

Design and Analysis of Smart Solar EV Charging System

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Abstract

The rising demand for electric vehicles (EVs) has generated an urgent requirement for sustainable and advanced charging systems. This study delineates the design and analysis of an intelligent solar EV charging system intended to reduce dependence on the grid and optimize the utilization of renewable energy. The system incorporates a solar photovoltaic (PV) array, battery energy storage, and an Internet of Things (IoT)-enabled smart controller to optimize power delivery. A maximum power point tracking (MPPT) technique is employed to optimize the energy harvesting efficiency of the photovoltaic system under fluctuating irradiance conditions. The photovoltaic system uses MPPT technology to improve energy harvesting efficiency in a variety of environmental circumstances. This method guarantees the best possible solar energy extraction even in the face of temperature and irradiance fluctuations. To carefully and effectively and economically control charging operations, the smart controller continuously checks system data, such as battery health, state of charge, and real-time solar availability. This clever control method increases battery life, reduces energy loss, and enhances system reliability. The smart controller ensures optimal performance and energy economy by controlling charging operations based on battery health and real-time sun availability. The efficacy of the suggested method in providing steady and very continuous charging is rigorously confirmed by modeling and validation using MATLAB/Simulink software. The system is a feasible and sustainable alternative for future EV infrastructure, as evidenced by simulation results showing enhanced energy utilization and decreased grid demand.

Keywords: Battery energy storage, IoT, MPPT, PV array, renewable energy, solar EV charging system

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INTRODUCTION

The rapid transition to electric mobility has resulted in an increasing dependence on electric vehicles (EVs) as a more environmentally friendly and efficient substitute for traditional fossil-fueled transportation. The rising demand for EVs presents a significant problem in establishing a highly sustainable and dependable charging infrastructure. Conventional EV charging stations predominantly receive electricity from the utility grid, which frequently depends on non-renewable resources. This behavior reduces the environmental benefits of EV adoption and adds to the strain on the grid. Eco-friendly and promising methods to address these issues involve incorporating renewable

energy, especially solar energy, into EV charging infrastructure. This study presents the design and analysis of an intelligent solar EVs charging system that uses solar photovoltaic (PV) energy as the principal power source. The system incorporates a battery energy storage system (BESS) and an intelligent energy management controller to optimize energy utilization and guarantee continuous charging. The key characteristics of the design encompass MPPT for optimal solar energy harvesting and an adaptive control system that responds to real-time variables, including solar irradiance, battery condition, and vehicle load requirements.

The proposed approach enhances energy optimization while facilitating load balancing and peak shaving in smart grid environments by diminishing dependence on traditional energy sources during peak demand periods. A comprehensive simulation of the system was conducted using MATLAB/Simulink to assess its performance under several operating conditions. The findings indicate that the intelligent solar charging system markedly improves energy efficiency and operational adaptability while reducing carbon emissions.

The objective of this study is to facilitate the creation of environmentally sustainable, cost-effective, and scalable EV charging infrastructures in accordance with the objectives of extensive global decarbonization. Additional advancements may involve the integration of Internet of Things (IoT) for adaptive control and real-time monitoring.

Background and Motivation

The worldwide shift to electric mobility has intensified the demand for sustainable and efficient EVs charging infrastructure. Traditional grid-dependent charging stations frequently depend on fossil fuels, thereby compromising the ecological advantages of EVs. Given the rising energy demand and concerns over carbon emissions, the incorporation of renewable energy sources, particularly solar power, into EVs charging systems represents a rational and environmentally sustainable solution. This project aims to develop an intelligent solar EVs charging system that optimizes renewable energy use while integrating advanced energy management to improve reliability, efficiency, and grid support in forthcoming smart energy networks.

LITERATURE REVIEW

The development of EV technologies has prompted significant investigation into effective and sustainable charging options. Numerous studies have highlighted the importance of renewable energy, advanced control systems, and grid support mechanisms to enhance EV charging infrastructures. Recent research has extensively examined the integration of renewable energy with EV charging infrastructures to address the dual concerns of energy sustainability and grid dependency. Ruan and Dahleh [1] presented a temperature-regulated intelligent charging system for EVs in frigid environments, highlighting the significance of adaptive charging methodologies. Arooj et al. [2] conducted an extensive assessment of smart charging systems, emphasizing the importance of energy sources and adherence to regulations. Stenstadvolden et al. [3] conducted a demand and sustainability analysis for level-3 EV chargers, highlighting the imperative for data-driven station development. To illustrate the possibilities of hybrid renewables, Singh et al. [4] evaluated the viability of combining solar-wind systems with EV charging stations. Kumar et al. [5] proposed a grid-interfaced PV-assisted charging approach that enhances power quality for residential consumers. Machine learning was used by Calero et al. [6] to regulate EV charging in distribution networks with solar integration. Yang et al. [7] improved scheduling accuracy by optimizing EV charging with PV systems using robust model predictive control. By creating a digital twin for EV charging stations, Francisco et al. [8] made fleet management more effective by simulating systems in real time. This research collectively provides a robust basis for intelligent, solar-powered EVs charging systems. However, most comprehensive studies lack simulation-based validation of both control logic and energy management in dynamic environmental settings. This study addresses this gap by developing a smart solar EVs charging system featuring intelligent control algorithms, real-time energy optimization, and extensive

performance analysis using MATLAB/Simulink.

Role of Smart Charging in EV Infrastructure

Smart charging is essential for enhancing EV infrastructure through intelligent, efficient, and adaptable energy management. Figure 1 illustrates a simplified design of the smart EV charging management system. In contrast to traditional charging systems, smart charging utilizes real-time data to enhance charging schedules according to energy availability, grid circumstances, and customer preferences. This alleviates the peak load strain on the grid and improves the overall system efficacy. When combined with renewable sources, such as solar energy, smart charging optimizes the use of clean energy while ensuring continuous service. It also facilitates load balancing, demand response, and remote monitoring, rendering it indispensable for the development of sustainable and future-ready EV charging infrastructures [9].

Proposed Smart Solar EV Charging Layout

Figure 2 shows the proposed smart solar EV charging layout, which depicts a sophisticated EV charging infrastructure that incorporates renewable energy sources, energy storage systems, bidirectional converters, and intelligent control mechanisms to guarantee efficient and sustainable functionality.

DESCRIPTION OF REQUIRED COMPONENTS

Renewable Energy Input

The system initiates with renewable energy sources, such as solar and wind, which produce direct current (DC) power. The system interfaces with these sources using power electronic converters to regulate variable inputs and guarantee compatibility with grid and storage systems.

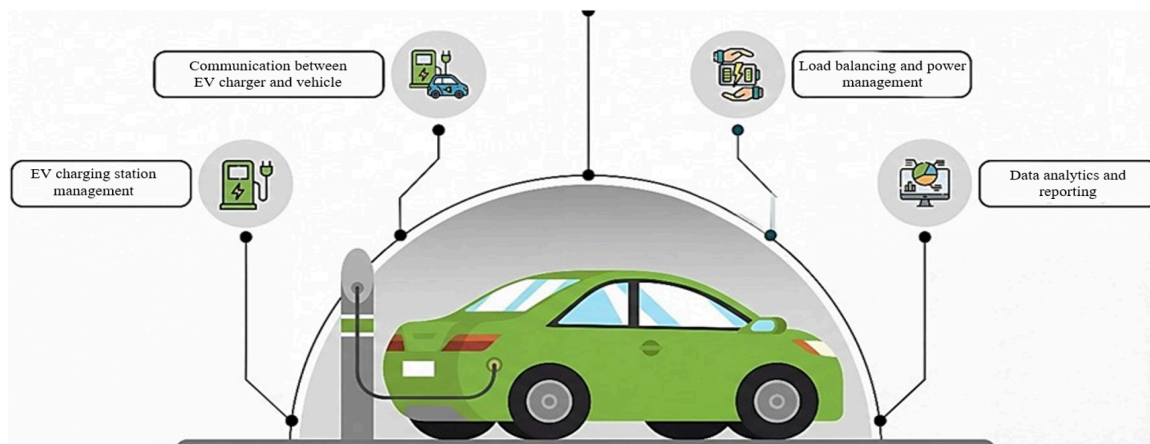


Figure 1. Smart EV charging management system.

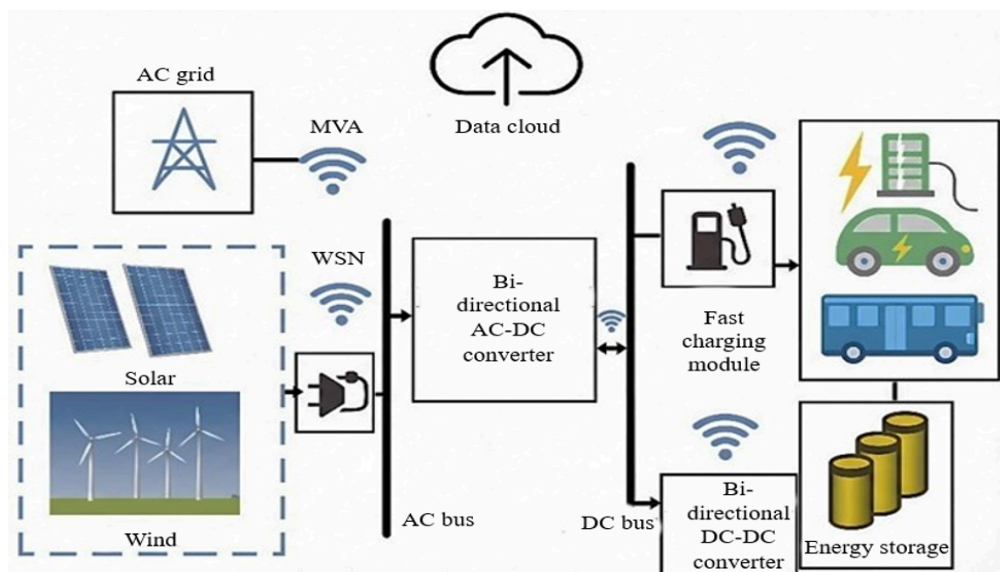


Figure 2. Wide range smart fast-charging station for electric vehicles.

Alternating Current Grid Interface

An alternating current (AC) utility grid connection is incorporated into the design for backup or supplementary power. The microgrid voltage analyzer (MVA) and wireless sensor network (WSN) allow for the real-time control and monitoring of the system and grid energy flows.

AC–DC Conversion and Data Cloud Integration

The AC bus (from the grid or renewables) and DC bus are connected by a bidirectional AC–DC converter. Smart energy management and predictive maintenance are facilitated by the data cloud, which enables remote monitoring, control, and analytics.

DC Bus and Load Management

The DC bus functions as the primary hub for energy delivery. It facilitates two principal pathways:

- *Fast-charging module*: Channels electricity to EVs (cars and buses), facilitating expedited charging functionalities.
- *Energy storage system (ESS)*: Regulated via a bidirectional DC–DC converter, which facilitates the charging and discharging of batteries according to system requirements.

METHODOLOGY

The planned smart ultra-fast mega EV charging station [10] represents a substantial advancement in next-generation level-4 charging infrastructure, intended to accommodate existing and developing electric car technologies. This modern system, equipped with IoT-enabled features, can provide charging voltages of up to 2 kV and a power output of 1 MW, rendering it suitable for electric automobiles and heavy electric vehicles (HEVs). The active dual-control method regulates both the DC bus and charging voltage, ensuring efficient energy transfer from the AC grid to EVs batteries while preserving a unity power factor. This facilitates adaptable and rapid charging for various vehicles [11]. The intelligent system incorporates a WSN for real-time surveillance of charging parameters and battery conditions. Information is transmitted to a central controller, cloud, service provider, and end-user. Cloud-based analytics facilitate functions, such as problem diagnosis, battery health notifications, and performance enhancement. These scalable stations facilitate the development of cleaner, more intelligent, and sustainable transportation systems. The block and flow diagrams of the proposed strategy based on the methodology are illustrated in Figures 3 and 4, respectively.

The smart solar EV charging system [12] functions using a systematic process designed for optimal energy efficiency. The process initiates by assessing solar energy availability and thereafter charges

the electric car if the solar power surpasses a designated threshold. In instances of inadequate solar energy, the system reevaluates the conditions or explores alternative sources; however, specifics are not provided in the flowchart. IoT technology is employed to monitor energy flow and system performance

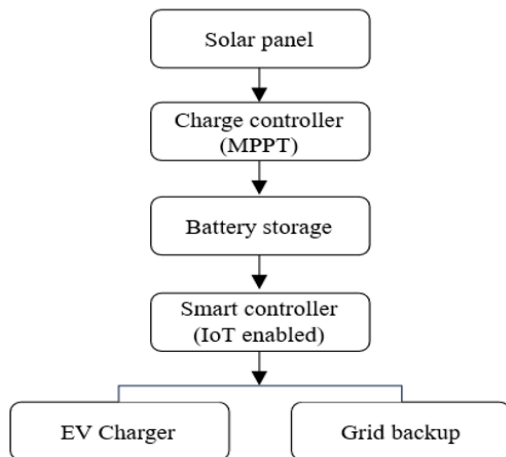


Figure 3. Block diagram of the proposed system.

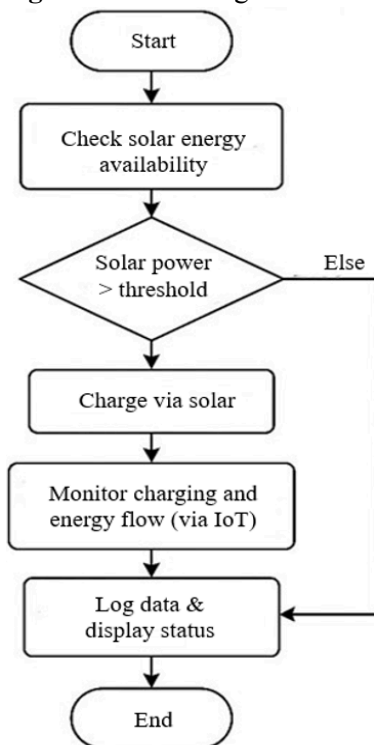


Figure 4. Flow diagram of the proposed system.

in real-time while charging. The system records data and presents status updates for user awareness. This guarantees a dependable and environmentally sustainable charging procedure with sophisticated control and energy management [13].

The flow diagram depicts the operational procedure of a smart solar EV charging system. The procedure commences with assessing the accessibility of solar energy. If solar power exceeds a specified threshold, the system initiates the charging of an electric car using solar energy [14]. The system utilizes IoT-based technology to actively monitor the charging process and energy flow while

charging. Subsequently, it records the data and presents the system state for real-time observation. If the available solar power is inadequate, the system reverts to evaluate solar energy availability to assure the optimal utilization of renewable resources.

Simulink Model of The Proposed System and Its Working Principle

Figure 5 shows a Simulink diagram of a smart solar EV charging system. This system integrates various renewable energy sources, including solar, wind, and battery storage, to facilitate efficient and sustainable vehicle charging. The solar photovoltaic system comprises a photovoltaic array that captures solar energy and converts it into direct current (DC) electricity. This electricity is subsequently increased in voltage by a boost DC–DC converter. An MPPT controller is utilized to optimize power extraction under fluctuating irradiance conditions using methods such as perturb and observe or incremental conductance. The wind energy system employs a wind turbine linked to a permanent magnet synchronous generator (PMSG) to transform wind energy into AC power. This is corrected and controlled using a boost converter equipped with its own MPPT mechanism to enhance energy output. The battery bank is regulated using a bidirectional DC–DC converter, facilitating both charging and discharging, and functioning as a backup during periods of insufficient renewable energy supply. All sources converge into a centralized DC microgrid operating at 300 V DC, facilitating power distribution to various loads. A DC/AC converter and filter supply three-phase 220 V AC for local loads, whereas an IoT-based smart controller manages energy flow, MPPT operations, and charging priority. The system supplies power to three electric vehicles (EV1, EV2, and EV3) using DC/DC chargers and regulators employing pulse modulation techniques to guarantee stable and balanced charging [15]. The

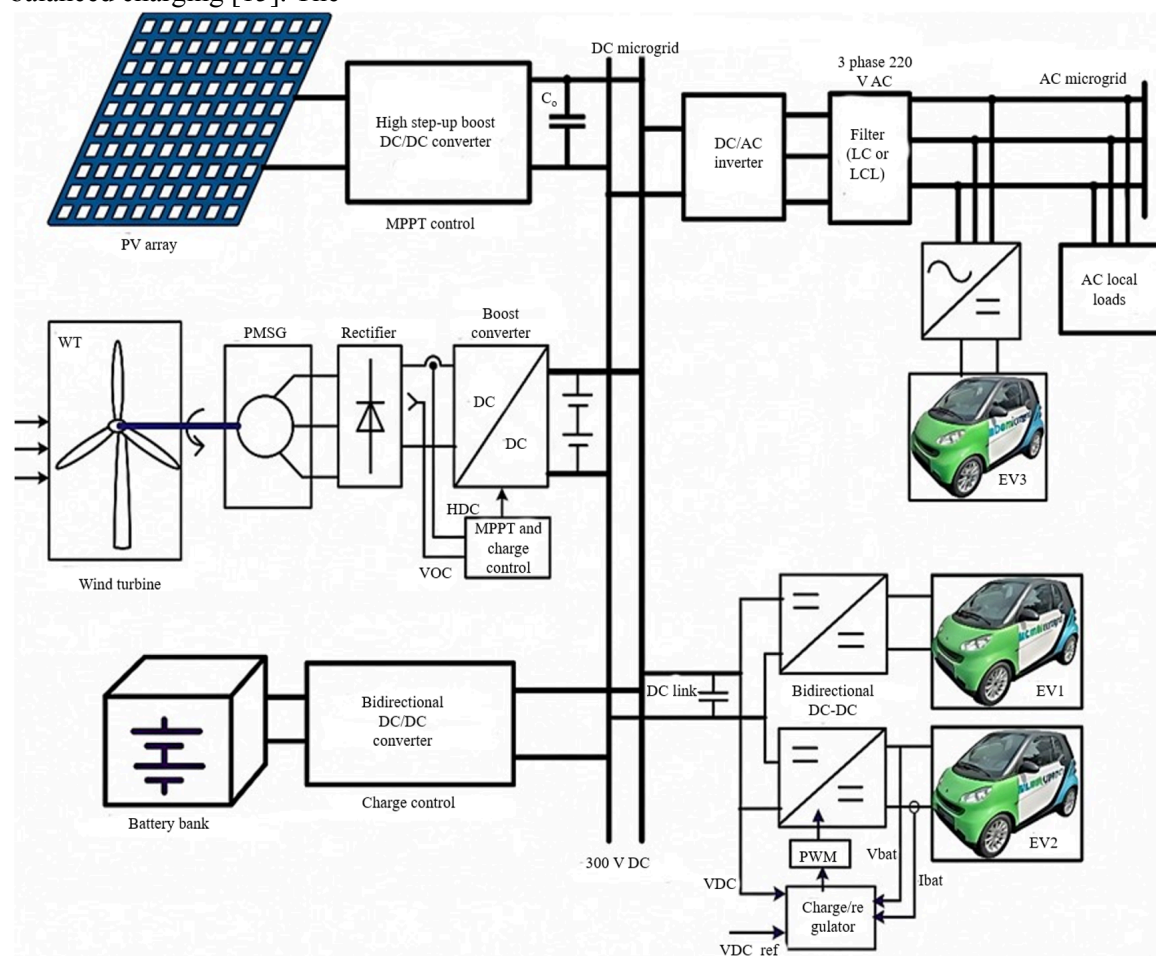


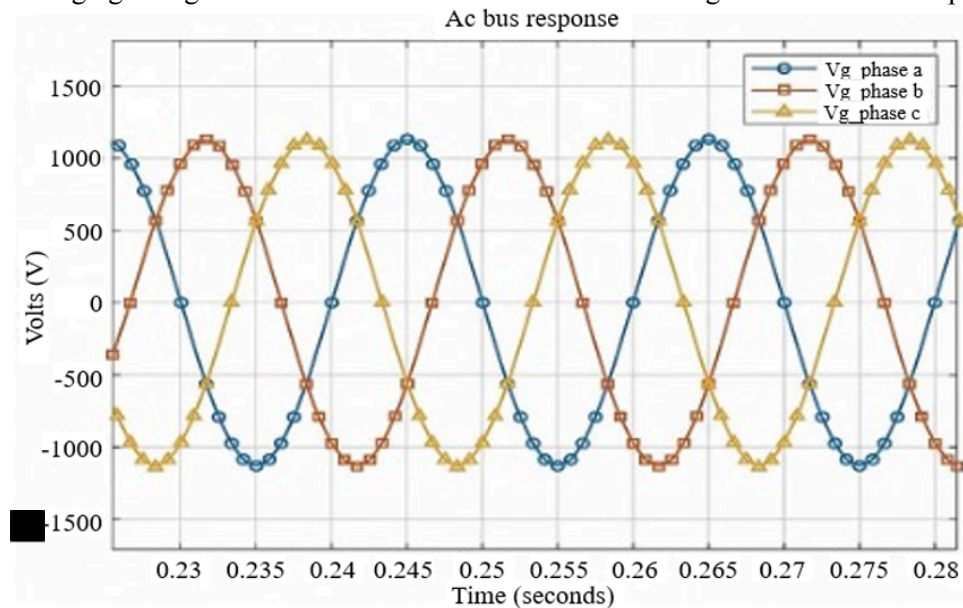
Figure 5. Simulink model diagram of the proposed system.

model, simulated with MATLAB/Simulink, assesses performance across varying irradiance and load conditions, emphasizing the reduction of grid dependence, enhancement of energy efficiency, and assurance of uninterrupted charging. The system exemplifies an intelligent, efficient, and scalable approach for sustainable EVs infrastructure.

Simulation Result and Analysis

The mathematical models described in this section are used to evaluate two charging modes: Mode 1 (EV) and Mode 2 (HEV) in the simulation analysis. Utilizing a 1-MVA transformer, the system reduces the 11-kV grid voltage to 1.4-kV AC. The necessary DC voltage for charging is produced by an AC/DC converter that is regulated by a smart controller. The DC bus voltage is adjusted to 1800 V in Mode 1, which supports EVs with battery voltages of up to 1200 V. Mode 2 is intended for HEVs (such as buses and lorries) that require a voltage of up to 2000 V. Consequently, the DC bus voltage is increased to 2500 V. In all modes, power is conveyed from the grid to the fast charger at approximately 1 MW. The simulation monitors grid behavior during steady-state conditions, transients, and mode changes, emphasizing the charger's peak current response and stability. The findings, illustrated in Figures 6(a) to (c) and 7, validate the efficacy of the Inductor–Capacitor–Inductor (LCL) Filter, as the grid current maintains a nearly sinusoidal waveform with low harmonic distortion. The intelligent controller maintains a power factor of 0.99 while guaranteeing steady voltage and current performance. The charger's dependable and optimal performance is confirmed by the system's unity power factor management, which enables effective power transmission without phase distortion.

The intelligent controller manages DC bus voltages at 1800 V for EVs and 2500 V for hybrid EVs through gate signals in the UWBG AC/DC converter. Voltage stabilization transpires within 0.2



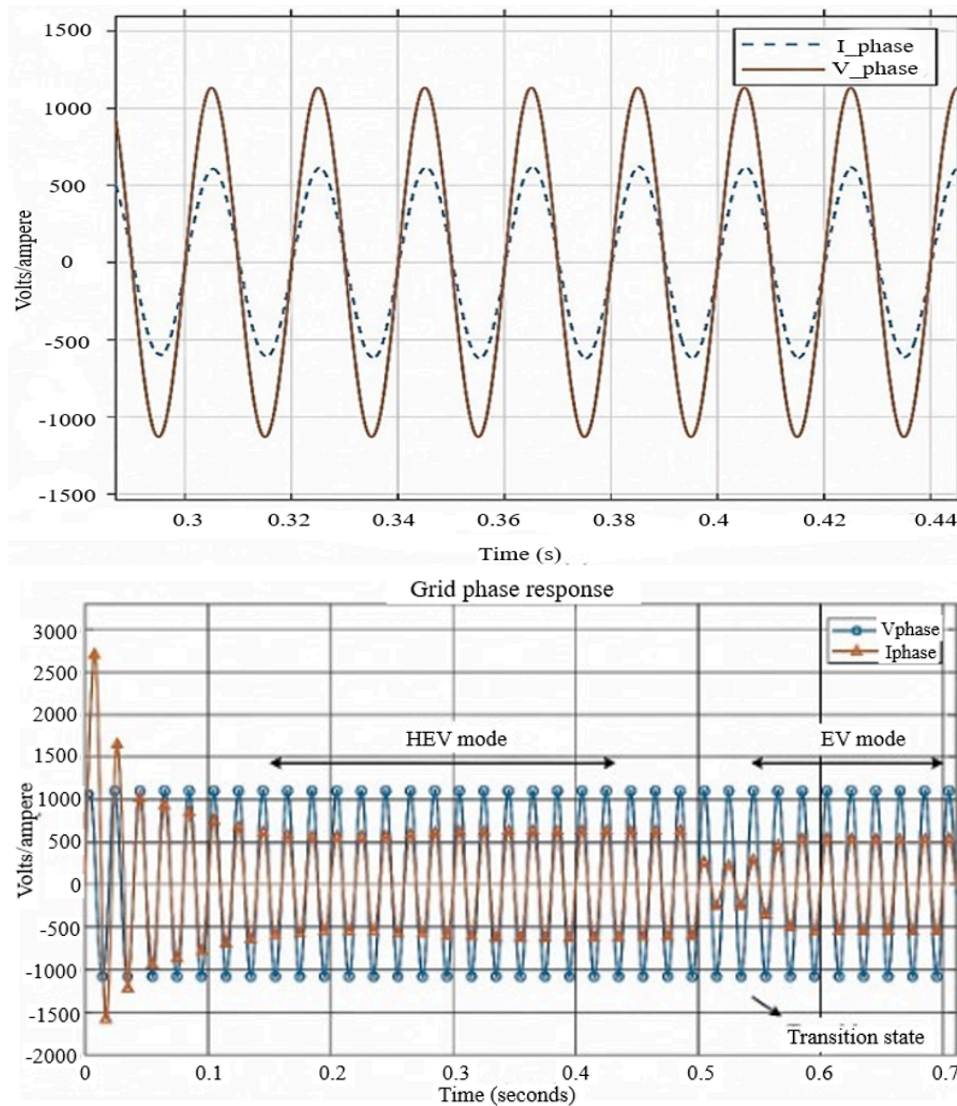


Figure 6. Three-phase response of AC bus; (a) grid voltage response, (b) grid current behavior, and (c) grid V-I phase response during HEV and EV charging.



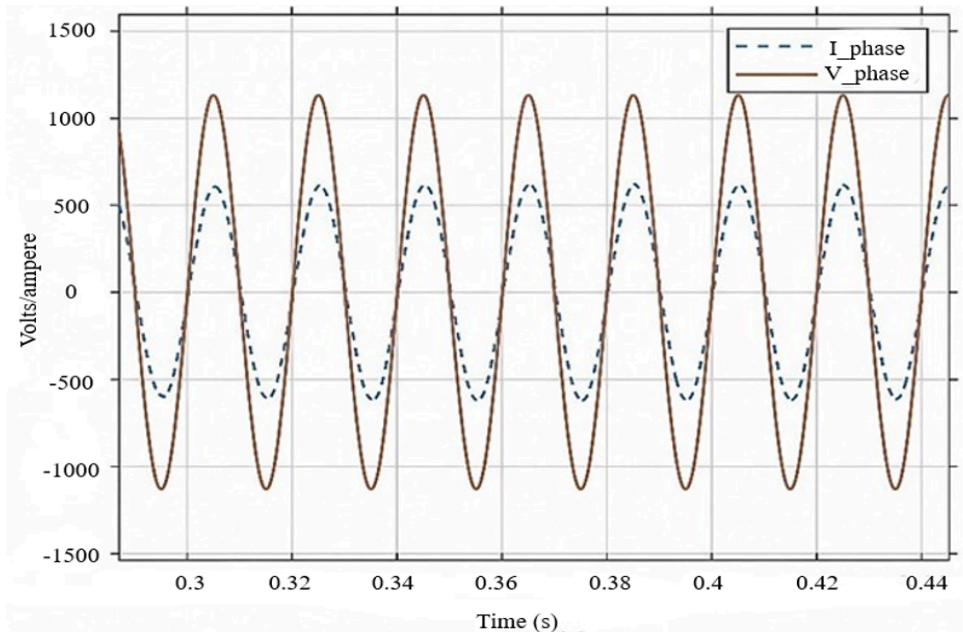


Figure 7. Unity power factor—controlled phase voltage and current response. Unity power factor—controlled phase voltage and current response.

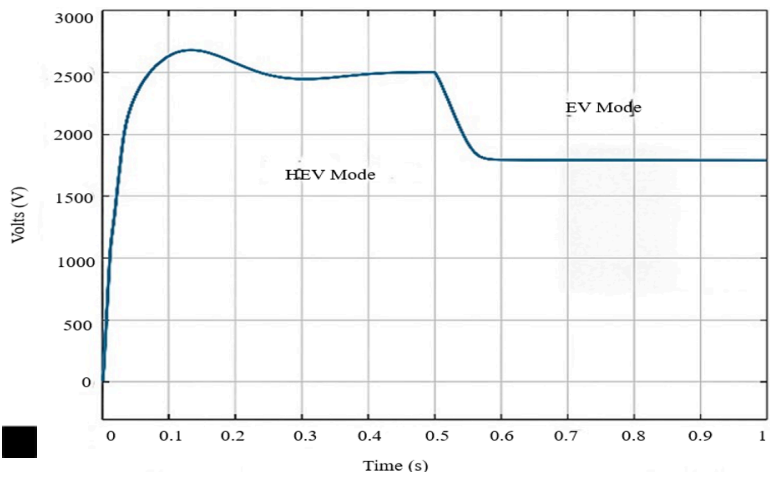
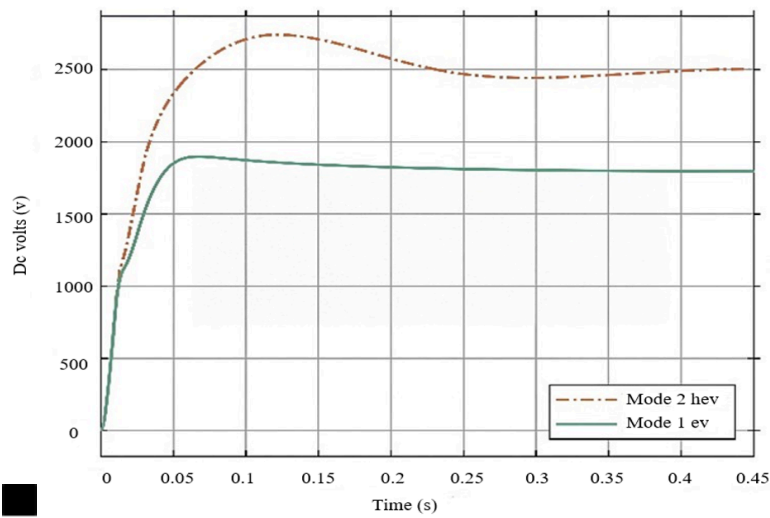


Figure 8. DC bus voltage response. (a) HEV and EV charging modes, (b) DC bus response during transition state.

seconds, accompanied by a rapid 0.1-second shift between charging modes, as illustrated in Figures 8(a) and (b), respectively. Additionally, this study introduces the design of an efficient EVs charger utilizing sophisticated AC–DC and DC–DC converters. An optimized LCL filter in a three-phase AC/DC converter minimizes harmonics and enhances the power factor. The discussion encompasses mathematical modeling, control strategies, and detailed converter equations. The LCL filter design, converter performance, and overall system efficacy for EV and HEV charging were validated by the simulation results.

CONCLUSION AND FUTURE SCOPE

The proposed smart solar EV charging system offers a thorough and sustainable solution to the increasing demand for electric mobility. By efficiently combining renewable energy sources—solar and wind—with battery energy storage and sophisticated power electronics, the system reduces grid reliance while guaranteeing uninterrupted and dependable EV charging. The integration of MPPT, bidirectional converters, and an intelligent IoT-based controller improves energy efficiency and real-time flexibility. The system's performance under various charging situations and climatic circumstances was tested through comprehensive modeling in MATLAB/Simulink. The results validate consistent voltage and current responses, few harmonics attributed to LCL filtering, and superior power quality with unity power factor regulation. The advanced dual-mode charging functionality for electric cars (EVs) and HEVs illustrate the system's adaptability and scalability. This study significantly advances the creation of intelligent, environmentally sustainable, and future-oriented charging infrastructure, which is vital for attaining global sustainability and clean energy objectives. Subsequent enhancements can augment the functionalities of this system. The use of artificial intelligence (AI) for predictive charging and energy management, blockchain for secure energy transactions, and vehicle-to-grid (V2G) capabilities can enhance flexibility and intelligence. The integration of ultra-fast DC charging and hybrid energy systems (e.g., solar, wind, and biomass) will expand applications. These technologies will facilitate the advancement of more intelligent, decentralized, and user-focused EVs charging networks in accordance with future energy and transportation objectives.

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