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Research Paper

EV CHARGING INFRASTRUCTURE WITH DISTRIBUTED ENERGY RESOURCES AND RELIABLE GRID CONNECTIVITY

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Abstract - The increasing penetration of electric vehicles (EVs) demands an efficient, reliable and environmentally sustainable charging infrastructure. Conventional grid-based charging systems are limited by power quality issues, high peak demand and dependence on the utility grid. To overcome these challenges, this work presents a distributed energy resources (DERs) based EV charging system utilizing a hybrid combination of solar photovoltaic (PV), fuel cell and battery storage integrated through a common DC bus architecture. The proposed model supports seamless transition between grid-connected and standalone modes using static transfer switches (STS), and ensures un interrupted EV charging during grid outage conditions. An adaptive comb-filter based control strategy is employed to enhance power quality, reduce harmonic distortion and maintain stable DC bus voltage. Simulation results validate the effectiveness of the system under varying load, weak grid scenarios, and fluctuating solar insolation, demonstrating reduced total harmonic distortion (THD), improved system reliability and fast charging capability. Thus, the proposed hybrid renewable-based EV charging station provides an efficient and sustainable solution for next-generation smart transportation and microgrid applications.

Keywords: Adaptive comb-filter, distribution network, EV charging, fuel cell stack, grid connected mode, islanded mode, power quality, seamless power transfer, solar PV array.

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I INTRODUCTION

The global transition toward sustainable and environmentally responsible transportation has intensified interest in Electric Vehicles (EVs), driven by concerns over fossil fuel depletion, greenhouse gas emissions, and urban air pollution. As EV adoption rapidly increases, the development of a robust, efficient, and scalable charging infrastructure has become a critical engineering challenge. Conventional EV charging stations predominantly depend on the electrical grid, which not only imposes a significant burden on peak power demand but also limits the overall sustainability benefits when the grid is powered by non-renewable sources. Therefore, integrating renewable energy resources into EV charging systems is essential for achieving energy security, economic feasibility, and environmental sustainability.

Hybrid Renewable Energy Systems (HRES), particularly those incorporating Solar Photovoltaic (PV) and Proton Exchange Membrane Fuel Cell (PEMFC) technologies, present a reliable solution for continuous, clean power generation suitable for EV charging applications. The complementary operating characteristics of solar and fuel cell systems ensure reliable energy availability by compensating for intermittency and variations in renewable generation. A common DC bus architecture further enhances system efficiency through reduced conversion losses, improved power quality, and flexible multi-level charging capabilities.

This project focuses on the design and implementation of a hybrid renewable EV charging system utilizing Solar PV and Fuel Cell sources interfaced through power electronic converters and integrated via a DC bus. The proposed system aims to achieve optimal energy management, stable voltage regulation, and seamless power sharing between distributed energy resources and storage units while supporting multiple levels of EV charging. Through detailed modeling, simulation, and performance analysis, the project demonstrates the feasibility and advantages of hybrid renewable power-based EV charging infrastructure for future smart mobility and sustainable power systems.

II SOLAR PHOTOVOLTAIC ARRAY

In the proposed hybrid renewable energy-based EV charging station, the Solar Photovoltaic (PV) array serves as the primary source of clean and sustainable power generation. The PV array is composed of multiple interconnected solar modules arranged in series and parallel to obtain the desired voltage and current ratings required for efficient EV charging. When solar radiation strikes the semiconductor material of the PV cells, the photovoltaic effect converts sunlight directly into DC electrical energy. This generated DC power is inherently variable due to changing climatic conditions such as irradiance, temperature, and shading. Therefore, a DC–DC boost converter integrated with a Maximum Power Point Tracking (MPPT) algorithm is employed to extract the maximum possible power from the PV array at all operating conditions. The regulated output from the converter is fed to the common DC bus, which acts as the central interface between power sources, storage units, and EV charging loads. During peak sunlight hours, the PV array supplies a major portion of the charging demand, thereby minimizing grid dependence and operational cost. Excess solar energy, if available, can be utilized to charge the battery storage system or support auxiliary loads. In periods of insufficient sunlight, the fuel cell compensates power shortages, ensuring uninterrupted charging capability. The integration of Solar PV technology enhances the overall system efficiency, environmental performance, and energy reliability. By reducing fossil fuel consumption and greenhouse gas emissions, the PV array contributes significantly to sustainable transportation and future smart mobility infrastructure.

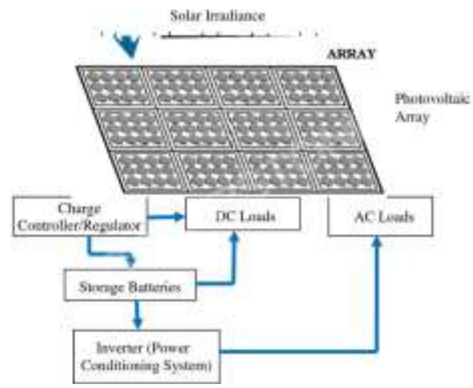


Figure 1: Comparison of Battery Technologies

III FUEL CELL STACK

A fuel cell stack is a key component used to generate electrical power by combining multiple fuel cells in a series or parallel arrangement to achieve the required voltage and current output. Since a single fuel cell typically produces only about 0.6–1.0 volts, many individual cells are layered together to form a stack, enabling practical power generation for industrial and transportation applications. Each fuel cell in the stack contains an anode, a cathode, and an electrolyte membrane where an electrochemical reaction takes place. Hydrogen supplied to the anode is split into protons and electrons; the protons pass through the electrolyte while the electrons travel through an external circuit to produce electricity. At the cathode, oxygen from air combines with the protons and electrons to form water and release heat. The stack includes bipolar plates for gas distribution and current collection, along with end plates, gaskets, and cooling channels for sealing and temperature control. Fuel cell stacks are widely used in electric vehicles, backup power systems, portable power units, and renewable hybrid energy systems due to their high efficiency, clean operation, and low noise, producing only water vapor as an emission.

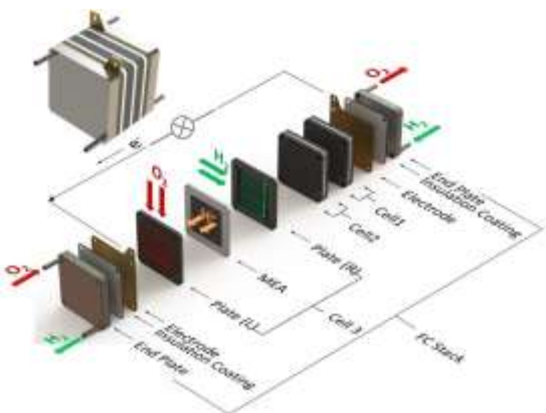


Figure 2: Components of Fuel Cell Stack

IV BATTERY ENERGY STORAGE SYSTEM(BEES)

The Battery Energy Storage System (BESS) in the proposed EV charging station plays a vital role in ensuring reliability, energy balance, and power quality. It works alongside solar PV and the fuel cell to form a hybrid energy system, storing excess renewable energy when generation exceeds demand and supplying power during low solar radiation or grid outages. The battery is interfaced through a bidirectional DC–DC converter, which allows both charging and discharging depending on system requirements. A PI-based control loop continuously monitors the DC-link voltage, and any deviation triggers the battery to either inject or absorb power to keep the DC bus stable. This stabilization is essential for fast EV charging, since the common DC bus directly feeds EV batteries with high power. During standalone (grid-absent) operation, the BESS provides crucial support by ensuring uninterrupted power to both EV loads and local loads, while in grid-connected mode it helps smooth renewable fluctuations and maintain seamless transitions through Static Transfer Switches (STS). Overall, the BESS enhances system resilience, prevents renewable curtailment, supports load balancing, improves dynamic response during disturbances, and ensures the charging station continues to meet IEEE power quality standards even under weak grid or unbalanced load conditions.

The Battery Energy Storage System (BESS) functions as a crucial backup and stabilizing unit within the hybrid EV charging station. It stores excess energy generated by the solar PV array and fuel cell, and supplies power whenever renewable generation is low or the grid becomes unavailable. The battery is connected to the common DC bus, allowing it to support fast EV charging and maintain a stable DC-link voltage. A bidirectional DC-DC converter with PI-based control enables smooth charging and discharging of the battery by regulating current according to DC-link voltage errors. This ensures uninterrupted power to EVs and local loads, seamless transition between grid-connected and islanded modes, and improved power quality during system disturbances such as load changes or fluctuating solar insolation.

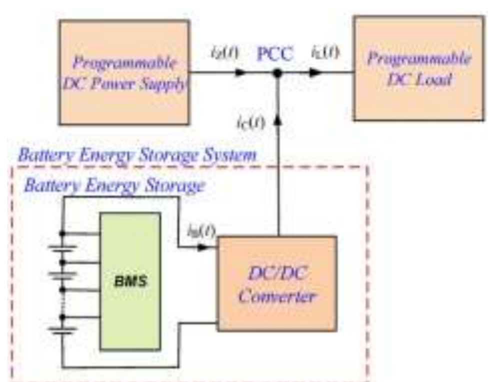


Figure 3: *Battery Energy Storage System*

V MAXIMUM POWER POINT TRACKING (MPPT)

Maximum Power Point Tracking (MPPT) is a crucial control technique used in solar photovoltaic (PV) systems to ensure that the PV array operates at its optimum power output under varying environmental conditions. Since solar panels produce different voltage and current levels depending on sunlight intensity, temperature, and load variations, they have a specific point called the Maximum Power Point (MPP) where the product of voltage and current is maximum. MPPT continuously monitors the PV array voltage and current, compares them to the ideal operating point, and dynamically adjusts the duty cycle of a DC–DC converter to extract the highest possible power from the solar panels. This significantly improves the efficiency and reliability of renewable power systems by preventing energy loss.

Use of MPPT in EV Charging: In electric vehicle (EV) charging systems powered by solar PV, MPPT plays a vital role in maximizing energy utilization for faster and stable charging. The MPPT controller sits between the solar PV array and the DC bus or battery charging unit. It ensures that even when sunlight fluctuates (e.g., due to clouds or temperature changes), the PV array continuously delivers the maximum available power to charge the EV battery. MPPT helps maintain optimal charging voltage and current, reduces dependency on the grid, and supports economic and eco-friendly charging. In hybrid renewable EV charging stations, MPPT coordinates solar energy with other sources (like fuel cells or grid power) to maintain uninterrupted and efficient charging. By increasing energy extraction from PV by 20–30%, MPPT enhances the performance, reliability, and sustainability of EV charging infrastructure.

Figure 4: Maximum power point tracking

VI UTILITY GRID INTERFERENCE

Utility Grid Interference refers to the impact and disturbances that occur in the power utility grid when integrating distributed energy resources (DERs) such as solar PV systems, fuel cells, and battery energy storage systems, particularly in applications like electric vehicle (EV) charging stations. When renewable energy sources are connected to the grid, variations in power generation caused by changes in sunlight, load fluctuations, or sudden charging demand from EVs can introduce issues such as voltage instability, frequency deviations, harmonic distortion, and power quality disturbances. High penetration of intermittent renewable sources may affect grid reliability, leading to imbalance between supply and demand, reverse power flow, transformer overloading, or flicker in voltage levels.

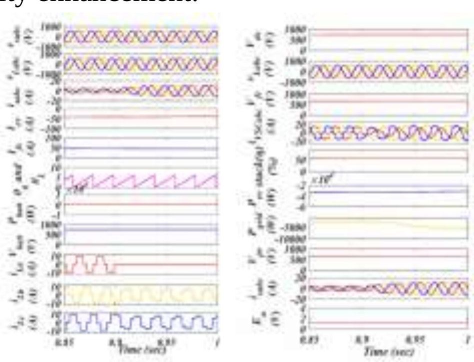
To mitigate these interferences, advanced power conditioning equipment such as inverters with proper synchronization control, filters, and smart energy management systems are used. Battery Energy Storage Systems (BESS) also help stabilize the grid by storing excess energy and supplying it during peak demand, thereby smoothing fluctuations. Additionally, Maximum Power Point Tracking (MPPT) ensures controlled power extraction from renewable sources, while grid synchronization techniques ensure that voltage, phase, and frequency of the system match utility standards. Effective mitigation of utility grid interference enhances system reliability, power quality, and safe integration of renewable-powered EV charging infrastructure.

VII EVs CHARGING STATION WITH RENEWABLE ENERGY SOURCES

An EV charging system with hybrid renewable energy sources is an advanced charging infrastructure that integrates multiple clean energy technologies such as solar photovoltaic (PV) panels, wind turbines, fuel cells, and battery energy storage systems to supply reliable and sustainable power for charging electric vehicles. Instead of depending solely on the utility grid, this hybrid arrangement combines the strengths of different renewable sources to ensure continuous energy availability even during fluctuating weather conditions. Solar PV modules generate power during daylight hours, while wind or fuel cell systems can supplement power generation during periods of low solar output. Excess energy is stored in a Battery Energy Storage System (BESS) and later used to meet peak charging demand or when renewables are insufficient. Power regulators, inverters, and Maximum Power Point Tracking (MPPT) controllers are incorporated to maximize energy extraction and maintain stable charging voltage and current. The hybrid charging system can operate in both grid-connected and stand-alone modes, enabling efficient load management, peak shaving, and reduced dependency on conventional fossil fuel-based electricity. This results in enhanced power reliability, improved charging efficiency, reduced carbon emissions, and increased economic benefits. Such hybrid renewable-powered EV charging stations are key components of future smart grids, supporting green energy transitions and sustainable transportation development.

VIII MODELLING AND SIMULATION RESULTS

The simulation results validate the performance and effectiveness of the proposed common DC bus EV charging system integrated with hybrid renewable energy sources solar PV, fuel cell stack, and battery energy storage operating under both grid-connected and islanded conditions. Different operational scenarios were analyzed to assess system stability, seamless transition capability, and power quality enhancement.



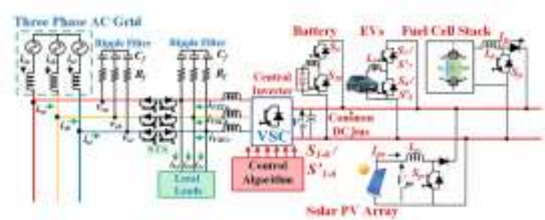


Figure 5: EVs charging system configuration with hybrid renewable energy source

Figure 6: Performance of common DC bus EVs charging system during load unbalancing condition.

It shows the transition from grid connected to disconnected mode of operation for common dc bus charging of EVs with distributed microgrid consisting of solar PV array, battery and fuel cell sources. The grid voltages and grid currents are Observed to reduce to zero at the instant of transition as presented. And power is delivered to the local loads along with Charging of evs. The fuel cell parameters are also presented such as fuel cell power (pfc), voltage (vfc) and the stack efficiency. In addition, the change in wave-shape of vsc currents, is observed along with the grid power, which reduces to zero During the grid outage conditions.

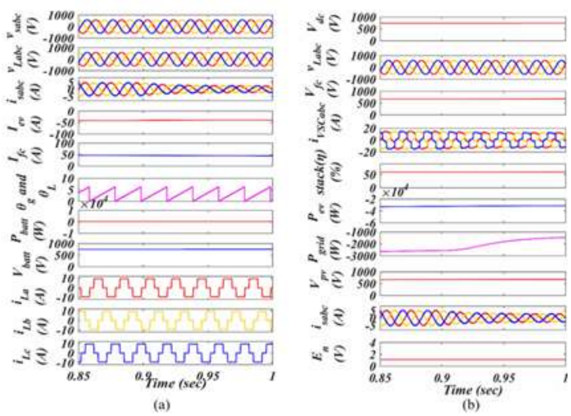


Figure7: performance of common dc bus evs charging system during variable solar insolation condition.

During variable solar insolation, the common DC bus EV charging system maintains stable performance by automatically compensating for reduced PV power using the grid and fuel cell sources. Even when solar irradiation drops, the DC bus voltage and EV charging current remain constant, ensuring uninterrupted fast charging. The adaptive comb-filter maintains high power quality, keeping grid current THD within IEEE limits. Battery usage remains minimal, preserving its life while fuel cell output smoothly adjusts. Overall, the hybrid control strategy ensures reliable, clean, and stable EV charging despite fluctuating solar conditions.

IX CONCLUSION

The performance analysis of the common DC bus EV charging system under variable solar insolation demonstrates that the hybrid architecture of PV, battery, and fuel cell ensures highly reliable operation. Despite fluctuations in solar irradiance, the system maintains a stable DC bus voltage and continuous EV charging without performance degradation. The grid and fuel cell effectively compensate for reduced PV power, ensuring uninterrupted energy supply. The adaptive comb-filter–based control significantly improves power quality, keeping current Total Harmonic Distortion. Battery power remains stable, avoiding unnecessary cycling and enhancing battery lifespan. The coordinated control enables seamless mode transitions between grid-connected and islanded operation. Under weak grid and unbalanced load conditions, the system still shows strong voltage and current stability. Overall, the hybrid DER-based charging system successfully mitigates solar variability effects. The results confirm that the proposed control strategy provides reliable, efficient, and high-quality EV charging.

X FUTURE SCOPE

In the future, this hybrid renewable EV charging system can be improved in many useful ways. More renewable sources like wind or biogas can be added to make the system work even when sunlight is low. Smart computer programs (AI) can be used to predict energy needs and manage power more efficiently. Excess solar energy can be used to produce hydrogen, making the fuel cell cleaner and cheaper to run. The charging system can be expanded to connect many stations together like a small power network. Fast-charging technology can be added so EVs can charge in a few minutes instead of hours. EVs themselves can give power back to homes or the grid during emergencies. The whole system can be monitored using mobile apps and IoT sensors for better control. In the future, real hardware testing can make the system ready for real-world use. Overall, this technology can help create cleaner cities, reduce pollution, lower electricity bills, and support fully renewable smart mobility.

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