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ANFIS-Driven Optimization for Off-Board EV Battery Charging Integrated with Solar Photovoltaic Arrays

RS Sai Praveen Kumar[1], A Teja[2], B Vinod Kumar[3], B Somanatha Reddy[4], D Surendra Naik[5], K Teja[6], T Umapathi[7]
Assistant Professor, Department of EEE, [1]
UG Student, Department of EEE[234567]
Siddharth Institute of Engineering and Technology, Puttur, India
saipraveensietk@gmail.com[1], tejaluru@gmail.com[2], vinnuboya@gmail.com[3], somanathreddy26@gmail.com[4], surendraeee87143@gmail.com[5], kkogilateja@gmail.com[6], umaumapathi749@gmail.com[7]

Abstract: *This paper presents an intelligent off board electric vehicle (EV) battery charging system enhanced by ANFIS optimization and powered by a solar photovoltaic (PV) array. The proposed system addresses challenges arising from the intermittent nature of solar energy by incorporating a backup battery and advanced control mechanisms. A SEPIC converter and a bidirectional dc-dc converter (BIDC) are employed to ensure continuous charging under varying solar irradiation. The Adaptive Neuro-Fuzzy Inference System (ANFIS) controller enhances system adaptability and optimizes charging performance by precisely managing power flow. Simulations conducted in MATLAB Simulink confirm the system's ability to maintain stable voltage and efficient energy transfer across diverse operating conditions. Comparative analysis demonstrates significant improvements in charging efficiency and reduced dependency on grid power. The simulation results validate the findings, establishing the effectiveness of this solution for sustainable EV charging infrastructure. This approach supports eco-friendly transportation by integrating renewable energy with advanced control strategies.*

Keywords: Solar PV, SEPIC converter, EV Battery, Bidirectional DC-DC converter, ANFIS controller

I. INTRODUCTION

The global transition toward ecological transportation has driven rapid growth of EVs as a solution to mitigate greenhouse gas releases [1]. However, traditional EV charging systems, which predominantly rely on grid power, face challenges like increased grid load and higher operational costs [2, 3]. To address these issues, renewable energy sources (RES), particularly solar PV systems, have emerged as a sustainable alternative [4, 5]. Solar PV systems, with their pollution-free and abundant energy potential, present an attractive solution for powering EVs. Despite these benefits, the intermittent nature of solar energy due to varying weather and irradiation levels hinders the reliability of standalone solar-powered EV charging systems [6]. Thus, ensuring consistent and uninterrupted EV battery charging remains a critical challenge [7, 8].

To overcome these limitations, this study introduces a novel off board Electric vehicle charging system that integrates a solar PV with a backup battery [9]. The proposed setup utilizes a SEPIC converter for stable voltage regulation and a BIDC to manage energy flow efficiently [10, 11]. This configuration ensures that EV batteries are charged during both sunshine hours and low-irradiation periods by seamlessly switching between solar and backup battery power sources [12, 13]. Unlike conventional systems, which often fail to adapt to dynamic energy conditions, this design enables consistent energy availability, making it highly suitable for real-world applications. Moreover, the off-board configuration minimizes the weight and complexity of the vehicle itself, improving overall system efficiency [14-16].

The core innovation of this work lies in implementation of an ANFIS controller to optimize energy management. ANFIS, which combines fuzzy logic and neural network capabilities, dynamically adjusts the system's control parameters to maintain optimal charging performance under varying operating conditions. This advanced control strategy ensures precise voltage regulation, enhances charging efficiency, and reduces energy losses. Furthermore, it provides the system with the adaptability required to handle real-time variations in solar power and load demand [17-20]. By integrating intelligent control with renewable energy, this work bridges the gap between sustainability and reliability in EV charging infrastructure [21, 22].

Simulations of the proposed system in MATLAB Simulink confirm its superior performance in terms of charging efficiency, energy utilization, and system stability. These results are validated through simulations testing, demonstrating that the proposed design consistently outperforms traditional methods. By reducing dependency on grid power and leveraging renewable energy [23-24], this system supports the global push for green transportation. The novelty of this approach lies in its intelligent optimization techniques and hybrid energy management strategy, which together establish a robust and sustainable framework for next-generation EV charging solutions [25, 26].

The organization of the following paper contains: Section II provides a comprehensive system description. Section III introduces a proposed method, focusing on the implementation of ANFIS controller for enhanced voltage regulation. Section IV presents the simulation results along with the corresponding discussions. Finally, Section V concludes the paper with key findings and suggests avenues for future research.

II. SYSTEM CONFIGURATION

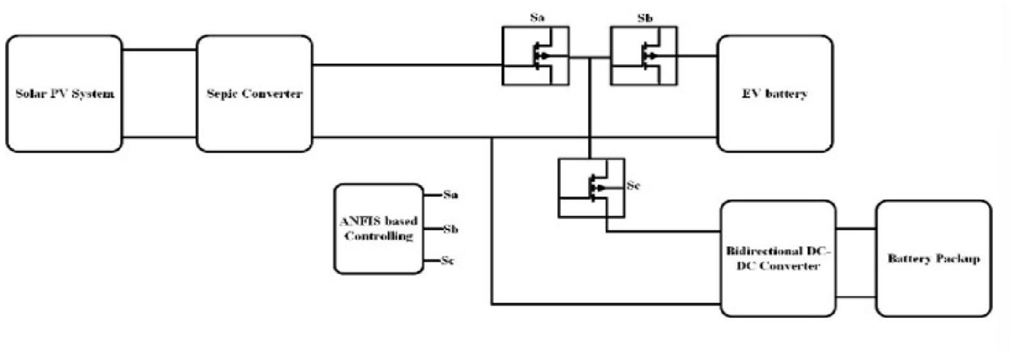

Fig.1 proposed block diagram

The proposed system for off-board electric vehicle (EV) battery charging integrates a solar PV array with a backup battery pack to ensure uninterrupted energy delivery as depicted in figure.1. This system addresses the intermittency of solar energy and optimizes energy management using an ANFIS controller. The configuration comprises four main components: a solar PV system, a SEPIC (Single-Ended Primary Inductance Converter), a bi-directional converter, and a control unit for switch operations.

A) Solar PV Array

It serves as the main RES in this paper, converting solar energy into electricity using the PV effect. The PV array is made up of numerous solar cells arranged in series and parallel to achieve desired voltage and current levels. The system's output is significantly influenced by environmental conditions, such as solar irradiance (G, measured in W/m²) and cell temperature (Tc, measured in °C). The simulation model of solar PV array is shown in fig. 2.

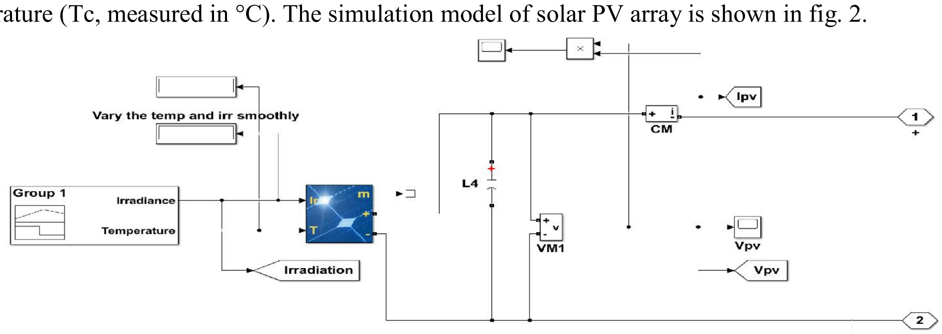

Fig.2 simulation model of solar panel

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The electrical output of PV array can be expressed mathematically by the photovoltaic current equation:

$$I = Iph - I0\left(e\frac{q(V+IRs)}{nkT} - 1\right) - \frac{V+IRs}{Rp} \quad 1$$

In this system, I represents output current, V is output voltage, Iph is photocurrent, which is proportional to solar irradiance (G), and I0 is reverse saturation current. The constants involved include qfor the electronic charge, n for ideality factor, k for Boltzmann's constant, and T for temperature in Kelvin. Rs and Rp denote series and parallel resistances of PV system, respectively. The power generated (P) is calculated as P = V × I. To maximize power output, a MPPT algorithm is implemented, ensuring optimal efficiency despite changing environmental conditions.

B) SEPIC Converter Voltage Gain

The Sepic is a critical component in the system, ensuring that the fluctuating voltage from solar PV array is conditioned to match required input for subsequent blocks. The SEPIC converter can either step up or step down input voltage depending on system requirements. It uses an inductor-capacitor network for energy transfer and provides a continuous current supply to the load, making it highly suitable for PV systems with variable input. The voltage gain is derived from the sepic converter on its duty cycle (D) and is expressed as:

$$Vo = \frac{Vin\,.\,D}{1-D} \quad 2$$

In Continuous Conduction Mode (CCM), the SEPIC ensures stable operation by maintaining the inductor currents above zero. The voltage gain equation shows that at a D of 0.5, the output voltage equals the input voltage, whereas higher duty cycles result in stepped-up voltage, and lower duty cycles step it down. The energy transfer mechanism involves the capacitors storing and transferring energy between the inductors, smoothing out fluctuations, the simulation model of sepic converter is shown in the below figure.3. Additionally, the use of diodes ensures unidirectional current flow, further enhancing the efficiency of energy conversion.

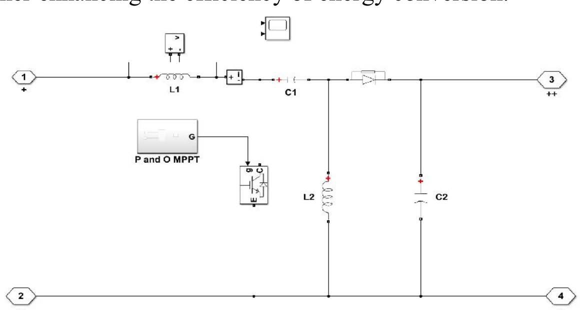

Fig.3 simulation model of sepic converter

This converter plays a pivotal role in maintaining a stable DC output, ensuring the EV battery and bi-directional converter receive a steady and controlled input voltage.

C) BIDC Energy Balance

BIDC is enabling energy transfer among the EV battery pack and solar PV system, while maintaining a stable voltage and current supply. It is capable of both discharging and charging the battery, depending on system's operating conditions. The bidirectional converter is responsible for regulating the energy flow in two directions: from the solar PV system to battery for charging, and from battery to the load when required, for instance, to power the electric vehicle (EV) during discharging. The model of simulation of battery pack with bidirectional converter as displayed in the figure.4 and 5.

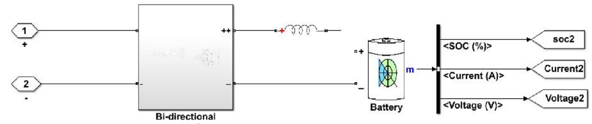

Figure.4 simulation model of Battery pack

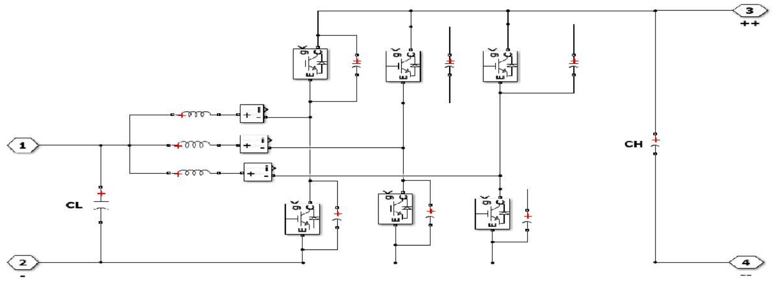

Fig.5 simulation model of bidirectional converter

The energy balance of the bidirectional converter can be represented by the following equations:

D) Energy Flow during Charging:

$$Pin = Pout \quad 3$$

Where Pin is the power supplied from SEPIC converter to the battery, and Pout is power stored in EV battery pack. The converter adjusts its duty cycle to control the power flow based on battery's charge status and the energy availability from the solar system.

E) Energy Flow during Discharging:

$$Pbattery = Vbattery.Ibattery \quad 4$$

Where Pbatteryis the power being drawn from the battery, V batteryis voltage of the battery, and I batteryis current being discharged. The BIDC controls the current flow from battery to load (such as the EV motor or other systems), maintaining the required voltage levels for efficient operation. The bidirectional converter is governed by energy balance equations that ensure power efficiency and minimize losses during both charging and discharging processes. The control mechanism adjusts the D of converter to regulate power flow, ensuring that the energy stored in battery is used effectively when required, and that the battery is charged optimally when there is excess solar energy.

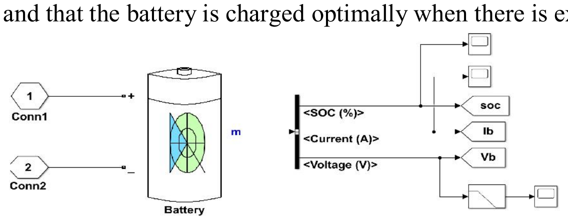

Fig.6 simulation model of EV battery

Additionally, the efficiency of converter is determined by its D, which is adjusted based on real-time voltage and current feedback. By maintaining an optimal energy flow, the converter ensures that the battery is charged and discharged within safe limits, maximizing the system's overall performance and reliability. The bidirectional converter, therefore, is crucial in enabling effective energy management in off-board EV battery charging systems, making it an essential part of this integrated solar-powered charging architecture.

F) Design of Controllers

The design of controllers in hybrid energy systems, particularly for solar photovoltaic (PV) integration, is crucial for optimizing the system's operation, enhancing its efficiency, and ensuring reliable energy delivery. For this hybrid system, P&O MPPT is used for the solar PV system, and an ANFIS is applied to manage energy flow in the BIDC.

The SEPIC converter is widely used in RES such as solar PV because of its ability to efficiently regulate voltage, either stepping it up or down. The controller of SEPIC converter plays a crucial role in adjusting the D of converter's switches (Sa and Sb) according to the MPPT technique, ensuring optimal power extraction from the solar panels. In this system, the P&O MPPT algorithm is used to track MPP of the solar PV array, as illustrated in fig. 7. The P&O algorithm works by perturbing the voltage (or current) and monitoring the resulting changes in power.

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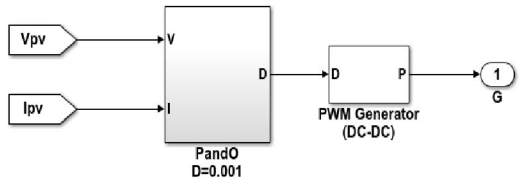

Fig.7 controlling of P and O MPPT as sepic converter

If power increases after a perturbation, the voltage is further increased; if power decreases, the voltage is reduced, driving the system toward the optimal operating point. This results in dynamic adjustment of duty cycle, which is continuously calculated by P&O algorithm to ensure maximum power extraction. The calculated duty cycle then generates PWM signals, which control the switching devices in SEPIC converter, ensuring efficient voltage regulation and optimal system performance.

G) Controller for BIDC

It is managing the energy flow between battery and load. The controller for this converter ensures that energy is either charged into the battery when excess power is available or discharged to the load when needed. A key aspect of this controller is the management of the SOC of the battery to prevent overcharging or deep discharge, which can degrade battery performance.

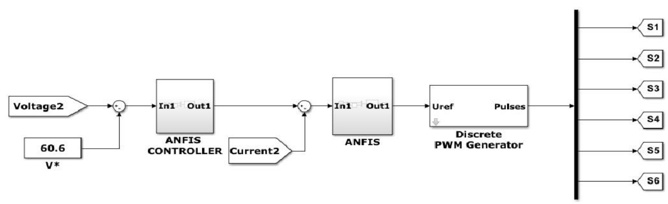

Fig. 8 controlling of bidirectional converter with ANFIS

To achieve this, a model-based adaptive controller is employed, such as the ANFIS, which combines the advantages of both NN and FLC. The ANFIS controller learns from historical data and adjusts the control parameters based on real-time system performance, ensuring optimal energy flow. By continuously regulating the D of converter switches (Sa, Sb, and Sc), an ANFIS controller enables efficient energy transfer between battery, solar PV system, and load.

H) Controller for Hybrid System Integration

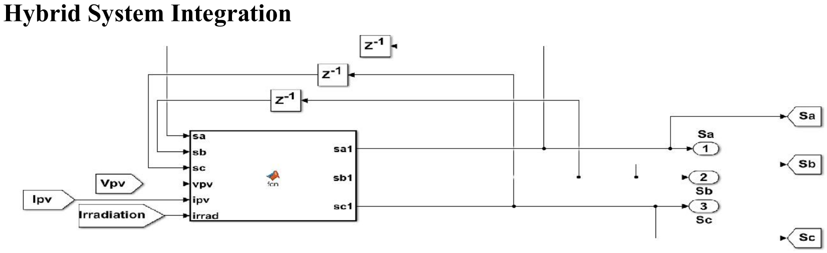

Fig. 9 Generation of gate pulses for auxiliary switches.

For the integrated hybrid system, where the solar PV system, Sepic converter, bi-directional dc/dc converter, and battery must operate harmoniously, an ANFIS-based controller provides an adaptive and intelligent approach. ANFIS combines the flexibility of FLC with the learning capabilities of NN, enabling the controller to dynamically adjust based on the operational conditions of the system. In the context of this hybrid system, the ANFIS controller adjusts the duty cycles of the SEPIC and bidirectional converters by learning from past data and continuously refining the fuzzy rules. The controller inputs include the SOC of the battery, the available solar power, and the current load demand, while the output is e duty cycle for controlling the converters. Through adaptive learning, the ANFIS controller can optimize the energy flow, ensuring that the system remains stable, efficient, and responsive to changing conditions.

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III. PROPOSED METHOD

The ANFIS is employed as control strategy for regulating operation of overall hybrid system, ensuring optimal energy management. ANFIS integrates the benefits of fuzzy logic systems and neural networks, which allows for adaptive, nonlinear control of complex systems such as the hybrid solar PV and battery system. The primary function of the ANFIS controller is to manage the flow of energy between solar PV system, the SEPIC converter, the EV battery, and the bidirectional converter, optimizing the system's performance under varying environmental and load conditions.

The ANFIS control law uses fuzzy rules to interpret inputs such as battery's SOC, solar irradiance, and load demand. Based on these inputs, the system dynamically adjusts the D of SEPIC converter and bidirectional converter to maintain a stable operation and maximize energy efficiency. The control law aims to minimize losses and ensure that energy is either stored in the battery when excess power is available or supplied to the load when needed.

The general structure of ANFIS control law can be designated by following fuzzy control rules:

1. Fuzzy Rule 1: If the battery SOC is high and solar power is abundant, then the converter duty cycle should be adjusted to maximize battery charging.

2. Fuzzy Rule 2: If the battery SOC is low and solar power is insufficient, then duty cycle of bidirectional converter is in tune to discharge battery to meet load requirements.

3. Fuzzy Rule 3: If the battery SOC is moderate, adjust the duty cycle to balance charging and discharging based on load demand.

Mathematically, the fuzzy rules can be conveyed in terms of linguistic variables and membership functions:

$$\mu A(x) = \frac{1}{1+e^{-(x-c)/d}} \quad 5$$

Where μA(x) represents the membership function of the input variable xxx, which could be the battery SOC or solar irradiance. The parameters c and d define the center and width of the membership function, respectively. Once the fuzzy inference system computes the output using these rules, a defuzzification process is performed to obtain the crisp output, which adjusts the duty cycle of the SEPIC and bidirectional converters. The output from the fuzzy system is combined with the control laws based on the current load demand and battery status, providing the optimal control signal.

The ANFIS controller uses a training algorithm to optimize the fuzzy rule base and the membership functions, adapting to the changing conditions in the system. This adaptability enables the system to respond effectively to various operating scenarios, ensuring high energy efficiency and maintaining a balanced flow of energy between the solar system, battery, and EV. The ANFIS control law ensures the hybrid system operates at its optimal efficiency, adjusting converters' switching mechanisms based on real-time inputs and providing an intelligent solution to the energy management problem in solar-powered EV charging systems.

IV. RESULTS AND DISCUSSION

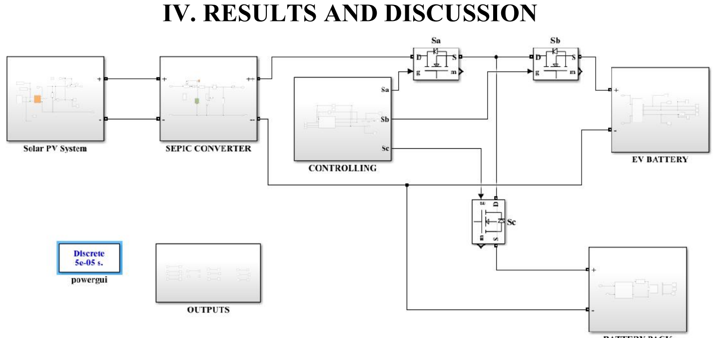

Fig. 10 Simulation of the proposed charger circuit

Figure 10 presents the simulation diagram of proposed converter circuit, which includes a PV array, SEPIC converter, BIDC converter, and an advanced ANFIS controller. The PV array is modelled using PV parameter values, while the SEPIC and BIDC converters are built with power MOSFETs, inductors, and capacitors from the library browser in Simulink. The control system utilizes the ANFIS controller, integrating FLC and NN for better performance, along with

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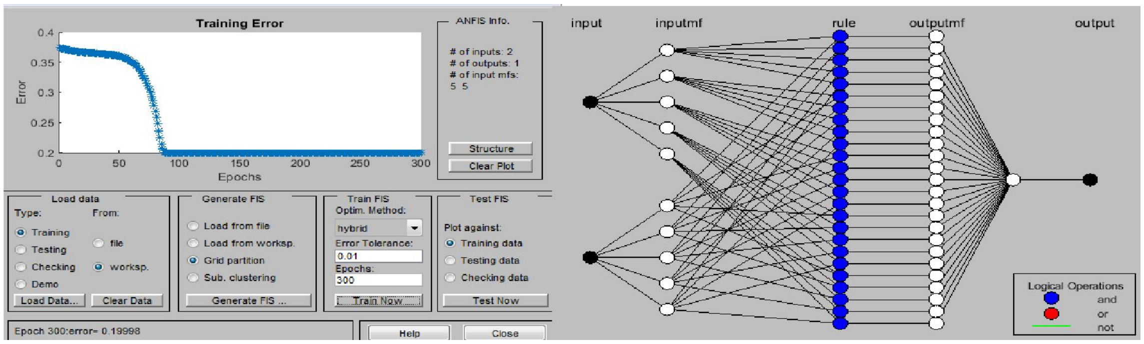
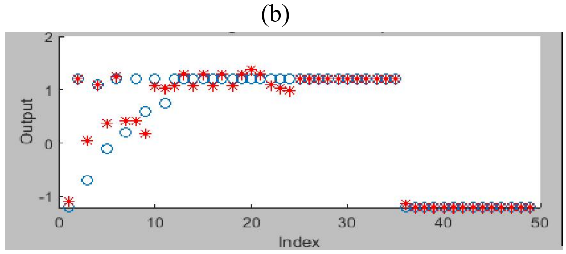
a PWM generator, logic gates, comparators, and multipliers. The PV array, converters, and battery models are combined to create a smart charging system that optimizes energy transfer and control.



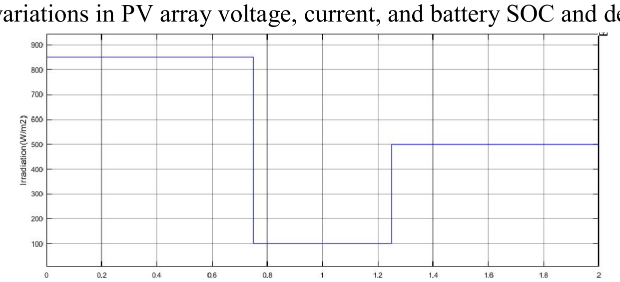
(b)



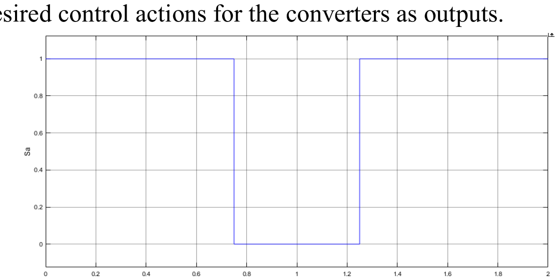
(c)

Figure 11 (a, b, c) shows the ANFIS controller taring data With Structure

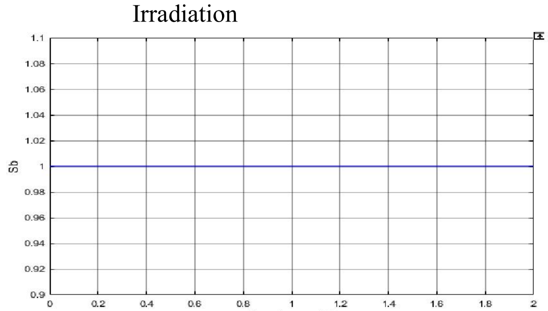
Figure 11 illustrates the ANFIS controller training data along with its structural configuration. The training process for the ANFIS controller involves a hybrid learning algorithm that combines gradient descent for parameter optimization and the least-squares estimator for rule tuning. The training data typically consists of input-output pairs, such as variations in PV array voltage, current, and battery SOC and desired control actions for the converters as outputs.



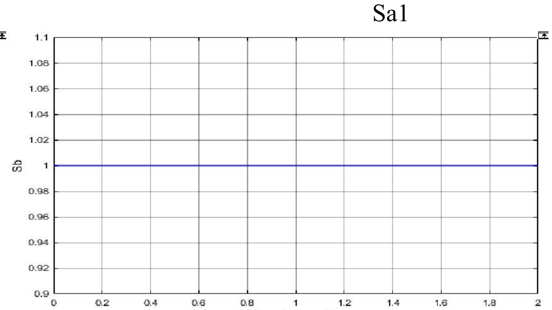
Irradiation



Sa1



Sb1



Sc1

Fig. 12 Waveforms of solar irradiance from the PV array and pulses of auxiliary switches.

Figure 12 shows the waveforms of PV irradiation, voltage, current, and pulses of auxiliary switches at different irradiation levels in three modes. In mode 1, with high irradiation (850 W/m²), both the EV and backup batteries are charged simultaneously, as all auxiliary switches receive active gate pulses. In mode 2, with low irradiation (100 W/m²), the backup battery discharges through the BIDC to charge the EV battery, as the PV array power is insufficient.

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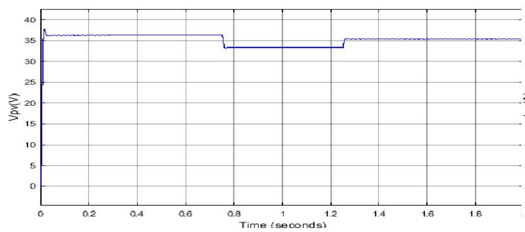
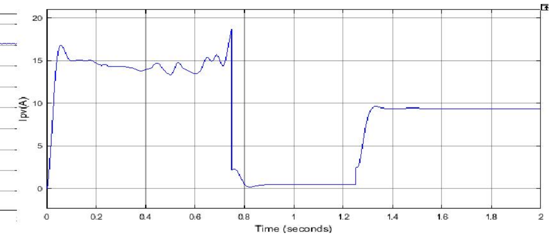
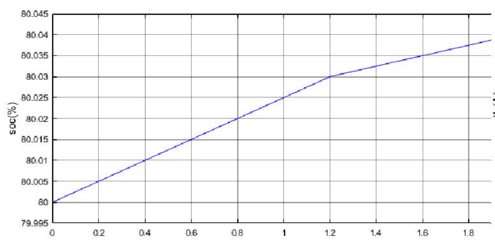
Mode 3, with intermediate irradiation (500 W/m²), charges only electric vehicle battery with backup battery disconnected. Throughout all modes, the gate pulse for switch Sb remains high to ensure continuous EV battery charging.



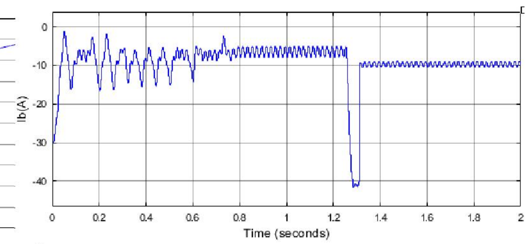
(a)Vpv



(V)Ipv

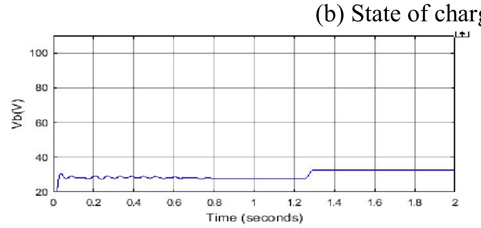


(A)

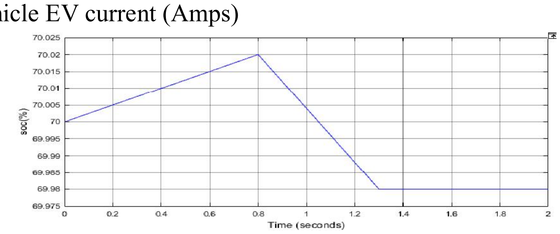


(B)

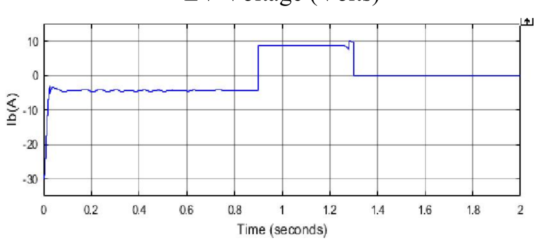
(b) State of charge electric vehicle EV current (Amps)

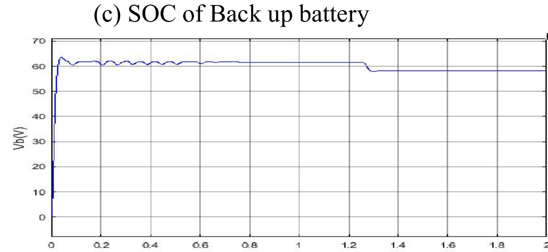


EV Voltage (Volts)



(c) SOC of Back up battery





Current (Amps) of Backup battery Voltage (Volts) of Back-up battery

Fig. 13 shows the waveforms of (a) solar voltage (VPV) and solar current (I_PV), (b) EV battery State of Charge, EV current (I_Bat), and EV voltage (V_Bat), and (c) backup battery SOC, backup battery current (I Backup Bat), and backup battery voltage.

The PV array, EV battery, and backup battery's dynamic waveforms under various irradiation circumstances are shown in Figure 13. In mode 1, the EV battery's increasing SOC and negative current indicate that the SEPIC converter is stepping down the PV array voltage to charge it. As evidenced by its rising SOC and charging current, the BIDC converter is charging the backup battery in boost mode.

In mode 2, the PV array is disconnected during non-sunshine or low-irradiation hours, which causes the voltage to achieve its open-circuit value and the current to decrease to zero. A drop in the backup battery's state of charge and positive discharge current indicate that the BIDC is now operating in buck mode, depleting the backup battery in order to charge the EV battery. The EV battery's state of charge (SOC) rises in the meantime, signalling that the backup battery is charging it.

In mode 3, a PV array voltage is stepped down by the Sepic converter to DC link voltage, which charges the EV battery. The EV battery SOC continues to rise with a negative current, confirming its charging state. In this mode, backup battery is insulated from system, maintaining a stable voltage and zero current. Across all modes, the waveforms demonstrate the system's ability to ensure continuous charging of EV battery, either directly from PV array or through backup battery, based on the operating conditions.

All the presented waveforms demonstrate the effective operation of the system under ANFIS-based closed-loop control, achieving precise regulation with minimal distortion. Compared to a conventional open-loop system, the ANFIS controller significantly enhances performance by adapting dynamically to varying operating conditions, such as changes in PV array irradiation. The closed-loop ANFIS control ensures efficient energy management between the PV array, EV battery, and backup battery, maintaining stable operation and continuous charging under all modes. This highlights the superiority of the ANFIS controller in improving system reliability and overall performance compared to conventional control methods.

V. CONCLUSION

This project presents a novel approach to optimizing the integration of a solar PV system with an electric vehicle (EV) battery using a SEPIC converter and BIDC, controlled by an ANFIS-based intelligent control system. The primary innovation lies in the integration of P&O MPPT for efficient solar power extraction, combined with an intelligent ANFIS control law to optimize energy flow between the solar PV system and the EV battery. The use of a SEPIC converter ensures efficient voltage regulation, while the bidirectional DC-DC converter facilitates effective discharging and charging of EV battery. The system dynamically adjusts the duty cycle based on real-time power demands, ensuring that the system operates at maximum efficiency. By combining advanced MPPT techniques with ANFIS control, this system improves overall energy management, enhances the reliability of solar-based charging stations, and offers a robust solution for sustainable energy use in electric vehicle applications.

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