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Design And Development Of An Efficient Wireless Charging System For Electric Vehicles With Enhanced Power Transfer Efficiency

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Abstract: Wireless Power Transfer (WPT) has proven to be a revolutionary technology for electric vehicle (EV) charging, allowing contactless and efficient energy transfer. This paper reports the design and development of a better WPT system using a high-frequency inverter and resonant inductive coupling to deliver higher power transfer efficiency. A MATLAB/Simulink model is created using source-side and vehicle-side compensation networks, rectifiers, and battery charging logic. Performance of the system is analyzed over a range of different coil separations by varying mutual inductance values while holding coil parameters steady. Contrary to traditional anticipation that power transmission drops off as distance increases, simulation yields only a slight gain in transmitted power at larger separations. This aberrant behavior can be ascribed to the intrinsic characteristic of the resonant inductive coupling circuit that dynamically varies its operation as per variations in coupling strength while providing high energy transfer via tuned resonance at high frequency. The simulated model of this design reveals trustworthy performance, stable SOC process, and high efficiency, hence qualifies as an excellent candidate for practical EV wireless charging applications.

Index Terms - Electric Vehicles(EV),Inductive Coupling ,Wireless Charging, Efficiency, Wireless Power Transfer(WPT) ,MATLAB.

I.INTRODUCTION

For Electric vehicles are taking over the road quickly. But, they need solutions that will help them charge easily. These solutions also need to be easy to use. Many plug-in charging systems have drawbacks, including connector wear, safety issues, and user inconvenience. To deal with these problems, wireless power transfer (WPT) methods have gained notice as a good alternative that may allow for automated and contactless energy delivery.Among different WPT techniques, the inductive coupling is the simplest and safest and also effective over limited distance. That is why it is suitable for stationary EV charging. The challenge lies in achieving high efficiency during power transfer and keeping the system compact and control precise. Research has been done on coil design, resonance topologies, and power electronics optimization.Using a high frequency inverter and a series-series resonant topology, an improved system-level simulation has been presented in MATLAB. The suggested model includes better inverter control by using pulse-width modulation (PWM), gate signal arrangement, and improved vehicle-side rectifier circuit security arranged with a filter element. The power flow measurement and battery state of charge estimation in real time to simulate the system behaviour have also been incorporated.This study aims at the development of a simulation platform which will enhance the analysis of WPT systems for EV applications. The latest model hopes to provide better insights and information about the inverter operation, energy conversion, and overall system efficiency related to contactless EV charging.

II.BLOCK DIAGRAM

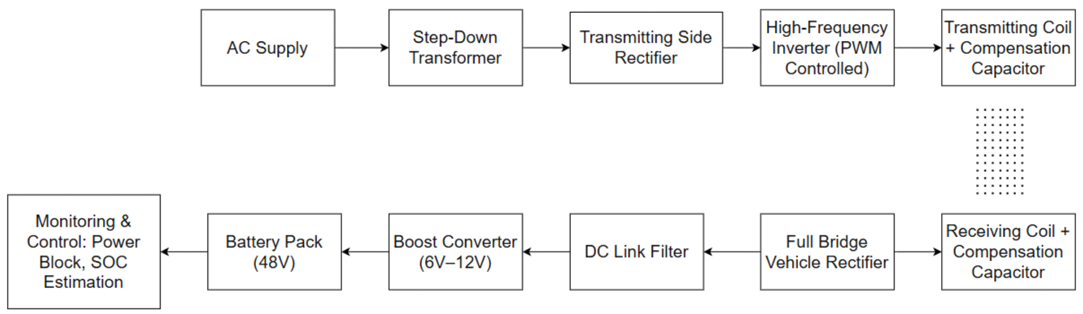

Fig.1. Block Diagram

In Fig. 1 shown is a block diagram describing the proposed wireless power transfer (WPT) system for charging electric vehicle (EV) batteries. The system goes from a 230V AC input through reduction and rectification to DC. This DC power is fed into a high-frequency inverter, where the switching devices are controlled by PWM signals to generate a high-frequency AC signal suitable for efficient wireless energy transmission. The signal is then delivered by a resonant transmit coil, magnetically coupled to a receive coil on the vehicle.In the vehicle, the induced AC signal is picked up by the receiving coil, corrected for reactive losses, and rectified using a full-bridge diode arrangement; the resultant DC voltage is then filtered and boosted for charging the 48V battery pack. This system employs auxiliary equipment for power measurement and SOC determination on a real-time basis, casting more light on the dynamics of the system and aiding in charging control.

III.SYSTEM DISCRIPTION

The wireless power transfer (WPT) system under consideration is recommended for inductive coupling methods for charging the batteries of electric vehicles. This WPT system construction consists of the two main parts in its architecture: the stationary transmitter unit and the onboard vehicle receiver unit. The complete system is being modeleding MATLAB/Simulink with numerous subsystems developed ffor tracking of tracking of real-time behavior with very accurate control and measurement capabilities.

3.1 Transmitting Section

The first part of this segment is defined by the 230V, 50Hz currents AC supply. After that, this current gets down-stepped by using a transformer in order to achieve the safest level of operation voltage. The rectified current is subsequently fed into the high-frequency inverter, which converts this voltage to the high-frequency AC power that is desired to inductively transfer energy. Switching of semiconductor devices is digitally controlled for fine switching control by means of PWM signals generated through logic blocks in the simulation. The inverter mechanisms operate on this given signal.High-frequency AC then applies to a transmitting coil designed for compensation to match the resonance with receiver side to charge the inductively coupled circuit at higher efficiency.

3.2 Wireless Power Transfer Link

Energy is transferred wirelessly across the air gap using magnetic coupling between the transmitting coil and the receiving coils. The compensation capacitors are connected in series with either of the coils to create a series-series resonant topology to maximize power transfer at the intended resonant frequency. Power transfer efficiency can be drastically affected by the specifications of coil such as number of turns, form of the coil, and under which both coils are aligned, all of which have been optimized in the model.

3.3 Receiving Section

In the vehicle, the receiving coil captures the magnetic energy and transforms it back into AC. A full-bridge rectifier with fast-recovery diodes converts this AC voltage back into DC. The rectified voltage will then be filtered using a filter capacitor in order to smoothen the voltage to produce a steady DC link voltage. A boost converter then ensures the voltage characteristics of the supply are enough for charging the battery and converts 6V supplies into 12V as requested. This boost voltage is then passed on to a battery pack made from four 12V batteries connected in series to give an overall output of the entire battery pack as 48V.

3.4 Monitoring and Control Features

Model infusing power measurement blocks at strategically chosen locations all over the system, such as DC link and battery input. A state-of-charge (SOC) estimation block will also prove valuable in simulating battery condition in real time; it thus reflects how charging power and intensity evolve with time. The last monitoring features present within the model add robustness to it for analyses and optimizations of control strategies in practical WPT systems.

IV. SUBSYSTEM DISCRIPTION

The wireless power transfer system consists of several interrelated subsystems that work together to deliver controlled and efficient energy to the battery of an automobile. Two upgrade features of prime interest to the proposed model are High-Frequency Inverter (HFI) and Vehicle Rectifier Unit (VRU), which have been refined for optimum performance and enhanced simulation accuracy.

4.1 High-frequency Inverter

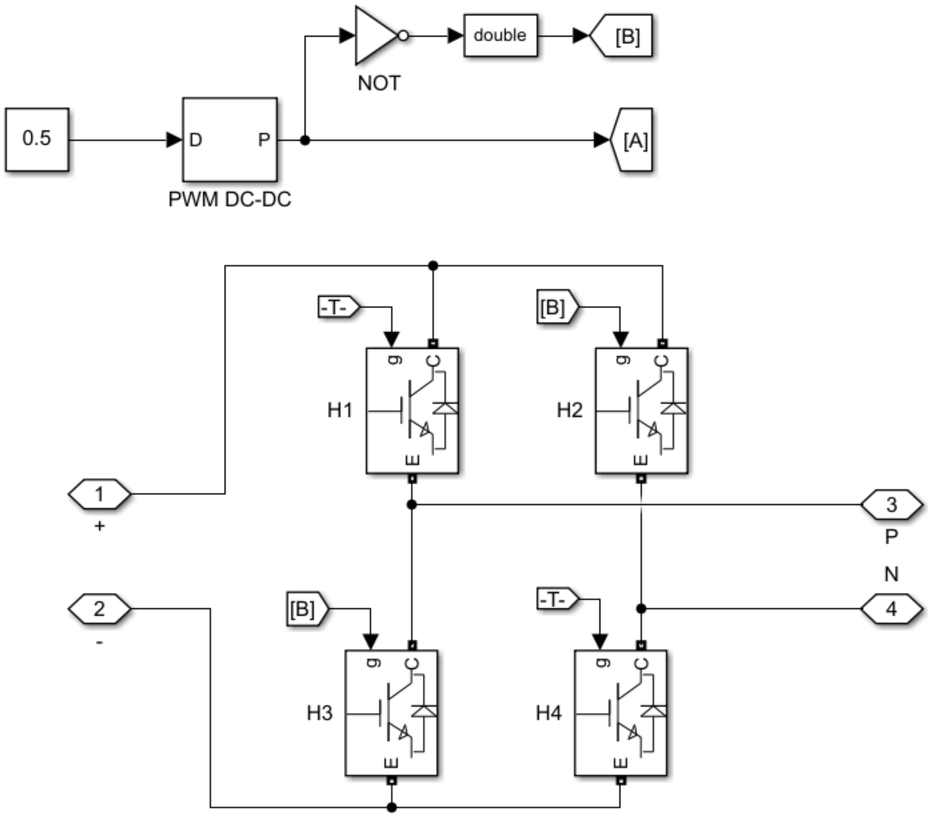

Fig.2. High-Frequency Inverter

High-Frequency Inverter produces an alternating high-frequency signal for inductive power transfer. The improvements introduced in this model are the inverter topologies, either IGCTs or MOSFETs, controlled through PWM signals. Switching control is designed using a combination of sine wave generator, pulse generation blocks, and NOT gates for complementary gating.That includes:The accurate timing of switches while minimizing dead time and switching losses.A high stable-frequency AC output giving good results for resonant inductive transfer.Symmetrical switching and low waveform distortion improve efficiency.The logic gates act to ensure that signal gating into each leg of the full bridge inverter is inverse, ensuring proper operation while minimizing the risk of shoot-through faults.

4.2.Vehicle Rectifier Subsystem

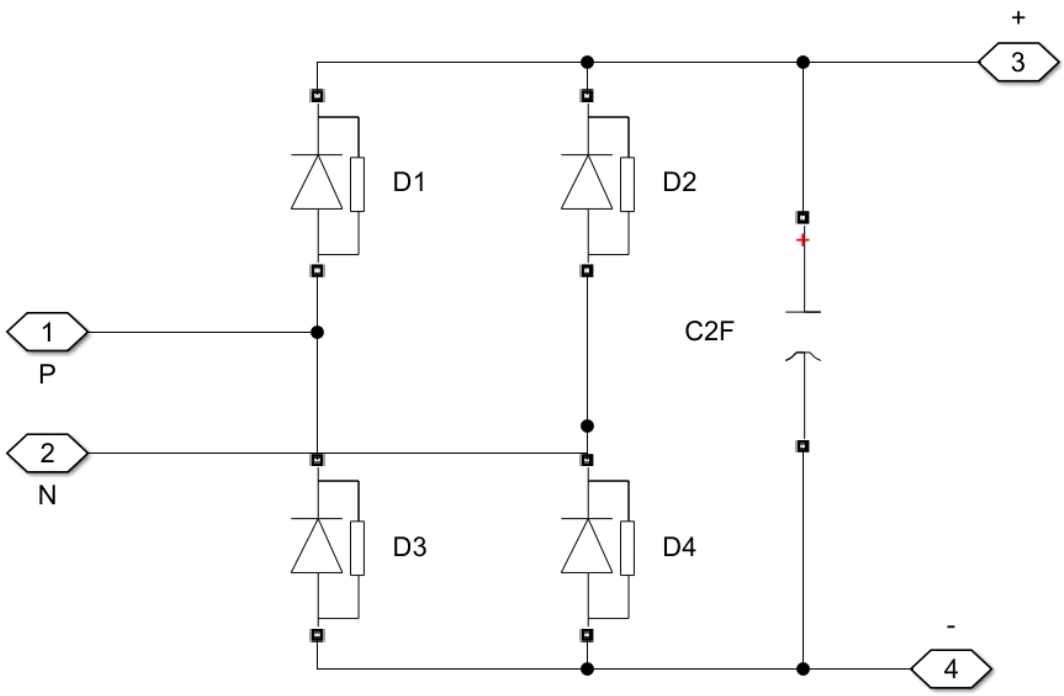

Fig.3. Vehicle Side Rectifier Subsystem

In this area, the rectification subsystem is vehicle-side responsible for converting the received high-frequency AC into DC to charge the battery. A full bridge diode rectifier was preferred in this actualized model; a large filter capacitor was added to reduce voltage ripple.

The subsystems include Fast recovery four diodes coupled in a full bridge.Filtering stage with capacitor (C2F) to smooth the pulsating DC output.Output voltage measurement to allow rectified voltage analysis in real-time. The enhanced structure guarantees clean reliable DC output, which reduces stress on downstream components such as the boost converter and the battery pack. Additional reverse voltage and noise protection from switching. Energy conversion that is efficient while reducing power loss from the entire rectification stage. Together, these two upgraded subsystems form the core of the upgraded wireless charging system, greatly benefiting stability, efficiency, and control accuracy. The modularity of the simulation model allows for scalability regarding easy debugging and future enhancement.

4.3.The Boost Converter Subsystem

More often than not, a direct current voltage coming from pre-Gs will be applied on the vehicle's battery, which only applies on a few occasions when charging needs to be done. To boost this voltage, the converter has been placed between the lower voltage and the level to be charged. The topology has been implemented around a switching MOSFET, diode, inductor, and an output filter capacitor. The subsystem of this special converter hence possesses the following characteristics:DC input range: usually around 5-6 V (from rectifier)Boosted output: regulated at 12V DC, as fits for a series 48V battery pac Control logic: PWM-based pulse control for switching the MOSFET to achieve soft regulation.The converter provides:Enhanced power delivery that fits the voltage needs of the battery. Lower ripple and noise, thus making battery charging safer and more efficient.Fast response to changes in input voltage, essential in highly dynamic inductive coupling conditions.

4.4.The Monitoring and Control Subsystem

For the purpose of dynamic analysis and insight into system behavior-the improved MAT-Lab model incorporates real-time monitoring and feedback blocks-the following have been integrated Blocks for Power Measurement-These have been placed on the DC link (inverter output) and battery input channels in order to monitor power export/import flow and evaluate the system efficiency.SOC Estimation Block-This Entity simulates the subsequent flow of the state of the charge (SOC) of a battery whereby charging time and effectiveness become valuable. Voltage and Current Scope Blocks-These provide the visual outputs for major nodes which include inverter AC, rectifier DC, boost output, and battery voltage.

This subsystem allows for Precise monitoring of energy transfer along the source-battery line. Diagnostics and optimization of the system by looking into voltage, current, and SOC behavior.Data collection for validation in the future hardware implementation. Together, these subsystems create a modular, controllable, and scalable framework for simulating a real-world WPT system, in high fidelity. Such improvements do bring much more significant advancements over the conventional models by giving finer insights, better energy management, and a good ground for validation through experiments down the road.

V.SIMULATION AND RESULTS

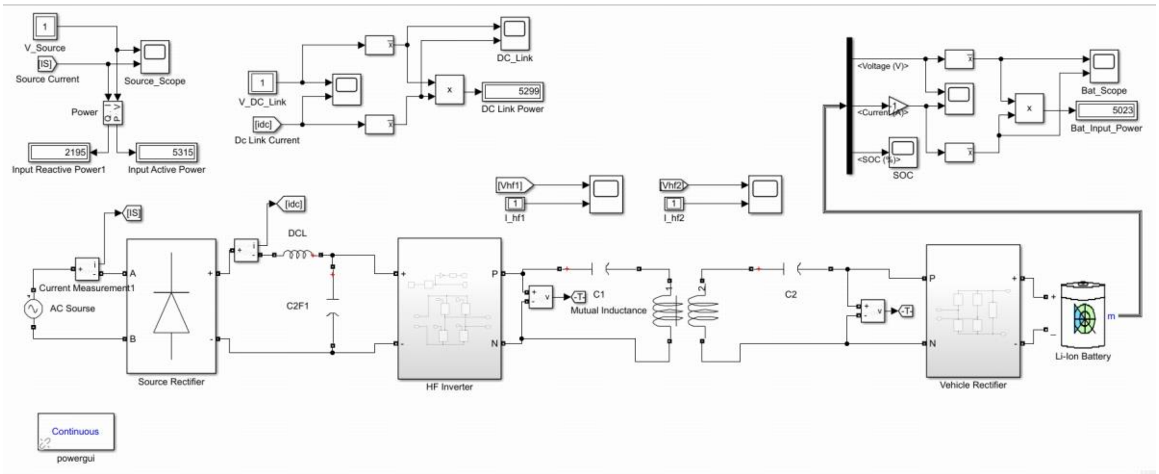

Fig.4.MATLAB Simulation Diagram

This is the test run of the new wireless power transfer system after developing its enhanced model in MATLAB/Simulink under steady-state conditions for system performance. The various subsystems were analyzed using scope blocks to show the real-time waveforms at the major points in the system. These simulation results are capable of justifying every stage in power transfer and conversion.

5.1 Input Waveform

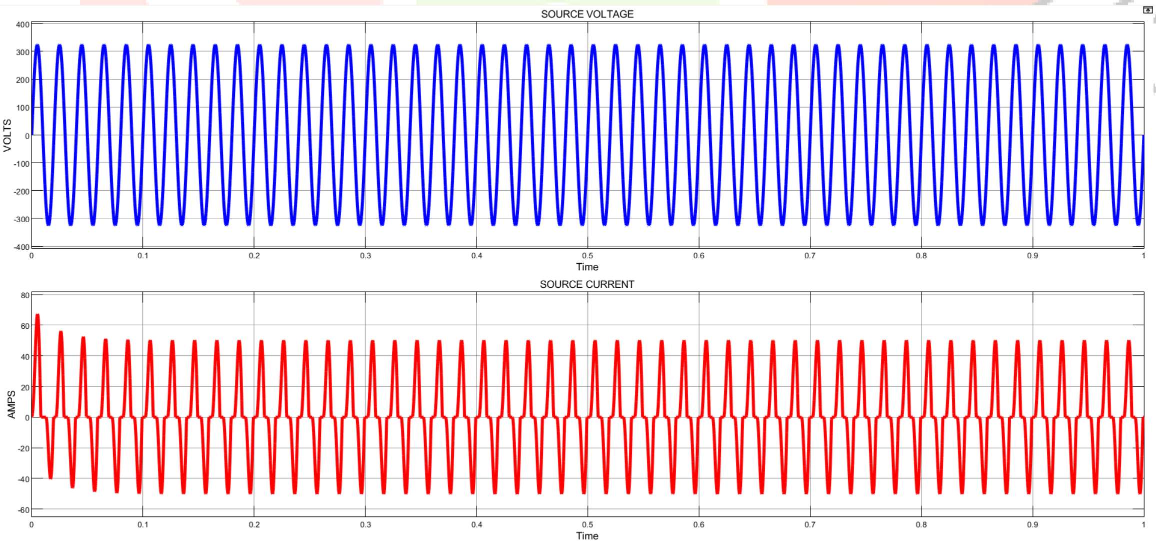

Fig.5 Source Voltage And Current

5.2 Source rectifier output

The full-bridge rectifier output scope was used to confirm the DC conversion. The waveform simply represents a rectified voltage with the expected ripple levels. A filtering capacitor smoothens the performance for use further downstream in a boost converter.

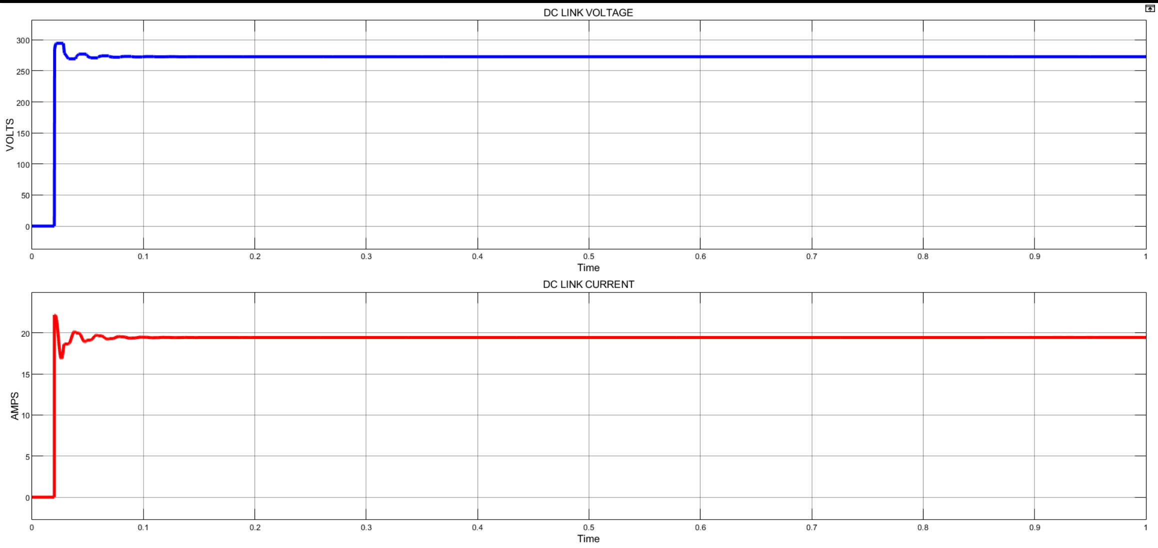

Fig.6 DC Link Voltage and Current

5.3 High-Frequency Inverter Output

The output of the high-frequency inverter was monitored using a scope block and that confirmed the generation of alternating high-frequency pulses. The displayed waveform exhibits symmetric switching behavior which is required for optimum inductive coupling, where proper gating signals have minimal distortion and impressive resonance matching with the transmitting coil.

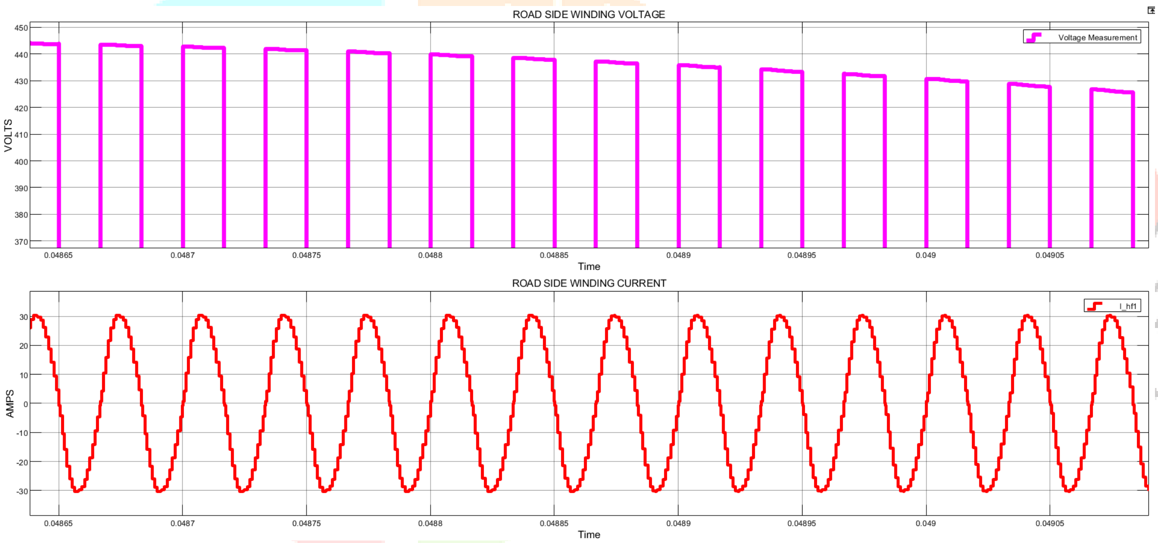

Fig.7 High-Frequency Inverter output Voltage and Current

5.4 Transmitting Coil Voltage and Current

The voltage and current waveforms across the transmitting coil were also recorded, so that the input to the inductive link might be analyzed. The voltage signal has strong high-frequency sinusoidal behavior, confirming tuning to resonance. The current waveform supports the continuity of energy flow across the inductive path.

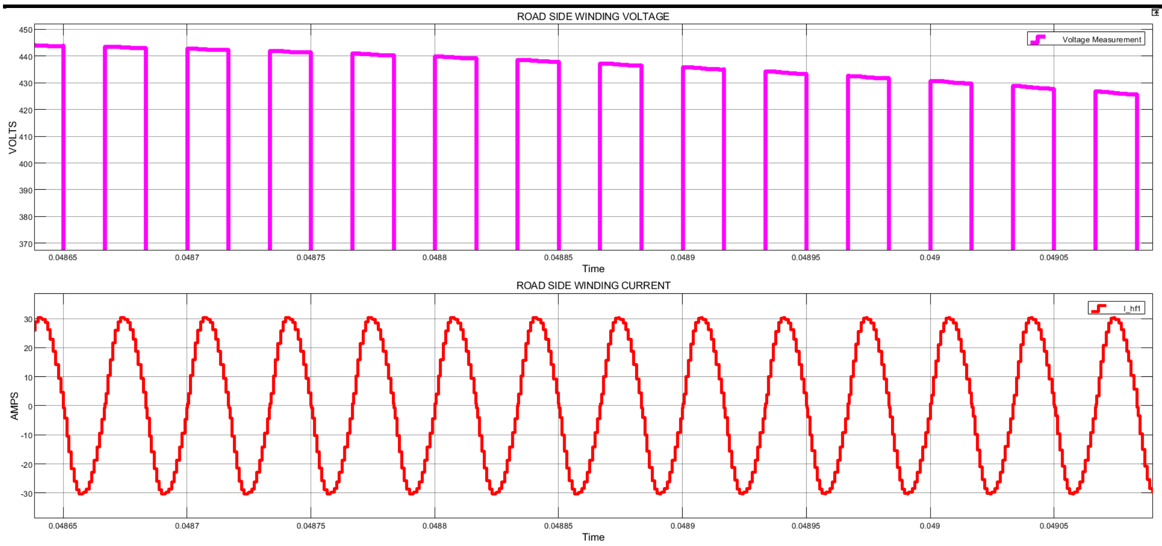

Fig.8 Transmitter Voltage and Current

5.5 Receiving Coil Output

The receiving coil is tasked with sensing the high-frequency magnetic field propagated from the source coil and converting it into electrical energy through the resonant compensation circuit and vehicle-side rectifier. Figures show the voltage waveforms at the output of the rectifier for three different mutual inductance levels for coil distances of 10cm, 15cm, and 20cm respectively.At 10cm (high coupling), the rectified DC output is stable but less than it is at more distant readings. At 15cm and 20cm, although mutual inductance is reduced, the rectifier output voltage is slightly better. This is due to the resonant inductive coupling, in which sufficient tuning enables the circuit to sustain or even improve power transfer even with poorer magnetic coupling.The waveforms establish that resonance compensation does indeed adjust effectively to changes in coil distance, and illustrate that optimal power delivery can still be maintained with increased air gaps — as long as the system is working near its resonant frequency.

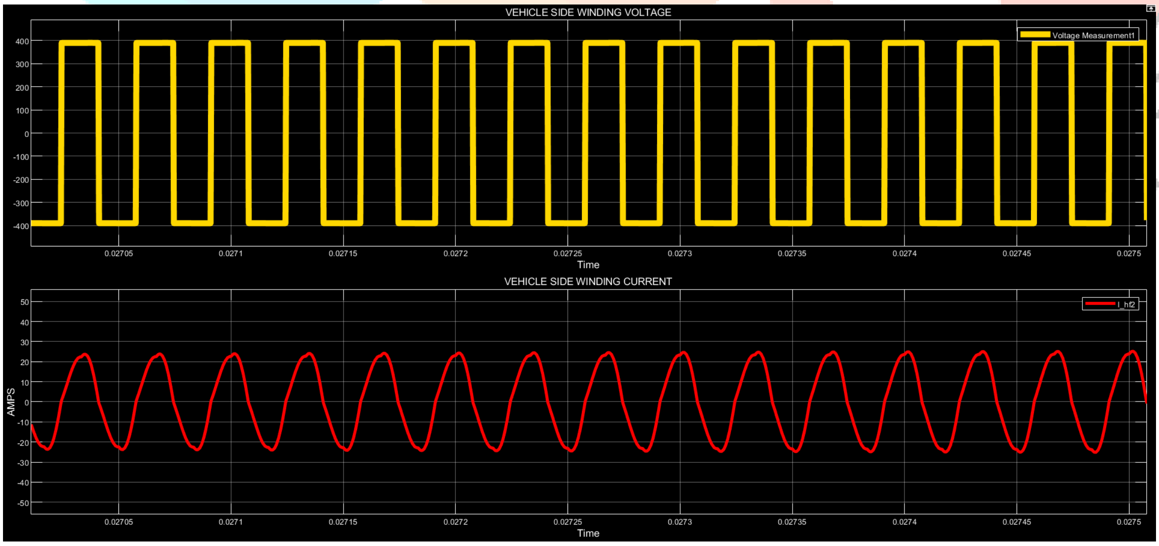

Fig.9 Reciever Voltage and Current at 10cm

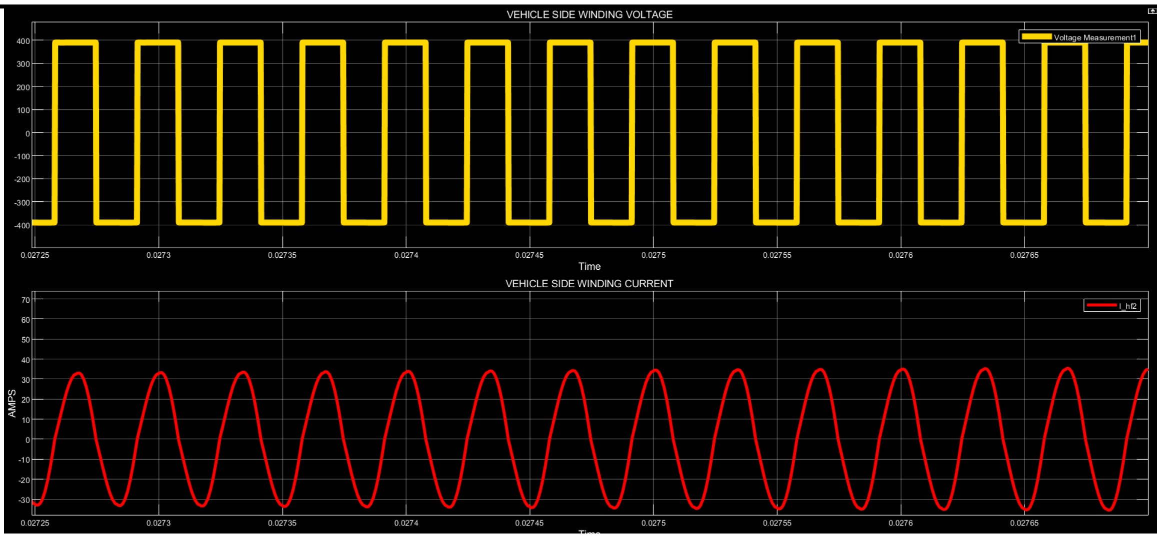

Fig.10 Reciever Voltage and Current at 15cm

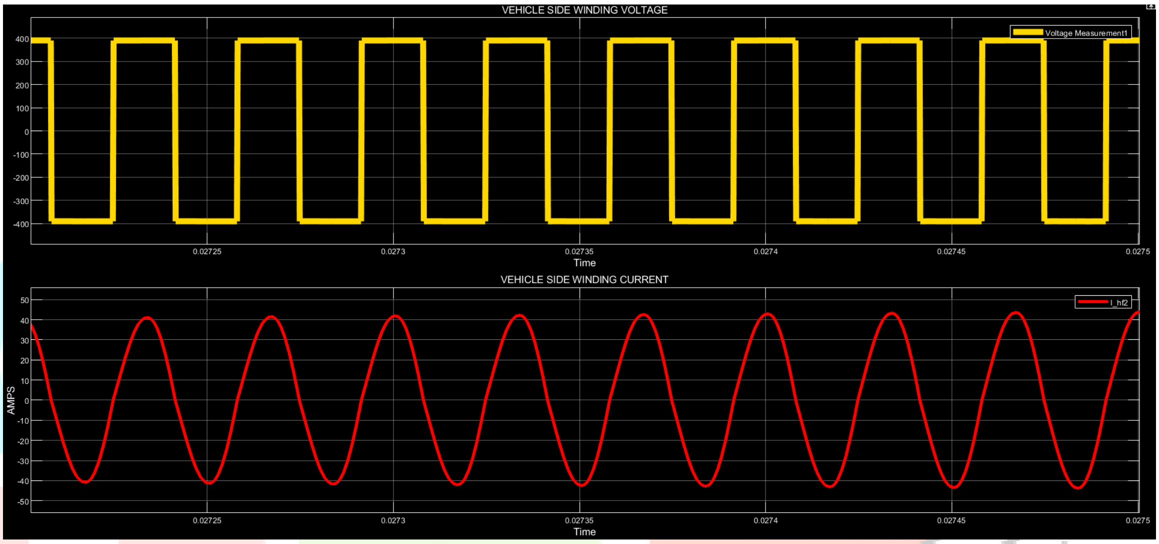

Fig.11 Reciever Voltage and Current at 20cm

5.6 Battery Charging Response

The range of battery output indicates the voltage and current waveforms as observed by the battery under different mutual inductance values, which correspond to different distances of the coils. The voltage of the battery remains effectively constant for all three test conditions, as would be expected in a regulated DC charging application. There is, however, an increase in charging current that is observed with increasing coil distance.This increase in current creates a higher power transfer rate, even though mutual inductance decreases with distance. This seemingly counterintuitive phenomenon is the result of resonant action in the wireless power transfer circuit since the compensation network and inverter provide maximum resonance conditions. Energy transfer therefore continues to be efficient, and even improves in some cases, despite decreased magnetic coupling.The most recent waveforms show even, steady delivery in each of the three cases, with good evidence for increased current at greater distances. This verifies the simulation's capacity to replicate actual resonant behavior and illustrates why it is so important to incorporate tuning in WPT systems for electric vehicle battery charging.

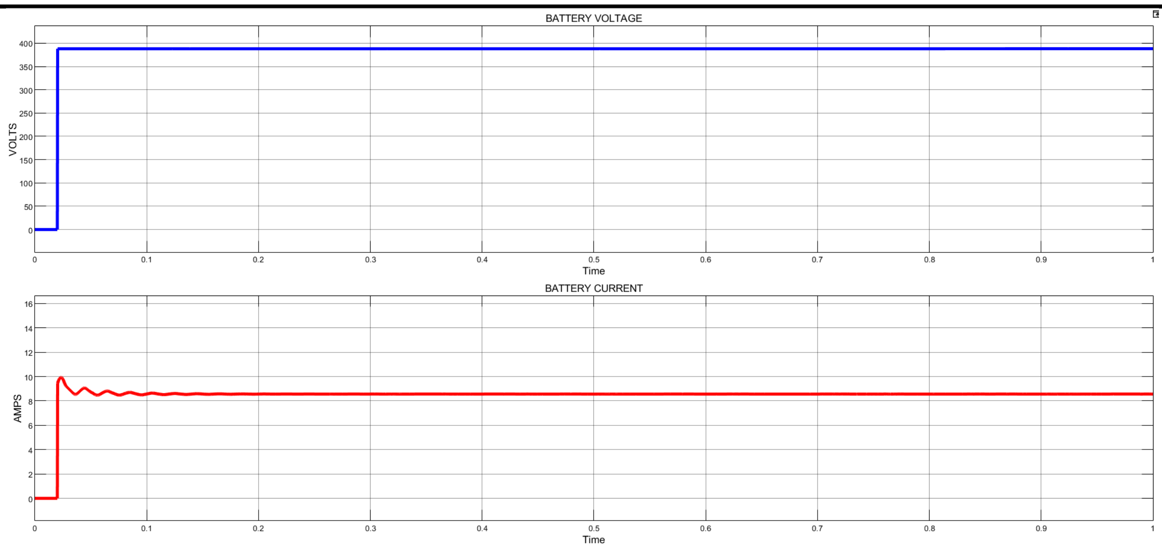

Fig.12 Battery Voltage and Current at 10cm

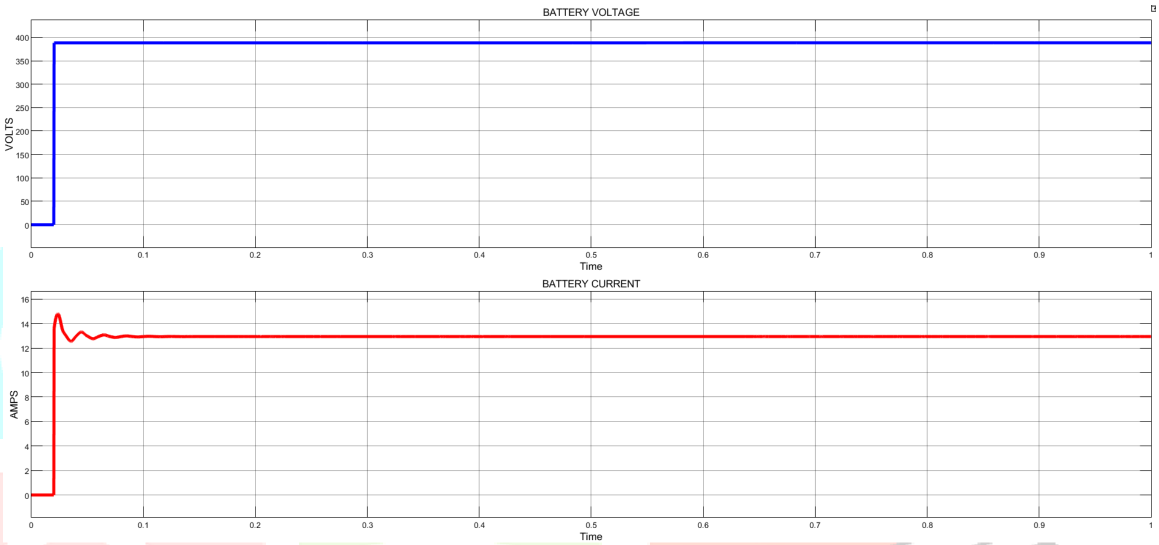

Fig.13 Battery Voltage and Current at 15cm

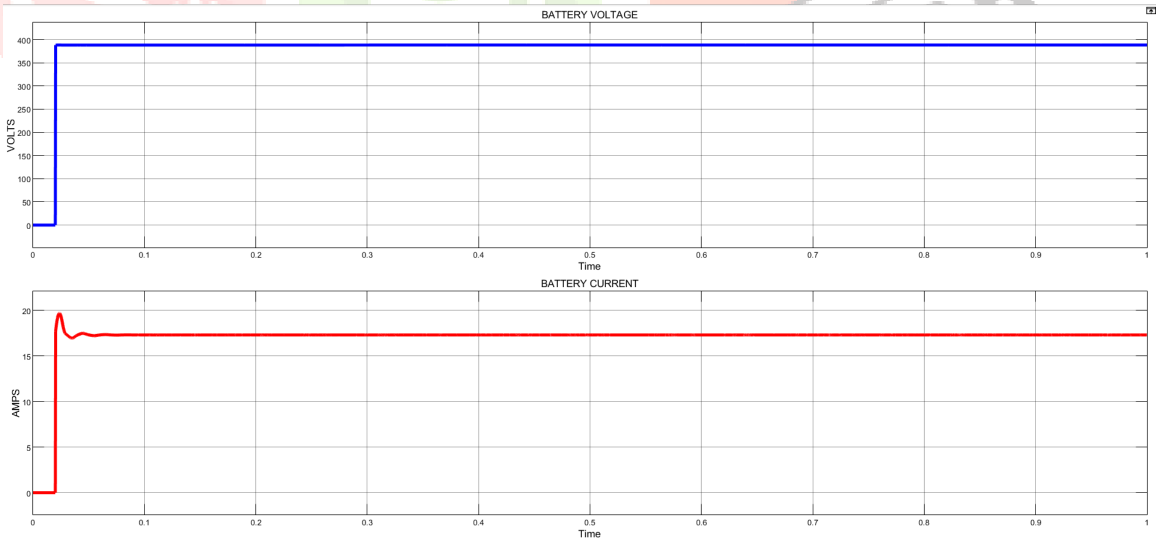

Fig.14 Battery Voltage and Current at 20cm

5.7 State of Charging Moniter (SOC)

The State of Charging (SOC) meter displays the trend in battery charge versus time for varying amounts of mutual inductance, which equal 10cm, 15cm, and 20cm of coil spacing. In every case, SOC rises linearly, indicating regular and continuous charging throughout the length of the simulation.But a more detailed comparison indicates that the increase in SOC is slightly more rapid at greater coil distances. This is consistent with the increased current at the battery side, which results in increased power delivery in the same time period. In spite of the decrease in mutual inductance with distance, the system compensates well by resonance tuning to sustain good energy transfer performance.The SOC curves therefore prove that the resonant wireless charging system not only guarantees stable performance under different coil distances but can also adjust to less coupling by facilitating increased current flow for better charging efficiency without upsetting voltage regulation.This state of charge or SOC battery is an important metric for any practical use as well as efficiency measurement of an electric vehicle charging system. In this enhanced MATLAB/Simulink model, the SOC estimation block has been included to show real-time simulation of the charging process when input current and voltage are applied.

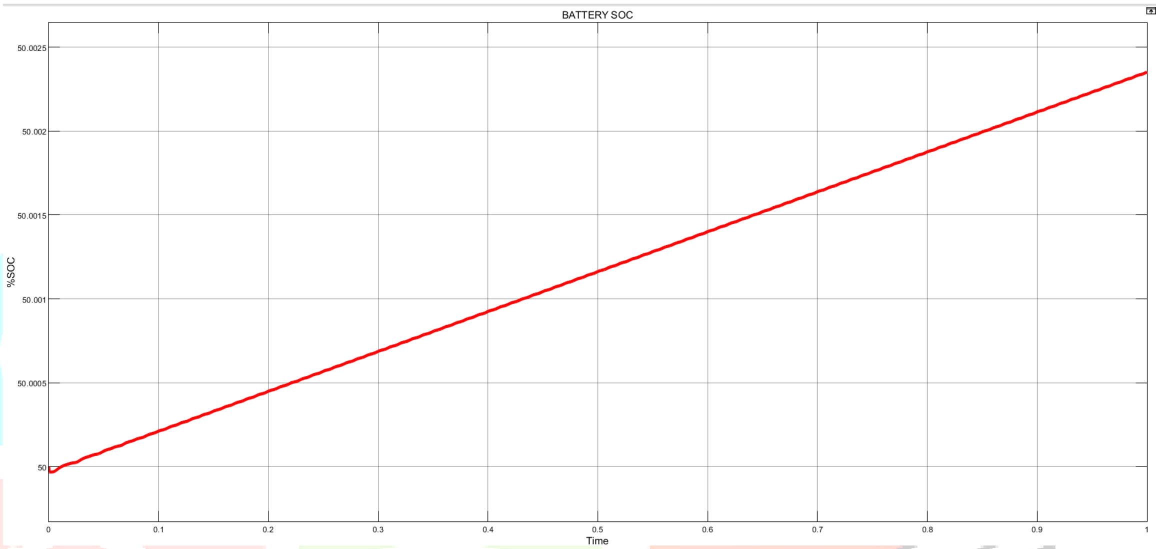

Fig.15 State of Charging at 10cm

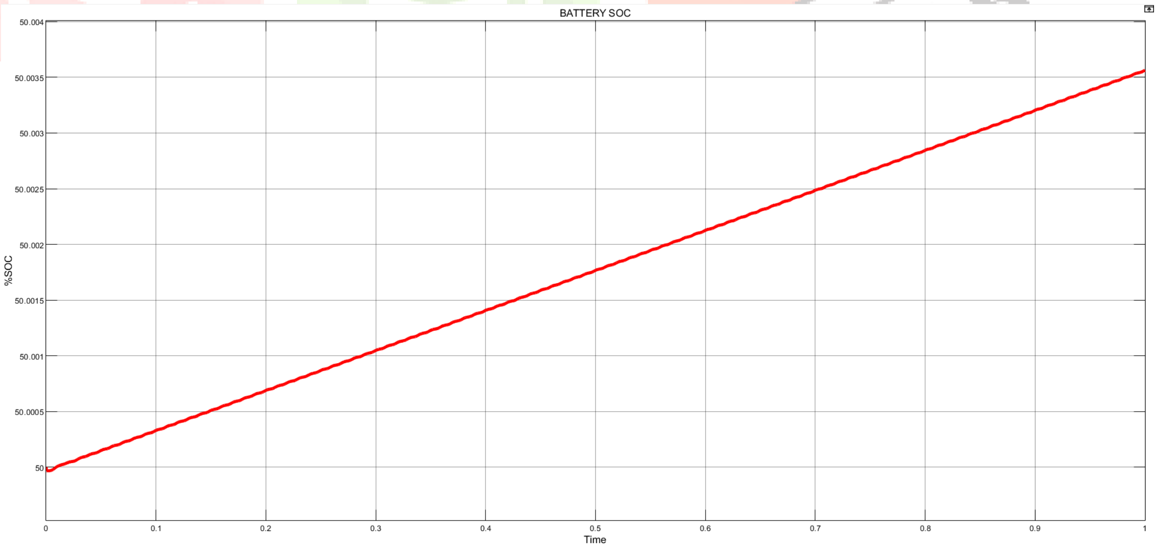

Fig.16 State of Charging at 15cm

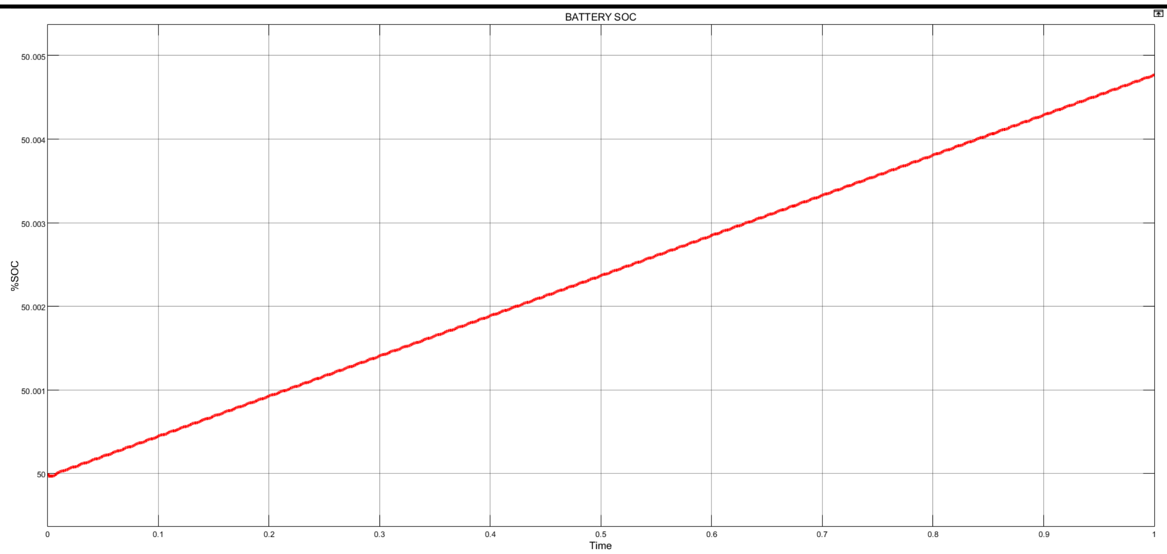

Fig.17 State of Charging at 20cm

VI. CONCLUSION

In the present research, an effective wireless power transfer (WPT) system for charging electric vehicle batteries was established and simulated through MATLAB/Simulink. The model consisted of a high-frequency inverter, compensating network, full-bridge rectifier, and battery with SOC tracking. The simulation was successfully able to show stable voltage regulation, smooth current flow, and safe battery charging under resonant conditions.One major improvement on this work was the addition of simulations under three distinct mutual inductance levels, equivalent to varying coil spacings (10cm, 15cm, and 20cm). As against traditional assumptions whereby power transmission tends to drop with increased separation, the experiments registered a moderate boost in power delivery at longer distances. The impact was experienced in battery current, SOC progression, and rectifier output. The enhancement is due to the resonant inductive coupling configuration of the system, which dynamically ensures efficiency in energy transfer by tuning into optimal resonance, even with lower magnetic coupling.These results highlight the pragmatic relevance of circuit compensation and tuning techniques within real-world WPT implementations. The results show that effective wireless energy transfer is possible under different distances, as long as the system is operated at or near resonance. Overall, the suggested WPT model is a resilient and adaptive solution for mid-range EV charging applications.

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