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Adaptive Super-Twisting Sliding Mode Energy Management for Hybrid PV–Fuel Cell EV Charging Stations

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ABSTRACT- With the growing adoption of electric vehicles (EVs), there is a significant need for sustainable and efficient renewable energy-powered charging stations. An Adaptive Super-Twisting Sliding Mode Control (Adaptive STSMC)-based Energy Management Strategy (EMS) is presented for an EV charging station PV and fuel cell (FC) powered in a DC micro grid. The proposed controller is designed to regulate the power flow between EVs charging load, PV, fuel cell, battery energy storage system and utility grid under various operating conditions. The proposed Adaptive STSMC does not need to define any membership functions and expert-designed control rules, which is also more suitable to deal with the nonlinear behavior of the system and the changing operating conditions in the conventional fuzzy logic-based EMS. The controller is designed in MATLAB/Simulink environment and its performance is compared with the existing fuzzy logic controller. From the simulation results, it is proved that the proposed method has the characteristics of faster dynamic response and better power sharing characteristics, stable system operation and better control performance under the different renewable generation and load demand. Thus, the proposed Adaptive STSMC can be used as an effective and practical solution for energy management in renewable energy-based EV charging stations.

KEYWORDS- Adaptive Super-Twisting Sliding Mode Control (Adaptive STSMC), Microgrid, EV Charging Station, Photovoltaic System, Fuel Cell, Renewable Energy, Power Management

I. INTRODUCTION

The fast expansion of electric vehicles (EVs) has revolutionized the transportation sector and hastened the shift to sustainable transportation solutions [1][2][3]. EV's offer a greater energy efficiency, lower running costs and considerably lower greenhouse emissions when compared with conventional internal combustion engine vehicles [4, 5]. However, as EVs are gaining popularity, there has been a tremendous need to develop charging infrastructure to facilitate safe and reliable charging services that can also satisfy the requirement of large scale charging without causing major disturbances on the existing power system [6].

To overcome these difficulties, non-conventional energy charging stations are recognized as an attractive alternative to the conventional charging stations which are dependent on an electric grid [7], [8]. Other non-conventional energy sources such as photovoltaic (PV) systems have been highly valued for their clean energy generation potential and their cost of installation is reducing as time passes [9]. But, the variability of solar energy generation complicates the performance of solar charging systems including charging reliability and power quality. To address this constraint, fuel cell (FC) systems are being increasingly combined with PV generation to make a stable and controllable energy source to meet EV charging loads at times of low PV energy generation [10], [11].

PV system integration with fuel cell and battery storage unit and EV charging loads in a DC microgrid has some advantages including energy efficiency, less power conversion stages and flexible operation [12],[13] For EV charging application, DC microgrid is particularly promising as most of the non-conventional energy sources, storage and EV batteries naturally work on DC electricity and therefore power conversion losses can be reduced and performance of the system can be increased.

Though all the above advantages, the PV-FC powered EV charging stations are still a difficult task to operate considering the stochastic nature of the non-conventional energy generation processes and continuously varying charging demands [14]. It is very important to have an efficient coordination of multiple energy sources to ensure a reliable energy supply, maintain system stability and maximize utilization of non-conventional energy. Therefore, Intelligent Energy Management Systems (EMSs) are essential research areas related to a modern EV charging infrastructure.

In the literature, different approaches of energy management have been reported for hybrid non-conventional energy-based EV charging stations and microgrid applications. The conventional proportional-integral controller has been extensively used due to their simplicity in tuning and easy design [15]. But their performance can be reduced under nonlinear and time varying operating conditions. For the better allocation of energy and system performance, optimization techniques like Genetic Algorithms, Particle Swarm Optimization etc.

metaheuristic methods are studied. While such techniques can give an acceptable performance level of optimization, they are possible with a lot of computation complexity and cannot be implemented in real-time.

To overcome these drawbacks, the fuzzy logic-based energy management system has intensively been used in non-conventional energy applications. To describe the behavior of nonlinear system and deal with the uncertainty during the operation, fuzzy controllers with linguistic rules and membership functions can be employed. Fuzzy logic has been shown to be effective in power-sharing capability and increase the operating flexibility in PV–FC powered EV charging stations. But, the design of membership functions and expert defined rule bases are crucial to the performance of fuzzy controllers. This requires a vast amount of knowledge about the behaviours of the system as well as numerous tuning procedures to construct an effective fuzzy controller. Moreover, such fuzzy rules are predetermined and they might not be sufficient to describe a complicated nonlinear relationship under the highly dynamic operating conditions [16],[17].

Despite the good results obtained when using fuzzy logic controllers in hybrid renewable energy systems, the controller's performance is also dependent on the choice of the membership function and the quality of the expert defined rule base. The controller parameters typically need quite complex tuning, and the fixed rule structure is not sufficiently flexible to enable the controller to adapt to fast changes in renewable power generation and in EV charging demand. Such constraints foster the creation of strong control methods that are able to keep the system performance stable in an uncertain and nonlinear operating condition[18].

Due to its good robustness against parameter external disturbances and changes, SMC has been of great interest. On the other hand, the phenomenon of chattering is a well-known drawback of the conventional SMC which leads to unwanted oscillations in the control signal and may impact the performance of the converter. In order to overcome this limitation, the STSMC algorithm that overcomes the drawback of sliding mode control and provides continuous control action has been developed [19], [20], [21]. In addition, adaptive gain mechanism is introduced to the controller to make the control effort automatically adapt to the varying operating conditions, so as to improve transient performance of system and avoid useless oscillations of control.

These benefits are a strong driving force to propose an Adaptive STSMC-based Management of Energy Strategy for the Fuel Cell and PV powered electric vehicle charging station in a DC micro-grid. The proposed controller replaces energy management system without affecting the overall system architecture, which is based on conventional fuzzy logic. It manages the power sharing of PV array, fuel cell, energy storage system of battery, the utility grid and EV charger loads in both islanded and grid connected mode. Adaptive control mechanism enhances the dynamic response while keeping stable operation with renewable energy fluctuations and varying charging demands.

The proposed Adaptive STSMC based Energy Management strategy is realized using MATLAB/Simulink and tested under various operating conditions. It is compared with the traditional energy management system based on fuzzy logic to evaluate the improvement in power-sharing capability, transient response and stability of the system.

This work has made the following key contributions:

- Design of an Adaptive STSMC
- The replacement of traditional energy management using fuzzy logic controller by a very powerful adaptive control approach.
- Developing and implementing an adaptive STSMC for coordinated power management in DC microgrid.
- Comparative analysis based on the transient response, power-sharing performance and system stability between the proposed Adaptive STSMC and the conventional fuzzy logic controller.

The further sections of this paper is structured as below. Overall system configuration and the proposed energy management framework are discussed in Section II. The mathematical modelling and design of the Adaptive STSMC controller is presented in Section III. The results of the simulation and performance evaluation are discussed in Section IV. The paper ends in section V, which provides some ideas for future research.

II. SYSTEM ARCHITECTURE AND PROPOSED ADAPTIVE STSMC-BASED ENERGY MANAGEMENT FRAMEWORK

A. System Architecture

The overall system configuration of Adaptive STSMC based energy management system for FC and PV powered EV charging station is shown in Figure 1. The proposed charging station is designed in a DC microgrid environment, which has a photovoltaic generation unit, fuel cell system, multiple EV charging stations, an Adaptive STSMC-based energy management system, and a battery-ultracapacitor (BUC) energy storage unit (ESU). These components work together to ensure that the renewable energy resources are utilized efficiently and the charging performance is reliable under various operating conditions.

The photovoltaic system is the main renewable energy; it converts the sun's energy into electrical energy. The power generated is fed into the common DC bus via PV dedicated DC-DC converter that regulates the PV output and facilitates efficient power transfer. The output power PV system is a function of ambient temperature and solar irradiance and hence fluctuates depending on the time of day.

When PV generation is low, the fuel cell serves as a secondary energy source in order to ensure the reliability of the charging station. It provides extra power to meet the power demand of the EV charging and power balancing of the DC microgrid. To regulate the output of the fuel cell, a DC-DC converter is used prior to connecting it to the common DC bus.

To improve dynamic performance of the proposed charging station, a battery–ultracapacitor hybrid energy storage system is embedded. The battery will be used to supply energy for long periods of time when there is a lack of energy, and the ultracapacitor will fill in the gaps when there are sudden power changes and transient disturbances.

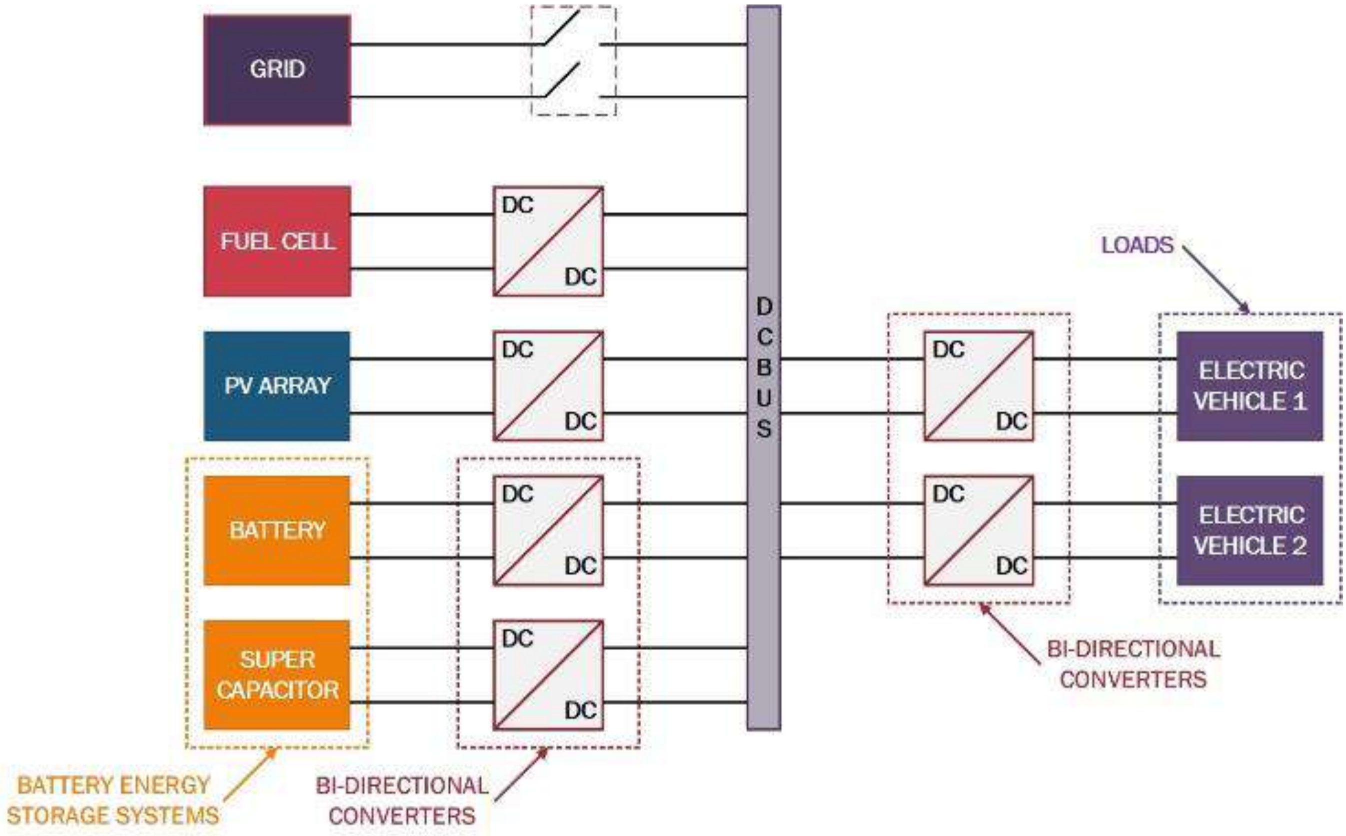


Figure 1: Overall architecture of the proposed Adaptive STSMC-based energy management system for a fuel cell and photovoltaic powered electric vehicle charging station operating in a DC microgrid.

A bidirectional DC-DC convertor connects energy storage system with the DC bus, which can charge and discharge the energy storage system as needed.

The DC microgrid is also interfaced with utility grid via an AC-DC converter, allowing both grid connected and islanded mode of operation. When the non-conventional energy generation and stored energy is not enough to meet the charging demand during the grid connected operation, the power is supplied by the utility grid as well. Islanded operation is where the charging station is completely independent and utilizes only the PV generation, fuel cell power and battery energy storage system.

Common DC bus power distribution platform of the proposed charging station. It can connect all the renewable energy sources, energy storage system, utility grid, and EV charging loads together, allowing coordinated sharing of energy with minimal conversion losses. The energy management system based on Adaptive STSMC always observes the working state of the charging station and gives out the necessary control actions according to the situation to control the power flow between all sources of energy. By using this coordinated control strategy, a stable DC bus operation, effective use of renewable energy, and reliable charging of EVs in different operating conditions can be achieved.

B. System Parameters

Table 1: General Test Scenario of ATM machine Generation

System Component	Specification
Nominal Fuel Cell Capacity	50 kW
Solar Generation Technology	Monocrystalline Photovoltaic Array
Individual PV Module Rating	250 W
PV Conversion Efficiency	20%
Number of Charging Outlets	2
Charging Infrastructure Type	DC Fast Charging Unit
Rated Charger Capacity	50 kW
Aggregate Charging Capacity	100 kW
Microgrid Topology	DC-Based Microgrid
Supported Operating Conditions	Grid-Connected and Islanded Modes
Energy Storage Configuration	Battery–Ultracapacitor Hybrid System
Solar Power Converter	DC–DC Boost Converter
Fuel Cell Power Converter	DC–DC Power Conditioning Converter
Storage System Converter	Bidirectional DC–DC Converter

Utility Grid Converter	AC–DC Interface Converter
Conventional Energy Management Strategy	Fuzzy Logic-Based EMS
Proposed Energy Management Strategy	Adaptive STSMC-Based EMS
Simulation Platform	MATLAB/Simulink Environment

The proposed system of PV–fuel cell powered EV charging station is implemented in DC micro-grid environment to guarantee the reliable and sustainable charging of EVs in different operating conditions. The technical specifications taken for the simulation model are summarised in Table 1. The rating of the renewable energy sources, the energy storage system, the EV charging stations, and the power electronic converters for use in this study are defined by these parameters. The same system configuration and operating conditions are used to implement both the conventional fuzzy logic-based energy management system and the proposed Adaptive Super-Twisting Sliding Mode Control (Adaptive STSMC)-based energy management strategy to improve the fairness of the energy management system performance evaluation. This makes it possible to compare the improvements the proposed controller can make with just the control performance and not due to the changes in the system architecture and ratings of its components.

C. *An energy management system using an adaptive STSMC is proposed.*

The power management is a key challenge in a DC micro-grid where the PV system, FC, battery-ultracapacitor storage system of electrical energy, utility grid, and EV charging loads are connected. Due to the intermittency of renewable energy sources and ever-changing charging demands, the controller should be able to react swiftly and stabilize the system's operation. To accomplish these goals, an Adaptive STSMC-based EMS is designed and implemented in the proposed charging station.
The proposed Adaptive STSMC is continuously monitoring the operating conditions of the charging station such as charging demand, PV input power, battery SOC and utility grid status. The controller uses these operating variables to calculate the necessary fuel cell reference power to maintain power balance and keep EV charging uninterrupted in both islanded and grid connected modes of operation.
The proposed Adaptive STSMC eliminates the need to predetermine membership functions or design rule bases by experts as is the case in the traditional fuzzy logic based controller. Rather, it uses a super-twisting sliding mode control algorithm with adaptive gain mechanism to control the system under the nonlinear operating conditions. The adaptive gain adapts the controller response automatically, to enhance the system robustness to renewable energy intermittency, load disturbances and parameter uncertainties.
The proposed controller yields a continuous control law that significantly reduces chattering effects as compared to conventional sliding mode controller, and guarantees robust system stability. Therefore, smoother control action, faster transient response, and improvement in the dynamic stability is obtained during the change in renewable generation and EV charging demand.
Hence, the proposed Adaptive STSMC based EMS ensures reliable co-ordination between sources, utility grid and EV loads. The controller performs stabilization of the DC bus, efficient power sharing, and effective utilization of available renewable energy resources, which improves the power quality and reliability of EV charging station based on DC microgrid.

III. MATHEMATICAL FORMULATION AND ADAPTIVE STSMC DESIGN

A. *Mathematical modelling of the proposed system*

This introduced DC microgrid consists of PV generation, battery-ultracapacitor energy storage, fuel cell system, utility grid support, and electric vehicle charging loads. These components are interconnected and form part of an energy management system where they operate in concert, managing power under different operating conditions. The overall energy management strategy is governed by the power balance relationship:

$$P_{\{PV\}} + P_{\{FC\}} + P_{\{BAT\}} + P_{\{GRID\}} = P_{\{EV\}} + P_{\{LOSS\}} \quad (1)$$

The power contribution of the PV source, fuel cell source, BSS and grid is accounted for on the left hand side of this expression. The right hand side is the charging demand for the EVs, including losses in the system. This balance is critical for the consistent and efficient functioning of the hybrid charging infrastructure, battery storage system and power grid, respectively. P (%) represents the charging demand of EVs and P (%) is system losses.
In the grid connected mode, the utility grid will help to achieve power balance as per operating conditions and requirements of charging. In the case of an islanded situation, the grid contribution is lost and a coordinated operation of PV system, fuel cell unit and energy storage systems is employed to meet charging requirements.

B. *Photovoltaic System Model*

The charging station is designed to utilize solar power as a main source of non -conventional energy, and the photovoltaic (PV) system is a key component of this design. The power produced by PV array is dependent upon the solar irradiance and environment. The PV generated power can be expressed as

$$P_{\{PV\}} = V_{\{PV\}}\ I_{\{PV\}} \quad (2)$$

The generated power is controlled via a DC/DC converter and sent to common DC bus.

C. *Fuel Cell System Model*

The fuel cell unit acts as controllable energy source to cover EV charging demand when PV generation is inadequate. The electric power that the fuel cell can produce is

$$P_{\{FC\}} = V_{\{FC\}}\ I_{\{FC\}} \quad (3)$$

Based on the operating conditions of the charging station, the reference power of fuel cell is created by the proposed Adaptive STSMC.

D. *Battery Energy Storage Model*

The battery–ultracapacitor system serves as a secondary power source and stabilizes the system, when there are sudden load changes. The battery SOC is given by:

$$SOC(t) = SOC(t_0) - frac\{Q_{\{BAT\}}\}\int i_{\{BAT\}(t)}, dt \quad (4)$$

The battery is used for charging and discharging in accordance with the power management decision made by the EMS.

E. Adaptive Super-Twisting Sliding Mode Controller Architecture

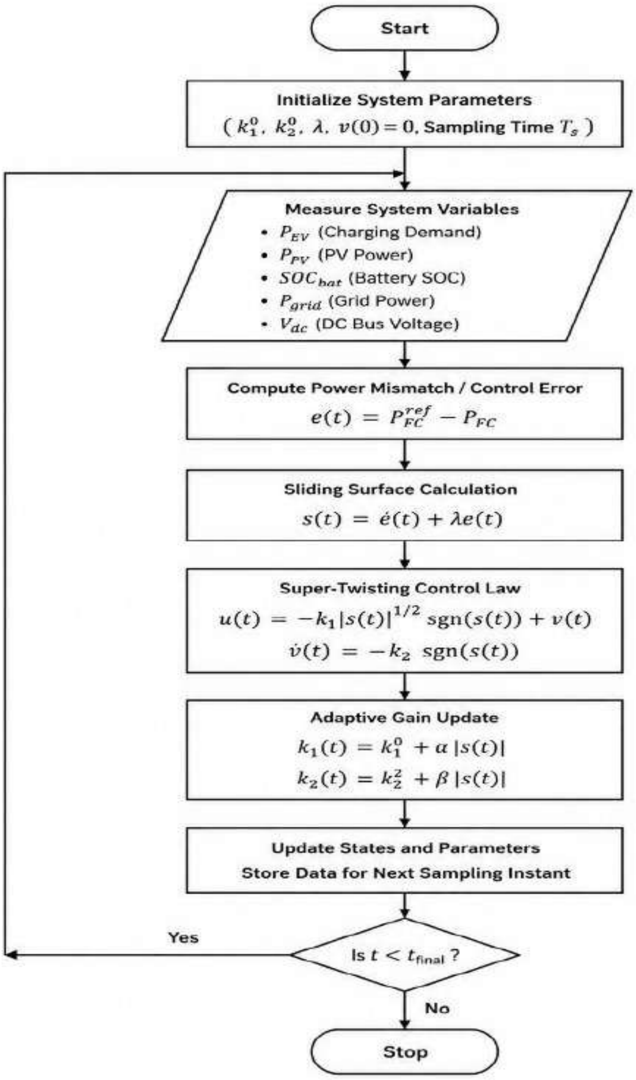


Figure 2: Proposed Controller Architecture

The proposed Adaptive STSMC, which will generate the desired reference power for the energy management system in the fuel cell under different operating conditions. The proposed controller does not rely on the predefined membership functions or expert defined rule base as in the conventional fuzzy logic-based energy management system. Rather, it relies on a powerful nonlinear control approach which adapts the control action on-line based on dynamics of the system. The adaptive gain mechanism automatically adjusts the parameters of controller to achieve better transient responses and stable operation when the renewable energy source fluctuates or when there is a load change or parameter uncertainty. Moreover, the super-twisting algorithm features a considerable decrease of the chattering that is typical of classical sliding mode control (SMC) without sacrificing robustness and finite-time convergence properties of SMC.

The designed Adaptive STSMC is made up of:

- Measurement of system operating variables
- Control error computation
- Sliding surface generation
- Super-twisting control law
- Adaptive gain update mechanism
- Fuel cell reference power generation

This control strategy enables effective coordination among the energy sources, utility grid, and EV charging loads, thereby ensuring reliable power sharing, improved dynamic response, and stable DC microgrid operation under both grid-connected and islanded operating modes.

F. Adaptive STSMC Mathematical Formulation

An Adaptive STSMC is proposed to generate the desired reference power for fuel cell system to achieve stable power sharing in the DC microgrid. The controller dynamically controls the system by minimizing the difference between desired and actual fuel cell power (called the tracking error). The proposed Adaptive STSMC avoids the necessity of defining control rules and fine tuning of the parameters that is needed in conventional fuzzy logic controllers. In contrast, it adopts a nonlinear control design that features an adaptive gain mechanism for robust performance under the renewable energy fluctuations and the variable EV charging demands. The tracking error is equal to

$$e(t) = P_{\{FC\}}^{\{ref\}} - P_{\{FC\}} \quad (5)$$

Here $P_{\{FC\}}^{\{ref\}}$ is the power of the F.C. produced by the strategy of energy management and $P_{\{FC\}}$ is the power output of the F.C. measured. The sliding surface is formulated as

$$s(t) = e^{\cdot}(t) + \lambda e(t) \quad (6)$$

Where $s(t)$ the sliding variable and λ is is a positive design constant which defines the convergence rate of the controller. The Super-Twisting control law is expressed as

$$u(t) = -k1 \mid s(t) \mid \frac{1}{2sign(s(t))} + v(t) \quad (7)$$

$$v^{\cdot}(t) = -k2sign(s(t)) \quad (8)$$

Where $u(t)$ represents the control signal that is fed into the fuel cell converter, v (t) is an auxiliary control signal, and k1 and K2 are positive controller gains. The gains of the controller are adaptively modified with respect to

$$k1 = k + \alpha \mid s(t) \quad (9)$$

Here, k1 and k2 are initial controller gains and α and β are adaptive gain coefficients. This adaptive mechanism allows the controller to adaptively change its control effort based on the operating conditions of the system, which helps to minimize chattering and enhance transient performance.

The control signal generated is finally used to generate reference power of fuel cell, so as to share the power among the PV system, fuel cell, battery energy storage system, utility grid and EV charging loads and to keep the stable operation of DC microgrid.

G. Proposed Adaptive STSMC-Based Control Strategy

The implementation of the proposed Adaptive STSMC based energy management strategy is shown in Figure 3. The controller maintains a constant check on the charging demand, PV generation, battery SOC and utility grid. The controller calculates the sliding surface and produces the necessary fuel cell reference power with the adaptive super-twisting control law, based on these operating variables. The adaptive gain mechanism automatically tunes the controller gains based on the operating conditions of the system, maintaining its strong performance despite fluctuations in renewable energy resources and disturbances in the load.

The generated reference power is added to the MPPT output and it is coordinated with the power sharing between PV, FC, battery storage unit, utility grid and EV charging loads.

The power electronic converters are controlled using a conventional PI controller and PWM generation with the reference signals generated by the Adaptive STSMC.

The proposed strategy continuously updates the control action, guaranteeing the DC bus stability and enhancing the transient response, as well as reducing the chattering and reliable EV charging operation under both grid-connected and islanded operating modes.

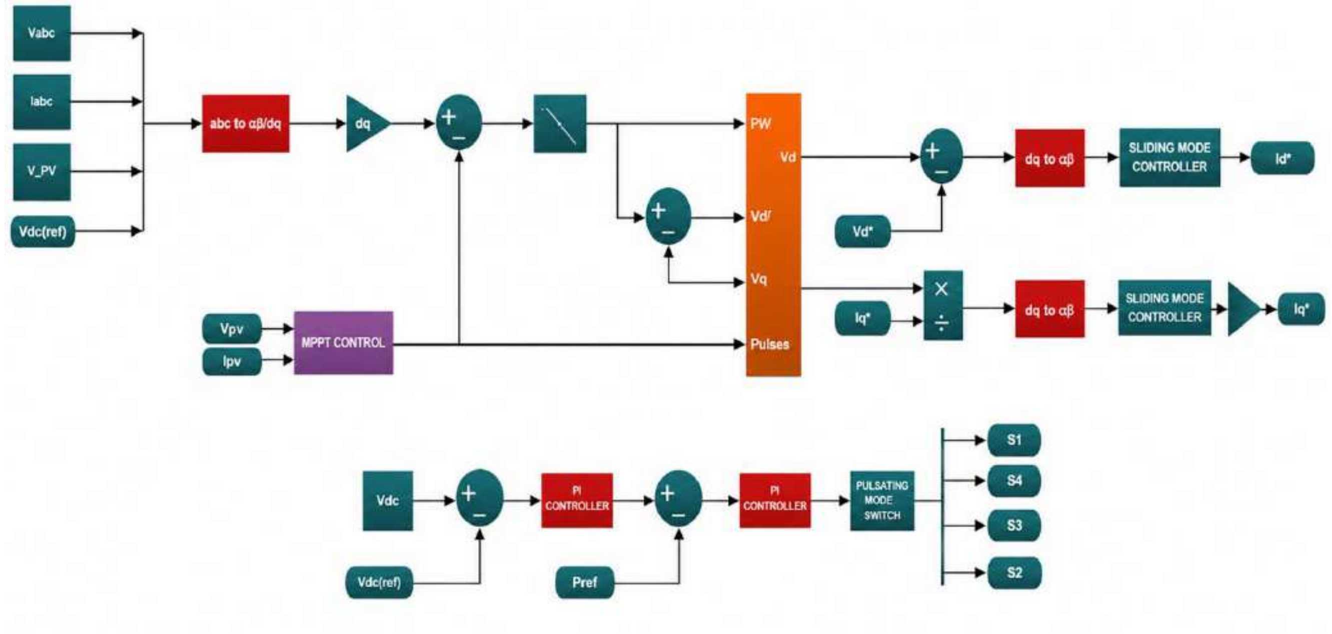


Figure 3: Simulink implementation of the proposed Adaptive STSMC-based energy management strategy for the PV-FC powered EV charging station

IV. RESULTS AND DISCUSSION

A MATLAB/Simulink simulation was performed to test Adaptive STSMC-based EMS for both grid connected and islanded modes of operation. The simulation studies were made with the system configuration described in Section II. The power-sharing capability, the utilization of renewable energy sources, power regulation of fuel cell, the satisfaction of the EV charging demand, the battery energy management and stability of overall system were tested and evaluated for proposed controller. The performance of proposed controller was compared to conventional energy management system using fuzzy logic for the same operating conditions to show effectiveness of proposed controller.

A. Demand Power and Non-conventional energy Profiles

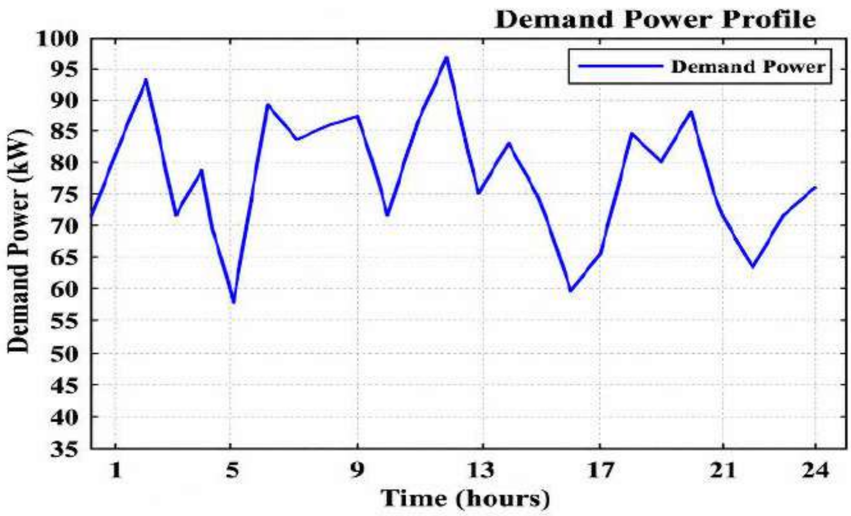


Figure 4: Daily EV charging demand profile

The demand profile for charging on a daily basis that has been used for this study is illustrated in figure 4. The charging requirement is continuously changed during the operating period, ranging from around 55kW to 95kW. Several peak demand periods throughout the day can be seen, which are more realistic EV charging periods. The energy management should be adaptive to these fluctuations, requiring coordination from multiple energy sources, and power balance of the DC microgrid. Therefore, the energy sources should be wisely controlled in order to guarantee reliability on charging operation.

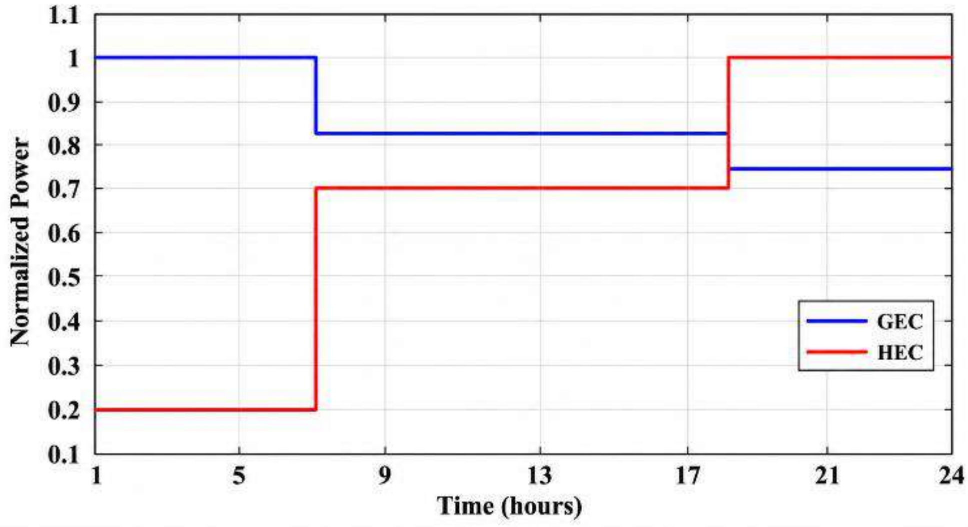


Figure 5: Variation of grid electricity cost (GEC) and hydrogen energy cost (HEC)

The changes of the grid electricity cost (GEC) and hydrogen energy cost (HEC) during the operating period are shown in figure 5. From the above, it can be observed that there is a difference in the cost of relative electrical energy of electricity grid and hydrogen-based fuel cell system as function of time of day. Such variations affect the decision-making process of energy management and show which source of power to use when operating under certain conditions. Hence, from the above system information it can be seen that proposed Adaptive STSMC-based EMS has the ability to allocate power efficiently with meeting the operating requirement of the DC microgrid.

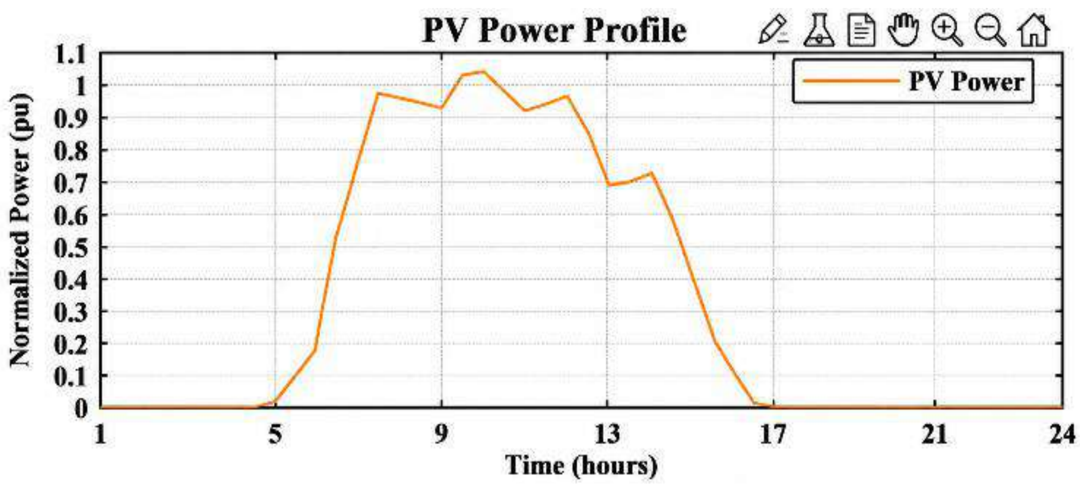


Figure 6: Photovoltaic power generation profile

The PV power generation profile is shown in figure 6 for the day cycle of the PV operation. Low PV output in the early morning (when the solar irradiance is low) the power produced by PVs is gradually growing with the intensity of the sun and is maximum in midday hours. As the day wears on, this PV output drops towards the evening, and after the sun sets, PV output is close to zero. This behaviour is intermittent and it suggests the need to include other energy storage and generation technologies, such as fuel cell and battery storage.

B. Grid-Connected Mode Performance Analysis

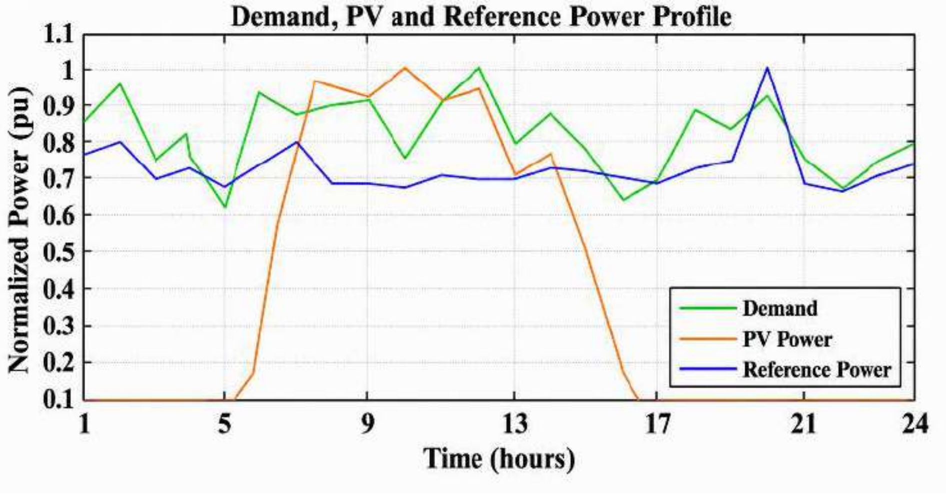


Figure 7: Demand power, photovoltaic power, and fuel cell reference power during grid-connected operation

The charging demand, fuel cell reference power and PV generation for the grid connected operating conditions is shown in figure 7. It is observed that reference power that is generated by proposed controller is varying based on the charging demand and PV power. The fuel cell reference power is decreased when PV generation is high as much of charging demand would be covered by PV generation. On the other hand, in the case of low PV generation, the controller adjusts fuel cell reference power to keep power balance in the micro-grid.

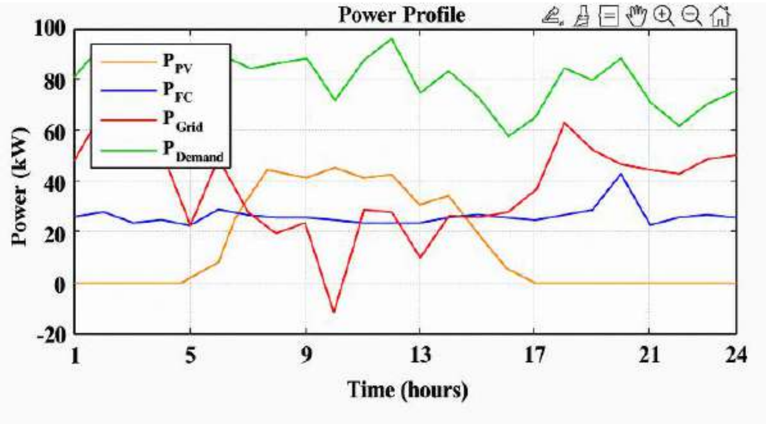


Figure 8: Power sharing among PV system, fuel cell, utility grid, and charging demand during grid-connected operation

Figure 8 illustrates the coordination between power sharing between PV system, fuel cell unit, grid and EV charging demand. The PV system is predominant non-conventional energy source during the day and accounts for a considerable power fraction for the charging load. At times of low renewable generation, the fuel cell provides the extra power. Utility grid supplies the remaining power as needed to accommodate the charging load to assure smooth operation of the grid. In grid-connected mode, the proposed Adaptive STSMC operates the fuel cell reference power continuously to adjust it as per charging demand and available photovoltaic (PV) power. As long as adequate PV power is available, the PV power will be used to the maximum extent, the fuel cell will only be used to a minimum extent, and hence renewable energy utilization will be optimized. The controller adaptively upscales the fuel cell output as the photovoltaic output drops, and cooperates with the electric utility grid to provide the necessary charging power. The results obtained show that proposed controller allows a smooth power sharing and stable DC bus operation during the charging cycle.

C. Islanded Mode Performance Analysis

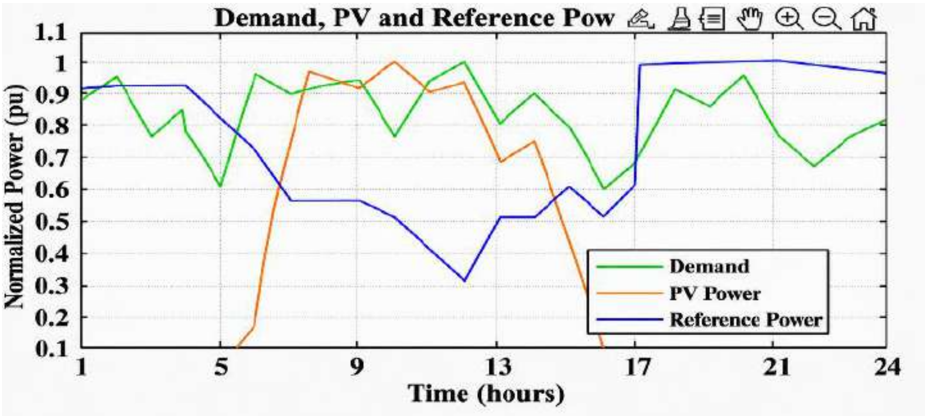


Figure 9: Demand power, photovoltaic power, and fuel cell reference power during islanded operation

The power management behaviour of the proposed system when it's operating in an islanded mode is shown in Figure 9. In this scenario, the utility grid cannot be utilized and the charging demand needs to be met with local energy resources. The generated reference power is dependent on the PV generation and charging demands. The Adaptive STSMC controller will increase the fuel cell's contribution to compensate for energy shortfalls during times when solar energy is not producing as much energy as required. This adaptive response is to provide continuous charging operation, even without the support of the grid.

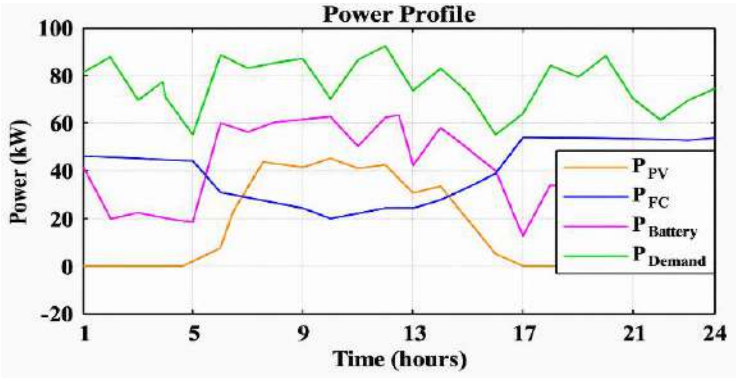


Figure 10: Power sharing among photovoltaic system, fuel cell, battery storage system, and charging demand during islanded operation

Coordinated operation of PV system, battery storage system, fuel cell unit and EV charging load during the islanded operation is shown in Figure 10. The battery storage unit actively compensates for short-term duration power disturbances, such as power fluctuations and transient disturbances. In the islanded mode, the charging station is not supported by the utility grid. In this scenario, the proposed Adaptive STSMC optimizes the energy management of the PV system, fuel cell, and battery storage system to meet the EV charging needs. The adaptive control strategy successfully tracks the fluctuations of renewable power by adjusting fuel cell power and battery power, thus charging process can be carried out continuously, which enhances the stability of the system.

D. Comparative Analysis Between Fuzzy Logic EMS and Proposed Adaptive STSMC-EMS

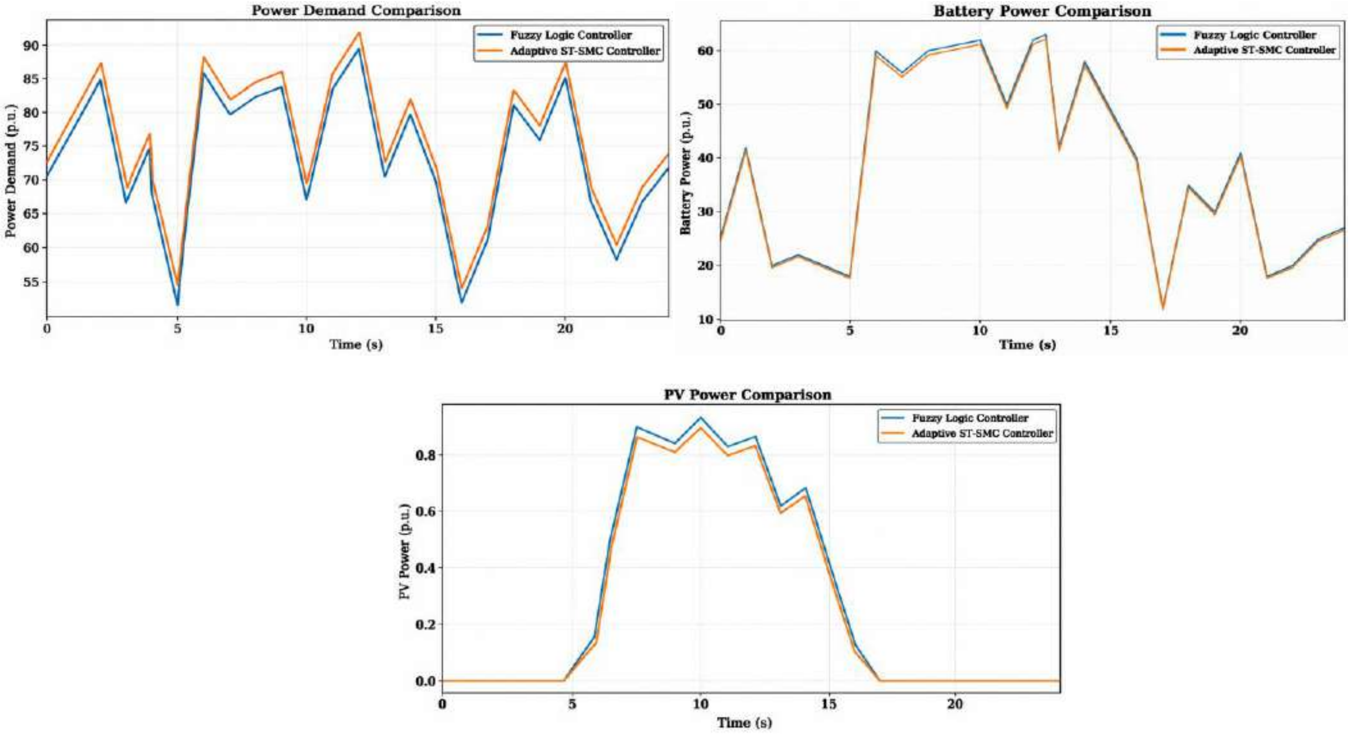
The comparison between the conventional and proposed is shown in Figure 11 and 12. Evaluation of dynamic behavior and power-sharing capability of proposed controller is done for both, grid connected and islanded operating conditions.

The proposed Adaptive STSMC can then, as shown in Figure 11(a), precisely track the charging demand and smoothen the grid power and PV power regulation during the grid connected operation. Likewise, Figure 11(b) shows that the proposed controller also successfully coordinates operation of the battery energy storage system, fuel cell and photovoltaic (PV) generation in the islanding mode, which provides uninterrupted power supply without the support of the utility grid.

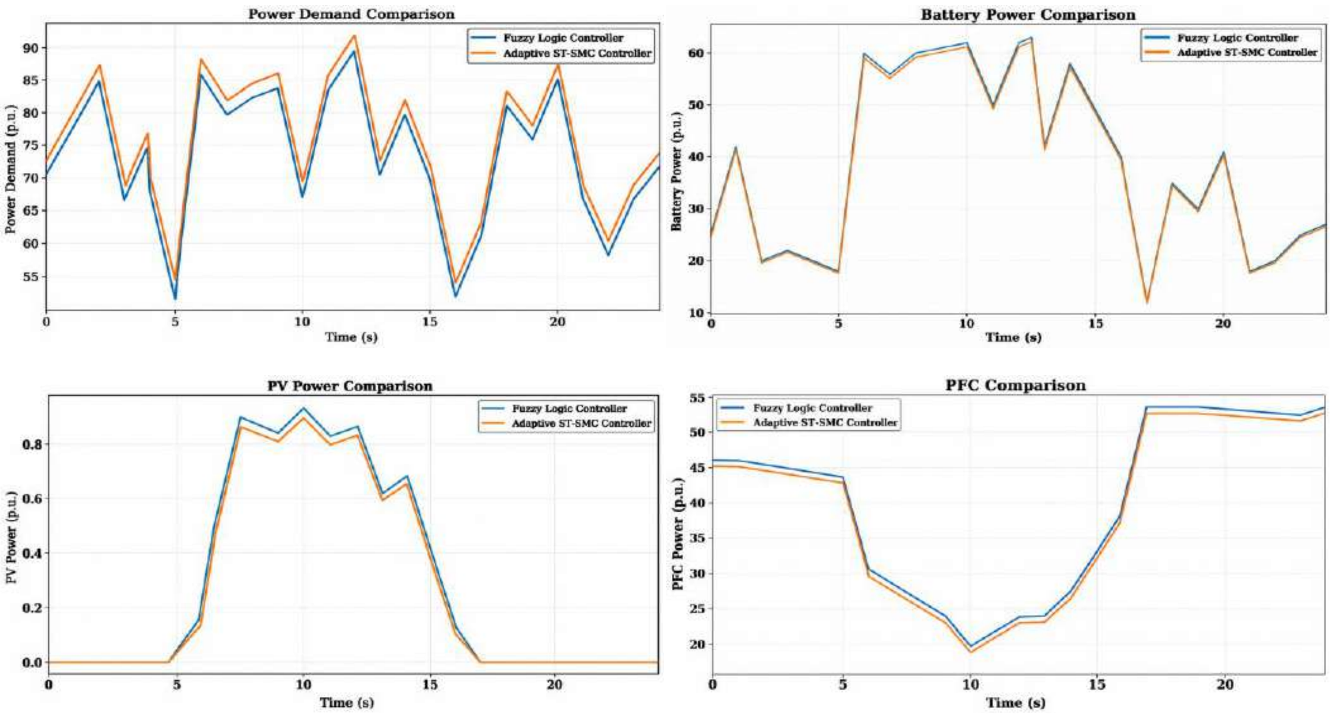
The transient performance of the proposed Adaptive STSMC is also compared to that of the conventional fuzzy logic controller, which shows that proposed controller has better transient performance in terms of faster response, smoother control action, and higher robustness under different operating conditions. The adaptive gain mechanism continually optimises the parameters of the controller, which would enable the system to operate in a stable manner despite intermittency in renewable energy and abrupt variations in the loading. Moreover, the super-twisting algorithm dramatically decreases the chattering effect which is a common problem in traditional sliding mode control, while preserving robustness of the sliding mode control.

A quantitative comparison included in Figure 12 further verifies the effectiveness of proposed controller. The Adaptive STSMC presents reduced rise time, improved settling characteristics and reduced peak overshoot when compared to the conventional fuzzy logic-based energy management system. The proposed controller's ability to achieve stable power sharing, efficient utilization of renewable energy sources, and reliable EV charging performance under various operating conditions is demonstrated through these improvements.

The overall simulation results confirm that the proposed energy management strategy with Adaptive STSMC offers a more robust and efficient solution as compared to conventional fuzzy logic controller for the PV–fuel cell powered EV charging station in a DC microgrid.



(a)



(b)

Figure 11: Comparative performance of the fuzzy logic controller and proposed Adaptive STSMC controller under different operating conditions: (a) Grid-connected mode showing demand power, grid power, and PV power comparisons; (b) Islanded mode showing demand power, battery power, fuel cell power, and PV power comparisons.

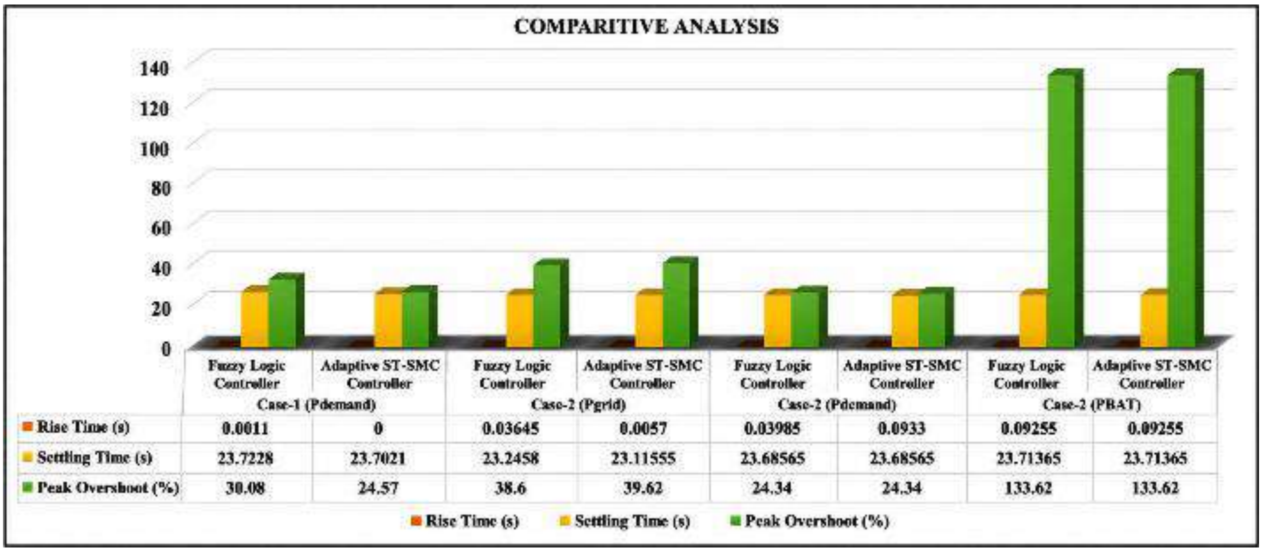


Figure 12: Comparative dynamic performance of fuzzy logic and Adaptive STSMC-based energy management strategies

Figure 12 illustrates the improved dynamic performance achieved by the proposed Adaptive STSMC compared with the conventional fuzzy logic controller. The controller reduces the rise time from 0.03645 s to 0.0057 s and lowers the peak overshoot from 30.08% to 24.57%, representing an 18.32% improvement. It also provides a smoother settling response with fewer oscillations, leading to enhanced system stability, greater robustness, and more reliable control under varying operating conditions.

V. CONCLUSION

In this paper, an Adaptive STSMC based Energy Management System for an electric vehicle charging station for fuel cell and photovoltaic power source which is operating in a DC microgrid has been introduced. To enhance performance of the system under different operating conditions, the conventional FC based energy management strategy was replaced by a robust adaptive control approach to designing the proposed controller. The proposed Adaptive STSMC successfully managed the power sharing in various operating scenarios, which were both grids connected and islanded, between the PV system, battery energy storage unit, fuel cell, utility grid, and EV charging loads. The results of simulation have shown that proposed controller achieved a stable power balance and also improved transient response with faster dynamic response. The proposed Adaptive STSMC reduced the peak overshoot by 30.08% to 24.57%, which is about 18.32% improvement as compared to the conventional fuzzy logic controller. Likewise, the grid power rise time has been minimized from 0.03645 s to 0.0057 s, which shows the fast response of the system and smooth power regulation. Furthermore, the adaptive gain mechanism made the controller more robust to renewable energy fluctuations and varying charging demand; also, it greatly reduced the control oscillations. In conclusion, the proposed Adaptive STSMC based EMS is a reliable, robust and efficient solution for intelligent energy management in renewable energy powered EV charging stations in DC microgrids.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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