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DESIGN AND IMPLEMENTATION OF WIRELESS POWER TRANSFER FOR POWER PAD CAPACTIVE TRANSFER SYSTEM FOR EV

Noor Qasim Atiyah Alsaedi

Master Thesis

Asst. Prof. Dr. Dogu Cagdas Atilla

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by

Noor Qasim Atiyah Alsaedi

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Dogu Cagdas Atilla

Supervisor

Examining Committee Members (first name belongs to the chairperson of the jury and the second name belongs to supervisor)

Asst. Prof. Dr.Dogu Cagdas Atilla	School of Engineering and Natural Sciences, Altinbaş University	____________
Asst. Prof. Dr. Çağatay AYDIN	School of Engineering and Natural Science, Altinbaş University	____________
Asst. Prof. Dr. Cahit Karakus	Faculty of Engineering and Architecture, Esenyurt University	____________

I certify that this thesis satisfies all the requirements as a thesis for the degree of Master of Science.

Asst. Prof. Dr. Çağatay AYDIN

Head of Department

Approval Date of Graduate School of Science and Engineering: ____/____/____

Prof. Dr. Oğuz BAYAT

Director

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Noor Qasim Atiyah Alsaedi

DEDICATION

Foremost, I would like to express my sincere gratitude to my supervisor, Prof. Dogu Cagdas ATILLA for giving me an opportunity to work under him as a Graduate Research Assistant. I have been exceptionally lucky to work under a world renowned Professor in the field of Electromagnetics, microwave, ref. I would like to thank him for his patient guidance, encouragement and advices that he provided throughout my time as His student. I would like to thank Him for the funding He provided to undertake this research and giving me the opportunity to attend conferences and meet many interesting people, insightful comments and support that enabled me to complete the work that I had undertaken of my family. My immediate family to whom this dissertation is dedicated to, has been a constant source of love, concern, support and strength all these years. I would like to express my heart-felt gratitude to my family. My extended family has aided and encouraged me throughout this endeavor. A special vote of thanks to my wife, who always made me feel as a stranger.

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To My Beloved Parents, Wife & SON.

Qasim A, Rbaeaa M ,Gassag Majeed & Hassan . Thank You for all your love and support.

ABSTRACT

DESIGN AND IMPLEMENTATION OF WIRELESS POWER TRANSFER FOR POWER PAD CAPACTIVE TRANSFER SYSTEM FOR EV

Noor Qasim Atiyah Alsaedi

M.Sc., Electrical and Computer Engineering, Altınbaş University,

Supervisor: Asst. Prof. Dr. Dogu Cagdas Atilla

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This study presented a capacitive coupler of four-plates and its circuit model for big distance air-gap capacitive power transfer (CPT). The research studied the effect of square and circular plates. To make comparison between the plates and to save the electric field of vehicle charging application, the plates coordinated horizontally and perpendicularly. In the vertical and horizontal coordination, the same side two plates are near to each other to get a large coupling capacitance, the study compared among the capacitive horizontal pads and vertical pads and find outcome for different size to maintain the coupling of two plates side. This model of coupler circuit is approaching, considering all coupling capacitors. Highly power transfer (high plate voltage) and resonating coupler have been supplied by using the Double-sided LCLC compensated circuit topology. The coupler circuit model simplified to design the parameters of compensation circuit. Analysis of Finite-element is used to simulate the coupling capacitance and choose the dimensions of the coupler. The performance of circuit is simulated in ANSYS to design the specific parameter values.

Keywords: Wireless Power Transfer, Square Power Pads, Circular Power Pads, Changing Geometry, Capacitive Power Transfer, Electrical Vehicle.

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LIST OF ABBREVIATIONS

IPT	Inductive Power Transfer
CPT	Capacitive Power Transfer
V	Voltage
Vin	Input Voltage
I	Current
Vout	Output Voltage
VDC	DC Voltage
W	Watts (Power)
K, M	Kilo, Mega
Hz	Frequency
ω	Frequency in rad/Sec
C	Capacitance (Farads)
L	Inductance (Henry)
Cc	Coupling Capacitance (Farads)
Fr	Resonant Frequency (Hz)
d	Distance in centimeters
ε0	Permittivity of free space 8.854e-12
εr	Permittivity of the material utilized
M	Voltage Gain

KC	Coupling Coefficient
R	Resistance (ohms)
Z	Impedance ›
X	Resistance ›
S	Total Power (Volt-Ampere)
Ps	Electric Polarization
D	Duty Cycle
A	Area (*cm*2)

1. INTRODUCTION

1.1 HISTORICAL BACKGROUND OF WPT

The world needs electricity as its need for air, food and water. Its operating by using electric energy. To transfer power from its generation station to consumption points trillions of dollars have been capitalized. The batteries can be considered one of the electrical source. They are applied in countless uses ranging from industrial to commercial. However, most of the batteries charging process achieved by using of power harmonies. The concept of transferring power without wires was first expressed and established by Nikola Tesla 1900's [1] [2]. The use of magnets made the system versatile to transfer power across the small and large air-gaps. IPT systems work on the principle of electromagnetic induction. IPT systems have found its application in many fields such as roadway lighting [7], transportation [6] [8], consumer electronics [9], and high power transmission [10]. Though IPT systems were widely accepted in many fields, the others discarded the system cause of its limitations [11]. The use of electromagnetic field has an adverse effect on health and the environment. The statistical details published by who [12] states that electromagnetic field causes general health problems, sensitivity and depression. The properties of magnetic fields are that they effort to form closed loops from pole to pole and they all have the same the same strength. So, the magnetic fields similar effect any electronics placed in its vicinity. Therefore, causing Electromagnetic Interference (EMI) issues. Due to the EMI present, the electronics in the environment would need extra protecting and go through difficult electromagnetic compatibility testing. Another property of magnetic fields is that, they look for the track of smallest reluctance between reverse poles and effort to form a closed loop from pole to pole. Therefore, from the above property, we notice that the IPT systems cannot be used in environments with metal enclosures nor transfer power across metal barriers. The following disadvantages made the IPT system to be unwanted in serious applications and sensitive. The main purpose was to improve a system which is dependable and repairs free for critical applications. The power transfer systems are categorized based on distance. The operational frequency, varieties among kHz - MHz The most common alternative to inductive power transfer were achieved with the help of capacitive coupling, magneto dynamic coupling, microwaves, light waves (laser, waves, optics) and acoustics. Acoustic contactless energy transfers [13] [14], working the use of electronic circuits and a transducer at the primary and secondary to act as antennas. The conversion efficiency of optical or acoustic to electrical is between 20% - 35% [15] [16]. The cost of wireless systems utilizing light, microwaves and sound is very expensive and therefore mainly used in military, drone and spacecraft platform applications. Power transfer achieved through capacitive coupling proved to be inexpensive and efficient. Therefore, can be well thought out as a suitable candidate, which could consider as an alternative to inductive power transfer systems. The wired power system extensively used and conventionally. It's very effective and unfailing systems have been ever established. The technology of wired is less expensive and can be used for any level of power. Also, this technology has plenty of disadvantages. Using of cables always needs human interference right from plugging and unplugging and at high levels of power, the cables are heavy and costly. One more difficulty is the damaging of cables that can be happened during transmission processes. Cables damaging can be produced by many ways, such as rodent bites, manhandling, tripping etc. The danger of conditions such as rain, snow or humid environment for electrical wired is well-known. Therefore, transfer power wirelessly has been offered which could transfer electrical power to the utilization without using cables or power cords. In some circumstances, the use of batteries has come to be jobless because of the developments in electrical technology. A very common example of wireless technology applied without recognizing, is in the field of AC machines which is consists of a rotor and stator. The energization of stator transferred power from the stator to the rotor across the air-gap.

1.2 CAPACTIVE POWER TRANSFER

The IPT system replaced by a substitution solution which is (CPT) technology. It's used electric fields instead of magnetic fields to transfer power [1]. transfer power by electric fields is more effective because it can pass across barriers of the metal without lose power. Therefore, the CPT technology is appropriate and economically method for the application of EV charging [2]. The metal plates in CPT systems, it's used to procedure capacitors for power transferring [3,4], while the coil of IPT systems, is manufacturing of expensive Litz-wire [5]. Aluminum plate is a very good selection, it has high conductivity, heaviness and low charge, Conversely, in general the current capacitive technique concentrations on transfer low power applications, which the result of coupling in plate is few numerous nF [2, 3]. Compensation topology can be limit the performance of CPT. The series for composition assembly is especially applied, which it connects in series a single inductor with the pads to supply resonance. So as the power of the system be able to amplified to high value, CPT system is to susceptible the variations of value for capacitance [4-6] It can be used an LCLC- For electric vehicle EV charging applications, [7]. the metal plates voltage can be increased to kV level and the power transferred is increase. Consequently, the power of the system has been achieved to 2.4kW with of 90.8% efficiency over a space of 15 cm of air-gap [7]. two couples of plates of aluminum were settled and unattached by 50 cm to decrease the cross-coupling. If there is misalignment, it can't avoid the cross-coupling and the compensation circuit will not be able to work suitably. If the pads are revolved by 90°, the power reached to zero. So, it is very important to improve the coupling construction. In this study, an additional built-in plate construction is presented, in case of the four metal plates are vertically and horizontally arranged.

This construction has aforementioned in [8] and [9]. In this study First, changing the geometry to square, circle for the power pads the coupling capacitance is examine. Second, the equivalent circuit model of the pads is offered and a LCLC compensated circuit is used. This research was arranged in three parts. Part one introduced the built-in pads construction. Part two debate the LCLC topology for the coupler. Part three display the coupler construction and conclude the equivalent circuit.

2. LITERATURE REVIEW AND CHALLENGES

2.1 PREVIOUS WORK

The capacitive technology had been unable to remember, until the year 2008. Since 2008 till date there has been research carried out transfer power using capacitive coupling. Its the technology that developing rapidly and companies such as Murata [30] and C Motive Technologies [31] have found the development of products based on the principle of Capacitive Coupling.

The CPT had the attention of the wireless community as it was a non-radioactive form of power transfer. Although, the technology is moderately new in wireless power transfer, it has found its way into several applications. The first time CPT used to be by Nikola Tesla in the year 1891, where he used the technology to power commonplace loads. The first officially recorded CPT application was a US patent in the year 1966 [32]. The application was for flood systems, to transmit and receive electric signals at a frequency of 100kHz. A second US patent was obtained in the year 1980 where CPT and IPT where used in racing bike for robot joints by transfer signals and power. CPT was used to transfer signals where as the power transfer was done with the help of Inductive coupling. Inter-chip data and power [33] was one such application where one of the previous uses of this system.

CPT had the capability to hand over power as well as data signals between the chips of a PCB board. The CPT system was used as a signal isolator [34] as it had the property of essential galvanic isolation [35] and low collective mode noise. As the system did not consume EMI problems they were investigated on for being used in biomedical applications. Based on this technology, biomedical device and biomedical implantations where researched upon by several universities [36]. The CPT system was used in production portable chargers for customer electronics [30]. A company based off of the University of Wisconsin [31] industrialized a power coupler that substitutes the slip ring of the twisted field synchronous machine, eliminating the need to contact due to the presence of slip rings. The technology was finally made used to charge an electric car [37] [38] wirelessly. The CPT system was made to charge a Cobin sparrow EV, which utilized a 1KW wireless CPT charger.

2.2 CHALLENGES

The benefits of capacitive coupled wireless system make it very smart for usage. However, there are some boundaries to the CPT systems which needs to be talked so it can be use the technique at its full potential.

Theories and Background: The first limitation of the CPT is the technology itself. The capacitive technology so fresh range of study. Therefore, the technology is quiet in its beginning time. There are no existing works accessible on the individualities of the system, power flow, electric field distribution for multiple secondary spontaneous etc.

Value of Coupling Capacitance: The CPT system is very challenging to design compared to the IPT system, due to the low value of the capacitance. To develop the capacitance of the coupling plates, dielectric materials with very high dielectric constant are used. The use of such materials growths the cost of the system and makes the technology too expensive.

Distance and Power: the understanding the evaluation of the CPT and IPT systems [39]. That the IPT systems have much better efficiency compared to the CPT technology. The efficiency for CPT is ranging between 60-80%. The other issues we notice is the usage of the CPT technology for applications less than 1mm. Most of the work offered online use the CPT system when the space between the plates are less than 1mm. The CPT technology is typically utilize in low power applications. The main cause is the very high voltages that are established between capacitor plates.

Operational Frequency: The other problem the system faces is the operation of the system at very high voltages. In [28], we see that the system is converted at 100MHz to decrease the voltage across the capacitor. Similarly, [29], changing the circuit at 27MHz causes the similar issue. Most of the systems are switched in MHz ranges. The frequency operation of the system is required to be high, but with the increase in frequency the parasite will be more predominant in such systems.

Power Flow and Control: the understanding of control systems must be launched for the CPT systems. Controls for misalignment, unexpected load variations, adjustment in the distance between the plates. The controllers that are finest suitable for the topology must be established.

2.3 COMPARISON WITH OTHER STUDIES

- The CPT system uses electric fields while IPT use magnetic field
- The capacitive coupling controls a CPT system while there is inductive coupling in an IPT system.
- CPT utilize the Inductive compensations to launch resonances with the coupler while IPT system used the Capacitive matching networks
- The series-series compensation circuit in an IPT system is similar to the double-sided LC compensation circuit in a CPT system, and they have the same frequency property.
- Negligible eddy-current loss, low cost and weight, and good misalignment performance than IPT system.
- In a CPT system, only several pieces of metal plates are used to build the capacitive coupler while in IPT system the inductive coupler contains two coil that work as loosely coupled transformer, a large amount of Litz-wire is required to build the coils.
- The experimental results show that the CPT system has much better misalignment

  performance than the IPT system.
- The power density of a CPT system is much smaller than that of an IPT system.
- In IPT system, the magnetic fields can be easily shielded by ferrite and aluminum plates and the leakage fields to the surrounding area can be reduced below safety level but in CPT it's difficult to be shielded.

2.4 THESIS SCOPE

The challenges of the CPT system are many. In this thesis, the main purpose is to address the efficiency and distance concerns faced by the wireless capacitive system. The CPT system is mainly functional in low power applications. In this study, it applied CPT system for large air gap application in Electrical vehicle (EV). The efficiency of these systems generally ranges between 60-80%. In the first part, is to improve a power electronic system that has efficiency more than 90% and one which could be applied specially for applications with high power concentrated on Large air-gap. The investigation and topology design is comprehensive. The study of the system with large air-gap systems are shown. The other part of the thesis addresses the distance concern of CPT systems. Generally, they are applied in large air gap applications (above10cm); reason: high voltages advanced across the capacitor. In this part a compensator is designed which could make the CPT system used for large distance and great power applications. The topology has the capability to decrease the voltage across the central transfer capacitors and operated the system at a high operating frequency.

• Chapter 1: Introduction

• Chapter 2: Deals (Detailed literature review)

• Chapter 3: Fundamental wireless capacitive coupled power transfer, Standard of Operation, and advantages of capacitive power transfer systems.

• Chapter 4: A guideline for the design of the capacitor is laid out. The information from this section is extremely important to solve the two problems addressed.

• Chapter 5: Study the effect of Coupling Capacitance The analysis of the converters along with the design and results are given. Factors Affecting on Coupling Capacitance, Coupling Structure The model and Circuit of the Plates geometry changing. Effect of horizontal and vertical plate The proposed topologies are compared with respect to the existing CPT systems.

• Chapter 6: concentrated about the future work and reviews for the main points of the study.

3. WIRELESS CAPACITIVE COUPLED POWER TRANSFER SYSTEMS

3.1 STANDARD OF OPERATION

The general diagram for the wireless power transfer for capacitive power transfer (CPT) just like. Figure 3-1 is representing (CPT).

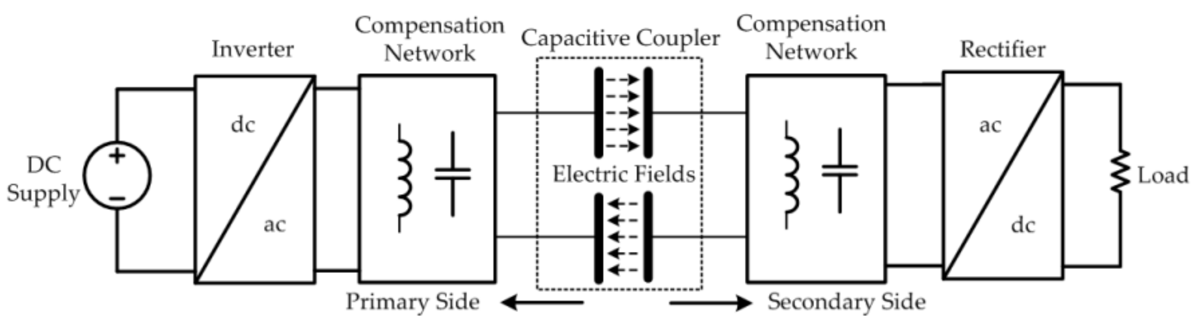

Figure 3.1: Diagram for Capacitive Power Transfer System (Contactless CPT) [30].

CPT scheme has been represented by coupling capacitors. The CPT system horsepower is the electronics, power of the system. An inverter was used to produce AC signals from a DC source after connecting the AC source for interface of Capacitive. Projection establishes by two metal plates of a coupling interface; a suitable dielectric insulator was used to coat the plates. The dielectric coating plates look like a useful coupled, capacitor [29].

The soul of the capacitive system of power transfer is coupling interface. Its produced from a frequency of high inverter. Therefore, when the main plate of the capacitor received electric energy an electric field built up between the two sides of the plate. The current forced by the possible difference to flow inside the antenna of the system allowing power to transfer.

The copper plates ranged in an especial technique used to manufacture the coupling capacitors. Different geometrical shapes can be used to construct the capacitor plates such as square parallel, cylindrical, circular (disk) and matrix. The reluctance of capacitor is much less than AC signal input, therefore, the level of frequency (high) inverter is used for handover the energy, and let’s passage of high frequency signals. In order to resonant the system, we use compensation network and in case of resonance some characteristic is display such as, lowest impedance that made current stream easily and extreme efficiency can be developed. So, almost all CPT technique utilize in resonant in nature.

CPT systems can be classified according to the coupling configurations, as:

1. Unipolar Configuration: Mainly made from two groups of asymmetric dipoles, which contain four plate active and passive electrodes as shown in Figure 3-2. The upper plate is linked to an inverter with very high frequency meanwhile the lower one (passive electrodes) linked to the load. The active electrode linked in series with an inductor to help resonance achieving and the passive electrodes used to complete the current flow cycle in the circuit. The coupling of the two groups of asymmetric dipoles transmitted power by electric field produced by the coupling process [30].

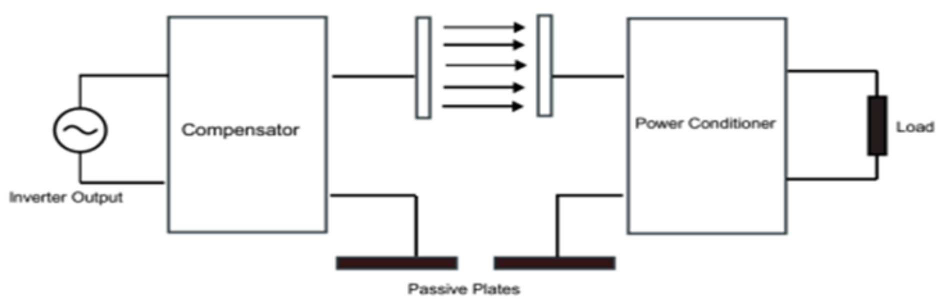

Figure 3.2: Unipolar Configuration [30]

2. Bipolar Configuration: It's the most public structure found in the previous studies. Bipolar Configuration consists of two groups of coupling capacitors made of a transmitter and receiver plates. High frequency inverter energies the transmitter plates with a 180-degree phase variance by a high alternating voltage. The receiver plates are connected to the load. As we see in Figure (3-3) when one primary plate is positively charged, the other primary plate has a negative charge and therefore there occurs phase altering potentials. This causes an alternating electric field and hence power is supplied to the load [30].

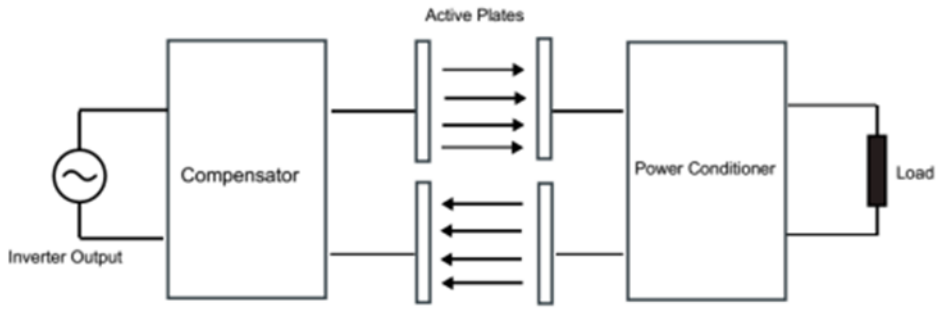

Figure 3.3: Bipolar Configuration [30]

3.2 ADVANTAGES OF CAPACITIVE POWER TRANSFER SYSTEMS

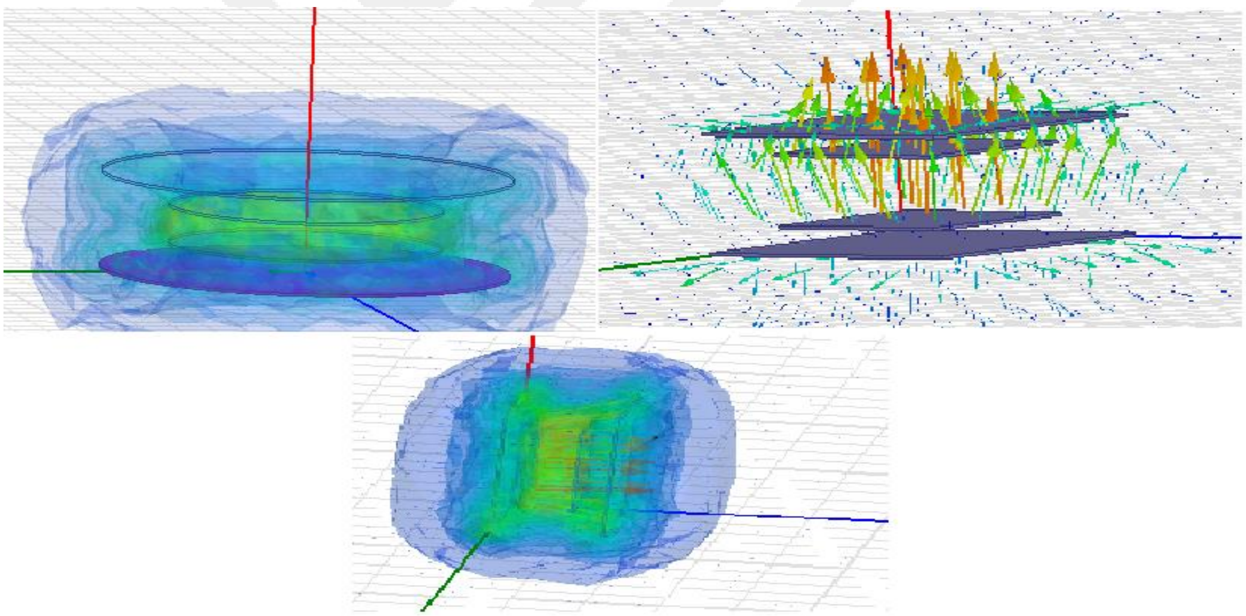

Figure 3.4: EV Enclosed Among the Plates of the Capacitor

Transferred power wirelessly by (CPT) systems was one of the substitutions that was devised in their chase to find an alternative wireless technology. The CPT has unequaled advantages more than conventional inductive systems of power transfer, some of them are scheduled below:

1. Minimum EMI/EMC Issues: Magnetic field is produced that simplifies the transfer power when inductors are used. The magnetic field has a property to form a closed loop from pole to pole and therefore affects all the electronics present in its vicinity. When it derives to capacitive systems, power is transferred with the assistance of electric field as shown in Fig (3.4).

To control the E-V between capacitor plates, it starts from passive plate and ending at active plates So it can control the E-V in capacitor. As the electric field is contained among the capacitor plates and zero voltage switching (ZVS) is employed.

2. Transfer Power Across Metal Barriers: The using of the IPT system in a different situation is not can be put a metal plate in the center between the first and second coil of the PTS, eddy currents are induced plates and finishes the magnetic field the pole to pole conclusion through the metal plates., The system has very low efficiency. And that cannot have allowed the power to transfer between the two metals. While in CPT systems, if we put metal barriers between the plate of CPT they will not effect on the transfer of power actually it will act like another plate of capacitor connect as a series with the system and that no influence on the power transfer. According to the characteristic mention the technique is appropriate for enforcement who contain metal items between the antennae. So, the systems could be applied in charge platforms of mobiles, laptops, especially electric vehicles etc.as shown in fig 3.5[32].

3. Low Standing Power Losses: According to the absence of eddy currents The CPT system can be very efficient. If we compare the CPT and IPT in the effect of eddy current, the transmitter and receiver coil is nothing but a loosely coupled transformer. At all times eddy current losses exist in a transformer. Eddy current losses are essential in transformers. When use IPT system the coils used can get heated due to the current pass through on them. A CPT system the best optimal system as eddy current losses are absent and the system consumes low standing power losses. So for this reason we can use the CPT system for biomedical implantations.

4. Simplicity in Design: The design of CPT system is rather traditional forward, which makes the CPT structure stand out and simply integral with other circuits. The design of IPT the magnets is a whole region by itself. For an IPT system to implement at max efficiency, the design of the components is precisely critical. The IPT design is more complex than the CPT system design.

5. The other advantages of the CPT system: The CPT can instantaneously transfer both data and power. The containment of the field in between the plates, permits the operation of two or more electric link which they have matching frequency. This cannot be possible using IPT as the magnetic field can interfere when operating more than one systems at matching frequency.CPT systems also possess large signal linearity, brilliant public mode refusal and worthy indicator to noise act.

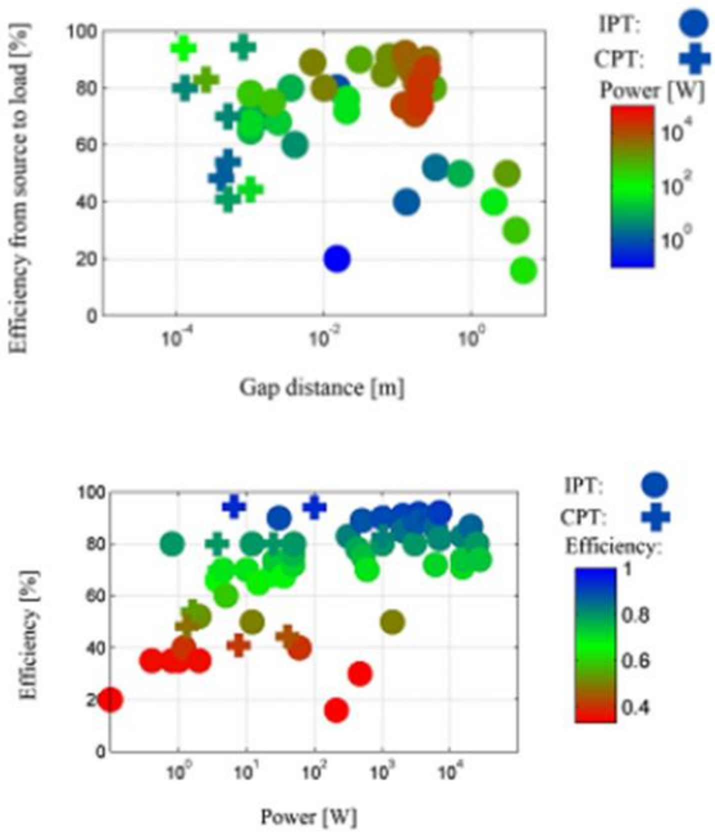

Figure 3.5: Efficiency graphs of the CPT system compared with IPT with respect to power and gap distance [32].

4. CAPACITIVE POWER TRANSFER SYSTEMS

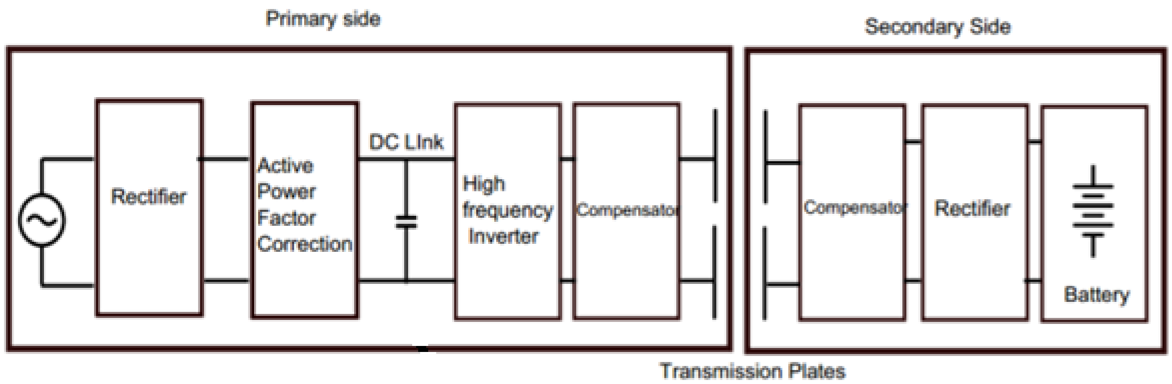

Figure 1.1: Capacitive Power Transfer System

4.1 WORKING OF CPT TECHNOLOGY

The elementary graph of a CPT scheme is displayed in Fig4.1, main purpose for this study is to improve a very high efficient power system for large air gap applications. So, the stage from the rectifier to the load is the area of importance in the CPT system. Figure 4.1[32] showed an elementary schematic of a generalized system. The schematic blocks of the CPT system are specified in the figure above. Power electronics is the driving force or the workhorse that can drive the transfer system of capacitive power. So, it's very clear to recognize and optimize the requirement of power electronics of a CPT system [32].

4.1.1 Power Electronics Requirement

Electronics of power presented a very important part of the WPT structure. It's essential for WPT as established in the Figure 4.1[32]. The contains of the system two sides first (a primary) and second (secondary) side. A comprehensive study on the changed points of the capacitive coupled system is clarified below.

The first point(primary): is of fundamental limitation and main part in essence. take the input to the primary almost about 220V ,16 A socket side. Also we use rectifier to The AC input signal with the connection to the power factor correction (PFC). We put the PFC stage according to the system meets with IEC 61000-3-2 [30] the IEEE standards. The input of the PFC side has been mention before [31] [32]. Then we storage the corrected output from the PFC stage in a huge capacitor that can be forge as constant DC source. Then connect the invertor with high frequency to the DC source. The variation of frequency channel is about the circuit ranges between KHz-MHz ranges. Also have points below some few high frequency converters that are appropriate for capacitive power transfer systems.

1. Half and Full Bridge Inverters: it's generally utilized in CPT systems. Comprehensive investigation of this full bridge and half bridge constructions in [33] [34] [35] [36]. The capacitor in the series resonance construction is adjusted to be suitable for CPT system. Half bridge inverter is favored than the full bridge because of its low cost, less real estate, ease of control, multiple output configurations can be implemented, inherent ZVS and low overall weight. Also, it can be seen that the full bridge voltage is double compare the half bridge and the pressure for voltage on each of the switches is fewer in a full bridge inverter.

2. Push-Pull Converter: It can be used to operates signals from its resonant tank to drive switches gates instead of an external driver. This method for CPT is mentioned in [37] [38]. The system is highly efficient when operated under ZVS conditions. An additional significant feature of the converter is the capability to recognize automatic startup. The demonstrating and study of the push pull converter for CPT is detailed in [37] [38]. The most advantage of this topology doesn't need exterior driver, circuit is necessary and the topology can have high efficiency with a difference of coupling capacitance. The disadvantage of the converter is that it has a huge amount of components and does not offer control of the frequency of operation.

3. Single Active Switch Converter: It's about using a DC-DC resonant converter to achieve power transfer and it refer in [39] [40]. The main indication was to use a single active switch converter to transfer power. Numerous converters like Cuk, SEPIC and ZETA were studied as they have capacitors that can be improved to fit a CPT system. Stated converters that we refer are not appropriate due to the presence of DC bias voltage through the capacitor. When we check the convertor it was observed that a buck boost converter may well be used as it has zero DC bias voltage across the capacitors. For the first time power over 1KW was transferred using electrostatic power transfer [40]. Between inverters the Class E inverters (single active switch) [41] that are commonly used in CPT systems. Secondary Stage: consists of either an uncontrolled full diode bridge rectifier or a controlled rectifier to convert AC to DC. DC is necessary. The output is given to a DC-DC converter which either steps up or steps down the power as per the requirement of the load. We also can use an active rectifier on the secondary side, but then will merely increase the charge of the overall system and hence diode bridge rectifiers are usually used in the secondary side. The Standards for Inverters Used in High Power Applications. How to choose inverter shows a vital role as the system efficiency and power level depends on this feature.

The second point is that for the secondary side which contains of each an uncontrolled full diode bride rectifier or a controlled rectifier to convert AC to DC. It is essential there a DC source connecting to the load. The power that out from the rectifier linked to a DC-DC converter that operate either steps up or steps down the power that deliver to the load. An active rectifier connecting to secondary side just to increase the charge of the overall system.

4.1.2 Need for Compensation

There are two types of equivalent series exist in capacitive interface, equivalent series resistance (ESR) and (ESL) an equivalent series inductance. Frequency is the main factor that the capacitor depending on so it is amplified the capacitor reactance decreases, lets AC indicators influx over element. Maximum power flow (resistive behavior is observed) carried out by ESL and capacitor at a specific frequency. This behavior named the self-resonant frequency of the capacitor, which is usually a small number of kHz -MHz so, the switching frequency of the converter also ranges between kHz-MHz range. In high frequency when the invertor is functional, that lead to switching losses because of higher efficiency of the converter. The on resistance ’RON’ and drain capacitance ’Cd’ are essential factors to be taken into concern [35].

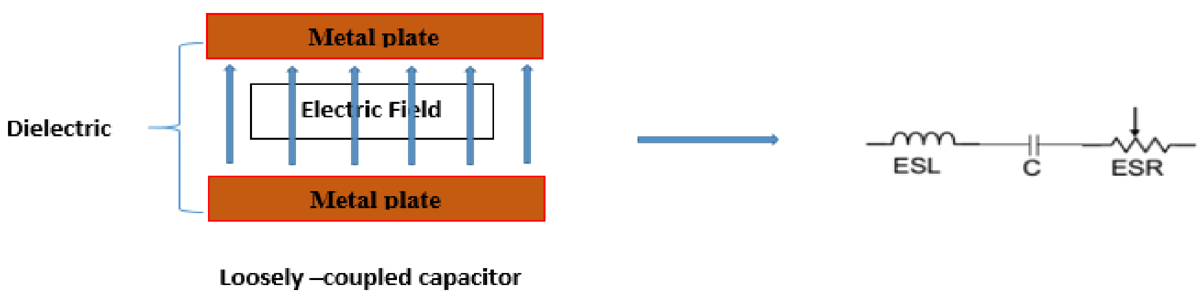

Figure 4.2: Coupling Capacitor

4.2 FIRST HARMONIC ANALYSIS OF RESONANT SYSTEMS

In CPT systems, totally are resonant in nature. The system as a full benefit from on the resonance of power transferring. There is a big different between analysis of resonant converters and the analysis of normal converters. The process extensively used for to investigates resonant converters is called first harmonic approximation (FHA) [43]. At the resonance, the network of resonance performances as a filter removing upper order harmonics and pushing the current to be sinusoidal in behavior which is in-phase the output voltage of the inverter. Then the output connected to the rectifier. As the system has negligible harmonics, the rectifier voltage VR harmonics is neglected and approached to its first harmonic. The CPT system equivalent given in Figure 4.3[43].

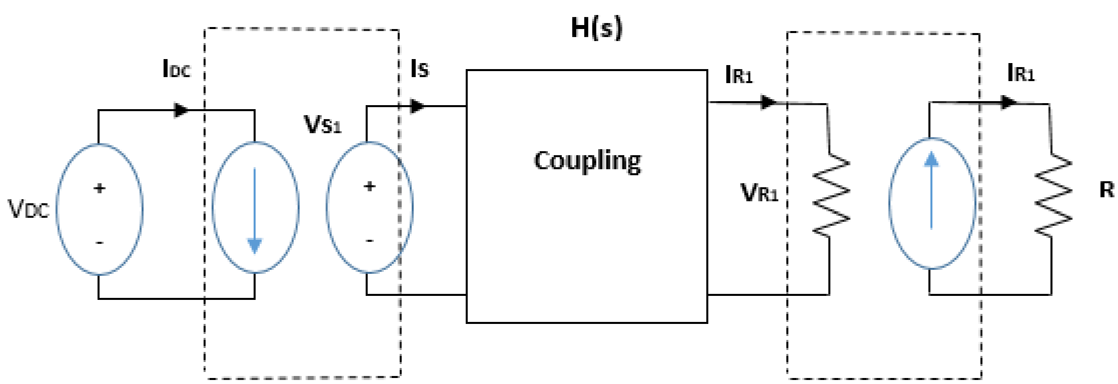

Figure 4.3: Equivalent circuit for FHA

$$VS = \frac{4VDC}{\pi} \tag{4.1}$$

$$Idc = \frac{2}{\pi} IS \tag{4.2}$$

Uncontrolled Rectified and Filter Capacitor

$$VR = \frac{4V0}{\pi} \tag{4.3}$$

$$IR\ load = \frac{2}{\pi} IR \tag{4.4}$$

Equivalent Load:

$$Re = \frac{8}{\pi} R \tag{4.5}$$

$$H(s) = \frac{VR(s)}{VS(s)} \tag{4.6}$$

Therefore, current iR can be obtained using the above equation

$$iR=\frac{VR}{Re}=\frac{Vs.H(s)}{Re} \quad (4.7)$$

$$VCR=\frac{Vo}{Vdc} \quad (4.8)$$

So The efficiency is

$$\eta=\frac{Pout}{Pin} \quad (4.9)$$

Where,

$$Pout=\frac{\pi^2.V^2g}{8R}.(H(s))^2 \quad (4.10)$$

$$Pin= Vdc.Idc= Vdc\frac{2}{\pi}.is \quad (4.11)$$

The resonant frequency is:

$$\omega=\frac{1}{\sqrt{LC}} \quad (4.12)$$

The Q factor:

$$Q=\frac{\omega L}{R} \quad (4.13)$$

4.3 NETWORK OF COMPENSATION

Many numerous network of Compensation which utilize in CPT system. Its divided for two part: small air gap and large air gap circuit.in this thesis we will concentration the large air gap, the capacitance of the capacitive interface (CC) is given as

$$Cc = \frac{Cc1\ Cc2}{Cc1 + Cc2} \tag{4.14}$$

4.3.1 Large Air Gap Applications

It's usually around among 1cm - 30cm in case of CPT systems. When the space is changing, capacitance magnitude change. If the distance increase, capacitance decrease and vice versa. The coupling capacitance of this applications are almost of few Pico farads. Usually use in large space applications composite multi-resonant networks. It's have lesser voltage established over the coupling interface.

4.3.2 Double Sided LCLC Topology

It was clarified by the figure 4.4 The double sided LCLC is about the capacitive interface is located intermediate two LCLC resonators [48]. Using the compact double sided LCLC outline it can save space, still there is a compromise on mutual capacitance of the system. Investigation of the configurations are detailed in [48]. In fig below illustrates double LCLC compensator. One of the benefit of the double LCLC compensator is to decrease the voltage over plates of the system. This is done by connecting the capacitive interface between two resonating circuits. This brings the coupling interface at resonance, but voltage over the plates was minimal resonance of the dual resonators [48].

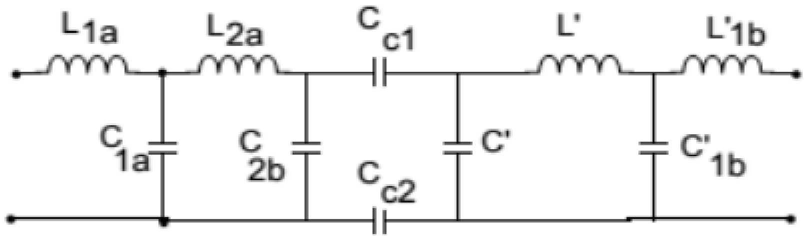

Figure 4.4: Double sided LCLC Compensated Capacitive Power Transfer System [48]

4.3.3 Operation Standard

To explain the working of the double LCLC resonant converter an asymmetrically half bridge (AHB) class D inverter is considered. The output is linked to the resonant tank, who its linked to the capacitive interface of the system. The double LCLC converter be made of two resonant LC circuits on both side of the coupling capacitors. All the components of the system are considered for a specific frequency of operation. The output of the resonant tank is connected to the input side of the rectifier circuit. The rectifier circuit consists of four diodes in a full bridge configuration. The output of the rectifier is supplied to the load which is connected across a filter capacitor. The modes of operation of the double LCLC, CPT is detailed in [48]. The circuit consumes two methods of operation. The circuit is tuned to work under the resonant frequency of the system.

4.3.4 Analysis of the Double LCLC Compensated Topology

The operational of the topology is very conventional onward associated with the behavior of the modified LCLC compensation network. The circuit is tuned to work under the resonant frequency of the system. At resonant the converter operates at ZVS region that confirms soft switching of the system. The equivalent circuit of the dual LC converter in fig (4.6) [45].

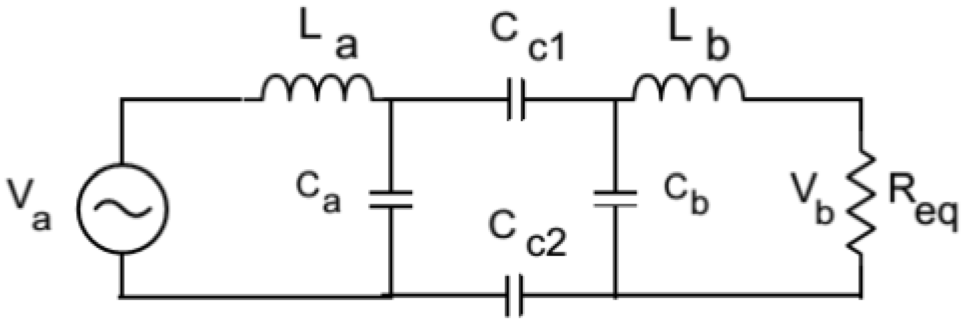

Figure 4.6 Equivalent Model of the double LCLC topology [45]

The vin is the output of the inverter. As below.

$$Va = \frac{4Vdc}{\pi} \tag{4.15}$$

$$Vb = \frac{4V0}{\pi} \tag{4.16}$$

When the voltage that out from the converter is assumed to be constant. The input to the rectifier bridge is +V0 when the current is positive through the inductor. When the current in the inductor is negative, the input to the rectifier bridge is −V0. In other words, we can say that the rectified load is getting reflected to input side of the full bridge rectifier. The equivalent load of the system is given by

$$Req = \frac{8}{\pi^2} R0 \tag{4.17}$$

$$Cr=\frac{Cc1Cc2}{Cc1+Cc2} \tag{4.18}$$

The equation of quality factor is

$$Q=\frac{\omega La}{RL}=\frac{\omega Lb}{RL} \tag{4.19}$$

All modules of double LCLC topology is regulated to a specific frequency. The magnitude of La, Lb, Ca and Cb, should be selected to please the following circumstances which the resonant frequency $\omega 0$ is given by

$$\omega 0=\frac{1}{\sqrt{LaCa}}=\frac{1}{\sqrt{LbCb}} \tag{4.20}$$

$$La=Lb \text{ and } Ca=Cb \tag{4.21}$$

$$Za=j\omega La+\frac{1}{j\omega Ca} \tag{4.22}$$

$$Zb=j\omega Lb+\frac{1}{j\omega Cb} \tag{4.23}$$

The operation of the system can be obtained from the gain characteristics of the system. Voltage Stress Across the components: Consider three currents i1, i2 and i3.

The three loops of the equivalent double LC circuit in figure 4.6. Applying KVL to the circuit, we get the following equations:

Loop 1:

$$Va = j\omega La\, i1 + \frac{1}{j\omega Ca(i1 - i2)} \tag{4.24}$$

Loop 2:

$$\frac{1}{j\omega Ca} \cdot (i2 - i1) + \frac{i2}{j\omega Cr} + \frac{1}{j\omega Cb} \cdot (i3 - i2) \tag{4.25}$$

Loop 3:

$$i3\, Req + j\omega Lbi3 + \frac{1}{j\omega Cb}(i3 - i2) \tag{4.26}$$

The current equations obtained are as follows:

$$i1 = \frac{Va\omega(C^2aLa\omega^2 - jC^2aCrReq + 2CaCrReq\omega - Ca - Cr}{jC^2La^2\omega^4 + j2CaCrLa^2\omega^3 + Ca^2LaReq\omega^3 + 2CaCrLaReq\omega^3 - j2CrLa\omega^2 - j2CrLa\omega^2 - CaReq\omega - CrReq\omega + 1} \tag{4.27}$$

$$i2 = \frac{j(jCaLa\omega^2 + CaReq\omega - j)CrVa\omega}{jC^2La^2\omega^4 + j2CaCrLa^2\omega^3 + Ca^2LaReq\omega^3 + 2CaCrLaReq\omega^3 - j2CrLa\omega^2 - j2CrLa\omega^2 - CaReq\omega - CrReq\omega + 1} \tag{4.28}$$

$$i3 = \frac{CrVa\omega}{jC^2La^2\omega^4 + j2CaCrLa^2\omega^4 + Ca^2LaReq\omega^3 + 2CaCrLaReq\omega^3 - j2CrLa\omega^2 - j2CrLa\omega^2 - CaReq\omega - CrReq\omega + 1} \tag{4.29}$$

Currents through the capacitors can be calculated using the current equations as given below:

$$Ica = i1 - i2 \tag{4.30}$$

$$Icb = i2 - i3 \tag{4.31}$$

$$Icr = i2 \tag{4.32}$$

So The voltage across the capacitors can be determined using the currents obtained:

$$VCa=\frac{i1-i2}{\omega Ca} \ or \ VCa = VCb + \frac{I2}{j\omega Cr} \tag{4.33}$$

$$VCb=\frac{i2-i3}{\omega Cb} \ or \ VCb = V0 + i3j\omega Lb \tag{4.34}$$

$$Vcr=\frac{i2}{\omega Cr} \tag{4.35}$$

$$V0=i3RL \tag{4.36}$$

Output Current:

$$I0=\frac{2I3}{\pi} \tag{4.37}$$

The current equations obtained are as follows: The voltage gain of the system is given:

$$\frac{v0}{vm} = \frac{RL}{ZaZb}\left[-j\omega Cr + \frac{1}{j\omega Cr}\left(-j\omega Cr + \frac{1}{j\omega Ca} + \frac{1}{Za}\right)\left(j\omega Cr + j\omega Cb + \frac{1}{Zb}\right)\right] \tag{4.38}$$

$$\frac{vo}{vm} = \frac{CrRLS}{(CaCbLaLb+CbCrLaLb)s^2+(CaCbLaRL+CaCbLaRL+CbCrLaRL)S^3+(CaLa+CbLb+CrLa+CrLb)S^2+(CbRL+CrRL)S+1} \tag{4.39}$$

4.3.5 Advantages of the Double LCLC Compensation Topology

1. The compensator uses fewer quantity of passive components compared to the LLC and LCL topologies. Which makes the system easy to design in practic.

2. The system has a unity voltage gain. Hence, at resonant and the secondary resonant frequency, the CPT system achieves unity gain. Hence, there are two points at which we can attain unity gain.

3. The proposed CPT system, has two operating frequencies. Operating at the second resonant frequency is lower that the natural resonant frequency of the system.

4. The chief advantage of the converter is the aptitude to transfer power across large air gaps. This is possible as the two resonating capacitors Ca and Cb have extremely high voltages built across them. Hence, the transfer capacitors are at slight resonance, ensuring reduced voltage stress across the transfer capacitors.

5. At resonance, the converter has a constant output. Hence, we can capitalize on this feature to use the system in Electric Vehicles (EV) and Industrial Electric Vehicle Applications (IEV).

6. The chief benefit of the scheme is to operate at the same frequency with modification in the distance among the plates. Such as, the distance among the plates variant, the capacitance changes as well. In other resonant converters the resonant frequency of the system will change. However, in the proposed double LCLC converter, the converter can work irrespective of the change in value of capacitance.

4.4 SUMMARY

This chapter in the thesis, clarifies the process of the CPT system. The elementary structure blocks of the CPT systems are discovered in detail. The power electronics requirement along with the need for compensation are discussed. There are many compensators' that are necessary for large air gap applications. The compensation topologies that are currently present in literature are detailed in the chapter4. Therefore, the inference we obtain from looking at the compensators are as follows:

1.The Large air gap compensator's have contributed the most to the development the CPT technology, permitting the technology to be used for large air gap application. The double sided LCLC topology has their benefits. However, this topology is very hard to implement practically. There are six to eight external components in the circuit which increases the complexity of the circuit. The analysis of these circuits is very tedious as well. As these topologies are multi resonant in nature, designing them become even harder. It is impossible to get two inductors of the same value. Therefore, design becomes hard. As the years go by, the value of inductance changes and then redesigning the circuit is also a problem. Therefore, a need for a simple yet effective compensation topology has risen. The topology must be able to transfer power over large air gaps, have low voltage stress across the plates, have ease of construction and must be highly efficient for low to high power applications.

3. The double sided LCLC compensator behaves as well as compensatory and can be used for large air-gap and high power applications.

5. STUDY ON THE PHYSICAL APPEARANCE AND CONDUCT OF THE COUPLING INTERFACE

5.1 NEED FOR STUDY OF THE CAPACITIVE INTERFACE

The earlier chapters provide a good study to recognize the principle that the how capacitive power transfer system work. All the works that have join with power electronics and compensation. Understanding the behavior of the coupler interface is of prime importance in order to find solutions to its limitations. The Coupler Interface is the greatest important portion for CPT system. System interface consists of plates which establish the passive and active pads, the pads are layered in an appropriate dielectric insulator. The plates establish a loosely coupled capacitor. Later, when power is provided to the primary side of the capacitor an electric field is generated among the two pads. So, the electric field sets up a displacement current between the two plates and hence energy is transferred from transmitter and receiver. This phenomenon is termed as electric field coupling. However, the CPT system has limitations. The building of the capacitive interface is the most pivotal portion of the whole system. The analysis of the coupling building [38] [48]. From Figure 5-1 (data tabulated from previous literature that was available). The systems limitations and drawbacks cannot be realized without the analysis of the coupling capacitors. The coupling building directly effects the output power, maximum power transferred, frequency and efficiency of the system [49].

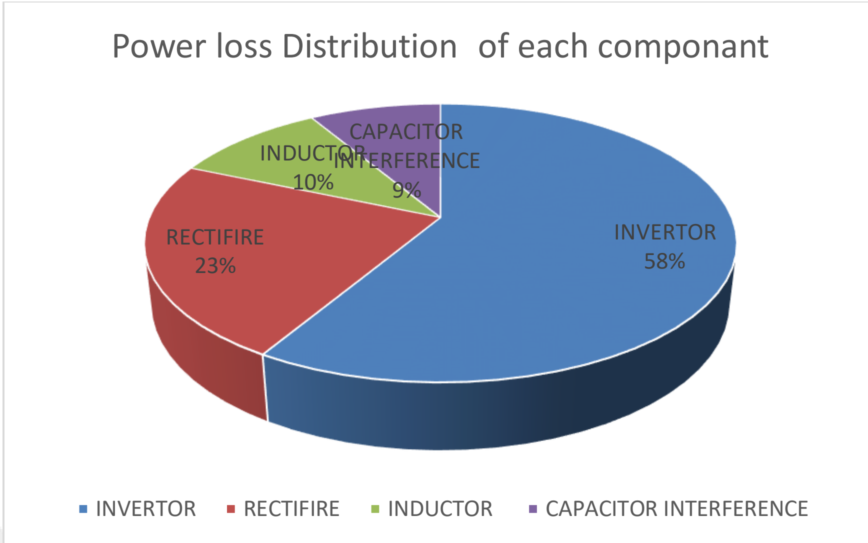

Figure 5.1. Power Loss in a CPT system [39]

The magnitude of the capacitance that is obtained among the coupling plates is very important. The value of the coupling plates depends primarily on the structure of coupling capacitance and the distance between the plates. The structure of the coupling capacitor can be disk, parallel plate, cylindrical, and matrix. To understand the behavior of the system we need to analyses the coupling capacitor. The arrangements of the coupling plates also determine the capacitance that is obtained. A factor called mutual capacitance, which dictates the available capacitance for power transfer. A detailed study on the coupling capacitance is undertaken in this chapter.

5.2 COUPLING CAPACITANCE

They exist two types of capacitive power transfer systems which is known to us from chapter 1. The bipolar configuration is the most popular form of coupling structure. The bipolar configuration consists of two pairs of capacitive plates which ensure complete flexibility and considerate amount of research has been focused on this configuration. However, the unipolar configuration is now gaining popularity and being used in commercial applications. So as to analyses coupling interface for the capacitive, the numerous capacitances shaped throughout perfect alignment and misalignment conditions need to study. However, due to its prime importance of the coupling capacitance, the analyses has been conducted which will aid to understand the effect of factors, the coupling capacitance. The behavior of the CPT system is far more complex than the traditional IPT system. In the situation of CPT systems, the analysis of the coupling structure is extremely complex and during misalignment conditions. The other factors that come into play in such conditions is the stray capacitance that exists between the capacitors and fringing fields that are very evident in the case of parallel plate capacitors However, for the case of simplicity the stray capacitances and fringing fields are ignored. Figure 5-2 [35] is a graphical representation of the CPT interface. The CPT interface consists of four plates A, B, C, D. The possible misalignments of the plates are given as well. The CPT system is said to be perfectly coupled when areas of Plate A = Plate C and Plate B= Plate D, forming capacitors CAC and CBD. When during cross coupling conditions Plate, A = Plate D and Plate B = Plate C forming capacitors CAD and CBC.

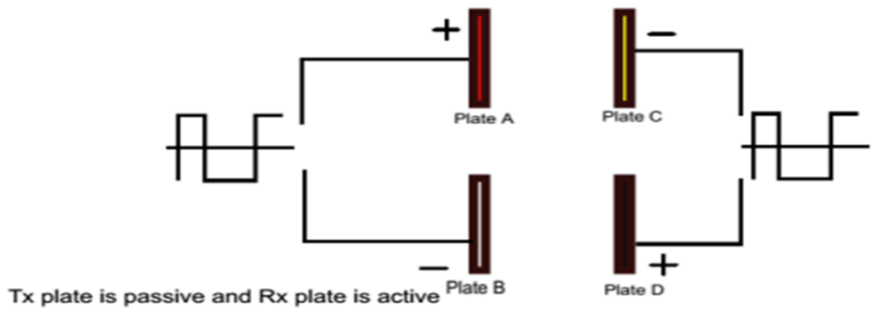

Figure 5.2. Capacitive Interface [35]

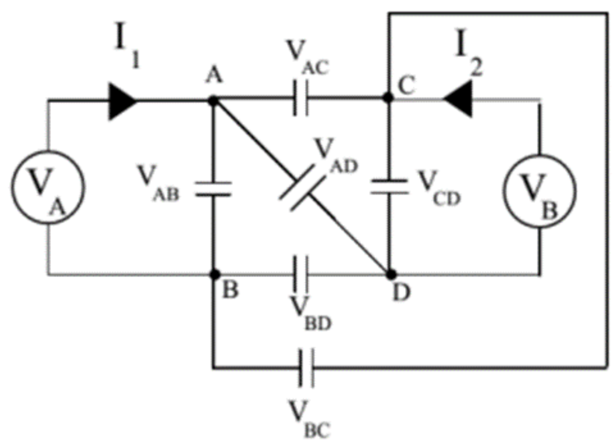

Figure 5.3. Electrical Representation of Misalignment Conditions [50]

The last condition is the self-capacitance that formed when the pads of the primary and the secondary face each other forming capacitors CAB and CCD. The system is modelled as an electric circuit represented in Figure 5-3[50].

The Capacitance of the coupling structure is obtained from [49] [50]. However, [50] gives the best method to calculate the coupling factor which can be utilized to calculate he coupling factor for any configuration of the coupling structure (example: bipolar configuration, unipolar configuration or 4 plate compact coupler). The calculation of the coupling structure plays a very vital role to determine the factors affecting the capacitive coupling structure. Voltages and currents in the capacitor are given as follows:

$$Vc = \frac{I}{\omega C} \tag{5.1}$$

$$I = j\omega Vc \tag{5.2}$$

Applying KCL to nodes A, B, C, D to the electrical circuit represented in Figure 5.3. We get the following equations:

$$Point\ A: \frac{I1}{J\omega} = Cac(VPa - VPd) + CabVPa \tag{5.3}$$

$$Point\ B: \frac{I1}{J\omega} = -CabVPa - CbcVPb - CbdVPd \tag{5.4}$$

$$Point\ C: \frac{I2}{J\omega} = (Cac - CbcCcd)V\,Pc - CcdVPd - CacVPa \tag{5.5}$$

$$Point\ D: \frac{-I2}{J\omega} = (Cad + Cbd + Ccd)VPd - CcdVPc - CadVPa \tag{5.6}$$

Where VPa to VPd, are the voltage that are developed at nodes A, B, C, D in Figure 5.3. From the circuit, consider point b to the reference of the system VPb =0. Therefore, VPa = VA and VPc -VPd = VB. The system is considered as a two port network and solved for the currents I1 and I2.

$$VA = \frac{I1}{J\omega C1} + V2\frac{Cm}{C1} \tag{5.7}$$

$$VB = \frac{I2}{j\omega c2} + V2\frac{Cm}{c2} \tag{5.8}$$

where Cm is the mutual capacitance between the plates. Capacitances C1 and C2 is the self-capacitance that obtained in each pad.

$$Cm = \frac{(Cbd + Cac)(Cad + Cbc)}{(Cbd + Cac + Cad + Cbc)} \quad (5.9)$$

$$C1 = Cab + \frac{(Cac + Cad)(Cbc + Cbd)}{(Cac + Cad + Cbc + Cbd)} \quad (5.10)$$

$$C2 = Ccd + \frac{(Cac + Cbc)(Cad + Cbd)}{(Cac + Cad + Cbc + Cbd)} \quad (5.11)$$

The k factor for of the CPT system is given by

$$\boldsymbol{Kc} = \frac{\boldsymbol{Cm}}{\sqrt{\boldsymbol{C1C2}}} \quad (5.12)$$

The voltage gains of the system.

$$\frac{VB}{VA} = \frac{cm}{c2} = kc\sqrt{\frac{c1}{c2}} \quad (5.13)$$

It can be representing the capacitor in different geometry such as square, circle, disk or matrix in construction. capacitance different from one shape of plates to another. The capacitance of each of the capacitor is calculated individually depending of the structure and then plugged into equation 5.14 which is the equivalent capacitance of the system. The equivalent capacitance of the system is required as it plays an energetic part in the calculation for compensator used and determining the resonant frequency of the system.

5.3.1 Coupling Structure

The coupling interface constitutes a pair of coupling structures which can be of any geometry. When the coupling structures are close enough to each other, an electric field is generated between them, which in-turn creates a displacement current which aids in the transfer of power. The primary side of the CPT system is usually fixed and the secondary side of the converter is movable. The capacitance of the coupling structure varies with the type of geometry that is chosen.

The capacitance that represented the coupler can be given as:

$$C = \frac{\varepsilon o \varepsilon r A}{d} \tag{5.14}$$

$$Cc = \frac{(Cc1Cc2)}{(Cc1+Cc2)} \tag{5.15}$$

1. Parallel Plate Structure: is the most common structure that is present in the CPT systems [46]. The capacitance of a parallel plate structure is given by equation 5.14. This equation holds good only when the capacitor is a pure parallel plate and the distance d between the plates is filled with a dielectric whose relative permittivity is given by εr. The equation can be used to calculate the capacitance of the structure only under such a circumstance. Figure 5-4(a) and 5-4(b) show the two types of parallel plate capacitance. The capacitor formed in 5-4 (b) is the most public form of a parallel plate capacitor that will be created for CPT system and therefore the capacitance of the coupling interface must be recalculated.

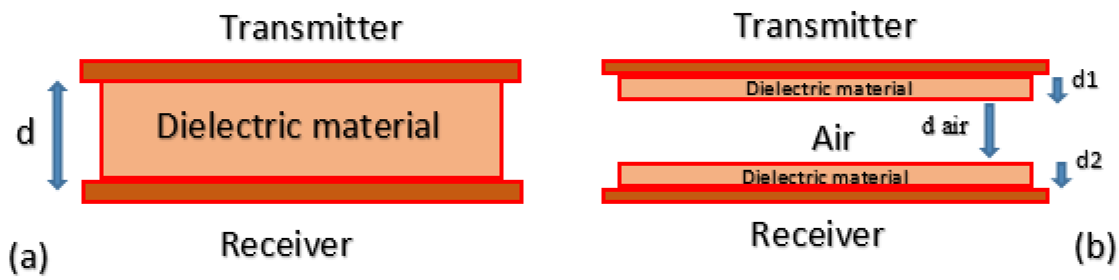

Figure 5.4: Parallel Plate Structure

From Gauss' law:

$$V=E1d1+E0dair+E2d2 \quad (5.16)$$

$$V=\frac{Qd1/A}{\varepsilon o\varepsilon r}+\frac{Qdair/A}{\varepsilon o}+\frac{Qd2/A}{\varepsilon o\varepsilon r} \quad (5.17)$$

$$C=\frac{Q}{V} \quad (5.18)$$

$$C=\frac{\varepsilon oA}{\left(\frac{d1+d2}{\varepsilon r}\right)+d\ air} \quad (5.19)$$

From equation 5.19, we observe that the capacitance depends on the value of dielectric constant just in case the depth of the dielectric coating is greater than that of air. When the air gap increase, we observe that the capacitance of the structure becomes independent of the value of dielectric constant. The inference obtained is that, the dielectric plays a vital role to improve the capacitance of the coupling structure as long as the thickness of dielectric coating is larger than the air gap. Once the air-gap becomes larger than the coating thickness, the dielectric constant has minimal effect on the value of capacitance.As the depth of the air-gap is larger comparing with the thickness of the dielectric in most cases. We assume that air is dielectric between the plates and this assumption is considered in the rest of our analysis.

2. Nonparallel Plate Structure: are the structures that are formed when one of the plates of the system are either inclined or deformed (Figure 5-5 and Figure 5-6). One plate can be deformed in many ways and makes computation very hard. Therefore, we consider two cases which are very valuable for our study.

Case 1: inclined Plate: when the secondary plate is inclined to a certain angle with respect to the primary making them no longer a parallel plate capacitor.

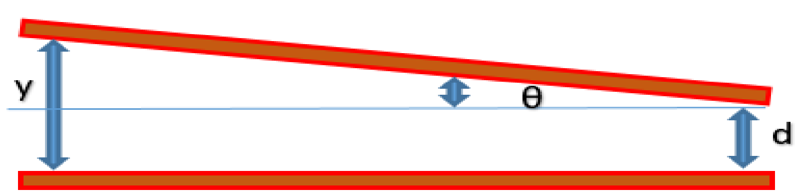

Figure 5.5: Inclined Plate Structure

$$C=\frac{\omega\varepsilon o.\varepsilon r.[ln(l.tan\,\theta+d)-ln\,d]}{tan\,\theta} \quad (5.20)$$

Case 2: Deformed Plates: is visible when one of the plates of the capacitive interface is placed in a car bumper. The flexibility of the plate determines the structure formed. If the plate is flexible, then the plate forms convex structures Figure 5-6 and if it is rigid, the plate forms a rigid body structure which can be observed in Figure 5-7. Calculating the value of capacitance of such systems are difficult as the capacitance at every point varies. The capacitance at the center is maximum and decreases as we move away from the center. In such cases, the capacitance of such structures is given by:

$$C=\frac{(2\ \varepsilon 0 \varepsilon r\ b)}{\sqrt{L1L2}}\ arc\ tan\sqrt{\frac{L1}{L2}} \tag{5.21}$$

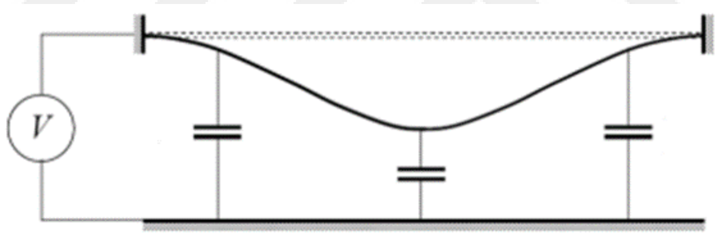

Figure 5.6: Deformed Structure [51]

Where b is the width and l is the length of the plate. The other kind of deformation that occurs is that of a rigid body which is given in Figure 5-7.

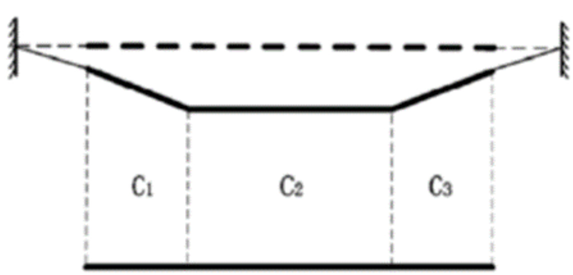

Figure 5.7: Deformed Rigid Structure [52]

The capacitance of such structures is given by:

$$C = \varepsilon 0 \boldsymbol{l}.\boldsymbol{b}(\mathbf{1}-\boldsymbol{\lambda})/\boldsymbol{d} + \frac{2\varepsilon 0.\boldsymbol{b}}{\sin\theta}\ln\left(\mathbf{1}+\frac{\lambda.l.\tan\theta}{d}\right) \tag{5.22}$$

3. Square and Circle Plate Structure:

Fig. 5.8 show the plates construction and sizes. Both of the three-D and forward-facing sight is offered. The *XYZ* axis are shown. The pads were designed to be symmetric from the primary to the secondary side. P_3 and P_4 are embedded in the ground as the power transmitter. P_1 and P_2 are installed on the vehicle as the power receiver. In Fig. 5.8 P_1 and P_4 are different than P_2 and P_3. Therefore, the coupling between P_1 and P_4 cannot be eliminated by P_2 and P_3. The plate shape does not affect coupling, so all the plates are designed to be square and circle to simplify the analysis. In the practical application, the plates can be designed into any shape to fit the installation on the vehicle by taking into account the only principle of maintaining plates area to transfer sufficient power. The length of P_1 and P_4 is l_1, the length of P_2 and P_3 is l_2, the distance of P_1-P_2 and P_3-P_4 is d, and the distance of P_2-P_3 is Ds, which is the air gap between the primary and secondary side.

The thickness of all the plates u. Coupling structures that are not very commonly use.

The circular coupling structure, Figure 5.8 has a maximum value of coupling capacitance compared to other coupling structures,

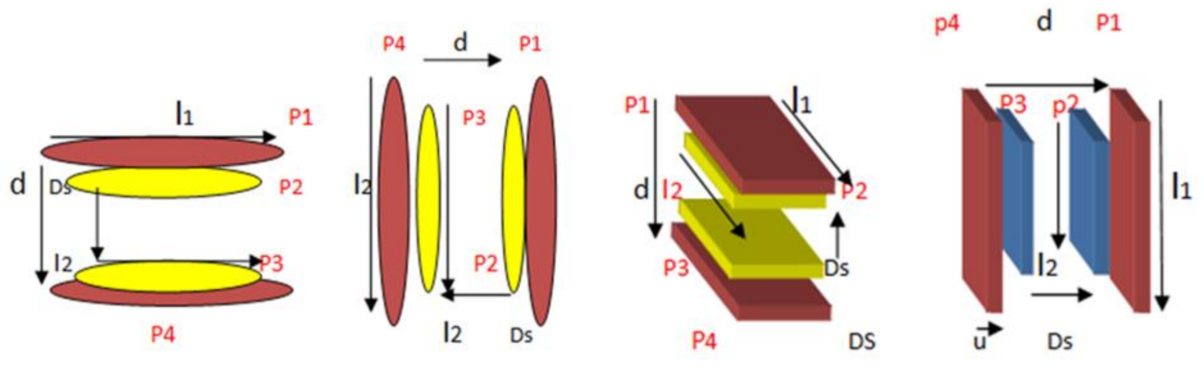

Figure 5.8: Vertical and Horizontal Power Pads

5.3.2. The Model and Circuit for Pads

In usual coupling capacitance is existing between each two pair, as shown in Fig. 5.8. distance d is much larger comparing with the pads distance *Ds* in electric vehicle charging applications, so *C14* and *C23* are much smaller than *C12* and *C34*. The cross-couplings of *C14* and *C24* were generated by the rim effect of *P1–P3* and *P2– P4*, so they are commonly smaller than *C12* and *C34*. However, they cannot be neglected in a precise circuit model as in fig (5.9). The resulted vertical four-plate circuit model is shown in Fig. 5.10 The plates equivalent input capacitances from the primary and secondary side are defined as *C,pri* and *C,sec* , respectively, which are fundamentally specified by *C12* and *C34*. Since *C12* and *C34* are mainly determined by the distance *Ds*, and they did not relate to the misalignment between the two plate side, so the resonance of this coupler is not sensitive to the misalignment.

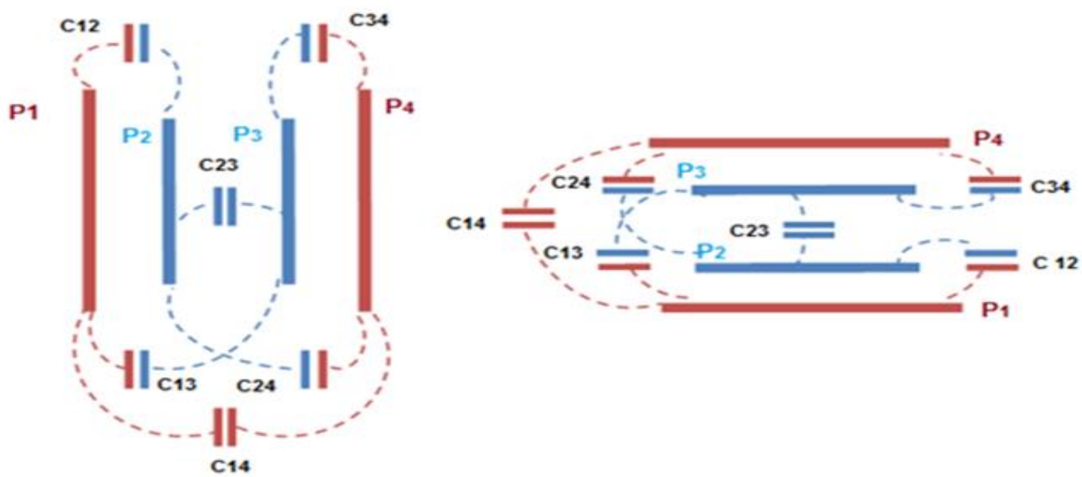

Figure 5.9: Coupling Capacitors in the Plates

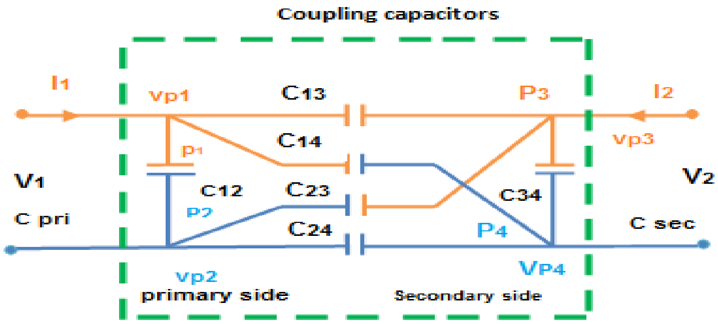

Figure 5.10: Circuit model of the coupling capacitors.

In Fig. 5.10, two independent voltage sources V_1 and V_2 are used on the plates to derive a relationship between the input and output. All the capacitors correspond to the couplings in Figure above. The voltage on each plate is defined as V_{p1}, V_{p2}, V_{p3}, and V_{p4}, respectively. Plate P_2 was selected as the reference, so $V_{p2} = 0$, $V_1 = V_{p1}$, and $V_2 = V_{p3}–V_{p4}$. As we got in (32) that we could find the capacitances C_1 , C_2 , and C_M can be defined as:

$$C1 = C12 +(C13 + C14) \cdot (C23 + C24)\ C13 + C14 + C23 + C24 \tag{5.23}$$

$$C2 = C34 +(C13 + C23) \cdot (C14 + C24)\ C13 + C14 + C23 + C24 \tag{5.24}$$

$$CM = C24C13 - C14C23C13 + C14 + C23 + C24 \tag{5.25}$$

Formulas (5.23), (5.24) and (5.25) represent the mutual inductance between each pair of the power pads (2) voltage and current relation can be defined in (5.26) and (5.27).

$$I1 = j\omega C1 \cdot V1 - j\omega CM \cdot V2 \tag{5.26}$$

$$I2 = j\omega C2 \cdot V2 - j\omega CM \cdot V1 \tag{5.27}$$

similar to that of the IPT, the capacitive coupling coefficient kc of the pads is known as with the parameters from (5.23), (5.24) and (5.25) as follows:

$$KC= \frac{CM}{\sqrt{(C1.C2)}} \tag{5.28}$$

$$KC=\frac{\sqrt{C23\ C14-C13C24}\sqrt{C23\ C14-C13C24}}{\sqrt{C12(C14+C13+C24+C23)+(C14+C13)(C24+C23}\sqrt{C34(C14+C13+C24+C23)+(C14+C13)(C13+C23)}} \tag{5.29}$$

Where Kc is the coupling coefficient and CM is the total mutual capacitance between the pads. For the straight structure in fig (5.8), the pads at the identical side were located 150 mm away, consequently, the coupling capacitance *C*12 and *C*34 are both close to zero. Cross-coupling capacitances *C*13 and *C*24 are also close to zero. As a result, the capacitive coupling coefficient *kc=1*. For the structure shown in Fig. (5.8) the plate distance *Ds* is much smaller than the distance of the air gap *Ds* so *C*12 and *C*34 are much larger than *C*14 and *C*23. As a result, the capacitive coupling coefficient *kc* = 1, which means it is an ineffective coupled CPT system.

5.3.3 Effect of Horizontal and Vertical Plate

The following forms related to the system of changing the geometric shapes of the power transmission system through the capacitive, the shape and direction of the plate is very effective, in horizontal or vertical, affect the transmission of energy clearly through several factors, including the surface area of the same shape, whether square or circular, horizontal or vertical. We Note the Table No 5.1 with the square shape and the horizontal direction shall have the capacity of C1 for the first panel less than the capacity of square C1 and also mutual capacitance is different, with the vertical direction of the first plate as well as for the he coupling coefficient in the horizontal direction plate is different from the horizontal to vertical. The best form of transmission of power in the system of capacitance is the horizontal circular shape because of the factors that are close to (1) and as soon as the coupling coefficient is near to this that mean transfer maximum power.

5.3.4 Capacitive Coupler Design

An effective coupled CPT system is implemented in this part to simplify the process. The capacitive coupler is designed to be nonsymmetrical, and the sizes are calculated as $l_1 = l_1$ =300 mm, $l_2 = l_2$ = 200 mm, d = 150 mm, and u = 2 mm. Maxwell ANYSES used to simulate the hole system shown in fig (5.11) coupling capacitances between the pads. As shown in table 1, the equivalent capacitances in Fig. 5 are calculated as table 1 according to the type of power pads and the geometry that we use. Table 5.1 represents the mutual capacitance between each pair of plates and the coefficient of the coupling of each plate to the power pads that used and its appear as it's known that when the coupling coefficient close to 1 the power pads transfer sufficient power and in this simulation the maximum power transferred by circulating one.

Table 5.1: Mutual capacitance between each pair of plates

Power pads	C1 (pf)	C2 (pf)	CM (pf)	Kc
Square horizontal	9.9	9.9	4.3	0.434
Square vertical	11.9	11.9	5.5	0.46
Circle horizontal	6.6	6.6	5.3	0.803
Circle vertical	7.9	7.9	6.3	0.7974

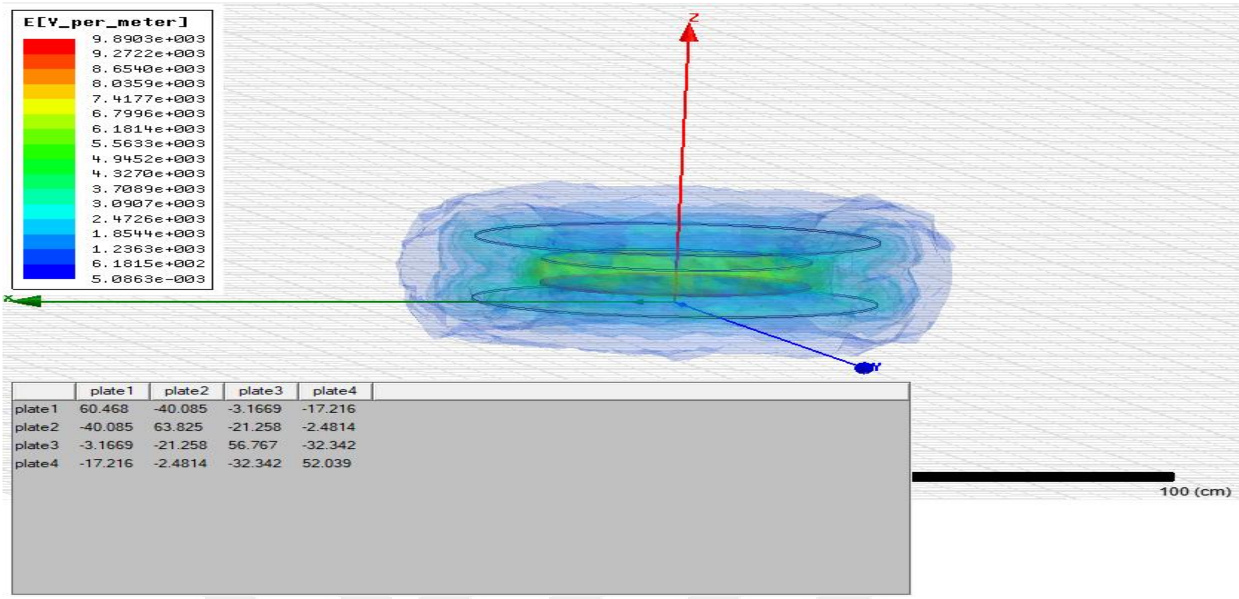

Figure 5.11: (a)ANSYS Simulation for Circle Pads

Fig (5.11) shows the simulation of power pads of vertical circle and if it compares with the other simulation of power pads for the square (horizontal and vertical) refers in (10) its look that the circle power pads is more efficient to transfer power than the other power pads and if we see the E-V field shows us the energy that transfer in the medium it seems much larger than the other E-V for the other power pads.

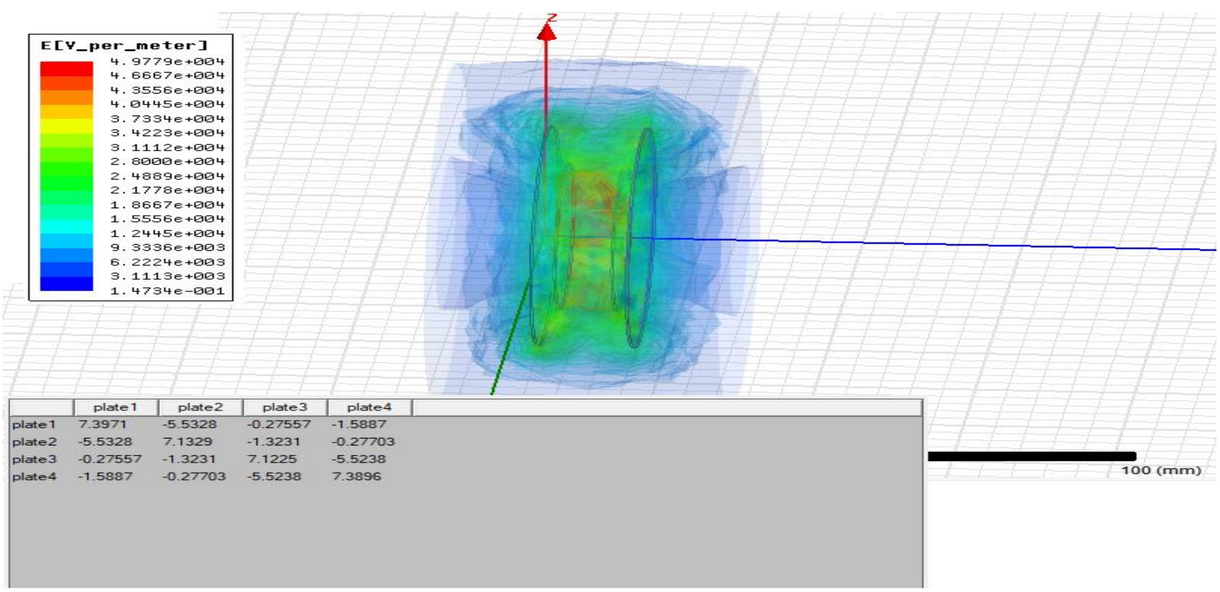

Figure 5.11: (b) ANSYS Simulation for circle Pads

5.3.5 Coupling Interface

There are three types of coupling configurations when it comes to the capacitive power transfer systems. They are:

1. **Row Arrangement:** This is commonly utilized in the construction of capacitive power transfer systems as seen in Figure (5.12) (a). The disadvantage with this structure is that the setup requires a lot of real estate.

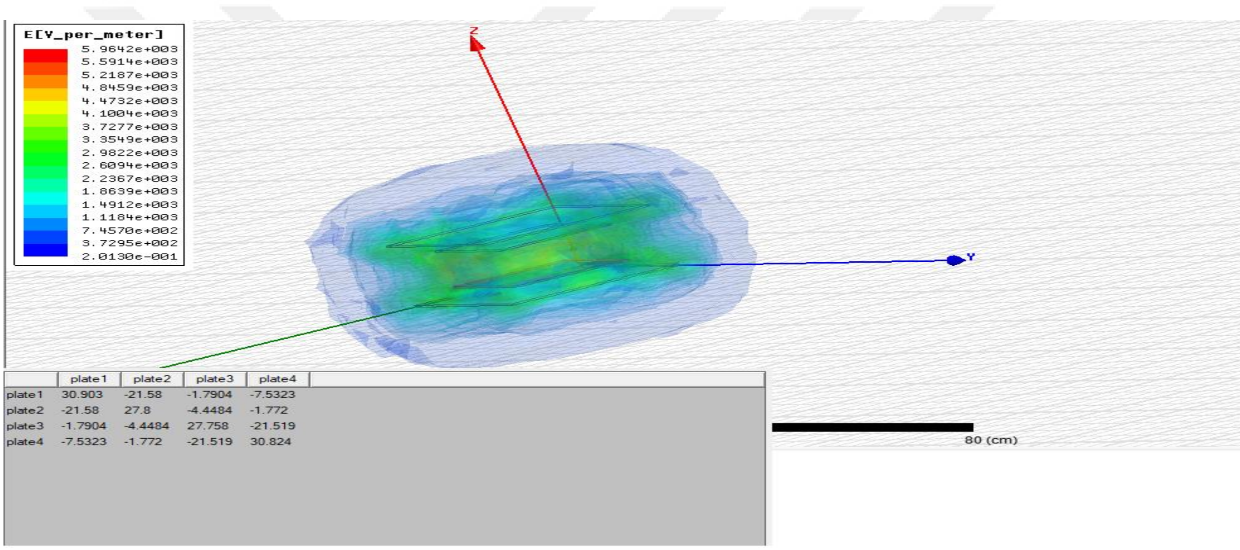

Figure 5.12: (a) Simulation ANSYS for square Power Pads

2. **Column Arrangement:** is recently begun researching upon as a replacement for row arrangements [50] (Figure 5.12 (b)) as they require less real estate. However, the drawback with this arrangement is that the mutual capacitance achieved by this structure is very low.

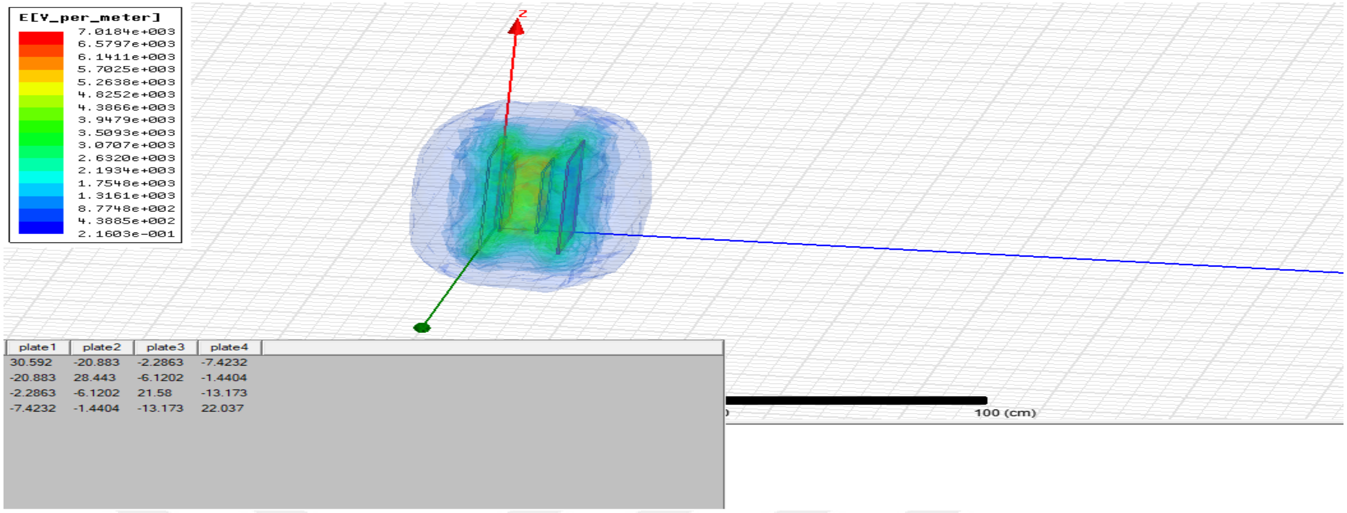

Figure 5.12: (b) Simulation ANSYS for square Power Pads

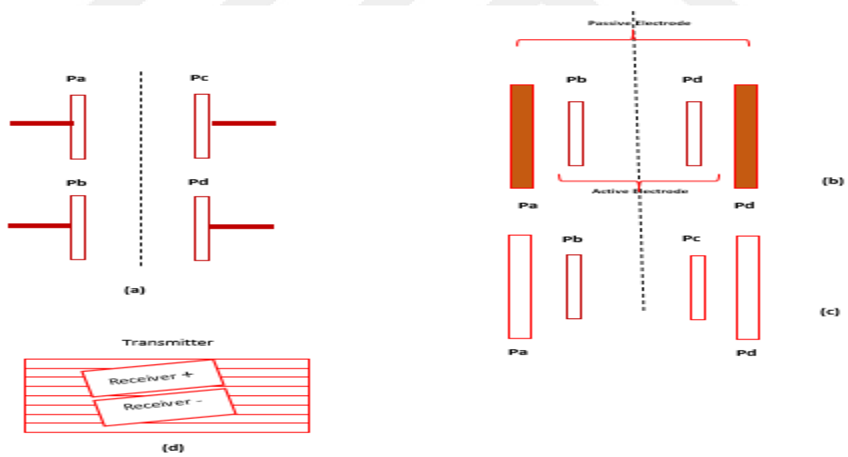

Figure 5.13: Coupling Arrangements

3. Matrix Arrangement: was proposed by [53] [54], the main advantage of this method is to avoid misalignment also to maintain appropriate the coupling capacitance irrespective of the misalignment for the location and arrangement of the secondary plates. The matrix coupling constructions (figure 5-13.c) is presents that inhibits the capacitance to drop to zero. Mutual capacitance and the voltage gain of the two arrangements are gotten from the results of the finite elemental analysis ANYSES MAXWELL are in the table below.

Table 5.2: Capacitances found for horizontal and vertical (15cm air gap) configuration for circle and square power pads.

Power pads	C11 (pf)	C22 (pf)	C33(pf)	C44(pf)	C12=C21	C13=C31	C14=C41
Square horizontal	30.503	27.8	27.750	30.820	21.50	1.794	7.4722
Square vertical	30.590	28.443	21.58	22.037	20.883	2.2963	7.4243
Circle horizontal	60.468	63.825	56.767	52.039	40.085	3.1669	17.216
Circle vertical	7.3971	7.1329	7.1225	7.3896	5.5328	0.27557	1.5887

5.3.6 Voltage Developed Across the Coupling Interface

CPT system can be effect and bound to be functional to extended air-gap applications is the voltage through the capacitor given by equation (5.28).

$$VC=\frac{I}{\omega Cc} \qquad (5.28)$$

By means of the increasing of space lead to decrease the coupling interface. So, voltage increasing through the pads. Its mention that as features that limited the system from utilize in large –gap application.

5.3.7 Frequency of operation

CPT system take advantage of the resonance to transfer power from point to point. The operational frequency is resolute by the magnitude of coupling capacitance. Equation (5.30) below it observes that the voltage conventional over the capacitor that operational frequency that the capacitance depends on, the capacitance will be in few Nano-farads, the CPT system able to operate in a small number of kHz range. If the value of capacitance will be in Pico-farads, the system is activated in the MHz range to decrease the voltage tension through the pads. Consequently, the procedure varieties of the CPT system collections from few hundreds kHz's to few MHz's. Beforehand the CPT system has been functioned in 100's of MHz to decrease the voltage across its interface. Yet, with the growth of frequency many indiscretions are presented in the system. The system has the propensity to suffer from EMI issues [55].

$$S=\frac{\left(Vc^{2}.\omega.A.\varepsilon\mathbf{0}.\varepsilon\boldsymbol{r}.(\boldsymbol{j}+\boldsymbol{DF})\right)}{d} \quad (5.29)$$

$$DF=\omega R\ SERIES\ Cc+\frac{1}{\omega.R\ dielectric.Cc} \quad (5.30)$$

$$ESR=DF/\omega Cc \quad (5.31)$$

$$Zcap=j\left(\frac{-1}{\omega Cc}+\omega L\ parasitic\right) \quad (5.32)$$

5.3.8 Atmospheric Conditions

In cases that CPT system is primarily designed for large air gap applications such as EV chargers etc., the atmospheric properties have to be considered. As greatest of the weather circumstances mainly establish of temperature, dampness in the atmosphere (humidity), water (rain) and ice (snow) are the three properties undertook in this particular study. With the variation in temperature the permittivity and loss tangent of the material changes. The humidity in the air constantly changes with respect to temperature, resulting in the change in the capacitance. The same goes with respect to the study related to water and ice.

5.4 COUPLING DESIGN CONSIDERATIONS

Interface Based on understanding that was obtained from factors that affect the CPT and the characteristic of the CPT systems, the design is undertaken. In general wireless systems are generally applied for small air gap applications. Newly, CPT systems developed to use in large gap application [48] [50]. It can get a large magnitude of capacitance if the design was perfectly for coupling interface than small air gap application. In the circumstance of large air gap applications, the dielectrics that are a selection of must be able to hold out the high voltages industrialized crossways the interface deprived of breakdown and essential to be able to have low losses at high frequencies. The choice of the dielectric shows a very energetic role in the structure of the capacitive interface. Almost, most of the dielectric cast-off are in solid state, but air and liquid dielectric are also used in convinced capacitors. Vacuum is an extremely active dielectric. If a dielectric is located in amongst two parallel pads, they make smaller the space between the places letting for small plate separation and therefore we get greater capacitance. The following point are the design contributions for the construction of the capacitive interface.

1. Capacitance magnitude: The capacitance is straightly relational to the value of the proportional permeability of the dielectric. Insulators have dissimilar permittivity and are used in capacitors to get the capacitance for numerous applications.

$$Pe = \frac{Z^2 e^2}{\omega^2 ZMe} \cdot \varepsilon \tag{5.33}$$

2. Frequency: The frequency of dielectric is must be considered on the plan and the design that oscillates and the frequency plays a crucial role in the selection of dielectric [55].

3. Capacitance per unit volume: Its explained in equation (5.34)

4. Operational Voltage: According to preceding equation the space between the pads reduction, capacitance per unit volume increases. This lead that voltage to decrease.

$$Cvol = \frac{C}{Ad} = \frac{\varepsilon 0 \varepsilon r A}{d 2 A} = \frac{\varepsilon 0 \varepsilon r}{d^2} \tag{5.34}$$

$$Vmax = \varepsilon br \cdot d \tag{5.35}$$

$$\eta = \frac{Vmax}{Vapplied} = \frac{\varepsilon^2 brd}{Vapplied} \tag{5.36}$$

$$\omega vol = \frac{\varepsilon^2 br \cdot \omega \cdot \varepsilon 0 \cdot \varepsilon r \cdot \tan\delta}{\eta^2} \tag{5.37}$$

5.5 SUMMARY

The chapter offers a dissimilar geometry shapes of power pads and compare between them to get the more effective one that can transfer highest power, Square and rectangular coupling plates design to transfers up to 146 W at an efficiency of 84%, while circular coupling plates having the same 150-cm2 area (13.8-cm diameter), also in same environment its design to transfers up to 1125 W at an efficiency of 92%. The circular plate is more effective in transfer power than the rectangular and square because of the surface area that effected on capacitance and the coupling coefficient is higher than any different geometry. Pads consist of four plates (circle &rectangular) compact coupler structure for CPT and the corresponding LCLC compensation topology. the capacitive coupler is designed to be no symmetrical, and the sizes are resolute as $l_1 = l_1$ =300 mm, $l_2 = l_2$ = 200 mm, d = 150 mm, and u = 2 mm. Finite element analysis by Maxwell The equivalent circuit model of the coupler is presented,

6. CONCLUSION

The study concentrations on new wireless power transfer system termed as capacitive power transfer systems. The system was primarily used only for low power applications.

Chapter 1 details the introduction of the system and gives us a summarized overview of the principle of operation. Moving forward, the various compensation topologies are detailed out. The pros and cons of the topology have been looked into. Most of the traditional topologies have numerous disadvantages and therefore cannot be used for various high power and long distance applications. We also notice that the efficiency of these converters usually ranges between 70% - 81%. To design a highly efficient system the behavior of the coupling capacitors has to be looked into. **Ansys Maxwell** software was used to compute the value of capacitance's and calculate the values of coupling coefficient. We, observe that the bipolar configuration has the best coupling coefficient with respect to the unipolar and the compact power transfer topology. Modified LCLC resonant topology exhibited exceptional results compared to the other existing topologies. The converter has the ability to ensure ZVS on the entire system, making the system efficient and power dense. The modified LCLC topology has the best performance with respect to the present converters for large air gap applications. Apart from the efficiency point of view the converter has good acceptance regarding change in distance and change in frequency. Transfer of power cross large air gap is very important. The topology has very low voltage stress across the capacitors for far distance applications. The system operates on the principle of placing the capacitive interface between two resonant circuits. Thereby we can achieve power transfer for large air gap with low voltage stress developed over the plates of the capacitor. Topology can be applied to large air gap applications. The analysis of the complete system has been completed. Based on the Double LC topology, two control strategies are implemented for the system which ensures the use of the converter for IEV charging systems. The variable duty cycle and phase shifted control exhibit exceptional control. The numerous advantages of the CPT system make the wireless system as an unparalleled contender in the field of wireless power transfer.

A comprehensive review on the existing capacitive has been document that would be extremely useful for the individuals that are looking to working the area of capacitive power transfer.

The characteristics and behavior of the coupling interface have been reported with respect to various parameters such as frequency, environment etc.

The problem with the CPT system was the distance of power transfer. In this case, a Double LCLC compensator has been proposed. The compensator utilized in applications ranging from low to high power. The proposed topology has benefit it has less passive components compared to the other multi resonant compensator's that are available. Voltage stress across capacitive plates is minimized. The topology performs regarding change in distance, however, the system cannot be used as variable frequency at high loading condition due to its voltage gain characteristic. Both the converters can work under 500KHz. Usually in CPT systems, the CPT system is designed to work in few MHz range due to the development of high voltages.

The last chapter deals with many geometry shapes of pads also compare between them to get the more effective one that can transfer maximum power and its consist of four plates (circle &square) compact coupler structure for capacitive power transfer and the corresponding LCLC compensation circuit topology. Finite element analysis by Maxwell FEA simulation results help design the parameters of the pads.

In the future there are some things to consider and that will help them develop the CPT systems.

1. As the region of the WPT is relatively new, the system is in its infancy stage. It would be beneficial if any behavioral changes in the CPT system can be reported. There are plenty of applications use the CPT system as an interface. Focus on the behavior and analysis rather than the application is of prime importance.

2. Simulation of the entire system with the help of finite elemental software's. There are not many good software's available for the simulation of electrostatic systems.

3. The CPT system can be control by Primary and secondary side. It's possible of controlling the switching of the inverter based on the voltages of currents in CPT primary side system. Similarly, secondary side control by using active switches instead of diodes which would give us total control.

Hence, the communication protocol can be eliminated. The use of predictive model of the system would be an area of interest.

4. Implementation of other topologies that could decrease voltage across capacitors to a lower voltage than that was achieved. As the area is new, there is no regulations have to make to realize safety of operation.

5. It can use another material and other shapes to avoid the misalignment and to improve the transfer of power. Also deals with control of the double LC CPT system. An example of an IEV has been considered to develop a wireless CPT charger. As the IEVs have battery packs ranging between 48V to 72V DC, also controller required to get voltage in the required range.

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