

SMART ENERGY MANAGEMENT OF HYBRID FUEL CELL – BATTERY STORAGE FOR RENEWABLE-POWERED EV CHARGING INFRASTRUCTURE

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ABSTRACT:

With the increasing uptake of EVs, there is a strong need for dependable, efficient, and environmentally friendly charging stations. Typically, traditional charging stations are powered by the electricity grid, which may face several problems, including electricity volatility, voltage problems, carbon emissions, and peak load stress. This project aims to tackle these challenges by designing a decentralized hybrid energy management system for a grid-interactive EV charging station, which incorporates PV generation, Battery Energy Storage Systems (BESS), Proton Exchange Membrane Fuel Cells (PEMFC), and utility grid support. The proposed architecture is based on a common DC bus configuration which enables an efficient transfer of power between different energy sources and allows for continued charging services. Adaptive energy management strategy, which is based on Line Resistance Corrected Droop Control (LRCD), is used to enable distributed energy resource power sharing coordination. PV is the main renewable energy, batteries are used for fast response to transient load fluctuations and fuel cells are used for long duration energy support when renewable energy generation is low. To improve battery life, reduce component stress and improve overall system performance, battery management and fuel cell efficiency optimization based on the State of Charge (SoC) are built in. The charging station can operate in both grid connected and islanded mode to increase system reliability and resilience when there are disturbances in the grid. The simulation and performance analyses reveal the stable DC bus voltage within the specified limits, accurate power sharing, utilization of renewable energy sources, reduction in the dependency on grid, low harmonic distortion and near unity power factor operation. The proposed hybrid charging system is a scalable, reliable and environmental friendly approach to future smart charging system and large scale transportation electrification.

Keywords: :Electric Vehicle (EV), Hybrid Energy Storage System, Battery Energy Storage System (BESS), Proton Exchange Membrane Fuel Cell System (PEMFC), Photovoltaic System (PV), Line Resistance Corrected Droop Control (LRCD), Decentralized Energy Management (DEM), Grid-Interactive Charging Station (GICS), Renewable Energy Integration, Smart Charging Infrastructure.

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1.INTRODUCTION

With the growing popularity of EVs globally, the transportation industry is changing and moving towards sustainable mobility. The increasing focus on environmental pollution, greenhouse gas emissions and fossil fuel depletion has motivated governments and industries internationally to encourage the use of EVs as an environmentally-

friendly option to traditional internal combustion engine (ICE) cars and 4WDs. The expanding demand for EV charging, however, poses a huge challenge to the existing electrical distribution network, such as peak load stress, voltage instability, rising operational costs, and power quality problems. The conventional charging

infrastructure based on utility grid electricity is difficult to meet the demand for large-scale charging and ensure the stability of the charging system. To meet these concerns, researchers have been working on integration of renewable energy sources like solar PV (solar panel) with EV charging infrastructure. The integration of renewable energy not only saves carbon emissions, but also lowers reliance on traditional energy generation methods. At the same time, renewable energy resources are intermittent and seasonal, and sensitive to weather and environmental conditions, affecting their power production capabilities. Therefore, more sophisticated energy management strategies are needed to guarantee continuous charging service, optimize energy utilization efficiency, and make sure to operate the system in a stable manner in the presence of fluctuations in load and generation. As such, the intelligent and sustainable charging infrastructure has emerged as a key research field in the contemporary power systems and transportation electrification [1, 2, 3].

The introduction of Battery Energy Storage Systems (BESS) has become a critical element in EV charging stations that are powered by renewable energy, because they can help mitigate the variability of renewable energy and they can respond fast to sudden load variations. Batteries are able to store surplus renewable energy generated when demand is low and use stored energy to backstop the system when demand is high, thereby improving charging reliability and flexibility. But batteries-only charging systems have a number of drawbacks such as degradation due to repeated charging and discharging cycles, thermal management issues, lower operational life and costly replacements. In order to overcome these limitations, hybrid energy storage configurations consisting of batteries and Proton Exchange Membrane Fuel Cells (PEMFCs) have received much attention. Fuel cells have high energy density, no emissions, and ability to supply long continuous power with little degradation. Batteries are very good at dealing

with transient load fluctuations, but fuel cells offer reliable long-term energy supply during extended charging times and low renewable energy supply. The synergies between batteries and fuel cells can lead to a well balanced hybrid energy storage solution that can help make charging stations more reliable, prolongs battery life, lowers stress on the storage device and increases energy efficiency. Hybrid schemes allow for a practical solution of supporting future scale of EV charging network operations, while also allowing for sustainable and economic operations [4, 5 and 6].

Advanced control and energy management strategies are crucial to ensure efficient management of multiple energy resources in the context of modern charging infrastructure. Centralized control approaches have the drawback of needing a wide range of communication networks, computational power, and complex system architectures, potentially reducing scalability and reliability. Meanwhile, decentralized energy management systems provide greater flexibility, modularity, fault tolerance and less dependence on communications. This project aims at a decentralized hybrid energy management system for a grid-interactive EV charging station, including photovoltaic generation, battery storage, fuel cells and support of the utility grid. A Line Resistance Corrected Droop Control (LRCD) approach is used to ensure accurate power sharing of all the DERs and keep the DC bus voltage stable for dynamic loads powering. The proposed system has the capability to operate both in grid connected and in islanded mode, providing continuous charging services in case of grid disturbances or fluctuations of renewable energies. There are intelligent state-of-charge (SoC) based battery management and fuel cell optimization techniques that are integrated to optimize the system, utilize more renewable energy and lessen total reliance on the grid. The suggested framework is expected to be reliable, scalable, and eco-friendly for the future smart charging stations, smart cities, and big transportation electrification projects [7, 8, 9, 10].

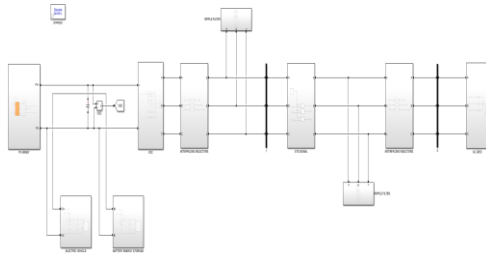


Fig 1 MATLAB/SIMULINK circuit of the Grid Connected PV Array and Battery Energy Storage Interfaced EV Charging Station

II.SURVEY OF RESEARCH

1. The Hybrid Fuel cell and Battery Storage Power management for Grid-interactive EV Charging Station will be published in IEEE Transactions on Smart Grid for November 2025, Volume 16, Issue 6, pp. 4576-4588. Khalid was speaking about the energy management system for Electric Vehicle Charging Stations which include a photovoltaic energy generation system, proton exchange membrane fuel cells and integration with the utility grid (using battery energy storage systems). The study was focused on reliability of charging, and tried to reduce the traditional power source usage. The proposed Droop Control algorithm is DCA based on the Line Resistance Corrected Droop Control, which is shown to provide accurate power sharing of DERs. The battery system was used for short duration energy support, the fuel cells were used for long duration energy support when there was no energy supply from the renewables. By simulation and experimental analysis, the performance of the DC bus voltage regulation and the reduction in the stress of the storage unit was verified and under various charge load situations, the enhanced charging continuity was verified. The proposed configuration worked well for both Grid Connected and Isolated configuration successful tested. The results indicated that the renewable energy usage has increased and unity power factor operation and the harmonic distortion has decreased. The study illustrated the benefits of the hybrid storage coordination for the future EV charging infrastructure in terms of sustainability, scalability and operational efficiency.

2. M.Yilmaz and P.T. Krein, Review of Battery Charger Topologies, Charging Power Levels, and Infrastructure for Plug-In Electric and Hybrid Vehicles, IEEE Transactions on Power Electronics, vol. 28, no. 5, pp. 1660–1678, 2013. 2151–2169, 2013. Yilmaz and Krein talked in detail about charging technologies in EVs, charging infrastructure, charging topologies of battery chargers. The study investigated the different charging standards (Level 1 and 2, Level 3 DC fast charging systems), and battery performance and grid operation effects. Various topological and charging architectures to enhance charging rate, reliability and efficiency were explored. The paper emphasized that smart charging stations will be needed to facilitate high EV penetration, but not be a burden on electricity grids. Several bidirectional charging solutions have been suggested to enable bidirectional energy flow and V2G applications with the smart grid. The authors emphasized the critical importance of intelligent charging control in the future of transportation and the need of integrating with renewable energy resources. Their research findings were key to the development of efficient EVs charging stations and would aid in the Sustainable Infrastructure of charging stations around the world.

3. J. A. Peças Lopes, F. J. Soares and P. M. Rocha Almeida, Proceedings of the IEEE, 99(1), p. 168–183, 2011. The goal of this study was to assess the effect this will produce in the modern power system as a result of the widespread adoption of EVs. The authors took into account the problems related to the growth of the EV market, voltage regulation, peak loading, transformer loading and power quality. Various charging and demand side management strategies were suggested to help achieve the goal of minimising impacts on distribution network. The study has confirmed that charging control and energy management co-ordination could play an important role in maintaining grid stability, and can help to meet the rising demand for charging. The potential to integrate V2G as an ancillary service and support to renewables was also explored. The outcome of

the simulation simulation can be used to create an intelligent charging scheduling to utilize the energy resources more efficiently and reduce the operational costs. The study highlighted the need for successful implementation of EV is to have high quality control mechanism and smart grid technologies. The results are still very relevant for the design of future grid interactive charging stations and sustainable mobility.

4. J. M. Guerrero, J. C. Vasquez, J. Matas, L. G. de Vicuna and M. Castilla, "Hierarchical Control of Droop-Controlled AC and DC Microgrids," *IEEE Transactions on Industrial Electronics*, vol. 58, no. 1, pp. 158–172, 2011. Guerrero et al. suggested a hierarchical control strategy for distributed energy resources (DERs) of AC and DC microgrids. The goal of this study was to improve the power sharing, voltage regulation and stability of the system via droop control method. Proposed architecture for the distributed multiple generators' coordination process was first, second and third level control layers. They showed that the hierarchical control can achieve an increase in the reliability of the system and reduce the number of energy source to energy source communications. The above mentioned load sharing accuracy and voltage deviation problems of decentralized energy systems were also considered. Validated in the real world that these gains in the performance of renewables that are dynamic and intermittent are accurate. The research led to the wide-spread use of the present decentralized control methods for hybrid energy systems and EV charging stations. The technologies it has developed can be directly applied for its innovative solutions on energy management for grid interactive applications powered by batteries, fuel cells and renewable energy sources.

5. T. Dragicevic, X. Lu, J. C. Vasquez and J. M. Guerrero, "DC Microgrids—Part I: A Review of Control Strategies and Stabilizing Techniques," *IEEE Transactions on Power Electronics*, vol. 31, no. 7, pp. 4876–4891, 2016. In a review article, Dragicevic et al. discuss in detail different control techniques and stabilisation methods for DC

microgrids. The paper focused on the challenges for the operation and integration of renewable energy systems, battery storage and distributed generation resources in the most frequently used DC bus topologies. The following bases were used for the evaluation of two control strategies (decentralized and centralized): stability, scalability, reliability and implementation. The authors pointed out the benefits of droop control approaches in the autonomous power sharing of distributed resources. Secondly, the concepts of energy management and voltage regulation were explained to deal with the intermittence in energy supply side due to renewable energy sources and uncertainty on the energy demand side. Using sophisticated converter controls and the need for a necessary steady operation of the DC bus under dynamic load were pointed out. The results demonstrated that the efficient stabilising methods can enhance the power system quality and make the power system more resilient. The book offers valuable theoretical background information for developing hybrid battery-fuel cell charging stations in decentralized control architectures and integration of renewables.

6. A. Khaligh, and Z. Li, "Battery, Ultracapacitor, Fuel Cell, and Hybrid Energy Storage Systems for Electric Vehicle Applications", *IEEE Transactions on Vehicular Technology*, 2010, vol. 59, no. 6, pp 2806-2814, 2010. Khaligh and Li talked about different energy storage technologies for EV application including: Battery, Ultracapacitor, Fuel cell and Hybrid Energy storage system. The Tech's studied, their pros and cons were dissected and their applicability for applications was analyzed. It was decided that batteries provide a high energy density, short duration energy support and fuel cells provide long duration energy support and are environmentally friendly. The scientists pointed out that none of the storage methods would be capable of satisfying all the EV performance requirements. Hence, hybrid energy storage system using different energy storage technologies was proposed to increase the efficiency, reliability and flexibility in the operations. The paper outlined the various

approaches that could be used to regulate the flow of energy to/from the energy storage devices as well as to maximise the performance of the vehicle. Experimental tests have demonstrated that the use of hybrid systems can lead to lower stresses in components, extended component life and optimal utilization of energy. This research finding is a good evidence of the effectiveness of a battery-fuel cell combination on the existing EV charging stations and to the sustainable transport system.

III. WORKING METHODOLOGY

The proposed system aims at designing a decentralized hybrid energy management system (HEMS) for grid-connected Electric Vehicle (EV) charging system (EVCS) that incorporates Proton Exchange Membrane Fuel Cell (PEMFC) power generation, Battery Energy Storage System (BESS), and utility grid support. The PV array is the main renewable energy source which continuously transforms solar energy into electrical energy. A Maximum Power Point Tracking (MPPT) controller is used to get maximum extraction from the solar system. Power generated by PV system is:

$$[P_{\{PV\}} = V_{\{PV\}} \times I_{\{PV\}}]$$

PV output power is ($P_{\{PV\}}$), PV voltage is ($V_{\{PV\}}$) and PV current is ($I_{\{PV\}}$). The power generated is delivered to the EV charging load via a common DC bus. In excess sun generation, extra energy is stored in the battery system or sent to the utility grid. The total load demand of the charging station is met based on the power balance equation:

$$[P_{\{Load\}} = P_{\{PV\}} + P_{\{Bat\}} + P_{\{FC\}} + P_{\{Grid\}}]$$

Note that ($P_{\{Bat\}}$), ($P_{\{FC\}}$) and ($P_{\{Grid\}}$) are the power contributions from battery, fuel cell and grid, respectively. This is a coordinated energy sharing mechanism that allows a continuous charging operation and optimizes the use of renewable energy and limits dependence on traditional electricity suppliers.

The Battery Energy Storage System (BESS) is the main short-term energy balancing component of the charging infrastructure. Batteries offer quick dynamic response in case of sudden charging demand fluctuations and renewable energy fluctuations. According to the State of Charge (SoC), the state of the battery is monitored continuously and is calculated as:

$$[SoC(\%) = \frac{Q_{\{remaining\}}}{Q_{\{rated\}}} \times 100]$$

where ($Q_{\{remaining\}}$) is the charge left on the battery, and ($Q_{\{rated\}}$) is the rated battery capacity. The charging and discharging power of the battery can be represented by:

$$[P_{\{Bat\}} = V_{\{Bat\}} \times I_{\{Bat\}}]$$

The controller ensures that the battery's operation is kept within certain limits, thereby conserving battery life, and it regulates the Depth of Discharge (DoD) which is defined as:

$$[DoD(\%) = 100 - SoC(\%)]$$

The battery is able to compensate for the power deficit instantly when renewable generation is low or EV charging demand is high. In periods of high sun production, batteries will store extra energy for use later. This smart battery management approach reduces thermal stress, maximizes storage efficiency and increases charging reliability in dynamic operational conditions.

The Proton Exchange Membrane Fuel Cell (PEMFC) subsystem supplies long duration energy support when renewable energy sources are not available, and battery charge is below minimum requirements. Fuel cell is connected to DC bus with a boost converter and provides continuous power for long periods of charging. The output power from the fuel cell is given as:

$$[P_{\{FC\}} = V_{\{FC\}} \times I_{\{FC\}}]$$

The fuel cell voltage ($V_{\{FC\}}$) and current ($I_{\{FC\}}$) are shown. The proposed system implements Line Resistance Corrected Droop Control (LRCD) to coordinate the power sharing

between PV, battery, fuel cell and grid resources. The droop control equation is:

$$[V_{DC}=V_{ref}-R_{dI}]$$

This is because the droop resistance coefficient (R_d) and the reference voltage (V_{ref}) are fixed, while the output current (I) is variable. The overall efficiency of the charging station is determined using:

$$[\eta=\frac{P_{out}}{P_{in}}\times 100]$$

P_{out} is the useful power delivered to the EV load and P_{in} is the total input power from all energy sources. The charging station seamlessly switches to islanded mode on a grid outage and continues to provide EV charging services. The proposed framework enhances both the reliability and power quality of the power supply, while also improving energy efficiency and sustainability, making it well suited to future smart EV charging infrastructure by coordinated utilization of renewable generation, battery storage, fuel cells and grid interaction.

IV. RESULTS EXPLANATIONS

A. Performance Under Variation of Solar Insolation

During rise in PV array irradiation from 600 to 1000 W/m², PV array generation increases, since EV and battery are in floating mode, as shown in Fig. 2

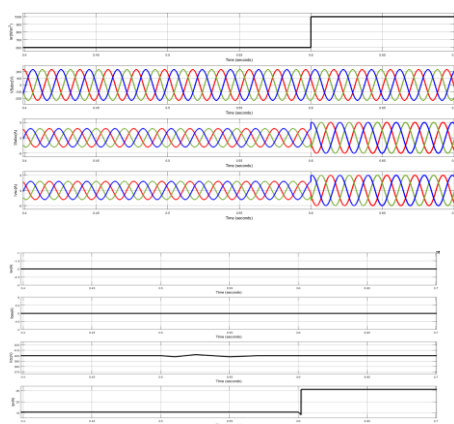
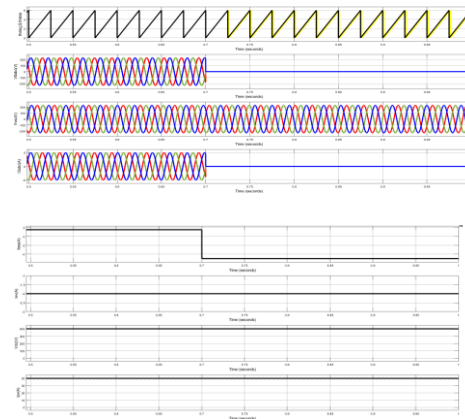


Fig 2 Simulated response of EV charging station under variation of PV insolation

B. Performance of System at Outage of Grid

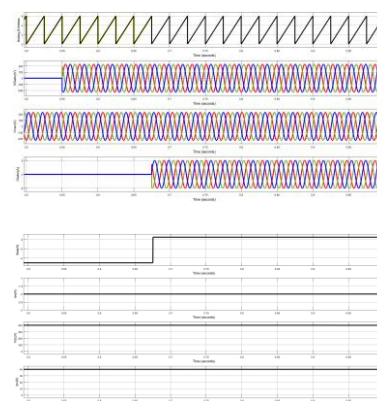
Simulated performance at grid outage is shown in Fig. 3 (a). When grid outage is observed, charging station operates in SM. Therefore, grid currents and voltages immediately become zero. The BES compensates for surplus power and starts charging. EV charging remains unchanged.



(a)

C. Performance of System at Grid Reconnection

The simulated response of system at grid recovery is presented in Fig. 8.3 (b). During grid restoration, the VSC synchronizes to the grid, and the grid voltages and the currents are appeared. The BES starts discharging without affecting the EV charging.



(b)

Fig. 3 Simulated performance at (a) grid disconnection and (b) grid reconnection

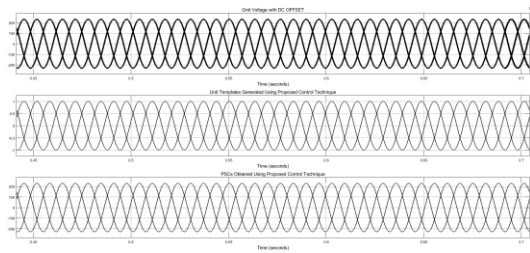
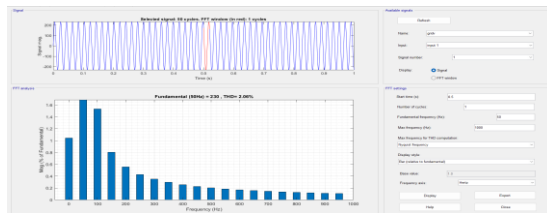
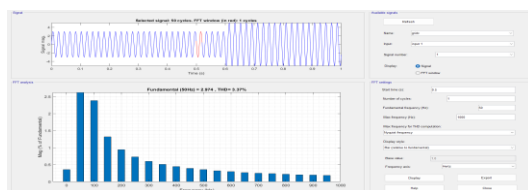


Fig. 4 Comparative of the proposed control with fractional order correntropy adaptive filtering algorithm at dc offset



(a)



(b)

Fig 5 THD of grid voltage and grid current

V.CONCLUSION

The hybrid fuel cell and battery storage power management system for grid-interactive electric vehicle charging stations is an effective and environmentally friendly solution to the growing need for quality and reliable EV charging systems. The system manages to address the issues of renewable intermittency, limited storage capacity and dynamic charging demands by incorporating photovoltaic generation, Battery Energy Storage Systems (BESS), Proton Exchange Membrane Fuel Cells (PEMFC) and grid support in a single system. The decentralized energy management strategy helps to coordinate multiple energy sources efficiently and allows for the optimal allocation of energy resources for uninterrupted charging operation under varying operating conditions. Adaptive control mechanisms and Line Resistance Corrected Droop Control had a

significant impact on load distribution, DC bus voltage regulation and overall system stability. This enabled the stress on the battery storage system to be reduced to mitigate the need for long duration energy support, which was provided by fuel cells, thus increasing the battery life. Experimental and simulation analyses showed that stable operation could be achieved during both grid-connected and islanded modes with increased renewable energy utilization and decreased reliance on the conventional utility infrastructure. Moreover, the system provided good power quality performance and low level of harmonics distortion with near unity power factor operation. The efficiency of intelligent coordination between renewable generation and hybrid storage resources enabled uninterrupted charging during renewables fluctuations and disturbances. The efficiency of intelligent coordination between renewable generation and hybrid storage resources ensured continuity of charging during renewable fluctuations and 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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