

# Model Based Design of Wireless Charging System For Electric Vehicle

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**Abstract:** The advancement of contactless battery charging presents a promising opportunity for electric vehicles. In contrast to conventional plug-in cables, this technology offers simplicity, durability, and weather resistance. Power transfer is achieved through magnetic coupling between inductive coils and a streamlined magnetic circuit, enhancing convenience and reliability. The aim of this project is to create an efficient and reliable wireless charging solution for Electric Vehicles and to establish a standard that enables the compatibility of Non-conductive charging in an inductive coupled system. To achieve this, an advanced and robust modelling approach of Wireless Power Transfer (WPT) is proposed. Using finite element methods, the electrical characteristics of the inductive system are computed. These computed values aid in designing the resonant converter. Different compensation topologies are considered, and a circuit model of the entire system is developed to accurately assess currents and voltages. Extensive simulation was designed and analyses are conducted to evaluate the system's performance Throughout the modelling process, sensitivity to configuration parameters is analyzed, and measurements are utilized to validate the model's accuracy. By enhancing WPT technology, the electric vehicles propel the shift towards a greener and readily accessible future of mobility.

**Keywords:** non-radiative power transfer, Finite Element Modelling, Compensation Topologies, Electric Vehicle.

## I. INTRODUCTION

The advent of Electric Vehicles has brought about a transformative shift in the automotive industry, leading in an era of cleaner and more sustainable transportation. However, the widespread adoption of EVs hinges on addressing several critical needs and challenges. To ensure the viability of EVs as practical alternatives to internal combustion engine vehicles, there is a pressing need for efficient and convenient charging infrastructure, especially in urban areas where EVs are becoming increasingly popular. Traditional charging methods involving physical cables can be time-consuming, often discouraging potential EV users.

Wireless power transfer for EVs has emerged as a compelling solution to these challenges. By enabling contactless energy transfer, wireless charging not only enhances user convenience but also simplifies the charging process, making it more accessible and seamless. This technology has the potential to drive the further proliferation of electric vehicles, reducing our reliance on fossil fuels and mitigating environmental impact. WPT not only accelerates the electrification of transportation but also contributes to reducing greenhouse gas emissions, making EVs a more practical and eco-friendly choice for the future of mobility, the practicality of electric vehicles and contributes to their broader acceptance.

Wireless Power Transfer (WPT) is classified into two primary categories based on the energy transfer mechanism: "radiative" and "non-radiative" types. In the case of short and medium-range applications, near-field power transmission occurs at distances smaller than the propagation wavelength of the transmitted signal [7]. For short-range charging, the receiver distance is less than the diameter of the transmitting coil. In contrast, for mid-range applications, the receiver distance ranges from 1 to 10 times the diameter of the transmitting coil [6]. The power transfer mechanism in these scenarios typically involves inductive or capacitive coupling, falling under the "non-radiative" category. Conversely, the "radiative" or "far-field" power transfer method operates effectively at distances greater than the wavelength of the transmitted signal [5]. Inductive coupling is recognized for its straightforward operational principle. The transfer of energy occurs from the primary coil to the secondary coil through the variation in magnetic flux, which, in turn, induces a secondary voltage at the receiving end. In essence, this inductive coupling mechanism facilitates wireless power transfer to a load. This paper will explore the needs and challenges associated with electric vehicles and delve into the compelling reasons behind the implementation of wireless power transfer technology for EVs.

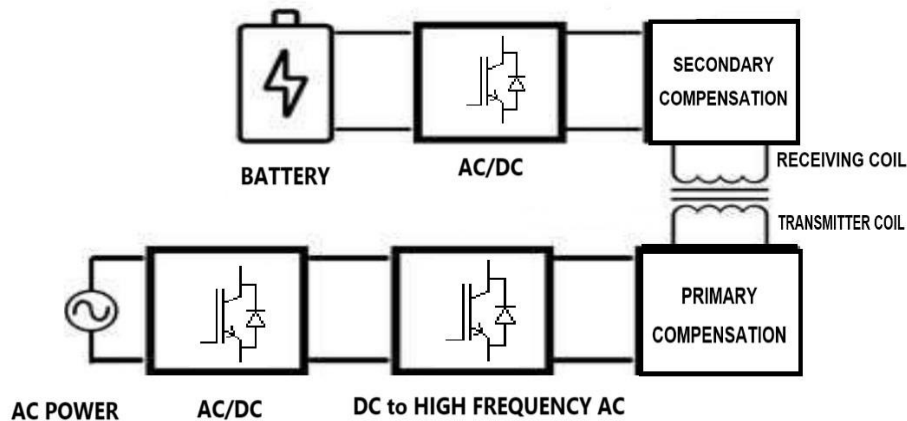
This paper aims to revolutionize the charging experience for electric vehicles by developing efficient Wireless Power Transfer systems. The primary objectives include enabling convenient charging without physical connections, enhancing user experience, and promoting everyday practicality of EVs. Key focus areas involve designing reliable coils for transmitting and receiving ends, ensuring safe power transfer at optimal distances while minimizing energy

losses. By facilitating dynamic and continuous charging, the paper seeks to extend EV driving range for long-distance travel, contributing significantly to environmental sustainability by reducing greenhouse gas emissions and dependence on fossil fuels. Additionally, the design of WPT systems incorporates scalability and adaptability to accommodate future power demands and emerging technologies, such as dynamic charging and autonomous EVs, ensuring ongoing relevance and growth potential.

## II. WIRELESS POWER TRANSFER

Wireless Power Transfer utilizes electromagnetic fields to transmit energy from a power source, such as a charging station, to the EV's battery, all without any physical contact. This functionality is based on the principle of resonance, wherein both the transmitting and receiving coils are precisely tuned to the same frequency to ensure highly efficient power transfer. The transmitting coil, connected to a power source, generates an alternating magnetic field when supplied with electrical current, which extends into the surrounding space. In contrast, the receiving coil, electrically isolated from the transmitting coil, is positioned within the magnetic field's range and is linked to the device or system requiring power or charging. Magnetic coupling between these coils facilitates power transfer, wherein the magnetic field generated by the transmitting coil induces a voltage in the receiving coil through electromagnetic induction. This induced voltage can then be utilized to charge the connected device. A crucial component of WPT systems is the power electronic converter, which on the primary side, generates high-frequency current in the sending coil. Typically adopting a resonant topology to enhance switching frequency and efficiency. On the secondary side, a rectifier converts the high-frequency AC current to DC current. Inductive coupling transformers, rooted in magnetic field induction, offer the essential feature of galvanic isolation between the power source and the recipient load, ensuring safety and reliability in the charging process.

A typical wireless EV charging system, as shown in Figure 1, involves a series of stages to facilitate wireless EV charging. The process begins with the conversion of utility alternating current (AC) power into a direct current (DC) power source through an AC to DC converter equipped with power factor correction (PFC). Subsequently, the DC power undergoes transformation into high-frequency AC, which drives the transmitting coil, facilitated by a compensation network. To enhance safety and safeguard against insulation failure of the primary side coil, a high-frequency isolated transformer is introduced between the DC-AC inverter and the primary coil.



**Figure 1:** Block Diagram of WPT for Electric Vehicle

The high-frequency current in the transmitting coil generates an alternating magnetic field, inducing an AC voltage on the receiving coil. The inclusion of a secondary compensation network improves the efficiency and transferred power significantly. Ultimately, the AC power is rectified for battery charging. The key components of a wireless EV charger include detached transmitting and receiving coils, often constructed with ferrite and shielding structures, a compensation network, and power electronics converters.

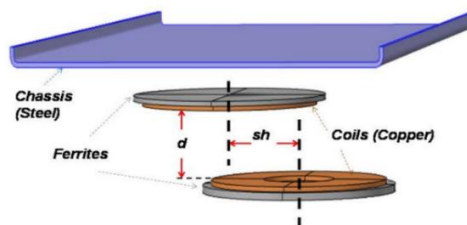
The overall system comprises two primary components: the contactless coupler and the associated power electronics system. Preceding the wireless transmission stage, the system undergoes two conversion phases, these conversion stages facilitate power level adjustment by regulating input voltage and frequency. Following the wireless transmission stage, a final conversion from high frequency AC to DC occurs to supply energy to the battery. Power levels typically vary from 0.8 W to 40 kW for a gap ranging from 1 to 140 mm. Due to the significant distance between the primary and secondary sides, coupling is weakened. Thus, to achieve the desired transferred power,

managing high reactive power is essential, assuring the use of resonant elements on both sides for compensation to ensure optimal efficiency. Additionally, regulating output parameters on the load side is necessary to maintain charger operation at a specific voltage while meeting the battery's current demands, thereby ensuring load protection.

### III. FINITE ELEMENT MODELLING

Finite Element Modelling (FEM) is a powerful numerical technique used for simulating and analyzing complex physical systems. It is preferred in Wireless Power Transfer systems due to its ability to provide detailed insights into electromagnetic field behaviors and system efficiency. FEM enables to simulate the models of WPT system, allowing for a comprehensive understanding of the interplay between coils, magnetic fields, and other components.

The Modelling of WPT with a contactless transformer employs two coupling methods: Inductive Coupling (IC) and Capacitive Coupling (CC). The Inductive Coupling Transformer (ICT), relying on magnetic field induction, provides galvanic isolation between the source and the load. Conversely, the CC type transformer relies on electric field for energy transfer. The preference for the Inductive Coupling Transformer stems from its ability to enhance coupling between coils. This improvement is achieved through the use of shielding, which strengthens mutual inductance,  $M$  by intensifying the magnetic flux between the coils. Typically, a non-conducting magnetic material is incorporated as shielding, with the two coils positioned between two layers of shielding. Ferrites are commonly employed for this purpose due to their minimal losses, even at frequencies reaching several hundreds of kHz, making them a cost-effective choice. The ICT is meticulously modelled using the FEM to gain insights into its physical characteristics and behavior. By creating the model of identical coil configurations for ICTs, the essential electrical parameters such as self-inductance ( $L_1, L_2$ ), the mutual inductance ( $L_m$ ), and coupling coefficients ( $k$ ) can be calculated. Each prototype of the ICT possesses its distinct set of parameters, although certain parameters remain constant across these models. The structure of the system's configuration comprises of two circular coils enveloped by circular ferrite components. These coils are positioned in such a way that the gap between the  $n$  turns coils is extremely narrow, effectively treating them as a single turn with a cross-sectional area equivalent to  $N$  times that of an individual wire. The three-dimensional depiction of the Inductive Coupling Transformer, coupled with the chassis, is visually represented. This comprehensive structure as seen in the Figure 2, encompasses a transmitter coil, a receiver coil, and two ferrite plates that provide complete coverage for the coils. In the design, a steel plate is also incorporated, which serves as a simplified representation of the Electric Vehicle chassis.



**Figure 2:** Model of ICT with EV consideration [12]

The alternating current supply in the transmitter coil  $L_1$  creates a varying magnetic field and then a magnetic flux through the circular area inside the receiving coil  $L_2$ . The Mutual inductance between two coils ( $L_1, L_2$ ) is,

$$M_{21} = M_{12} = M \quad (1)$$

The magnetic coupling coefficient is used to determine the quality of the linkage between the coils:

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (2)$$

The modelling with the consideration of EV chassis has certain parametric influences like, the Coupling coefficient can be influenced by the variation of parameters like distance between the coils (Air gap,  $d$ ) and the deviation in Axis Shift ( $sh$ ). The variations in self-inductances are significant for small air gaps but get decreased for larger ones [12]. This variation arises from the influence of ferrites and the electric vehicle (EV) chassis on the magnetic flux distribution within the coupler when air gaps are small. As the air gap increases, mutual inductance consistently decreases due to the rise in leakage magnetic flux, resulting in a drop, in the coupling factor. Additionally, the Inductive Coupling Transformer is not symmetrical due to the presence of the chassis.

$$L_1 \neq L_2 \tag{3}$$

The structure of the model is tailored to replicate an RNO Prototype, specifically designed to emulate the configuration of a Renault Kangoo electric vehicle [10]. The ICT has been modelled based on the parameters mentioned in Table 1, which mainly focus on the considerations of EV structure. An important characteristic of this model is the distinction between L1 and L2, denoting the primary and secondary coils, respectively. These two inductors exhibit dissimilar inductance values, a feature essential for their distinct roles within the wireless power transfer system. This differentiation in inductance values reflects the specialized functions of the coils in facilitating efficient power transfer.

**Table 1:** Parameters of ICT with EV consideration

Side	Parameter	Value
	Length	1.6m
Primary	Turns	20
	Cross sectional area	855 mm <sup>2</sup>
Secondary	Turns	20
	Cross sectional area	855 mm <sup>2</sup>

The system of both primary and secondary side is modelled at the single resonance frequency of  $f_0=30\text{Khz}$ . The Self-inductance values  $L_1, L_2$  can be calculated by,

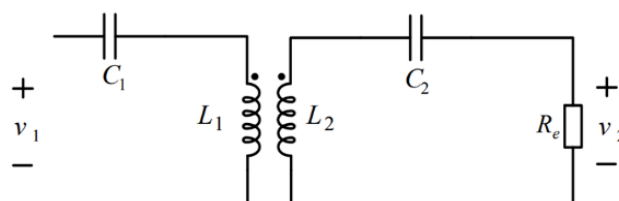
$$L = \frac{\mu_0 N^2 A}{l} \tag{4}$$

$$f_{01} = f_{02} = f_0 = \text{Resonant Frequency} \tag{5}$$

The modelling of ICT enables the determination of the electrical characteristics. The compensation of inductive elements to the model is necessary to maximize the power transfer to the load. Moreover, addressing the reactive component of power transfer is crucial to maximize the transmission of real power to the load. The compensation of an inductance entails the connection of a capacitor, either in series or parallel, depending on the chosen topology. The capacitor's value is carefully selected to nullify the equivalent impedance at the designated frequency. The resonance frequency of the overall system, which may vary from the frequency considered during compensation, is the frequency at which the imaginary component of power is effectively neutralized.

$$S = P + jQ \tag{6}$$

The complex power (VA) denoted as S, encompasses both the real power (W), referred to as P, and the reactive power (VAR), symbolized as Q. There exist four principal topologies of resonant circuits applicable in Inductive Power Transfer systems. These topologies are named based on how resonant capacitors are incorporated at each winding side, specifically through Parallel (P) and/or Series (S) connections. Among the topologies listed SS Self Inductance Compensation Topology is noted to be a preferred configuration within the realm of wireless power transfer systems.



**Figure 3:** SS Self Compensation

The transfer of appreciable electric power requires the compensation of the inductive parts, the capacitors ( $C_1$ ,  $C_2$ ) are used to compensate and tune them out. This topology is named after the compensations of  $L_1$ ,  $L_2$  which are the self-inductors of the transformer model as shown in the Figure 3. Then the values of the compensation capacitors  $C_1$ ,  $C_2$  at resonant frequency  $f_0$  are given by,

$$f_0 = \frac{1}{2\pi\sqrt{L_1 C_1}} \Rightarrow C_1 = \frac{1}{(2\pi f_0)^2 L_1} \quad (7)$$

$$f_0 = \frac{1}{2\pi\sqrt{L_2 C_2}} \Rightarrow C_2 = \frac{1}{(2\pi f_0)^2 L_2} \quad (8)$$

As the decision has been made to consider the self-series-series Inductance compensation, the behavior of this topology for different interoperability systems study is performed [12]. The interoperability between any two systems combines an independent structure for both of them. It also considers that each system has its compensation capacitor that is calculated in the predesign to tune out the self-inductance at the resonant frequency of 30Khz.

A resonant DC-DC converter comprises two stages that are connected to the compensated Inductive Coupling Transformer sides. In the primary stage of DC/AC conversion, the DC input is derived by rectifying the alternating source into DC and subsequently filtering it using an input capacitor. Following this DC input stage, an inverter operates at a switching frequency ( $f_0$ ), converting the input DC into a high-frequency AC waveform. The output current of this inverter serves as the input current for the primary resonant side ( $L_1$  and  $L_m$ ) at a fundamental frequency ( $f_0$ ). In the secondary stage of AC/DC conversion, the AC output generated by the resonant inverter, facilitated by the transformer, undergoes rectification and filtration. The approximately sinusoidal current is rectified using a diode bridge rectifier and further filtered using a large capacitor. This results in the provision of a constant current ( $I_{out}$ ) and voltage ( $V_{out}$ ) to supply a DC load. This resonant DC-DC converter configuration is instrumental in enabling efficient and effective power transfer within Inductive Power Transfer systems, particularly in the system of wireless battery charging, contributing to the ongoing evolution of power supply technologies.

#### IV. SIMULATION OF SSL RESONANT WPT SYSTEM

The Model to employ the SSL compensation topology, the compensated Inductive Coupling Transformer is seamlessly integrated with all other electronic components, culminating in the formation of the complete resonant Inductive Power Transfer system, as depicted in Figure 4. This comprehensive system is meticulously designed and analyzed using MATLAB-Simulink, facilitating time domain simulations. The study commences with the open-loop system, devoid of any parameter control. All system values remain fixed throughout the simulation. Importantly, the DC-DC resonant converter plays a central role in this configuration. The system starts with the DC source connected to the DC bulk capacitance of the filter.

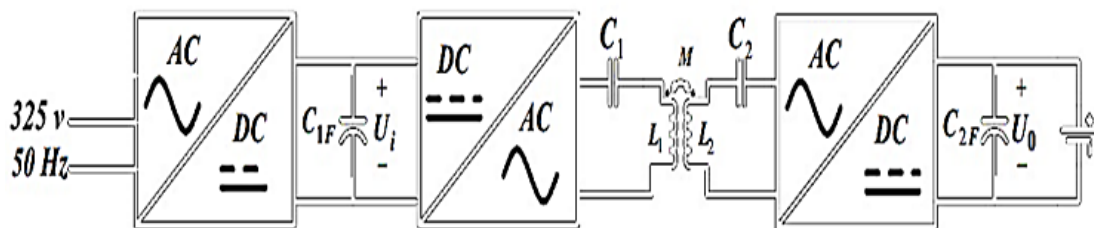


Figure 4: WPT System with SSL Compensation

This open-loop system simulation is conducted, where a resistive load effectively emulates a battery model, particularly during steady-state conditions. This comprehensive analysis serves as a crucial step in evaluating and optimizing the performance of the complete resonant IPT system. In the simulation, a 325V AC power source is initially converted into DC voltage using a Source Rectifier. The mean DC voltage is then obtained to assess the system's steady-state performance, yielding a constant value throughout the simulation. The DC voltage undergoes further processing through a high-frequency inverter operating at 30kHz under resonance conditions.

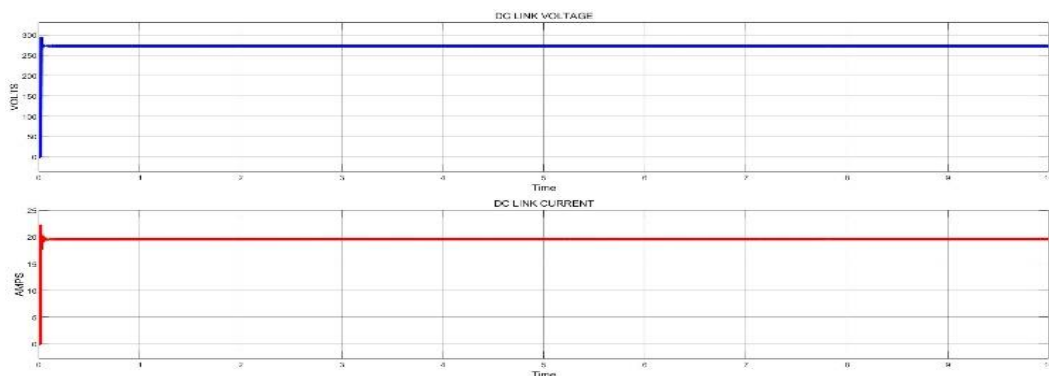
**Table 2:** Electrical Parameters of WPT system

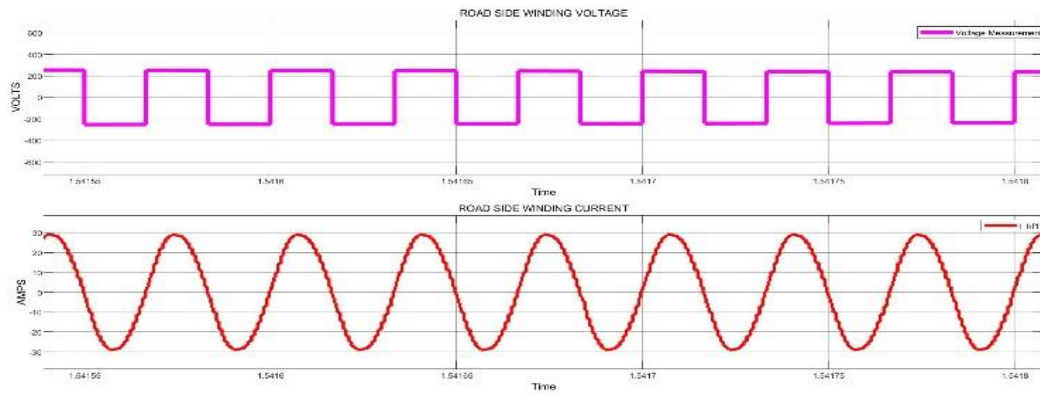
S. No	Simulation Parameters	Values
1	Source Voltage – AC Source	325V
2	Resonant Frequency	30KHz
3	Duty Cycle	0.5
4	Capacitance – $C_1$	$105.74e^{-9}$ F,
	Capacitance – $C_2$	$109.69e^{-9}$ F
5	Winding 1 Self Impedance [ $R_1(\Omega)$ $L_1(H)$ ]	[ $1e^{-3}$ $\Omega$ $266.16e^{-6}$ H]
6	Winding 2 Self Impedance [ $R_2(\Omega)$ $L_2(H)$ ]	[ $1e^{-3}$ $\Omega$ $256.79e^{-6}$ H]
7	Mutual Impedance [ $R_m(\Omega)$ $L_m(H)$ ]	8 $5.46e^{-6}$ H]

Utilizing IGBT switches controlled via PWM techniques, a self-inductance compensation topology is utilized, and capacitors and inductors are selected with values obtained through calculations, as listed in a tabulation, Table 2. The Model of WPT System is designed in MATLAB - SIMULINK software and the simulation are executed for the duration of 10 Seconds.

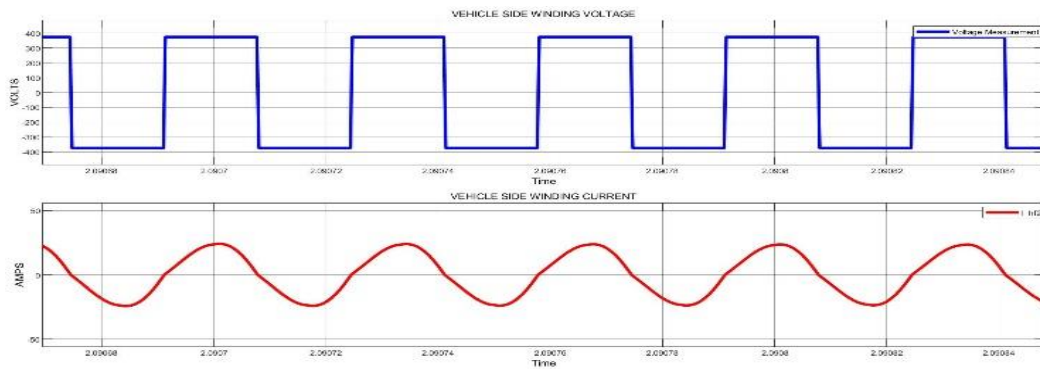
## V. RESULTS AND DISCUSSION

The simulation of the WPT system model in MATLAB for EV charging provides valuable insights into its performance. This simulation helps in assessing the power transfer, and electromagnetic field behavior, facilitating the development of efficient and reliable wireless charging solutions for electric vehicles. A 325V AC power source was provided as input for the simulation. The AC voltage is converted into DC voltage using a Source Rectifier. After the conversion, it is subjected to a mean block to obtain the average or mean component of the DC voltage.

**Figure 5:** DC Link Voltage



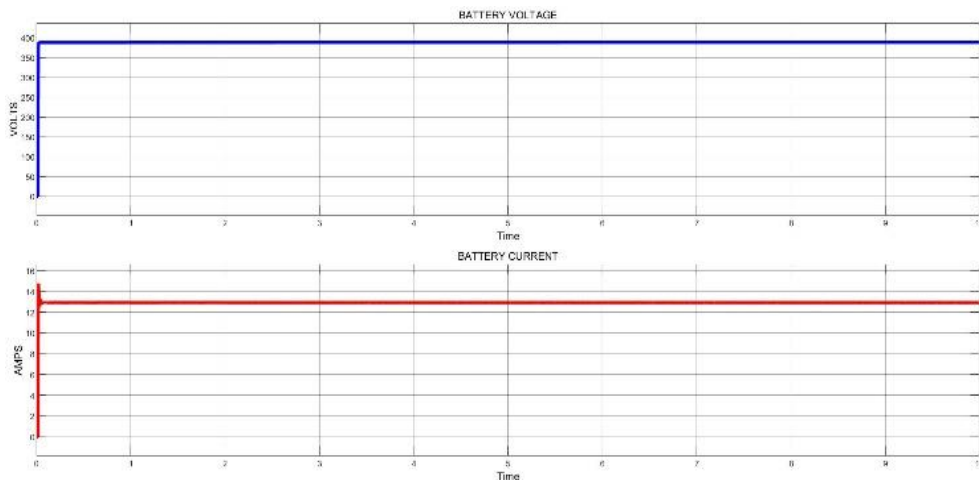
**Figure 6:** Dynamic response of Transmitting coil



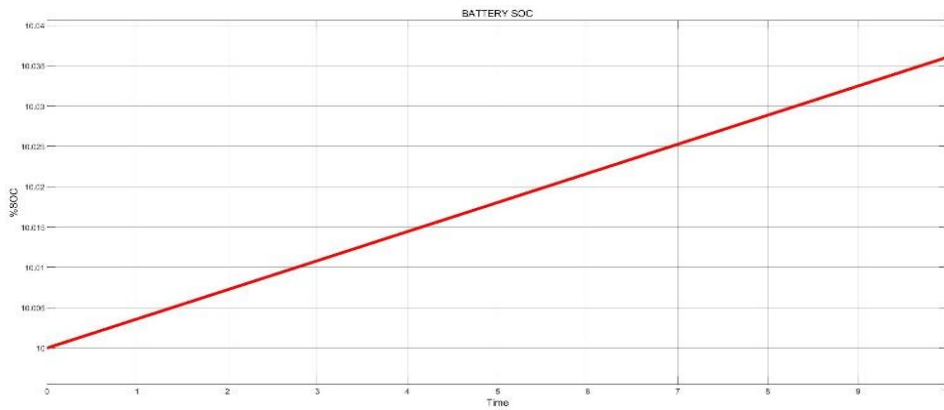
**Figure 7:** Dynamic response of Receiving coil

Measuring the mean DC voltage allows to assess the steady-state performance and stability of the system, as well as to check if it meets the desired voltage level requirements. Hence the steady state value of DC voltage is noted as 285V, a constant voltage throughout the system duration as shown in the Figure 5.

The DC voltage is subjected to high-frequency inverter with a 30kHz switching frequency operating under resonance condition. This inverter is designed as a current source inverter and incorporates specific filters. The primary compensation of high frequency inverter and the resonant elements provides the supply to the transmitting coil, and the voltage on the transmitting end is studied as the waveform of the transmitting coil, as observed in the Figure 6., reveals an AC voltage of 410V and a current of 30A. The high-frequency current flowing through the transmitting coil produces an oscillating magnetic field that, in turn, triggers the generation of AC voltage in the receiving coil by resonating with the compensation network. The current waveforms in the transmitting coil exhibit some fluctuations at high frequencies. Conversely, the receiving coil's waveform demonstrates sinusoidal nature with a voltage of 400V and a consistent current of 30A as studied in the Figure 7.



**Figure 8:** Battery of the vehicle



**Figure 9:** SOC of the battery

The AC voltage in the receiving coil is converted into DC voltage using a diode rectifier. This DC voltage is subsequently harnessed to power the vehicle's battery as shown in the Figure 8, which receives 380V of voltage and a current of 12A. At the outset of the simulation, the battery's state of charge stands at 10%. The state of charge (SOC) of the battery is diligently monitored and recorded. After a 10-second simulation, the increase in the state of charge becomes visually apparent, as illustrated in the Figure 9.

**Table 3:** Simulation Results

S. No	Simulation Parameters	Values
1	Input Active Power	5155W
2	Input Reactive Power	2121W
3	DC Link Power	5135W
4	Battery Input Power	4841W

The parametric values obtained from the simulation model are tabulated, as shown in the Table 3. Under steady state condition the real power of the source is 5135W and the Real power received by the battery is 4841W. Therefore, the Efficiency of WPT in EV charging is of 94%.

## VI. CONCLUSION

The Finite Elements modelling of WPT System is carried out with respect to electrical parameters and variations. The presence of the chassis affects the values of the self and mutual inductances and makes the values of self-inductances at each side non equal due to the asymmetry of the system. A compromise is taken to choose the Series-Series Self compensation that meets the industrial goals. The Complete WPT system starting with the input DC stage and ending with an equivalent load that presents the battery and a battery model are analyzed and simulated in MATLAB/Simulink using open loop system and the result scopes are obtained.

## VII. FUTURE WORK

By conducting a thorough study of magnetic flux transmission, it is possible to gain valuable insights into the efficiency, safety, and performance of the WPT system. The optimization of coil geometries, winding patterns, and materials can be processed to maximize magnetic flux generation and transmission. These efforts align with the broader goal of sustainable transportation, making WPT technology a promising solution for the future of electric mobility.

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