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Intelligent PV-BESS Integrated EV Charging Station Using ANFIS MPPT and Novel Battery Controller

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Abstract—

Enhanced power management and grid support are features of this work's grid-connected electric vehicle (EV) charging station, which incorporates a photovoltaic (PV) array and battery energy storage system (BESS). To maximize energy extraction in settings of variable solar irradiance and temperature, a maximum power point tracking (MPPT) system called an adaptive neuro-fuzzy inference system (ANFIS) is used by the PV array. We provide a new BESS controller that can govern charge/discharge cycles in a way that keeps the grid stable and reduces power fluctuations. At the DC link, a bidirectional DC-DC converter interfaces the EV and BESS, allowing for smooth energy flow from the PV array to storage, the EV, and the grid. The PV array provides the majority of the energy needed to charge electric vehicles during the day, with backup from the grid when solar power is not available. By boosting power quality and reliability, the technology maintains grid synchronization at the point of common coupling (PCC). A hardware-in-the-loop prototype proves the suggested method works by showing it can handle changing operational circumstances and make good use of renewable energy.

Index Terms— Adaptive neuro-fuzzy inference system (ANFIS), battery energy storage system (BESS), electric vehicle (EV) charging station, maximum power point tracking (MPPT), photovoltaic (PV), power quality.

I. INTRODUCTION

A sustainable, dependable, and energy-efficient charging infrastructure is in high demand due to the soaring number of electric vehicles (EVs) [1]. The utility system experiences increased peak demand, grid stress, and operating expenses due to conventional EV charging stations' heavy reliance on the grid [2]. A potential solution to these problems, which include lowering carbon emissions and increasing energy autonomy, is to integrate renewable energy sources, especially photovoltaic (PV) systems, with energy storage [3]. While electric vehicle charging stations that use photovoltaic technology may harness solar power directly, their efficiency is quite sensitive to factors like temperature and sun irradiation [4]. Because of these fluctuations, maximum power point monitoring (MPPT) is crucial for efficient energy harvesting. The use of intelligent control methods is driven by the fact that traditional MPPT approaches frequently fail to adapt to situations that are changing at a rapid pace [5]. Nonlinear and time-varying PV features are well-suited to adaptive neuro-fuzzy inference systems (ANFIS) because they combine the learning power of neural networks with

the resilience of fuzzy logic [6]. When it comes to improving system dependability and grid support, intelligent PV control is just half the story [7]. A battery energy storage system (BESS) is also essential. When operated correctly, a BESS can absorb power spikes and dips, store renewable energy for later use, and keep the lights on even when the sun isn't shining. Integrated electric vehicle charging settings have unique challenges that traditional battery controllers might not be able to meet, such as the need for bidirectional power flow, dynamic charging, and grid interface [8] – [10]. An intelligent grid-connected PV-BESS integrated EV charging station with an ANFIS-based MPPT algorithm and a unique battery control technique is proposed in this study to overcome these problems. The PV array, BESS, EV load, and utility grid may all interchange energy in a flexible manner thanks to the system's bidirectional DC-DC converter at the DC link [11] – [13]. When it's sunny outside, priority-based energy management makes sure that solar power is used to charge electric vehicles as much as possible. When that isn't enough, the grid steps in. Enhancement of power quality and grid stability is further achieved by maintaining synchronization at the point of common coupling (PCC). A hardware-in-the-loop (HIL) experimental prototype is used to validate the efficacy of the proposed system [14], [15]. The outcomes show that the MPPT efficiency is enhanced, the battery operation is steady, the grid reliance is minimized, and the performance is resilient even while running in dynamic settings. Supporting future smart grid and sustainable transportation goals, this study helps to the creation of intelligent, renewable-based electric vehicle charging infrastructure.

II. PROPOSED SYSTEM TOPOLOGY

The proposed system topology of the intelligent PV–BESS integrated EV charging station is illustrated in Fig. 1. The architecture is designed to enable efficient energy exchange among the photovoltaic (PV) array, battery energy storage system (BESS), electric vehicle (EV), and the utility grid through a common DC link and a grid-interfaced voltage source converter (VSC).

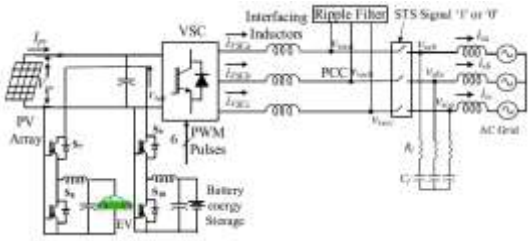


Fig. 1. System topology.

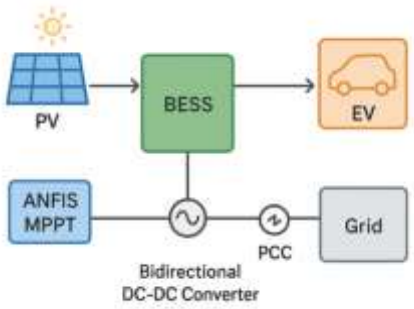


Fig. 2. Proposed Block diagram of the system.

A. DC-Side Configuration

The PV array serves as the primary renewable energy source and is connected to the DC link through a DC–DC power conversion stage. The PV output voltage $V_{pv}$and current $I_{pv}$are regulated to operate at the maximum power point using an intelligent MPPT controller. A DC link capacitor is employed to stabilize the DC bus voltage and decouple the PV

generation from load and grid-side disturbances. The EV and BESS are interfaced to the DC link via a bidirectional DC–DC converter consisting of power switches S_7–S_{10} and associated inductive elements. This configuration allows controlled bidirectional power flow, enabling both battery charging and discharging operations. The EV charging unit draws power directly from the DC link, while the BESS supports energy buffering, peak shaving, and power balancing.

B. Battery Energy Storage and EV Interface

The battery energy storage system is connected in parallel with the EV through the bidirectional converter. This arrangement enables coordinated energy management between the EV load and the storage system. During excess PV generation, the BESS is charged to store surplus energy, whereas during insufficient solar generation or high EV demand, the battery discharges to support the DC link. The EV charging current is regulated to ensure safe and efficient charging operation.

C. Grid-Connected Voltage Source Converter

A three-phase voltage source converter (VSC) interfaces the DC link with the utility grid. The VSC is controlled using pulse-width modulation (PWM) techniques to regulate active power exchange and maintain DC link voltage stability. The converter outputs three-phase currents i_{vsca}, i_{vscb}, and i_{vscc}, which are injected into the grid through interfacing inductors.

D. Interfacing Inductors and Ripple Filter

Interfacing inductors are employed between the VSC and the point of common coupling (PCC) to limit current ripple and improve power quality. Additionally, a ripple filter composed of a series resistor R_f and capacitor C_f is connected at the PCC to suppress high-frequency switching harmonics generated by the inverter. This ensures compliance with grid harmonic standards and enhances system reliability.

E. Static Transfer Switch and Grid Synchronization

A static transfer switch (STS) is incorporated at the PCC to control grid connectivity. The STS operates based on a binary control signal (‘1’ or ‘0’), allowing seamless connection or disconnection of the charging station from the utility grid during abnormal grid conditions or maintenance operations. Grid voltage synchronization is maintained through appropriate phase and frequency control, ensuring smooth power transfer and stable operation.

F. AC Grid Interface

On the AC side, the system is connected to the three-phase utility grid, delivering or absorbing power depending on operating conditions. The grid currents i_{sa}, i_{sb}, and i_{sc} are regulated to maintain unity power factor and minimize reactive power exchange. This configuration enables grid support functions such as voltage regulation and reduced power fluctuations.

III. MATHEMATICAL ANALYSIS OF THE PROPOSED SYSTEM

This section presents the mathematical modeling of the photovoltaic (PV) system, bidirectional DC–DC converter, battery energy storage system (BESS), grid-connected inverter, and the theoretical foundation of the ANFIS-based MPPT algorithm used in the proposed EV charging station.

A. Photovoltaic System Modeling

The PV array is modeled using the single-diode equivalent circuit, which provides an accurate representation of the electrical characteristics of a solar cell. The output current of the PV array is given by

$$I_{pv} = I_{ph} - I_o\left[\exp\left(\frac{q(V_{pv} + I_{pv}R_s)}{nkT}\right) - 1\right] - \frac{V_{pv} + I_{pv}R_s}{R_{sh}}$$

where $I_{ph}$is the photo-generated current, $I_o$is the diode reverse saturation current, $q$is the electron charge, $V_{pv}$and $I_{pv}$are the PV output voltage and current, $R_s$and $R_{sh}$are the series and shunt resistances, $n$is the diode ideality factor, $k$is the Boltzmann constant, and $T$is the cell temperature in Kelvin.

The output power of the PV array is expressed as

$$P_{pv} = V_{pv}I_{pv}$$

Maximum power point operation is achieved when

$$\frac{dP_{pv}}{dV_{pv}} = 0$$

which forms the basis for the MPPT control strategy.

B. DC–DC Boost Converter Modeling

The PV array is interfaced to the DC link through a DC–DC boost converter. The relationship between the input and output voltages of the boost converter is given by

$$V_{dc} = \frac{V_{pv}}{1 - D}$$

where $V_{dc}$is the DC link voltage and $D$is the duty cycle of the converter. By adjusting the duty cycle D, the operating point of the PV array can be shifted to track the maximum power point.

C. ANFIS-Based MPPT Algorithm

The adaptive neuro-fuzzy inference system (ANFIS) is employed to generate the optimal duty cycle for the boost converter. The inputs to the ANFIS controller are defined as the error and change in error of PV power:

$$e(k) = \frac{P(k) - P(k-1)}{V(k) - V(k-1)}$$

$$\Delta e(k) = e(k) - e(k-1)$$

The ANFIS architecture consists of five layers: fuzzification, rule base, normalization, defuzzification, and output layer. The output of the ANFIS controller is the duty cycle increment ΔD, which updates the converter duty cycle as

$$D(k) = D(k-1) + \Delta D$$

This adaptive structure allows rapid convergence to the maximum power point under changing irradiance and temperature conditions.

D. Battery Energy Storage System Modeling

The BESS is modeled using an equivalent circuit comprising an open-circuit voltage $V_{oc}$and internal resistance R_b. The terminal voltage of the battery is given by

$$V_b = V_{oc} - I_b R_b$$

The state of charge (SoC) of the battery is calculated as

$$SoC(t) = SoC(t_0) - \frac{1}{C_b}\int_{t_0}^{t} I_b(\tau)d\tau$$

where $C_b$is the battery capacity and $I_b$is the battery current (positive during discharge).

E. Bidirectional DC–DC Converter Analysis

The bidirectional DC–DC converter regulates power flow between the BESS and the DC link. In buck (charging) mode, the voltage relationship is

$$V_b = DV_{dc}$$

In boost (discharging) mode, the relationship becomes

$$V_{dc} = \frac{V_b}{1 - D}$$

Current control is implemented to ensure safe battery operation and smooth transition between charging and discharging modes.

F. EV Charging Power Model

The EV charging power demand is represented as

$$P_{EV} = V_{dc} I_{EV}$$

where I_{EV} is the charging current drawn by the EV. The proposed energy management system prioritizes PV and BESS power to meet the EV load demand.

G. Grid-Connected Inverter Modeling

The three-phase voltage source inverter (VSI) connects the DC link to the grid. The active and reactive power exchanged with the grid are expressed as

$$P_g = \frac{3}{2}(v_d i_d)$$

$$Q_g = \frac{3}{2}(v_d i_q)$$

where v_d is the d-axis grid voltage, and i_d and i_q are the d–q axis currents. Unity power factor operation is achieved by setting $i_q = 0$.

H. DC Link Voltage Stability

The DC link capacitor dynamics are governed by

$$C_{dc} \frac{dV_{dc}}{dt} = I_{pv} + I_b - I_{EV} - I_g$$

where I_g is the grid current. Maintaining a constant DC link voltage ensures stable system operation and coordinated power flow.

IV. RESULTS AND ANALYSIS

This section analyzes the simulated performance of the proposed PV–BESS integrated EV charging station under varying operating conditions, including changes in PV insolation and grid disconnection–reconnection events. The effectiveness of the ANFIS-based MPPT and the proposed battery control strategy is evaluated in terms of power balance, voltage stability, and system reliability.

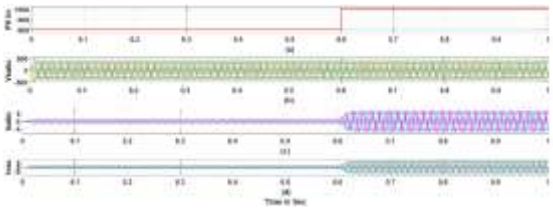


Fig. 3. The figure includes PV irradiance, grid-side voltages, source currents, and converter currents.

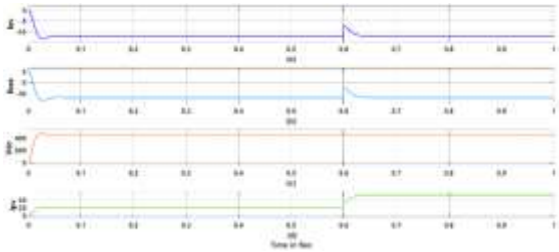


Fig. 4. illustrates the dynamic response of the EV current, battery energy storage current, DC link voltage, and PV current under a step change in PV irradiance.

A. Performance Under Variation of PV Insolation

Figure illustrates the simulated response of the EV charging station under varying PV insolation levels. As the solar irradiance changes, the PV output power varies accordingly. It can be observed that the ANFIS-based MPPT controller rapidly tracks the new maximum power point following each irradiance change, ensuring optimal power extraction from the PV array with minimal oscillations. During periods of high insolation, the PV array supplies the majority of the EV charging demand, and excess energy is directed toward charging the BESS. When insolation decreases, the PV power reduces proportionally; however, the DC link voltage remains stable due to the coordinated action of the BESS and grid interface. The battery compensates for the power deficit by discharging, thereby maintaining uninterrupted EV charging. This demonstrates the robustness of the

proposed control strategy in mitigating the intermittent nature of solar energy.

PV Current Response

The PV array current $I_{pv}$is depicted in Figure. As expected, the PV current increases significantly following the irradiance step at $t = 0.6$s. The smooth transition and fast settling indicate accurate and rapid tracking of the new maximum power point by the ANFIS-based MPPT algorithm.

B. Performance During Grid Disconnection

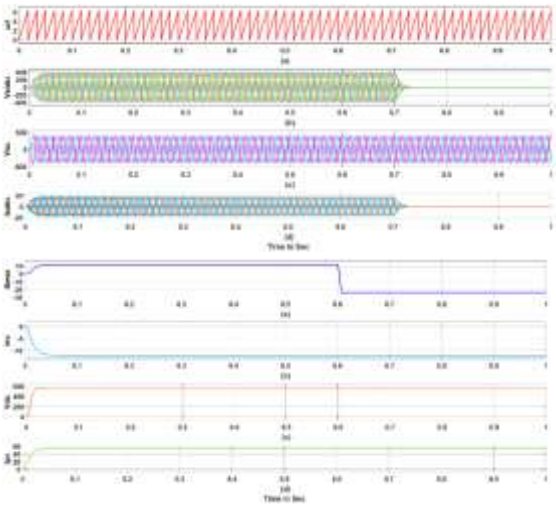


Fig. 5. Simulated performance when grid disconnected.

Figure shows the system response during grid disconnection. At the instant of grid isolation, the static transfer switch disconnects the charging station from the utility grid. Despite the sudden change in operating condition, the DC link voltage remains within acceptable limits, indicating effective power balancing by the BESS. The EV charging current continues without interruption, supplied by the PV array and the battery energy storage system. This confirms the capability of the proposed system to operate in islanded mode while ensuring reliable EV charging.

C. Performance During Grid Reconnection

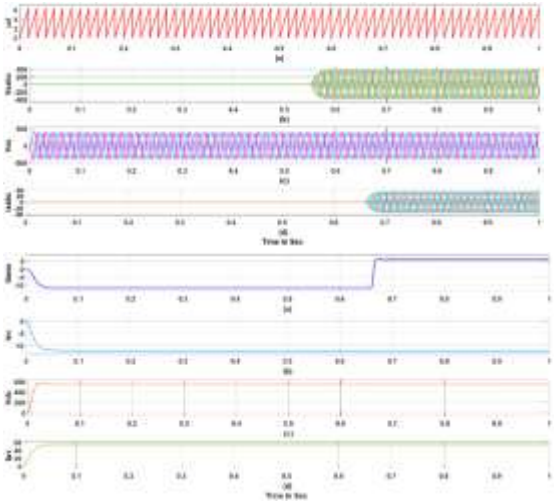


Fig.6. Simulated performance when grid is reconnected.

Figure presents the system behavior during grid reconnection. When the grid is reconnected, the voltage source converter synchronizes the system voltage, frequency, and phase with the grid before power exchange resumes. The transition occurs smoothly, with negligible transients in grid current and DC link voltage. The absence of significant overshoot or oscillations demonstrates effective synchronization and control of the inverter. Following reconnection, the grid resumes supporting the EV load and battery charging as required.

D. Discussion

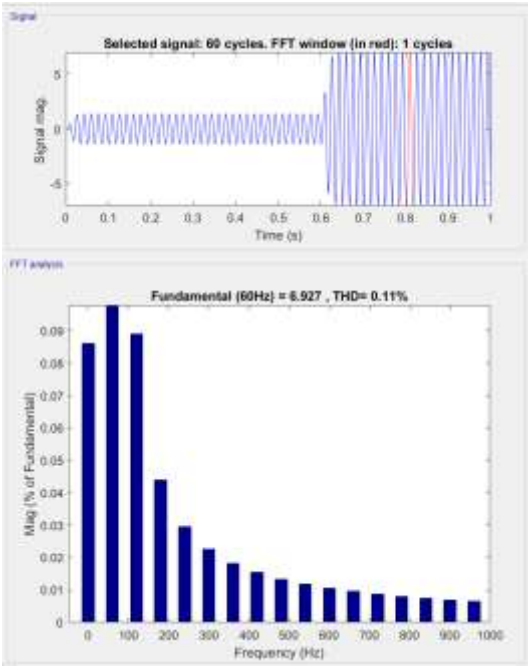


Fig. 7. THD % of the Grid Isabc.

The simulation results validate the proposed intelligent control framework under both normal and abnormal operating conditions. The ANFIS-based MPPT enhances PV energy utilization under dynamic irradiance, while the novel BESS controller ensures voltage stability and uninterrupted EV charging during grid disturbances. The smooth transition between grid-connected and islanded modes highlights the suitability of the proposed system for real-world EV charging applications with high renewable penetration.

CONCLUSION

This paper presented an intelligent grid-connected PV–BESS integrated EV charging station employing an ANFIS-based MPPT algorithm and a novel battery energy storage control strategy. The proposed system architecture enables efficient energy management among the photovoltaic array, battery storage, electric vehicle load, and utility grid through a common DC link and bidirectional power converters. The ANFIS-based MPPT ensures fast and accurate tracking of the maximum power point under varying solar irradiance, leading to improved renewable energy utilization. Simulation results demonstrate that the proposed control scheme effectively maintains DC link voltage stability and uninterrupted EV charging during dynamic operating conditions, including rapid changes in PV insolation and grid disconnection–reconnection events. The battery energy storage system plays a crucial role in compensating power fluctuations, supporting islanded operation, and enabling smooth transition during grid synchronization. The grid-interfaced voltage source converter ensures high power quality and reliable operation at the point of common coupling.

Overall, the proposed intelligent EV charging station enhances grid support capability, reduces dependency on conventional power sources, and improves system reliability. The results confirm that the developed approach is a promising solution for sustainable EV charging infrastructure and future smart grid applications integrating renewable energy and energy storage systems.

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