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ADAPTIVE SLIDING MODE CONTROLLED SOLAR-INTEGRATED RESIDENTIAL EV CHARGING SYSTEM WITH REAL-TIME PRICING OPTIMIZATION

[1]Pedda Reddy P, [2]P Abdul Nabi, [3]Dr. K Chitambaraiah Setty
[1]Associate Professor, [2]Student, [3]Professor
Department of EEE
St. John's College of Engineering & Technology, Yerrakota, Yemmiganur, Kurnool, A.P

Abstract

The rapid penetration of electric vehicles (EVs) in residential environments significantly increases energy demand and introduces operational challenges for distribution grids, especially during peak tariff periods. This paper proposes an advanced solar-assisted residential EV charging architecture employing a Sliding Mode Control (SMC) strategy combined with real-time electricity price-based optimization for intelligent energy management. The system integrates rooftop photovoltaic (PV) generation, a bidirectional DC–DC converter, battery energy storage, and EV charging infrastructure to enable flexible power flow between the grid, storage, and load. The SMC technique ensures robust regulation of DC-link voltage and charging current under varying solar irradiance, load disturbances, and grid fluctuations, outperforming conventional control methods in dynamic conditions. A dynamic pricing-based scheduling mechanism is incorporated to prioritize renewable energy utilization and battery discharge during high-cost intervals while permitting grid-dependent charging during low-price periods. Simulation validation carried out in MATLAB/Simulink demonstrates enhanced system stability, reduced peak grid dependency, improved energy efficiency, and notable cost savings. The proposed framework provides a resilient, economical, and scalable solution for next-generation smart residential EV charging systems integrated with renewable energy sources.

I. INTRODUCTION

The increasing concerns over environmental sustainability and depletion of fossil fuels have accelerated the global transition toward electrified transportation systems, particularly electric vehicles (EVs). The integration of EVs into residential power systems offers significant environmental benefits; however, it also introduces challenges such as increased peak demand, grid instability, and higher operational costs [1], [2]. Uncoordinated charging of EVs during peak hours can lead to voltage fluctuations, transformer overloading, and degradation of power quality in distribution networks [3], [4].

To mitigate these issues, the integration of renewable energy sources, especially solar photovoltaic (PV) systems, has gained considerable attention. Solar-assisted EV charging systems provide a sustainable and cost-effective solution by reducing dependence on grid power and utilizing locally generated clean energy [5], [6]. However, the intermittent nature of solar energy and dynamic load variations necessitate advanced control strategies to ensure stable and efficient system operation [7].

Conventional control techniques such as proportional–integral (PI) controllers have been widely used in EV charging systems, but they often suffer from poor dynamic response and reduced robustness under uncertainties and disturbances [8]. In contrast, Sliding Mode Control (SMC) has emerged as a powerful nonlinear control technique due to its robustness, fast convergence, and ability to handle parameter variations and external disturbances effectively [9], [10]. SMC-based approaches have demonstrated superior performance in maintaining DC-link voltage stability and regulating charging currents in renewable-integrated systems.

In addition to control strategies, energy management based on electricity pricing plays a crucial role in optimizing the operational cost of EV charging. Dynamic pricing mechanisms, such as time-of-use (ToU) and real-time pricing, enable intelligent scheduling of charging activities by shifting energy consumption to low-tariff periods [11], [12]. Recent studies have explored price-adaptive and demand response strategies to minimize grid stress and enhance economic benefits for consumers [13].

Furthermore, bidirectional power flow capabilities, including vehicle-to-grid (V2G) and vehicle-to-

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home (V2H) operations, provide additional flexibility in energy management. These technologies allow EVs to act as distributed energy storage units, supporting the grid during peak demand and improving overall system efficiency [14]. However, effective coordination between renewable generation, storage systems, and EV charging requires an integrated control and optimization framework.

Motivated by these challenges, this paper presents a Sliding Mode Control-based solar-assisted residential EV charging system with dynamic price adaptation. The proposed approach combines robust control with intelligent energy scheduling to achieve improved stability, reduced grid dependency, and enhanced cost efficiency.

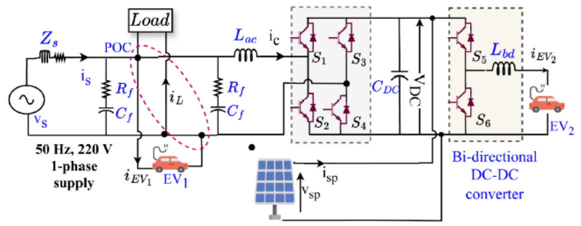

Fig1: System topology.

II. LITERATURE SURVEY

Recent advancements in electric vehicle (EV) charging systems have focused on improving energy efficiency, grid stability, and cost optimization through the integration of renewable energy sources and intelligent control strategies. Various research efforts have explored different control techniques, system architectures, and energy management approaches to address the challenges associated with EV charging in residential environments.

Adaptive filtering-based control techniques have been widely investigated for improving power quality in grid-connected EV charging systems. In [16], a least mean square (LMS)-based control approach was implemented for harmonic mitigation; however, it exhibited slower convergence under dynamic conditions. Similarly, [17] introduced a least mean fourth (LMF) algorithm that improved steady-state performance but suffered from increased computational complexity. To overcome these limitations, synchronous reference frame (SRF)-based control methods were proposed in [18], offering better harmonic compensation but requiring precise synchronization and complex implementation.

The integration of renewable energy sources with EV charging infrastructure has also gained significant attention. In [19], a solar PV-based EV charging system was developed with battery storage support to enhance energy reliability. However, the system lacked real-time adaptability to changing load and pricing conditions. A hybrid renewable energy-based charging station incorporating wind and solar sources was presented in [20], demonstrating improved energy utilization but increasing system complexity and cost.

Energy management strategies based on optimization techniques have been explored to minimize electricity costs and grid dependency. In [21], a rule-based energy management system for PV-integrated smart homes was proposed, focusing on load scheduling and cost reduction. However, the absence of bidirectional power flow limited its flexibility. A real-time energy management framework combining forecasting and optimization was presented in [22], achieving better performance but requiring high computational resources and accurate prediction models.

Dynamic pricing-based EV charging strategies have emerged as an effective solution for demand-side management. In [23], a time-of-use pricing mechanism was utilized to shift EV charging to off-peak hours, reducing grid stress. Similarly, [24] proposed a price incentive-based charging strategy to optimize user cost and system efficiency. However, these approaches did not fully exploit renewable energy availability or advanced control techniques for system stability.

More recently, integrated approaches combining control strategies with economic optimization have been investigated. In [25], a price-adaptive solar-assisted EV charging system was developed, demonstrating improved cost savings and grid support capability. Nevertheless, the control strategy relied on adaptive filtering techniques, which may not provide sufficient robustness under severe disturbances and nonlinear operating conditions.

From the reviewed literature, it is evident that while significant progress has been made in EV charging technologies, challenges remain in achieving a unified framework that ensures robust control,

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efficient renewable energy utilization, and real-time cost optimization. Therefore, this work proposes a Sliding Mode Control (SMC)-based solar-assisted residential EV charging system with dynamic price adaptation to address these limitations and enhance overall system performance.

III. PROPOSED METHODOLOGY

A. System Overview

The proposed system consists of a single-phase grid supply connected to the point of common coupling (PCC), which feeds the residential load and electric vehicle (EV_1). A rooftop photovoltaic (PV) system is directly interfaced to the DC-link to provide renewable energy support. A voltage source converter (VSC) with switching devices (S_1–S_4) regulates power exchange between the AC grid and DC-link. Additionally, a bidirectional DC–DC converter (S_5–S_6) connects a secondary EV (EV_2) or battery storage system, enabling both charging and discharging operations. Passive filters (Rf, Cf) are used to mitigate harmonics and improve power quality. The DC-link capacitor (C_DC) stabilizes the intermediate voltage, which is critical for system performance.

B. Sliding Mode Control (SMC) Design

To ensure robust performance under varying solar irradiance, load fluctuations, and grid disturbances, a Sliding Mode Control (SMC) strategy is employed. The SMC is designed to regulate two key parameters: DC-link voltage (V_DC) and grid current (i_s). The control objective is to drive the system states onto a predefined sliding surface and maintain them despite uncertainties.

The sliding surface is defined as:

$$S = k1(VDC - Vref) + k2(is - iref)$$

where VrefV_{ref}Vref is the reference DC-link voltage and irefi_{ref}iref is the desired grid current. The control law ensures that the system trajectory reaches and stays on the sliding surface using a discontinuous switching function, providing high robustness and fast dynamic response.

C. Grid-Side Converter Operation (VSC Control)

The voltage source converter (VSC) operates under SMC to maintain DC-link voltage stability and ensure sinusoidal grid current with unity power factor. The controller continuously monitors the error between actual and reference DC voltage and adjusts switching signals of S_1–S_4 accordingly.

During high PV generation, excess power is transferred to the grid or used for EV charging. Under low solar conditions, the grid compensates for the deficit. The SMC ensures minimal steady-state error and eliminates the need for complex tuning compared to conventional PI controllers.

D. PV Energy Integration and MPPT Operation

The photovoltaic (PV) array supplies power directly to the DC-link, reducing dependency on the grid. Maximum Power Point Tracking (MPPT) algorithms ensure optimal extraction of solar energy under varying irradiance conditions. The generated PV current (ispi_{sp}isp) contributes to load demand and EV charging, while excess energy can be exported to the grid. The SMC-based DC-link regulation ensures smooth integration of intermittent PV power without voltage instability.

E. Bidirectional DC–DC Converter Control (EV_2 Interface)

The bidirectional converter enables energy exchange between the DC-link and EV_2 battery. During low electricity price periods or excess PV generation, EV_2 is charged (G2V mode). Conversely, during peak demand or high tariff periods, EV_2 can discharge power back to the system (V2H/V2G mode).

SMC is applied to regulate the battery current and maintain stable DC-link voltage. The converter operates in buck mode during charging and boost mode during discharging, ensuring efficient energy transfer.

F. Dynamic Price-Based Energy Management

A real-time pricing algorithm is integrated with the control system to optimize energy usage. During low tariff periods, EV charging is prioritized using grid power. During peak price intervals, the system relies on PV generation and battery discharge to minimize grid dependency.

The SMC framework ensures seamless transition between operating modes without affecting system stability. This coordinated control reduces operational costs and alleviates grid stress.

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G. Overall System Working

The overall operation of the system is governed by the interaction between PV generation, grid supply, EV charging demand, and pricing signals. The SMC continuously adjusts converter switching to maintain system stability under all conditions. When solar power is sufficient, EVs are charged using renewable energy. In case of high demand or low generation, the grid and battery support the system. During peak pricing, stored energy is utilized to reduce electricity cost.

IV.CONTROL DESIGN

The control architecture of the proposed solar-assisted EV charging system is structured into multiple coordinated control loops to ensure stable, efficient, and robust operation under varying conditions. At the core, a Sliding Mode Control (SMC) strategy replaces conventional linear controllers to enhance system robustness against disturbances such as solar intermittency, load variations, and grid fluctuations.

The first stage of control involves DC-link voltage regulation and reference current generation. The error between the reference voltage (Vref) and actual DC-link voltage (Vdc) is processed through an SMC-based controller, which generates a control signal to maintain voltage stability. Simultaneously, the combined EV and load current (iEV1+iL) is extracted and processed, while a PV feedforward term (Ppv/Vt) is incorporated to improve dynamic response. The SMC ensures that the system states are driven toward the sliding surface, resulting in fast convergence and minimal steady-state error compared to PI-based methods.

In the grid-side control loop, unit template generation is used to derive synchronized sinusoidal references from the grid voltage (vsv_svs). These templates are multiplied with the reference current to produce the desired grid current waveform. The actual grid current (isi_sis) is compared with the reference, and the error is passed through a hysteresis current controller, which generates switching pulses for the voltage source converter (VSC) switches (S_1–S_4). The integration of SMC with hysteresis control ensures accurate current tracking, reduced harmonic distortion, and near-unity power factor operation.

The bidirectional DC–DC converter controlling EV_2 operates through a separate SMC-based loop. The DC-link voltage error is used to generate a reference battery current (IEVref), which is compared with the actual EV current. The resulting error is processed to produce PWM signals for switches (S_5–S_6), enabling seamless transition between charging (G2V) and discharging (V2H/V2G) modes. Additionally, a price-based mode selector dynamically adjusts system operation, allowing the controller to prioritize grid support or cost optimization during peak tariff periods. Overall, the coordinated SMC-based control framework ensures high efficiency, stability, and intelligent energy management in the proposed system.

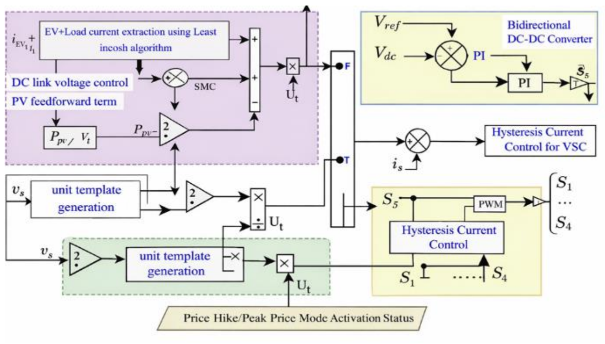

Fig2: Control diagram of the system

V.SIMULATION RESULTS

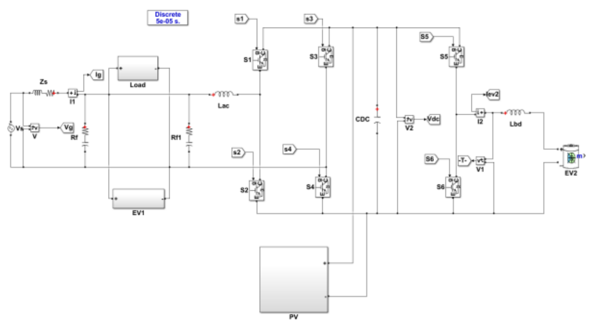

Fig. 3. Matlab System topology.

The performance of the proposed Sliding Mode Control (SMC)-based solar-assisted EV charging system is evaluated under dynamic operating conditions, including variations in electricity tariff, solar irradiance, EV charging/discharging, and load demand. As

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illustrated in Fig. 4, the system demonstrates adaptive behavior in response to real-time pricing signals. During low tariff intervals, the EV operates in charging mode with increased power intake, while during high tariff periods, the system reduces grid dependency by utilizing stored energy and PV generation. The SMC ensures smooth transitions between operating modes without causing instability or oscillations in system variables.

The photovoltaic (PV) power profile shows a gradual reduction in generation due to decreasing solar irradiance, eventually reaching zero during later time intervals. Despite this variation, the system maintains a balanced power flow by coordinating between the grid and EV battery. The EV power (PEV_2) dynamically switches between charging (negative values) and discharging (positive values), supporting the load during peak demand conditions. Simultaneously, the grid power (Pg) is regulated effectively, showing reduced import during high tariff periods and controlled export when excess energy is available.

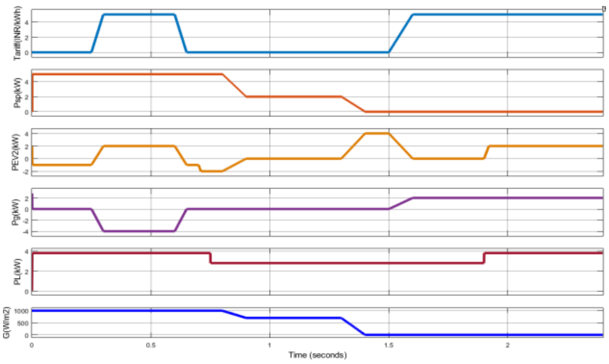

Fig.4. Simulation results depicting various dynamic variations.

Furthermore, the load power (PL) variations are handled efficiently without affecting system stability, highlighting the robustness of the SMC strategy. The controller maintains DC-link voltage stability and ensures consistent power delivery even under sudden changes in load and generation. Compared to conventional controllers, the SMC-based system exhibits faster response, reduced steady-state error, and improved overall efficiency. These results validate the effectiveness of the proposed control approach in achieving cost optimization, grid support, and reliable EV charging in a renewable-integrated residential setup.

VI.CONCLUSION AND FUTURE SCOPE

This paper presented a Sliding Mode Control (SMC)-based solar-assisted residential EV charging system integrated with dynamic price adaptation to achieve efficient, stable, and cost-effective energy management. The proposed system successfully coordinated photovoltaic generation, grid supply, and bidirectional EV operation to minimize grid dependency and optimize charging during varying tariff conditions. Simulation results demonstrated that the SMC approach provides superior robustness, fast dynamic response, and improved DC-link voltage regulation compared to conventional control techniques, while effectively handling fluctuations in solar irradiance, load demand, and pricing signals. The system also enabled intelligent switching between charging and discharging modes, ensuring reduced peak power consumption and enhanced economic benefits.

Future work can focus on extending the proposed framework to real-time hardware implementation and incorporating advanced forecasting techniques using artificial intelligence for load, solar generation, and pricing prediction. Additionally, integration with smart grid communication protocols, multi-EV coordination, and battery health-aware control strategies can further enhance system scalability and reliability. Expanding the system to include hybrid renewable sources and implementing advanced optimization algorithms will contribute to developing fully autonomous and intelligent EV charging infrastructures for next-generation smart homes and cities.

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