

Residential EV Charging System with Solar Assistance and Price-Adaptive Control

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Abstract - The rapid growth of electric vehicles (EVs) has increased the demand for intelligent charging infrastructure capable of reducing grid dependency, minimizing charging costs, and maintaining power quality. This work presents a solar-assisted residential electric vehicle charging system integrated with a real-time price adaptive control strategy for efficient energy management. The proposed framework combines photovoltaic (PV) generation, bidirectional EV operation, and adaptive control algorithms to optimize energy exchange among residential loads, the utility grid, and EV batteries. An adaptive pricing threshold based on day-ahead electricity tariffs is introduced to distinguish low-price and high-price operating intervals, enabling cost-effective charging and controlled vehicle-to-home (V2H) operation during peak pricing periods. During low tariff intervals, EV batteries are charged at higher rates, while during expensive periods, stored battery energy supports household loads and reduces grid dependence.

The system further incorporates a least In cosh-based control algorithm for voltage source converter operation, improving harmonic suppression, reactive power compensation, and maintaining unity power factor under varying load conditions. Simulation studies evaluate system performance under fluctuating solar irradiance, dynamic electricity pricing, load variations, and grid disturbances. Experimental validation confirms stable operation, effective power balancing, and improved energy utilization. Results indicate significant reductions in grid energy consumption and operating cost while maintaining power quality within acceptable standards. The proposed strategy demonstrates an efficient, reliable, and economically beneficial approach for residential EV charging applications integrated with renewable energy resources and smart energy management techniques.

Key Words: Electric vehicle (EV), power quality, price adaptive, solar PV array, vehicle-to-grid (V2H).

1.INTRODUCTION

The global transition toward sustainable energy systems has accelerated the adoption of electric vehicles (EVs) as a practical solution for reducing greenhouse gas emissions, decreasing fossil fuel dependency, and improving transportation efficiency. Conventional

transportation systems contribute significantly to environmental degradation through excessive carbon emissions, air pollution, and dependence on non-renewable energy resources. Consequently, governments, industries, and research organizations worldwide are promoting electric mobility through supportive policies, subsidies, and infrastructure development. However, widespread EV penetration introduces several technical and economic challenges, particularly related to charging infrastructure, grid stress, charging cost, and power quality.

Residential EV charging has emerged as one of the most common charging approaches because of its convenience and ease of accessibility. Nevertheless, uncontrolled charging behavior during peak demand periods can significantly increase stress on utility grids and create instability in distribution systems. The integration of renewable energy resources, especially solar photovoltaic (PV) systems, with residential EV charging stations offers a promising approach to mitigating these challenges. Solar-assisted charging infrastructure enables direct utilization of renewable energy for charging applications, thereby reducing dependence on grid electricity and minimizing operational expenses.

2. Working Methodology

The proposed solar-assisted residential electric vehicle charging system is designed to provide intelligent energy management by integrating photovoltaic (PV) generation, electric vehicle charging infrastructure, bidirectional energy exchange capability, and adaptive control mechanisms. The system architecture primarily consists of a solar photovoltaic array, voltage source converters, residential loads, utility grid interface, electric vehicle battery system, and an adaptive control unit. The PV array acts as the primary renewable energy source, generating electricity according to solar irradiance and environmental conditions. Generated solar power is supplied directly to residential loads or utilized for EV battery charging depending on system operating conditions. When solar generation exceeds residential demand, excess energy is redirected toward battery charging or exported to the utility grid.

Conversely, during insufficient solar generation periods, power is drawn from either the utility grid or the EV

battery depending on electricity pricing conditions and battery state-of-charge. The proposed methodology aims to reduce dependence on conventional grid power while minimizing electricity cost and improving renewable energy utilization. Multiple operating modes are implemented to support energy flow flexibility, including Grid-to-Vehicle (G2V), Vehicle-to-Home (V2H), photovoltaic-assisted charging mode, and utility support mode. Bidirectional power converters facilitate seamless energy exchange between the EV battery and the residential system. The architecture enables efficient coordination among generation sources, storage devices, and household demand.

This integrated methodology creates an intelligent residential energy ecosystem capable of reducing operational costs, improving sustainability, and maintaining reliable charging performance under varying environmental and load conditions. The photovoltaic generation subsystem serves as the primary renewable energy source within the proposed framework and is modeled to maximize renewable energy utilization. Solar panels convert incident solar radiation into electrical power using semiconductor photovoltaic principles.

Because output power from PV arrays varies continuously according to irradiance and temperature conditions, Maximum Power Point Tracking (MPPT) techniques are implemented to extract maximum available energy. A DC-DC boost converter interfaces the PV array with the DC-link system and regulates output voltage according to load requirements. The converter operates dynamically to maintain optimal operating conditions under fluctuating environmental scenarios. Generated solar energy is first allocated to residential loads because local consumption minimizes conversion losses and reduces grid dependency.

If surplus energy exists after satisfying household demand, the excess power is directed toward charging the electric vehicle battery. During periods of insufficient solar generation, the charging controller evaluates available utility tariffs and battery conditions before selecting the most economical operating mode. Power electronic converters ensure regulated voltage levels and stable power transfer throughout system operation. Solar intermittency introduces challenges associated with power fluctuations; therefore, control algorithms continuously monitor generation levels and dynamically adjust power-sharing ratios among system components.

The integration of solar generation significantly reduces energy drawn from the utility network while decreasing charging costs and carbon emissions. Through continuous monitoring and adaptive converter operation, the photovoltaic subsystem maintains reliable operation and contributes to achieving sustainable residential charging infrastructure with improved energy

independence. Power quality improvement and converter control constitute critical components of the proposed charging system because power electronic interfaces introduce harmonic distortion and reactive power issues within residential networks. To address these challenges, Voltage Source Converters (VSCs) are employed for controlling power exchange between the grid, EV battery, and photovoltaic system.

The converter control structure utilizes adaptive filtering algorithms to extract reference currents required for harmonic compensation and power factor correction. A least IncoSh-based control algorithm is implemented because of its improved robustness against impulsive disturbances and nonlinear operating conditions. The control system continuously measures source voltages, load currents, and converter operating variables to generate switching signals for converter operation. Pulse Width Modulation (PWM) techniques regulate converter switching and maintain stable DC-link voltage levels during dynamic operating conditions.

Harmonic currents generated by nonlinear loads are compensated by injecting equal and opposite currents through converter interfaces, thereby improving source current quality. Reactive power support functionality enables operation at near-unity power factor, reducing utility penalties and improving energy efficiency. The converter controller also regulates bidirectional power flow during charging and discharging operations while ensuring smooth transition between operating modes. Voltage regulation mechanisms maintain stable residential supply conditions despite changes in solar generation or load demand. These power quality enhancement techniques improve overall system reliability and ensure compliance with grid standards while supporting efficient charging operation.

The overall system operation is validated through coordinated interaction among renewable generation, battery storage, adaptive control algorithms, and converter control mechanisms under varying operating conditions. Multiple operating scenarios are evaluated, including varying solar irradiance, dynamic electricity pricing, changing household demand, and different EV battery states. During daytime conditions with high solar generation, renewable energy primarily supplies residential loads while excess energy charges EV batteries. During nighttime or low-generation periods, energy management algorithms determine whether grid energy or stored battery energy should be utilized based on pricing conditions.

Converter controllers continuously regulate voltage levels, current quality, and power flow directions to maintain stable operation. The adaptive scheduling framework ensures that battery charging is completed according to user requirements while minimizing charging cost. Fault-handling mechanisms are incorporated to maintain safe operation during abnormal

conditions such as converter overloads, low battery conditions, or grid disturbances. System performance metrics including charging cost reduction, renewable energy utilization, harmonic distortion levels, and grid power consumption are monitored continuously to evaluate effectiveness.

3.Results Explanations

The simulation results primarily evaluate the effectiveness of the proposed solar-assisted residential EV charging architecture under varying electricity prices, renewable generation fluctuations, and dynamic load conditions. The proposed system integrates photovoltaic generation, residential loads, electric vehicles, and adaptive control mechanisms to maintain optimal power flow while minimizing grid dependency. Figure 5 presents multiple dynamic operating scenarios where pricing signals, solar irradiance, and load variations continuously influence system operation.

During normal daytime operation, the photovoltaic array operates at Maximum Power Point (MPP) and generates approximately 5.2 kW under irradiance conditions of 1000 W/m². This generated power simultaneously supports household loads and battery charging operations while reducing grid dependency. The simulation duration is configured such that every 0.1 seconds represents one hour of system operation, enabling analysis of long-term charging behavior within short simulation intervals. The proposed adaptive pricing mechanism continuously compares utility tariffs against a dynamic threshold derived from day-ahead pricing schedules.

When electricity prices remain below this threshold, electric vehicles primarily operate in charging mode while excess PV generation supports local loads. However, when pricing signals exceed threshold values, operating modes automatically shift to reduce grid consumption. These results demonstrate that the proposed controller successfully adapts charging behavior according to changing market conditions without affecting system stability. Moreover, the coordinated interaction between solar generation, grid supply, and EV batteries ensures continuous power balance and reliable operation throughout multiple operating scenarios. The results confirm that adaptive pricing significantly improves energy utilization efficiency while minimizing operational expenses and

reducing dependency on utility power sources.

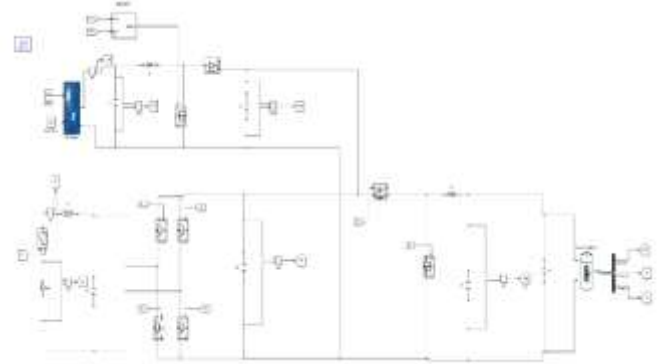


Fig 1 MATLAB/SIMULINK circuit of the system

A major objective of the proposed system is reducing grid stress during high electricity price intervals while maintaining uninterrupted charging and residential power supply. Figure 5 illustrates system performance when utility pricing exceeds the adaptive threshold and grid demand suddenly increases. Under this condition, EV2 changes its operating mode from charging to discharging, thereby injecting energy back into the system. Negative EV power values represent charging operation, whereas positive values indicate discharging behavior.

The simulation results demonstrate that EV2 successfully supports grid requirements, assists residential loads, and simultaneously maintains charging operation for EV1 without disruption. During high-price periods, increased grid power demand is compensated by coordinated contribution from photovoltaic generation and battery discharge. This operating strategy prevents excessive power withdrawal from the utility grid and reduces network stress during peak demand intervals. The proposed control algorithm therefore effectively transforms electric vehicles into flexible energy storage devices capable of participating in demand-side management. Another important observation is that despite dynamic energy exchange, load reliability remains unaffected. Residential loads continue receiving uninterrupted power even during significant price variations.

The adaptive pricing controller dynamically allocates energy resources according to system priorities while maintaining operational constraints associated with battery State of Charge (SoC) and power limits. These findings demonstrate that adaptive charging not only minimizes electricity expenditure but also contributes toward peak demand reduction and grid stability improvement. Therefore, the proposed architecture successfully combines economic optimization with operational reliability under realistic residential operating conditions.

CASE-1. Electric Vehicle Charging with PV

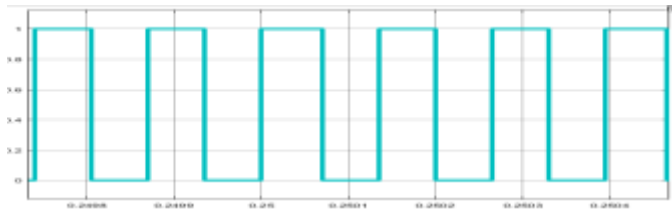


Fig.2. PV Boost Converter Switching pulses (T1)

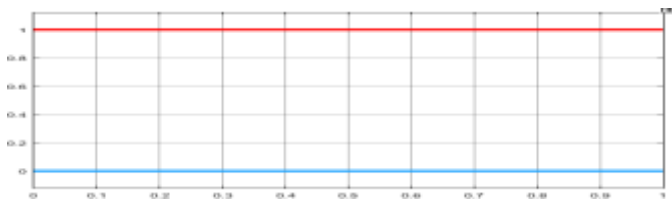


Fig.3. Buck Converter Switching Pulses (ON) and Boost Converter (OFF)

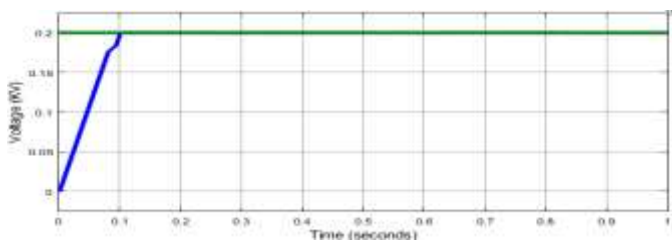


Fig.4 Solar PV Array and MPPT Voltages Tracking

The robustness of the proposed system under varying environmental conditions was evaluated by introducing sudden solar irradiance variations while maintaining constant power export conditions. Solar intermittency remains one of the major challenges associated with renewable-energy-assisted charging systems because fluctuations in irradiance directly affect power availability. To validate controller robustness, solar irradiance was reduced from 1000 W/m^2 to 600 W/m^2 , causing photovoltaic output power to decrease from approximately 5.2 kW to nearly 4 kW . Despite this reduction in renewable generation, the simulation results show that residential load demand and power export remain almost unchanged. The adaptive control mechanism compensates for reduced solar generation through dynamic coordination between battery storage and utility power exchange. This behavior confirms that the proposed controller maintains power balance even under unfavorable weather conditions. Furthermore, maintaining constant load supply despite generation variability indicates effective energy scheduling capability.

The controller continuously monitors generation conditions and adjusts power-sharing ratios among available sources. During reduced solar availability, grid power contribution increases only when necessary, thereby preserving renewable utilization priority. Such behavior is particularly important for residential charging infrastructure where weather variability

significantly affects charging performance. The results clearly indicate that the adaptive controller effectively mitigates renewable intermittency without compromising charging functionality or residential supply reliability. Therefore, the proposed framework demonstrates strong resilience against environmental disturbances and improves operational stability under realistic renewable generation scenarios.

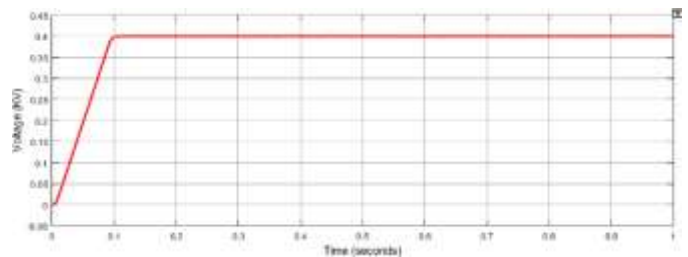


Fig.5. Boost Converter Output DC Voltage

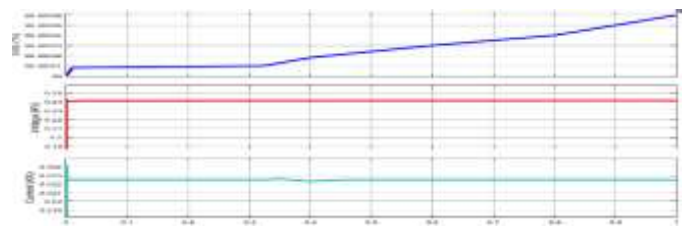


Fig.6. Battery State of Charge, Voltage and Current during charging

Power quality enhancement capability was evaluated using harmonic analysis and comparative studies involving different adaptive filtering algorithms. The proposed least Incosh algorithm was compared against conventional approaches such as LMS, LMF, and SRF methods under load disturbance conditions. Comparative analysis shown in Figure 6 demonstrates that the proposed control method provides superior transient performance and faster adaptation during sudden operating changes. One of the major advantages of the least Incosh algorithm is its ability to maintain robust performance under impulsive disturbances and large outliers.

CASE-1 ELECTRIC VEHICLE CHARGING FROM GRID

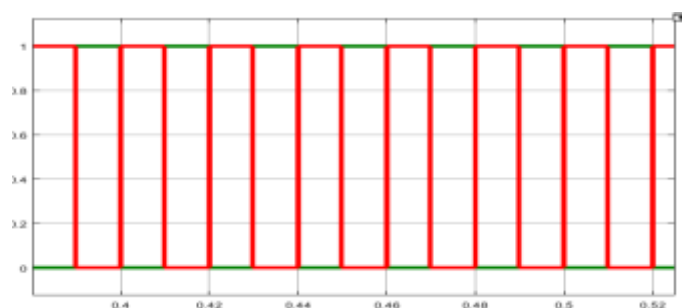


Fig.7. Switching pulses to the Bidirectional AC-DC Converter switches

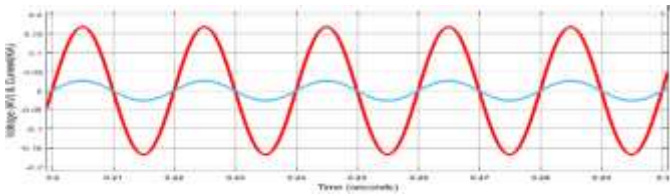


Fig.8. Grid Voltage and Current waveforms during charging



Fig.9 Battery State of Charge, Voltage and Current during charging

Dynamic load behavior analysis was performed to evaluate system stability during sudden load reconnection and disconnection scenarios. Figures 10 and 11 demonstrate the capability of the proposed system to maintain voltage stability and power balance despite abrupt changes in residential demand. During load reconnection, load current increases rapidly from zero, requiring immediate compensation from converter interfaces and energy sources. The simulation results show that converter current increases to support additional demand while source voltage remains unaffected.

The DC-link voltage remains stable during transient conditions, indicating effective energy exchange coordination among converters, photovoltaic generation, and electric vehicle batteries. Similarly, during sudden load disconnection, source current decreases while converter compensation requirements reduce accordingly. Despite abrupt load reduction, voltage waveforms remain sinusoidal and no significant disturbances appear in DC-link regulation. The adaptive controller continuously updates current references according to operating conditions and maintains stable operation throughout transient events. Battery current also adjusts dynamically according to changing demand requirements while maintaining charging constraints. Importantly, photovoltaic current remains largely unaffected during both load reconnection and disconnection events, demonstrating effective decoupling between renewable generation and dynamic load disturbances.

These results confirm that the proposed architecture maintains strong dynamic stability, effective power sharing, and reliable operation under rapidly changing operating conditions. Overall, the simulation and experimental outcomes validate that the solar-assisted residential EV charging system successfully achieves cost minimization, power quality enhancement, renewable utilization maximization, and robust operation under realistic residential scenarios.

CASE-2. ELECTRIC VEHICLE SUPPORT TO GRID

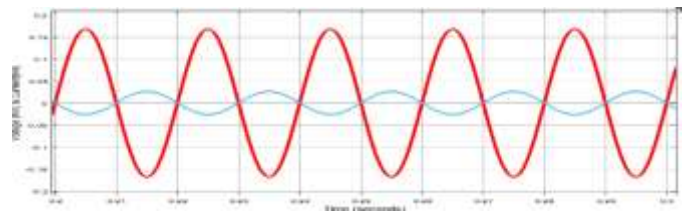


Fig.10 Grid Current and Voltage Current waveforms

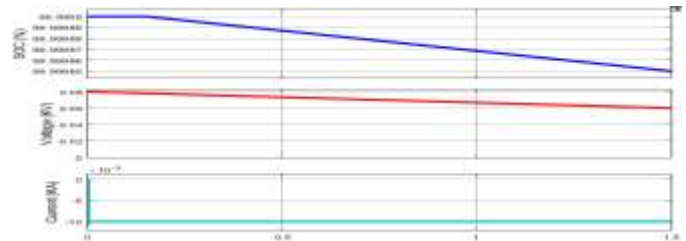


Fig.11. Battery State of Charge, Voltage and Current during charging

4. CONCLUSIONS

The proposed solar-assisted residential electric vehicle charging system with price adaptive control demonstrates an effective solution for addressing the increasing challenges associated with EV charging, renewable energy integration, grid stress, and electricity cost optimization. The developed system successfully integrates photovoltaic generation, residential loads, electric vehicle batteries, and adaptive energy management strategies to ensure reliable and efficient operation under varying environmental and operating conditions. Through the implementation of dynamic price-based control, the charging behavior of electric vehicles is intelligently adjusted according to electricity tariff variations, thereby minimizing energy costs while improving grid stability.

The proposed control framework effectively utilizes vehicle-to-home (V2H) functionality during peak demand periods, enabling EV batteries to support household loads and reduce dependency on utility power. Simulation and experimental investigations confirm that the system maintains stable operation under changing solar irradiance, load disturbances, and fluctuating electricity prices while preserving power balance and operational reliability. Furthermore, the application of the least Incosh control algorithm significantly enhances power quality by reducing harmonic distortion, improving current waveform quality, and maintaining near-unity power factor operation.

Comparative analysis verifies that the proposed controller provides faster convergence, improved disturbance rejection, and superior dynamic

performance compared with conventional approaches. The results also demonstrate improved renewable energy utilization, lower grid energy consumption, and enhanced system flexibility. Overall, the proposed architecture offers a practical, economical, and sustainable charging solution capable of supporting future smart residential energy systems while contributing toward reduced emissions, improved energy efficiency, and enhanced charging infrastructure reliability.

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