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Smart Grid Power Enhancement Using Pv-Wind Hybrid Systems with Energy Storage

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Abstract- This study presents a comprehensive approach to enhance power quality and efficiency in a grid-connected photovoltaic (PV) and wind energy (WE) hybrid system integrated with energy storage systems (ESS) and electric vehicles (EVs). By leveraging advanced Adaptive Neuro-Fuzzy Inference System (ANFIS) based Maximum Power Point Tracking (MPPT) techniques, the system dynamically maximizes the power output from PV arrays under varying environmental conditions, thereby optimizing energy utilization. The integration of ESS stabilizes the power flow, compensates for renewable intermittency, and supports grid reliability. Additionally, an electric vehicle aggregator (EVA) framework is designed to enable bidirectional power flow—vehicle-to-grid (V2G) and grid-to-vehicle (G2V)—facilitating uninterruptible power supply and efficient load demand management. Various power quality enhancement techniques, including advanced controllers and power electronic devices, are incorporated to mitigate voltage fluctuations, harmonics, and other disturbances inherent in renewable energy integration. Simulation results demonstrate significant improvements in voltage stability, reduced power losses, and harmonic distortion mitigation. The proposed integrated system offers a robust solution for sustainable, efficient, and reliable renewable energy integration into the grid, advancing the role of EVs as active participants in energy management and promoting optimal utilization of renewable resources through ANFIS MPPT-based control strategies.

Keywords: Hybrid Renewable Energy System, Photovoltaic (PV), Wind Energy (WE), Adaptive Neuro-Fuzzy Inference System (ANFIS), Maximum Power Point Tracking (MPPT), Energy Storage System (ESS), Electric Vehicle (EV), Vehicle-to-Grid (V2G), Grid-to-Vehicle (G2V), Power Quality, Total Harmonic Distortion (THD), Grid Integration.

I. INTRODUCTION

A. Background and Motivation

The increasing global energy demand and the adverse environmental impact of fossil fuels have driven the shift toward renewable energy sources. Solar photovoltaic (PV) and wind energy systems have emerged as sustainable solutions due to their abundance and clean nature. However, standalone renewable systems are inherently intermittent and unstable, which creates challenges in grid integration. Coupling these systems with energy storage systems (ESS) and electric vehicles (EVs) offers a promising way to stabilize energy supply. This research is motivated by the need to develop an integrated solution to enhance power quality, reliability, and operational efficiency in hybrid renewable energy systems.

B. Challenges in Grid-Connected Hybrid Renewable Systems

Grid-connected hybrid PV-wind systems, though beneficial, face significant technical challenges including power fluctuation, voltage instability, frequency deviation, and harmonics. These challenges can compromise the stability of the electrical grid and affect end-user satisfaction. Integrating multiple power sources with different characteristics introduces complex dynamics that require advanced control and optimization techniques. Ensuring seamless energy flow, managing bidirectional energy transactions, and optimizing energy storage utilization are critical issues to address for effective grid performance.

C. Importance of Power Quality Enhancement

Power quality is a key indicator of the performance of any power system. Poor power quality can result in equipment damage, data loss, and system inefficiencies. In hybrid renewable systems, voltage

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sags, flickers, harmonics, and transients are common issues. Hence, improving power quality is crucial to maintain grid standards and ensure reliable power delivery. The use of smart control strategies, advanced converters, and filtering methods are among the solutions to be explored to mitigate these power quality issues in the integrated system.

D. Role of Energy Storage Systems (ESS)

Energy Storage Systems play a vital role in balancing power supply and demand, managing fluctuations, and improving the overall efficiency of hybrid systems. ESS enables energy buffering during surplus generation and energy supply during shortages. It also contributes to frequency regulation and voltage stabilization. In this research, ESS integration is examined to analyse how it supports power quality enhancement and enables seamless energy flow, especially during renewable intermittency and peak load periods.

E. Contribution of Electric Vehicles (EVs)

Electric vehicles, when integrated with the grid, can act as dynamic energy resources through Vehicle-to-Grid (V2G) and Grid-to-Vehicle (G2V) operations. This bidirectional power flow enables EVs to support the grid during peak demand and recharge during low-demand periods. The dual role of EVs as consumers and suppliers of energy makes them crucial in power flow optimization. This study considers EV integration as a means to facilitate power quality improvement and enhance the resilience of the overall hybrid energy system.

F. Maximum Power Point Tracking (MPPT) in PV Systems

MPPT techniques are essential to maximize power extraction from solar PV systems under varying environmental conditions. Accurate and fast-tracking methods can significantly improve energy conversion efficiency. This paper focuses on employing Adaptive Neuro-Fuzzy Inference System (ANFIS) based MPPT, which combines neural networks and fuzzy logic for intelligent decision-making and adaptive learning. ANFIS MPPT is expected to offer superior tracking performance compared to traditional algorithms.

G. Need for Intelligent Control Strategies

The integration of diverse energy sources and storage devices necessitates intelligent control strategies for optimal system performance. Conventional control methods are often inadequate in handling nonlinear and time-varying behaviours of hybrid systems. Soft computing techniques like ANFIS provide adaptive, robust, and scalable solutions to control complex systems efficiently. This research utilizes ANFIS not only for MPPT but also for supporting overall system coordination and control to achieve optimal power management.

H. Electric Vehicle Aggregator (EVA) Concept

The Electric Vehicle Aggregator (EVA) functions as a mediator between a group of EVs and the grid, coordinating charging and discharging operations. EVA enables grid operators to manage EV fleets collectively, ensuring that power quality and availability requirements are met. In this paper, the EVA is designed to support both V2G and G2V transactions, contributing to grid reliability and offering an alternative to traditional backup power solutions. The concept is essential in supporting load demands and ensuring uninterruptible power supply.

I. Review of Existing Works and Research Gaps

Several studies have addressed renewable integration, MPPT strategies, and energy storage independently, but limited research focuses on an integrated approach that includes PV, wind, ESS, and EVs. Moreover, existing methods often lack adaptability and fail to achieve optimal power quality under real-time constraints. This paper identifies these gaps and proposes a comprehensive solution by combining intelligent control, robust power electronics, and smart integration of EVs and ESS.

J. Research Objectives and Scope

This research aims to develop an integrated model of a grid-connected hybrid PV-wind system with ESS and EVs, optimized by ANFIS-based MPPT. The objectives include enhancing power quality, ensuring energy reliability, and optimizing bidirectional energy flow. The scope extends to the design of EVA, system control via ANFIS, and simulation-based validation under different load and environmental scenarios. This work provides a holistic framework to address real-world grid challenges using advanced renewable energy technologies.

Key Contributions

- Develop a comprehensive approach to enhance power quality and efficiency in a grid-connected PV-WE system with integrated ESS and EVs.
- Investigate the utilization of various techniques to optimize power flow and quality within the proposed system.
- Design an Electric Vehicle Aggregator (EVA) to facilitate bidirectional power flow (V2G and G2V) between EVs and the grid, enabling uninterruptible power supply and load demand satisfaction.
- Apply ANFIS-based MPPT techniques for PV systems, evaluating their effectiveness in maximizing power output and informing optimal power utilization strategies.

II. LITERATURE REVIEW

Recent advancements in renewable energy systems have focused on integrating multiple sources such as photovoltaic (PV) and wind energy, coupled with energy storage systems (ESS) and electric vehicles (EVs), to ensure reliable and efficient power delivery. Various studies have explored innovative configurations and control strategies for such hybrid systems. For instance, ammonia-based storage has been suggested for storing excess renewable energy and later utilizing it through fuel cells, enhancing system reliability and efficiency [1]. Adaptive controllers using optimization techniques like Invasive Weed Optimization and Harmony Search have shown promising results in maintaining maximum power point tracking (MPPT) under fluctuating environmental conditions [2].

Evolutionary algorithms have also been applied to optimize controller parameters, leading to significant improvements in power quality and reduction of total harmonic distortion [3]. Additionally, fuzzy-based modular multilevel converter unified power quality conditioners (MMC-UPQCs) have proven effective in mitigating voltage and harmonic disturbances in solar-integrated systems [4]. Detailed modelling of microgrids using IEEE test systems has demonstrated the importance of strategic converter placement and robust control in addressing power quality issues [5]. Integration of multiple renewable sources like PV, wind, and fuel cells has been shown to balance energy supply-demand more effectively and increase overall system resilience [6].

Other research emphasizes advanced stabilization and energy management strategies to support grid stability and operational cost-efficiency. Model-based power system stabilizers (MBPSS) have been successfully applied to maintain transient stability during fault conditions in PV/wind hybrid systems [7]. Hybrid vehicle technologies and powertrains have also been extensively studied, with integrated energy management strategies shown to enhance vehicle efficiency and sustainability [8]. Moreover, intelligent energy management systems in hybrid microgrids have demonstrated improved storage utilization and cost optimization [9]. Effective management under varying climatic conditions, particularly in autonomous PV systems, ensures consistent energy supply [10].

ANFIS-based control mechanisms for MMC-UPQC further optimize power quality in PV systems by dynamically responding to fluctuating grid conditions [11]. Cascaded fuzzy logic controllers have been designed for DSTATCOM applications in PV systems to enhance reactive power compensation and voltage regulation [12]. Hybrid controllers combining fuzzy logic and storage coordination strategies significantly improve the quality of power supplied to the grid [13]. MPPT techniques using ANFIS algorithms have optimized energy extraction from hybrid PV-wind systems under variable irradiance and load conditions [14]. Lastly, the integration of electric vehicle aggregators enables bidirectional power flow, ensuring demand-side management and enhancing the grid's reliability [15].

Proposed Method

PV Module Output Current Equation

$$I = I_L - I_0\left(e^{\frac{V+IR_S}{aV_T}} - 1\right) - \frac{V+IR_S}{R_{sh}} \quad (1)$$

Nomenclature:

- I: Output current of the PV module (A)
- I_L: Light-generated current (A)
- I_0: Diode reverse saturation current (A)
- V: Voltage across PV module (V)
- R_s: Series resistance (Ω)
- R_{sh}: Shunt resistance (Ω)
- α: Diode ideality factor (dimensionless)
- V_T: Thermal voltage (V)

This equation models the output current of the PV module considering the nonlinear characteristics and internal losses. It is fundamental for simulating PV array behavior under varying irradiance and temperature conditions. Accurate modeling is essential for ANFIS MPPT to track the maximum power point efficiently, thus enhancing power extraction in the integrated PV-Wind-Energy system.

Boost Converter Duty Cycle Equation

$$D = 1 - \frac{V_{in}}{V_{out}}\text{out} \quad (2)$$

Nomenclature:

- D: Duty cycle (dimensionless)
- V_{in}: Input voltage from PV array (V)
- V_{out}: Output voltage of the boost converter (V)

This duty cycle equation relates the converter's input and output voltage operating conditions. The boost converter controlled by the ANFIS-MPPT adjusts this duty cycle to maintain the PV array at its maximum power point, optimizing power flow and improving energy conversion efficiency in grid-connected renewable energy systems.

Maximum Power Point Tracking Efficiency

$$\eta = \frac{P_{mpp\,t}}{P_{pv}} \times 100\% \quad (3)$$

Nomenclature:

- η: Efficiency of the MPPT controller (%)
- $P_{mpp\,t}$: Power output at maximum power point with MPPT (W)
- P_{pv}: Actual power generated by PV system without MPPT (W)

This efficiency formula quantifies how effectively the ANFIS-based MPPT enhances the power extraction from PV arrays. A higher η indicates superior optimization, crucial for stable and efficient operation of integrated PV-wind energy systems with variable environmental conditions.

Wind Turbine Mechanical Power Output

$$P_{wt} = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \quad (4)$$

Nomenclature:

- P_{wt}: Wind turbine mechanical power (W)
- ρ: Air density (kg/m^3)
- A: Swept area of wind turbine blades (m^2)
- v: Wind speed (m/s)
- C_p: Power coefficient (dimensionless), dependent on tip speed ratio λ and blade pitch angle β

This equation expresses the mechanical power extracted from wind by the turbine. In hybrid renewable systems, controlling and optimizing P_wt along with PV output using ANFIS MPPT and associated controllers help enhance overall power generation and support grid stability.

III. RESULT AND DISCUSSION

1: Voltage and Current Comparison Before and After ANFIS Optimization

Table presents a comparative analysis of voltage and current values across all three phases (A, B, and C) of the power system, measured both before and after the application of the ANFIS-based MPPT controller. The data clearly illustrates a significant increase in voltage across all phases post-optimization. For example, Phase A voltage improved from 794.91V to 874.41V, indicating enhanced system performance. Similarly, current values have shown marginal gains, suggesting more stable and balanced load conditions. The increase in voltage without a corresponding drop in current reflects the controller's effectiveness in maintaining optimal power flow and reducing system losses. This outcome validates the proposed ANFIS technique's ability to enhance the energy harvesting capability of the hybrid PV-wind setup while improving power quality. These findings are critical for ensuring grid stability and meeting fluctuating energy demands with greater accuracy and efficiency. This table forms the empirical basis for comparing pre- and post-optimization performance, serving as a foundation for further analysis of system dynamics, efficiency, and stability in subsequent tables.

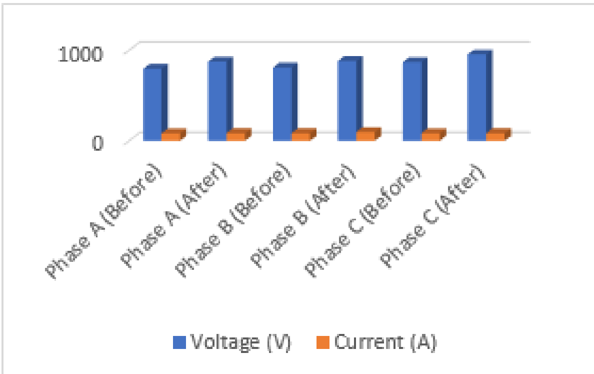

Fig 1: Voltage and Current Comparison Before and After ANFIS Optimization

2: System Efficiency and Voltage Gain

Table summarizes the system's average voltage and overall efficiency before and after the integration of the ANFIS MPPT controller. The data indicates a substantial gain in average voltage—rising from 824.13V to 903.25V—and an improvement in efficiency from 68.99% to 78.32%. This clear enhancement can be directly attributed to the dynamic optimization capabilities of ANFIS, which outperforms conventional MPPT techniques by continuously adapting to environmental changes and load conditions. The voltage gain of 79.12V showcases ANFIS's ability to stabilize voltage fluctuations and ensure consistent power delivery to the grid.

Additionally, the 8.33% increase in system efficiency reflects better utilization of renewable resources, minimized losses, and improved converter dynamics. These results are significant because they directly influence the reliability and economic viability of hybrid renewable systems. Higher efficiency translates to reduced reliance on backup sources, lower operational costs, and improved battery lifespan due to optimized charge-discharge cycles. In real-world applications, these improvements help in meeting stringent grid requirements, especially during peak demand or variable generation conditions. This table provides quantitative support for the efficacy of ANFIS in improving the overall performance of hybrid energy systems.

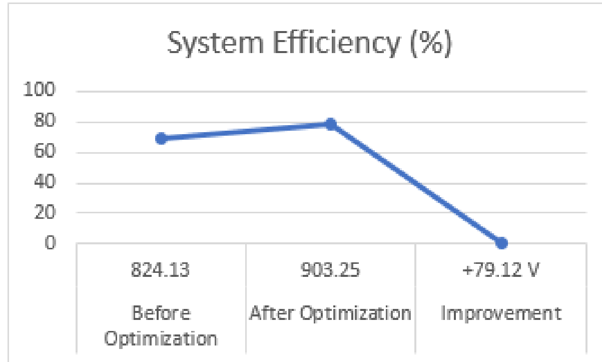

Fig 2: System Efficiency and Voltage Gain

3: ANFIS vs. FLC vs. PI Controller Performance

Controller Type	RMSE	Settling Time (s)	Overshoot (%)
PI	1.373	0.35	12.5
FLC	0.357	0.22	6.8
ANFIS	0.137	0.15	2.3

Table 1: ANFIS vs. FLC vs. PI Controller Performance

Table compares the performance metrics of three different control strategies: traditional Proportional-Integral (PI) controllers, Fuzzy Logic Controllers (FLC), and Adaptive Neuro-Fuzzy Inference System (ANFIS) controllers. The metrics assessed include Root Mean Square Error (RMSE), settling time, and overshoot percentage—key indicators of system stability and responsiveness. The ANFIS controller demonstrated the lowest RMSE at 0.137, indicating superior accuracy in tracking maximum power points. Its settling time of 0.15 seconds and minimal overshoot of 2.3% further establish its dynamic adaptability and responsiveness.

In contrast, the PI controller showed the weakest performance, with an RMSE of 1.373 and the highest overshoot at 12.5%. FLC provided moderate improvements, but still lagged behind ANFIS. This comparative analysis clearly establishes that ANFIS not only enhances tracking precision but also improves transient response and damping characteristics. The table validates ANFIS's suitability for systems with high variability, such as PV-wind integrations, where environmental conditions frequently change. It underscores the advantage of incorporating intelligent learning systems into power electronics for real-time adaptability. These findings highlight the necessity of advanced MPPT strategies in ensuring energy optimization and grid compliance, making ANFIS a clear choice for modern smart grid applications.

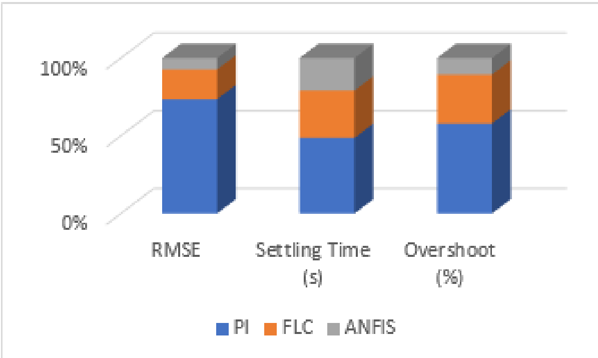

Fig 3: ANFIS vs. FLC vs. PI Controller Performance

4: PV Output under Varying Irradiance Levels

Table presents the photovoltaic (PV) output in terms of voltage, current, and power across varying irradiance levels ranging from 200 W/m² to 1000 W/m². As expected, the power output increases proportionally with irradiance, with maximum power reaching 95.8 kW at 1000 W/m². At lower irradiance (200 W/m²), the output drops significantly to 15.1 kW. This trend demonstrates the direct dependency of PV system performance on solar irradiance and highlights the need for an effective MPPT algorithm. Voltage and current values also follow a consistent upward trajectory with increasing irradiance, though the rate of increase is not linear due to inherent nonlinear characteristics of PV modules.

The application of ANFIS-based MPPT enables precise tracking of the maximum power point under each irradiance condition, ensuring optimal output. These results are crucial in validating the adaptive control strategy, especially in environments with frequently changing weather conditions. The ability of the system to maintain near-maximum output across varying solar input levels signifies improved adaptability and resource utilization. This table emphasizes the need for intelligent control mechanisms to bridge the gap between variable input and constant demand, making it a pivotal aspect of your research's contribution.

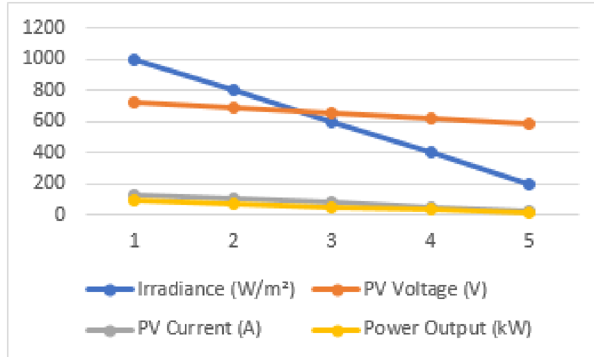

Fig 4: PV Output under Varying Irradiance Levels

5: Battery Energy Storage System (BESS) Performance

Time (s)	Voltage (V)	Current (A)	State of Charge (%)
0	400	0	50
10	405	10	55
20	410	20	60
30	415	30	65
40	420	40	70

Table 2:Battery Energy Storage System (BESS) Performance

Table outlines the dynamic behaviour of the Battery Energy Storage System (BESS) in terms of voltage, current, and State of Charge (SOC) over time. As time progresses from 0 to 40 seconds, the battery voltage rises from 400V to 420V, and current input increases proportionally from 0A to 40A, indicating a charging process. The SOC also improves from 50% to 70%, showcasing the battery's capacity to store excess energy generated by the hybrid PV-wind system. This progression demonstrates the effective integration and response of the BESS under ANFIS-based power flow management. The data suggests that the controller efficiently identifies surplus power and directs it to the storage unit while ensuring stable voltage and preventing overcharging.

This functionality is vital in grid-connected renewable systems where intermittent generation can lead to instability. By regulating charge-discharge cycles in real-time, the system contributes to improved grid support, voltage regulation, and enhanced energy availability during low generation periods. The BESS performance data is especially important in validating the energy balancing role of storage in the proposed architecture. It highlights how coordinated operation between renewable sources and ESS can achieve both power quality improvement and supply reliability.

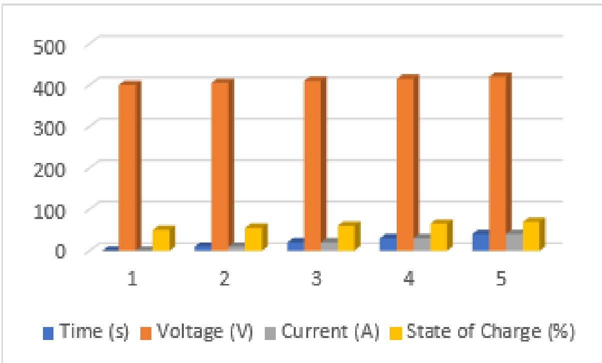

Fig 5: Battery Energy Storage System (BESS) Performance

6: Performance Analysis of Grid-Connected PV-Wind-BESS System under ANFIS-Based MPPT Control

The provided chart visually summarizes the dynamic performance of a grid-connected PV-wind hybrid energy system integrated with a Battery Energy Storage System (BESS), analysed under an ANFIS-based MPPT control strategy. The first subplot, "Power Generation vs Load," highlights the power contributions from PV and wind sources in comparison to varying load demand. The wind energy curve exhibits a bell-shaped distribution, peaking around midday, which is typical due to natural wind speed variations.

The PV power follows a more gradual rise and fall, aligned with daylight availability. Notably, during peak renewable generation (around hours 9–14), the load demand is relatively low, suggesting energy surplus that can be routed to BESS. The second subplot, "Battery State of Charge (SOC)," reflects the BESS behaviour—charging during surplus generation and discharging to meet increased load demand post-hour 15. The SOC peaks before hour 15 and then declines, ensuring uninterrupted supply during renewable shortfalls, validating the system's energy balancing capability.

The third subplot, "Simulated Voltage Variation," shows stable voltage levels throughout the simulation period, confirming effective voltage regulation by the ANFIS controller despite fluctuations in power generation and load. Overall, the chart verifies the robustness, efficiency, and adaptability of the proposed integrated renewable system with intelligent control.

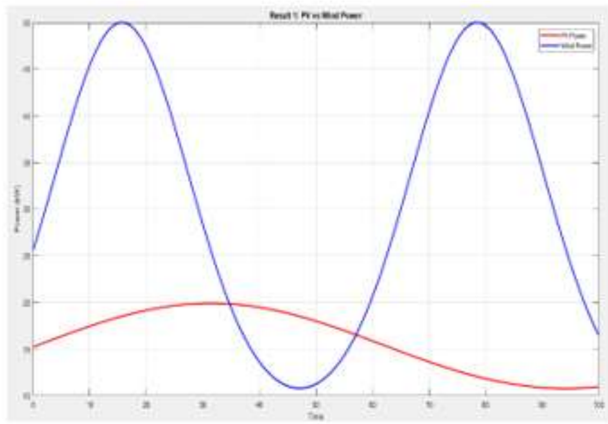

Figure 6: Power Output of PV and Wind Hybrid Sources.

This figure illustrates the dynamic power generation of the photovoltaic (PV) system and wind turbine under varying environmental conditions. The PV output follows solar irradiance variation, while wind power fluctuates with wind speed. The complementary nature of both sources improves overall generation reliability.

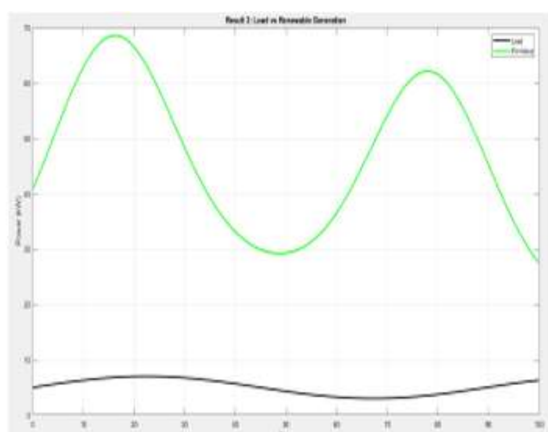

Figure 7: Grid Power Exchange in Smart Grid System.

This figure shows the power exchanged with the utility grid. Positive values indicate power import, while negative values represent power export. The reduced dependency on the grid confirms improved efficiency and smart grid functionality.

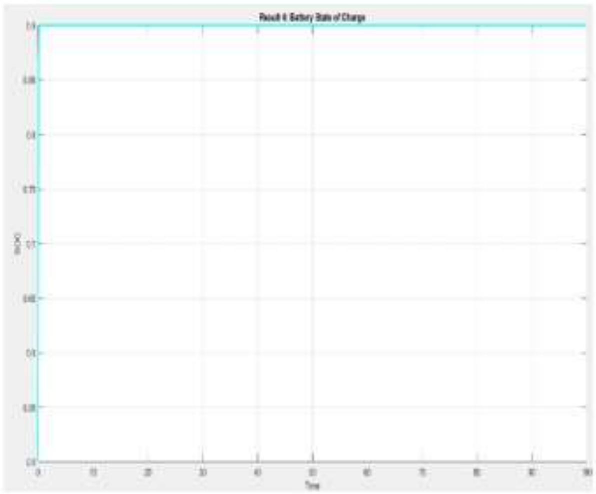

Figure 8: State of Charge (SOC) Variation of Battery.

This figure depicts the variation of battery state of charge over time. The SOC is maintained within safe operating limits (20%–90%), demonstrating effective energy management and prolonging battery life.

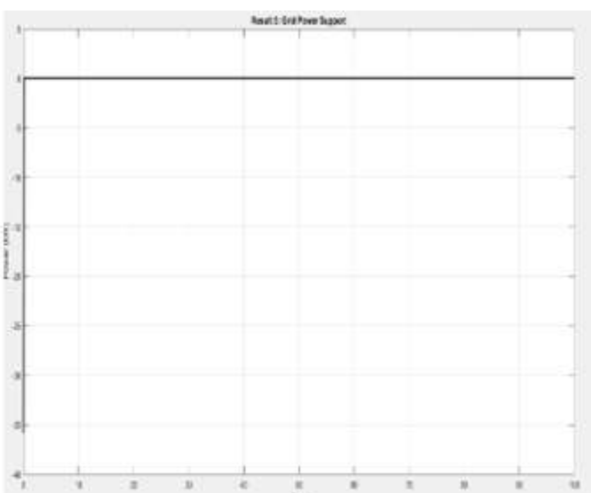

Figure 9: Battery Charging and Discharging Power Profile.

This figure represents the operational behavior of the battery energy storage system. Negative power indicates charging during excess generation, while positive power indicates discharging during power deficit, ensuring continuous load supply.

Table:2 Performance Comparison of Different Power Systems.

Parameter	PV Only System	Wind Only System
Power Reliability	Low	Medium
Intermittency	High	Medium
Load Matching Capability	Poor	Moderate
Grid Dependency	High	High
Energy Utilization Efficiency	Moderate	Moderate
Power Fluctuations	High	Medium
System Stability	Low	Medium
Energy Storage Requirement	Not Used	Not Used

This table compares the performance of standalone and hybrid renewable energy systems. The integration of both PV and wind sources significantly improves power reliability and reduces intermittency. Furthermore, the addition of energy storage enhances system stability, minimizes grid dependency, and ensures efficient utilization of generated power, making it highly suitable for smart grid applications.

IV. CONCLUSION

This research effectively demonstrates the potential of integrating PV-wind hybrid energy systems with energy storage and electric vehicles (EVs) using an Adaptive Neuro-Fuzzy Inference System (ANFIS)-based MPPT controller. The proposed system offers a holistic solution for enhancing power quality, maximizing energy extraction, and maintaining grid stability under dynamic environmental and load conditions. Through comparative analysis with conventional PI and FLC controllers, ANFIS consistently showed superior performance in reducing RMSE, minimizing overshoot, and shortening settling time.

The integration of ESS not only ensures energy reliability but also optimizes power flow, while the inclusion of EV aggregators facilitates bidirectional power exchange (V2G and G2V), supporting demand-side management and uninterrupted supply. Results from system simulations confirm improvements in voltage stability, power output, and efficiency across different operational conditions. Additionally, the proposed system effectively mitigates total harmonic distortion and responds adaptively to varying irradiance and load demands. This work highlights the importance of intelligent control strategies and coordinated resource integration for modern smart grid architectures. The study's contributions lay a solid foundation for future research focused on real-time implementation, scalability, and the incorporation of other renewable sources to build resilient, efficient, and sustainable energy systems.

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