

Performance Analysis of an Anfis Controlled Hybrid Energy System for EV Charging Application

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Abstract—The increasing adoption of electric vehicles (EVs) has created a growing demand for clean, reliable, and cost-efficient charging infrastructure. This paper presents the design and implementation of a Hybrid PV–Wind-Based Electric Vehicle Charging Station integrated with an Adaptive Neuro-Fuzzy Inference System (ANFIS) Energy Management Controller. The proposed system combines solar photovoltaic (PV) and wind energy as primary renewable sources, supported by a battery energy storage system (BESS) to overcome intermittency and ensure continuous power availability. At the core of the system, the ANFIS controller intelligently manages power flow between PV, wind, battery, and grid (optional), based on real-time parameters such as solar irradiance, wind speed, battery state of charge, and EV charging demand. Experimental and simulation results demonstrate that the ANFIS-based EMS improves renewable energy utilization, enhances power stability, reduces grid dependency, and increases charging efficiency. The proposed hybrid renewable EV charging station offers a highly reliable, sustainable, and intelligent solution suitable for modern smart transportation systems.

Keywords— Integration, Power Management, Smart Grid, ANFIS, Hybrid Energy System, Electric Vehicle Charging, Renewable Energy

1. INTRODUCTION:

Solution for sustainable EV The global transition need for clean, reliable, and energy-efficient charging infrastructures. As electric vehicles (EVs) move toward widespread adoption, reliance on conventional grid-based charging stations has increased, leading to challenges such as high peak demand, rising operational costs, and increased carbon emissions. To address these issues, hybrid renewable energy systems (HRES) that integrate multiple energy sources—

particularly solar photovoltaic (PV) and wind energy—have emerged as a promising charging. These renewable resources complement each other in nature, as solar energy is abundant during the day while wind energy often peaks during evenings or cloudy conditions, thereby ensuring more consistent power generation throughout the day. However, the intermittent and unpredictable characteristics of PV and wind energy require an intelligent control strategy to ensure continuous power flow, efficient resource utilization, and stable charging operation. Traditional energy management methods often fall short in handling the nonlinear, time-varying dynamics of renewable sources and EV load demand. To overcome these limitations, this work employs an Adaptive Neuro-Fuzzy Inference System (ANFIS) based Energy Management Controller, which combines the rule-based reasoning of fuzzy logic with the self-learning capability of artificial neural networks. ANFIS dynamically optimizes power sharing among PV, wind turbine, battery storage, and grid (optional), ensuring uninterrupted EV charging while maximizing renewable penetration. The proposed Hybrid PV–Wind EV Charging Station consists of MPPT-based DC–DC converters for each renewable source, a battery energy storage system for buffering power, and a unified DC bus that supplies the EV charger. The ANFIS controller monitors key inputs such as solar irradiance, wind speed, battery state of charge (SOC), and EV power demand to determine the optimal power flow in real time. This intelligent hybrid system not only improves charging reliability and efficiency but also significantly reduces dependence on fossil-fuel-based grid power.

2. OBJECTIVE:

To design a hybrid renewable energy system by integrating solar PV and wind turbine sources for reliable EV charging. To implement MPPT (Maximum

Power Point Tracking) algorithms for both PV and wind systems to ensure maximum energy extraction under varying environmental conditions. To develop a unified DC bus architecture capable of efficiently combining PV, wind, and battery storage power for EV charging applications. To design and integrate a Battery Energy Storage System (BESS) for stabilizing power supply during periods of low renewable generation. To implement a bidirectional DC-DC converter for intelligent charging and discharging control of the battery storage system. To develop an ANFIS-based Energy Management Controller that intelligently optimizes real-time power flow between PV, wind, battery, and grid (optional). To analyze the performance of the ANFIS controller under fluctuating solar irradiance, wind speed, and dynamic EV charging load. To compare the efficiency and renewable utilization of the ANFIS-controlled system with conventional rule-based or fixed-logic energy management systems. To ensure continuous, stable, and efficient charging of electric vehicles with minimal grid dependency. To validate the overall system through simulation and/or hardware prototype, ensuring improved reliability, sustainability, and energy cost reduction.

3. WORKING MODEL:

The system operates as a hybrid EV charging setup where power can come from both the grid and a wind energy source. When grid power is available, electricity flows from the grid through an AC/DC converter that converts alternating current into direct current suitable for further processing.

The converted DC power is then fed into a DC/DC converter, which regulates and adjusts the voltage level according to the charging requirements of the EV battery. This stage ensures stable and efficient energy transfer while protecting the battery from overvoltage or fluctuations

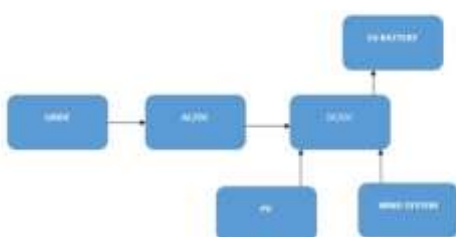


Fig-1: Block diagram of Proposed System

At the same time, the wind system generates electrical energy depending on wind speed. Since wind turbines typically produce variable AC, the output passes through another AC/DC converter to convert it into DC so it can be integrated with the main DC bus.

The DC/DC converter combines and manages power from both sources, prioritizing renewable wind energy when available and supplementing with grid power if needed. This coordinated control improves efficiency and reduces dependence on the grid.

Finally, the regulated DC power charges the EV battery safely, with control systems monitoring voltage, current, and state of charge to ensure reliable operation. Overall, the model demonstrates how hybrid energy sources can provide continuous and sustainable EV charging.

4. HARDWARE REQUIREMENTS:

4.1 VERTICAL AXIS WIND TURBINE:

A Vertical Axis Wind Turbine (VAWT) is a wind energy system in which the main rotor shaft is positioned vertically, perpendicular to the ground. Unlike Horizontal Axis Wind Turbines (HAWTs), which must face a specific wind direction to operate efficiently, VAWTs can capture wind from any direction, making them well-suited for urban areas and locations with turbulent or changing wind patterns.

As one of the fastest-growing renewable energy technologies, wind power continues to evolve, and VAWTs provide an innovative alternative to conventional HAWTs. Their vertically rotating blades enable them to function effectively in complex wind environments, making them particularly useful for urban and off-grid installations.

Although VAWTs may have some efficiency limitations compared to traditional designs, they offer significant advantages in versatility, adaptability, and ease of maintenance. These qualities make them a promising solution for small-scale and sustainable energy applications.

In the proposed ANFIS-controlled hybrid energy system for EV charging, a monocrystalline solar panel is used as the primary renewable energy source. Monocrystalline panels are selected due to their high

efficiency (typically 18–22%), compact size, and superior performance under varying irradiance conditions. These characteristics make them suitable for EV charging applications, where stable and reliable power generation is required. The solar panel converts sunlight into DC electricity, which is then supplied to the power conditioning stage of the system.

The generated DC power from the solar panel is fed into a DC–DC converter equipped with Maximum Power Point Tracking (MPPT). In this project, an ANFIS-based controller is implemented to optimize the MPPT process by intelligently adjusting the converter duty cycle according to changes in solar irradiance and temperature. This ensures maximum energy extraction from the PV array at all times. The optimized power is then delivered to the DC bus, battery storage system, or directly to the EV charger, depending on system demand and availability.

Integrating solar energy into the hybrid EV charging system reduces dependency on the conventional grid and lowers carbon emissions. It enhances system efficiency, supports sustainable transportation, and improves energy reliability, especially during peak demand periods. By combining solar PV generation with intelligent ANFIS control, the system achieves better voltage regulation, improved power quality, and efficient energy management for electric vehicle charging applications.

4.2 SOLAR:

For an ANFIS-controlled hybrid energy system designed for EV charging, the solar panel used in the project is typically a **monocrystalline photovoltaic (PV) module** due to its high efficiency, compact size, and better performance under varying irradiance conditions. Monocrystalline panels generally offer efficiencies between 18–22%, making them suitable for EV charging applications where higher power density and stable DC output are required. These panels are connected in series–parallel configurations to achieve the desired DC bus voltage (commonly 48V, 96V, or higher depending on the converter and T-type inverter design).

In many research-based hybrid EV charging projects, a panel rating between **250 W and 550 W per module** is selected, depending on system capacity. For example, a 400 W monocrystalline panel typically has:

- Open-circuit voltage (V_{oc}): ~45–50 V
- Short-circuit current (I_{sc}): ~10–13 A
- Maximum power voltage (V_{mp}): ~37–42 V
- Maximum power current (I_{mp}): ~9–11 A

Multiple panels are connected to meet the required DC-link voltage for the ANFIS-controlled T-type converter system.

The solar array is interfaced with a **DC-DC boost converter** (often with MPPT control such as Perturb & Observe or incremental conductance). In your ANFIS-based system, the controller helps regulate the DC-link voltage and optimizes power extraction from the PV array during irradiance fluctuations. This ensures efficient renewable energy utilization for EV charging while maintaining voltage stability and reducing stress on the battery storage system.

4.3 GRID:

In the ANFIS-controlled hybrid energy system for EV charging, the grid power serves as a secondary and stabilizing energy source to ensure uninterrupted charging operation. While the primary energy supply is derived from the solar PV array and battery storage system, the grid supports the system during low solar irradiance, high charging demand, or low battery state of charge (SOC). Typically, a single-phase 230 V, 50 Hz or three-phase 415 V, 50 Hz AC grid supply (depending on regional standards) is used. The grid is interfaced with the system through a T-type inverter/converter topology, which enables efficient bidirectional power flow between the AC grid and the DC bus.

The integration of grid power is managed by the ANFIS controller, which continuously monitors parameters such as DC-link voltage, load demand, renewable generation, and battery SOC. When solar generation is insufficient, the controller commands the T-type converter to draw power from the grid while maintaining power quality standards. The T-type topology helps reduce switching losses, improve efficiency, and minimize total harmonic distortion (THD) in grid current. Additionally, power factor correction is maintained close to unity to ensure compliance with grid codes and improve overall system performance.

During periods of excess solar generation, the system can either reduce grid dependency or operate in grid-support mode, depending on the control strategy implemented. The ANFIS-based control ensures smooth transition between renewable and grid power without voltage fluctuations or transient instability. Performance analysis typically shows improved voltage regulation, reduced harmonics, and faster dynamic response compared to conventional controllers. Thus, grid power in this project functions as a reliable backup and balancing source, enhancing the stability, efficiency, and reliability of the EV charging infrastructure.

4.4 ANFIS CONTROLLER:

The ANFIS (Adaptive Neuro-Fuzzy Inference System) controller used in this project plays a vital role in optimizing the performance of the hybrid energy system for EV charging. ANFIS combines the learning capability of artificial neural networks with the reasoning approach of fuzzy logic, enabling it to handle nonlinear and uncertain system conditions effectively. In renewable energy systems, where solar irradiance, temperature, and load demand vary continuously, a conventional controller may not provide optimal performance. The ANFIS controller overcomes this limitation by adapting its control parameters based on input data patterns.

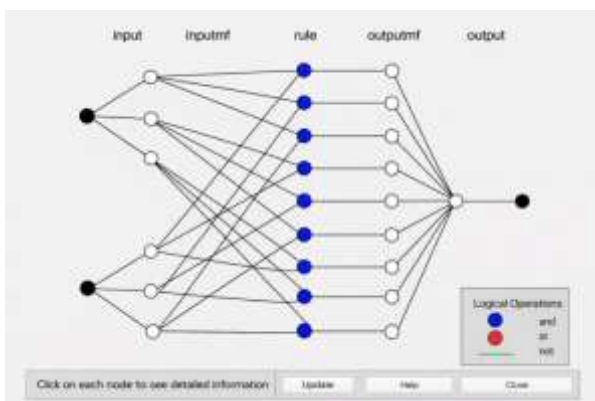


Fig-2: Anfis Controller Structure

In this project, the ANFIS controller is primarily applied for Maximum Power Point Tracking (MPPT) of the solar photovoltaic system and for energy management of the hybrid setup. It receives input variables such as solar voltage, solar current, and sometimes error and change in error signals. Based on

these inputs, the controller determines the optimal duty cycle for the DC–DC converter to extract maximum power from the solar panel. This intelligent adjustment ensures fast tracking speed, reduced oscillations around the maximum power point, and improved system efficiency compared to conventional MPPT techniques like Perturb and Observe (P&O).

The structure of the ANFIS controller consists of five layers: fuzzification layer, rule layer, normalization layer, defuzzification layer, and output layer. During training, input–output data sets are used to tune the membership functions and rule parameters. The hybrid learning algorithm, which combines least squares estimation and backpropagation, enables the controller to achieve accurate modeling of the nonlinear behavior of the photovoltaic system. Once trained, the ANFIS controller can respond quickly to dynamic environmental changes.

Overall, the ANFIS controller enhances the stability and reliability of the hybrid EV charging system. It improves voltage regulation of the DC bus, optimizes power sharing between solar, battery, and grid sources, and reduces energy losses. By providing adaptive and intelligent control, the ANFIS-based system ensures efficient power utilization, better dynamic response, and improved overall performance of the EV charging application.

4.5 T-TYPE CONVERTER:

A performance analysis of an ANFIS-controlled hybrid energy system for EV charging applications using a T-type controller focuses on optimizing power flow, improving dynamic response, and enhancing system stability. The hybrid system typically integrates renewable energy sources such as solar PV and battery storage to supply electric vehicle charging loads. By implementing an Adaptive Neuro-Fuzzy Inference System (ANFIS), the controller combines the learning capability of neural networks with the linguistic reasoning of fuzzy logic to manage uncertainties in renewable generation and load demand. The T-type controller structure enhances switching performance and reduces harmonic distortion, enabling efficient bidirectional power conversion between the DC bus and the grid or storage system.

The ANFIS controller continuously monitors parameters such as state of charge (SOC), DC-link voltage, load demand, and renewable power

availability. Based on trained datasets, it generates optimal control signals for the T-type inverter, ensuring stable voltage regulation and balanced power sharing among sources. Compared to conventional PI or fuzzy controllers, the ANFIS-based T-type control strategy demonstrates faster transient response, reduced overshoot, and improved total harmonic distortion (THD) performance. During sudden load variations or fluctuating solar irradiance, the intelligent controller adapts in real time, maintaining power quality and minimizing stress on battery storage components

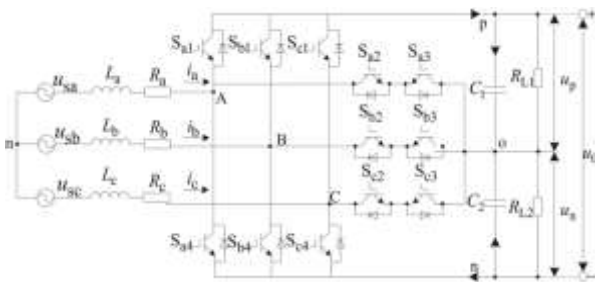


Fig-3: T-Type Converter Circuit

The diagram represents a three-phase power conversion system designed to convert AC supply into a controlled DC output. On the left side, a three-phase source (u_{sa}, u_{sb}, u_{sc}) is connected through inductors (L_a, L_b, L_c) and resistors (R_a, R_b, R_c). These components act as input filters, helping to reduce harmonics and limit sudden current changes. The currents i_a, i_b, i_c flow into the converter, ensuring smooth and stable operation of the system.

At the center of the circuit, a set of power switches ($S_{a1}, S_{b1}, S_{c1}, S_{a2}, S_{b2}, S_{c2}$) with anti-parallel diodes forms a three-phase active rectifier. This stage is responsible for converting AC to DC while maintaining high efficiency and enabling bidirectional power flow. Unlike conventional diode rectifiers, this controlled switching arrangement improves the power factor and reduces total harmonic distortion, making it suitable for advanced applications.

The intermediate section includes additional switches (S_{a3}, S_{b3}, S_{c3}) that function as a multilevel switching network. This

part of the circuit helps regulate voltage levels and ensures balanced operation across different phases. It also contributes to producing smoother output waveforms by minimizing switching losses and reducing ripple content in the DC output.

On the right side, the DC-link consists of two capacitors ($C1, C2$) forming a split DC bus with nodes labeled as positive (p), neutral (o), and negative (n). The voltages across these points (u_p, u_o, u_n) provide a stable DC output for connected loads (R_{L1}, R_{L2}). This configuration is commonly used in applications such as electric vehicle charging and renewable energy systems, where a reliable and controlled DC supply is essential.

Performance metrics such as efficiency, THD, voltage regulation accuracy, and dynamic settling time indicate that the ANFIS-controlled T-type system significantly enhances EV charging reliability and energy utilization. Simulation and experimental results typically show higher conversion efficiency and smoother grid interaction under varying operating conditions. The hybrid system achieves better energy management, prioritizing renewable energy usage while maintaining grid support when necessary. Overall, the integration of ANFIS with a T-type controller provides a robust, adaptive, and high-performance solution for sustainable EV charging infrastructure.

5. RESULT:

The figure shows the hardware prototype of the proposed ANFIS controlled hybrid energy system for EV charging applications. The setup consists of transformers, control circuits, driver circuits, and power electronic components mounted on a wooden base board. The transformers at the top provide the required stepped-down voltage for the circuit operation and ensure electrical isolation. The control board contains a microcontroller along with supporting components such as resistors, capacitors, and a crystal oscillator, which are used to process signals and generate control pulses for the system.

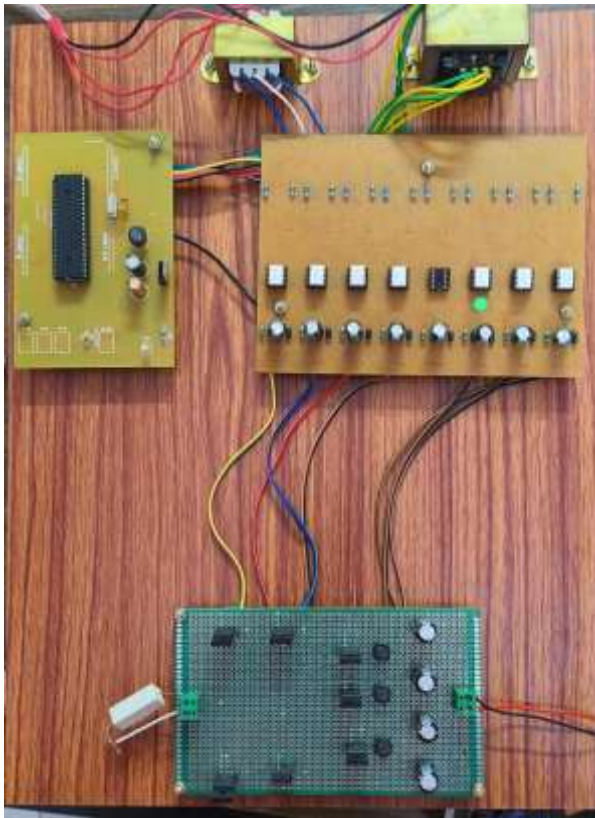


Fig-4: Working Model kit

The driver and power converter circuits are used to regulate and convert the electrical energy for efficient EV battery charging. The driver circuit amplifies the control signals from the microcontroller and sends them to the switching devices in the power converter stage. The power converter section contains components like MOSFETs, capacitors, and filtering elements that help in converting and stabilizing the output power. With the help of the ANFIS control technique, the system efficiently manages power flow and improves the overall performance of the EV charging process.

6. OUTPUT:

Charging Time – Existing System:

Charging Type	Power Rating	Battery Capacity (Typical EV: 40 kWh)	Charging Time
Level 1 (Slow Charging)	2–3 kW	40 kWh	12–18 hours
Level 2 (AC Charging)	7–22 kW	40 kWh	3–8 hours
DC Fast Charging	50–150 kW	40 kWh	40–90 minutes

Table 1: Charging Time – Existing System

Electric vehicles (EVs) can be charged using different charging methods, each varying in power level and charging time. The most basic method is Level 1 charging, which operates at a power range of 2–3 kW. It uses a standard household power outlet and is mainly suitable for overnight charging. For a typical EV battery capacity of 40 kWh, Level 1 charging requires approximately 12 to 18 hours to fully charge the battery.

The next level is Level 2 (AC) charging, which provides a higher power output ranging from 7 kW to 22 kW. This charging method is widely used in residential setups with dedicated chargers as well as in public charging stations. Compared to Level 1, it significantly reduces charging time. A 40 kWh battery can be charged within 3 to 8 hours depending on the charger rating and system efficiency.

The fastest method is DC fast charging, which operates at a high power range of 50 kW to 150 kW. This method is ideal for long-distance travel and commercial applications. Using DC fast charging, a 40 kWh battery can be charged in approximately 40 to 90 minutes.

Overall, the choice of charging method depends on factors such as time availability, infrastructure, and application requirements. While Level 1 is suitable for slow overnight charging, Level 2 offers a balance between speed and convenience, and DC fast charging

provides the quickest solution for urgent charging needs.

Charging Time – Proposed System:

Charging Mode	Effective Power Available	Battery Capacity (40 kWh EV)	Charging Time
PV Only (Daytime)	5–10 kW	40 kWh	4–8 hours
Wind Only	5–15 kW	40 kWh	3–7 hours
Hybrid (PV + Wind)	15–25 kW	40 kWh	1.5–3 hours
Hybrid + Battery + ANFIS Control	25–40 kW	40 kWh	1–2 hours
Hybrid + Grid Support (Fast)	40–60 kW	40 kWh	30–60 minutes

Table 2: Charging Time – Proposed System

The proposed EV charging system integrates renewable energy sources such as solar photovoltaic (PV) and wind energy to improve charging efficiency and reduce dependency on conventional grid power. In the PV-only mode, the system operates using solar energy during daytime, delivering an effective power of 5–10 kW. Under this condition, a typical 40 kWh EV battery can be charged in approximately 4 to 8 hours, depending on solar irradiance and system efficiency.

In the wind-only mode, the system utilizes wind energy with an effective power output ranging from 5 kW to 15 kW. Since wind availability can vary, the charging time for a 40 kWh battery is estimated between 3 to 7 hours. This mode is particularly useful in regions with consistent wind flow, including nighttime operation.

The hybrid mode (PV + wind) combines both solar and wind energy sources, increasing the available power to 15–25 kW. This significantly reduces the charging time to around 1.5 to 3 hours for a 40 kWh battery. The hybrid approach ensures better reliability and

continuous energy supply compared to single-source systems.

Further enhancement is achieved using hybrid energy with battery storage and ANFIS (Adaptive Neuro-Fuzzy Inference System) control. In this configuration, the effective power increases to 25–40 kW. The intelligent ANFIS controller optimizes energy management and power flow, resulting in faster and more efficient charging. Consequently, the charging time is reduced to approximately 1 to 2 hours.

Finally, the hybrid system with grid support (fast charging mode) provides the highest power range of 40–60 kW. By supplementing renewable sources with grid power, the system achieves rapid charging capability. In this mode, a 40 kWh EV battery can be charged within 30 to 60 minutes, making it suitable for fast-charging applications and commercial charging stations.

Overall, the proposed hybrid system demonstrates significant improvement in charging speed, efficiency, and reliability compared to conventional charging methods, while promoting the use of clean and sustainable energy sources.

7. FEATURE SCOPE OF THE PROJECT:

- Intelligent ANFIS-Based Control:**

Utilizes an Adaptive Neuro-Fuzzy Inference System (ANFIS) for smart energy management, ensuring optimal power flow between solar PV, battery storage, and the grid.

- High-Efficiency T-Type Converter:**

Implements a T-type inverter topology to reduce switching losses, improve conversion efficiency, and minimize total harmonic distortion (THD).

- Reliable Hybrid Energy Integration:**

Combines solar, battery, and grid power to provide uninterrupted EV charging under varying load and weather conditions.

- **Improved Power Quality and Stability:**

Maintains stable DC-link voltage, fast transient response, and near-unity power factor for enhanced system performance.

- **Scalable and Future-Ready Design:**

Suitable for smart EV charging stations, microgrids, and future expansion into fast charging, vehicle-to-grid (V2G), and IoT-based monitoring systems.

8. CONCLUSION:

The design and implementation of a Hybrid PV–Wind-Based Electric Vehicle Charging Station using an ANFIS Energy Management Controller present an efficient, reliable, and sustainable solution for modern EV charging needs. By combining solar and wind energy, the system significantly reduces the dependency on conventional grid power and ensures continuous energy availability even under fluctuating environmental conditions. The ANFIS-based controller plays a crucial role by intelligently managing power flow between multiple sources and the EV load, enabling optimal decision-making under uncertainty. Overall, the proposed system not only supports green mobility initiatives but also contributes to reducing carbon emissions, addressing energy challenges, and promoting sustainable transportation infrastructure.

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