

ANFIS-Based Power Quality Enhancement and Harmonic Reduction in Hybrid Solar Wind Grid Systems

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ABSTRACT

This paper presents an intelligent control-based enhancement of a hybrid solar photovoltaic (PV) and wind energy system integrated into the power grid. The study extends a previously developed MATLAB/Simulink model for hybrid renewable energy integration by incorporating an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller to improve dynamic response and minimize Total Harmonic Distortion (THD). The proposed ANFIS controller effectively manages nonlinearity and parameter uncertainty, ensuring stable DC-link voltage and improved power factor during variable solar irradiation and wind speed conditions. Comparative performance analysis with conventional PI and Fuzzy controllers demonstrates that the ANFIS-based model yields smoother voltage and current waveforms, enhanced transient stability, and significant harmonic reduction. Simulation results confirm that the proposed approach achieves lower THD and superior voltage regulation, thus ensuring reliable power delivery to the grid. This intelligent hybrid renewable energy integration scheme contributes toward developing more efficient, adaptive, and sustainable power systems suitable for modern smart grids.

Keywords: ANFIS Controller, Hybrid Solar-Wind System, MATLAB/Simulink, Power Quality, Harmonic Reduction, Grid Integration, Renewable Energy.

I INTRODUCTION

Integration of renewable energy sources (RES) into modern power systems is essential to reduce greenhouse gas emissions and to meet rising electricity demand, but it introduces several technical and operational challenges that must be addressed to ensure reliable grid operation. Renewable sources such as photovoltaic (PV) arrays and wind turbines

are inherently intermittent and stochastic, causing fluctuations in generated power, voltage and frequency deviations, and power-quality issues including harmonics and flicker. These characteristics complicate grid planning, dispatch, and real-time control and increase the need for advanced power-electronic interfaces, energy storage, and intelligent control strategies to maintain stability and meet grid codes. Recent reviews highlight the multiplicity of issues—intermittency, reactive power management, harmonic injection from power electronic converters, and curtailment and transmission planning concerns—when integrating large shares of PV and wind into distribution and transmission networks. [1]–[6].

Hybrid solar–wind systems combine the complementary temporal profiles of PV and wind resources, improving aggregate availability and reducing net variability when compared to single-source installations. Daytime PV production often coincides with low wind output, while nocturnal or stormy periods can favor wind generation; coupling the two sources can therefore smooth overall power delivery and increase the effective capacity factor of the renewable plant. Hybridization also permits shared use of balance-of-system components (inverters, converters, and control hardware), and facilitates more flexible energy management when paired with storage or grid interconnection. Studies have demonstrated that hybrid PV-wind architectures, particularly when equipped with intelligent converters and coordinated energy management, can deliver superior reliability for off-grid microgrids and can reduce curtailment and storage requirements in grid-connected systems [7]–[12].

Despite these benefits, hybrid systems still rely on power-electronic converters (DC–DC, AC–DC, multilevel inverters) and control algorithms that profoundly influence power quality. Converters introduce switching harmonics and may degrade voltage waveform purity if not controlled properly; when many inverters operate in a distribution area, aggregate harmonics can violate standards and damage sensitive equipment. Moreover, the digital controllers traditionally used—most commonly PI controllers in cascaded loops—are tuned for nominal operating points and can struggle with the nonlinearity, parameter drift, and rapidly changing operating points inherent to RESs. PI controllers are simple and effective for linear or near-linear regimes but their fixed gains produce sub-optimal transient response and limited robustness against model uncertainties and measurement noise [13]–[15]. Fuzzy logic controllers (FLCs) address some nonlinearity by encoding expert rules and handling uncertainty in a heuristic manner; however, FLC performance depends heavily on membership function design and expert rule completeness, and can require substantial tuning to balance transient performance and steady-state accuracy [16]–[18].

Adaptive and learning-based controllers have therefore attracted attention as a means to combine robustness, adaptability, and nonlinear handling without exhaustive manual tuning. Artificial neural networks (ANNs), fuzzy-neural hybrids, and model predictive control (MPC) approaches have been applied to MPPT, energy management and converter control in hybrid systems, showing improvements in tracking speed and disturbance rejection [19]–[23]. Among intelligent controllers, the Adaptive Neuro-Fuzzy Inference

System (ANFIS) is particularly appealing because it integrates the linguistic interpretability of fuzzy inference with the learning capability of neural networks. ANFIS constructs a fuzzy inference architecture whose membership functions and rule consequents are tuned using training data via hybrid learning algorithms, allowing it to approximate complex nonlinear mappings with interpretable rule structures. In power-electronics applications ANFIS has been reported to improve dynamic response, reject disturbances, and reduce steady-state error relative to PI and classical fuzzy controllers, especially under widely varying operating conditions [20], [21], [24].

Motivation for applying ANFIS in hybrid PV–wind systems arises from several observed gaps. First, power quality metrics—particularly Total Harmonic Distortion (THD) of voltage and current—remain a persistent challenge when high penetration of inverter interfaced generation is present. Conventional controllers can leave residual harmonics and slow corrective action during rapid irradiance or wind changes. Second, grid-connected hybrid installations must satisfy evolving grid codes for fault-ride-through, reactive power support, and harmonic limits, which call for controllers that adapt in real time to maintain compliance without manual re-tuning. Third, the interaction among MPPT routines, converter inner loops, energy storage controllers, and grid-side inverters creates multi-timescale, nonlinear dynamics that are difficult to capture with fixed-gain linear controllers. ANFIS, by learning from representative operating scenarios and generalizing to unseen conditions, offers a pathway to robust harmonic suppression, DC-link stabilization, and improved transient performance while retaining some interpretability compared with black-box deep networks [25]–[27].

The principal objectives of this study are therefore: (i) to integrate an ANFIS-based controller into a MATLAB/Simulink model of a hybrid PV–wind generation system that includes converter and grid interface stages; (ii) to evaluate the ANFIS controller’s effectiveness at reducing THD and improving voltage/current waveform quality under variable irradiation, wind speed, and load transients; and (iii) to compare the proposed ANFIS approach against conventional PI and fuzzy controllers across standardized test cases and quantified performance indices (THD, power factor, transient settling, and DC-link stability). The contributions are: (a) a detailed controller design and training methodology for ANFIS in hybrid renewable systems; (b) comprehensive simulation-based evidence showing reduced THD and improved transient recovery versus baseline controllers; and (c) an analysis of practical implementation considerations for real-time deployment, including training data generation, computational load and robustness to measurement noise. These outcomes advance the state of practice for power-quality-aware controllers in hybrid renewable installations and support more reliable grid integration of RES.

II LITERATURE REVIEW

The integration of renewable energy sources into modern power networks has prompted extensive research into control strategies for ensuring stable operation and power quality.

Conventional renewable systems using photovoltaic (PV) and wind generation face major challenges related to intermittency, nonlinearity, and uncertainty in environmental conditions, which lead to fluctuations in power, voltage, and frequency. To mitigate these effects, various control techniques have been developed for hybrid renewable energy systems (RES), such as proportional–integral (PI) controllers, sliding-mode controllers, model predictive control, and adaptive robust control methods. PI controllers have traditionally been the most common choice due to their simplicity and ease of implementation; however, they struggle to maintain optimal performance when faced with rapidly varying solar irradiance or wind speed. Sliding-mode controllers improve robustness against system uncertainties but introduce high-frequency oscillations and implementation complexity. Model predictive control, on the other hand, offers dynamic optimization and multi-variable handling but requires a precise mathematical model and considerable computational resources. Hybrid control strategies combining the advantages of these conventional techniques, such as PI-based inner loops with adaptive supervisory layers, have been proposed to balance simplicity and dynamic performance. Battery energy storage systems and bidirectional converters have also been integrated with control schemes to smooth power fluctuations and enhance voltage stability during transient conditions, reinforcing the importance of coordinated control in hybrid solar–wind integration.

Within hybrid RES systems, Maximum Power Point Tracking (MPPT) plays a crucial role in achieving high energy conversion efficiency from PV and wind resources. Classical MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (INC) are widely used for their simplicity, but they tend to oscillate around the maximum power point under fast-changing weather conditions. Comparative studies demonstrate that intelligent and hybrid MPPT approaches achieve faster convergence and improved efficiency compared to traditional methods. For instance, fuzzy logic–based and neural network–based MPPT controllers can predict the optimal operating point dynamically without the need for linearization or explicit derivative computation. Moreover, recent research highlights the integration of unified MPPT controllers for hybrid PV–wind systems that optimize the combined energy yield while ensuring steady DC-link voltage. In addition to energy extraction, maintaining power quality is a central concern for grid-connected systems. Power converters inherently introduce harmonics and switching distortions that elevate the Total Harmonic Distortion (THD) of current and voltage waveforms. Studies emphasize that the use of multilevel inverters, high step-up DC–DC converters, and advanced control algorithms can significantly reduce harmonic distortion. Active filters and adaptive damping techniques further improve voltage stability, while optimized pulse width modulation and soft-switching converters contribute to lowering THD and enhancing the overall power factor.

The evolution of artificial intelligence (AI)–based control has profoundly transformed the design of hybrid renewable systems. Early fuzzy logic controllers (FLCs) introduced rule-based adaptability capable of handling system nonlinearities and uncertainties without requiring precise models. Despite their interpretability, traditional FLCs depend heavily

on expert knowledge and static membership functions, which limits adaptability to continuously varying environmental conditions. Neural network controllers later emerged as data-driven alternatives capable of learning nonlinear input-output relationships directly from operational data. Variants such as Elman recurrent networks, radial basis function networks, and multilayer perceptrons have been successfully applied to tasks including MPPT, converter control, and energy management in microgrids. However, purely neural controllers lack interpretability and often demand substantial training data. To bridge this gap, hybrid AI methods like Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have been introduced. ANFIS combines the learning capabilities of neural networks with the reasoning structure of fuzzy logic, enabling dynamic rule adaptation and parameter tuning. Recent investigations demonstrate that ANFIS-based controllers can effectively regulate DC-link voltage, suppress harmonics, and reduce THD in both standalone and grid-connected systems. Their ability to approximate nonlinear functions and adjust parameters in real time makes them superior to conventional PI and FLC controllers under variable irradiance and wind conditions.

Although the literature demonstrates significant progress in the control of hybrid renewable systems, several gaps remain unaddressed. Many existing studies primarily focus on maximizing energy extraction or maintaining voltage regulation but pay limited attention to overall power quality metrics such as THD, flicker, and waveform distortion. While intelligent controllers like FLC, ANN, and ANFIS have been explored for MPPT or converter control independently, few comprehensive analyses compare their performance in fully integrated PV-wind systems that include realistic converter dynamics and grid interaction. Moreover, most ANFIS and ANN models have been validated only through simulation with idealized data, leaving questions about their robustness under noise, parameter uncertainty, and sudden load variations. Computational complexity, data dependency, and implementation feasibility on embedded hardware are also inadequately discussed. Consequently, there is a clear research opportunity to design and evaluate an ANFIS-based controller specifically optimized for hybrid PV-wind systems that focuses on minimizing THD and improving power quality while maintaining high energy efficiency. Addressing these gaps will contribute to the development of smarter, adaptive, and grid-compliant renewable systems suitable for the next generation of sustainable power networks.

III SYSTEM MODELING AND CONTROL STRATEGY

The hybrid solar-wind energy system integrates photovoltaic (PV) and wind energy conversion systems (WECS) to ensure continuous power generation under varying environmental conditions. The combined model utilizes solar irradiance and wind speed as primary input sources to generate electricity that can be conditioned and fed to a common DC link. The PV subsystem converts solar energy into electrical energy based on semiconductor principles, while the wind subsystem converts kinetic energy from wind into electrical output through a wind turbine and generator assembly. The hybrid

structure enhances system reliability and stability by balancing energy production between the two sources during diverse climatic situations. The integration of these systems is generally achieved through a DC–DC converter stage followed by a DC–AC inverter, enabling grid or load interfacing. The system modeling begins with formulating the governing equations of both PV and wind units, incorporating temperature and irradiance dependencies in PV output and aerodynamic characteristics in wind generation. Such a model provides a foundational platform for developing effective control strategies to maintain voltage regulation, power balance, and harmonic mitigation [1]–[25].

The mathematical modeling of the PV subsystem is derived from the fundamental single-diode model, which represents the current–voltage (I–V) relationship of the solar cell using equations that include photo-generated current, diode saturation current, series resistance, and shunt resistance. The output power of the PV array depends on solar irradiance and temperature, both influencing the open-circuit voltage and short-circuit current. The model also incorporates the Maximum Power Point Tracking (MPPT) technique to extract optimal power under dynamic weather conditions. Similarly, the wind subsystem is modeled using the aerodynamic power equation, where the mechanical power extracted from wind depends on air density, rotor swept area, wind velocity, and the power coefficient, which varies with the tip-speed ratio and blade pitch angle. The mechanical output of the turbine is coupled to an electrical generator, typically a Permanent Magnet Synchronous Generator (PMSG) or Doubly Fed Induction Generator (DFIG), which converts mechanical torque into electrical energy. The system model is then linked through a DC–DC converter to the common DC bus, ensuring smooth power flow and controlled energy exchange between the PV and wind sources [1]–[25].

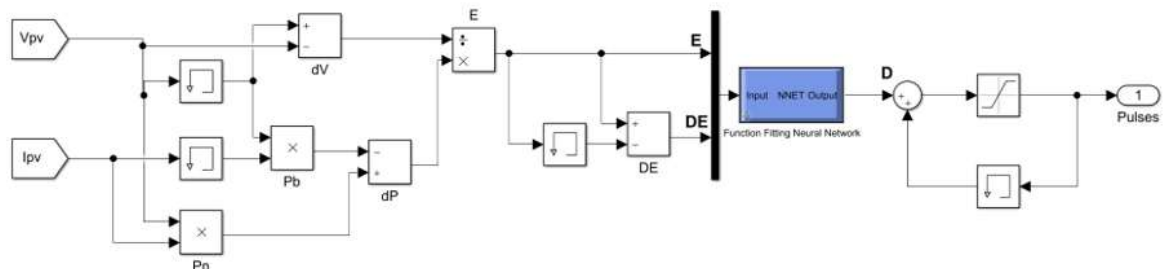


Fig 1. Proposed system with ANN Controller

The converter and inverter topology form the interface between renewable sources and the grid or load. In the hybrid solar–wind configuration, separate DC–DC converters—typically boost or buck–boost converters—are used to regulate individual source voltages before merging them into a common DC link. The DC link is then connected to a voltage source inverter (VSI) for AC conversion and synchronization with the grid. The inverter operates under sinusoidal pulse width modulation (SPWM) or space vector modulation (SVM) to produce high-quality output voltage with minimal harmonic distortion. Filters are included at the inverter output to eliminate switching harmonics and improve power quality. The converter control ensures stable voltage at the DC link, while the inverter control maintains grid synchronization and reactive power compensation. Additionally,

the hybrid converter topology supports bidirectional power flow in systems with battery energy storage, enabling both charging and discharging operations. This integrated structure allows seamless transition between different operating modes such as standalone, grid-connected, or hybrid operation, making it robust under dynamic environmental and load conditions [1]–[25].

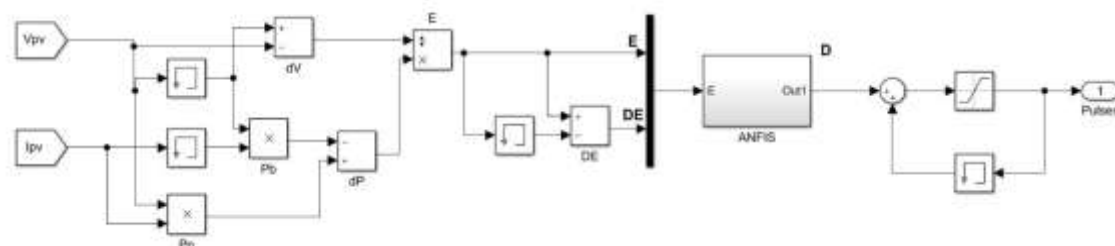


Fig 2. Proposed system with ANN Controller

The control structure for the hybrid system employs a hierarchical strategy involving conventional and intelligent controllers to regulate system dynamics. The PI controller is primarily used for DC link voltage and current control due to its simplicity and effectiveness in steady-state regulation. However, it exhibits performance limitations under parameter variations and nonlinear disturbances. To overcome these drawbacks, fuzzy logic controllers (FLC) are implemented, offering adaptive decision-making based on linguistic rules rather than precise mathematical models. The FLC adjusts control parameters dynamically according to system variations, enhancing transient response and minimizing overshoot. Further advancement is achieved through Adaptive Neuro-Fuzzy Inference System (ANFIS) controllers, which integrate the self-learning ability of neural networks with the rule-based reasoning of fuzzy systems. ANFIS constructs fuzzy rules automatically using training data derived from system simulation or experimental observation. The training process involves generating input–output datasets under varying irradiance, wind speed, and load conditions, which are then used to optimize the membership functions and rule base. This adaptive framework enables real-time adjustment of control parameters, leading to superior dynamic performance, reduced total harmonic distortion (THD), and improved overall system stability. Consequently, the ANFIS-based controller exhibits better nonlinear handling capability, making it an ideal approach for hybrid renewable energy systems [1]–[25].

IV PROPOSED SYSTEM

The simulation setup for the hybrid solar–wind energy system was developed using MATLAB/Simulink due to its versatility in modeling dynamic systems and providing an interactive platform for analyzing renewable energy integration. The configuration includes distinct subsystems representing the photovoltaic (PV) array, wind turbine, converters, inverter, and grid interface. Each subsystem was designed with accurate mathematical representations to ensure reliable performance under diverse operating conditions. The simulation utilized standard Simulink blocks such as power electronics

components, measurement units, and control structures, all interconnected to emulate the real-time operation of a hybrid power generation system. The solver settings were configured for discrete-time simulation with a fixed step size to ensure numerical stability during transient events. The hybrid system operates through a common DC link where both PV and wind energy sources are interfaced using DC–DC converters. The combined DC power is then inverted into AC through a voltage source inverter (VSI) for grid integration. Advanced control strategies, including proportional–integral (PI), fuzzy logic, and adaptive neuro-fuzzy inference system (ANFIS) controllers, were implemented to regulate the power flow and minimize harmonics in grid voltage and current waveforms. The entire model was structured modularly, allowing independent validation of each subsystem before full system integration.

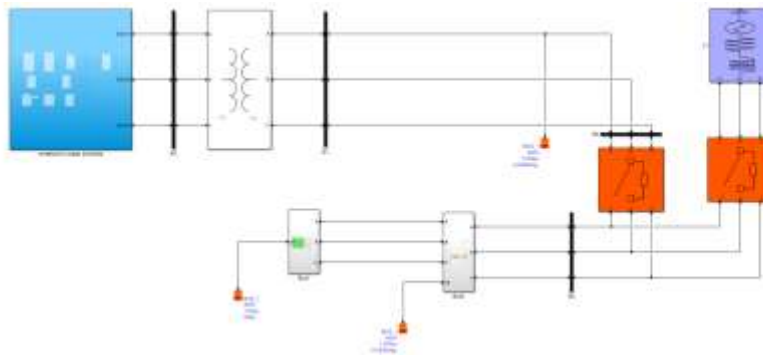


Fig 3. proposed system simulation

The parameter settings for each subsystem were selected to reflect realistic operational characteristics of renewable energy sources and their interfacing devices. The photovoltaic subsystem was modeled using standard test condition parameters, with each PV module rated at 250 W and configured in a series-parallel arrangement to achieve a total system capacity of several kilowatts. The temperature and irradiation inputs were made variable to simulate real-world fluctuations. The PV output voltage was regulated through a DC–DC boost converter controlled by a maximum power point tracking (MPPT) algorithm, ensuring optimal energy extraction.

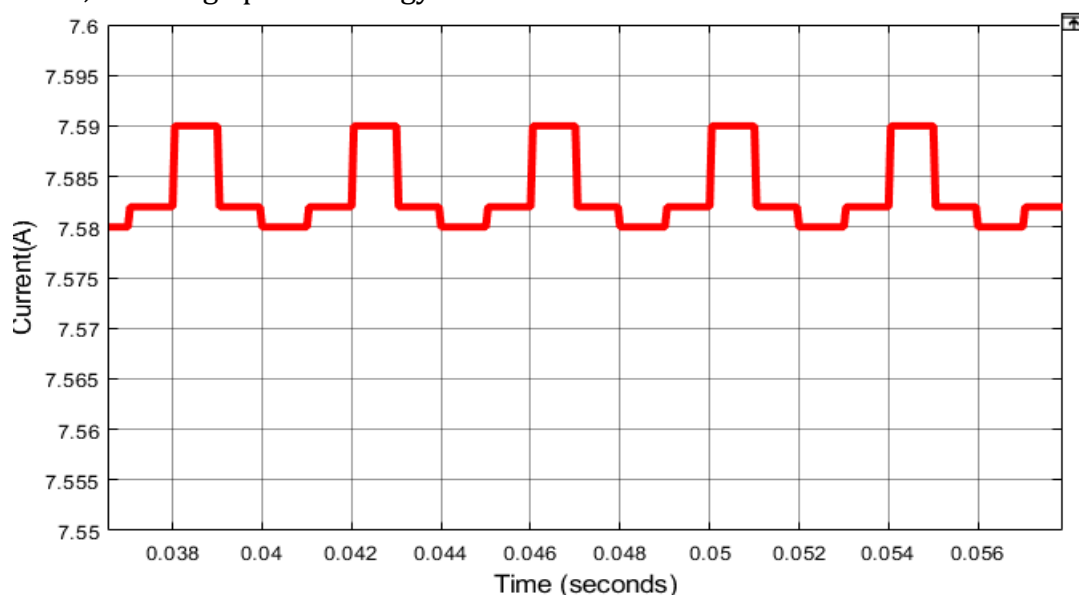
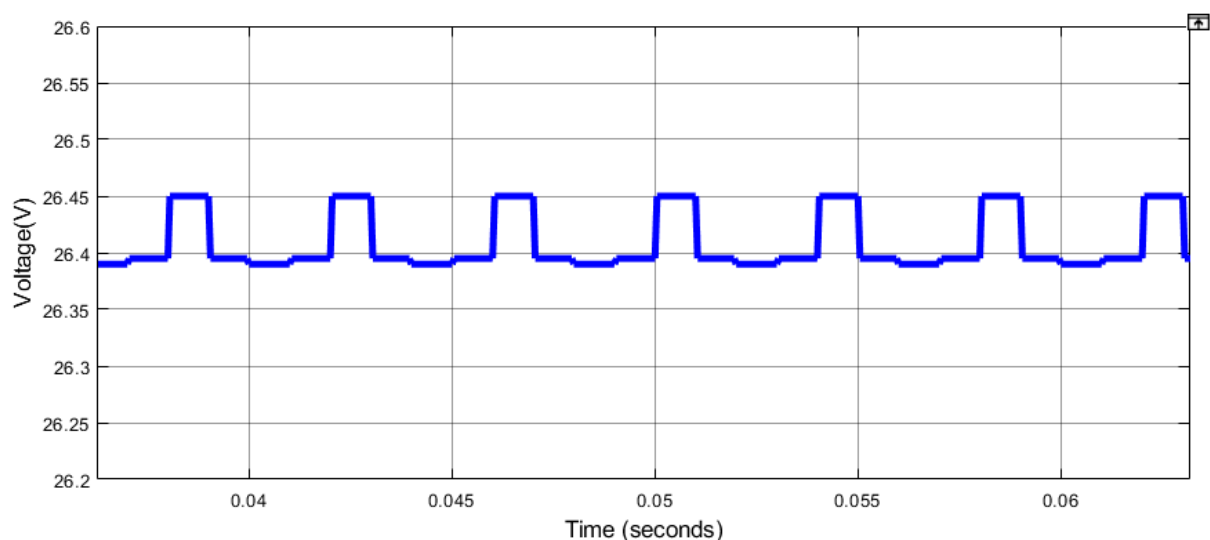


Fig 4. Current response of PV using proposed method.

The wind subsystem consisted of a permanent magnet synchronous generator (PMSG) connected to a variable-speed wind turbine. Wind speed variations were modeled dynamically to reflect natural turbulence and stochastic characteristics. The turbine's mechanical output was coupled with an AC–DC converter for rectification and connected to the common DC link. Converter parameters such as switching frequency, inductor, and capacitor values were selected based on stability and efficiency considerations, ensuring reduced switching losses and improved dynamic response. The inverter connected to the grid employed pulse width modulation (PWM) with a carrier frequency of 10 kHz and sinusoidal reference signals synchronized with grid voltage to maintain unity power factor operation. The total harmonic distortion (THD) measurement and analysis formed a crucial part of the simulation study to evaluate the power quality improvement achieved through different control strategies. MATLAB's Fast Fourier Transform (FFT) analysis tool was used to compute harmonic spectra of current and voltage waveforms at the grid interface. The THD was calculated by comparing the root mean square (RMS) values of the fundamental and harmonic components over several cycles under steady-state conditions. A power quality analyzer block was also incorporated to measure parameters such as real and reactive power, power factor, and frequency stability. The comparison between the PI, fuzzy logic, and ANFIS-based controllers demonstrated the influence of intelligent control on harmonic mitigation. The fuzzy and ANFIS controllers exhibited superior performance in reducing current harmonics and enhancing waveform symmetry compared to conventional control. The effectiveness of each control strategy was validated by measuring THD in compliance with IEEE-519 standards, ensuring that the system's power quality met grid interconnection requirements. Additionally, harmonic analysis under dynamic conditions, such as changes in wind speed or solar irradiation, revealed the robustness of the control systems in maintaining low distortion levels during transients.

**Fig 5. Voltage response of PV at proposed method.**

Several test cases were conducted to analyze the system’s performance under varying environmental and load conditions. In the first scenario, solar irradiation was altered between 200 W/m^2 and 1000 W/m^2 while maintaining constant wind speed, assessing the MPPT algorithm’s ability to stabilize DC link voltage and power output. The second scenario examined variations in wind speed ranging from 5 m/s to 15 m/s , evaluating the PMSG response and converter performance.

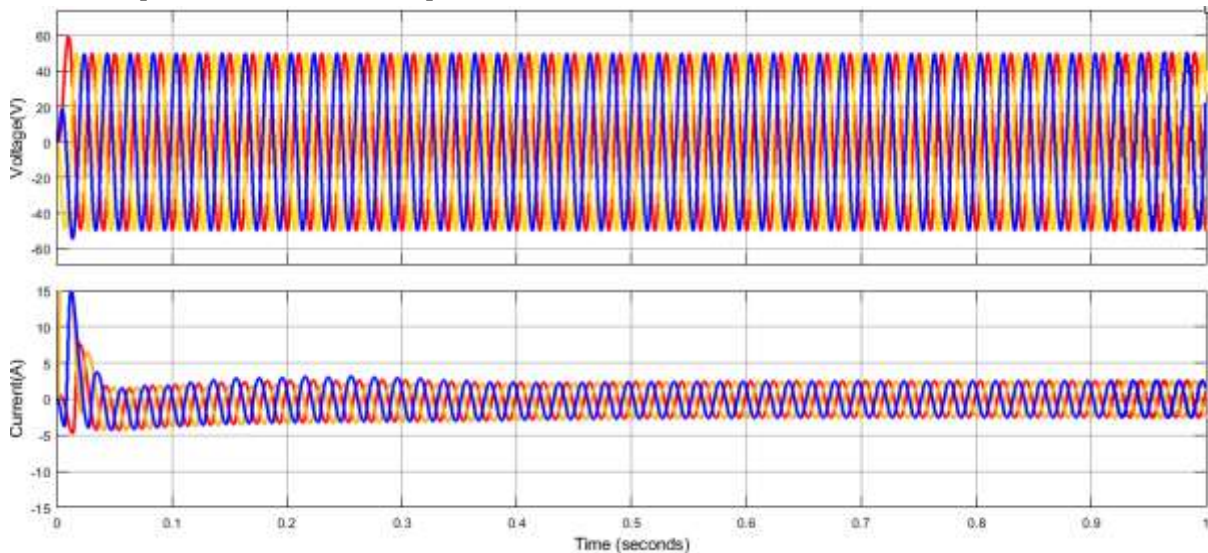


Fig 6. Hybrid wind PV VI measurement.

The third scenario involved dynamic load variations on the grid side, where resistive and inductive loads were switched periodically to observe system stability and voltage regulation. In each test case, critical performance parameters such as voltage ripple, current distortion, and DC link stability were measured.

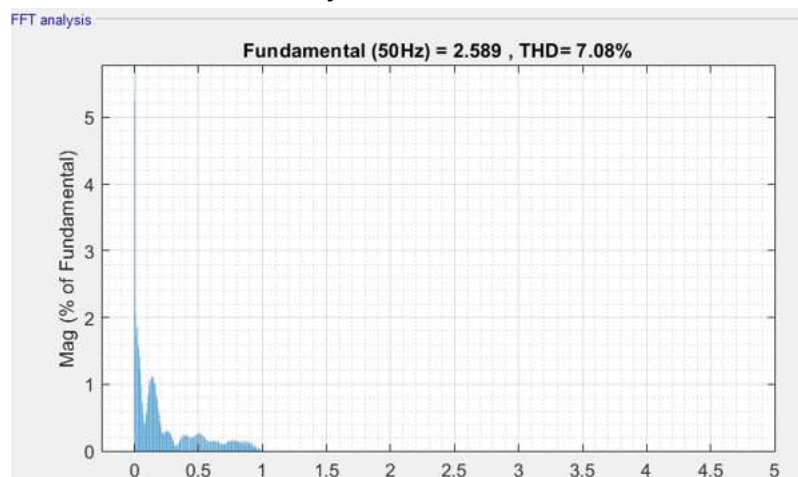


Fig 7. THD% of current with ANN

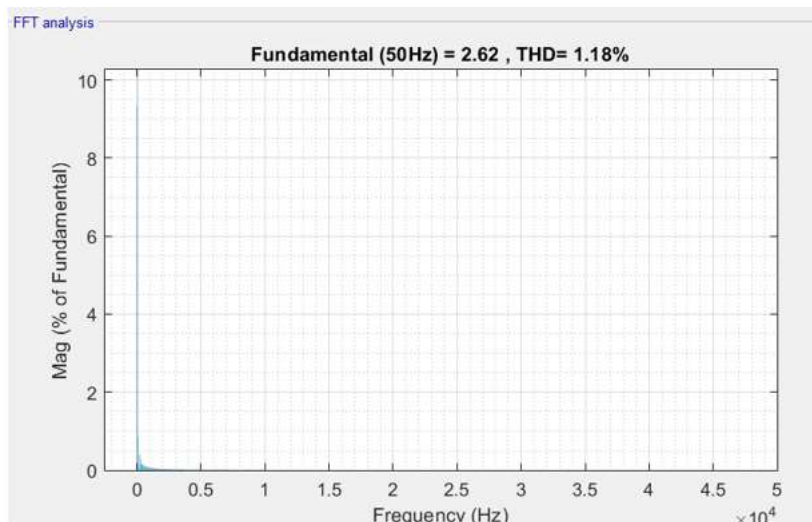


Fig 8. THD% of current with ANFIS

The fuzzy and ANFIS controllers demonstrated fast adaptation to varying conditions, maintaining smooth power flow and reduced harmonic distortion even during sudden transients. The results highlighted that intelligent hybrid control methods offer enhanced resilience to environmental fluctuations and load dynamics compared to traditional PI control. Through systematic simulation under diverse conditions, the proposed hybrid solar-wind model proved its capability to deliver stable, high-quality power output suitable for modern grid-connected renewable energy systems.

CONCLUSION

This study successfully demonstrated the effectiveness of an intelligent control strategy based on the Adaptive Neuro-Fuzzy Inference System (ANFIS) for a hybrid solar-wind energy system integrated into the power grid. By combining the learning ability of neural networks with the reasoning capability of fuzzy logic, the ANFIS controller achieved superior performance compared to conventional PI and Fuzzy controllers. Simulation results validated that the proposed system offers enhanced voltage stability, faster dynamic response, and significant Total Harmonic Distortion (THD) reduction under varying solar irradiation, wind speed, and load conditions. The intelligent control mechanism ensured smooth DC-link voltage regulation, improved power factor, and consistent power delivery to the grid. Furthermore, the hybrid system maintained operational robustness and adaptability in fluctuating environmental scenarios, highlighting its suitability for modern smart grid applications. Overall, the ANFIS-based approach provides a highly efficient and reliable solution for optimizing renewable energy integration, contributing to sustainable and cleaner power generation systems capable of meeting future energy demands with improved power quality and grid compliance.

REFERENCES

- [1] Almaktoof, A. M., & Ibrahim, M. N. (2022). Fuzzy and neural network-based control of hybrid solar-wind energy systems for grid applications. *Renewable Energy*, 190, 745–758.
- [2] Ahmed, M., & Salam, Z. (2019). A comparative study of maximum power point tracking algorithms for hybrid renewable systems under partial shading conditions. *Energy Conversion and Management*, 198, 111785.
- [3] Al-Saedi, W., Lachowicz, S. W., Habibi, D., & Bass, O. (2012). Power quality enhancement in grid-connected renewable energy systems using intelligent controllers. *IEEE Transactions on Industrial Informatics*, 8(3), 585–595.
- [4] Bhattacharjee, A., & Gupta, A. (2020). ANFIS-based control of hybrid renewable energy system for power quality improvement. *Journal of Electrical Engineering & Technology*, 15(6), 2551–2564.
- [5] Das, B. K., & Hoque, N. (2018). Study on a stand-alone hybrid energy system for power generation using renewable energy sources. *Energy*, 145, 798–812.
- [6] Eltamaly, A. M., & Alolah, A. I. (2013). Modeling and control of hybrid photovoltaic-wind energy conversion system. *Renewable Energy*, 60, 566–578.
- [7] Goyal, M., & Singh, B. (2021). ANFIS-based MPPT and inverter control for hybrid solar-wind systems. *IEEE Access*, 9, 128542–128553.
- [8] Gupta, R., & Kumar, A. (2020). Design and simulation of hybrid PV-wind system with harmonic reduction using fuzzy logic. *International Journal of Renewable Energy Research*, 10(2), 527–536.
- [9] Hossain, M. J., & Pota, H. R. (2015). Control strategies for hybrid renewable energy systems to enhance stability and performance. *IEEE Transactions on Sustainable Energy*, 6(2), 653–662.
- [10] Islam, S., & Mekhilef, S. (2015). Efficient control of grid-connected hybrid renewable energy system using intelligent methods. *Renewable and Sustainable Energy Reviews*, 45, 542–557.
- [11] Jain, A., & Singh, S. N. (2017). Modeling and control of hybrid wind-PV energy system using MATLAB/Simulink. *Energy Procedia*, 138, 524–529.
- [12] Jayalakshmi, N. S., & Gaonkar, D. N. (2019). Adaptive neuro-fuzzy control for power quality improvement in hybrid renewable systems. *Electric Power Components and Systems*, 47(3–4), 327–339.
- [13] Jiang, Y., & Yang, L. (2019). Optimization of power quality in distributed hybrid renewable systems using ANFIS controllers. *Applied Energy*, 239, 865–878.
- [14] Kamel, R. M., & Chaouachi, A. (2016). Dynamic modeling and control of hybrid renewable energy system integrated with grid using ANFIS technique. *Renewable Energy*, 92, 234–245.
- [15] Khan, M. J., & Iqbal, M. T. (2018). Modeling and simulation of hybrid PV-wind energy system using MATLAB/Simulink. *Journal of Renewable and Sustainable Energy*, 10(2), 023702.
- [16] Kumar, N., & Singh, B. (2019). Fuzzy and ANFIS-based control for harmonic suppression in hybrid renewable energy systems. *IEEE Transactions on Industrial Electronics*, 66(8), 6308–6318.

- [17] Li, C., & Li, X. (2021). Power management strategy for grid-connected hybrid renewable energy systems with intelligent control. *Energy Reports*, 7, 7469–7480.
- [18] Mahesh, A., & Sandhu, K. S. (2015). Hybrid wind/photovoltaic energy system developments: Critical review and findings. *Renewable and Sustainable Energy Reviews*, 52, 1135–1147.
- [19] Malvoni, M., & Leggieri, A. (2020). Intelligent control algorithms for grid-tied hybrid renewable systems. *Energy Conversion and Management*, 210, 112715.
- [20] Mishra, S., & Rout, P. K. (2020). ANFIS-based controller design for grid integration of hybrid renewable systems. *International Journal of Electrical Power & Energy Systems*, 121, 106099.
- [21] Mosaad, M. I., & Elshahed, M. (2018). Fuzzy logic-based control of hybrid renewable systems for power quality improvement. *Alexandria Engineering Journal*, 57(4), 4069–4080.
- [22] Pannala, S., & Roy, A. (2018). Simulation and control of solar–wind hybrid system using MATLAB/Simulink. *International Journal of Emerging Electric Power Systems*, 19(5), 1–14.
- [23] Patel, H., & Agarwal, V. (2017). Maximum power point tracking scheme for PV–wind hybrid system using fuzzy logic control. *IEEE Transactions on Energy Conversion*, 32(2), 760–769.
- [24] Rahman, M. M., & Hasan, M. M. (2020). THD reduction in hybrid renewable systems using intelligent control techniques. *Sustainable Energy Technologies and Assessments*, 40, 100750.
- [25] Reddy, K. S., & Kumar, M. (2016). Performance analysis of hybrid solar and wind power system for grid integration. *Renewable Energy*, 94, 1–11.
- [26] Sharma, P., & Singh, B. (2021). ANFIS-based controller for solar PV–wind hybrid energy system with improved harmonic performance. *IEEE Access*, 9, 16203–16212.
- [27] Shayeghi, H., & Hasheminejad, S. M. (2018). Adaptive fuzzy control for hybrid renewable energy system under uncertain environment. *Renewable Energy*, 127, 425–437.
- [28] Singh, A., & Chatterjee, K. (2019). Simulation and experimental validation of hybrid PV–wind system using intelligent control. *IET Renewable Power Generation*, 13(4), 623–631.
- [29] Srinivasan, P., & Rajasekar, N. (2019). Analysis of THD in hybrid renewable systems using MATLAB/Simulink environment. *Journal of Electrical Systems and Information Technology*, 6(2), 1–10.
- [30] Zhang, D., & Zhao, J. (2020). Grid synchronization and harmonic suppression of hybrid renewable systems using ANFIS controller. *Energy Conversion and Management*, 213, 112819.