

A Grid-Interactive Hybrid Fuel Cell and Battery Storage Power Management System Station for EV Charging

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Abstract - The rapid growth of electric vehicle (EV) adoption has increased the demand for reliable, efficient, and sustainable charging infrastructure. This study presents a decentralized energy management framework for a grid-interactive EV charging station integrating photovoltaic (PV) generation, battery energy storage (BES), and proton exchange membrane fuel cell (PEMFC) systems. A hybrid control methodology based on Line Resistance Correction Droop (LRCD) control is proposed to improve power-sharing accuracy, enhance battery life, and maintain stable operation under varying load and renewable generation conditions. The proposed architecture prioritizes renewable energy utilization while dynamically coordinating battery and fuel cell resources according to battery state-of-charge (SoC), grid availability, and charging demand. To extend battery lifespan, adaptive SoC regulation and depth-of-discharge control mechanisms are incorporated. Additionally, the fuel cell operates within its optimal efficiency region, minimizing degradation and improving overall system performance.

The developed control framework supports both grid-connected and islanded operating modes, ensuring uninterrupted charging service during grid disturbances. Experimental and simulation analyses demonstrate improved DC bus voltage regulation, reduced current stress on storage components, and enhanced transient response during sudden load variations. Furthermore, the charging station maintains near-unity power factor operation and total harmonic distortion within acceptable standards during dynamic transitions. The findings indicate that integrating hybrid storage with decentralized control significantly enhances charging station reliability, reduces grid dependency, and provides a scalable solution for future renewable-powered EV infrastructure.

Key Words: Decentralized energy management, PV-BES system, fuel cell, EV charging station.

1.INTRODUCTION

The global transition toward sustainable transportation has accelerated the adoption of Electric Vehicles (EVs), creating an urgent demand for efficient and reliable charging infrastructure. Conventional charging systems that depend entirely on centralized grid networks face

numerous challenges, including peak load stress, voltage instability, higher operational costs, and increased carbon emissions. As EV penetration increases rapidly, power systems are expected to accommodate large-scale charging loads without compromising grid stability. This challenge has encouraged researchers and industries to integrate renewable energy sources such as solar photovoltaic (PV), wind, and distributed storage systems into EV charging stations. Among these renewable solutions, photovoltaic-powered charging stations have emerged as promising alternatives because of their low operating costs and environmentally friendly nature. However, renewable sources inherently suffer from intermittency and variability, leading to fluctuations in generated power. These variations significantly affect charging reliability, especially during unfavorable environmental conditions. Consequently, modern EV charging infrastructure requires advanced energy management strategies capable of coordinating multiple energy sources and storage systems to guarantee uninterrupted power supply, improved efficiency, and enhanced system resilience.

Integrating distributed generation with hybrid storage technologies provides a practical pathway toward developing grid-interactive charging systems that support renewable penetration while maintaining stable operation under dynamic conditions. Battery Energy Storage Systems (BESS) play a crucial role in compensating renewable energy fluctuations and balancing charging demand in EV charging stations. Batteries provide fast response characteristics, making them highly suitable for handling transient power variations and short-duration load demands. However, battery systems alone experience several limitations, including degradation due to frequent charging and discharging cycles, reduced lifespan under deep discharge conditions, thermal management issues, and high replacement costs. Continuous operation under dynamic loading conditions accelerates battery aging, thereby affecting overall charging station economics. To overcome these drawbacks, researchers have proposed combining battery systems with alternative energy storage technologies such as fuel cells. Fuel cells, particularly Proton Exchange Membrane Fuel Cells (PEMFCs), offer several advantages including high energy density, zero-emission operation, scalability, and stable long-duration power delivery. Unlike batteries, fuel cells are capable of supplying continuous power

during extended charging periods without severe degradation. However, fuel cells possess slower transient responses due to electrochemical and thermodynamic limitations. Therefore, integrating batteries with fuel cells creates a complementary hybrid storage architecture where batteries manage rapid load variations while fuel cells provide sustained energy support. This hybrid approach enhances reliability, extends battery lifespan, reduces stress on individual components, and improves overall charging efficiency. The increasing complexity of hybrid renewable charging systems has created the need for intelligent energy management mechanisms capable of coordinating power flow among multiple sources.

Traditional centralized energy management approaches depend heavily on communication infrastructure and extensive computational resources, limiting scalability and flexibility. In contrast, decentralized control architectures have gained attention because they offer higher reliability, reduced communication dependency, modular expansion capability, and improved fault tolerance. Decentralized Energy Management (DEM) allows each energy source and storage unit to make local operational decisions based on system conditions such as load demand, battery state-of-charge, renewable availability, and grid status. Droop control methods are commonly employed in decentralized systems for power sharing among distributed resources. Conventional droop techniques, however, often suffer from poor load-sharing accuracy and DC bus voltage deviations due to line resistance effects and unequal source characteristics. To address these limitations, advanced control strategies incorporating adaptive droop mechanisms and compensation techniques are increasingly being investigated. Such strategies enable precise power allocation while maintaining system stability during sudden disturbances, renewable fluctuations, and charging demand variations. Effective decentralized control is therefore essential for ensuring seamless operation of future grid-interactive EV charging stations.

Grid interaction introduces additional operational challenges and opportunities within EV charging infrastructure. During peak demand periods, uncontrolled charging activities can overload distribution networks, create voltage instability, increase transformer stress, and deteriorate power quality. Conversely, intelligent charging stations equipped with bidirectional power flow capability can support grid operation by participating in demand response, peak shaving, and ancillary services. Hybrid storage-integrated charging stations can function in both grid-connected and islanded modes, thereby improving resilience during grid outages and emergency conditions. Stable DC bus regulation becomes particularly important in such operating scenarios because charging stations must continuously coordinate renewable generation, storage units, and charging loads.

Furthermore, maintaining high power quality through low harmonic distortion and near-unity power factor operation is essential for compliance with modern grid standards. Adaptive control based on battery State of Charge (SoC), fuel cell operating conditions, and load priorities can significantly enhance operational efficiency while minimizing unnecessary grid dependency. The ability to transition smoothly between different operating modes under varying load conditions makes hybrid storage systems highly attractive for next-generation charging infrastructure. Considering these challenges and opportunities, the development of hybrid fuel cell and battery-based energy management systems represents a promising direction for future EV charging technologies. Combining renewable energy integration with advanced decentralized control strategies offers substantial benefits in terms of reliability, efficiency, sustainability, and operational flexibility.

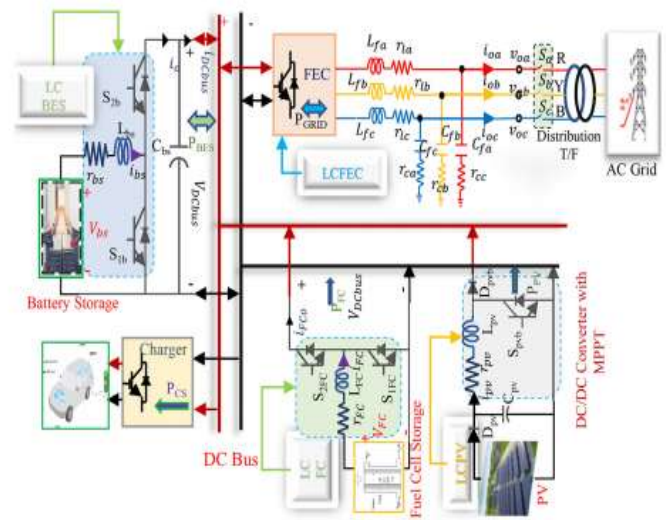


Fig. 1. Grid interactive DCMG architecture for the electric vehicle charging station.

2. Proposed System Explanation

The proposed system introduces a hybrid energy management framework for a grid-interactive electric vehicle charging station integrating photovoltaic generation, Battery Energy Storage Systems (BESS), Proton Exchange Membrane Fuel Cells (PEMFC), and utility grid connectivity. The main objective of the proposed architecture is to provide uninterrupted charging services while minimizing dependency on conventional grid resources and maximizing renewable energy utilization. Conventional charging infrastructure often experiences operational challenges due to fluctuating renewable generation, peak charging demand, and instability caused by sudden load variations.

To overcome these issues, the proposed architecture combines multiple distributed energy resources using decentralized control principles. The charging station

consists of photovoltaic arrays functioning as primary renewable generators, battery systems serving as fast-response storage units, fuel cells providing sustained backup power, and an intelligent front-end converter responsible for grid interaction. A common DC bus architecture is selected because it allows easier integration of multiple sources while reducing conversion stages and improving overall efficiency. The system continuously monitors charging demand, renewable availability, battery state-of-charge, and grid conditions to dynamically allocate energy among different resources. By integrating hybrid storage with adaptive control mechanisms, the charging station achieves improved reliability, reduced power interruptions, and enhanced charging efficiency. The proposed framework supports both grid-connected and islanded operation, ensuring uninterrupted charging even during grid outages or abnormal operating conditions. The photovoltaic subsystem acts as the primary renewable energy source within the proposed charging architecture. Solar energy generation significantly reduces carbon emissions and operating costs while supporting sustainable transportation objectives. However, photovoltaic systems inherently experience fluctuations due to varying irradiation levels, cloud movement, and environmental changes.

To maximize energy extraction from available solar resources, the proposed system employs Maximum Power Point Tracking (MPPT)-based control integrated with a DC-DC boost converter. During normal operating conditions, photovoltaic power is prioritized for charging operations and auxiliary loads connected to the charging station. Excess generated energy is directed toward battery charging or grid export depending on system operating conditions. When renewable generation decreases because of poor environmental conditions, energy support automatically shifts toward storage resources. The proposed architecture includes adaptive switching mechanisms allowing photovoltaic converters to transition between maximum power mode and voltage regulation mode according to battery state and grid conditions. By incorporating intelligent photovoltaic control, the charging station improves renewable penetration while minimizing energy wastage. The solar subsystem therefore functions not only as a power generator but also as an important component within the energy management framework responsible for maintaining charging continuity and reducing reliance on utility supply.

Battery Energy Storage Systems play a major role in balancing energy flow and compensating for renewable variability within the charging station. Batteries provide fast transient response capability, making them suitable

for handling sudden charging demand fluctuations and short-duration disturbances. The proposed architecture employs battery storage systems connected through bidirectional DC-DC converters capable of both charging and discharging operation. Battery management is performed using State of Charge (SoC)-based control strategies that continuously monitor storage conditions and regulate charging behavior accordingly.

The proposed control framework divides battery operation into multiple operating zones such as low, medium, high, and critical states to improve battery utilization and lifespan. Charging and discharging decisions are determined according to renewable generation availability, load demand, and grid operating conditions. To prevent battery degradation, the controller limits operation within predefined state-of-charge boundaries and avoids excessive Depth of Discharge (DoD). Adaptive charging algorithms regulate current levels to minimize thermal stress and extend operational life. During transient load increases, batteries immediately respond by supplying additional power while fuel cells gradually adjust output. Experimental analysis indicates that proper battery coordination significantly reduces converter stress, improves charging reliability, and increases storage system lifetime. Thus, battery storage functions as the primary short-term balancing mechanism within the proposed architecture.

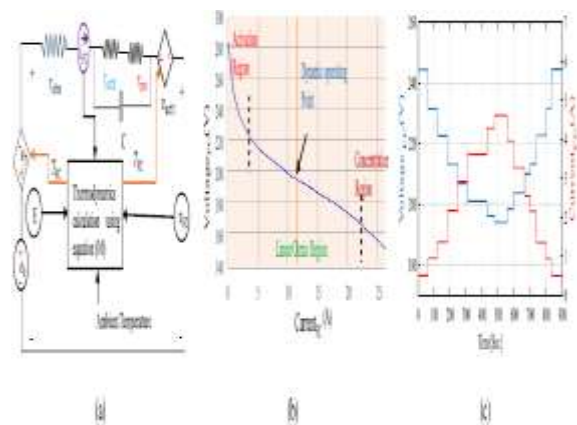


Fig. 2. (a) Equivalent electrical model of FCs (b) V-I characteristic of FC (c) Dynamic response of FC.

Fuel cell integration within the proposed system provides long-duration energy support and enhances overall charging station resilience. Proton Exchange Membrane Fuel Cells are selected because of their high efficiency, low emissions, and suitability for distributed energy applications. Unlike batteries, fuel cells provide sustained power output without significant degradation during prolonged operation.

However, fuel cells exhibit slower transient response due to electrochemical and thermodynamic characteristics. Therefore, the proposed framework utilizes fuel cells primarily during extended charging periods, low renewable generation conditions, or when battery state-of-charge falls below predefined thresholds. Fuel cells are connected through boost converters interfaced with the common DC bus and operate using adaptive control rules that maintain operation within optimal efficiency regions. Hydrogen consumption optimization algorithms regulate output power while minimizing fuel usage. The proposed controller continuously monitors fuel cell health indicators and adjusts operating conditions to reduce degradation effects. By coordinating fuel cells with battery storage, the system distributes load demand effectively between fast and slow response resources. This hybrid coordination reduces battery stress, improves charging continuity, and increases overall energy availability during long-duration charging cycles. Consequently, fuel cells serve as reliable secondary storage resources that enhance system sustainability and reduce dependency on utility infrastructure.

The energy management mechanism implemented within the proposed architecture employs decentralized control principles to coordinate multiple energy sources efficiently. Conventional centralized approaches require extensive communication infrastructure and introduce scalability limitations. Therefore, the proposed framework utilizes decentralized control where each subsystem independently performs local decision-making using operational measurements. A Line Resistance Corrected Droop Control mechanism is introduced for power sharing among batteries, fuel cells, and grid resources.

This control approach improves load distribution accuracy while minimizing DC bus voltage deviations. The controller dynamically adjusts droop gains according to battery state-of-charge, charging demand, and renewable availability. During power deficit conditions, battery resources are prioritized because of their fast response capability, followed by fuel cell activation when additional support is required. During excess renewable generation, storage systems absorb surplus power or transfer energy back to the utility grid. The decentralized architecture also enables plug-and-play capability for future expansion. Grid islanding detection mechanisms allow seamless transition between grid-connected and standalone operation without affecting charging continuity. Adaptive power-sharing algorithms continuously regulate converter operation to maintain stable DC bus voltage and balanced energy distribution. The proposed energy management system therefore improves scalability, operational reliability, and fault tolerance within charging infrastructure.

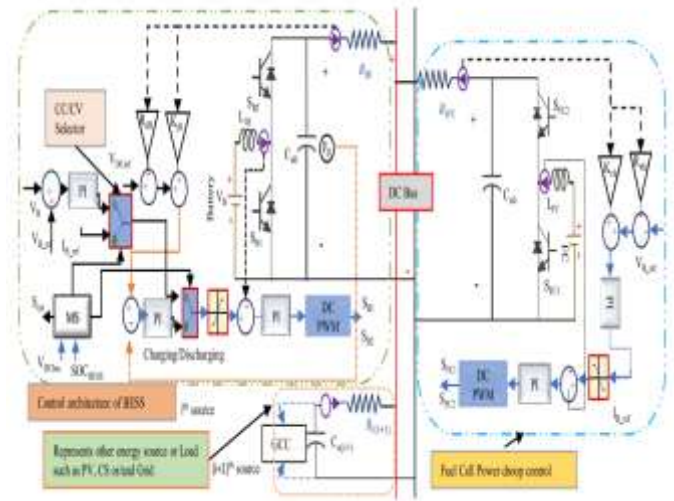
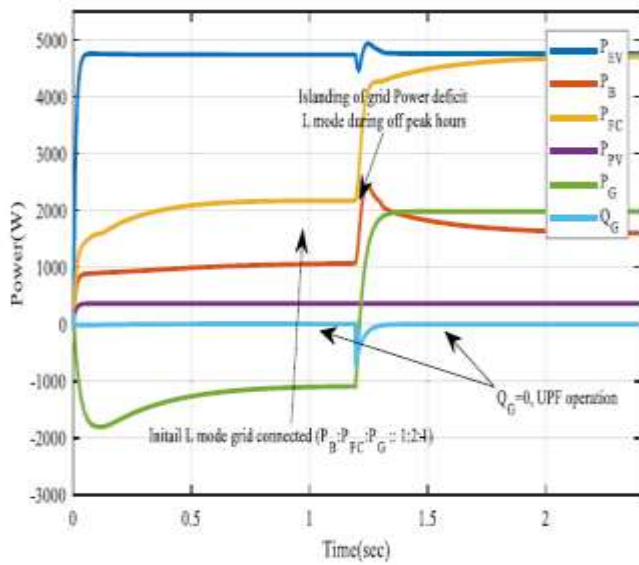


Fig. 3. Detailed control architecture of various power sources and loads.

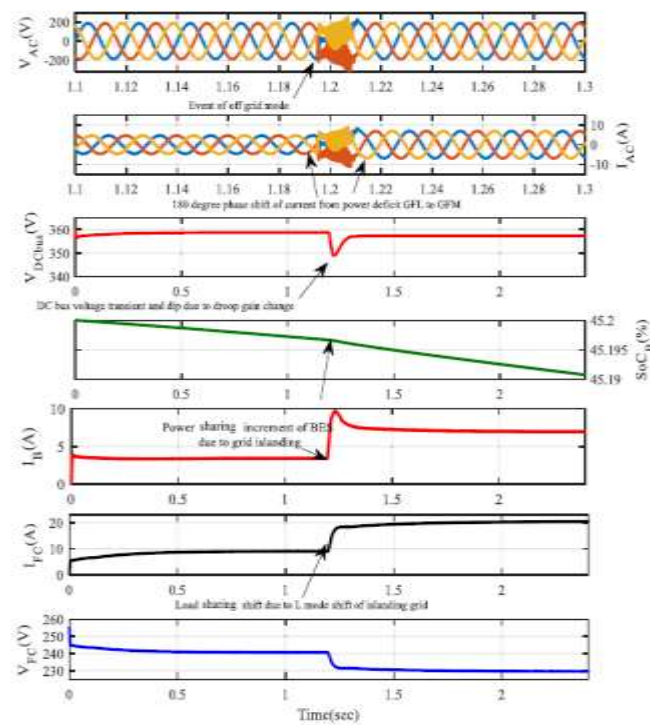
Grid interaction forms the final component of the proposed charging architecture and enables efficient integration with utility networks. The front-end converter operates in both grid-following and grid-forming modes depending on system operating conditions. Under normal conditions, the charging station exchanges power with the grid while maintaining unity power factor operation and minimizing harmonic distortion. During peak charging periods, additional power support is imported from utility sources when renewable generation and storage resources become insufficient. Conversely, surplus renewable energy may be exported back to the grid during excess generation periods.

In the event of grid outages or disturbances, the proposed system automatically transitions into islanded mode, where storage resources and renewable generation maintain charging continuity. Advanced converter control techniques regulate voltage and frequency during autonomous operation. Harmonic mitigation strategies ensure compliance with power quality standards while reducing stress on electrical equipment. Furthermore, grid interaction enables participation in demand response programs, peak shaving applications, and future vehicle-to-grid services. Simulation and experimental investigations indicate that the proposed architecture maintains stable voltage profiles, low harmonic distortion, and reliable charging performance under varying load conditions. Overall, the proposed hybrid charging framework provides a sustainable, reliable, and scalable solution capable of supporting future large-scale electric mobility infrastructure.

3.Simulation Results Explanations

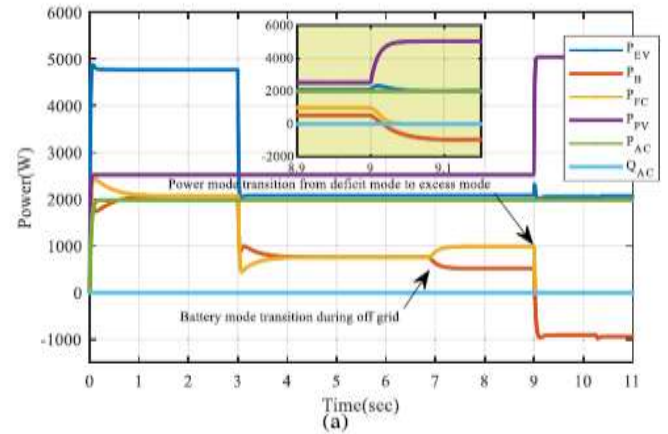


(a)

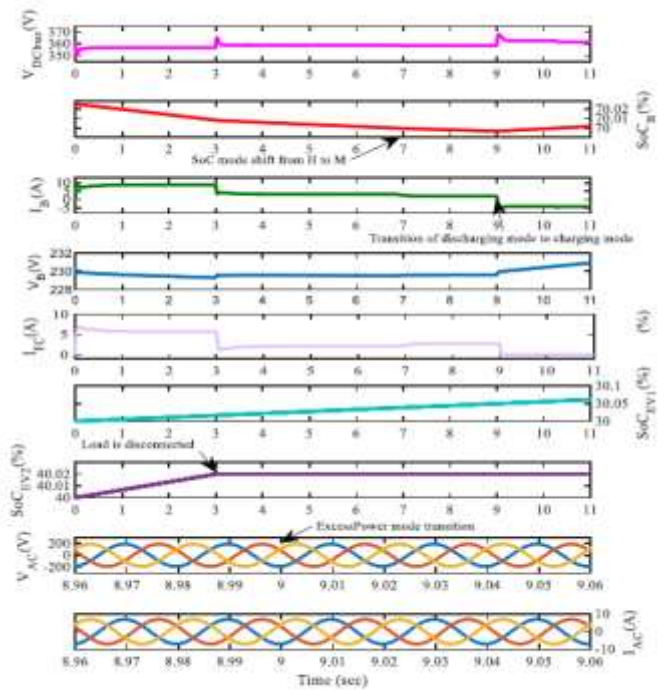


(b)

Fig. 5. (a) Power transition of various units from grid-connected Mode to off-grid (b) performance of MG with proposed DEM for the grid-connected mode to off-grid: FEC voltage and current, DC bus voltage, BES SoC, current,

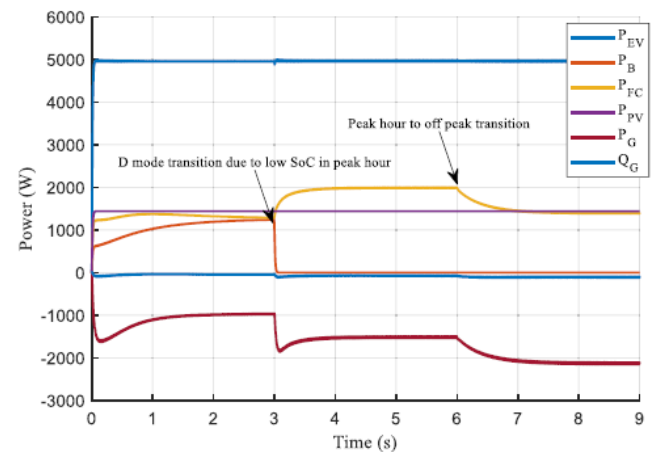


(a)



(b)

Fig. 6. System performance (a) Power transition in D mode transition and off-peak hour transition (b) DC bus voltage, BES SoC and current and FC



(a)

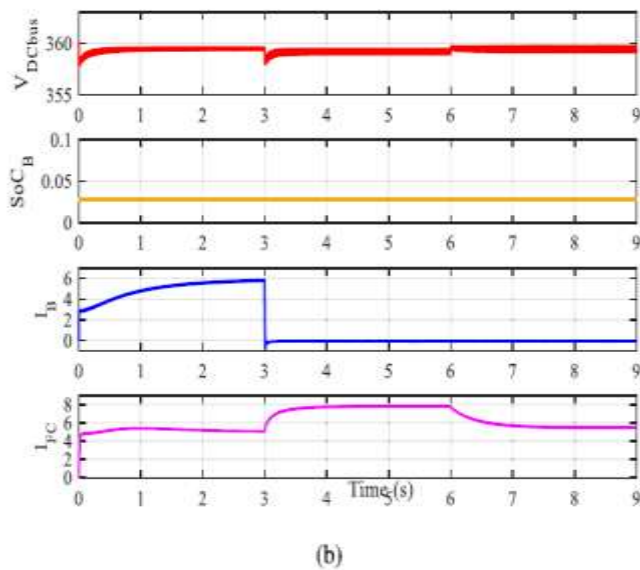


Fig. 7. (a) Power transition of all units in the autonomous grid under load and source variation(b) Performance of MG with proposed DEM for off-grid mode: DC bus voltage BES SoC, current and voltage, FC current, SoC of EV load, and FEC voltage and current.

During normal operating conditions, photovoltaic generation contributed the majority of charging power, reducing dependence on utility supply. The common DC bus remained stable throughout operation with minimal voltage deviation despite frequent transitions between renewable and storage resources.

Dynamic load variations introduced by connecting and disconnecting charging loads showed that the proposed decentralized control algorithm rapidly redistributed power among available resources without interrupting charging operation. Experimental observations indicated improved system responsiveness compared to conventional charging systems because the hybrid storage architecture effectively compensated for transient conditions. Additionally, converter operation remained stable with reduced switching stress due to adaptive power allocation mechanisms. These findings demonstrate that the proposed charging framework successfully achieves stable operation under practical charging conditions while maintaining high renewable utilization and minimizing energy interruptions.

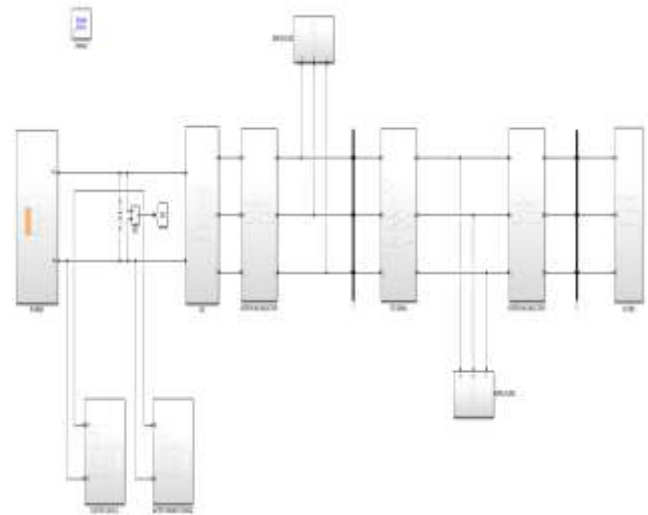


Fig.8. A grid-connected photovoltaic array and battery energy storage interfaced electric vehicle charging station's MATLAB/SIMULINK circuit The Effect of Solar Insolation Variations on Performance

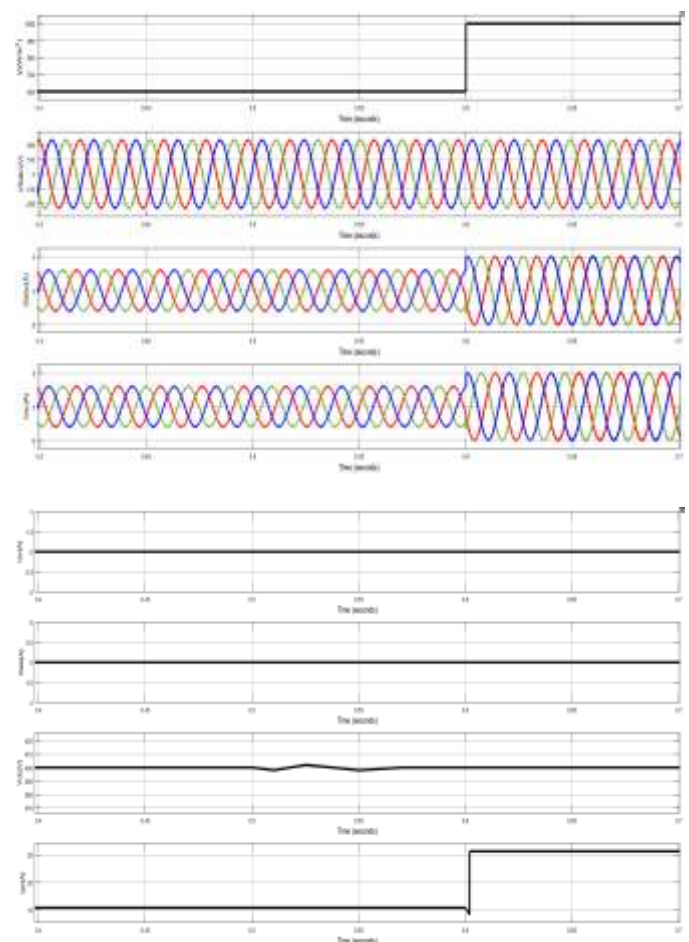
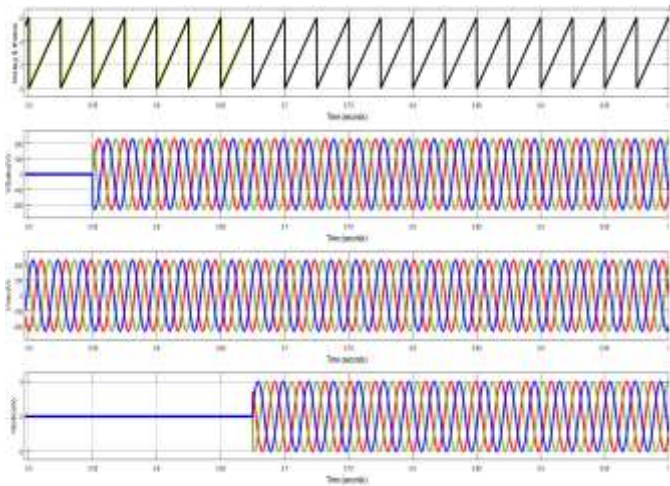


Fig.9.Electric vehicle charging station's simulated reaction to changes in PV insolation B. System Performance During Grid Outages



10. Effects of Grid Reconnection on System Performance

Figure.10. the system's simulated reaction during grid recovery. When the power grid is restored, the VSC becomes grid-synchronized, and the voltages and currents of the grid become visible. The EV charging is unaffected while the BES begins to discharge.

3. CONCLUSIONS

The proposed hybrid fuel cell and battery storage power management system for grid-interactive electric vehicle charging stations provides an efficient and sustainable solution for addressing the increasing demand for reliable EV charging infrastructure. By integrating photovoltaic generation, Battery Energy Storage Systems (BESS), Proton Exchange Membrane Fuel Cells (PEMFC), and utility grid support within a unified framework, the system successfully overcomes challenges associated with renewable intermittency, storage limitations, and dynamic charging requirements.

The decentralized energy management strategy enables intelligent coordination among multiple energy sources, ensuring optimal power sharing and uninterrupted charging operation under varying operating conditions. The implementation of adaptive control mechanisms and Line Resistance Corrected Droop Control significantly improved load distribution accuracy, DC bus voltage regulation, and overall system stability. Battery storage effectively handled transient load variations, while fuel cells provided long-duration energy support, thereby reducing storage stress and extending battery lifespan. Experimental and simulation analyses demonstrated stable operation during grid-connected and islanded modes, with improved renewable energy utilization and reduced dependency on conventional utility infrastructure.

Furthermore, the system maintained acceptable power quality performance with low harmonic distortion and near-unity power factor operation. Intelligent coordination between renewable generation and hybrid storage resources improved charging continuity during renewable fluctuations and grid disturbances. Overall, the proposed hybrid charging framework offers enhanced reliability, scalability, sustainability, and operational flexibility, making it a promising solution for future smart charging infrastructure and large-scale transportation electrification initiatives.

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