But safety and reliability are the major concern when the consumer is dealing with high voltage conductor for charging. The recurring of plugging in the switch for charging is an undeniable disadvantage. So, to eliminate the human intervention in charging of a battery, Wireless power transfer will be the most effective methodology to charge the electric vehicle. This project aims in building the prototype of 1kWatt inductive WPT with ultra-capacitor as energy storage element and at high frequency supply with power converters. Incorporating the standards to design an Electric Vehicle charging system.

Identifying a suitable coil structure for the given EV model as per the standards. Considering a few aspects like the mismatch or misalignment of the receiver coil, air-gap between receiver-transmitter (i.e. proximity) and compensation techniques. The efficient design of Power Electronics converter for both Transmitter and receiver side. Integrating both coil design model and the PE system to test its performance. Development of a prototype/retrofitting into existing two-wheeler.

Keywords: WPT- Wireless Power Transfer, Ultra-capacitor, and PE- Power Electronics, EV-Electric Vehicle

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CHAPTER - I

INTRODUCTION

1.1. BACKGROUND

Wireless Power Transmission is not a recent invention of growing world, this technique is in use for the previous two centuries and the evolution of WPT. It operates very much similar to that of microwave oven principle available for cooking, laser technology used for scanning and in X-ray devices and Step up, step down transformers are designed using the tesla's coil of wireless transmission. The WPT strategy was first invented by Nicola Tesla who is known as the father of wireless charging, in the 20th century. So many aspects of our modern life are directly influenced to be created by Nikola Tesla. His AC (Alternate Current) power systems are being used worldwide in several appliances and in transferring power via copper wires, because AC can be transferred with minimum loss for a long distance. Tesla is basically responsible for the principles of electricity in entire modern world. It's been around more than a decade that demand of electric vehicle is increasing, potentiality in the field of charger and battery is advancing into the market. Govt of India has come up with many schemes to reduce environment pollution, global warming and greenhouse gases produced by the electric vehicles. Scheme FAME-I and FAME-II for Fast Adoption and Manufacturing of Electric Vehicles (FAME), introduced by Dept. of Heavy Industries (DHI). Since then there are many e-bike, electric cars and electric autorickshaw's has sold in India. Tata, Mahindra and other china companies are the major companies started investments in Indian EV market. Bangalore is the first city get charging station for electric vehicles in India. Govt. has given charging standards in its first draft 2015 for both AC and DC charging. But still India has not considered Wireless power transfer for charging electric vehicles. Standardizing the charging infrastructure in WPT will take another few years. This thesis proposes a best method that India can adopt to build wireless charging infrastructure.

Wireless Power Transfer is an enormous strategy of transferring the electrical power from the source to the destination load such as consuming devices without the need of wires or any particles. WPT provides mobility among the devices or gadgets. In this innovative approach the electrical power is transmitted across any medium (such as wall, air or, water) in between the power source and the consuming device. In this technology copper coils or antennas are used to transmit and receive the electrical power wirelessly. The emerging areas in which the wireless charging strategy is used in medical implants, electrical vehicles, wireless grid and home-based devices. This technology provides a compact and efficient charging of electric and electronic devices under stationary and dynamic conditions.

1.2. OBJECTIVE

- Determining the standardized design consideration for development of WPT system according to the Indian Standards.
- Designing a suitable coil structure for required parametric configuration in Maxwell Software.
- Plotting the flux distribution and analysing the inductance and coupling coefficient values for change of airgap.
- Equivalent circuit design and determining the suitable Compensation parameters for resonance coupling of transmitter and receiver coils.

1.3 METHODOLOGY

In order to get the basic understanding of the wireless charging system, different articles, reports and mainly research paper from the IEEE are gathered. There were many fields that has to be concentrated in WPT. Considering the best topology for the investigation for Bharath EV standards has been our goal. This includes the design and modeling of WPT system. It is very easy to design a WPT as comparatively with standardized design.

At an early innovation phase of WPT system, there are many organizations like SAE (Society of Automotive Engineering), ISO (International Organization for Standards) and IEC (International Electrotechnical Commission). Adopting those standards isn't a great way deal. So, it is required consider other standards in terms of wired charging in India.

There are many things that has to be analyzed before building a 1 kW WPT system. Input power supply, resonance frequency, compensation topology and output voltage at the battery end. Difficult level in parameter determination is very high due to many unknown variables.

Another field that is design of coil simulation in ANSYS Maxwell software to obey the all the parametric values from the circuit simulation software LTSpice. V-I characteristics and inductance values are analyzed for case study and a determined value.

1.4 OUTLINE OF THE CHAPTERS

A brief outline of the various chapters of the thesis is as follows.

Chapter 2 consist of research ongoing in the field of wireless charging for both dynamic and static methods. Many articles have been referred to understand the present technology.

Chapter 3 deals with all the aspects that are important to be considered selecting the best method for WPT. The method that used impedance matching technique. Classification of wireless charging methods are dealt and analyzed the solution to build the system. It also deals with important topics like q-factor, coil winding, self-inductance calculations and bifurcation.

Chapter 4 includes the standardization specifications and methods are derived from the SAE, ISO and IEC organizations. Developing a WPT system required to follow these mandates from the internationally acceptable standards. Discussion of SAEJ2944 standards have given so many key takeaways.

Chapter 5 design of complete setup for 1 kW WPT system adopting the LCC topology. Resonant coupling is selected in development out of all the three methods, which has many advantages in terms of power consistence and longer distance. Eliminating the SS topology from the system and determine the parameters for LCC circuit analysis.

Chapter 6 dedicated to coil design and consideration of coil architecture for the better coupling. Ansys Maxwell is used to design the mutually coupling coils.

Chapter 7 focuses on the results that are obtained by the simulations. A case study on paper [1] is also discussed. Followed by the results from the values that we have found for 1 kW power transfer system.

Chapter 8 explains the safety concerns published by ICNIRP. Vehicles and its communication at higher bandwidth of frequency. Vehicle to grid benefits are discussed.

Chapter 9 discusses the conclusion and future scope of the project work.

In appendix chapter 10, software (LTSpice and Ansys Maxwell) that are used in the project are detailed to get the intuitive knowledge about it.

CHAPTER – II

LITERATURE SURVEY

As the electric vehicles hitting into the big market of automobiles, wired charging has shown many disadvantages. That has led to advancement in the wireless technology. Resonant coupling is increasing used for WPT system due to its consistency in power transfer. Research papers that are mainly used to build constant power transfer to the system is not a sufficient way to declare the development. Standardization has to be considered while adopting in this Indian Govt. Experimental analysis has been done in many of the papers and few are given below.

Deshmukh et al. have simulated 1 kW inductive power transfer in MATLAB and Maxwell. The paper focuses on the bifurcation phenomena, closed loop control at the secondary voltage. With 88.5% efficiency is analyzed for complete simulated system. It deals with 15 kHz fundamental frequency over 10cm distance.

Chris Mi et al. “Hybrid energy storage system of an electric scooter based on Wireless power transfer” developed a 600 W secondary side controlled electric scooter charging system. It uses supercapacitor and battery to charge depending on SoC (state of charge). Coil design parameters in detailed explained format. 86.4% efficiency has been taken form source dc to battery.

Chris Mi et al. “Wireless power transfer for electric vehicle applications” discuss the magnetic resonance technology in building an electric vehicle charging station for inductive power transfer system. It discusses the fundamental theory and formula to design compensation and power electronic converters.

Chris Mi et al. “Comparison study on SS and Double-sided LCC Compensation Topologies for EV/PHEV Wireless chargers” it characterizes the differences in the performances for different topology in development of EV charger. It deals with tuning methods, power displacement and load variations. For 7.7 kW output powered WT system built with 96% efficiency from DC source to battery load.

Chun T. Rim et al. “Wireless Power Transfer for Electric Vehicles and Mobile Devices” Detailed study of WPT system research papers are analyzed chapter wise. Different application of dynamic and static charging system. Design and development of different topologies are discussed with equations. Electromagnetics and compensation circuit with gyrators. Design and experimental verifications are done according to references. Coil design and simulations are analyzed for misalignment and large tolerance EV chargers.

Maria Nisshagen et al. “Wireless power transfer using resonant inductive coupling” have discussed analytical calculation to design of two-coil system. Electromagnetic field analysis has been carried out. Construction prototype has been dealt for q-factor calculation and inverter design for testing IPT.

Aqueel Ahmad at al. “A comprehensive review of wireless charging technology for electric vehicles” detailed description of static wireless charging, dynamic wireless charging, and quasi dynamic wireless charging. Standardization of wireless charging system are the deliberated. Economic analysis, social implications, the effect on sustainability, and safety aspects to evaluate the commercial feasibly of wireless charging.

Phaneendra Babu Bobba et al. “investigations and Experimental study on magnetic resonant coupling based wireless power transfer system for neighborhood EV’s” magnetic resonant technique (MRT) based WPT system has been used to transfer the power wirelessly over larger airgaps. TI controller used to as a central control unit to monitor variables. Supercapacitor is used as a storage element of power and compensation topologies like SS, SP, and PS.

Chris Mi et al. “A High efficiency 3.3 kW loosely-coupled power transfer system without magnetic material” proposes loosely coupled wireless power transfer system without magnetic material, which has 95% dc-to-dc efficiency working at 1Mhz and 3.3 kW output power. 150mm air-gap distance, coupling coefficient k as 14.0%. It provides high-frequency and high efficiency. WPT system design.

CHAPTER - III

ANALYTICAL STUDY ON WPT

When dealing with non-radiative magnetic power transfer, the system is classified to be either near-range or mid-range. By definition mid-range is when the distance between the coils is larger than the coil dimensions, and near-range is defined as a system with a distance between coils smaller than the coil dimensions. Hence, in this report, the region between near-range and midrange is when the coil dimension and the air gap is the same size. An IPT system consisting of two coils is made up by a primary rectifier, an inverter, a primary coil, a secondary coil, and a secondary rectifier. The primary rectifier, the inverter, and the primary coil together are called the transmitter as shown in fig. 3.1. The secondary coil and the secondary rectifier makes up the receiver. Since the load in this project is purely resistive the rectifier on the secondary side is not necessary.

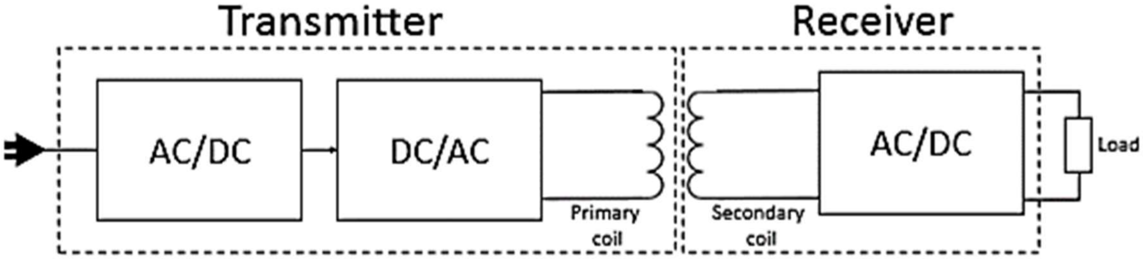


Fig.3.1 Overview of the total wireless power transfer system

Resonant coupling in mid-range IPT systems the coupling between the sending and receiving side is poor, due to the long distance between the coils. To get good power transfer efficiency high frequency is needed. However, when using high frequency, the system impedance as seen by the source becomes more and more inductive, thus making the power factor (PF) smaller and smaller (voltage and current more out of phase). This means that more reactive power circulates in the system, hence the inverter needs high VA rating. The circulating reactive power also decreases power transfer.

To get better power transfer capability and to decrease the size of the inverter, capacitive compensation is needed. As a consequence, the impedance as seen by the source becomes purely resistive. In other words, resonant coupling takes advantage of resonance of inductance and capacitance in a LC tank to compensate for the leakage inductance. The compensation could either be done by adding capacitors to the circuit or letting the coils resonate at its' own resonance frequency. It has been seen that two systems that resonates at the same frequency, exchange power efficiently, therefore it is beneficial if the sending and the receiving side resonates at the same frequency. The capacitance is chosen such that it cancels out the inductance, specifically it is calculated by

$$\omega = \frac{1}{\sqrt{LC}} \qquad 3.1$$

Two-coil system the four most common topologies in a two-coil system are: Series-Series (SS), Series Parallel (SP), Parallel-Series (PS), and Parallel-Parallel (PP), where the series or parallel refers to how the capacitors should be placed in relation to each other on the primary side and the secondary side.

General SS compensated IPT system has two advantages. The compensation capacitors on both primary and secondary side are independent of the load and the mutual inductance. Reflected impedance on secondary winding only has areal component, thus it will only draw active power.

3.1 IMPEDANCE MATCHING

An IPT system can also be represented by a source impedance and a load impedance visualized in fig. 3.2. Maximum power transfer occurs when the source impedance and the load impedance equal each other (R_s = R_1 and X_s = $-X_1$). This is called impedance matching

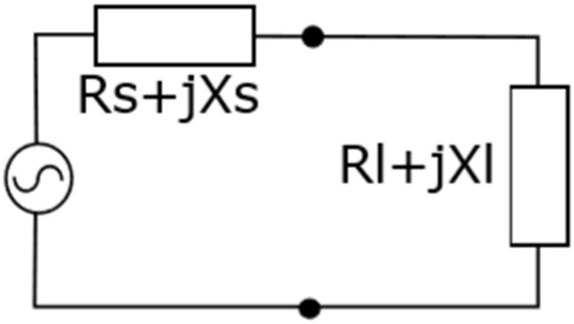


Fig.3.2 Simplified electrical circuit representation of an IPT system

The efficiency of the system when the circuits are compensated can be derived as follows.

$$\eta = \frac{Rl}{R_s + R_l} \qquad 3.2$$

Thus, when the impedance matching condition is fulfilled the efficiency is equal to 50 %. It can be seen that if $R_l > R_s$ the efficiency will increase.

3.2 CLASSIFICATION OF WPT

Wireless power transfer is not a new concept that is advancing into the field of power transfer. This was first thought by Nikolas Tesla in 19th century. He wanted to show the world the power of electromagnetic fields can enable to transfer power more than the kilometers. Recently the importance WPT led us to utilize it into day to day life. Like induction, phone charger and many more. This feature has more scope into the electric vehicle field application to transfer energy through coil and resonance.

1. **Radiative-capacitive coupling**
2. **Radiative magnetic coupling**
3. **Non-radiative capacitive coupling**
4. **Non-radiative magnetic coupling**

The first two capacitive coupling are used in microwave and laser to transfer information rather than power, due to its low power efficiency. Radiation are the main concern to the safety of the human beings. As we can statistics of the death of birds due to the use of cellphone and its radiation endangering the lives. Radiations causes mental illness, skin cancer and mutation of DNA etc.

Hence, using non-radiative coupling is the alternative in transfer of power. There are many designs that are based on the magnetic as well as capacitive coupling tested and applied.

It uses higher voltage and current to transfer power in unidirectional. Contactless power transfer (CPT) or Inductive Power Transfer (IPT) are basically magnetically coupling systems. IPT uses coils as their main component and magnetic field lines mutually interact to induce current into the other coil. Hence the application of Fleming's and Lenz's yields the power transfer with long airgap. The technology used in the transfer of information via radiative coupling is resonance. It has given the best connectivity and reliability in the data transfer. Hence the same technology in the field of IPT can have higher efficiency. The coils used in the IPT has an unwanted component called leakage inductance, which can be remove if you use capacitor along with coils. They are different configurations that can be placed the capacitor into the system. The frequency that can be used to resonance varies typically from “20kHz to few MHz”. Applications of IPT has increased in fields like cellphone charging, healthcare sector, electronic sensor communication and electric transportation. IPT has been used on many of the places where it is not safer to transfer power via cables like chemical labs, mining areas and few places where low ignition temperature oils and coals are extracted.

3.3 Wireless Electric Vehicle Charging

Humanity towards the elimination of pollution and making the earth a green and eco-friendly land. It has led to decrease in the use of diesel/petrol engine vehicles. Renewable sources of nature are future sources of energy for the future living being. Hence the govt. and industries have taken further step in utilization of electric vehicle for the future transportation. But electric vehicles run on battery and requires charging regular interval of time. Which has led to slow growth in sales rate.

But now it is all over. As technology has solved many limitations of conventional wired charging. Now we have Wireless Charging structure to overcome all the issues. Dynamic charging helped in roadway powered while momentum, hence no need has higher capacity batteries to charge, and Charging when you have parked your vehicle for lounge or hotels or homes or office without worrying about the connecting wires. Flow chart of complete classification is shown in fig. 3.2.

Classification of Wireless Charging Methods

1. Static Charging
2. Quasi-Dynamic Charging
3. Dynamic Charging

Charging Benefits of static charging include eliminating the shock hazard due to wires and the ability to be installed in convenient locations such as home garages or parking lots. The QWC system provides charging to EVs as they are stopped for short periods of time, such as at traffic lights, which prolongs the vehicle range while en route and decreases energy storage requirements of the vehicle The DWC system continuously charges the EV while en route through specified charging lanes on the road, also increasing driving range and decreasing battery size of the EV. WPT with 230-V ac charging at the rate of 7.2 kW has been achieved via wireless charging systems with an efficiency up to 88.5% Technical concerns related to charging infrastructure include its design, construction, operation, and maintenance

Deployment of efficient and reliable charging infrastructure at short distances would support an unrestricted range for Evs. Nowadays, a very effective way of wireless charging is the resonant WPT used for dynamic charging at dedicated lanes and the resonant IPT employed in both SWC and DWC Researchers have improved efficiency, power level, and air gap by using improved compensation techniques

WPT system is classified by methods such as IPT, coupled magnetic resonance (CMR), permanent magnet coupled transfer (PMC), and laser and microwave or radio wave. CMR is very effective for low- or medium power WPT; IPT is better for high-voltage power transfer since there is no resonant circuit involved Magnetic coupling coefficient defines the degree of close coupling between the primary and secondary winding for transferring high power, the value of coupling coefficient must be as high as possible. The OLEV project has realized high power transfer efficiency at a high frequency of 20 kHz with 83% efficiency for 60 kW using a large air gap of 20 cm and a lateral tolerance of 24 cm.

Wireless Charging Using Near-Field Wireless Technology-

Near field means the energy remains within a small region of the Tx. The Tx does not emit power if there is no receiver range. The range of these fields is very small and depends on the size and shape of the Tx and receiver. In the near field region, the electric and magnetic fields are separate, hence power can be transferred through the electric field via electrodes and the magnetic field via coils. Power decays by (1/r 3) factor, with an increase in distance (r), and energy remains at short distance between the Tx and the receiver Electric field WPT can transmit power to a very less distance due to a very high decay rate, but magnetic field WPT can transmit power at a distance more than electric because of the ability that magnetic field can penetrate the wall, furniture, and people.

- **Inductive Power Transfer-Based Wireless Charging:**
  IPT-based wireless charging uses the principle of magnetic induction to transmit power without a medium. It is based on Lenz's law and Faraday's law, where a time-variant current in a conductor creates the magnetic field around the conductor, and a secondary loop (receiver) gets voltage generated due to time-variant magnetic flux. The receiver is connected to the load which closes the circuit to transfer the power without wires.
- **Coupled Magnetic Resonance-Based Wireless Charging:**
  Magnetic resonance was developed by MIT, USA, and consists of transmitting and receiving coils and capacitances for the purpose of compensation and PFC, finally creating a resonant condition for MPT. The OLEV is among the top 50 inventions of 2010 worldwide. Commercialization of OLEV is in progress. Global motor companies, such as Tesla, Toyota, Nissan, and so forth, are employing magnetic resonance coupling for WPT Various research groups are working on two major aspects: 1) as magnetic resonance coupling.2) as electric resonance coupling for EV. CMR technology follows coupled mode theory, which can transfer power to a significant distance. Qiu developed a dynamic WPT system with 90% efficiency for the range of 1m and developed the system having two antennas which resonate at the same frequency in megahertz range.
- **Permanent Magnet Coupling-Based Wireless Charging:**
  The "magnetic gear effect," where a permanent magnet (Neodymium permanent magnets) acts as a magnetic coupler. The primary-side permanent magnetized rotor rotates the secondary rotor with the same speed, known as synchronous speed. A permanent magnet WPT prototype was developed by Covic, which transfers the power with 81% efficiency at 150-Hz frequency for 150-mm distance. There are many drawbacks to this system because of vibrations and noise of many mechanical components. Another major problem with this scheme is alignment and maintenance issues. For EV charging application, this method is not suitable due to the large system, low efficiency, mechanical rotation, etc.

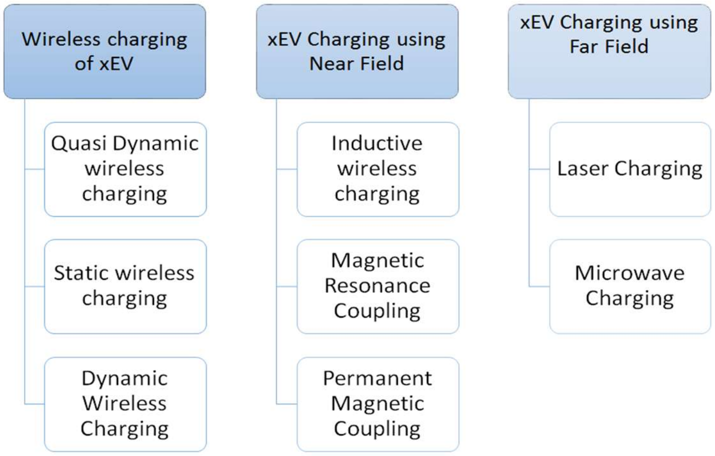


Fig.3.3 Classification of Wireless Charging Technology

3.4 SCHEMATIC CIRCUIT OF WPT SYSTEM

There are two major parts in wireless charging, one is the primary side which consist of supply power, ac to dc converter and dc to ac inverter with 85 kHz frequency is called transmitter as shown in fig. 3.3 and secondary side has compensation coil similar to primary with rectifier circuit to feed it to battery for charging.

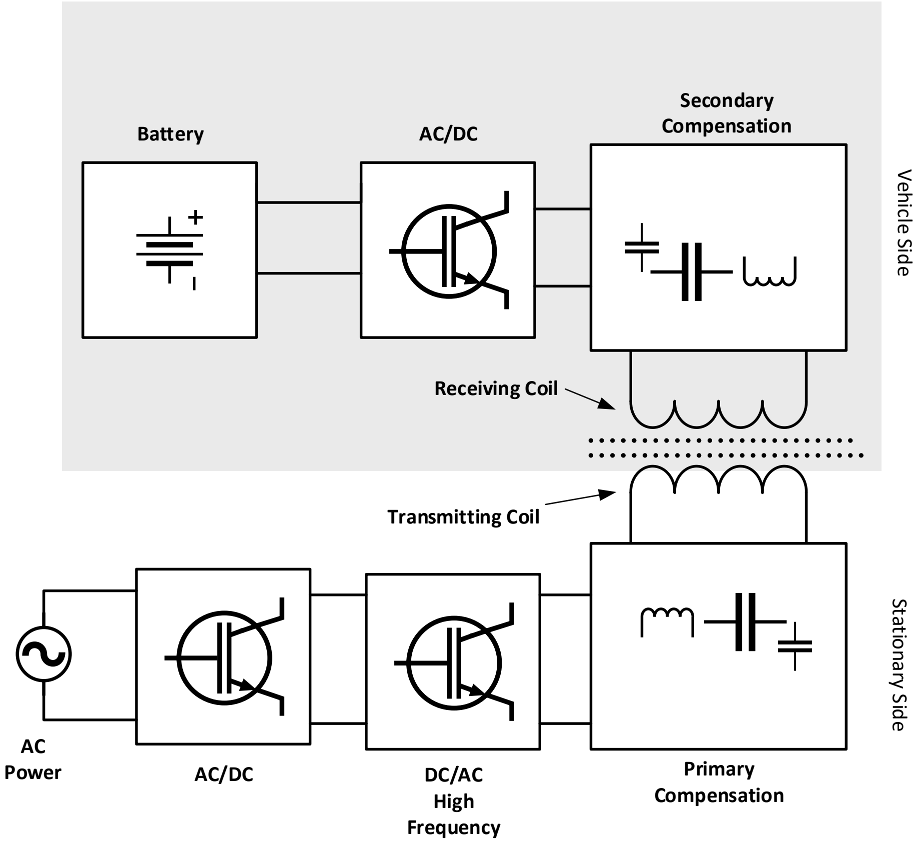


Fig. 3.4 Architecture of Wireless Power Transfer System

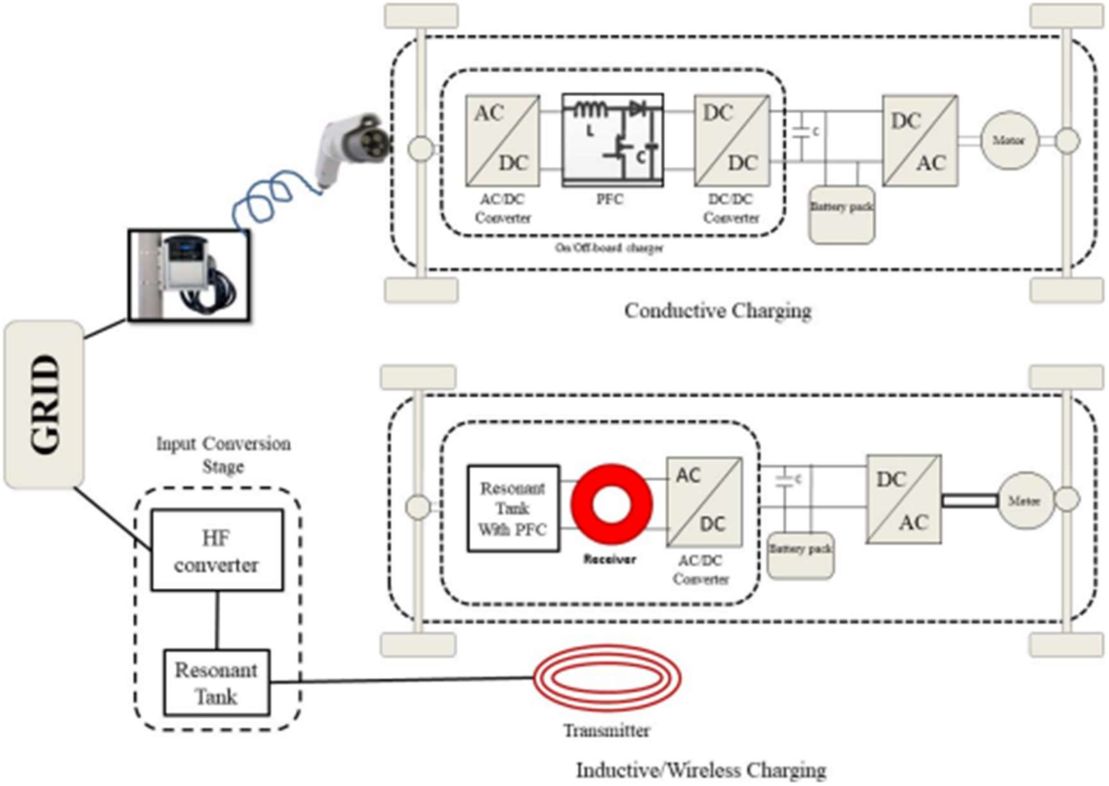


Fig.3.5 Typical architecture of Wired and Wireless charging system from the grid

3.5 Q-FACTOR

The Q-factor (quality factor) is a dimensionless parameter used to tell how efficient a system oscillates. A high Q-factor indicates that the oscillations goes further with more energy, while a low Q-factor make the oscillation attenuate faster. When a high Q-factor is achieved, the frequency has to be close to the actual resonant frequency (smaller bandwidth). Thus, a high Q-factor has more energy but is more difficult to tune.

The primary Q-factor is calculated as

$$Q_1 = \frac{(L_a+\mathrm{M})R_L}{\omega_0 M^2} \tag{3.3}$$

where La is the primary leakage inductance, M is the mutual inductance, RL is the load and ω0 is the resonance frequency.

The Q-factor of the receiving side is calculated as

$$Q_2 = \frac{\omega_0(L_b+\mathrm{M})}{R_L} \qquad 3.4$$

The Q-factor can also be determined by $Q = f_0/\Delta f$, where f_0 is the mid-resonance frequency and Δf is the bandwidth, at which resonance occurs. A loosely coupled system will have a narrow bandwidth.

3.6 COIL WINDING

There are mainly two ways to design a coil in a resonant IPT system. One is to turn the wire outwards in a flat, spiral direction. This coil is sometimes referred to as spiral or pancake coil. In this report it is called flat coil. There are more complex coil designs which are used to reduce stray capacitance. However, that is outside the scope of this project.
Coil resistance The DC resistance [Ω] of a conductor depends on wire length, wire area and electrical conductivity of the material. It is calculated by

$$R_{dc}= \mathrm{l} / \sigma \mathrm{A} \qquad 3.5$$

where σ is the electrical conductivity [S/m] of the material used in the wire, l is the length of the wire [m], and A is the area of the wire [m2]. To get low resistance in the coils the electrical conductivity of the material σ needs to be high. Conductivity of some common materials used in conductors Material Conductivity, σ [S/m] Copper. ·At high frequency AC applications, the main resistance comes from skin effect which makes the current press towards the edges of the conductor which create a smaller effective area.
The skin depth, δ, defines the area where the current flows and is calculated by

$$\delta = \frac{1}{\sqrt{\pi f \mu \sigma}} \qquad 3.6$$

where μ is the permeability of the used material in the wire, f is the frequency [Hz], and σ is, as previously mentioned, the conductivity of the material [S/m].
When the frequency increases, the skin depth decreases. The most common way to get around this is to use a litz wire that consists of multiple, thin strands. The number of strands and the thickness of each strand depends on how much current and at which frequency the system is designed.

3.7 ANALYTICAL SELF-INDUCTANCE CALCULATION

Analytical equation given below will provide the self-inductance of a flat square coil by using few factors i.e. - n number of turns d_{avg} - average diameter of coil and fill factor and

$$L = \frac{1.27\mu_0 n^2 d_{avg}}{2}\left[ln\left(\frac{2.07}{\varphi}\right) + 0.18\varphi + 0.13\varphi^2\right] \qquad 3.7$$

permeability of copper coil (μ_0 = 4n*10^{-7}Hm^{-1}).

φ can be calculated by using next equation.

$$\varphi = \frac{d_0 - d_i}{d_0 + d} \qquad 3.8$$

3.8 BIFURCATION

Bifurcation (Design of 1 kW Inductive power transfer for electric vehicle)

The Power transfer efficiency improves, as the system operate at resonance frequency which means phase angle between voltage and current should be zero. The phenomenon occurrence of the more than once it is called bifurcation. To avoid this "bifurcation-free criterion" has been designed.

$$Q_s < \sqrt{\frac{1}{2(1-\sqrt{1-k^2})}} \qquad 3.9$$

Q_s – Quality factor of secondary coil

$$Q_s = \frac{2\pi f L_{self}}{R_L} \qquad 3.10$$

K = Coefficient of coupling

L_{self} = self-inductance of secondary side coil

R_L – Load at the secondary side

A "bifurcation-free" phenomenon criterion depends on quality factor of IPT coils and k.

$$k = \frac{L_M}{\sqrt{L_P L_S}} \qquad 3.11$$

This equation also should obey to eliminate bifurcation phenomena.

3.9 FACTORS THAT AFFECT WIRELESS CHARGING

Advantage of EV wireless charging over contact charging is its convenience and galvanic isolation for the users. Instead of carefully charging and discharging, vehicles battery can be topped off frequently while parked at various charging spots such as at home, work, while shopping, or at traffic light, eliminating the cables and cords. Even DWC can eliminate the fast charging infrastructure thru building charging lane into the highways enabling charging while driving. Comparing with wired charging, wireless charging includes relatively low efficiency and power density, cost, size, and manufacturing complexity. Fig. 3.5 shows the factors that affect charging system. The EV wireless charging has challenges to be considered in order to efficiently transfer power. WPT requires energy conversion and limits the efficiency on conversion. And transfer; therefore, it requires optimization and improvement in transfer efficiency. These all factors are challenges for industries to replace conductive charging with wireless charging. Each factor is a significant research dimension for wireless charger deployment.

To summarize, Table 3.1 shows the comparison of various types on wireless power transfer technique the detailed difference between three major WPT methods.

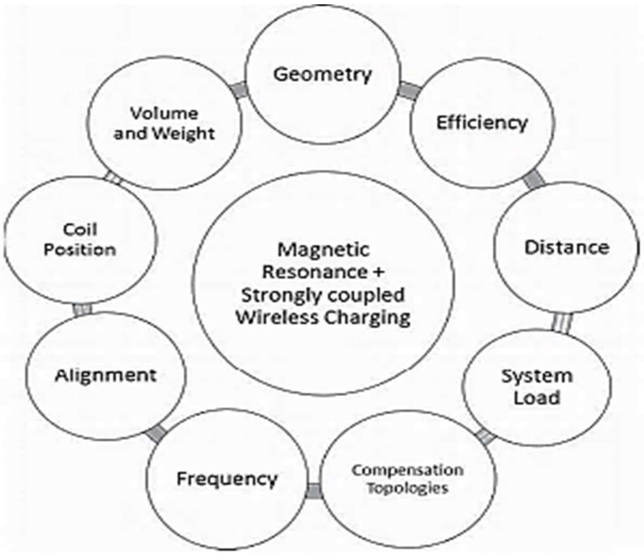


Fig. 3.6 Factors affect wireless charging

Table 3.1 Comparison of various types on wireless power transfer technique

Types of WPT	Induction Coupling	Resonant Coupling	Microwave Power Transfer
Transmitted Power Source	Electromagnetic Induction	Electromagnetic Resonance	Microwave, Radio wave and Laser
Transmitter	Few turns of copper coil	Few turns of primary coil with small gaps and secondary coil 10 times of turnings as in the primary coil without gap	Transmitting Antenna with a wave guide
Receiver	Few turns of *copper* coil	Few turns of copper coil	Rectenna with SCR
No. of Receivers get into	Single receiver is possible	Multi receiver is applicable	Single receiver
Direction Row of power	EMI on the same axis (max. 25% misalignment)	Omni directional power transfer	Single direction (need line of sight for transmission)
Complexity	Low	Medium	High
Efficiency	Low	High	High
Radiation Power	Non-radiant energy	Non-radiant energy	Radiant energy
Frequency Range	110 - 205 kHz	6.78MHz for power transfer and 2.4GHz for control signals	300MHz - 300GHz
Safety	Harmless	Possible danger of sparks produced at several million volts	Harmful to human beings such as telecommunications
Distance	5mm distance	Maximum 1Km distance achieved (But Testa himself achieved up to 42km)	50mm
Loss during Transmission	High	Medium	Low
Power Wave	Continuous	Oscillated power signal (Sparks)	Continuous

CHAPTER - IV

STANDARDIZATION IN WIRELESS CHARGING

4.1 EV WIRELESS CHARGING STANDARDS

There are many companies which have given their project specifications to the standardization to the world. Table 3.1 provides the detailed information about the four-project related to static and dynamic charging system ranging from 4.7 kW to 20 kW power transfer.

Table 4.1 EU Research on wireless charging of EVs

Project Title	Status	Charging mode	Charging targets
Unplugged	Ended	Static charging	3.7kW – Passenger Cars 50kW- Light Commercial Vehicles
FastInCharging	Ongoing	• Static-charging • On-route charging	30kW – Light Commercial Vehicles
ecoFEV	Ended	Dynamic Charging	10kW- Light commercial vehicles
Fabric	Ongoing	Dynamic Charging	10-20kW Light Commercial Vehicles

4.1.1 International Electrotechnical Commission (IEC)

- IEC 61980: Electric vehicle wireless power transfer (WPT) systems
  - Part 1: General requirements (Published - July 2015)
  - Part 2: specific requirements for communication between electric road vehicle (EV) and infrastructure with respect to wireless power transfer (WPT) systems
  - Part 3: specific requirements for the magnetic field power transfer systems
  - Part 4: specific requirements for the electric field power transfer systems
  - Part 5: specific requirements for the microwave power transfer systems

4.1.2 International Organization for Standards

- ISO 19363: Electrically propelled road vehicles -- Magnetic field wireless power transfer -- Safety and Interoperability requirements
- ISO 15118: Road vehicles — Vehicle to grid communication interface
  - Part 6: General information and use-case definition for wireless communication
  - Part 7: Network and application protocol requirements for wireless communication
  - Part 8: Physical layer and data link layer requirements for wireless communication

4.1.3 Society of Automotive Engineering

- SAE 12954: Wireless Charging of Electric and Plug-in Hybrid Vehicles
- SAE 11773: Electric Vehicle Inductively Coupled Charging (Published - June 2014) (Recommended practice for North America)

As wireless charging is becoming a pioneer in the field of EV charging, standardization is required for reliable commercialization of high-voltage and high-power WPT for EV charging.

Standardization includes the safety criteria, efficiency, EM limits, and interoperability targets, along with test setup for getting wireless charging. Ubiquity is a very important requirement for EV which is possible after standardization. Customers need not worry about its compatible charging station. IEC-61980-1 standard contains the total system of WPT from supply network to EVs charging the battery or any equipment of the same at the standard supply of 1000-V ac or 1500-V dc. These all are addressed by SAE in its standard SAE TIR J2954. This is the first standard developed by SAE in WPT for an EV charging application. This standard is developed specifically for SWC. The frequency band, interoperability, safety, coil definitions, and EMC/ EMF limits from SAE TIR J2954 allow any attuned vehicle to charge wirelessly from its wireless home charger, office or a commercial charger with the same charging ability Table 4.2 shows key standards for wireless charging.

Table 4.2 Standards for wireless charging

Standard Developer	Standard Name	Published/Update Date	Description	Status
IEC	IEC 6180-1Ed. 1.0-New Addition	2015-07-01	Electric Vehicle wireless power transfer (WPT) System-Part 1: General Requirements	Active
IEC	IEC 61980-1Ed2.0	2020-03-30	Electric Vehicle wireless power transfer (WPT) System-Part 1: General Requirements	ACD
IEC	IEC 61980-1/IAMD I Ed1.0	2015-07-24	Electric Vehicle wireless power transfer (WPT) System-Part 1: General Requirements	ACD
IEC	IEC 61980-1/COR1A	2017-01-01	Electric Vehicle wireless power transfer (WPT) System-Part 1: General Requirements	VALID
IEC	DRAFT IEC/TS 61980-2Ed.1.0	Will be published in 2017	Electric Vehicle wireless power transfer (WPT) Systems- part2: Specific Requirements for communication between Electric Road Vehicle (EV) and Infrastructure concerning WPT	Active
IEC	Draft IEC/TS61980-3Ed1.0	2015-08-28	Electric vehicle WPT systems-part3: Specific Requirements for the magnetic field power	Draft, Valid

			transfer system	
SAE	J2954SAE	WIP	Wireless charging Electric and Plug in Hybrid vehicles	WIP
SAE	J2954_201605	2016-05-26	Wireless power transfer for light duty plug in /Electric vehicles and Alignment methodology	Issued
SAE	J1773_201406	2014-06-05	SAE electric Vehicles inductively coupled charging	Stabilized
SAE	J2847-6	2015-08-05	Communication between Wireless charger charged vehicles and wireless EV Chargers	Issued
SAE	J2831	2015-8-27	Signaling Communication for wireless charged Electric vehicle	Issued
UL	Subject 2750	NA	Outline of Investigation for Electric Vehicle wireless charging	Draft Released

4.2 OPERATIONAL FREQUENCY

SAEJ2944 Standard: Switching frequency or operating frequency plays crucial role in all aspects of the wireless power transfer, mainly in static WPT. Selection of the perfect range of frequency is very difficult due to the many factors. The SAE has come up with standards on EV wireless power transfer. Under SAEJ2954 article given by SAE will lead us consider using 85kHz (81.38-90.00kHz) as operating frequency.

There are three power level that SAE has given in SAEJ2944

- 3.7kW – overnight charging
- 7.7kW- private/public parking
- 22kW – fast charging

International Commission on Non-Ionizing Radiation Protection (ICNIRP) is established to provide the safety from the human exposure to electro-magnetic fields. The standard guidelines provided by ICNIRP restricts the industrial or domestic use of electrified fields upon the health of human body. After replacing the 1998 guidelines "ICNIRP Guidelines 2010" provides the frequency range that can be utilized in the wireless power transfer. It is somewhere between 3kHz to 10MHz. It also provides the ICNIRP exposure to the electric field is 83V/mand for industrial exposure is 170V/m. Magnetic field exposure is 27uT, and for industrial or public utilities 100uT.

The factors that affect the operational frequency are Coil size, power induced voltage, core loss, switching loss of inverter and rectifier and also there are other important factors to affect, those are overall cost and efficiency, temperature of device and skin effect on wire/coil.

Advantages:

- Omnidirectional and line of sight power transmission is possible.
- It is very much useful for home-based devices, industrial load and working environment.
- It is convenient, safe and effective way to transfer power in any medium.
- Doesn't harm or injure human or any living being.
- Make devices more reliable and environmentally sound.
- Used in medical implants results in quality of life improvement and reduces risk if infection.

Limitations

- There are several limitations which equalize the advantages of WPT such as best efficiency when the distance between the transmitter and receiver is minimized, various
- environmental conditions are treated well only by magnetic flux, low current reception in the present of ferromagnetic substance and energy theft is easily applicable.

CHAPTER - V

DESIGN OF OVERALL ARCHITECTURE WPT

Resonant coupling based on LCC topology is used in developing the overall architecture of WPT system including the different. Series capacitor and parallel capacitor are used to design with additional inductor to compensate the sudden power variations. It is complete open loop system with constant output frequency. Double sided LCC compensation has given advancement into the dynamic charging system also. Rectification at the end and the filter circuit with high magnitude of inductor value is used to get the constant output. IGBT are used to get the high frequency current for the coils connected to it.

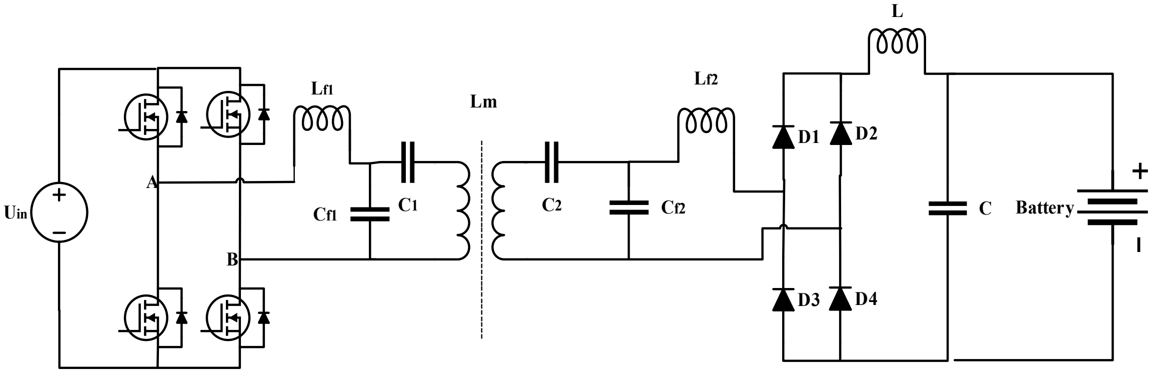


Fig.5.1 LCC topology based overall WPT system

L_m- Magnetizing inductance referred to the primary

L_1 – Self-inductance of the transmitting coil

L_2 - Self-inductance of the receiving coil

k – coupling coefficient between the transmitting and receiving coils

n - Equivalent turns ratio between the transmitting and receiving coils

C_2 – Secondary-side series compensation capacitor

C_1 - Primary-side series compensation capacitor

C_{f2} - Secondary-side parallel compensation capacitor

C_{f1} - Primary-side parallel compensation capacitor

U_{ab} – First order rms value of the input voltage before the coils

5.1. SELECTION OF RESONANCE COUPLING

5.1.1 Resonance Power Transfer

In mid-range IPT systems the coupling between the sending and receiving side is poor, due to the long distance between the coils. To get good power transfer efficiency high frequency is needed. However, when using high frequency, the system impedance as seen by the source becomes more and more inductive, thus making the power factor (PF) smaller and smaller (voltage and current more out of phase). This means that more reactive power circulates in the system, hence the inverter needs high VA rating. The circulating reactive power also decreases power transfer.

To get better power transfer capability and to decrease the size of the inverter, capacitive compensation is needed. As a consequence, the impedance as seen by the source becomes purely resistive. In other words, resonant coupling takes advantage of resonance of inductance and capacitance in a LC tank to compensate for the leakage inductance. The compensation could either be done by adding capacitors to the circuit or letting the coils resonate at its' own resonance frequency. It has been seen that two systems that resonates at the same frequency, exchange power efficiently, therefore it is beneficial if the sending and the receiving side resonates at the same frequency. The capacitance is chosen such that it cancels out the inductance, specifically it is calculated by ω.

The ideas and inventions that tesla conducted and experimented on wireless power transmission are designed on the basis of resonance coupling. Table 3.1 shows the comparison of the different ways of WPT system. The resonant coupling method is similar to the concept of inductive coupling based on the principle of electromagnetic field and has slight variations among them. Instead of magnetic induction, magnetic resonance took place and additionally capacitors are added to the circuit in order to release high power EMF in the method of resonant coupling. Coils with few turns are formed with oscillating current that generates an oscillating magnetic field. Due to high resonance of the coil, the energy of the coil is depleted as electrical arcs over a period of time. This wastage can be absorbed by placing a receiver coil, which can pick up the electrical power before it lost. This type of energy is called resonant power transfer and its better than inductive coupling. The omnidirectional power transfer is possible (the emission of electrical power does not flow through an axis) only in the power transmission of resonance coupling. Dissimilar to induction power transfer it uses multi-receiver concept by placing the receiver coils inside the charging area. Apart from the basic principle of resonance there are some other techniques to increase the efficiency of power up to some million volts using resonant coupling.

5.1.2 Resonant circuits

The meaning of resonating in LC circuits in the IPT and CPT is to provide amplified power or energy by using the Q- quality factor. Resonance is very much important for small power delivery as well as lower voltage drop of leakage inductance of the coil and due to small current. Efficiency or power delivered will get maximized with resonating circuits.

Characteristics of Resonating circuits

1. Switching Harmonics filtering: It passes fundamental component of switching converter via LC resonance and eliminates higher or lower harmonics.
2. Power flow can be improved by nullifying the resonance of inductance and capacitance.
3. Slowed dynamics and transient peaks.

5.2 ANALYTICAL CALCULATIONS

There are many types of wireless charging, like magnetic flux induction, two-coil loosely coupled transformer. Loosely coupled circuits are the most efficient ways of transferring power. Four basic topologies are based on the arrangement of capacitor added to the transmitting and receiving coils. Most recent and advanced compensation is double side LCC topology.

Advantage over the other topology circuits is that the output power is proportional to the coupling coefficient, which is convenient in a practical application. For a misalignment in the transmitter and receiver coil, LCC compensated system transfer lower power, whereas the ss topologies system power increases significantly which may damage whole system.

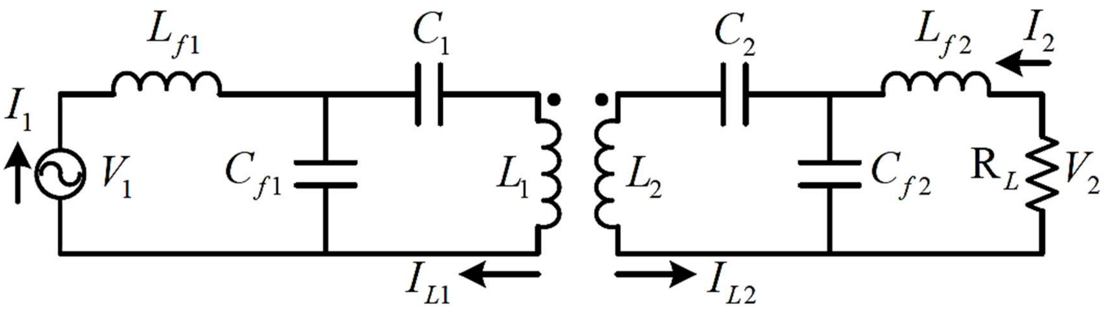


Fig.5.2 LCC topology equivalent WPT with coil sign convention

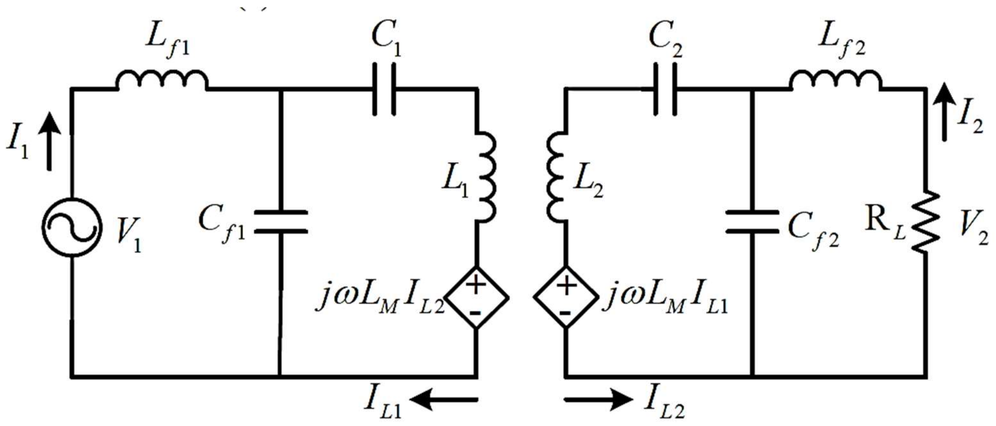


Fig. 5.3 Equivalent circuit

From the above equivalent circuit. Voltage equation can be obtained as shown below.

$$\begin{bmatrix} V_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} a & \frac{-1}{j\omega C_{f1}} & 0 & 0 \\ \frac{-1}{j\omega C_{f1}} & b & j\omega L_M & 0 \\ 0 & j\omega L_M & c & \frac{-1}{j\omega C_{f2}} \\ 0 & 0 & \frac{-1}{j\omega C_{f2}} & d \end{bmatrix} \begin{bmatrix} I_1 \\ I_{L1} \\ I_{L2} \\ I_2 \end{bmatrix} \qquad 5.1$$

$$a = j\omega L_{f1} + \frac{1}{j\omega C_{f1}}, \; b = \frac{1}{j\omega C_1} + \frac{1}{j\omega C_{f1}} + j\,\omega L_1 \qquad 5.2$$

$$c = \frac{1}{j\omega C_2} + \frac{1}{j\omega C_{f1}} + j\omega L_2, \; d = j\omega L_{f2} + \frac{1}{j\omega C_{f1}} + R_L \qquad 5.3$$

Basically, the resonance can be obtained in many ways. The useful conditions are obtained when all the diagonal elements are real and no imaginary part is present. Thus, the following resonant conditions can be derived:

$$L_{f1} * \ C_{f1} = \frac{1}{{\omega_o}^2} \quad 5.4$$

$$L_{f2} * \ C_{f2} = \frac{1}{{\omega_o}^2} \quad 5.5$$

$$L_1 - \ L_{f1} = \frac{1}{{\omega_o}^2 C_1} \quad 5.6$$

$$L_2 - \ L_{f2} = \frac{1}{{\omega_o}^2 C_2} \quad 5.7$$

Thus, note that $L_m = k\sqrt{L_1 L_2}$ stands for the mutual inductance and k is the coupling coefficient.

From the above equations it is clear that, ω should be controlled to control the system.

Under this condition, resonance frequency of above formula is related to inductances and capacitances. Independent of coupling and load condition.

$$\begin{aligned} V_1 &= \frac{-1}{j\omega C_{f1}} I_{L1},\ 0 = \frac{-1}{j\omega C_{f1}} I_1 + j\omega L_M I_{L2} \\ 0 &= j\omega L_M I_{L1} + \frac{-1}{j\omega C_{f2}} I_2,\ 0 = \frac{-1}{j\omega C_{f2}} I_{L2} + R_L I_2 \end{aligned} \quad 5.8$$

Output current can be determined by using these above equations.

Delivered power in secondary side is considered as below due the same phase of secondary current and voltage.

$$I_2 = \frac{jL_M}{\omega L_{f1} L_{f2}} V_1 . \quad 5.9$$

$$P \ = \mathbf{U}_{AB} \cdot \ \mathbf{I}_{Lf1} = \frac{\sqrt{L_1 L_2}}{\omega_o L_{f1} L_{f2}} \cdot k U_{AB} U_{ab} \quad 5.10$$

P – Power transferred or output power

$\mathbf{U}_{AB}$ – input voltage

U_{ab} – output voltage

$\mathbf{I}_{Lf1}$ – input current

$$L_{f1} = \ L_{f2} = \sqrt{\frac{k_{max} U_{AB} U_{ab}}{\omega_o \, P_{max}} \cdot L_1} \quad 5.11$$

5.2.1 The working of LCC model

A double sided LCC-compensation network is provided for a wireless power transfer system. It includes send unit and receive unit. The send unit transfer power using inductive power and receive unit receives the power from the send unit. The send unit includes an inverter configured to receive a DC input signal and convert the DC input signal from the inverter and generate an alternating electromagnetic field, and send side compensation circuit interconnecting the invert with send coil. To be more precise send side compensation circuit is comprised of a send side inductor a send side series capacitor serially coupled together and coupled to positive terminal of the send coil, as well as a send side parallel capacitor coupled in a parallel with the send coil.

The receiving unit includes a receiving coil configuration to receiving the alternating electromagnetic field from the send coil of the send unit and output an AC charging signal, a receive side converter configured to receiving the ac charging signal to a DC charging signal, and receiving side compensation circuit interconnecting the receive coil with the receive side converter. Likewise, the receive side compensation circuit is comprised of a receiving side inductor and received side series capacitor serially coupled together and coupled to positive terminal of the received coil, as well as a receive coil.

5.3. COMPENSATION TOPOLOGY

In the MR based WPT system, compensating capacitors plays a vital role for tuning the resonance frequency at both transmitter and receiver sides of the system. They are mainly four basic type of compensation topologies namely SS, SP, PS and PP. The position of the capacitor on each side of the coils, tunes and matches the referred value of the frequency to enhance maximum power transfer between them. These capacitors in turn known as tuned or compensating capacitors and their values are determined using formulas given in Table .4.2

Table 5.1 Basic Compensation Topologies

Compensation Topology	**Primary Capacitance**
SS	$\frac{C_2 L_2}{L_1}$
SP	$\frac{C_2 {L_2}^2}{L_1 L_2 - M^2}$

PP	$\frac{(L_1L_2 - M^2)C_2{L_2}^2}{\frac{M^4C_2R}{L_2} + (L_1L_2 - M^2)^2}$
PS	$\frac{C_2L_2}{\frac{M^4}{L_1L_2C_2R} + L_1}$

The analysis is extended and has proved the SS topology as a durable solution to make fast/frequent charging for neighborhood electric vehicles.

5.4. COMPARISON OF SS AND DOUBLE SIDED LCC

Comparison between the double-sided LCC and SS Compensation topologies

For similarities, there are two main points.

1. The resonant frequency has no relationship between coupling and loads in any topologies.
2. Both are current sources, the output currents are independent on the load condition (output voltage), only dependent on the input voltage, resonance frequency and mutual inductance.

Differences in the SS and LCC topologies:

1. SS requires low components than the LCC
2. Output power of SS topologies has increasing effect as the mutual inductance decreases. Hence it requires position sensing or power limiting to detect and disconnect or protection. However, this is not necessary for the double-sided aligned receiver and transmitter coils.
3. Output power of SS is dependent on the resonant frequency, coil structure and misalignment tolerance.
4. Lf1 and Lf2 parameters in the LCC topologies helps to adjust output power.
5. Current in the input side is constant, it is calculated by input voltage.
6. Furthermore, parameters are considered like output displacement, voltage and current stresses on components and efficiency.
7. LCC compensation wireless charger. Since the transfer power decreases with decreasing of the mutual inductance. Maximum power can be met for well.

Efficiency Comparison

Due to Equivalent series resistance (ESR) of the capacitor, copper loss and core loss of the inductor and dissipative loss, these resonant inductor and capacitor will lower the efficiency in the main power paths. If the in-put voltage and load are same as the SS compensation topology. Even under the different misalignment at rated power of charging system also varies. SS topology used in WPT under the circumstance of maximum mutual inductance, while double sided LCC is used when the mutual inductance is minimum. Output power is controlled by using the input voltage. When the mutual inductance is maximum, the input voltage of the SS compensation topology will be higher than that of LCC. Then current of SS compensation topology will lower if transferring the nominal power. So, efficiency will be higher if the mutual inductance is maximum in SS topology. On the other hand, efficiency of LCC compensation is high, if the mutual inductance is lower. The loss on the compensation circuit increases in the same way the loss on the transmitter coil decreases when the mutual inductance increases. [5].

Higher frequency current is supplied to the transmitter side coil. Power electronic converter helps to achieve high switching frequency with required magnitude. At the receiver side, rectification of the output voltage by using the diode bridge and converter like, buck-boost converter helps to provide the required amount of voltage the battery. There is another method which can applied is the controlled rectifier at the secondary/receiver side helps control the voltage. Transmitter side converter can be voltage or current source converter. Because the of bulky requirement of inductors for the Current Source converter. At the transmitter side, converter outputs high frequency square voltage, by adopting LCC compensation topology, a constant high frequency current can be maintained in the coil.

There are many control methods that are used to control the transfer power. It can be of transmitter side control, receiver side control and dual side control. Its usage is depending on its advantage. Transmitter side control is used for single primary pad and single pickup pad, whereas the dual side is used for single pickup pad. The receiver side control is used where the multiple pickup pads are powered by single track/transmitter pad.

Transmitter side controlling will be done by changing few parameters like duty cycle, phase between two legs and frequency. In some cases, switching frequency or the operating frequency is used to control at the transmitter side.

CHAPTER - VI

COIL DESIGN

6.1. SELECTION OF COIL GEOMETRY

In the previous analysis, it is shown that the FOM = kQ limits the maximum transmission efficiency of IPT systems, independently of the compensation method. Hence, an optimization of the IPT coil geometry with respect to the two parameters, magnetic coupling k and inductor quality factor Q, is the next step. For coil designs that include core materials or that have unconventional geometric shapes, FE tools are required for the optimization as analytical calculations are hardly possible. These tools allow calculating equivalent circuit parameters of the coil, predicting the electromagnetic losses in the used materials, dimensioning of the core to avoid saturation, as well as calculation of the stray fields. However, as a starting point for an FE-based efficiency and power density optimization, a fundamental coil geometry and guidelines on how to scale this coil geometry are needed.

The results of analytical models and measurement shows that the ferrite material equipped in the coils can enhance the mutual coupling notably between two coils. As for coil geometry, square coil is proved to be a better option for WPT systems.

Advantage of square planar coil over circular planar coil

Influence of ferrite substrate in the coil design: Nature of coil design as shown in [5] self and mutual inductance increases suddenly for threshold value of permeability in square planar coil. Under higher permeability the coupling coefficient decreases due to decrease of mutual inductance. But self-inductance acts faster than that of mutual inductance.

Influence of spacing between the turns- line spacing and coupling coefficient of circular coils are directly proportional to each other, whereas square coils are inversely proportional to each other. For values of coupling coefficient less than the threshold value in line spacing, square coil k is higher than the circular coil.

Square coil has been proven to be best method to adopt in WPT systems. Ferrite materials can be included while designing the system to enhance the mutual coupling [5].

6.2. DESIGN PROCEDURE

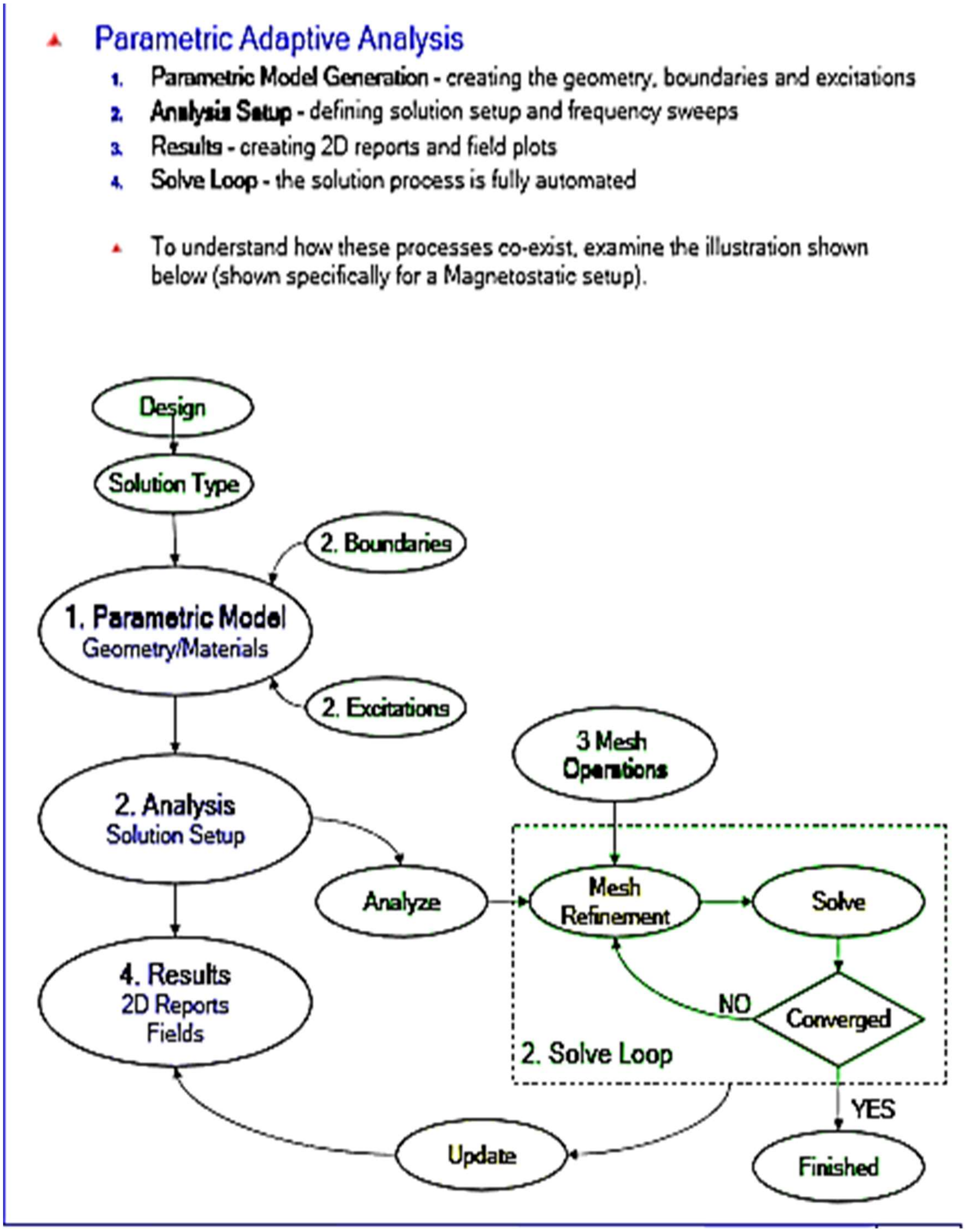
Simulation approach enjoy widespread use in the electronics design space, both in industry and academia, because they can be used to find out the characteristics of the designed devices without investing the money needed to build prototypes that may not work. They allow visualization of how the components react to variations in different parameters, like applied voltage and frequency. They are also used to change physical, electrical and magnetic characteristics of the device under study and then to reassess its performance. Thus, engineers can make more informed decisions when selecting materials and choosing between competing designs. Nowadays, many software packages for electromagnetic field simulation are available. Some examples are COMSOL Multiphysics, CST EM STUDIO and ANSYS Maxwell.

The last one was chosen to validate the values from the analytical approach. Ansys is a comprehensive program for 3D design and simulations in the fields of fluids, electronics, semiconductors, structural analysis and embedded software, among others. The electronics suite can simulate antennas, automotive radars, RF and microwaves, low-frequency electromagnetics, power electronics and others.

Ansys Maxwell, used during this thesis work, was developed for static, Magnetic field simulation. It contains several solvers, including the magnetostatics solvers used in this project. The magnetostatics solver, as its name implies, assumes the magnetic field is constant. This makes it less accurate than the eddy currents solver for low frequency cases, but it is more computationally efficient. The frequency range used during the experiments is around 15 kHz. In this range, the maximum distance between the coils considered was 100 mm, this solver was not accurate enough to study the effects of metals placed close to the coils. The eddy currents solver was used for this kind of scenarios. This solver computes steady-state, time-varying (AC) magnetic fields at a given frequency. For the most part, the same models defined for use with one solver can be reused for the other, and only new excitation sources had to be defined. After choosing the correct solver, the next step is to create the structure to be simulated. The base structures considered were based on predefined structures included in the program. There is a library of common materials such as copper, ferrite, FR4, etc.

6.3. ANSYS MAXWELL 3D DEIGN

Ansys Maxwell 3D Overview



▲ Parametric Adaptive Analysis

1. **Parametric Model Generation** - creating the geometry, boundaries and excitations
2. **Analysis Setup** - defining solution setup and frequency sweeps
3. **Results** - creating 2D reports and field plots
4. **Solve Loop** - the solution process is fully automated

▲ To understand how these processes co-exist, examine the illustration shown below (shown specifically for a Magnetostatic setup).

Fig. 6.1 Overview of ANSYS Maxwell coil Design and simulation solver algorithm

6.4 MAGNETIC COUPLER DESIGN

6.4.1 Geometry of coils

A coil size and air-gap distance (ground clearance) are the primary concern, when we build a wireless charging system for Electric Vehicle. The transmitting coil and receiving coil can have the same size to reduce the installation cost and to simplify the system design. To provide a good coupling coefficient k, the coil with w is varied, as the number of turns doesn't affect the k. The thickness of the coil and number of strands are considered to avoid skin-effect.

In deigning of the coil, two parameters have to be given importance, one is the coupling coefficient and self-inductance Ls. The coupling coefficient determines the power capability of the WPT system. Self-inductance closely related to the system efficiency.

6.4.2 Litz wire and its design

DC or low frequencies are less. However, from Fig. I it is seen that the coils are fed with high frequency voltage which causes high frequency current to flow through them. This time varying current produces time varying magnetic field in the coils which results into induced eddy currents. Skin effect and proximity effect are the two types of eddy current. If a solid conductor is used to make a coil, these effects are dominant and because of which AC resistance of coil becomes high. This affects the WPT efficiency. Therefore, it is recommended to use bunch of stranded wires at high frequency to reduce these losses. Litz wire is the best suitable option which is made with no. of thin insulated strands. Resistance of these type of conductor is very less which improves the WPT efficiency.

CHAPTER - VII

RESULT AND ANALYSIS

7.1 CASE STUDY:

A case study conducted on [1] to verify the results taken from the Maxwell and LTSpice Software. Coil design parameters are simulated in software and got 48.03uH mutual inductance and 59.867 self-inductance for square coil as given in Table 7.1 & 7.2 and fig. 7.1. Coupling coefficient of coil is 0.18 as same as [1]. But the area covered by square is smaller comparative to circular coil.

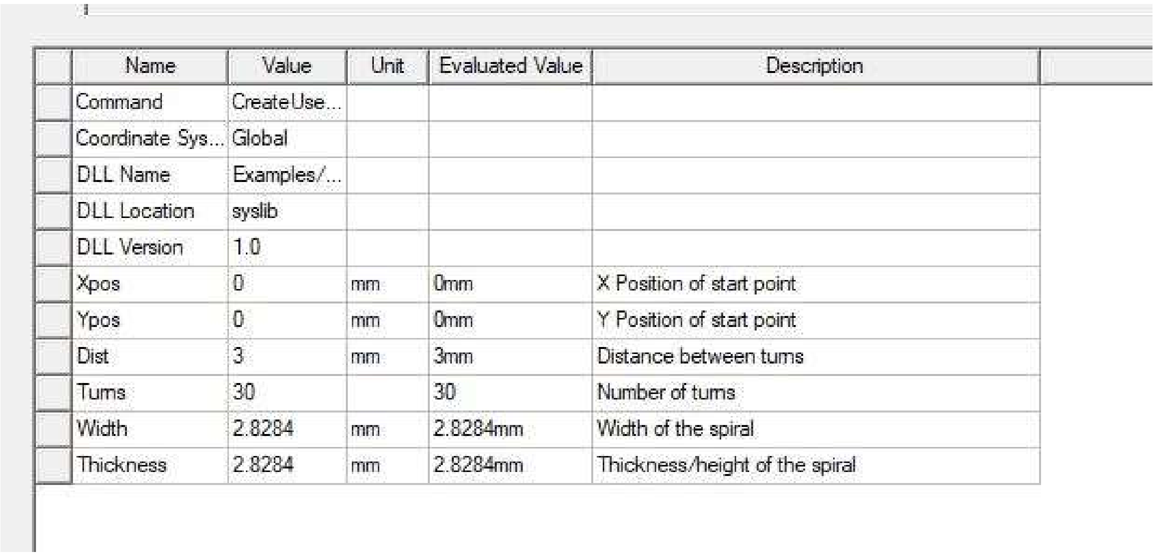
Table 7.1 Comparing the referred values from [1] with simulated results

SL. NO.	PARAMETER	Simulation results	Values from [1]
1	Thickness of Coil	2.8mm	2.8
2	Number of Turns	30	30
3	Width of the spiral	2.8mm	2.8mm
4	Distance Between turns	3mm	3mm
5	Self-Inductance	59.867uH	60uH
6	Mutual Inductance	48.03uH	49.1uH
7	Air Gap between coils	150mm	150mm
8	Copper wire (Litz) material	100%ACS, 100 um Diameter	-
9	Coupling Coefficient(k)	0.0319943674	0.18
10	Quality factor (Qs)	13.9616	

Table 7.2 Parametric values given in [1]

Parameter for Design of coil	Values
Permeability of Copper (μ_o)	$4*pi*10^{-7}Hm^{-1}$
Fill factor(φ)	0.949927
Number of Turns(n)	30

Outer diameter(do)	153.0277mm
Inner Diameter(di)	3.9296mm



Name	Value	Unit	Evaluated Value	Description
Command	CreateUse...			
Coordinate Sys...	Global			
DLL Name	Examples/...			
DLL Location	syslib			
DLL Version	1.0			
Xpos	0	mm	0mm	X Position of start point
Ypos	0	mm	0mm	Y Position of start point
Dist	3	mm	3mm	Distance between turns
Turns	30		30	Number of turns
Width	2.8284	mm	2.8284mm	Width of the spiral
Thickness	2.8284	mm	2.8284mm	Thickness/height of the spiral

Fig.7.1 ANSYS Maxwell Coil design parameters for square planar coil

Square coil design with air as boundary has been designed in Maxwell as shown in fig. 7.2. With airgap of 100mm and copper as coil material with 4*pi*10^{-7} Hm^{-1} has been assigned. It is parallelly aligned to get the higher coupling fields upon each other. Lower coil is the transmitter with 30Amps of current and given the same current as excitation to both coils and the upper coil called as receiver or secondary coil.
For coil design assigned with many strands to eliminate skin effect from the ac current.

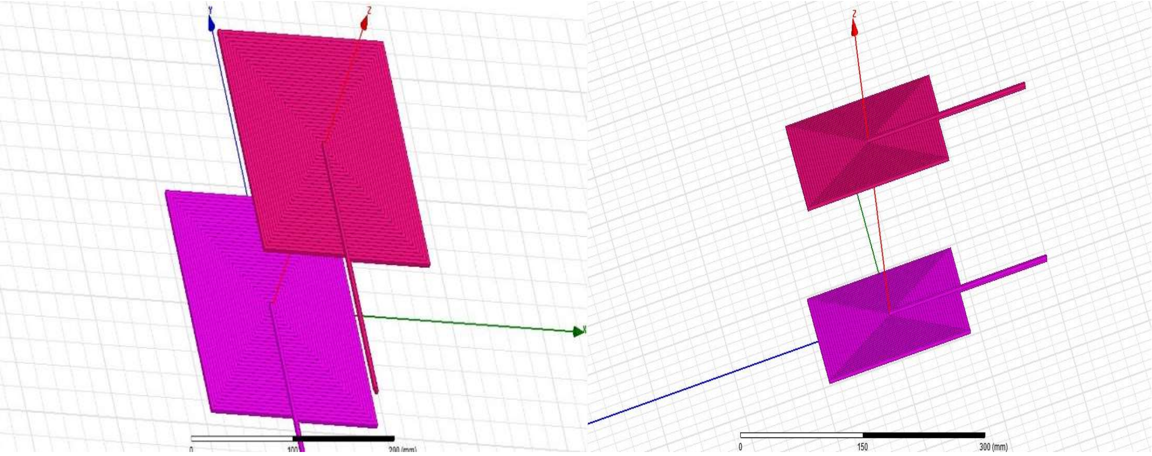


Fig.7.2 Side views of coil designed in Maxwell.

A non-model has been created in between the coils to capture the flux plot in a concentrated form on a plane sheet as shown in fig.7.3. A we observe on that plane it is very clear that the red represents the maximum field at the center comparative to the edge.

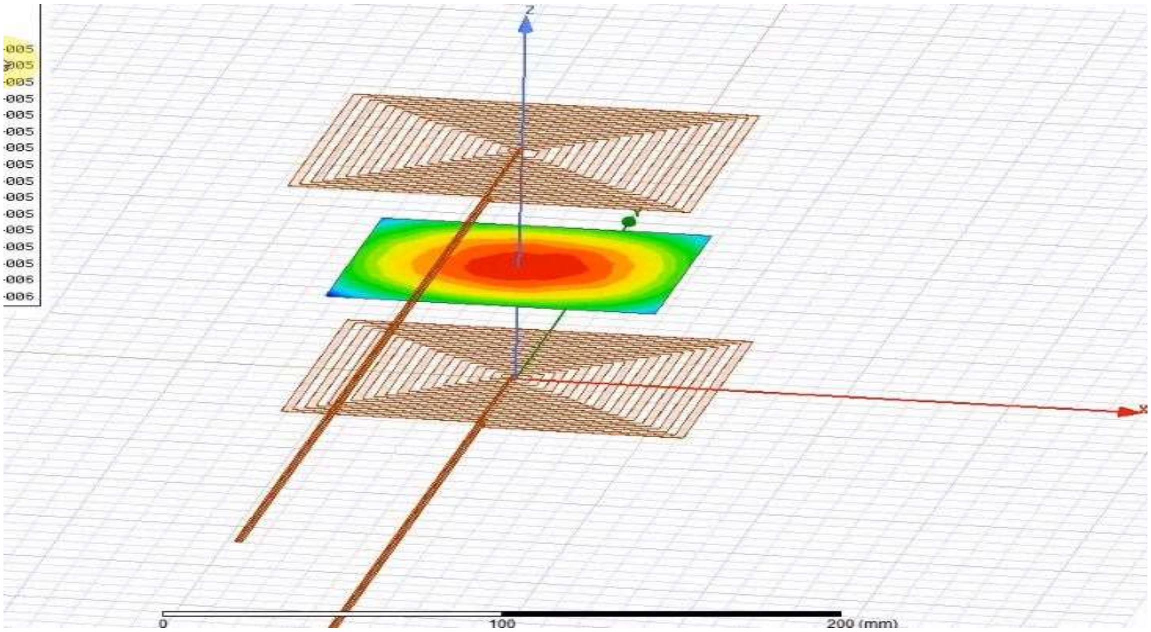


Fig.7.3 Flux plot distribution for 0.6kW power transfer simulated in Maxwell

The below figure has been plotted to analyze the relationship between the airgap and the mutual inductance of the coils. As the distance is increasing between the coils the mutual coupling between them is reducing hence the field or flux affecting on one another is depleting. Another main important factor helpful to achieve maximum efficiency is coupling coefficient between the current coils.

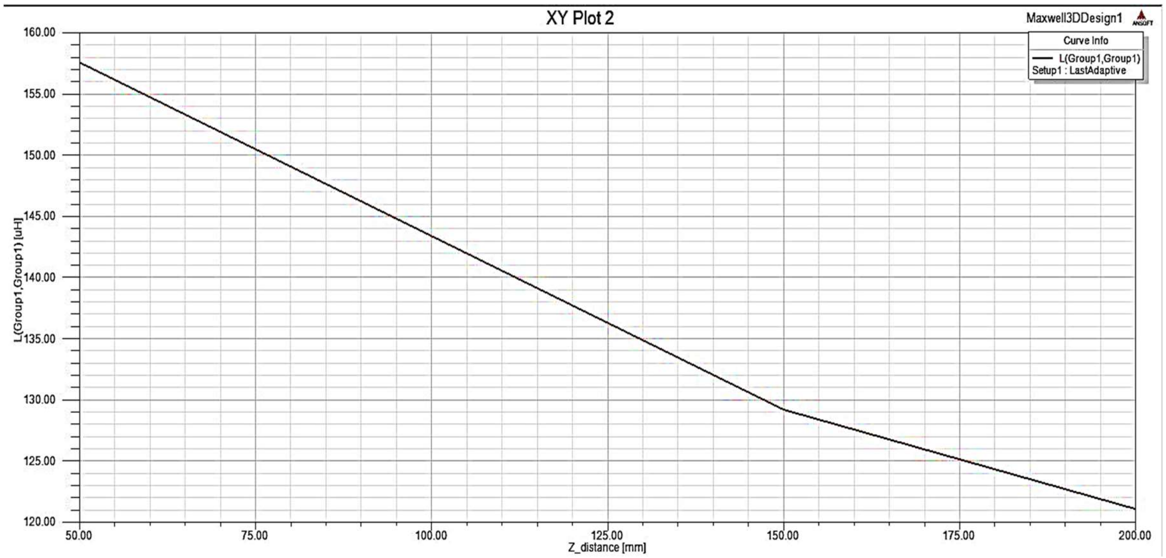


Fig.7.4 Mutual inductance vs airgap between the coils

7.2 1 KW WIRELESS POWER TRANSFER

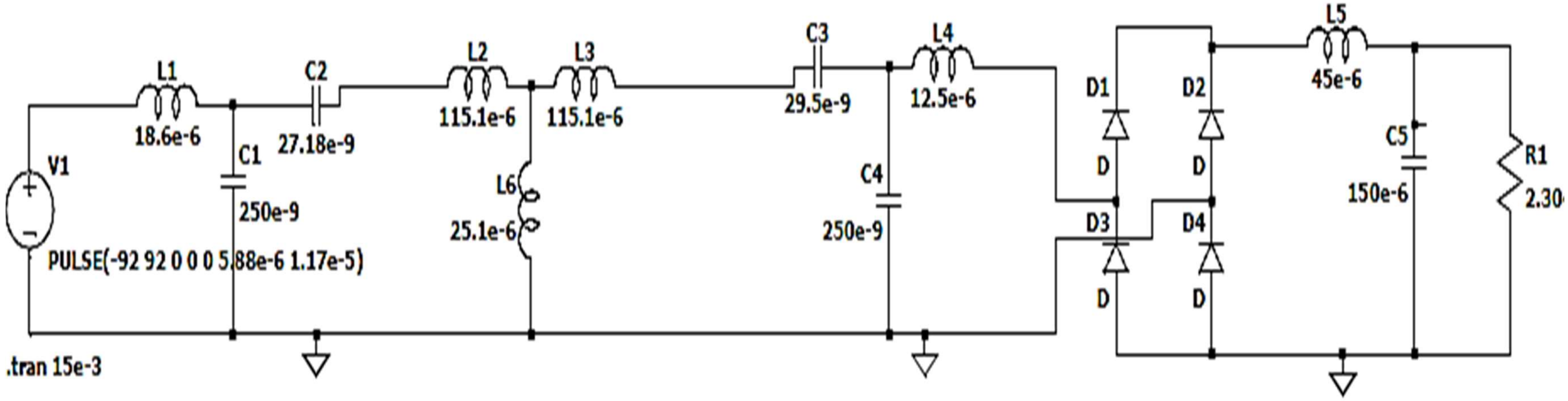


Fig.7.5 LCC topology-based equivalent circuit simulation in LTSpice.

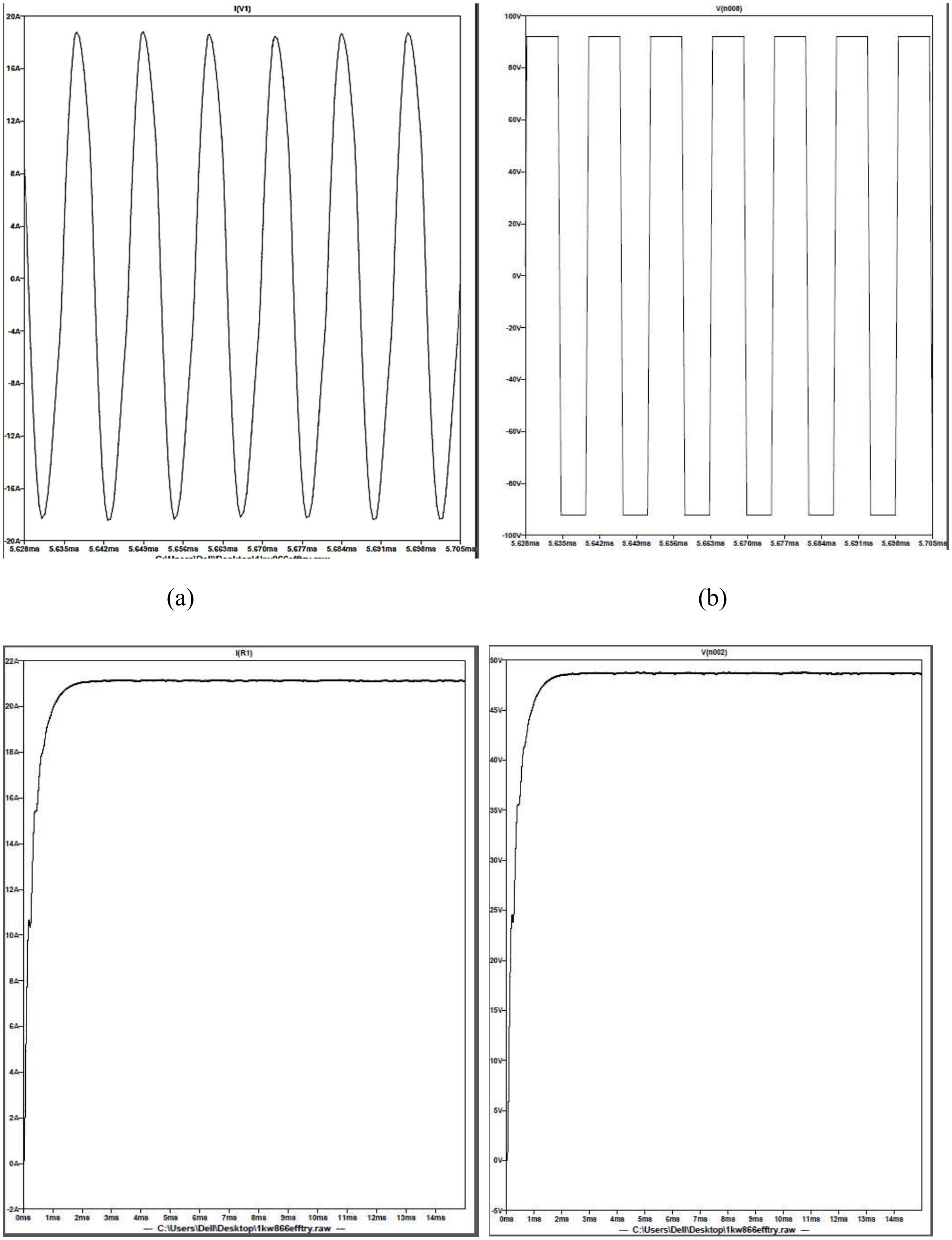
Circuit specifications for the above figure

L_m = 25.1uH
L_{s1} = L_{s2} = 115.1uH
k = 0.18

n = 1
C_2 = 29.5nF
C_1 = 27.18uF

C_{f2} = 250nF
C_{f1} = 250nF
Lf1 = 18.6uH

Based on the several advantages that LCC has given to the design of a WPT. The parameters that are given above are calculated theoretically calculated and modified to get the output results. Considering the 100V dc supply provided to the high frequency out generator i.e. 85 kHz resonance frequency provided to the compensation topology for the specification given above as well as shown in fig. 7.5. Battery connection at the output is replaced with equivalent load and to avoid the ripple capacitor is connected parallel.
Equivalent circuit simulation is conducted above by replacing the coil with a mutual inductor in parallel to series inductors on both side coils, which is similar to transformer equivalent circuit. Fig. 7.6 has graphs after simulating in LTSpice, (a) has input sinusoidal current due to the pulse voltage provide as the supply to the transmitter coil. (c)&(d) shows the transient and steady state of current and voltage provided to the load(battery) respectively.



(a) (b)

(c) (d)

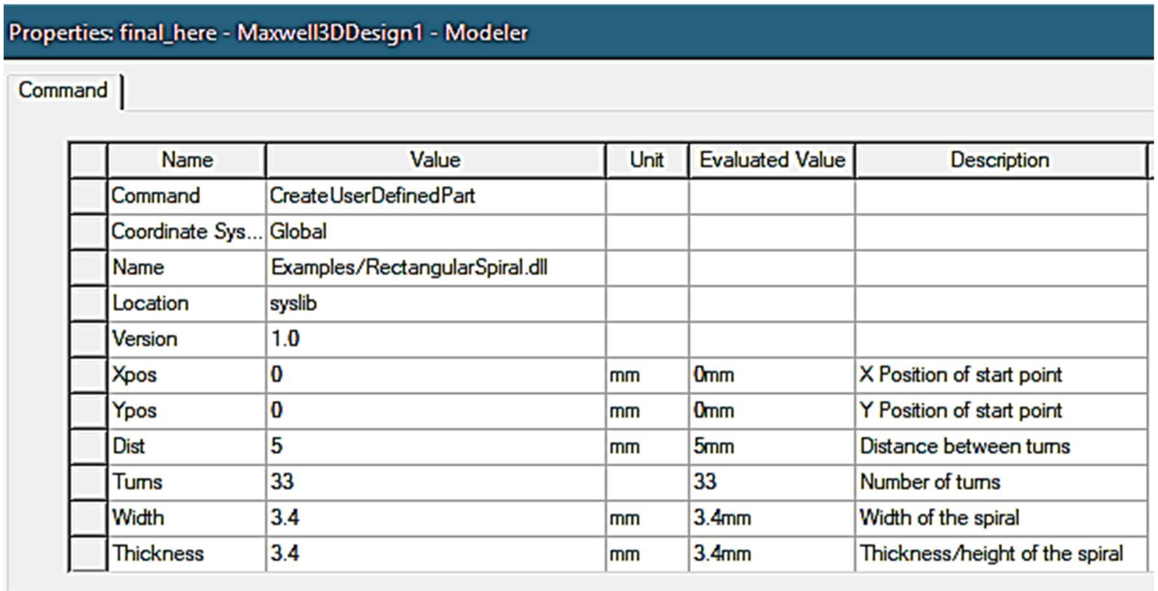
Fig. 7.6 (a) Sinusoidal input current of 18 Amps(peak). (b)Pulsating input voltage 92Volts. (c)Output current at receiver side 21Amps. (d)Output voltage of 48volts for battery

7.3 MAXWELL COIL DESIGN CONFIGURATIONS

After determining the mutual inductance and self-inductance, it is necessary to design the coils according to the used parameter in simulating the circuits. Like number of coils both sides should be same, coupling coefficient at particular airgap should provide 0.18 and fundamental frequency is nearly 85 kHz. Table 7.3 and fig. 7.7 shows the detailed study of coil design parameters for 1 kW power.

Table 7.3 Specifications for design of 1 kW WPT

Parameter	Values
Input DC Voltage	100V
Output DC Voltage	48V
Coupling Coefficient	0.18
Transmitting Coil inductance	143.8uH
Receiving Coil inductance	143.8uH
Switching frequency	85000Hz
Maximum Power	1000
Maximum Efficiency	87%
Nominal Gap	150mm
Mutual Inductance	25uH



Name	Value	Unit	Evaluated Value	Description
Command	CreateUserDefinedPart			
Coordinate Sys...	Global			
Name	Examples/RectangularSpiral.dll			
Location	syslib			
Version	1.0			
Xpos	0	mm	0mm	X Position of start point
Ypos	0	mm	0mm	Y Position of start point
Dist	5	mm	5mm	Distance between turns
Turns	33		33	Number of turns
Width	3.4	mm	3.4mm	Width of the spiral
Thickness	3.4	mm	3.4mm	Thickness/height of the spiral

Fig.7.7 Coil Design configuration in Maxwell

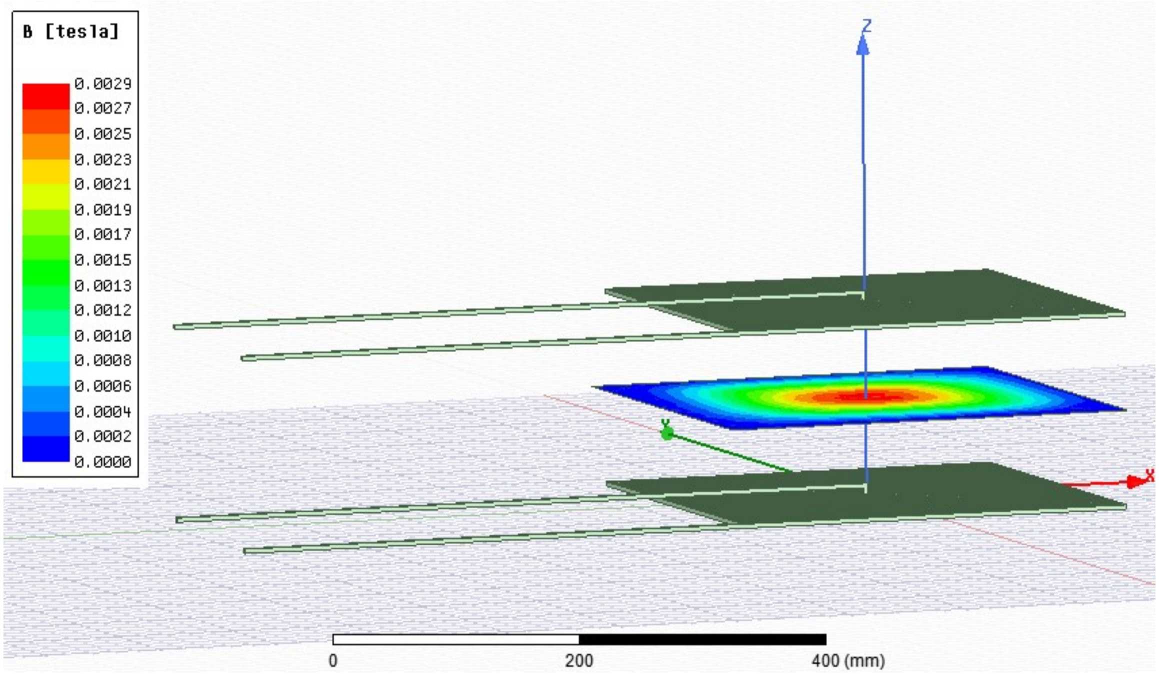


Fig. 7.8 Flux distribution and side of coupling coils

As we have studied earlier section 7.1 regarding the flux plot on a plane sheet. Similarly, it has been solved to get the flux plot on it. Then its magnitude range can be seen in left of figure 7.8. Magnetic field concentrated at the center plays major role in coupling between each coil. Further study we will be regarding its change of alignment and its impact on it.

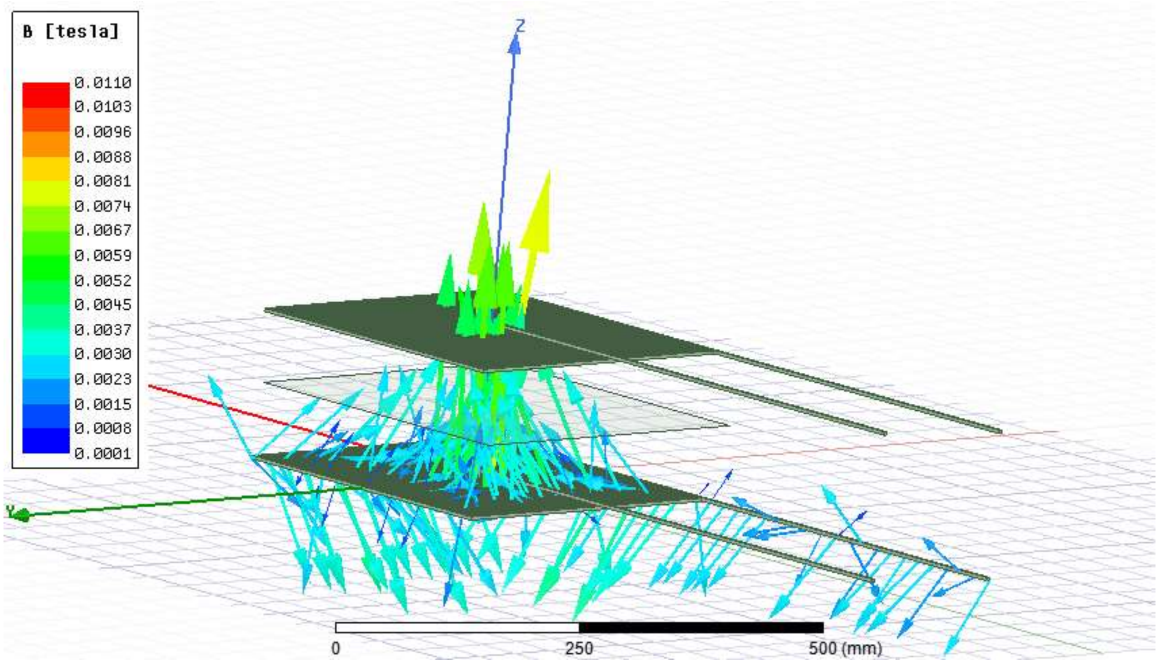


Fig.7.9 B Vector of transmitter and Receiver coil

As fig.7.9 shows field lines for excited 18Amps of current to both coils. In the fig. magnetic field vector is towards positive z-direction, which is representation of flux lines inducing the current into the receiver coil or the secondary coil. Similarly, if you observe the below figure it follows the same direction as that of transmitter coil with acceptance and power delivery to the system.
Observing the field lines in the below figures as they direct towards upward representing the power from the transmitter to receiver side transfer.

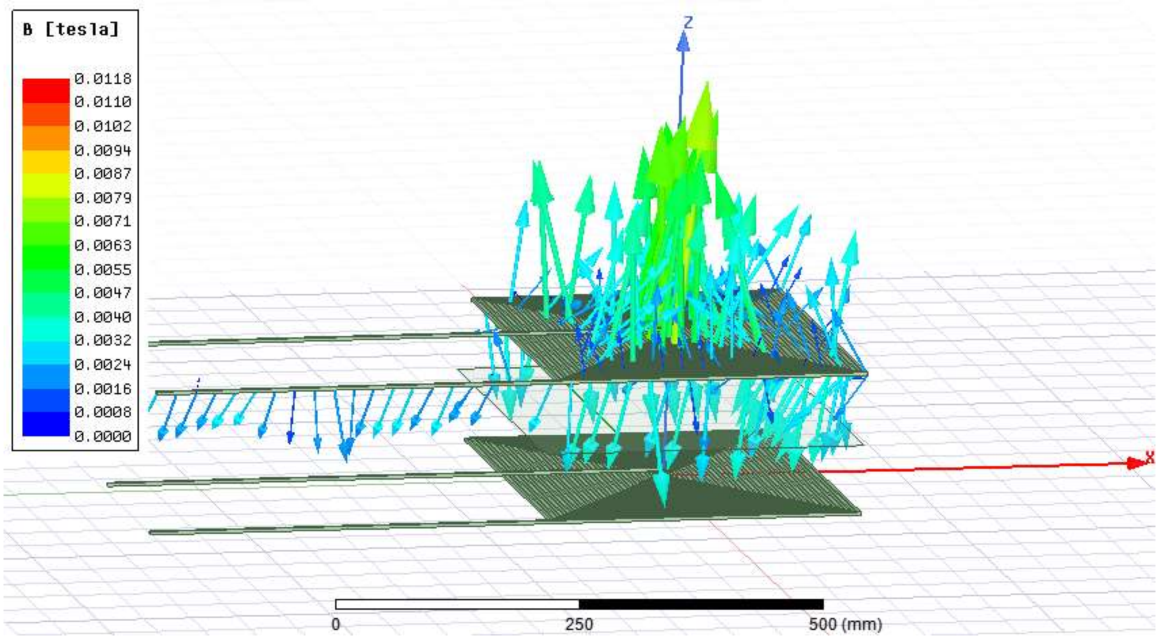


Fig.7.10 Magnetic field vector at the receiver side coils

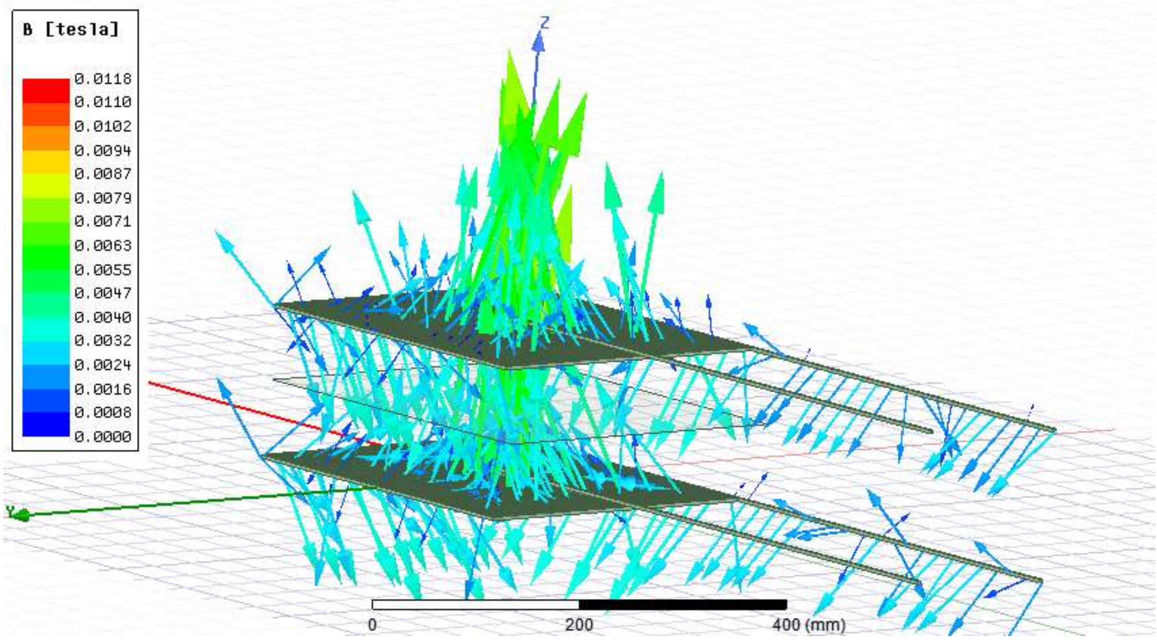


Fig.7.11 Magnetic field vector for both transmitter and Receiver coils.

7.4 MISALIGNMENT

It is not always a possible to park a car exactly parallel to the coils without creating misalignment. Hence it is necessary to consider the consequences of misalignment on the coil inductance and coupling coefficient.

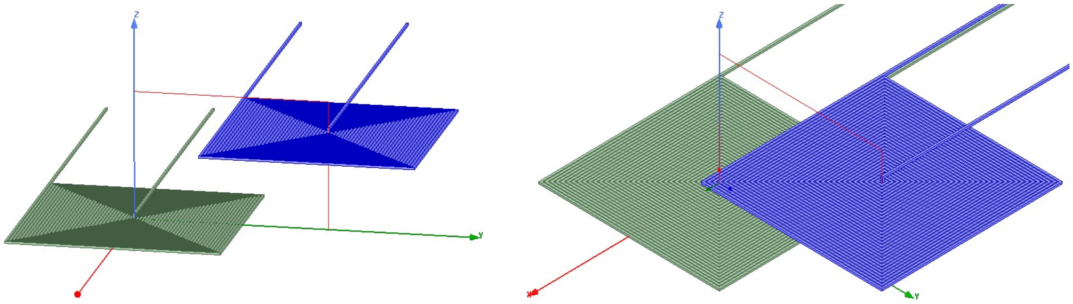


Fig.7.12 Side views of parallel misalignment

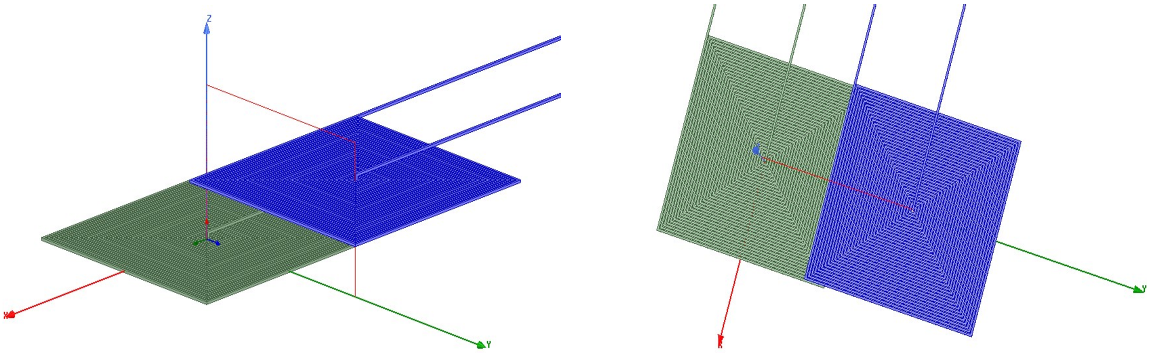


Fig. 7.13 Side views of angular misalignment

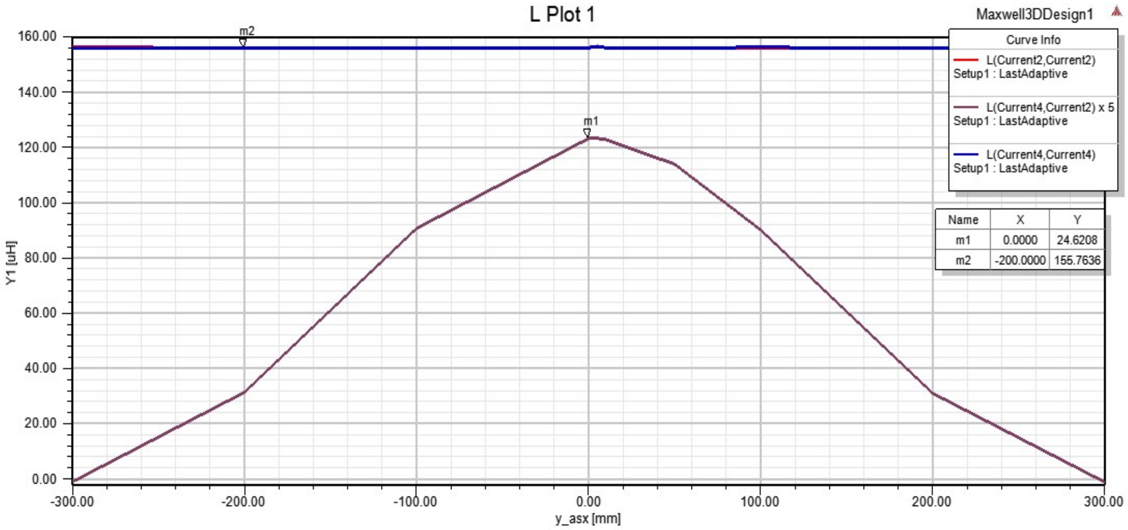


Fig.7.14 Inductance vs misalignment in y-axis(horizontal)

The fig. 7.14 is graph plotted between inductance of coils versus the varying coil pads in horizontal axis of -300mm to +300mm. This misalignment is the major concern dealing with WPT chargers. Hence its plot indicates that, at perfect alignment maximum mutual inductance can be achieved. As the distance between coils in horizontal increases, then mutual inductance decreases leading to zero.

Angular Misalignment of coil pads

Maximum filed lines crossing with higher intensity due to near airgap from the receiver coil for 30-degree angle of coil misalignment as shown in fig. lead to give higher mutual inductance as you see in the fig. 7.16. indicating higher power transfer is possible. But in LCC topology it happens slow due to the presence of compensation inductor L_{f1} &L_{f2} .

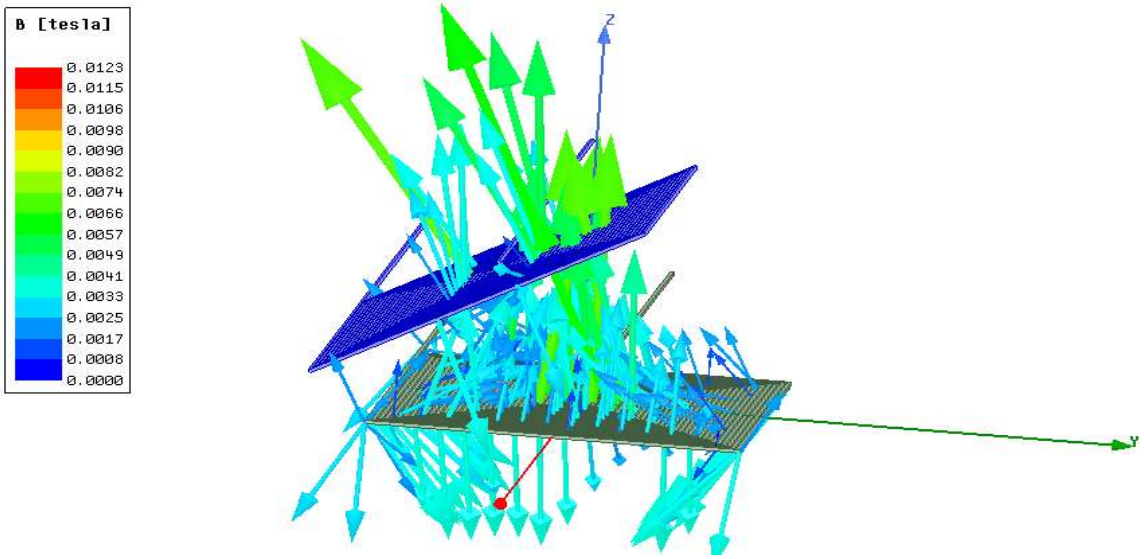


Fig. 7.15 B Vector of primary and secondary coil

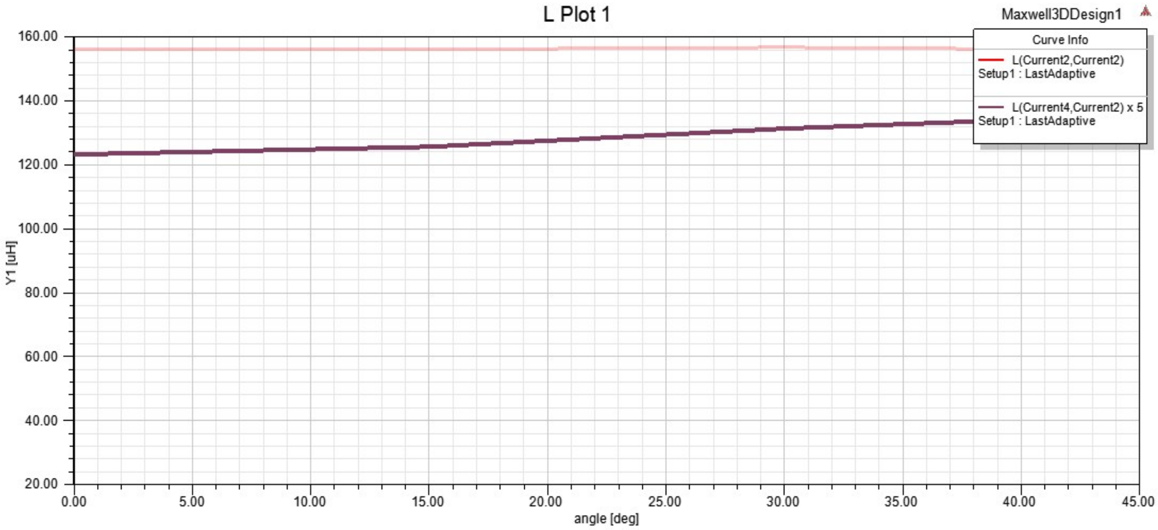


Fig. 7.16 Graph plot between secondary coil angle and mutual inductance

CHAPTER -7

ADDITIONAL DISCUSSION

7.1 SAFETY CONCERNS

Wireless power transfer avoids the electrocution danger from the traditional contact charging method. But, when charging an EV battery wirelessly, there is a high frequency magnetic field existing between the transmitting and receiving coils. The magnetic flux coupled between the two coils is the foundation for wireless power transfer, which cannot be shielded. The large air-gap between the two coils causes a high leakage field. The frequency and amplitude of the leakage magnetic field should be elaborately controlled to meet the safety regulations. A safe region should always be defined for a wireless charging EV.

We should ensure that the magnetic flux density should meet the safety guidelines when people are in normal positions, such as standing outside a car or sitting inside a car. Fortunately, a car is usually made of steel, which is a very good shielding material. The guideline published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) is the most referenced standard to ensure the human safety. There are two versions of ICNIRP standards. The first one was published at 1998. In ICNIRP 1998, there are two reference levels for occupational and general public exposure respectively. At frequency 0.8-150 kHz, which covers most of the EV WPT frequency, the limit for general public exposure is 6.25 μT. For occupational exposure, it is a little different. At frequency 0.82-65 kHz, the limit is 30.7 μT. While at 0.065~1MHz, the limit is 2.0/f. f is the frequency measured in MHz. Under the ICNIRP 1998 guideline, the safety evaluation for a 5 kW stationary EV WPT system was conducted. The average magnetic field exposed to a 1500 mm height body was 4.36 μT. For a 35-kW dynamic EV WPT system, the magnetic flux density at 1 meter from the center of the road is 2.8 μT. Both the stationary and dynamic WPT system design could meet the ICNIRP 1998 safety guidelines. A good thing for EV WPT is that, after another ten years of experience on the health affection of time-varying electromagnetic, ICNIRP revised the guideline at 2010 and increased the reference level significantly. For occupational exposure, the reference level is relaxed to

100 μT. For general public, the value changes from 6.25 μT to 27 μT. The increase in the reference level is because the former guideline is too conservative.

There is another standard about the electromagnetic field safety issues, IEEE Std. C95.1-2005, presented by the IEEE International Committee on Electromagnetic Safety. In IEEE Std. C95.1-2005, the maximum permissible exposure of head and torso is 205 μT for general public, and 615 μT for occupation. The maximum permissible exposure for the limbs is even higher, which is 1130 μT for both the general public and occupation. Compared with the IEEE Std., the ICNIRP 2010 standard is still conservative. According to ICNIRP 2010, the exposure safety boundaries of our 8 kW EV WPT system for both occupation and general public people are shown in Fig. 10. Together with the chassis, the safety zone is quite satisfactory. On the premise of safety, higher power WPT system could be developed according to the ICNIRP 2010. According to FCC part 18, ISM equipment operating in a specified ISM frequency band is permitted unlimited radiated energy. However, the lowest ISM frequency is at 6.78 MHz, which is too high for EV WPT. When the WPT operates at a non-ISM frequency, the field strength limit should be subjected to §18.305. The Society of Automotive Engineers (SAE) has already formed a committee, J2954, to look into many issues related to EV WPT systems. Among one of their goals will be safety standards. It is projected that a SAE standard on EV WPT systems will be released in June 2014 by this committee. More standards and regulations from different regions are summarized in a paper from Qualcomm Incorporated.

7.2 VEHICLE TO GRID BENEFITS

As the ongoing develop of EV, the vehicle to grid (V2G) concept, which studies the interaction between mass EV charging and the power grid, is also a hot research topic in smart grid and EV areas. It is recognized that if the EV charging procedure could be optimized, it could have many benefits for the grid. The EV could balance the loads by valley filling and peak shaving. The batteries in the EVs are like an energy bank, thus some unstable new energy power supply, like wind power, could be connected to the grid more easily. When the secondary rectifier diodes are replaced by active switches, a bidirectional WPT function is realized. The bidirectional WPT could provide advanced performance in V2G applications. Studies show that by introducing WPT technology, the drivers are more willing to connect their EV into the grid, which could maximize the V2G benefits.

7.3 WIRELESS COMMUNICATIONS

In a WPT system, it is important to exchange information between the grid side and vehicle side wirelessly to provide a feedback. Thus, the power flow could be controlled by the methods mentioned in section V. The communication design could be classified by whether the signal is modulated on the power carrier or uses a separate frequency band. The Qi standard for wireless low power transfer modulates a 2 kHz signal onto the power carrier frequency. The communication signal is transmitted through the power coils. The 2 kHz signal is very easy to process even by using the existing microcontroller in the device. In this way, the extra antennas and control chips for the communication could be saved. In EV WPT system, for the high voltage on the power coils, isolation is required for the communication control circuit which may increase the cost. For advanced information exchange, general wireless communication protocols, like Bluetooth, near field communication (NFC), and so on, could be adopted. In the EV WPT prototype from Oak Ridge National Laboratory (ORNL), the Dedicated Short-Range Communications (DSRC) Link is used [95]. The DSRC is a technology based on global position system (GPS) and IEEE 802.11p wireless fidelity (Wi-Fi), which could realize the connection between vehicle-to-vehicle (V2V) and vehicle-to infrastructure (V2I). The FCC already allocates 75MHz band at 5.9GHz for DSRC. It is being committed to use by the U.S. department of transportation in the Intelligent Transportation System (ITS). As the IEEE and SAE standards were already published, the DSRC could provide an easier way to implement the smart grid functionalities and maximize the vehicle to grid benefits.

7.4 COST

An importance factor that affects the future of WPT is its cost. Actually, from Fig. 8 we see the WPT has only a little difference with a wired charger. The extra cost in a WPT is mainly brought by the magnetic coupler. For the dynamic WPT design, the infrastructure cost including converter and track for 1km one-way road is controlled to $0.4 million. The investment of electrification is much lower with the construction cost of the road itself. With the road electrification, the EV on-board batteries could be reduced to 20%. The savings on the batteries might be much more than the investment on the infrastructure. The road electrification time is coming.

CHAPTER - 8

CONCLUSION AND FUTURE SCOPE

Designing a wireless power transfer system requires to consider many parameters. Main factors that affect and designed this thesis work are type of WPT, compensation topology, coil design and coupling coefficient. Modeling these on software helped to analyze the complete architecture for 1kW WPT for electric vehicle.

Magnetic Resonance coupling technology has given greater results for longer distance of transfer power. LCC topology is compared with SS topologies to understand the critical condition drawback the SS possess under misalignments. The constant output power can be derived for misalignment coils, but reduction in the magnitude. It is open loop system with IGBT/MOSFET as to produce the resonating frequency as output current for given input. Concentration of flux in the middle of the coil is more compare with at the edge.

Square coil with ferrite material provided the better coupling coefficient for low turns of coils. Circuit parameters are very sensitive to one another variable. Mutual inductance and k value are reducing for change of airgap. Standardization is very necessary due to the compatibility issue that vehicles face after deployment. Also, it is very important to consider static and dynamic charging should have same topology for compatibility.

Future Scope of Work

- ☐ Coil design techniques for large gap: There are different methodologies are applied to develop a most suitable coil for higher misalignment tolerance. DD, DQ and DDQ are among them considered better.
- ☐ Misalignment tolerance consideration for variable airgap and maximum power efficiency.
- ☐ Prototype of this design by using litz wires and power electronic circuit and retrofitting it on vehicles.
- ☐ LCC compensation technique can be used to design, dynamic charging of vehicles while in momentum.
- ☐ LCC compensation design used for both static as well as dynamic vehicle charging for a same coil pad.

REFERENCES

[1] Ahmad, A., Alam, M. S., & Chabaan, R. (2018). A Comprehensive Review of Wireless Charging Technologies for Electric Vehicles. IEEE Transactions on Transportation Electrification, 4(1), 38–63

[2] Kavitha, M., Bobba, P. B., & Prasad, D. (2016). Investigations and experimental study on Magnetic Resonant coupling based Wireless Power Transfer system for neighborhood EV's. 2016 IEEE 6th International Conference on Power Systems (ICPS).

[3] Lu, F., Zhang, H., Hofmann, H., & Mi, C. (2015). A high efficiency 3.3 kW loosely-coupled wireless power transfer system without magnetic material. 2015 IEEE Energy Conversion Congress and Exposition (ECCE).

[4] W. Li, H. Zhao, J. Deng, S. Li and C. C. Mi, "Comparison Study on SS and Double-Sided LCC Compensation Topologies for EV/PHEV Wireless Chargers," in IEEE Transactions on Vehicular Technology, vol. 65, no. 6, pp. 4429-4439, June 2016.

[5] Z. Luo and X. Wei, "Analysis of Square and Circular Planar Spiral Coils in Wireless Power Transfer System for Electric Vehicles," in IEEE Transactions on Industrial Electronics, vol. 65, no. 1, pp. 331-341, Jan. 2018.

[6] S. Chopra and P. Bauer, "Analysis and design considerations for a contactless power transfer system," in Telecommunications Energy Conference (INTELEC), 2011 IEEE 33rd International, pp. 1–6, IEEE, 2011. [2] W. C. Brown, "The history of power transmission by radio waves," IEEE Transactions on Microwave Theory and Techniques, vol. 32, no. 9, pp. 1230–1242, 1984.

[7] Z. Bi, T. Kan, C. C. Mi, Y. Zhang, Z. Zhao, and G. A. Keoleian, "A review of wireless power transfer for electric vehicles: Prospects to enhance sustainable mobility," Applied Energy, vol. 179, pp. 413–425, 2016.

[8] S. Y. R. Hui, W. Zhong, and C. K. Lee, "A critical review of recent progress in mid-range wireless power transfer," IEEE Transactions on Power Electronics, vol. 29, no. 9, pp. 4500–4511, 2014.

[9] A. P. Hu, Wireless/Contactless Power Supply:-Inductively Coupled Resonant Converter Solutions. VDM Publishing, 2009.

[10] B. H. Choi, V. Thai, E. S. Lee, J. H. Kim, and C. T. Rim, "Dipole-coil-based wide-range inductive power transfer systems for wireless sensors," IEEE Transactions on Industrial Electronics, vol. 63, no. 5, pp. 3158–3167, 2016.

[11] T. S. Chandrasekar Rao [1*], K. Geetha Categories, Standards and Recent Trends in Wireless Power Transfer: A Survey

[12] K.A.Grajski, R.Tseng, and C.Wheatley, "Loosely-coupled wireless power transfer: physics, circuits, standards,"in Microwave Workshop Serieson Innovative Wireless Power Transmission: Technologies, Systems, and Applications(IMWS), 2012 IEEE MTT- S International, 2012, pp.9–14.

[13] Analysis of Square and Circular Planar Spiral Coils in Wireless Power Transfer Systems for Electric Vehicle.

[14] J. M. Miller, O. C. Onar, and M. Chinthavali, "Primary-side power flow control of wireless power transfer for electric vehicle charging," IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 3, no. 1, pp. 147-162, March 2015.

[15] O. C. Onar, J. M. Miller, S. L. Campbell, C. Coomer, C. P. White, and L. E. Seiber, "Oak Ridge National Laboratory Wireless Power Transfer System Development for Sustainable Campus Inititative," in Proc., IEEE Transportation Electrification Conference and Expo (ITEC), pp. 1-8, June 2013, Dearborn, MI.

[16] L. Tang, M. Chinthavali, O. C. Onar, S. Campbell ,and J. M. Miller, "SiC MOSFET based single phase active boost rectifier with power factor correction for wireless power transfer applications," in Proc., IEEE Applied Power Electronics Conference and Exposition (APEC), pp. 1669-1675, March 2014, Fort Worth, TX.

[17] M. Chinthavali, O. C. Onar, S. Campbell, and L. M. Lotbert, "Isolated wired and wireless battery charger with integrated boost converter for PEV applications," in Proc., IEEE Energy Conversion Congress and Exposition (ECCE), pp. 607-614, September 2015, Montreal, Canada.

[18] M. Chinthavali, O. C. Onar, S. Campbell, and L. M. Lotbert, "Integrated charger with wireless charging and boost functions for PHEV and EV applications," in Proc., IEEE Transportation Electrification Conference and Expo (ITEC), pp. 1-8, June 2015, Dearborn, MI

[19] O. C. Onar, S. L. Campbell, L. Seiber, C. P. White, and M. Chinthavali, "A high-power wireless charging system development and integration for a Toyota RAV4 Electric Vehicle," in Proc., IEEE Transportation Electrification Conference and Expo (ITEC'16), June 2016, Dearborn, MI.

[20] O. C. Onar, S. L. Campbell, L. Seiber, C. P. White, and M. Chinthavali, "Vehicular integration of wireless power transfer systems and hardware interoperability case

studies," in Proc., IEEE Energy Conversion Congress amd Exposition (ECCE'16), September 2016, Milwaukee, WI.

[21] C. Wang, O. Stielau and G. Covic, 'Design Considerations for a Contactless Electric Vehicle Battery Charger', IEEE Trans. Ind. Electron., vol. 52, no. 5, pp. 1308-1314, 2005.

[22] O. H. Stielau and G. A. Covic, "Design of loosely coupled inductive power transfer systems," in Proc. Int. Conf. Power System Technology, vol. 1, Dec. 2000, pp. 85–90.

APPENDIX - A

LTSPICE

LTspice® is a high-performance SPICE simulation software, schematic capture and waveform viewer with enhancements and models for easing the simulation of analog circuits. Included in the download of LTspice are macromodels for a majority of Analog Devices switching regulators, amplifiers, as well as a library of devices for general circuit simulation.

LTspice provides a schematic capture and waveform viewer with enhancements and models to speed the simulation of switching regulators. Supplied with LTspice are macro models for most of Linear Technology switching regulators and operational amplifiers, transistors, MOSFETs, and passive components. After Analog Devices purchased Linear Technology, models for Analog Device parts are slowly being added over time. LTspice is node-unlimited and third-party models can be imported. Circuit simulations based on transient, AC, noise and DC analysis can be plotted as well as Fourier analysis. Heat dissipation of components can be calculated and efficiency reports can also be generated. LTspice is used by many users in fields including radio frequency electronics, power electronics, digital electronics, and other disciplines. LTspice IV does not generate printed circuit board (PCB) layouts, but netlists can be imported into layout programs. While LTspice does support simple logic gate simulation, it is not designed specifically for simulating logic circuits. The software was created by and currently maintained by Mike Engelhardt.

Benefits of Using LTSpice

- Stable SPICE circuit simulation with Unlimited number of nodes Schematic/symbol editor Waveform viewer LTSpice is also a great schematic capture Library of passive devices
- Fast simulation of switching mode power supplies (SMPS) Steady state detection Steady Turn on transient Step response Efficiency / power computations

APPENDIX – B

ANSYS MAXWELL

ANSYS Maxwell is the industry-leading electromagnetic field simulation software for the design and analysis of electric motors, actuators, sensors, transformers and other electromagnetic and electromechanical devices. With Maxwell, you can precisely characterize the nonlinear, transient motion of electromechanical components and their effects on the drive circuit and control system design. By leveraging Maxwell's advanced electromagnetic field solvers and seamlessly linking them to the integrated circuit and systems simulation technology, you can understand the performance of electromechanical systems long before building a prototype in hardware. This virtual electromagnetic lab gives you an important competitive advantage with faster time to market, reduced costs and improved system performance.

Maxwell includes the following solvers:

- Magnetic transient with rigid motion
- AC electromagnetic
- Magnetostatic
- Electrostatic
- DC conduction
- Electric transient
- Expert design interfaces for electric machines and transformers
- Simplorer (circuit and system simulation)

ANSYS simulation technology enables you to predict with confidence that your products will thrive in the real world. Customers trust our software to help ensure the integrity of their products and drive business success through innovation.

Industry Leading Low Frequency Electromagnetic Field Simulation

Trusted simulation of low-frequency electromagnetic fields in industrial components that includes 3-D/2-D magnetic transient, AC electromagnetic, magnetostatics, electrostatic, DC conduction and electric transient solvers to accurately solve for field parameters including force, torque, capacitance, inductance, resistance and impedance.

High Performance Design Delivery

Customizable modeling capabilities, automatic adaptive meshing and advanced high-performance computing technology allows designers to solve complete high-performance electromechanical power systems.

High Fidelity, Model-Based Design

Automatically generate nonlinear equivalent circuits and frequency-dependent state-space models from field parameters that may be further used in system and circuit simulation to achieve the highest possible fidelity on SIL (software-in-the-loop) and HIL (hardware-in-the-loop) systems.