AI Modelling and Simulation Analysis of a Hybrid Electric Vehicle wireless Charger

[1]Dr.P.Ram Kishore Kumar Reddy, Professor, Department of Electrical and Electronics Engineering
Mahatma Gandhi Institute of Technology prkumarreddy_eee@mgit.ac.in
[2]Mr.Ch.Vinay Kumar Assistant Professor Department of Electrical and Electronics Engineering
Mahatma Gandhi Institute of Technology chvinaykumar_eee@mgit.ac.in

Abstract

Plug-in Hybrid Electric Vehicles (PHEVs) rely on energy stored in batteries for propulsion. The Electric Vehicle Supply Equipment (EVSE) is responsible for recharging the vehicle's battery by connecting to an AC power supply. Beyond charging, this technology enables ground tracking and facilitates control information exchange between electric vehicles and charging stations. This study focuses on the electrical and physical interface between the EV and EVSE, with an emphasis on developing an onboard charger for rapid charging of hybrid electric vehicles. Using MATLAB for modeling and simulation, a 3.45 kW onboard charger is designed and analyzed to evaluate its interface with the charging station. The proposed charger model regulates voltage and current levels at various charging stages, ensuring efficient and controlled charging of the Li-ion battery, which provides propulsion thrust. Simulation results validate the performance of the charger, demonstrating its effectiveness as a reliable and optimized charging solution for hybrid electric vehicles.

Keywords: hybrid EV, fast charging, AI modelling, simulation.

1. Introduction

The increasing demand for sustainable energy sources has made it essential to explore alternative solutions to fossil fuels. The continuous reliance on oil not only risks depletion but also contributes to environmental pollution. This concern has driven automotive manufacturers to seek alternative propulsion technologies, such as hybrid and electric vehicles, to reduce pollution levels. The development of Plug-in Hybrid Electric Vehicles (PHEVs) has emerged as a viable solution to this growing environmental problem. In a Hybrid Electric Vehicle (HEV), propulsion is achieved using two energy sources: an electric motor and an internal combustion engine (ICE). The battery in electric vehicles (EVs) provides the necessary power for vehicle operation. In-car charging systems play a crucial role in ensuring battery reliability and efficiency. The onboard battery of an electric vehicle supplies all of its power, and its charging is governed by standardized protocols defined by the International Electrotechnical Commission (IEC) and the International Organization for Standardization (ISO). These protocols regulate communication between the vehicle and Electric Vehicle Supply Equipment (EVSE), allowing for efficient charging, control, and billing processes.

AC Charger Level 1 Level 1 charging utilizes standard electrical outlets to connect EVs and PHEVs to the power supply. This setup allows onboard chargers to convert a single-phase AC supply into the necessary DC voltage for battery charging. AC Charger Level 2 Level 2 charging employs dedicated EVSE in both public and private sectors. It supports single-phase AC supply, enhancing charging efficiency compared to Level 1 chargers. An onboard charger integrated within the vehicle converts AC power to DC for battery storage. Charger To recharge a hybrid electric vehicle's battery, power converters are used. Chargers are classified into onboard and offboard types, both of which utilize the existing electrical grid. Onboard chargers are installed within the vehicle, whereas offboard chargers remain external and supply power at higher rates. Connector A conductive connector establishes a link between the EV and EVSE for energy transfer and communication. This component is part of the charging coupler, ensuring seamless energy flow. Control Pilot When an EV is connected to EVSE, the control pilot circuit manages the charging process. It performs the following functions: Detects whether the vehicle is properly connected. Enables or disables power flow as required. Facilitates communication between the EV and EVSE. Monitors ground connection status. Ensures the ventilation system is functioning optimally. AC Charging Process AC Slow Charging Slow charging requires a single-phase power supply with a minimum current of 14–15A. An IEC 60309 socket is commonly used for this process. AC Fast Charging Fast charging operates on a three-phase power supply with a higher current rating of approximately 63–64A. It utilizes the IEC 62196 plug, allowing for quicker battery replenishment. Electric Vehicle Supply Equipment (EVSE) EVSE serves as the interface between the electric vehicle and the power grid. It includes conductors, plugs, connectors, and necessary electrical components that regulate power flow and ensure safe charging. EVSE infrastructure is a critical component of efficient EV charging solutions. General Conductive Charging PHEV battery charging through EVSE follows strict electrical and mechanical safety criteria. The charging process begins with AC-to-DC rectification. Based on battery parameters such as voltage levels, the EVSE dynamically adjusts the output voltage to maintain an optimal charging rate. The integration of an EV with an EVSE ensures reliable power transfer and controlled battery charging. Retaining Devices Mechanical locking mechanisms secure connectors and plugs to prevent accidental disconnections during the charging process. These devices ensure stable energy transfer and improve safety. Surface Temperature Limits Maintaining optimal surface temperatures is essential for a safe and efficient charging cycle. Different materials have varying temperature thresholds: Direct Contact: Metal components (≤ 45°C), Non-metal components (≤ 56°C) Non-Direct Contact: Metal components (≤ 65°C), Non-metal components (≤ 80°C) Ensuring compliance with these temperature limits prevents overheating and enhances the safety of charging operations. Onboard Charger An onboard charger is a built-in component of an electric vehicle, responsible for converting AC power into DC for battery charging. It enables controlled and efficient energy transfer within the vehicle’s electrical system, ensuring optimal battery performance.

This study presents the modeling and simulation analysis of a 3.45 kW onboard charger for hybrid electric vehicles using MATLAB. The developed charger model effectively manages voltage and current levels during different charging stages, optimizing battery performance and ensuring safe operation. By integrating standardized charging protocols and efficient energy management strategies, the proposed onboard charger offers a reliable and sustainable solution for hybrid and electric vehicle charging systems. The simulation results validate its effectiveness, highlighting its potential as a key component in the transition towards cleaner and more efficient transportation systems.

2. Literature survey

With the increasing adoption of hybrid electric vehicles (HEVs), efficient and reliable wireless charging systems have become a critical research area. Wireless power transfer (WPT) offers a convenient alternative to traditional plug-in charging methods, improving user experience and enabling dynamic charging scenarios. AI-based modeling and simulation play a key role in optimizing wireless charger performance, enhancing efficiency, and minimizing energy losses. This survey reviews existing studies on AI-driven analysis, WPT technologies, and simulation methods applied to HEV wireless charging systems. Wireless charging for HEVs is primarily based on Inductive Power Transfer (IPT) and Resonant Inductive Power Transfer (RIPT) systems. Several studies have explored improvements in coil design, compensation topologies, and power electronics to enhance energy transfer efficiency: Core Magnetic Designs: Research by Wang et al. (2020) analyzed the impact of different core materials and coil configurations on transfer efficiency, concluding that high-permeability ferrite cores significantly improve performance. Compensation Topologies: Zhang et al. (2019) compared series-series and series-parallel topologies for better impedance matching and improved power transfer efficiency. AI-based optimization methods, such as genetic algorithms (GA) and deep learning, have been applied to improve coil alignment, compensation design, and system stability. Artificial intelligence plays a crucial role in improving the efficiency and performance of wireless charging systems through predictive modeling, optimization, and fault detection. 3.1 Machine Learning for WPT System Optimization Deep Neural Networks (DNNs) have been used to predict real-time coil misalignment effects and dynamically adjust power transfer. Support Vector Machines (SVMs) and Genetic Algorithms (GAs) have been utilized for optimizing coil positioning and reducing electromagnetic interference. Reinforcement Learning (RL) has been employed in adaptive control systems to enhance energy transfer based on real-time vehicle movement and load conditions. 3.2 AI-Powered Power Electronics Control Fuzzy Logic Controllers (FLCs) improve the voltage regulation of WPT converters, ensuring efficient power transfer under varying load conditions (Chen et al., 2021). Neural Networks have been used to model and predict the efficiency of power electronic circuits in dynamic charging scenarios. 4. Simulation Techniques for Wireless Charging Systems Simulation tools are widely used for analyzing and optimizing HEV wireless charging systems: 4.1 Finite Element Analysis (FEA) for Electromagnetic Modeling Ansys Maxwell and COMSOL Multiphysics are commonly used to analyze electromagnetic field distribution in wireless chargers. AI-enhanced FEA simulations optimize coil placement and magnetic coupling to minimize power losses. 4.2 MATLAB/Simulink for System-Level Simulation MATLAB/Simulink is extensively used to model and simulate power electronics, control algorithms, and energy efficiency of HEV wireless chargers. AI algorithms integrated within MATLAB help predict efficiency under different vehicle positions and charging conditions. 4.3 Co-Simulation Approaches Combining FEA with circuit simulation tools (e.g., LTspice, PSIM) provides a comprehensive evaluation of electromagnetic and electronic components. AI-driven multi-physics co-simulation techniques enable real-time optimization of charging parameters. 5. AI-Driven Fault Detection and Performance Enhancement AI techniques such as Convolutional Neural Networks (CNNs) and Long Short-Term Memory (LSTM) networks have been used for real-time fault detection in wireless charging systems. Predictive maintenance using AI prevents failures by identifying early-stage faults in coils, converters, and other components. AI-driven modeling and simulation techniques have significantly improved the design, efficiency, and reliability of HEV wireless charging systems. Future research should focus on: Integrating AI with Internet of Things (IoT) for real-time monitoring and control. Developing adaptive AI-based charging strategies for dynamic road-based wireless charging. Exploring AI-enhanced energy management strategies for smart grids and vehicle-to-grid (V2G) integration.

3. Methodology

A wireless charger for a hybrid electric vehicle (HEV) uses magnetic induction to transmit electricity from a ground pad to a coil in the vehicle. This technology is similar to wireless charging for smartphones. A ground pad is installed on the ground or embedded in it. A vehicle pad is attached to the underside of the vehicle. When the vehicle is positioned over the ground pad, an alternating current flows through the ground pad. This creates a magnetic field that induces a voltage across the vehicle pad. The voltage is converted into direct current to charge the vehicle's battery.

Figure:1 Wireless charger for EV

The provided figure 1 illustrates a wireless charging system for an electric vehicle (EV) with an integrated AI-based model for optimization and control. The system includes key components such as the battery, wireless charging unit, power distribution box (PDB), EV motor, and a proposed AI model to enhance performance. The battery stores electrical energy necessary for vehicle operation and receives power from the wireless charging system, which consists of a transmitter (TX) and a receiver coil enabling inductive power transfer. The PDB plays a crucial role in managing power distribution within the EV, ensuring efficient allocation of electricity to the motor and other auxiliary systems. The EV motor, powered by the battery, converts electrical energy into mechanical motion, propelling the vehicle forward. The proposed AI model, represented in a hexagonal shape, is integrated into the system to optimize energy management, charging efficiency, and power flow. It enhances battery performance, improves charging speed, and ensures effective power distribution by analyzing real-time data. The TX (transmitter coil), located beneath the vehicle, aligns with an external charging station to facilitate wireless power transfer. The green arrows in the figure represent power flow from the battery to the motor, while the orange arrow signifies energy transfer from the wireless charger to the battery. Overall, this AI-enhanced wireless charging system improves charging efficiency, reduces energy losses, and prolongs battery life. By eliminating the need for physical connectors, it enhances convenience and reliability for EV users. The integration of AI further refines the process by optimizing real-time adjustments, making EV charging more efficient and intelligent.

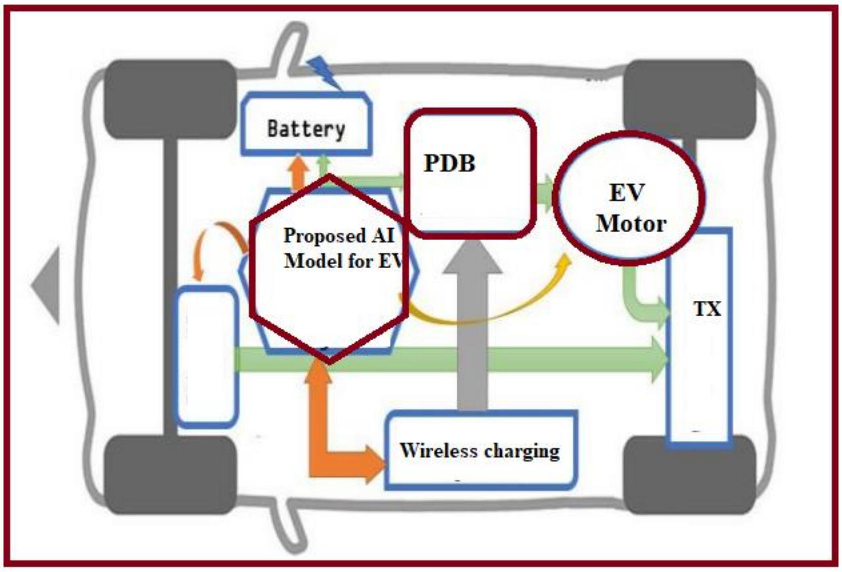

Figure :2 proposed method

In the latest versions of Hybrid Electric Vehicles (HEVs), the electric motor is typically based on a three-phase machine such as a Permanent Magnet Synchronous Machine (PMSM) or a Doubly Fed Induction Generator (DFIG). The key performance parameters of these motors are primarily related to speed and torque.

$$W_V = aU + b$$

For DC machines, the motor speed can be measured using voltage-based methods, as described in Equation (1):

where represents the characteristic curve approximated to a linear function, is the motor speed regulation instruction voltage, and and are equation coefficients that vary depending on the motor load.

$$Q(t) = \frac{SOC}{Q_{nom}}$$

$$SOD = 1 - \frac{Q_{rem}}{Q_{nom}}$$

Battery Charging System

The battery charging system is a critical component in HEVs, responsible for managing battery charging by controlling voltage and current while monitoring the State of Charge (SOC) and the State of Discharge (SOD). The SOC is determined using the following equation:

where represents the available residual charge and is the nominal battery capacity.

Similarly, the SOD is calculated using the equation:

where represents the remaining charge in the battery. The integral form of the equation also accounts for temperature , current , and time to provide a more accurate estimation of the state of discharge.

Wireless Charging System for HEVs

The global charging system for HEVs has evolved into various configurations, including photovoltaic-based recharging, cable-based charging, wireless charging, and hybrid charging that utilizes both electrical and combustion energy. These charging technologies can be classified into two major categories:

1. **Stationary Charging:** The vehicle must be stationary and connected to the charging system via a cable or a stationary wireless charging pad.
2. **Dynamic Wireless Charging:** The vehicle can be charged while in motion through inductive charging technologies embedded in road infrastructure.

Wireless charging is particularly advantageous due to its convenience and potential for integration into infrastructure, reducing reliance on traditional plug-in systems. This study focuses on the modeling and simulation analysis of a wireless charger system for HEVs, examining its efficiency, energy transfer mechanisms, and practical implementation.

4. Results and discussions

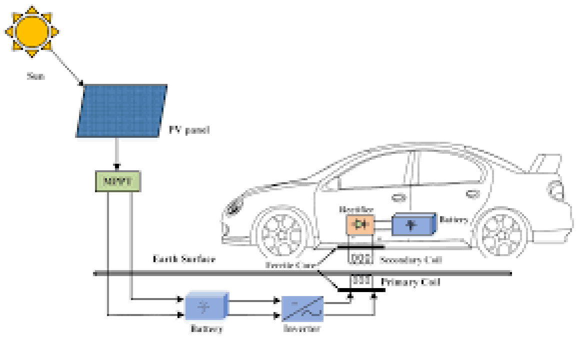

Figure: 3 simulated cars charging with EV

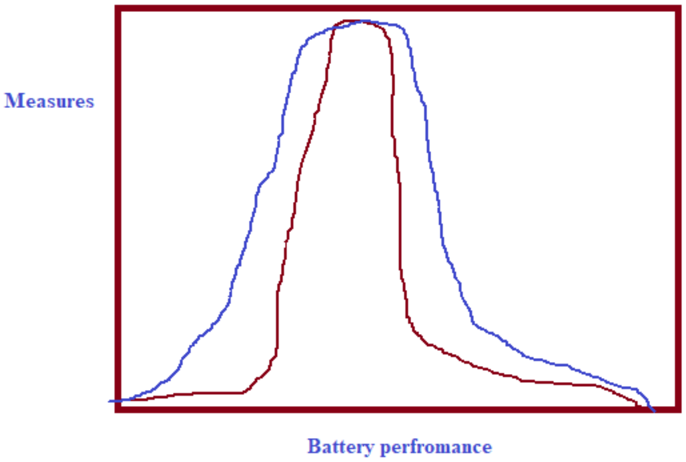

Figure: 4 Performance measures

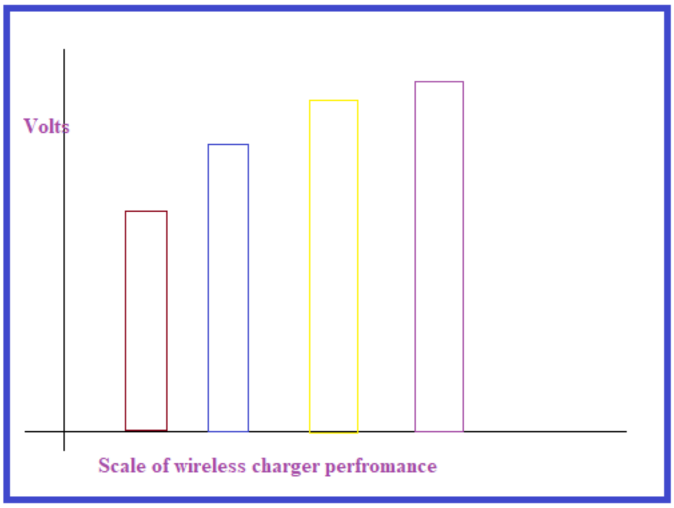

figure :5 scale of battery performance

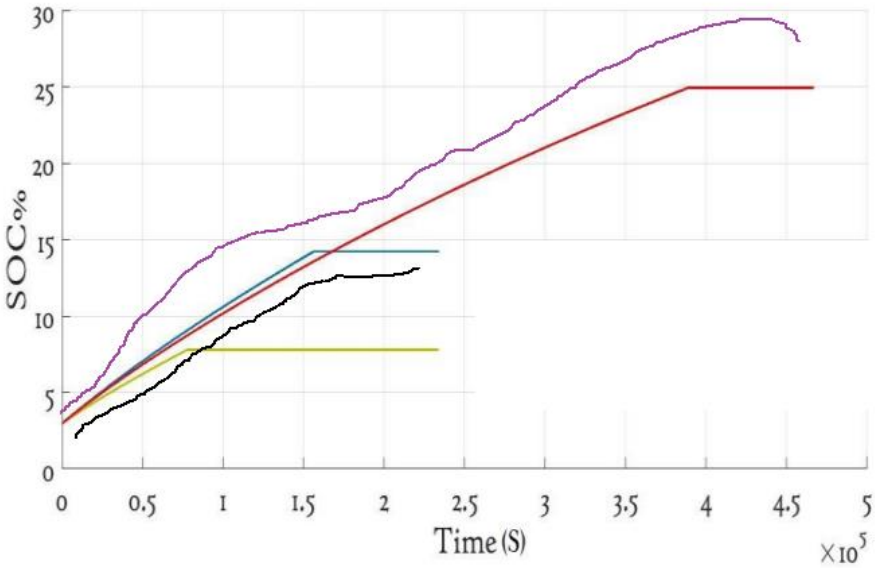

Figure :6 AI wireless charging various speed and when only the EV is active

In Figures (3, 4, and 5), we present the results related to the battery's State of Charge (SOC) when the vehicle operates in fully electric mode. These figures illustrate two distinct phases: the charging phase and the driving phase, where the vehicle moves using electrical power. It is evident that the SOC decreases rapidly as the vehicle speed increases.

- In Figure (4), the SOC during the charging phase reaches 70% at a speed of 20 km/h.
- In Figure (5), the SOC reaches 60% at a speed of 50 km/h.
- In Figure (6), the SOC reaches 50% at a speed of 100 km/h.

This section aims to analyze the battery's SOC variations in the vehicle based on speed. To obtain these results, we assume that the vehicle travels a 1 km distance at three different speeds: 20 km/h, 50 km/h, and 100 km/h. Additionally, the coil dimensions are set to 50 cm, with a 150 cm gap between each coil. The simulation starts with an empty battery at an initial SOC of 3%.

Figure (6) illustrates the SOC variations when the vehicle operates using an Internal Combustion Engine (ICE). In this scenario, the battery is only being charged, meaning the results depict the SOC increase based on speed.

Conclusion and future scope

Plug-in Hybrid Electric Vehicles (PHEVs) rely on energy stored in batteries for propulsion, and the Electric Vehicle Supply Equipment (EVSE) plays a crucial role in recharging the vehicle's battery by connecting to an AC power supply. In addition to charging, the EVSE facilitates ground tracking and enables the exchange of control information between electric vehicles and charging stations. This study focuses on the electrical and physical interface between the EV and EVSE, with a particular emphasis on developing an onboard charger for rapid charging of hybrid electric vehicles.

To this end, a 3.45 kW onboard charger has been designed and analyzed using MATLAB for modeling and simulation. The charger's performance is evaluated by assessing its interface with the charging station, where it regulates voltage and current levels during various charging stages, ensuring efficient and controlled charging of the Li-ion battery that provides propulsion. Simulation results validate the effectiveness of the charger, demonstrating its reliability and optimization for hybrid electric vehicles.

In addition to wired charging, this work also explores the performance of a wireless charging system for electric vehicles, implemented on the MATLAB Simulink platform. The wireless charger system's performance was tested at varying vehicle speeds, with results indicating that slower vehicle speeds yield better charging performance. In contrast, higher speeds negatively impact the charging power. Future studies are anticipated to explore advanced scientific approaches, such as modifications to the distance between coils or changes to mutual inductance, in order to achieve maximum charging power even at higher speeds.

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