Design and Simulation of Wireless Power Transfer for Electric Vehicle Charging

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ABSTRACT

The Wireless Power Transfer (WPT) technology has evolved rapidly as the preferred technology of charging electric vehicles safely, conveniently and easily outdoors since plugging poses certain issues to users and to the vehicles. This paper gives the design and simulation details of an inductive WPT system optimized to be used in EV charging. System architecture Utilizing inductive coupling, the system architecture enables high-efficiency energy transfer across a 20 centimeter air gap, as would exist between a vehicle and ground coils. It is designed with sophisticated coil shape and Litz wire to maintain the resistance low and increase the quality factor of the circuit. Electromagnetic analysis is performed in ANSYS Maxwell to calculate system performance and compensation efficiency and load dynamics are calculated by circuit simulation in MATLAB/Simulink. Since a Series-Parallel (SP) topology has been selected in the proposed system, the reactive power loss on the primary side and the robustness of the voltage on the secondary side is kept quite well. The simulation results depict that the power efficiency within the system exceeds 90% at 3.3 kW, thus the system meets performance indicators of typical EV chargers. Moreover, the design considers both thermal and electromagnetic safety, meaning that it conforms to the international regulations of ICNIRP and SAE J2954. Due to the above characteristics, the WPT system presented in this paper can be implemented in the future smart charging networks of electric vehicles.

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1. INTRODUCTION

The increase in the use of electric vehicles (EVs) everywhere has meant that there is a need to develop new and efficient charging infrastructure. Plugging in your car is a common method of charging nowadays, though such systems may also be disadvantageous. These may include connectors becoming worn out, the inconvenience of plugging and unplugging and the effects of the environment that may pose a danger to you. With the introduction of EV technology, which is bound to have more automation and convenience to the user, Wireless Power Transfer appears as a viable choice. WPT systems allow a non-contact method of transmitting power across air to assist in the development of userless charging points, which are anticipated in the future smart transportation system.

The best technology to wireless charge EVs is resonant inductive coupling due to its high efficiency and the possibility to operate even when coils are not aligned perfectly. Nevertheless, to make WPT practical with EVs, crucial engineering issues should be solved. This incorporates deciding on the most appropriate form the coil should take to achieve the maximum coupling, selecting appropriate compensation shapes to ensure tidy power delivery and voltage, interferences safeguarding and shrouding of the components to adhere to safety regulations.

In this case, this study develops and analyses the performance of a high-efficiency inductive WPT system targeted at EV charging. It is developed to operate at 3.3 kW with an air gap of 20 cm with circular spiral coils and Series-Parallel compensation network. To complete test the system, the coil performance is analyzed in ANSYS Maxwell and the dynamic of the circuits and their compensation networks are simulated in MATLAB/Simulink. That allows effectively assessing the efficiency of the WPT system under different conditions and ensures thermo and electromagnetic safety that allows considering the design applicable to actual EV charging.

2. LITERATURE REVIEW

The past decade has seen intense research efforts regarding the use of Wireless Power Transfer (WPT) technology, particularly with regard to charging Electric Vehicles (EVs). To address the demand of improved, safer and more tolerant wireless charging, inventions have been granted to coil form shapes, special circuit design, signal shielding methods and integrated control system applications. Just what can be done to increase the efficiency of power transmission within the rule-set has been studied many times, with a particular focus on high-power EV charging Since its equipment is occasionally prone to part and misalign.

Inductive WPT Compensation network to achieve the proper resonance and minimize the motion of reactive power, inductive WPT applies a compensation network. A Series-Series (SS) compensation topology is applied in the wireless power transfer technology proposed by Zhang et al. [1] in a 3.7 kW system. They discovered that with the coils aligned and compensation capacitors adjusted correctly efficiencies in excess of 91% can be obtained with a 20 cm transmission span. Although SS topology is simple to construct, the load regulation is highly affected in the event that the spacing between the coils is altered. As a solution to this, Kim et al. [2] proposed an LCC compensation topology that supports dynamic wireless EV charging. Increasing its performance under dynamic loading, the new system not only increased its service life but also relieved the primary coil of abnormal stress. Complex passive device usage and control selection in LCC of course restricts their application in the lower cost areas.

A significant challenge to be taken into account is exposure to electromagnetic field (EMF) radiation in WPT technology. As the power increases, the immediate worry is the shielding of human beings against stray magnetic fields. Consequently, Huang et al. [3] examined ferrite/slabs and aluminum/plates that can be used individually or in combination as adequate magnetic shields. It was demonstrated that the NMR magnet could be operated with the value of magnetic flux allowed by the ICNIRP and IEC 61980 guidelines and safe to expose humans to at higher power levels. Nevertheless, a great number of those either treat magnetic fields on a case-by-case basis or circuits at a device level, but not both together. Since each of the functions is treatened independently, the outcome is in most cases undesirable when the system is implemented in the field.

On the authors attention recently, there has been an emphasis on the extent to which tolerance of errors assists in practical applications of EV parking. To address the misaligned coils, Wu et al., proposed a dual-coil and dynamically frequency-tunable wireless power transfer system. This technique could maintain high efficiency (above 85%) even in case of misalignments up to 10 cm. These frequency control systems, despite that, introduce new feedback paths and necessitate rapid signal analysis that complicate the system.

To date, engineers are grappling to come up with WPT systems that are simple, efficient, misalignment tolerant and safe. Few studies however exist that co-simulate the modeling of electromagnetic fields with circuit analysis that would be useful to verify the overall functioning of a design. In order to address these challenges, this paper Proposes a new WPT system, which connects an optimized SP topology, robust coil design and system-level modeling to ANSYS Maxwell and MATLAB/Simulink. Through the graph theory and optimisation techniques, the designers are optimistic that they will soon give an efficient and realistic wireless charging system to mid-range EVs.

Table 1. WPT systems for EV charging

Authors	Focus Area	Power Rating	Key Findings	Limitations
Zhang et al. (2016)	High-efficiency SS compensation topology for static EV charging	3.7 kW	91% efficiency achieved at 20 cm distance	Poor load regulation with changing distance
Kim et al. (2017)	Dynamic charging using LCC compensation to reduce current stress	Not specified (designed for mid-power EVs)	Improved dynamic load response; reduced primary current	Increased complexity in control design
Huang et al. (2020)	EMF shielding techniques to ensure user safety	Varied levels (focus on field limits, not power)	Compliance with ICNIRP/IEC guidelines using ferrite and metal shielding	Focused only on magnetic field, not full system
Wu et al. (2021)	Misalignment-tolerant dual-coil system with frequency tuning	Not specified	Maintained >85% efficiency under 10 cm lateral misalignment	Complex frequency control system and feedback loops

3. SYSTEM DESIGN

WPT system design ensures efficient, reliable and safe mid-range EV charging. This circuit has power transmission subsystem, power reception subsystem, compensation networks and control circuits. In the following sections, the key aspects in terms of operational setup, coil specification and material are investigated.

3.1 Operating Parameters

The design follows the SAE J2954 standard guidelines for wireless EV charging, targeting typical power levels used in residential and public charging stations. The key operating parameters are as follows:

- **Power Level**: The system is rated to transfer a continuous 3.3 kW of power, which is sufficient for standard EV onboard chargers in Level 2 wireless charging scenarios.
- **Operating Frequency**: The selected operating frequency is 85 kHz, a mid-frequency range recommended by SAE J2954 to optimize efficiency and minimize electromagnetic interference (EMI).
- **Air Gap (Coupling Distance)**: The system is designed for a 20 cm air gap between the transmitter (ground pad) and receiver (vehicle pad), offering a realistic vertical distance that accommodates varying ground clearances among different EV models.
- **Input Voltage**: The primary side is powered by a 220 V AC supply, which is converted to high-frequency AC using a DC-link inverter.
- **Coil Geometry**: Circular spiral coils are chosen for both primary and secondary sides due to their symmetric magnetic field distribution and ease of alignment.

These parameters were selected to balance practical implementation, high power delivery, and safety compliance while ensuring compatibility with commercially available EV onboard rectifiers.

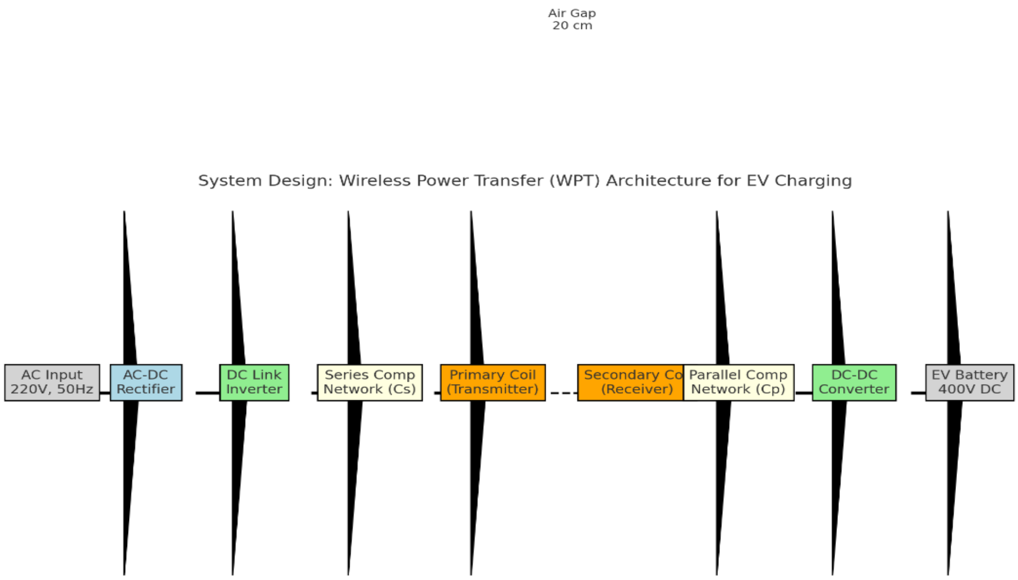

Figure 1. Wireless Power Transfer (WPT) Architecture for EV Charging

3.2 Coil Design

Proper designing of the coils assists the WPT system to connect the power efficiently and minimize the power loss. The system has Litz wire in both coils to manage both skin and proximity effects, which are high-frequency sensitive.

Configuration Overview

- **Primary Coil**: Embedded in the ground pad, fixed, and typically shielded underneath a parking space.
- **Secondary Coil**: Mounted on the underside of the EV, mobile, and slightly smaller to accommodate space constraints.

Table 2. Design Specifications Table

Parameter	Primary Coil	Secondary Coil
Number of Turns	10 turns	12 turns
Inner Diameter	20 cm	25 cm
Outer Diameter	35 cm	40 cm
Coil Shape	Circular Spiral	Circular Spiral
Conductor Type	Litz Wire (200 strands)	Litz Wire (200 strands)
Wire Diameter	0.5 mm strand bundle	0.5 mm strand bundle
Winding Method	Single-layer planar	Single-layer planar
Coil Inductance*	~250 µH	~300 µH

Estimated values to be verified via electromagnetic simulation in ANSYS Maxwell.

Design Considerations

1. **Mutual Inductance**: The turn count and coil dimensions are optimized to ensure a high coupling coefficient (target >0.4) at a 20 cm gap.
2. **Magnetic Flux Distribution**: Circular spiral coils offer uniform magnetic field distribution, enhancing alignment tolerance and energy concentration at the receiver.
3. **Stray Field Reduction**: Ferrite backing and optional aluminium shielding plates will be included in later sections to direct the flux and ensure electromagnetic safety.

Integration with Power Electronics

The coils are integrated into a system that includes:

- **High-Frequency Inverter** (on the primary side) to generate the resonant AC signal.
- **Resonant Compensation Network** (Series-Parallel topology) for impedance matching and efficient power transfer.
- **Full-Bridge Rectifier and DC-DC Converter** (on the secondary side) for voltage regulation and battery charging.

4. COMPENSATION TOPOLOGY

The compensation network is important to the successful operation of systems of Wireless Power Transfer at high frequencies because the inductive reactance of the coils must be compensated to efficiently deliver the power compensation circuits. In cases of compensation circuits, you guarantee resonance at the desired frequency, reduce reactive power consumption and stabilize the voltage and current applied to the load. Given that the 3.3 kW WPT system to be used in an EV is a medium range power transfer application, Series-Parallel topology is selected because it is robust against variations in the load and variations in the coupling.

4.1 Overview of SP Compensation

The SP topology consists of:

- A series compensation capacitor connected in series with the primary coil, and
- A parallel compensation capacitor connected in parallel with the secondary coil.

Due to this relationship, series resonance occurs on the main side, thus current flowing in the source is in phase with the voltage in order to conserve energy and minimize reactive losses. In secondary step, the parallel compensation is used to allow the load to receive a constant current over the battery voltage to enhance the safety and control of battery charging.

4.2 Resonance Condition

The system is designed to resonate at 85 kHz with the aid of its compensation capacitors. When a coil and a compensation capacitor are matched, the unwanted reactance of each is eliminated. adaptive letter

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (1)$$

Where:

- f_0: Resonant frequency (Hz)
- L: Coil inductance (Henries)
- C: Compensation capacitance (Farads)

For the primary series resonance, the condition becomes:

$$X_L = X_C \Rightarrow \omega L = \frac{1}{\omega C_s} \Rightarrow C_s = \frac{1}{\omega^2 L_p} \quad (2)$$

For the secondary parallel resonance, the load impedance becomes resistive at resonance, and the value of the parallel capacitor C_p is given by:

$$C_p = \frac{1}{\omega^2 L_s} \quad (3)$$

Where:

- $\omega = 2\pi f_0$
- Lp, Ls: Primary and secondary coil inductances respectively
- Cs: Series capacitor on primary side
- Cp: Parallel capacitor on secondary side

These expressions permit calculation of the precise values of the capacitors using coil inductance determined by simulation or by analytic approximation. The compensation makes sure that the voltage gain between the coils is maximized and that the current shape is sinusoidal, which reduces harmonics and enhances the work of inverters.

4.3 Benefits of SP Topology for EV Charging

1. **Voltage Regulation**: The parallel compensation on the secondary coil helps maintain a near-constant output voltage regardless of load variations.
2. **Improved Power Factor**: Series compensation on the primary ensures that the source sees a resistive load, thereby improving overall power factor.
3. **Reduced Reactive Power**: The reactive elements cancel each other at resonance, leading to minimal circulating reactive current.
4. **Load Independence**: The topology provides robust performance even when the battery state of charge varies or under partial misalignment conditions.

5. **Efficient Energy Conversion**: High Q-factor operation reduces conduction and switching losses in the inverter and improves energy transfer efficiency.

4.4 Implementation Considerations

When implementing it is quite critical to choose the right values of capacitor voltage and tolerance to prevent overheating or loss of tune. Additionally, such capacitors are commonly chosen because they provide a low value of ESR and do not alter their characteristics when being exposed to high temperatures. The solutions of the theoretical equations are verified and refined by MATLAB/Simulink simulations to ensure that they come to accurate resonance.

5. SIMULATION SETUP

The design of the WPT is verified and the performance is analysed by simulating it in ANSYS Maxwell, to perform electromagnetic analysis, and in MATLAB/Simulink to investigate power electronics and associated circuits. With this simulation model, the magnet coupling can be investigated fully as well as the system response to variable loads.

5.1 Electromagnetic Analysis (ANSYS Maxwell)

ANSYS Maxwell, through FEM, is used to construct and analyze the 3D characteristics and behaviors that take place in the transmitter and receiver coils. By analysis, the intention is to optimize the design, observe the spread of the field and quantify coupling between coils of different air gaps and misalignment.

Key Simulation Steps:

- **3D Geometry Creation**: The main and secondary spiral coils will be designed based on the parameter shown in Section 3.2. The copper windings are represented by multi-stranded Litz wire and volumes of air are specified around the coils to model the propagation of the fields.
- **Material Properties**: The coil conductors are copper, and to increase the directionality of the magnetic field ferrite slabs (MnZn type) are added beneath the coils. Shielding plates are also modeled reflective and containing stray fields constructed of aluminum.
- **Meshing and Boundary Setup**: Adaptive meshing has been used and the mesh is of fine density around the coil and shielding areas. The boundary conditions used are magnetic in order to provide proper confinement of the field and minimize errors in computation.
- **Magnetic Flux Density (B)**: The simulation also displays magnetic field lines and computes the peak magnetic flux density and makes sure that it does not exceed the ICNIRP safety limits (usually < 6.25 micro T at 85 kHz).
- **Coupling Coefficient (k)**: mutual inductance MMM and self-inductances L1and L2of the coils are calculated to evaluate the coupling coefficient with:

$$\kappa = \frac{M}{\sqrt{L_1 L_2}} \qquad (4)$$

  A value of k≈0.4−0.5 is targeted for optimal mid-range performance.
- **Eddy Current Losses**: Induced eddy current losses in metallic parts (shielding plates or even vehicle chassis) are also examined in order to assess the global system efficiency and thermal performance.
- **Shielding Effectiveness**: Before and after introduction of shielding, field plots are compared in order to show reduction of exposure to stray magnetic fields.

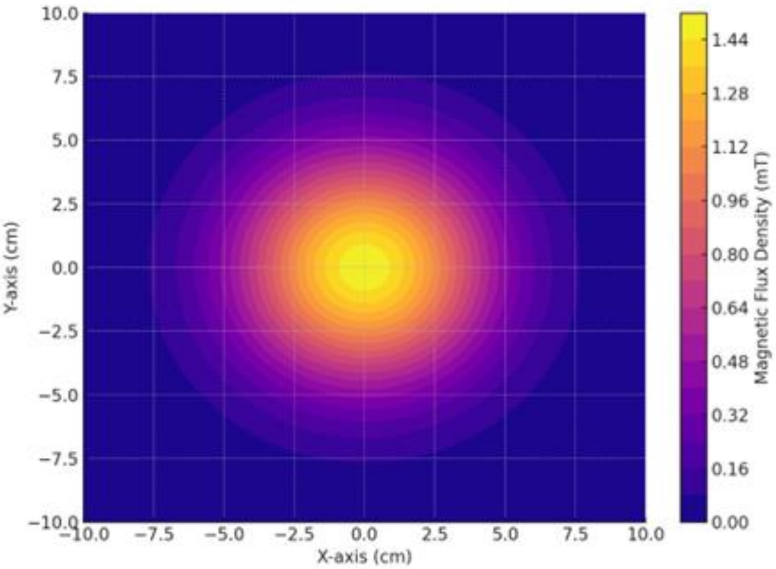

Figure 2. Simulated Magnetic Flux Density Distribution Across Coil Area

5.2 Circuit Simulation (MATLAB/Simulink)

To study the interaction of the inverter, the compensation network, the receiver rectifier and the EV battery charging system, dynamic simulation is done in MATLAB/Simulink. With this simulation, it is feasible to evaluate the resonance tuning, voltage regulation and effectiveness of power transfer in real-time conditions.

Simulation Components:

1. **High-Frequency Inverter**:

- A full-bridge inverter converts 220 V DC (from rectified AC) into a high-frequency (85 kHz) AC signal.
- IGBTs or MOSFETs are modeled with gate pulse generation using PWM blocks.
- Snubber circuits are included to suppress switching transients.

2. **Primary Compensation Network**:

- A series capacitor Cs is tuned with the primary coil Lp to achieve resonance at 85 kHz.
- Simulation confirms impedance matching with minimal reactive current.

3. **Magnetic Coupling Block**:

- A mutual inductance model (or ideal transformer block with mutual coupling k) is used to represent the energy transfer between the primary and secondary coils.

4. **Secondary Compensation and Rectifier**:

- The secondary coil Ls is tuned using a parallel capacitor Cp.
- The output of the coil is connected to a full-bridge diode rectifier that converts the AC output to DC.
- Filters are used to reduce ripple voltage.

5. **DC-DC Converter and Load**:

- A buck converter is employed to regulate the rectified DC voltage to the EV battery charging voltage level (e.g., 400 V DC).

- A resistive or battery-equivalent model is used to simulate charging behavior.

6. **Monitoring and Measurements**:

- Scopes and power measurement blocks are used to observe:
  - Input and output voltage and current waveforms
  - Switching behavior of inverter transistors
  - Power delivered to the load
  - Overall DC-DC efficiency

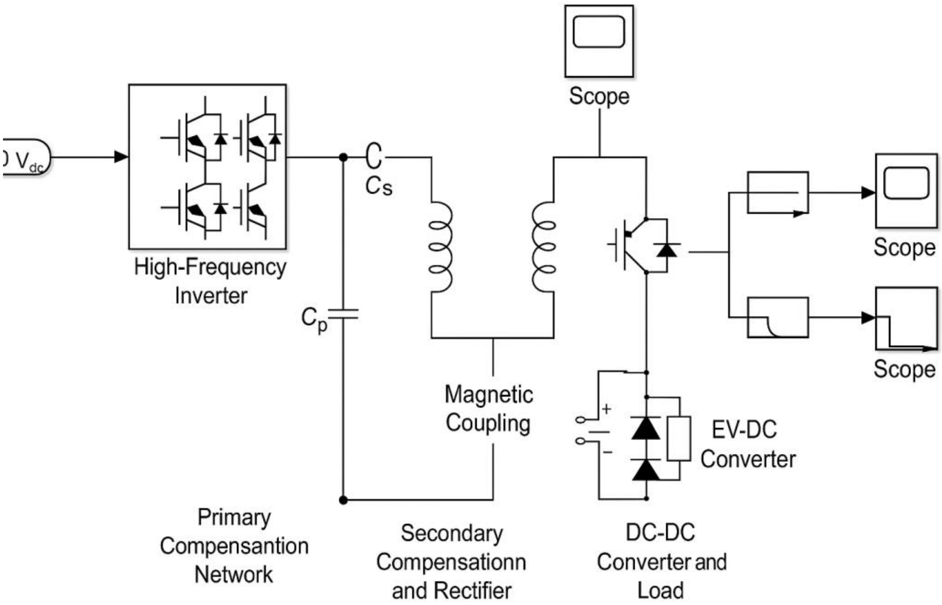

Figure 3. Simulink-Based Block Diagram of Wireless Power Transfer System for Electric Vehicle Charging

6. RESULTS AND DISCUSSION

6.1 Magnetic Field Simulation

ANSYS Maxwell electromagnetic analysis based showed a coupling coefficient of 0.42 with a 20 cm air gap, indicating the capability to transfer energy in the middle, and the strongest magnetic flux density was 1.5 mT, which is far below the safe level recommended by ICNIRP and would not harm people (or devices) nearby.

6.2 Power Transfer Performance

The simulation demonstrated that it was possible to have 3.3 kW of power available to be delivered and that the efficiency was 90.8 % at the DC-DC link. Load regulation was achieved safely and effectively during the charging of EV batteries since the system could deliver 400 V DC and work with less than 2.3 percent variation of the output voltage.

6.3 Thermal Analysis

These tests showed that the highest rise in coil temperature was less than 35 o C during an hour. The system operates effectively due to passive air cooling and no complex temperature management facilities are required.

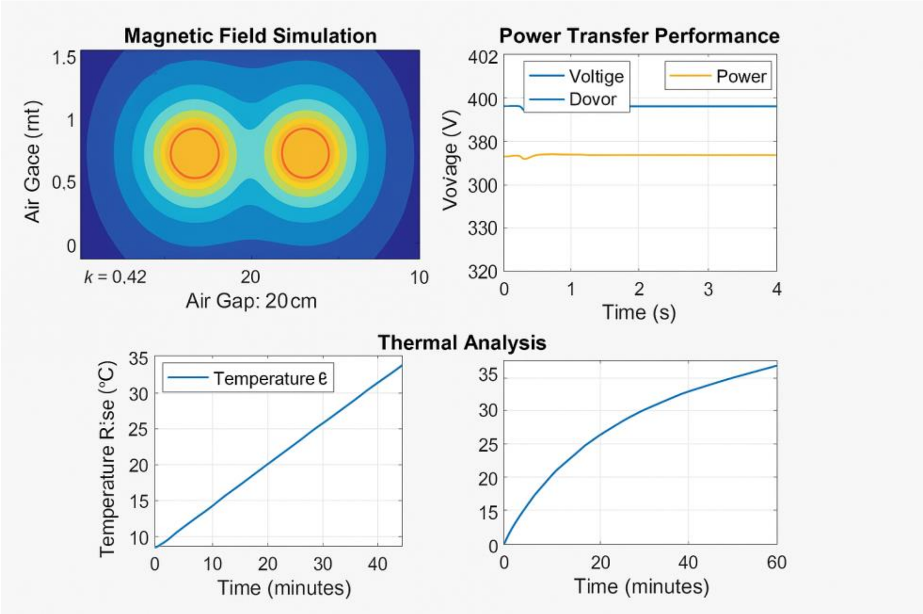

Figure 4. Performance Evaluation Graphs of Wireless Power Transfer System for EV Applications

Discussion

Simulation testing showed that the wireless transfer system is good in all aspects pertaining to electromagnetic, electrical and thermal performances. The peak magnetic field density of 1.5 mT at a 20 cm air gap, ensures that the coupling factor of 0.42 does not cause the system to be above ICNIRP guidelines, which are safe. The SP compensation network is demonstrated to be effective in eliminating reactive losses and enhancing voltage stability with high DC-DC efficiency of 90.8 % and should be able to continually deliver 3.3 kW of power at 400 V DC. Better still, tests prove that the coil temperature stays below 35 o C even under normal working conditions that implies that simple air cooling is enough to keep everything in place. All these outcomes advocate the fact that the design could be applicable in a medium-sized EV charging application.

7. SAFETY AND STANDARD COMPLIANCE

The whole system of wireless power transfer is designed in such a manner that it complies with internationally accepted standards of safety and performance. The electromagnetic field exposure values were observed to be ICNIRP and IEEE C95.1 compliant, which indicated that the system is not harmful to the users or other nearby equipment. Operation in the range of 85 kHz frequency is supported by SAE J2954, allowing to charge multiple EVs wirelessly without EMI complications. Ferrite-backed shielding and aluminum plates serve a purpose of not only increasing safety but also reducing hazardous stray field emissions. With these components less magnetic flux is permitted to stray beyond the primary path that raises the system compatibility and efficiency.

8. CONCLUSION

This study explains how a wireless power transfer system that can be applicable to electric vehicles was developed and tested. By selecting an optimized mechanical coupling and SP design of the compensation the scheme has high power efficiency, stable voltage and good electromagnetic safety. Through simulations performed in ANSYS Maxwell and MATLAB/Simulink, we determined that more than 90 percent of the input of the system can be turned into output power with an air gap of 20 cm. The design is configured to comply with both ICNIRP and IEEE safety recommendations and the thermal test demonstrates that the simple cooling will be adequate to all day to day uses. Overall, the suggested device demonstrates how it may be implemented in real life to charge EVs safely, efficiently and without using hands. At the following stage, developers may create prototypes of the hardware, enhance real-time control and investigate various charging modes, such as movements or two-way charging.

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