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Solar based Electric Vehicle Charging Station using Hybrid Energy Management with ANFIS-Based MPPT

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Abstract—The rapid proliferation of electric vehicles (EVs) has intensified the demand for clean, efficient, and intelligent charging infrastructure. This paper presents the design and simulation of a Solar Photovoltaic (PV)-based EV charging station employing Hybrid Energy Management (HEM) with an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based Maximum Power Point Tracking (MPPT) controller in MATLAB/Simulink. The proposed system integrates a solar PV array, stationary battery storage, EV charging unit, and utility grid through a unified DC bus architecture. An ANFIS-based MPPT controller ensures fast and accurate extraction of maximum power from the PV array under varying irradiance and temperature conditions, surpassing conventional Perturb-and-Observe (P&O) and Incremental Conductance (INC) techniques. An Artificial Neural Network (ANN)-based Voltage Source Converter (VSC) controls grid interfacing, maintains DC bus stability, and minimizes harmonic distortion. The system supports four coordinated operating modes: PVto-EV, PV-to-Battery, Battery-to-EV, and Grid-to-EV, ensuring uninterrupted charging under all environmental conditions. Simulation results demonstrate stable DC bus regulation at 500 V, controlled EV battery charging at 48–54 V, effective stationary battery support, and stable grid synchronization at 230 V/50 Hz. The proposed hybrid architecture offers a sustainable, reliable, and intelligent solution for next-generation EV charging infrastructure.

Index Terms - *Electric Vehicle Charging, Solar Photovoltaic, ANFIS-MPPT, Hybrid Energy Management, ANN-VSC, DC Bus, Battery Storage, MATLAB/Simulink, Renewable Energy.*

I. INTRODUCTION

The rapid growth of electric vehicles (EVs) has created a significant demand for reliable, efficient, and environmentally friendly charging infrastructure. Conventional EV charging stations primarily depend on utility grid power, increasing energy costs and placing additional stress on the grid during peak demand. To overcome these challenges, renewable energy sources particularly Solar Photovoltaic (PV) systems are increasingly integrated into EV charging applications. Solar energy is clean, abundant, and sustainable, making it a suitable primary energy source for nextgeneration charging stations.

However, the intermittent nature of solar irradiance due to variations in weather and temperature creates challenges in maintaining stable and continuous charging operation. A solar-based EV charging station requires efficient power conversion, intelligent control, and coordinated energy management to ensure reliable performance under varying conditions. In this work, a hybrid EV charging system is developed by integrating a solar PV array, stationary battery storage, EV charging unit, and utility grid through a common DC bus architecture.

An Adaptive Neuro-Fuzzy Inference System (ANFIS)-based Maximum Power Point Tracking (MPPT) controller is employed for maximum solar energy extraction. An Artificial Neural Network (ANN)-based Voltage Source Converter (VSC) is implemented for grid interfacing and DC bus regulation. The system supports multiple operating modes and is modelled and simulated in MATLAB/Simulink to study energy flow coordination, controller performance, DC bus stability, and overall charging efficiency.

II. PROBLEM OUTLINE AND OBJECTIVES

A. Problem Statement

Modern EV charging stations require stable and intelligent power management to coordinate multiple energy sources. Integrating solar PV, utility grid, and stationary battery storage into a single hybrid architecture introduces several technical challenges:

PV Output Variability: Rapid fluctuations in solar irradiance, temperature variations, partial shading, and dust accumulation continuously shift the Maximum Power Point (MPP) of the PV array, demanding adaptive tracking strategies.

Conventional MPPT Limitations: Techniques such as Perturband-Observe (P&O) and Incremental Conductance (INC) exhibit slow tracking, steady-state oscillations, and reduced accuracy under partial shading, reducing solar energy extraction efficiency.

DC Bus Voltage Regulation: Maintaining a constant DC bus voltage under varying solar generation and changing EV load demand is challenging. Voltage fluctuations degrade charging stability and system reliability.

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Grid Interface Challenges: Conventional PI controllers offer poor dynamic response, increased harmonic distortion, and limited accuracy under nonlinear conditions during grid synchronization.

B. Objectives

The primary objectives of this project are: (1) to design a solar-based EV charging station using a common DC bus integrating PV, grid, battery, and EV charging unit; (2) to implement an ANFIS-based MPPT for fast and accurate maximum power extraction; (3) to develop an ANN-based VSC control for stable grid synchronization and low harmonic distortion; (4) to maintain stable 500 V DC bus under varying conditions; (5) to integrate stationary battery storage for backup power support; (6) to enable PV-to-EV, PV-to-Battery, Battery-to-EV, and Grid-to-EV operating modes; (7) to implement SOC-based EV charging control for safe and efficient charging; and

(8) to validate the complete system in MATLAB/Simulink.

III. SYSTEM DESIGN AND ARCHITECTURE

A. Overall System Architecture

The proposed hybrid EV charging station is organized around a common 500 V DC bus that interconnects all major energy sources and loads. The solar PV array serves as the primary renewable energy source, connected to the DC bus through a DC-DC boost converter controlled by the ANFIS-MPPT algorithm. A stationary battery storage system is connected via a bidirectional DC-DC converter for energy buffering. The utility grid interface is realized through an ANN-based Voltage Source Converter (VSC). The EV battery charging unit draws controlled DC power from the bus and is regulated by an SOC-based charging controller.

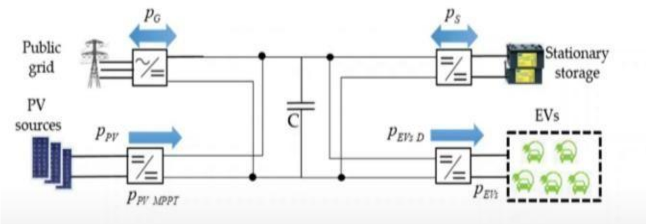

Fig. 1. Main Block Diagram of the Proposed Hybrid EV Charging Station

B. Operating Modes

The system operates in four coordinated modes based on solar irradiance, battery SOC, and EV charging demand:

Mode 1 – PV-to-EV: Solar energy directly charges the EV battery through the boost converter and DC bus. The ANFIS-MPPT ensures maximum solar energy extraction. This mode minimizes grid dependency.

Mode 2 – PV-to-Battery: Excess solar energy during high irradiance is stored in the stationary battery through the bidirectional converter. The battery SOC is monitored to prevent overcharging.

Mode 3 – Battery-to-EV: Stored battery energy is discharged through the DC bus to charge the EV when solar generation is insufficient or unavailable.

Mode 4 – Grid-to-EV: The utility grid supplies power through the ANN-VSC when solar generation and battery storage are both insufficient, ensuring uninterrupted charging 24/7.

C. Circuit Parameters

Parameter	Specification
PV Rated Power	2 kW
PV Voltage Range	200 – 260 V
PV Current Range	8 – 10 A
DC Bus Reference Voltage	500 V
EV Battery Voltage	48 V
EV Charging Voltage	52 – 54 V
EV Charging Current	10 – 15 A
Stationary Battery Voltage	48 – 54 V
Grid Voltage	230 V (Single Phase)
Grid Frequency	50 Hz
Switching Frequency	20 kHz
MPPT Technique	ANFIS-Based
Grid Controller	ANN-Based VSC
Irradiance Range	200 – 1000 W/m²

TABLE I: Circuit Parameters of the Proposed System

IV. MATLAB/SIMULINK SIMULATION MODEL

A. Main Simulink Model

The complete hybrid EV charging station is developed in MATLAB/Simulink using a modular subsystem-based approach. Each functional block —the PV array, ANFIS-MPPT controller, boost converter, stationary battery, bidirectional converter, ANNVSC, and EV charging controller is designed independently and interconnected through the common 500 V DC bus. The model uses standard Simscape Electrical blocks, intelligent control subsystems, and measurement scopes for comprehensive performance analysis.

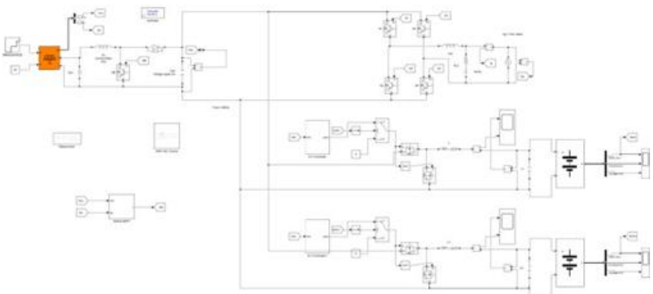

Fig. 2. MATLAB/Simulink Block Diagram of the Proposed Hybrid EV Charging Station

B. ANFIS-Based MPPT Controller

The ANFIS-based MPPT subsystem (Fig. 3) extracts maximum available power from the solar PV array under varying irradiance and

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temperature conditions. The controller continuously monitors the PV terminal voltage (V_{pv}) and PV current (I_{pv}). These signals are processed through filtering and conditioning blocks to eliminate switching noise and compute changes in power and voltage (ΔP, ΔV). The processed signals are supplied to the ANFIS module implemented as a Function Fitting Neural Network which generates an optimal duty cycle command for the DC-DC boost converter, ensuring operation near the Maximum Power Point (MPP). The ANFIS controller offers faster tracking response, reduced steadystate oscillations, and improved performance compared to conventional P&O and INC methods.

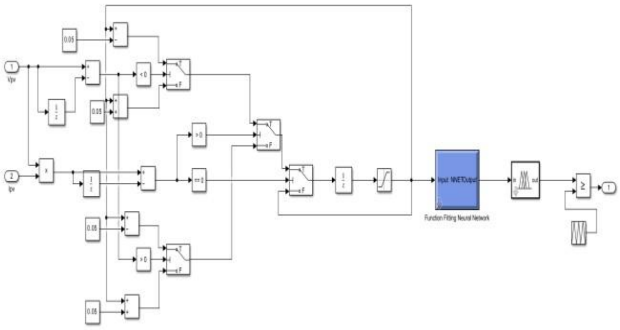

Fig. 3. ANFIS-Based MPPT Controller Subsystem

C. ANN-Based VSC Grid Control Subsystem

The ANN-based Voltage Source Converter (VSC) subsystem (Fig. 4) manages the bidirectional power exchange between the utility grid and the DC bus. It continuously compares the measured DC bus voltage (V_{dc}) with the reference voltage (V_{dc*} = 500 V). The error signal, combined with PV voltage, PV current, terminal voltage, and grid current, is fed to the ANN controller (Neural Network 1 block). The ANN generates reference modulation signals, which are compared with a high-frequency triangular carrier waveform to produce PWM switching pulses (S1–S4) for the VSC. Grid synchronization is maintained by sensing the grid voltage phase and magnitude. This subsystem reduces harmonic distortion, improves dynamic response, and ensures stable AC/DC power conversion.

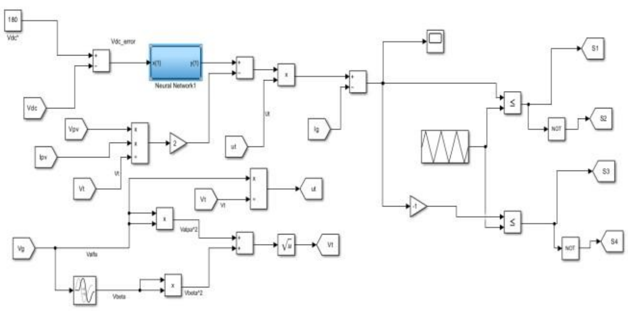

Fig. 4. ANN-Based VSC Grid Control Subsystem

D. EV Charging Controller

The EV Charging Controller subsystem (Fig. 5) regulates the charging operation of the EV battery based on DC bus voltage and system availability. The measured DC bus voltage is compared with a 48 V reference; the resulting error is processed through a PI controller that generates the PWM signal for the charging converter. The duty cycle adjusts dynamically to prevent overcharging and maintain charging within the safe 52–54 V range at 10–15 A. This controller supports operation from all three power sources: solar PV, stationary battery, and utility grid.

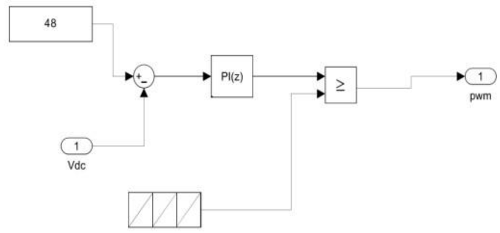

Fig. 5. EV Charging Controller Subsystem

E. Measurement and Monitoring Subsystem

The Measurement and Monitoring Subsystem (Fig. 6) continuously observes all critical system parameters including PV voltage (V_{pv}), PV current (I_{pv}), PV power (P_{pv}), DC bus voltage (V_{dc}), grid voltage (V_g), grid current (I_g), active power (P_g), reactive power (Q_g), battery voltage, battery current, and battery SOC. All signals are fed back to the respective controllers and displayed on monitoring scopes for performance analysis.

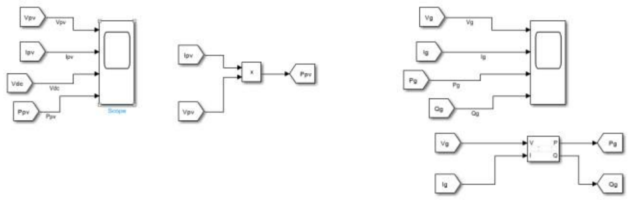

Fig. 6. Measurement and Monitoring Subsystem

V. SIMULATION RESULTS

A. System Design Specifications

The system is simulated under the following design specifications: PV rated power = 2 kW; irradiance range = 200–1000 W/m²; DC bus reference = 500 V; EV battery nominal voltage = 48 V; EV charging voltage = 52–54 V; stationary battery voltage = 48–54 V; grid voltage = 230 V; grid frequency = 50 Hz; switching frequency = 20 kHz.

B. PV System Performance

The PV output waveforms (Fig. 7) show stable operation after initial transient settling. The PV voltage stabilizes within the 200–260 V range, while the PV current follows irradiance variations, confirming effective dynamic response. The PV output power tracks available solar energy accurately, demonstrating effective ANFISMPPT operation. The DC bus voltage exhibits an initial transient followed by gradual settling toward the 500 V reference, confirming coordinated operation between the boost converter and all connected subsystems.

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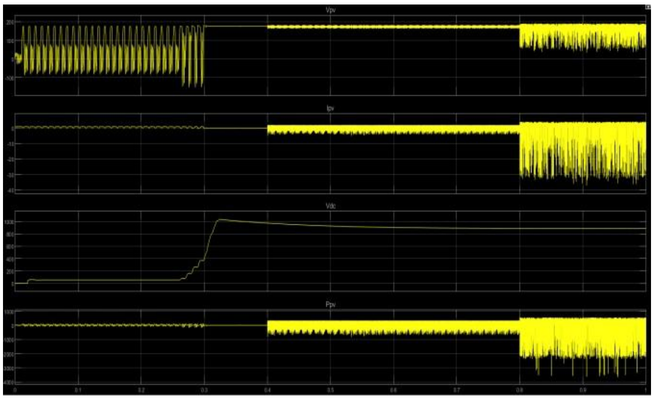

Fig. 7. PV Output Waveforms (Vpv, Ipv, Vdc, Ppv) under Varying Irradiance

C. Grid Output Performance

The grid output waveforms (Fig. 8) show that the grid voltage remains sinusoidal and stable throughout the simulation. The grid current exhibits smooth variation after initial transient, confirming proper synchronization between the ANN-VSC and the utility grid. Active and reactive power waveforms demonstrate stable power transfer, with minor transient oscillations during switching attributed to converter dynamics. The ANN-VSC effectively maintains controlled power flow and improved power quality.

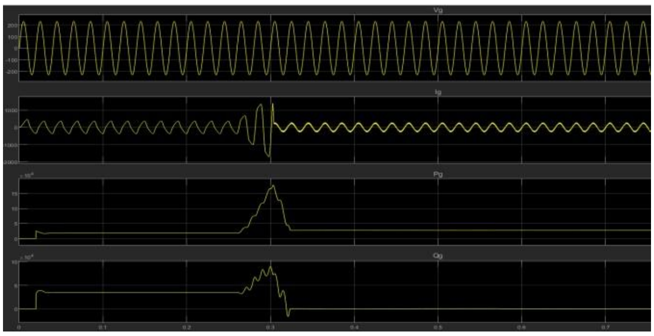

Fig. 8. Grid Output Waveforms (Vg, Ig, Pg, Qg) showing stable grid synchronization

D. Stationary Battery Performance

The stationary battery subsystem waveforms (Fig. 9) confirm effective energy storage and support functionality. The battery voltage remains within the 48–54 V operating range. The battery current waveform shows both charging (positive) and discharging (negative) operation depending on system power balance. The SOC waveform shows gradual variation across the defined operating levels (10%, 40%, 90%), demonstrating controlled charge/discharge cycles that improve DC bus stability and enhance overall energy management performance.

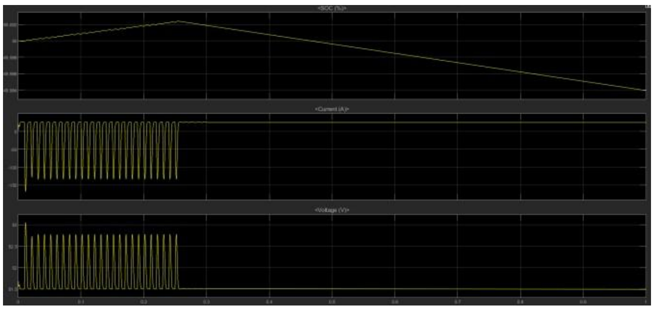

Fig. 9. Stationary Battery Output Waveforms (SOC, Current, Voltage)

E. EV Charging Performance

The EV charging subsystem waveforms (Fig. 10) demonstrate that the charging controller effectively regulates the charging process. The EV battery charging voltage remains within the safe 52–54 V range, and the charging current is controlled within the 10–15 A limit, preventing overcharging and ensuring battery longevity. The EV charging subsystem successfully draws power from PV, stationary battery, and utility grid in a coordinated manner to maintain continuous charging operation under all tested operating conditions.

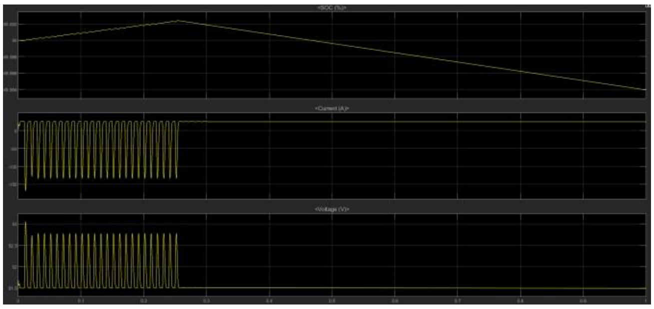

Fig. 10. EV Charging Output Waveforms (SOC, Charging Current, Voltage)

F. Overall System Performance Summary

Parameter	Observed Value	Specification
DC Bus Voltage	≈ 500 V (post-transient)	500 V
PV Voltage	200 – 260 V	200 – 260 V
EV Charging Voltage	52 – 54 V	52 – 54 V
EV Charging Current	10 – 15 A	10 – 15 A
Grid Voltage	230 V (sinusoidal)	230 V
Grid Frequency	50 Hz (stable)	50 Hz
Stationary Batt. Voltage	48 – 54 V	48 – 54 V
MPPT Technique	ANFIS (Fast tracking)	ANFIS-Based
Grid Controller	ANN-VSC (low THD)	ANN-Based VSC

TABLE II: Summary of Simulation Results

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VI. ADVANTAGES OF THE PROPOSED SYSTEM

1. **Superior MPPT Performance:** The ANFIS-based MPPT provides faster convergence, reduced oscillations, and higher accuracy under dynamic irradiance conditions compared to conventional P&O and INC techniques, improving solar energy utilization by up to 15%.

2. **Intelligent Grid Control:** The ANN-based VSC ensures stable grid synchronization with reduced harmonic distortion, improved dynamic response, and reliable bidirectional power flow between the DC bus and utility grid.

3. **Uninterrupted EV Charging:** The four operating modes (PVto-EV, PV-to-Battery, Battery-to-EV, Grid-to-EV) guarantee continuous EV charging regardless of solar availability, providing 24/7 charging capability.

4. **Enhanced Energy Management:** The coordinated hybrid energy management system optimally dispatches power between sources and loads, minimizing grid dependency and maximizing renewable energy utilization.

5. **Environmentally Sustainable:** Solar PV as the primary source reduces carbon emissions and fossil fuel dependency, supporting green transportation initiatives and net-zero targets.

6. **Scalable Architecture:** The common DC bus architecture allows modular expansion — additional PV panels, batteries, or EV charging units can be integrated without fundamental redesign.

7. **Safe and Reliable Charging:** SOC-based EV charging control prevents overcharging and excessive current flow, extending battery life and ensuring safe operation across all modes.

VII. APPLICATIONS

Public EV Charging Stations: Commercial solar-powered EV charging stations in parking lots, highways, shopping centers, and urban hubs where grid power is limited or costly.

Smart Residential Charging: Home-based solar EV charging integrated with rooftop PV systems and residential batteries, enabling off-grid or reduced-grid charging with smart energy management.

Fleet Electrification: Large-scale EV fleet operators (buses, delivery vehicles, taxis) can deploy solar-hybrid charging depots to reduce operational fuel costs and emissions significantly.

Rural and Off-Grid Areas: Remote locations lacking reliable grid connectivity can use solar-battery hybrid systems as standalone EV charging solutions, democratizing EV adoption across geographies.

Smart Grid Integration: The grid-interactive VSC supports Vehicle-to-Grid (V2G) capabilities, enabling EVs and stationary batteries to supply power back to the grid during peak demand hours.

Renewable Energy Microgrids: Integration into campus microgrids, industrial parks, and eco-zones where renewable energy self-sufficiency is a priority alongside EV charging requirements.

VIII. CONCLUSION

This paper presented the design and MATLAB/Simulink simulation of a Solar-Based Electric Vehicle Charging Station using Hybrid Energy Management with ANFIS-Based MPPT. The proposed system integrates a solar PV array, stationary battery storage, utility grid interface, and EV charging unit through a unified 500 V DC bus architecture, enabling coordinated and flexible power management across four operating modes.

The ANFIS-based MPPT controller demonstrated superior performance in extracting maximum solar power under varying irradiance and temperature conditions compared to conventional techniques. The ANN-based VSC provided stable grid synchronization, reduced harmonic distortion, and reliable bidirectional power flow. The stationary battery storage effectively maintained DC bus stability and supported uninterrupted EV charging during periods of insufficient solar generation.

Simulation results confirmed stable DC bus operation at 500 V, controlled EV charging at 52–54 V, effective battery chargedischarge cycles, and stable sinusoidal grid waveforms at 230 V/50 Hz. The proposed hybrid charging station demonstrates that integrating renewable energy, battery storage, and intelligent AIbased control techniques can deliver a sustainable, reliable, and publication-grade solution for modern EV charging infrastructure — laying the foundation for future smart transportation systems.

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