OPTIMIZES ANFIS BASED ROBUST NONLINEAR CONTROL OFF GRID CHARGING STATION FOR ELECTRIC VEHICLE

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Abstract

This project presents an optimized off-grid electric vehicle (EV) charging station powered by photovoltaic (PV) energy integrated with advanced intelligent control techniques. The system is designed to operate independently of the conventional power grid, making it highly suitable for remote and rural areas. A key feature of the proposed model is the implementation of Maximum Power Point Tracking (MPPT) using an Adaptive Neuro-Fuzzy Inference System (ANFIS), which effectively enhances the efficiency of solar energy extraction under varying environmental conditions such as temperature and irradiance. To ensure stable and robust operation, a conditioned super-twisting sliding mode controller (CST-SMC) is developed, overcoming common drawbacks like chattering and windup associated with conventional controllers. The system incorporates a quadratic buck-boost converter to regulate voltage levels efficiently for battery storage and EV charging applications. Additionally, the controller parameters are optimized using intelligent techniques, improving dynamic response characteristics such as rise time, overshoot, and settling time. The proposed system is validated through simulation in MATLAB and hardware-in-the-loop (HIL) implementation, demonstrating superior performance compared to traditional methods. Results indicate improved energy management, enhanced stability, and reliable charging performance, making the system a sustainable and efficient solution for modern EV infrastructure. Overall, this work contributes to the advancement of renewable energy-based EV charging systems with improved control strategies and practical applicability.

Keywords: Electric Vehicles, Off-Grid Charging Station, Photovoltaic System, ANFIS, MPPT, Sliding Mode Control, CST-SMC, Renewable Energy, Battery Storage, Quadratic Buck-Boost Converter, MATLAB, HIL Simulation.

I INTRODUCTION

The rapid growth of electric vehicles (EVs) has emerged as a promising solution to address environmental challenges such as air pollution, greenhouse gas emissions, and dependence on fossil fuels. EVs contribute significantly to sustainable transportation by offering higher energy efficiency and reduced carbon footprint compared to conventional internal combustion engine vehicles [1]. However, the widespread adoption of EVs depends heavily on the availability of efficient and accessible charging infrastructure [2]. In remote and rural areas, where grid connectivity is limited or unreliable, off-grid EV charging stations provide a viable alternative [3]. These systems utilize renewable energy sources such as solar photovoltaic (PV) panels to generate clean electricity locally [4]. Solar-based charging stations are particularly advantageous due to their scalability, low maintenance, and environmental benefits [5]. However, the intermittent nature of solar energy poses challenges in maintaining consistent power supply [6]. To overcome this, energy storage systems such as batteries are integrated to store excess energy during peak generation and supply it during low irradiance conditions [7]. Furthermore, efficient power conversion and control mechanisms are essential to ensure optimal energy utilization and system stability [8].

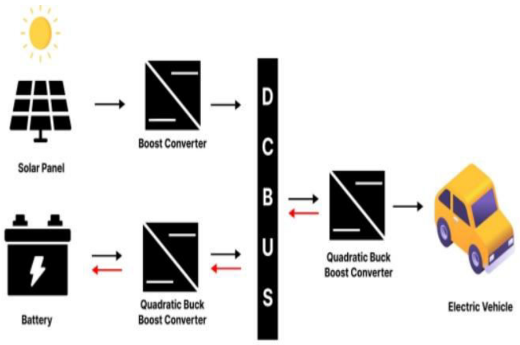

Fig.1 Block diagram of off-grid charging station.

One of the key techniques used in PV systems is Maximum Power Point Tracking (MPPT), which ensures that the solar panels operate at their maximum efficiency under varying environmental conditions [9]. Conventional MPPT methods such as Perturb and Observe and Incremental Conductance often suffer from slow response and oscillations around the maximum power point [10]. To address these limitations, intelligent techniques like Adaptive Neuro-Fuzzy Inference System (ANFIS) have been introduced, combining the advantages of neural networks and fuzzy logic for improved performance [11]. In addition, power electronic converters such as quadratic buck-boost converters are employed to regulate voltage levels efficiently for battery charging and EV supply [12]. Controlling these nonlinear systems requires robust control strategies, where Sliding Mode Control (SMC) has been widely used due to its robustness against disturbances and parameter variations [13]. However, traditional SMC suffers from issues like chattering and steady-state error [14]. Advanced techniques such as Super-Twisting Sliding Mode Control (ST-SMC) and Conditioned ST-SMC (CST-SMC) have been developed to overcome these drawbacks and enhance system performance [15]. Therefore, integrating intelligent MPPT algorithms with advanced nonlinear control techniques plays a crucial role in improving the efficiency, reliability, and sustainability of off-grid EV charging stations.

II LITERATURE SURVEY

Recent studies highlight the growing importance of integrating renewable energy sources, particularly photovoltaic (PV) systems, with electric vehicle (EV) charging infrastructure to achieve sustainability and energy independence. Off-grid and hybrid PV-based EV charging stations have been widely investigated due to their ability to operate without reliance on conventional power grids, especially in remote locations [1]. Researchers have explored PV-battery integrated systems to ensure continuous power availability despite the intermittent nature of solar energy [2]. Advanced energy management strategies involving battery energy storage systems (BESS) have been proposed to improve system reliability and reduce power fluctuations [3]. Maximum Power Point Tracking (MPPT) techniques play a crucial role in enhancing PV efficiency, with various classical methods such as Perturb and Observe (P&O) and Incremental Conductance being commonly used [4]. However, these conventional techniques suffer from limitations such as slow convergence and oscillations around the maximum power point [5]. To overcome these drawbacks, artificial intelligence-based approaches including fuzzy logic, artificial neural networks, and hybrid techniques have gained significant attention [6]. Among these, Adaptive Neuro-Fuzzy Inference System (ANFIS) has been identified as a powerful tool due to its ability to handle nonlinearities and adapt to changing environmental conditions [7]. Studies demonstrate that ANFIS-based MPPT provides improved tracking accuracy and faster response compared to traditional methods [8].

In addition to MPPT advancements, significant research has been conducted on control strategies for power converters and EV charging systems. Sliding Mode Control (SMC) has been widely adopted due to its robustness against system uncertainties and disturbances in nonlinear systems [9]. Comparative studies show that SMC-based approaches outperform classical controllers in terms of dynamic response and stability under varying operating conditions [10]. However, conventional SMC suffers from chattering issues, which can degrade system performance and cause wear in power electronic components [11]. To address these challenges, advanced variants such as Super-Twisting Sliding Mode Control (ST-SMC) and hybrid intelligent controllers have been developed [12]. Recent works integrate SMC with artificial intelligence techniques like neural networks and ANFIS to further enhance system performance and reduce control errors [13]. Moreover, modern EV charging systems incorporate bidirectional power flow and microgrid integration, requiring sophisticated control algorithms for efficient energy management [14]. Hardware-in-the-loop (HIL) validation and real-time implementation have also been emphasized to ensure practical feasibility and reliability of proposed systems [15]. Overall, the literature indicates a clear trend toward intelligent control techniques and hybrid renewable energy systems to improve the efficiency, stability, and adaptability of off-grid EV charging stations.

III PROPOSED SYSTEM

The proposed system presents an advanced off-grid electric vehicle (EV) charging station powered by a photovoltaic (PV) energy source integrated with a battery storage system and intelligent control techniques. The system is designed to operate independently of the conventional grid, making it highly suitable for remote and rural applications. Solar PV panels are used as the primary energy source to generate electricity, which is then regulated through a DC-DC boost converter to maintain a stable voltage level. To ensure maximum energy extraction from the PV system under varying environmental conditions such as temperature and irradiance, an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based Maximum Power Point Tracking (MPPT) technique is implemented. The generated energy is either directly supplied to the EV or stored in a battery system for later use during low solar availability. A quadratic buck-boost converter is employed to efficiently manage the power flow between the PV system, battery, and EV load, providing both step-up and step-down voltage capabilities.

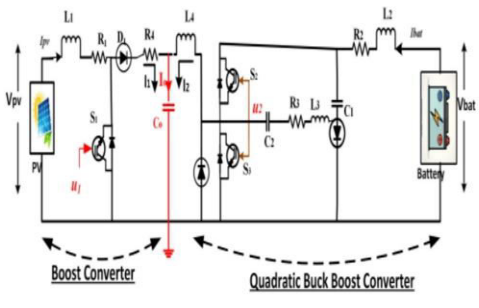

Fig.2 Circuit diagram of charging station.

To achieve robust and stable system performance, a Conditioned Super-Twisting Sliding Mode Controller (CST-SMC) is designed to regulate voltage and current within the system. This controller effectively eliminates issues such as chattering and windup that are commonly associated with conventional sliding mode controllers. The

CST-SMC ensures smooth operation during both constant current and constant voltage charging modes, thereby enhancing battery life and charging efficiency. Additionally, intelligent optimization techniques are applied to tune controller parameters for improved dynamic response, including reduced rise time, minimal overshoot, and faster settling time. The proposed system is modeled and simulated in MATLAB/Simulink and validated through hardware-in-the-loop (HIL) testing to ensure real-time applicability. Overall, the integration of intelligent MPPT and advanced nonlinear control strategies significantly enhances the efficiency, reliability, and performance of the off-grid EV charging station.

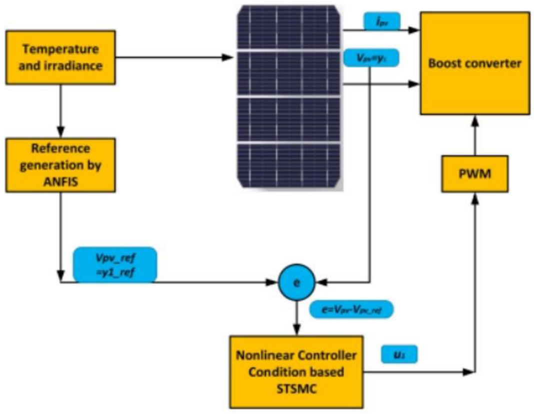

Fig.3 PV reference generation through MPPT.

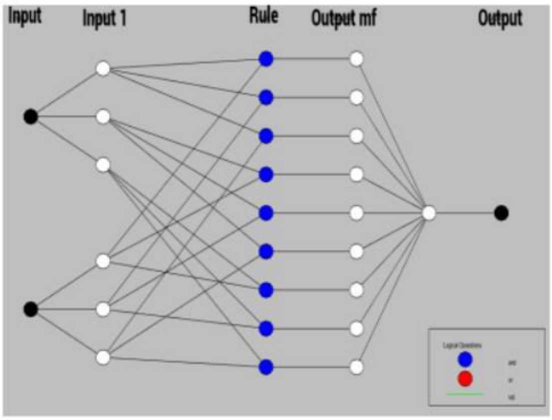

Fig.4 Fuzzy inference system network structure.

IV SYSTEM DESIGN

The system design of the proposed off-grid electric vehicle (EV) charging station is based on the integration of a photovoltaic (PV) energy source, power electronic converters, battery storage, and an advanced control unit. The PV array acts as the primary energy source, converting solar energy into electrical power. This output is fed into a DC-DC boost converter, which regulates and steps up the voltage to a desired level suitable for further processing. To ensure optimal energy extraction, an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based Maximum Power Point Tracking (MPPT) controller continuously adjusts the operating point of the PV system according to variations in irradiance and temperature. The regulated DC power is then connected to a quadratic buck-boost converter, which plays a crucial role in managing power flow between the PV array, battery storage system, and EV load. The battery serves as an energy buffer, storing excess energy during peak generation and supplying power during low or no sunlight conditions, ensuring uninterrupted operation.

The control architecture of the system is designed to maintain stability and improve dynamic performance under varying operating conditions. A Conditioned Super-Twisting Sliding Mode Controller (CST-SMC) is implemented to regulate the voltage and current of the converters efficiently. This controller minimizes chattering effects and prevents windup issues, ensuring smooth and reliable operation. The system operates in two main modes: charging mode, where energy is stored in the battery or supplied to the EV, and discharging mode, where stored energy is utilized to meet load demands. Sensors are used to measure key parameters such as voltage, current, and temperature, which are fed back to the controller for real-time decision-making. The entire system is modeled and simulated using MATLAB/Simulink to analyze performance characteristics such as efficiency, response time, and stability. This well-structured design ensures high efficiency, reliability, and adaptability, making it suitable for sustainable EV charging applications in off-grid environments.

V RESULTS & ANALYSIS

The performance of the proposed off-grid EV charging system was evaluated through MATLAB/Simulink simulations and hardware-in-the-loop (HIL) implementation. The results demonstrate that the system achieves superior dynamic performance compared to conventional control techniques. The Conditioned Super-Twisting Sliding Mode Controller (CST-SMC) exhibits a faster rise time of 0.0564 seconds, significantly lower overshoot of 0.00389, and a reduced settling time of 0.4256 seconds, whereas the conventional ST-SMC shows slower response characteristics with higher overshoot and longer settling time. The ANFIS-based MPPT effectively tracks the maximum power point under varying irradiance and temperature conditions, ensuring optimal power extraction from the PV array. Additionally, the system maintains stable voltage and current during both constant current and constant voltage charging modes. The battery performance is also improved due to smooth power regulation, resulting in enhanced efficiency and reliability.

TABLE 2. Parameters of the hybrid energy system.

PV array	
Parameters	**Values**
Series connected strings	10
Parallel strings	10
Voltage at MPP, V_{mpp}	$290V$
Short circuit current, I_{sc}	$70.84A$
Open circuit voltage, V_{OC}	$363V$
Current at MPP, I_{mpp}	$70.35A$
Maximum power	$21315W$
Battery	
Battery maximum current	35A
Battery nominal voltage	288V
Battery capacity	100Ah

TABLE 3. Circuit parameters.

Parameter	Value
UC module C_1, C_2, C_3, C_4	$2000\mu F$
Resistance R_1, R_2, R_3, R_4	0.025Ω
Inductor $L_1, L_2, L_3, L_4, L_5, L_6, L_7$	$0.0033H$
Switching frequency	$100KHz$

TABLE 4. Parameters of the controller.

Parameters	Values
k_1, k_2, k_3, k_4, k_5	$2000, 3000, 2000, 5000, 5000$
a_1, a_2, a_3, a_4, a_5	$10, 20, 40000.4, 10000$
$\alpha_1, \alpha_2, \alpha_3$	$0.9, 0.9, 0.8$
m_1, m_2, m_3	$3, 0.0033, 0.00005$
ϕ	0.8

TABLE 5. EV charger specifications.

Parameters	Values
C_b, C	$4.79, 900000\mu F$
Resistance R_s, R_p	$0.0006, 10000\Omega$
V_{dc}	400

TABLE 6. Parameters of grey wolf optimization.

Parameters	Symbols	Values
No. of search entities	N	10
No. of iterations	t	40

TABLE 7. Comparative analysis of various nonlinear controllers.

Controller	Rise time (sec)	Overshoot%	Settling time(sec)
ST-SMC	0.137	0.38095	3.8071
CST-SMC	0.0564	0.00389	0.4256

VI CONCLUSION

In conclusion, the proposed off-grid electric vehicle (EV) charging station demonstrates an efficient and sustainable solution for addressing the growing demand for clean transportation and reliable charging infrastructure, particularly in remote and rural areas. By integrating photovoltaic (PV) energy generation with battery storage, the system ensures continuous power availability despite the intermittent nature of solar energy. The implementation of an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based Maximum Power Point Tracking (MPPT) technique significantly enhances the efficiency of solar energy extraction under varying environmental conditions. Furthermore, the use of a quadratic buck-boost converter enables effective voltage regulation and flexible power flow management between the PV system, battery, and EV load. The incorporation of a Conditioned Super-Twisting Sliding Mode Controller (CST-SMC) addresses the limitations of conventional control methods by reducing chattering, eliminating windup issues, and improving overall system stability and dynamic performance. Simulation and hardware-in-the-loop (HIL) validation confirm that the proposed system achieves faster response, reduced overshoot, and improved settling time compared to traditional approaches. Additionally, the system ensures smooth operation during both constant current and constant voltage charging modes, thereby enhancing battery life and charging efficiency. Overall, this work highlights the potential of combining intelligent control strategies with renewable energy systems to develop reliable, efficient, and eco-friendly EV charging solutions, contributing to the advancement of sustainable energy infrastructure and the widespread adoption of electric vehicles.

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