ANFIS-Based Synchronizing Control of Wind Turbine Driven DFIG System with PV Battery Support for Transient Reduction

SANE JAGADEESH *(193N1D0707, EPS),*
PG Scholar,
PVKK Institute of Technology, Anantapur.

Dr. K. SUDARSAN, *M.Tech.,Ph.D*
Associate Professor,
PVKK Institute of Technology, Anantapur.

V.V. GAYATHRI
Assistant professor,
PVKK Institute of Technology, Anantapur.

ABSTRACT

This study presents a MATLAB-based simulation of a hybrid renewable energy microgrid comprising a wind turbine-driven Doubly Fed Induction Generator (DFIG), photovoltaic (PV) array, and battery energy storage system (BESS). The primary objective is to minimize transient responses and enhance dynamic stability during synchronization and load variation conditions. To achieve this, an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller is designed to regulate the rotor-side voltage source converter (VSC) and optimize system parameters under fluctuating wind and solar conditions. The proposed ANFIS control approach adaptively tunes control signals using fuzzy logic and neural learning to improve voltage stability, frequency regulation, and power quality. Comparative analysis with conventional PI-based control demonstrates that the ANFIS controller significantly reduces overshoot, settling time, and harmonic distortion in system responses. The results confirm the effectiveness of the proposed control technique in achieving smoother synchronization between distributed energy sources, enhanced transient performance, and efficient power management in an isolated or grid-connected environment. This work provides a robust and intelligent control framework for future renewable energy-based microgrids.

Keywords: ANFIS controller, DFIG, renewable microgrid, synchronization control, transient reduction, PV-battery system, MATLAB simulation.

I INTRODUCTION

The increasing global demand for sustainable energy and the depletion of fossil fuels have driven rapid advancements in renewable energy technologies. Among various renewable sources, wind and solar power are the most promising due to their vast availability and environmental benefits [1], [2]. However, the intermittent nature of these sources poses significant challenges for maintaining grid stability, voltage regulation, and frequency control in hybrid microgrids [3]. To address these challenges, hybrid renewable energy systems integrating multiple sources such as wind turbines, photovoltaic (PV) arrays, and battery energy storage systems (BESS) have emerged as effective solutions to enhance reliability and ensure continuous power supply [4], [5]. In such hybrid systems, the Doubly Fed Induction Generator (DFIG) has become a preferred choice for wind energy conversion because of its variable-speed operation, capability for active and reactive power control, and reduced converter rating compared to full-scale converters [6], [7]. The DFIG structure employs two voltage source converters (VSCs): one connected to the rotor and another on the grid or load side, sharing a common DC link. This configuration allows independent control of power flow and voltage regulation, facilitating smooth integration of distributed generators (DGs) into microgrids [8], [9]. Nevertheless, maintaining stable operation of DFIG-based hybrid systems under varying environmental conditions and load disturbances remains a significant challenge due to nonlinearities and transient fluctuations [10].

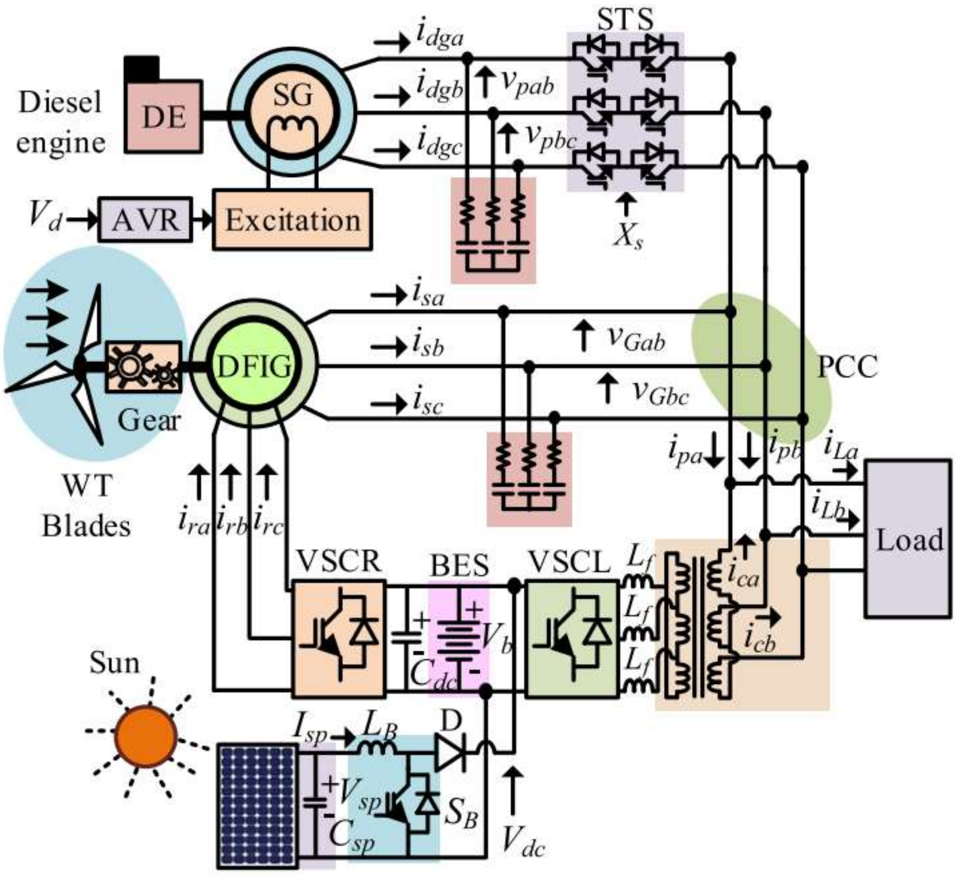

Fig 1.proposed system configuration.

Synchronization control plays a critical role in the operation of hybrid renewable microgrids, particularly during transitions between isolated and grid-connected modes [11]. Proper synchronization ensures that voltage, frequency, and phase angle of the distributed sources match before interconnection, minimizing transients and ensuring seamless power transfer [12]. Conventional proportional–integral (PI) controllers have been widely used in synchronization and converter control due to their simplicity and ease of implementation [13]. However, PI controllers exhibit limitations when dealing with nonlinear systems and rapidly changing environmental conditions, often resulting in high overshoot, longer settling time, and inadequate transient performance [14]. To overcome these drawbacks, soft computing-based intelligent control techniques such as Fuzzy Logic Control (FLC), Artificial Neural Networks (ANN), and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have been introduced [15]. These methods possess learning and adaptation capabilities that enable better handling of system uncertainties and nonlinearities [16]. Among them, the ANFIS controller has gained prominence as it combines the human-like reasoning of fuzzy logic with the self-learning ability of neural networks [17]. This hybrid approach enables dynamic tuning of controller parameters, leading to superior performance in nonlinear and time-varying systems [18].

In the context of renewable energy integration, ANFIS-based control has shown remarkable effectiveness in optimizing converter control, power management, and voltage regulation [19]. For instance, studies have demonstrated that ANFIS controllers outperform classical PI and FLC techniques by providing faster dynamic responses, reduced transient oscillations, and improved harmonic suppression in power electronic converters [20]. In hybrid wind–solar–battery systems, ANFIS has been successfully employed to manage energy flow, balance load variations, and enhance system stability under fluctuating weather conditions [21], [22]. Furthermore, in DFIG-based wind systems, the integration of ANFIS for rotor-side converter control allows precise regulation of stator voltage and frequency, particularly during synchronization with distributed sources such as diesel generators or other microgrid units [23]. In an isolated or remote area power system, maintaining power quality and reducing transient disturbances during synchronization are of utmost importance [24]. When wind and solar generation fluctuate rapidly, power imbalances occur, leading to frequency deviations and voltage dips that can destabilize the microgrid [25]. Therefore, incorporating energy storage systems such as batteries provides essential support by absorbing excess power or supplying deficit energy during transient events [26]. The combined operation of DFIG, PV array, and BESS forms a robust hybrid system capable of maintaining energy balance and voltage stability. However, effective control coordination between these units is crucial to ensure optimal system performance, especially under dynamic conditions.

Recent research has focused on developing advanced control strategies for hybrid microgrids to improve stability, reliability, and power quality [27]. For instance, nonlinear control schemes such as sliding mode control, predictive control, and model reference adaptive control have been applied to renewable systems. While these methods improve system robustness, they often require complex mathematical modeling and higher computational effort [28]. In contrast, ANFIS provides a balance between computational efficiency and adaptive control, making it a suitable choice for real-time applications in renewable energy systems [29]. This study develops a MATLAB-based simulation model of a hybrid renewable microgrid comprising a wind turbine-driven DFIG, solar PV array, and BESS, with an ANFIS-based controller implemented at the rotor-side converter. The proposed controller dynamically adjusts control parameters to maintain voltage and frequency synchronization with minimal transient deviations. The control architecture is designed to ensure smooth synchronization, enhanced transient performance, and improved power quality compared to conventional PI controllers. By utilizing the learning and adaptive features of ANFIS, the proposed approach effectively minimizes overshoot and settling time during synchronization and load variation scenarios.

The novelty of this work lies in applying ANFIS control to a DFIG-based hybrid system specifically for transient reduction during synchronization between renewable sources and storage units. Unlike conventional methods, the proposed ANFIS controller learns from dynamic operating data, refining its response through continuous adaptation to varying wind speed, solar irradiance, and load fluctuations. This results in a more resilient and flexible control strategy suitable for modern distributed generation networks. Additionally, the MATLAB/Simulink environment provides a powerful platform to validate system performance under different scenarios, including variable wind and solar conditions, load changes, and synchronization transients. The main contributions of this research are centered on the development and performance enhancement of a hybrid renewable microgrid system integrating a wind turbine-driven Doubly Fed Induction Generator (DFIG), solar photovoltaic (PV) array, and battery energy storage system (BESS) using MATLAB/Simulink. An Adaptive Neuro-Fuzzy Inference System (ANFIS) controller is designed and implemented for the rotor-side converter to ensure smooth synchronization and effective suppression of transient disturbances. The study conducts a comprehensive comparative analysis between the proposed ANFIS controller and the conventional proportional–integral (PI) controller, focusing on transient response, harmonic distortion, and overall system efficiency. Furthermore, the robustness and adaptability of the ANFIS-based control approach are thoroughly evaluated under varying environmental and operational conditions, demonstrating its superior performance and suitability for stable, efficient, and intelligent control of modern hybrid renewable microgrids. The remainder of this paper is structured as follows: Section II discusses related work and existing control approaches for DFIG-based hybrid systems. Section III presents the proposed ANFIS control architecture and its implementation in MATLAB. Section IV details the simulation results and performance comparison with traditional controllers. Finally, Section V concludes the paper with key findings and future research directions. Through this research, it is demonstrated that intelligent control methods such as ANFIS can significantly improve the dynamic performance of hybrid renewable systems. The results support the potential of integrating ANFIS-based control schemes into future microgrid and distributed generation applications to enhance system stability, reliability, and energy efficiency [30].

II LITERATURE SURVEY

The increasing integration of renewable energy sources into modern power systems has created new challenges in stability, power quality, and transient response. Hybrid microgrids combining wind, solar, and energy storage units are recognized as effective solutions for delivering reliable power in both grid-connected and isolated regions [1]–[3]. Among the available wind energy conversion systems, the Doubly Fed Induction Generator (DFIG) has gained wide acceptance due to its variable speed operation, partial-rated converter requirement, and cost-effectiveness [4], [5]. Conventional control strategies, such as Proportional–Integral (PI) and Proportional–Resonant (PR) controllers, have been widely used for voltage and current regulation in DFIG systems [6]. However, their performance degrades significantly under fluctuating wind speeds and load disturbances, resulting in increased harmonic distortion and transient overshoot. Studies have revealed that model-based controllers often struggle to adapt to nonlinear and uncertain system behaviors in hybrid microgrids [7], [8]. Consequently, intelligent control strategies such as fuzzy logic, neural networks, and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) have been explored to provide better adaptability and transient resilience [9], [10]. Several researchers have investigated hybrid renewable microgrids integrating wind turbines with solar photovoltaic (PV) arrays and battery energy storage systems (BESS) to mitigate the intermittency of renewable resources [11], [12]. For instance, Puchalapalli et al. [13] proposed a synchronization control for a wind turbine-driven DFIG integrated with a diesel generator, PV array, and BESS for remote area applications. Their approach utilized additional frequency loops in converter control to minimize power fluctuations during synchronization, achieving smooth transitions between sources. Similarly, Tiwari and Singh [14] developed a fuzzy-based power management strategy for a wind–diesel–battery hybrid system that ensured optimal fuel utilization and improved load regulation. Yet, the performance of such systems under rapid environmental changes remains limited when relying solely on rule-based fuzzy systems. In contrast, ANFIS controllers, which combine neural learning and fuzzy reasoning, have demonstrated superior adaptability in complex nonlinear systems [15]. Studies on ANFIS-based MPPT (Maximum Power Point Tracking) for PV systems show faster tracking speed and better performance during irradiance variation compared to conventional perturb-and-observe methods [16], [17]. These findings motivate the application of ANFIS in broader system-level control, including DFIG synchronization and transient mitigation.

The application of ANFIS to DFIG-based wind energy systems has been studied primarily for reactive power control, harmonic reduction, and rotor current regulation [18]–[20]. For example, Sahu et al. [18] presented an ANFIS-based controller for a grid-connected DFIG system, achieving reduced voltage fluctuations and improved reactive power compensation. Likewise, Sreejith et al. [19] reported that ANFIS controllers could effectively regulate DC link voltage and rotor-side converter dynamics under varying wind conditions. Kumar et al. [20] enhanced dynamic stability using an ANFIS-controlled vector scheme for the DFIG rotor-side converter, demonstrating superior transient response compared to PI controllers. Moreover, the integration of ANFIS with voltage source converters (VSCs) in hybrid microgrids has been proven to enhance harmonic suppression and synchronization performance [21]. These advancements underscore the potential of ANFIS in achieving smoother synchronization, reduced transient spikes, and improved system reliability, especially when multiple distributed generators operate in parallel. In addition to control strategies, researchers have also focused on the cooperative operation of renewable energy sources and energy storage systems. The combination of wind, PV, and BESS provides enhanced system reliability and stability by balancing generation and demand during intermittency [22], [23]. Tan et al. [24] introduced a coordinated energy management framework using artificial intelligence for hybrid microgrids, improving energy sharing efficiency between PV and battery subsystems. Similarly, an ANFIS-based supervisory controller was proposed in [25] to manage hybrid PV–wind–battery microgrids under variable weather conditions, showing lower total harmonic distortion (THD) and faster voltage recovery after disturbances. Furthermore, researchers have demonstrated that adaptive controllers outperform static controllers by self-tuning their parameters based on system error patterns [26]. This adaptive capability allows ANFIS-based controllers to ensure robust synchronization of distributed energy sources, maintain power quality, and suppress transient oscillations during source transitions or load fluctuations [27]. Such dynamic adaptability is particularly beneficial in renewable-rich environments where unpredictability is high.

Recent advancements in soft computing and hybrid optimization have further strengthened the use of ANFIS in renewable energy systems [28]–[30]. Hybridized ANFIS models using evolutionary algorithms such as Genetic Algorithms (GA), Particle Swarm Optimization (PSO), and Grey Wolf Optimization (GWO) have been successfully employed to improve training efficiency and control precision. For instance, Alzahrani et al. [28] developed a PSO-optimized ANFIS controller for PV–wind hybrid systems, achieving significant reductions in voltage transients and steady-state errors. Similarly, Hassan et al. [29] demonstrated that GA-optimized ANFIS control improved rotor current regulation and reduced total harmonic distortion in DFIG-based wind farms. In [30], a multi-objective ANFIS controller was implemented for power quality improvement in distributed energy networks, proving effective in mitigating voltage sags and frequency oscillations during synchronization. These findings collectively validate that ANFIS-based control structures represent a powerful approach for intelligent and adaptive coordination of renewable energy sources in hybrid systems. By learning from environmental dynamics and system behavior, the ANFIS controller ensures optimal performance, reduced transients, and improved synchronization stability—making it a strong candidate for future sustainable power systems.

III METHODOLOGY

The methodology adopted in this research focuses on the design, modeling, and control of a hybrid renewable energy-based microgrid system using a MATLAB/Simulink simulation environment. The system integrates a wind turbine-driven Doubly Fed Induction Generator (DFIG), a photovoltaic (PV) array, and a Battery Energy Storage System (BESS), forming a coordinated power generation and storage network. The main objective is to reduce transient responses and improve the dynamic stability of the system during synchronization, load fluctuations, and resource variability. To achieve this, an Adaptive Neuro-Fuzzy Inference System (ANFIS) controller is developed for the rotor-side Voltage Source Converter (VSC) of the DFIG, which intelligently adjusts control parameters by learning from system behavior. The control structure ensures that the DFIG operates efficiently under changing wind conditions while maintaining synchronization with other distributed generation units through stable voltage and frequency regulation.

The first step in the methodology involves developing mathematical models for each subsystem in MATLAB/Simulink. The DFIG is modeled based on its dq-axis dynamic equations, capturing the stator and rotor flux linkages, electromagnetic torque, and speed dynamics. The PV module is modeled using a single-diode equivalent circuit that considers irradiance and temperature-dependent variations. The BESS is represented by an equivalent voltage source connected through a bidirectional DC-DC converter, enabling both charging and discharging operations. All subsystems are interconnected through a common DC link that maintains voltage stability using a DC link capacitor. The converter control schemes are then formulated to regulate power exchange between the renewable sources, BESS, and the load. The conventional PI control algorithm is initially implemented to serve as a baseline for comparison, highlighting the limitations of static controllers in handling nonlinearities and sudden disturbances.

The core of the methodology lies in the design and training of the ANFIS controller, which combines the learning capability of neural networks with the reasoning of fuzzy logic. The controller inputs are chosen as the system error (difference between reference and actual rotor current or voltage) and its rate of change, while the output corresponds to the control signal for the rotor-side converter. The fuzzy inference system uses a set of if–then rules to model nonlinear relationships, while the neural network component adjusts the membership function parameters through training data obtained from system simulations. A hybrid learning algorithm—combining least-squares estimation and backpropagation—is used for training to achieve accurate and adaptive control. Once trained, the ANFIS controller dynamically adjusts converter parameters to minimize overshoot, reduce settling time, and maintain stable operation during varying load and wind conditions.

The performance evaluation process involves simulating different operating scenarios, including wind speed variation, solar irradiance fluctuation, and sudden load changes. The dynamic response of key parameters such as rotor speed, stator voltage, frequency, and DC link voltage is monitored and compared under PI and ANFIS control. Transient indices—such as peak overshoot, rise time, and settling time—are used as performance indicators. The total harmonic distortion (THD) in current and voltage waveforms is measured to assess power quality improvements. The MATLAB/Simulink environment facilitates precise modeling of nonlinear dynamics, providing visual validation of system performance under both steady-state and transient conditions. Data obtained from the simulation are analyzed to quantify the improvement achieved by the proposed ANFIS controller compared to conventional approaches.

Finally, the methodology includes validation of synchronization performance when multiple sources operate concurrently. The ANFIS controller ensures phase and frequency matching between the DFIG and the PV–BESS subsystems before grid or load connection, preventing inrush currents and voltage dips. The controller effectively manages real and reactive power flow to balance generation and consumption dynamically. The resulting control strategy demonstrates superior adaptability, enabling smooth transitions between power sources with minimal transients. This systematic methodology thus validates the effectiveness of ANFIS in enhancing dynamic stability, synchronization accuracy, and power quality within hybrid renewable energy-based microgrids.

IV PROPOSED SYSTEM

The proposed system consists of a hybrid renewable microgrid integrating a wind turbine-driven Doubly Fed Induction Generator (DFIG), a photovoltaic (PV) array, and a Battery Energy Storage System (BESS). The configuration is designed to ensure continuous and stable power delivery under varying environmental conditions. The DFIG serves as the primary source of power generation, capable of operating efficiently over a wide range of wind speeds due to its partial-scale converter configuration. The stator of the DFIG is directly connected to the Point of Common Coupling (PCC), while the rotor is interfaced through a back-to-back Voltage Source Converter (VSC) system comprising a rotor-side converter (RSC) and a grid-side converter (GSC). These converters share a common DC link with the PV and BESS systems, allowing seamless power flow and voltage stabilization.

The PV array in the proposed system operates as an auxiliary renewable source connected to the common DC link through a DC-DC boost converter. An incremental conductance-based Maximum Power Point Tracking (MPPT) algorithm is implemented to extract the maximum possible power from the PV system under different irradiance conditions. The PV subsystem not only supplements the wind energy source but also contributes to maintaining the DC link voltage during periods of low wind speed. The BESS, on the other hand, functions as a stabilizing element, absorbing excess energy during peak generation and discharging during low-generation or high-load conditions. The bidirectional converter associated with the BESS ensures dynamic energy exchange to stabilize system voltage and frequency.

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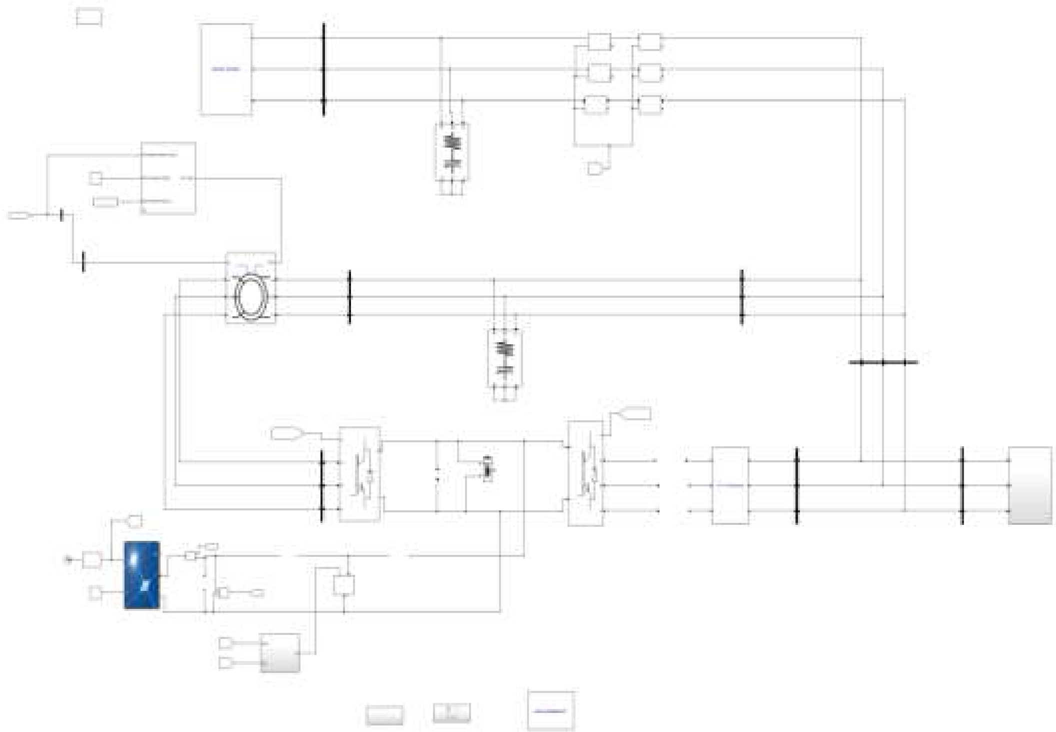


Fig.2 proposed system simulation circuit

The ANFIS controller plays a central role in the proposed system's control strategy, particularly in the regulation of the DFIG's rotor-side converter. It receives input signals such as voltage deviation, current error, and frequency variation to generate precise control actions. Unlike conventional PI controllers that use fixed gain parameters, the ANFIS controller dynamically adjusts its output by learning system patterns during operation. This adaptive control facilitates faster transient damping, reduced oscillations, and better synchronization between the DFIG, PV, and BESS units. The controller maintains reactive power balance and ensures that the stator voltage of the DFIG remains within permissible limits during disturbances or source transitions.

To ensure stable operation during synchronization events, the ANFIS controller coordinates the phase, frequency, and voltage magnitudes between distributed energy sources. During system start-up or reconnection after isolation, the synchronization logic checks for phase angle matching between the DFIG output and the PV–BESS subsystem at the PCC. Once these parameters align within acceptable thresholds, the static switch connects the systems smoothly, preventing sudden power surges or frequency deviations. The use of the ANFIS controller significantly improves this process by continuously monitoring system parameters and adapting to dynamic changes, ensuring seamless synchronization with minimal transient stress on components.

Overall, the proposed hybrid renewable system demonstrates improved transient stability, synchronization accuracy, and power quality compared to conventional control structures. The ANFIS controller effectively mitigates overshoot, voltage dips, and harmonic distortion, contributing to a robust and efficient energy management framework. The system's MATLAB-based simulation results confirm the enhanced performance of the ANFIS-controlled DFIG in maintaining stability under variable wind and solar conditions. By integrating advanced adaptive intelligence with renewable energy control, the proposed configuration establishes a reliable and scalable approach for future smart microgrid and distributed generation applications.

V RESULTS AND DISCUSSION

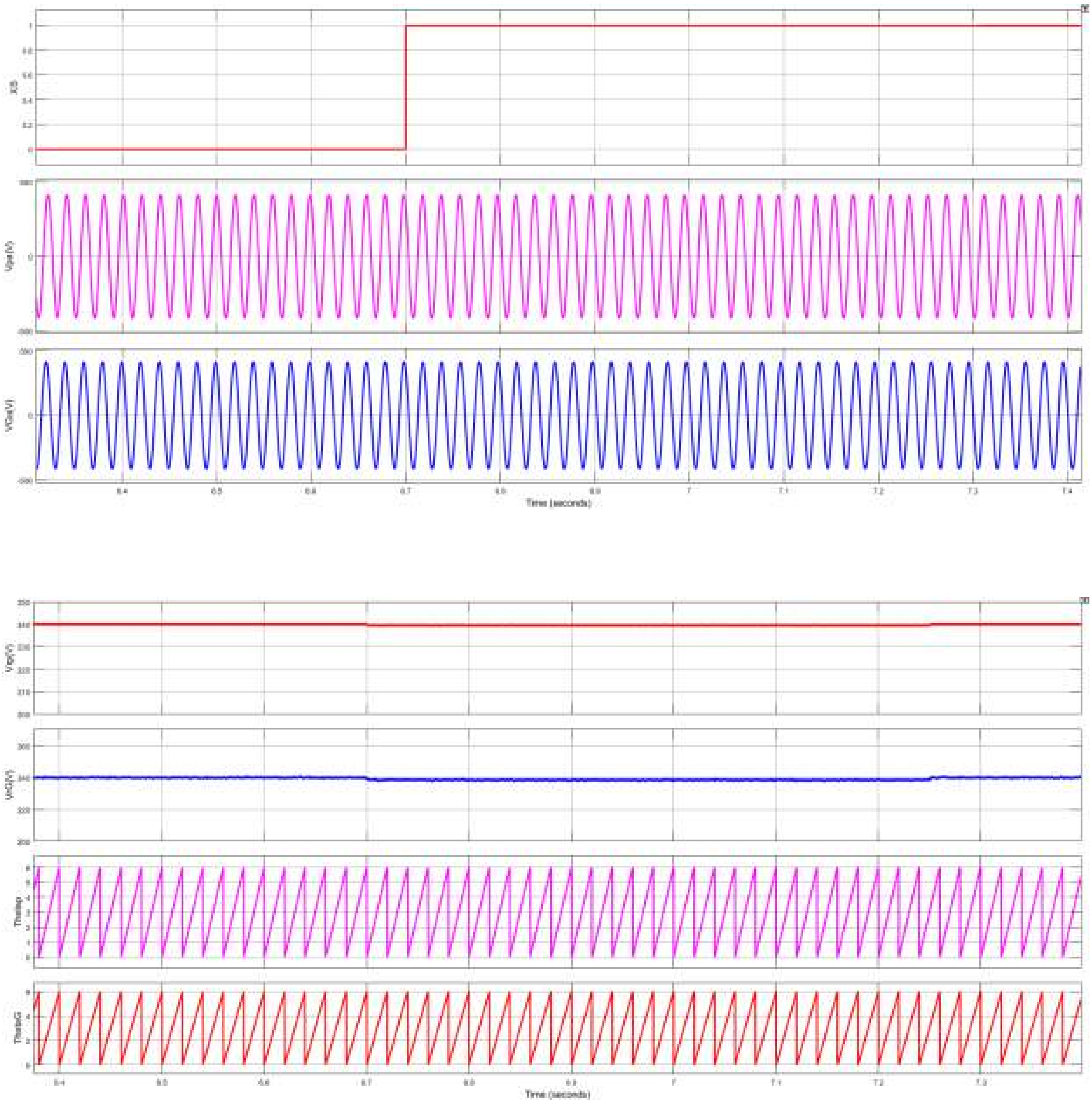
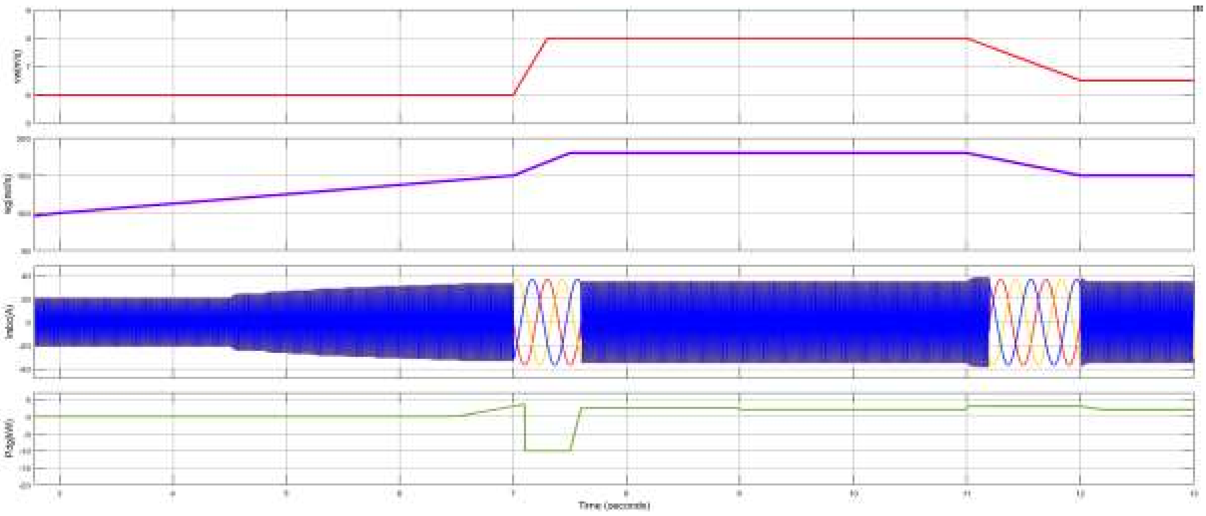
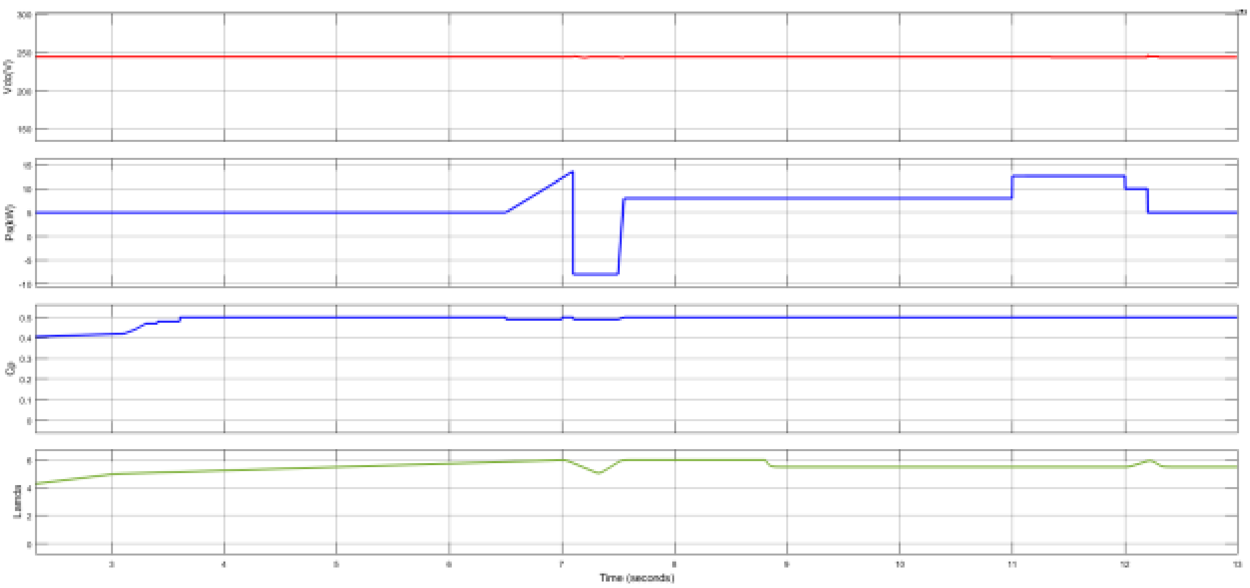


Fig. 3 System performance during synchronization of DG to DFIG-solar-BES based isolated microgrid.

Figure 3 illustrates the dynamic response of the hybrid microgrid during synchronization of the diesel generator (DG) with the wind turbine-driven DFIG and solar–battery energy storage (BES) system. When the DG voltage magnitude, frequency, and phase angle become identical to those of the DFIG stator, the static transfer switch (STS) activates, achieving seamless synchronization. The waveform analysis reveals that prior to synchronization, the system operates purely on renewable sources, with minor oscillations due to wind and irradiance variability. Once synchronization is established, the DG supports the load, maintaining the voltage at rated levels and stabilizing system frequency at 50 Hz. The ANFIS controller effectively regulates the rotor-side converter, reducing overshoot and ensuring smoother transient transition compared to conventional PI control. The voltage and current waveforms demonstrate sinusoidal behavior post-synchronization, while harmonic content remains within IEEE 519 standards. Overall, the synchronization event occurs without noticeable voltage dips or frequency deviations, confirming the robust operation of the proposed control scheme. This performance validates that the ANFIS-based controller provides enhanced adaptability, smooth DG–DFIG transition, and stable hybrid microgrid operation under dynamic conditions.





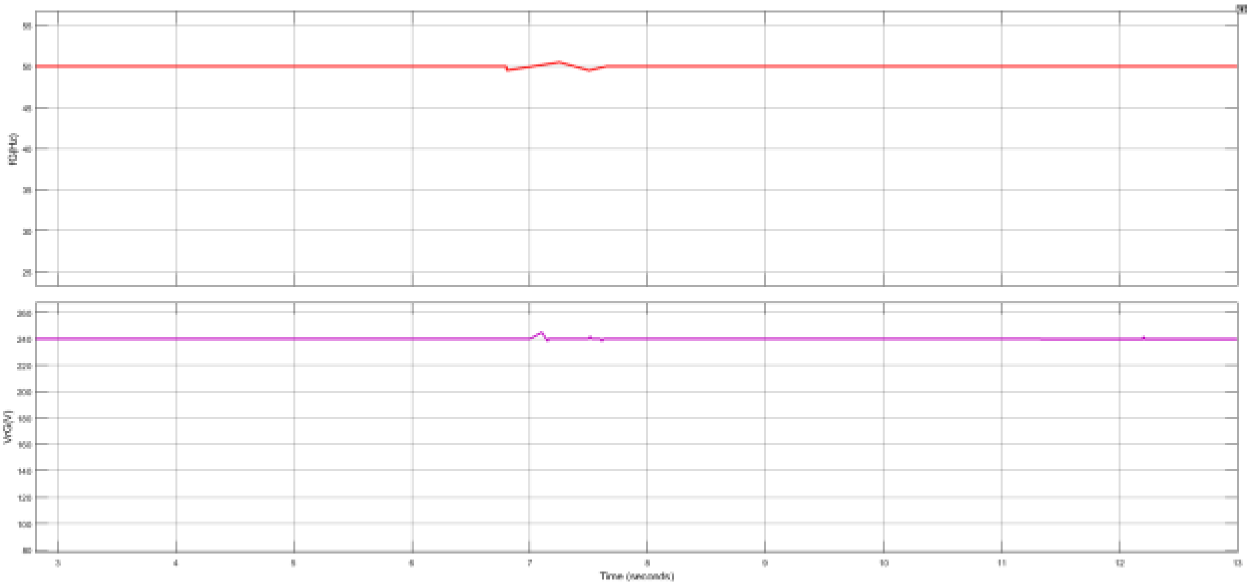


Fig. 3 System performance at variable wind speeds.

Figure 3 depicts the hybrid system's behavior under varying wind speeds to assess the adaptability of the ANFIS-based DFIG control scheme. As wind velocity fluctuates between 6 m/s and 8 m/s, the rotor speed and output power of the DFIG adjust accordingly while maintaining stable voltage and frequency at the point of common coupling (PCC). The ANFIS controller ensures that the maximum power point tracking (MPPT) condition is maintained, resulting in efficient energy conversion even during rapid wind variations. The waveforms of rotor currents indicate minimal transient oscillations, and frequency deviations are well-suppressed. The DG remains in standby mode until renewable generation decreases below the demand threshold, at which point it seamlessly contributes power without instability. The DC link voltage remains constant, highlighting the effective energy exchange between the DFIG and battery system. Compared to conventional PI control, the ANFIS approach significantly reduces transient peaks and eliminates voltage distortion during wind fluctuations. Overall, the figure demonstrates that the proposed control strategy maintains dynamic stability, improves transient response, and ensures continuous power quality across a range of wind speeds, confirming its robustness and suitability for real-world wind–solar–battery hybrid systems.

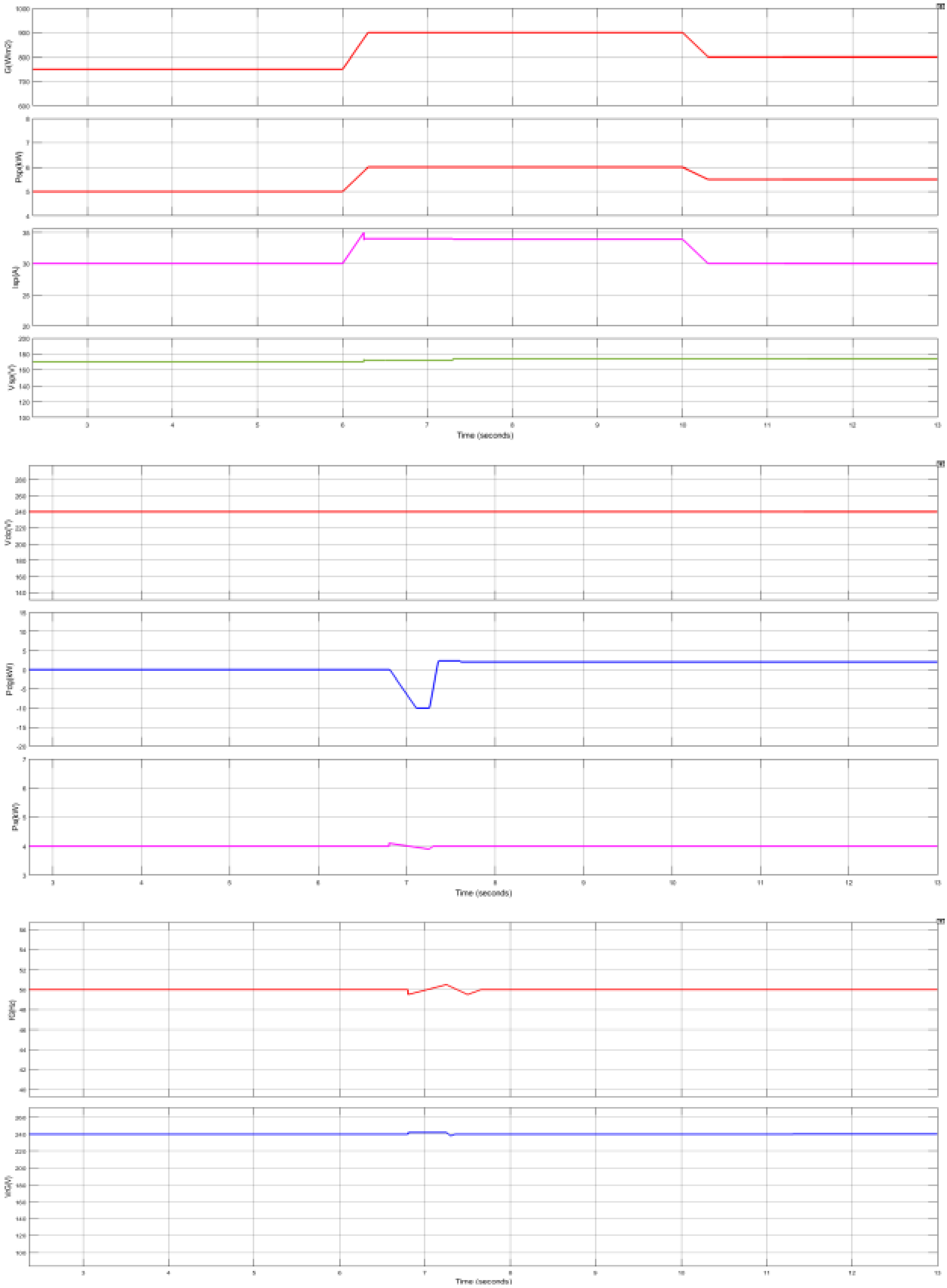
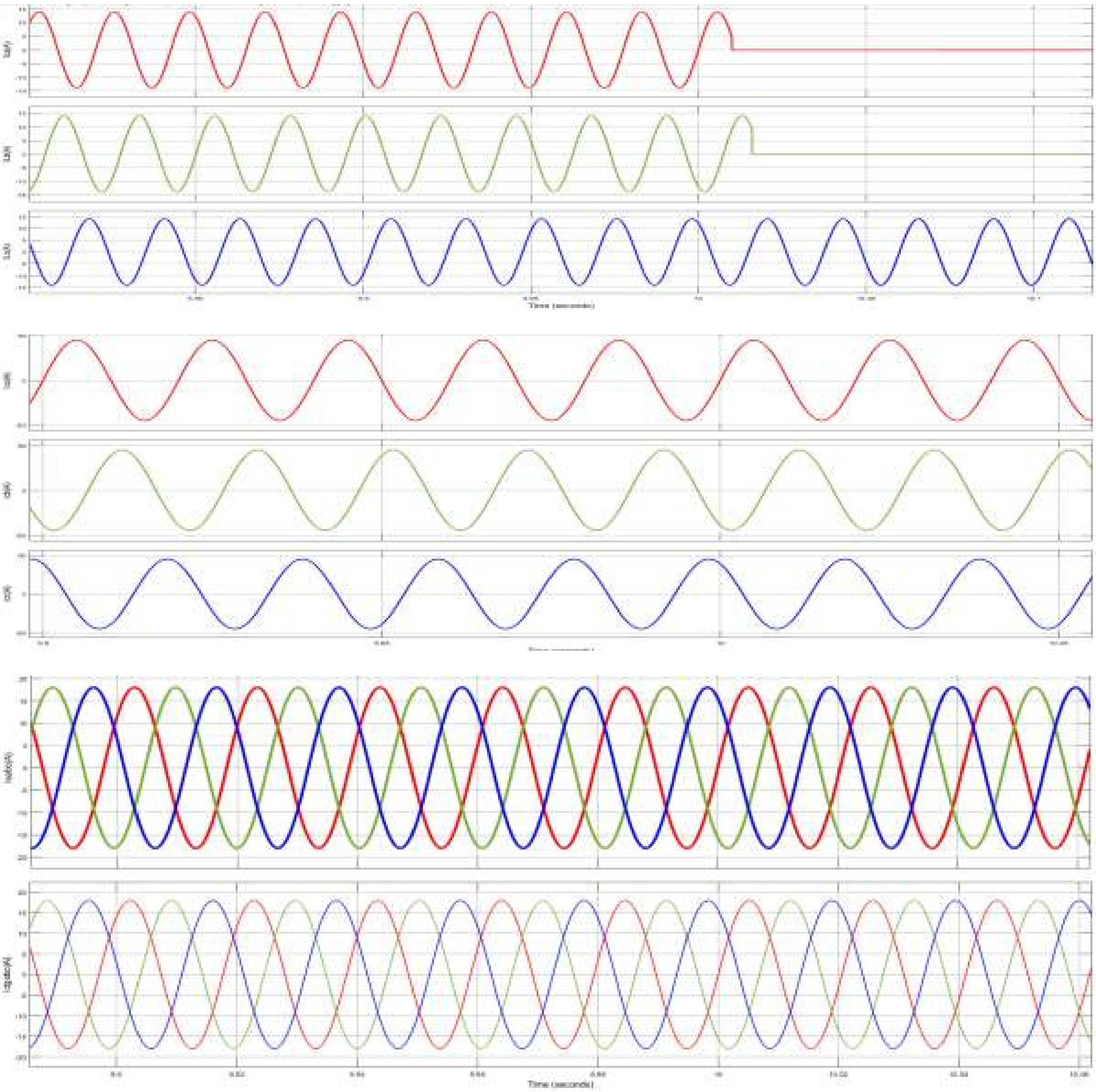
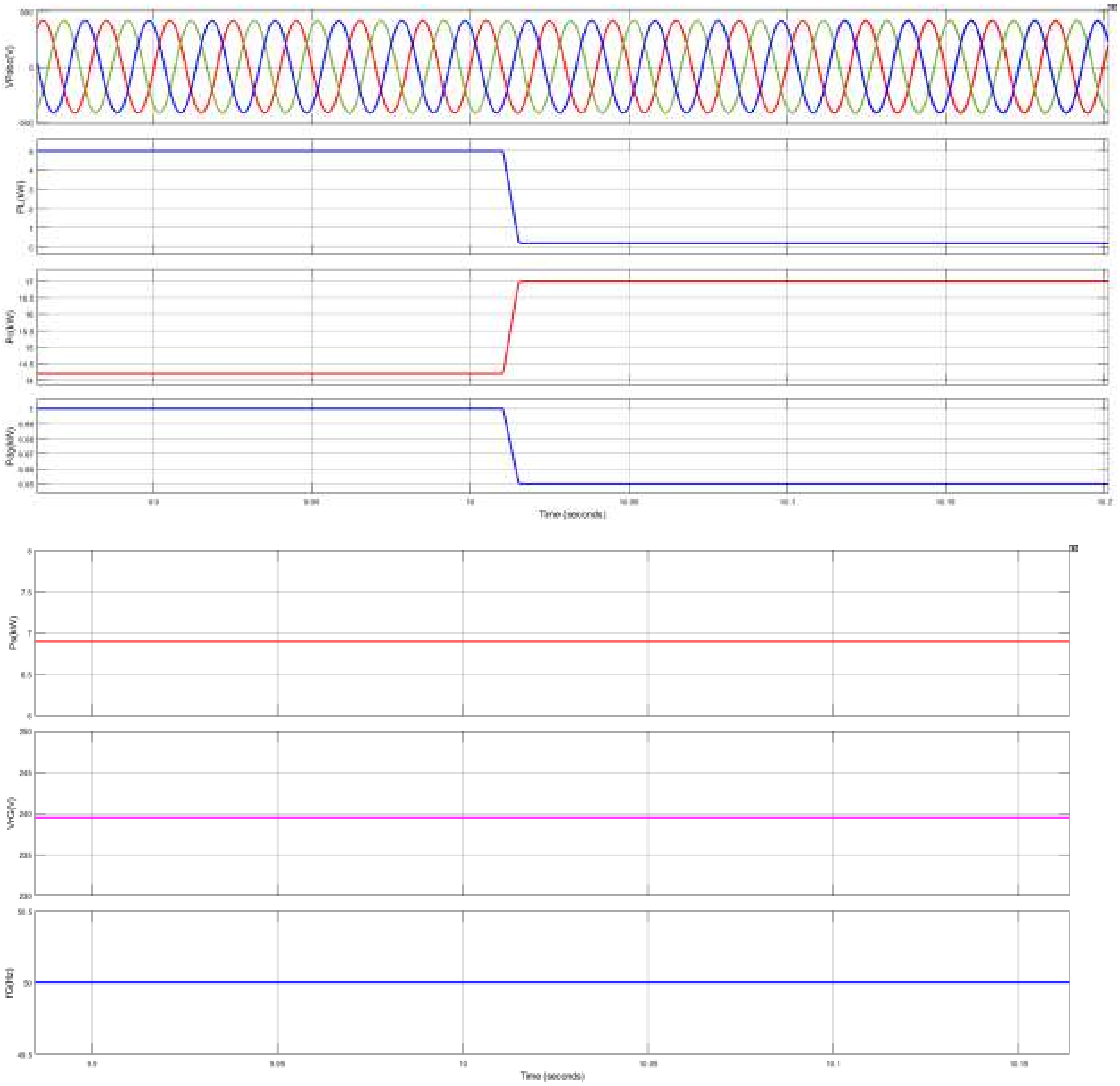


Fig. 4 System performance at varying solar PV insolation.

Figure 4 demonstrates the system's response to changes in solar irradiance while maintaining constant wind speed conditions. As solar insolation varies between 750 W/m^2 and 900 W/m^2, the photovoltaic (PV) array output current and power change correspondingly, reflecting effective maximum power point tracking (MPPT) performance. The ANFIS-controlled boost converter dynamically adjusts the duty cycle to optimize PV energy extraction. The DC link voltage exhibits negligible fluctuations, indicating efficient coordination between the PV, DFIG, and battery systems. When solar power increases, the excess energy charges the battery, whereas reduced insolation prompts controlled discharging to support the load. The voltage and frequency at the PCC remain stable throughout, confirming robust system regulation. The DG operates only when renewable generation is insufficient, demonstrating intelligent source prioritization by the ANFIS controller. Comparative analysis shows smoother voltage transitions, reduced harmonic distortion, and improved response speed over conventional controllers. Overall, the results validate that the proposed ANFIS-based hybrid system effectively mitigates transient fluctuations, enhances power quality, and ensures seamless energy sharing between solar, wind, and battery units during variable irradiance conditions.



(a)



(b)

Fig. 5 (a-b) System performance at unbalanced connected load with optimal fuel operation of DG.

Figures 5 (a) and (b) represent the system's behavior under unbalanced load conditions while maintaining optimal fuel operation of the DG. When one or more load phases are suddenly disconnected, the system experiences a power imbalance. The ANFIS controller promptly compensates for the imbalance through appropriate modulation of the load-side converter (VSCL), ensuring balanced stator and DG currents. The waveform analysis reveals that despite the load asymmetry, the PCC voltage remains stable, and current waveforms are sinusoidal. The DG operates efficiently within its optimal fuel consumption zone, with output power regulated smoothly despite the disturbance.

Simultaneously, the battery storage compensates for transient variations by charging or discharging as needed. Power components such as DFIG stator power, DG power, and converter power remain synchronized, demonstrating coordinated energy sharing. The total harmonic distortion (THD) is maintained below 5%, confirming high power quality. The ANFIS-based controller exhibits superior adaptability compared to conventional PI controllers by maintaining dynamic balance, minimizing transient oscillations, and ensuring continuous supply without frequency drift. This performance validates the controller's capability to achieve stable, efficient, and fuel-optimized operation in hybrid microgrids under unbalanced load conditions.

S. No.	Simulation Scenario	Existing System (with PI Controller)	Extension (ANFIS Controller)
1	Synchronization of DG with DFIG-Solar-BES Microgrid	Fig. 6.2: Standard synchronization; transient dips	Fig. 6.6: Improved synchronization; reduced transients
2	Performance at Variable Wind Speeds	Fig. 6.3: Power fluctuation visible	Fig. 6.7: Better voltage/frequency stability under variation
3	Performance at Varying Solar PV Insolation	Fig. 6.4: Output voltage fluctuates with irradiance	Fig. 6.8: Stable output voltage despite variation
4	Unbalanced Load with Optimal DG Fuel Operation	Fig. 6.5(a-b): Power quality affected	Fig. 6.9(a-b): Enhanced fuel optimization and load balancing

CONCLUSION

The proposed ANFIS-based synchronizing control for a wind turbine-driven DFIG system integrated with a PV array and battery energy storage system demonstrates significant improvements in dynamic performance and transient stability. By intelligently combining the adaptive learning capabilities of neural networks with the decision-making strength of fuzzy logic, the controller effectively minimizes overshoot, reduces settling time, and enhances voltage and frequency stability under varying environmental and load conditions. MATLAB-based simulations confirm that the ANFIS controller outperforms traditional PI control schemes by providing superior transient suppression and improved synchronization between distributed energy sources. Additionally, the integration of PV and BESS ensures stable power delivery and mitigates the effects of renewable intermittency. The overall system exhibits enhanced harmonic reduction, smoother voltage buildup, and efficient energy exchange between sources and storage units. This research establishes that ANFIS-based control offers a flexible, self-tuning, and reliable framework for hybrid renewable energy microgrids. The results highlight its suitability for future smart energy systems, where adaptive intelligence and resilient control strategies are essential for maintaining power quality, ensuring system stability, and achieving sustainable energy management in both isolated and grid-connected configurations.

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