

Fuzzy Logic Controller-Based Intelligent Control for Enhanced Performance in Hybrid Solar-Wind Energy Systems

Gudala Satya Pratap¹, Dr. Midhunchakkaravarthy², Dr. K R Krishna Vara Prasad³

1. Lincoln University College, Malaysia satyapratapgindia@gmail.com, gspratap.phdscholar@lincoln.edu
2. Faculty of Computer Science and Multimedia Lincoln University College, Malaysia midhun@lincoln.edu.
3. Aditya University, Kakinada-India. krprasad219@gmail.com

Abstract

Despite the effectiveness of Carrier PWM and SVPWM in managing hybrid solar-wind renewable energy systems, challenges such as nonlinearity in power generation, dynamic environmental conditions, and suboptimal power quality remain unaddressed. These limitations often result in slower system response and increased total harmonic distortion (THD), particularly under highly variable operating conditions. This paper proposes a Fuzzy Logic Controller (FLC) as an advanced solution to overcome these challenges. The FLC leverages the capabilities of fuzzy logic to provide adaptive and intelligent control for hybrid renewable energy systems. By dynamically adjusting to nonlinear variations in solar irradiance and wind speed, the proposed FLC ensures optimal power tracking, improved voltage regulation, and reduced THD compared to conventional Carrier PWM and SVPWM techniques. The hybrid system integrates FLC control for both solar and wind energy subsystems, replacing traditional static PWM methods. Faster response times, improved system stability, and efficient energy distribution under varied load and climatic circumstances are some of the ways in which the FLC excels in simulations. Fuzzy logic-based control systems have the ability to enhance the efficiency and dependability of hybrid renewable energy systems, as demonstrated in this study.

Keywords: Fuzzy Logic Controller, Solar power system, Wind Energy Systems.

1. INTRODUCTION

There has been a lot of focus on PV/Wind energy conversion systems because of the many benefits they offer. Among these systems' greatest strengths is their ability to intelligently generate energy from several sources, meeting both the load demand and the batteries' charging needs, regardless of changes in the load or the weather. A number of hybrid energy system designs have been put forward, each with its own unique set of power management controls (PMC) [1]. Intelligent algorithms and logical states form the basis of several of them. In particular, for solitary uses (remote control), the others are more appealing. There is a lot of material that looks into PMCs. Electricity and smart grids, water pumping, and communications are the main areas of interest for the applications. Generally speaking, power balance is the foundation of management in all the papers. Control based on fuzzy logic (Ref. 2), flatness (Ref. 3), frequency deviation (Ref. 4), and microcontroller (Ref. 5) are some of the methods proposed by various writers for managing power. The modelling of the various sources is based on popular mathematical frameworks. FLC has been used in many different contexts, including maximum power point tracking (MPPT) for solar PV and frequency regulation, controlling voltage in wind/battery hybrid systems, enhancing the accuracy of wind power projections, and managing current in batteries' output chargers. Because of its adaptability and ability to deal with uncertainties and unpredictable variables using rules drawn from human knowledge and experience, Fuzzy Logic Control (FLC) is selected for this study. Hybrid energy systems, which have numerous types of incorrect inputs, variables, and disturbances, can benefit from FLC if their power comes from renewable sources and their consumption is unpredictable.

Several papers have also discussed how FLC can be used to control hybrid energy systems and energy storage batteries. In order to distribute power fairly among solar PV, wind, and storage batteries, FLC has been used in Refs. [6] according to a pre-defined rule. Using a field-effect

converter (FEC) to regulate the state of charge (SOC) of lesser energy capacity storage batteries improved the performance of the hybrid producing system, as described in reference [7]. We propose a Fuzzy Logic Controller (FLC) based controller that can effectively manage the whole hybrid power system and choose the power source for communications loads at the right time. For standalone applications, a fuzzy logic controller can be used to govern the electricity moving into and out of the batteries and their state of charge, regardless of changes in load or intermittent power from renewable sources. This controller is specifically designed for use with hybrid systems that combine solar photovoltaics with wind power. Wind energy conversion systems (WECSs) help us consume less fossil fuels, which means we release fewer greenhouse gas emissions and have a smaller impact on the planet. Wind energy conversion systems (WECSs) aim to reduce greenhouse gas emissions and promote sustainable energy in the long run [9]. Additionally, due to their operability in grid-connected systems, WECSs are among the top choices for clean energy production. This makes them a highly viable alternative for sustainable energy transitions globally. Many countries, China included, are keen on exploring renewable and clean energy options. This is due to the fact that these technologies may substantially facilitate China's energy transition, which in turn will assist the nation in accomplishing its goals of attaining its carbon peak by 2030 and achieving carbon neutrality by 2060.

There are significant optimisation and management issues with wind power in particular when it is integrated into the power system. The inherent uncertainties and variability brought forth by weather fluctuations might make wind energy conversion system (WECS) management problematic [10]. To ensure stability, dependability, and optimal electrical energy utilisation, power regulation is essential for successfully integrating WECSs into smart and traditional networks. The unpredictability of wind makes it all the more important to regulate wind turbine output in order to reliably integrate them into the power grid. Optimising energy generation while minimising grid interruptions (like frequency and voltage fluctuations) is the primary goal of modern power control strategies. In order to make power control more reliable and efficient, newer methods use complex tools including machine learning algorithms, predictive controllers, and fuzzy logic. These methods allow for more precise management of wind energy integration into the power system and better adaptation to changing wind conditions. One new and promising approach to wind energy management system efficiency and stability is the use of fuzzy controllers [11].

Wind power conversion systems are increasingly incorporating FL controllers to enhance their performance and efficiency. The extremely nonlinear and unpredictable behaviour of wind is well-managed by FL controllers. This allows them to adjust to changing wind speeds and directions without relying on precise mathematical models, which might be difficult to grasp or don't perform well in practice.

2. LITERATURE REVIEW

There are a number of articles discussing WECS control in the literature, with different authors concentrating on different parts of the control process. For the WECS to reach its reference values for active and reactive power, the fuzzy logic controller (FLC) suggested in [12] must be able to generate the rotor voltages appropriately. In such a situation, fuzzy controllers often request rather little adjustments. A control rule that combines sliding mode control with a single-input FLC is presented in the study in [13] with the purpose of cheaply and effectively managing a static synchronous compensator, making it more stable and enhancing its performance. Our goal is to create an asynchronous WECS with a more stable voltage profile that can withstand fluctuations in wind speed and load. But, experimenting with various FLCs, especially those that change the PI reference value, is an attractive alternative. In order to improve the quality of the extracted power while limiting it at its rated value, an adaptive controller that uses fuzzy logic is proposed in [14]. The load on the turbine and drive train can be decreased by modifying the pitch angle when operating at full load.

In [15], we find a model for Load Frequency Control (LFC) that can fix both the frequency control problem and the economic dispatching control.

Both the immediate and distant management of power grids depend on frequency stability. An LFC model is proposed in [27] that looks at how hydro-turbines fit into power systems that have a lot of wind energy. Along with that, it aims to deduce the role that hydro-turbines play in the PID controller-based secondary frequency control system. To prove that an adaptive PID controller with an FCL loop is superior, another group of researchers is developing a renewable energy-powered six-area power system. Recent studies have also examined the function of energy storage systems (ESSs) and innovative control methods in regulating the frequency of power systems that are mostly powered by wind. A cascaded dual-FLC approach was employed to develop an adaptive energy management system that can withstand and respond to changes in demand, wind speed variations, and solar irradiation [17].

The proposed algorithm may regulate the load, the microgrid mode, and the operation of the batteries, all of which contribute to increased stability. According to [18], an adaptive fuzzy logic controller is the best choice for controlling a WECS that uses a permanent magnet synchronous generator. Quick changes to the references usually lead to excessively optimistic outcomes. Presented in [19] is a novel single-input variable (FLC) approach to designing WT-driven doubly fed induction generators (DFIGs) that incorporate battery energy storage and operate autonomously.

Such a command is delicate because it relies on the internal characteristics of the system. In [20], there isn't a comparative study to back up the claims made about managing and controlling an energy conversion system in a microgrid configuration with several renewable power sources and battery storage. In order to solve the problems of nonlinearity, changing environmental circumstances, and less-than-ideal power quality that hybrid solar-wind renewable energy systems encounter, this research proposes a Fuzzy Logic Controller (FLC). This work introduces a smart control method for managing hybrid systems that uses FLC instead of conventional Carrier PWM and SVPWM methods. This enables the system to be controlled more efficiently and with more adaptability. Thanks to the FLC's enhanced power tracking, better voltage management, and reduced total harmonic distortion (THD), the system's performance is guaranteed to increase under different operating scenarios. The simulation results demonstrate that the FLC may significantly improve the reliability and efficiency of hybrid renewable energy systems by increasing stability, decreasing response times, and distributing energy more efficiently.

3. METHODOLOGY

System Design and Modeling:

- A hybrid renewable energy system is modeled, consisting of solar photovoltaic (PV) and wind energy subsystems.
- The system architecture includes power converters for each subsystem, which interface with a common load.

Fuzzy Logic Controller Development:

- A Fuzzy Logic Controller (FLC) is designed for adaptive control of the hybrid system.
- Key inputs to the FLC include solar irradiance, wind speed, and load demand.
- The FLC utilizes a rule-based inference system to handle the nonlinear and dynamic behavior of the renewable energy sources.
- Membership functions for inputs and outputs are defined, and control rules are developed to optimize performance metrics such as power tracking, voltage regulation, and total harmonic distortion (THD).

Fuzzy Logic Controller:

Among the many potential applications of fuzzy logic, reasoning, and fuzzy sets, fuzzy logic control (FLC) has attracted the greatest amount of attention from researchers. From biological instruments and securities to industrial process control, FLC has many potential uses. When dealing with complicated, poorly-defined situations that a skilled human operator can manage

effectively without understanding their underlying dynamics, FLC has proven to be more effective than traditional control techniques. A control system can be defined as any arrangement of physical components whose function is to regulate the operation of another arrangement of physical components. Modern control systems can be either open-loop or closed-loop. In an open-loop control system, the output of the physical system is not dependent on an input control action. Another option is a closed-loop control system, where the input control action is determined by the physical system's output. You may hear feedback control systems referred to as closed-loop control systems. The first step in modifying a physical variable is to take readings of it. A device that can pick up the modulated signal, A plant is an example of a physically regulated system. The responses from the system's output determine the input forcing signals of a closed-loop control system. This is the core issue with control:

In order to change the regulated physical system's output, an error signal is utilised. The discrepancy between the actual (calculated) and ideal (plant) replies is known as the error signal.

Adding a second system, known as a controller or compensator, to a closed-loop control system allows it to achieve desired responses and characteristics. In Figure 1 we can see the closed-loop control system's fundamental block diagram. An IE-THEN rule is the basic building block of fuzzy control rules.

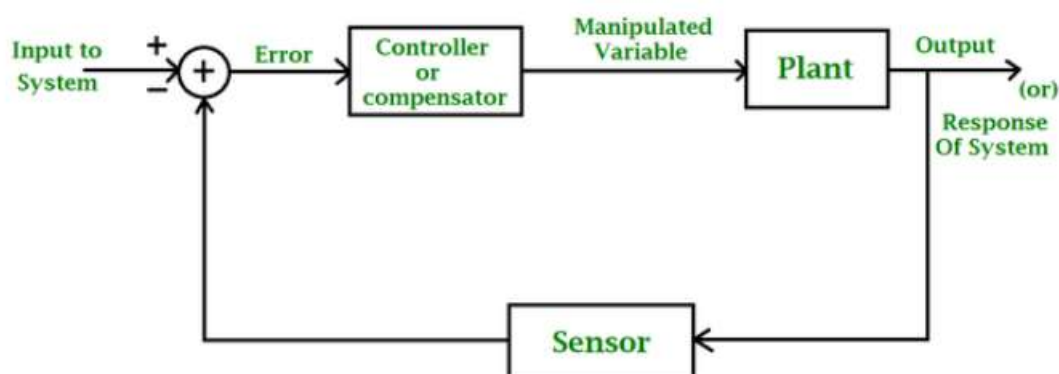


Fig 1: Control System Block Diagram for a Closed-Loop System

Control System Design:

These are the stages involved in designing a physical system controller:

1. Breaking down the complex system into its component parts.
2. Modulating plant dynamics gradually and bringing nonlinear plane dynamics into linearity around a set of operational points.
3. Compiling a set of the system's output characteristics, control variables, or state variables.
4. Developing fundamental P, PD, and PID controllers for the systems below. Furthermore, perfect controllers are attainable.

Uncertainties may arise in the remaining processes as a result of external environmental factors. The control engineer's professional knowledge should inform the controller's design to the best of their ability. There are a number of numerical observations that may be made of the input-output relationship based on knowledge about the plant's dynamics and its external environment, including linguistic and intuitive data. At last, a supervisory control system—automatic or manual—creates an additional feedback control loop to fine-tune the controller's parameters and compensate for variational effects brought on by nonlinear and remodelled dynamics.

In the event that an FLC system design is chosen, it is recommended to make the following assumptions in contrast to a traditional control system design. It is important that the plant being studied can be easily observed and managed. An existing body of information covering several domains should serve as the basis for a fuzzy rule. This body of knowledge could

include input/output data, basic engineering common sense, or guidelines for expert language use. In addition, the control engineer should be striving for a "good" solution rather than an ideal one, and the problem should have a clearly defined solution.

In this instance, the controller's design should be as precise as possible while still falling inside reasonable bounds. Note that optimality and stability are persistent issues with fuzzy controller design.

The formation of fuzzy rules is an essential part of constructing a fuzzy logic controller. The fuzzy production rule system, as described by Weiss and Donnel (1979), consists of four main **structures**:

1. The expert decision-maker's policies and heuristic techniques are represented by a set of rules.
2. A group of supporting facts that are evaluated just before the final call.
3. A technique for determining if a proposed action complies with the stated rules when relevant data is available.
4. A process for coming up with potential courses of action and knowing when to quit looking for improvements.

The fuzzy logic controller relies on membership functions to specify all of its parameters. Approximate reasoning and interpolative reasoning are some of the methods used to assess the rules. These four fuzzy rule structures can be used to derive the control surface, which is the map from the control action to the measured state or output variable. Data collected from a small-point sampling of the control surface can be used to construct a look-up table. The look-up table allows for the transfer of control surface data onto a read-only memory chip. The chip in question would act as the controller for the plant continuously.

Applications:

FLC systems are widely used in many different products and systems in the commercial and industrial sectors. FLC systems have outperformed more traditional control methods in a number of contexts, including those involving complex systems, nonlinear and time-varying systems, and ill-defined systems. Some of the uses for FLC systems are:

1. Traffic Control
2. Steam Engine
3. Aircraft Flight Control
4. Missile Control
5. Adaptive Control
6. Liquid-Level Control
7. Helicopter Model
8. Automobile Speed Controller
9. Braking System Controller
10. Process Control (includes cement kiln control)

Simulation Setup:

- MATLAB/Simulink is used to simulate the hybrid system and evaluate the performance of the proposed FLC.
- The simulation incorporates real-world variability in environmental conditions and load demands.

Performance Evaluation:

- The performance of the FLC is compared against conventional Carrier PWM and SVPWM techniques.
- Metrics evaluated include system response time, THD levels, voltage stability, and energy distribution efficiency.
- Sensitivity analysis is conducted to assess the robustness of the FLC under varying operating conditions.

Analysis and Validation:

- Simulation results are analyzed to determine the efficacy of the FLC in addressing the challenges posed by nonlinear power generation and dynamic environmental conditions.
- Comparative results highlight the advantages of the FLC, including faster response times, reduced THD, and enhanced system stability.

4. RESULTS AND STUDY

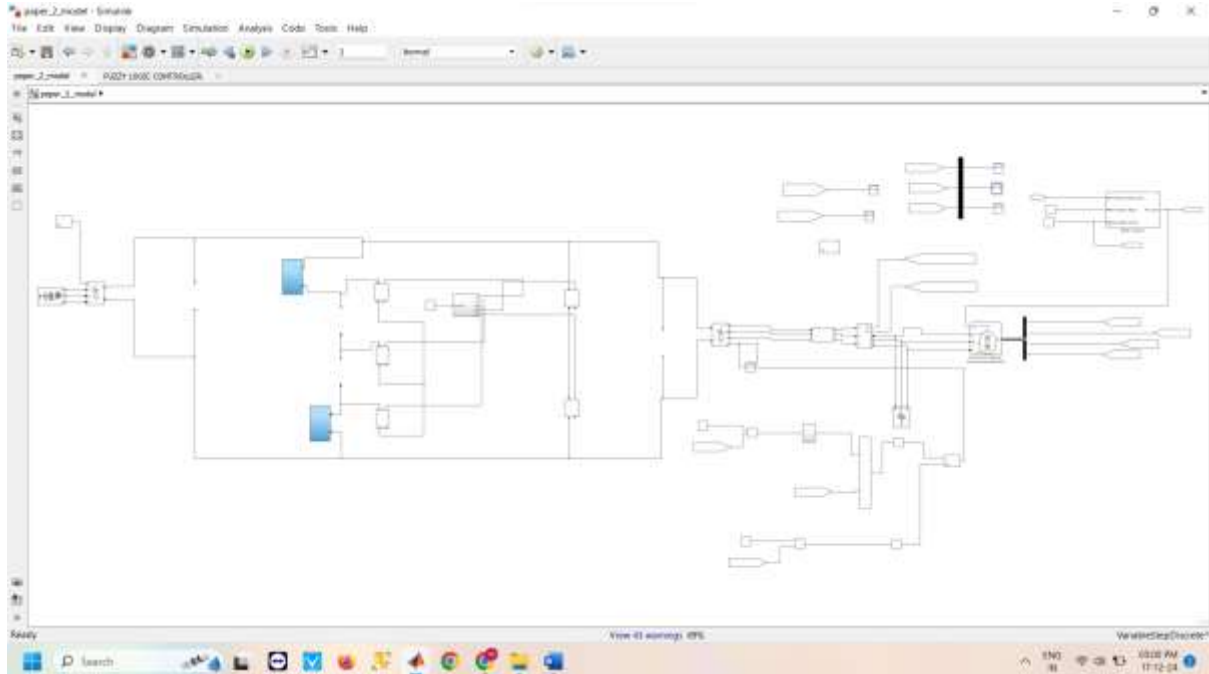


Fig 2: Simulation diagram.

"Fig 2 presents the simulation block diagram, illustrating the integration of the solar and wind energy systems within the hybrid setup. It outlines the key components, including the fuzzy logic controllers and energy management system, that coordinate the flow of energy and ensure stable operation under dynamic conditions, optimizing performance through adaptive control.

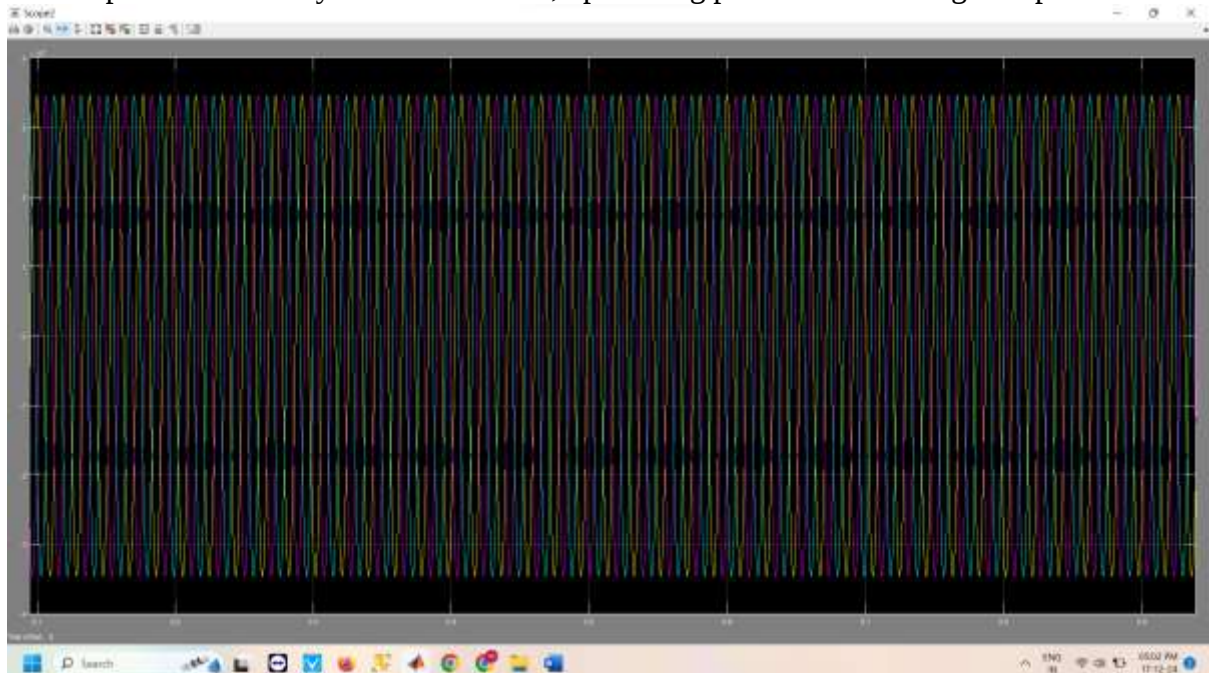


Fig 3: Three-phase Generated Voltage.

Fig 3 shows the three-phase generated voltage, representing the output waveform from the wind turbine-driven system. The use of fuzzy logic control leads to a reduction in harmonic disturbances, improving the overall quality of the generated voltage.

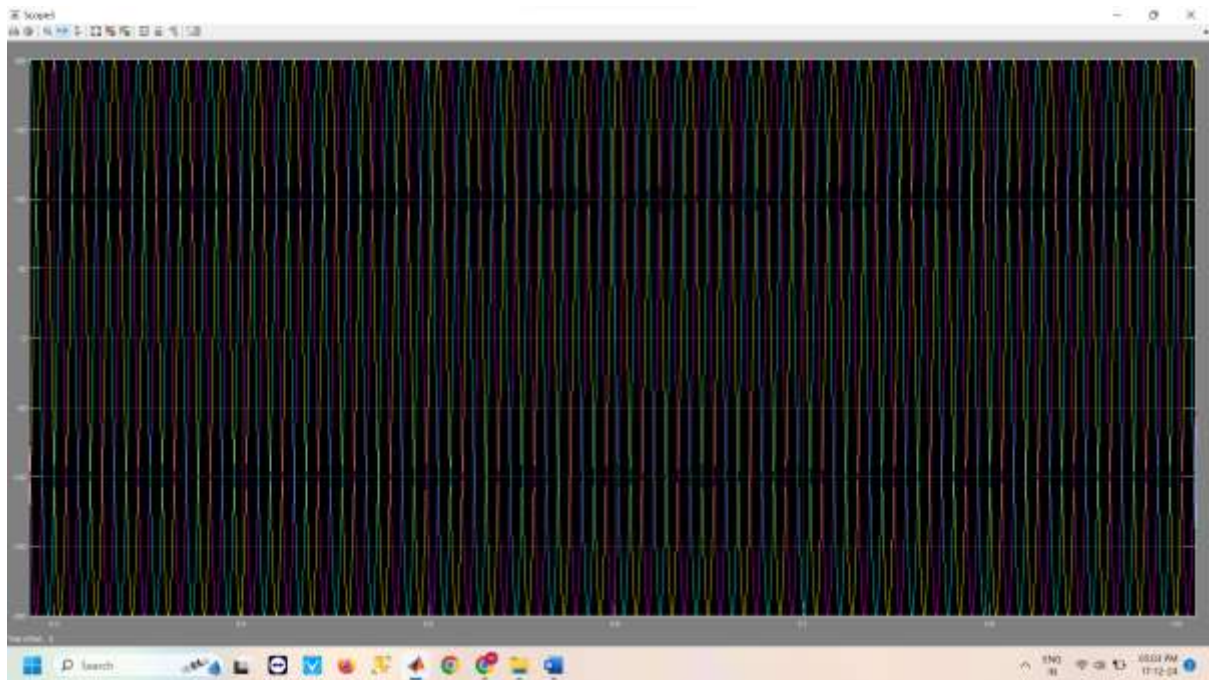


Fig 4: Three-phase Generated Current.

"Fig 4 displays the three-phase generated current, which corresponds to the current output from the wind turbine system. The application of fuzzy logic control results in a reduction of harmonic disturbances, enhancing the quality of the generated current



Fig 5: Rotor speed.

Fig 5 illustrates the rotor speed of the wind turbine system, showing how the speed fluctuates in response to changes in wind conditions.

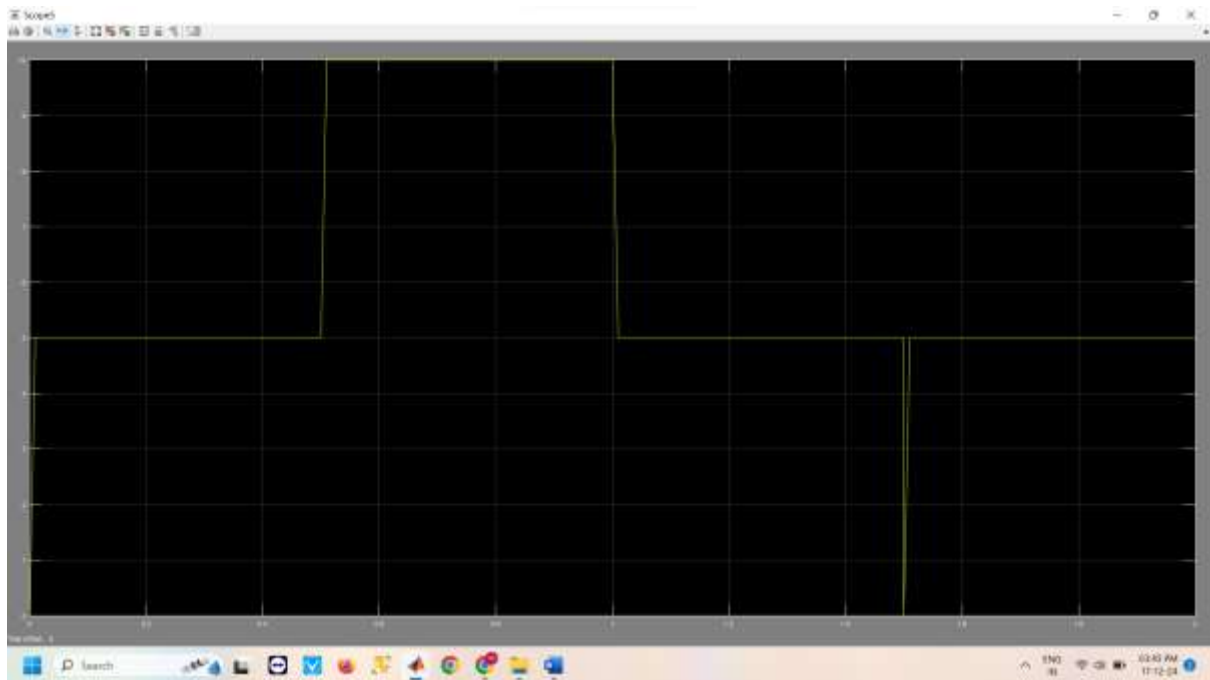


Fig 6: Torque.

Fig 6 shows the torque generated by the wind turbine, depicting its variation in response to changing wind speeds.

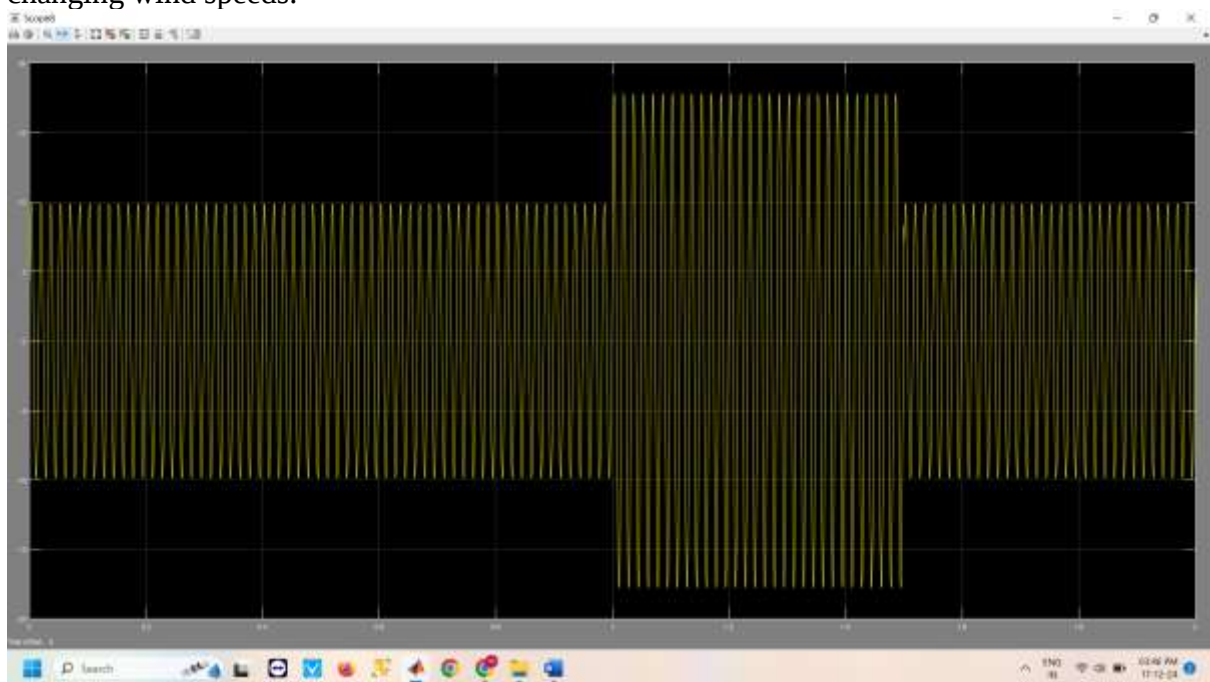


Fig 7: Stator current.

Fig 7 displays the stator current of the wind turbine system, illustrating its behavior under varying load and wind conditions.

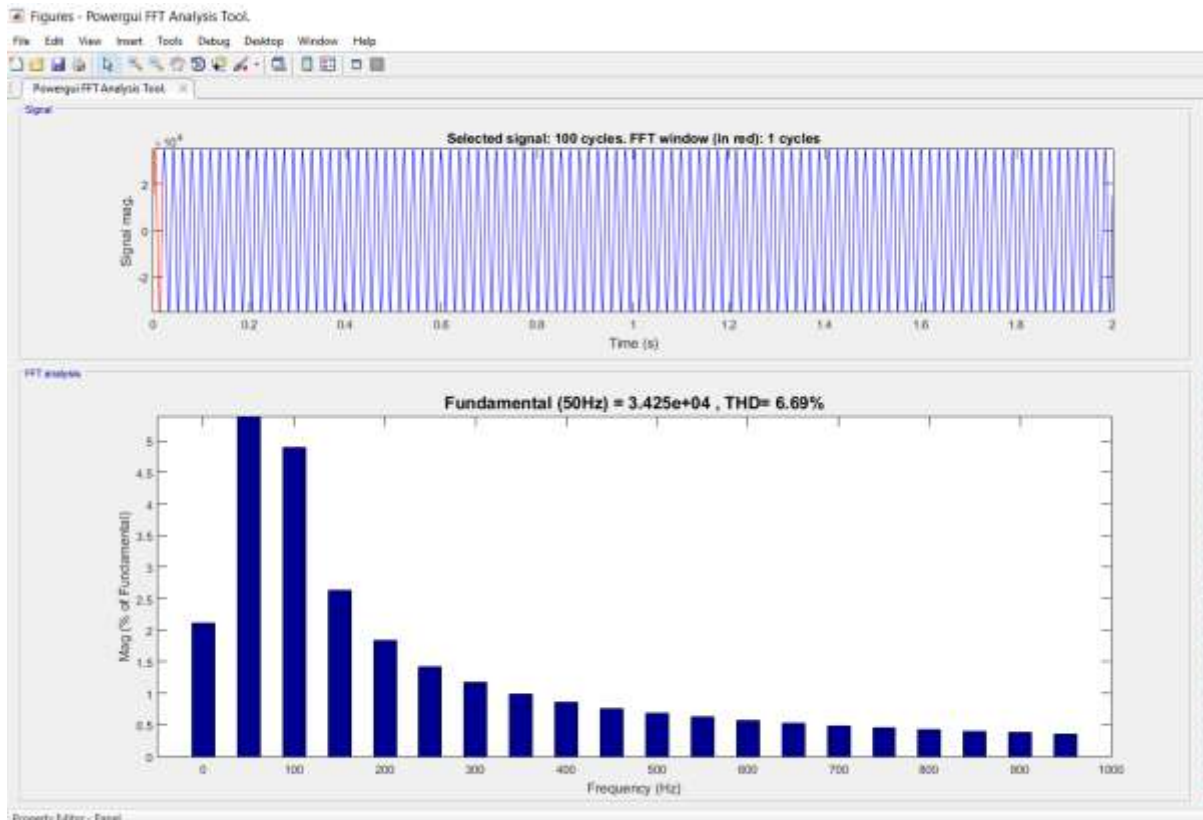


Fig 8: THD for Three-phase Generated Voltage.

"Fig 8 presents the Total Harmonic Distortion (THD) for the three-phase generated voltage, showing the level of harmonic content in the voltage waveform. The use of fuzzy logic control results in significantly lower THD compared to traditional methods, demonstrating its effectiveness in reducing harmonic distortion and enhancing voltage quality."

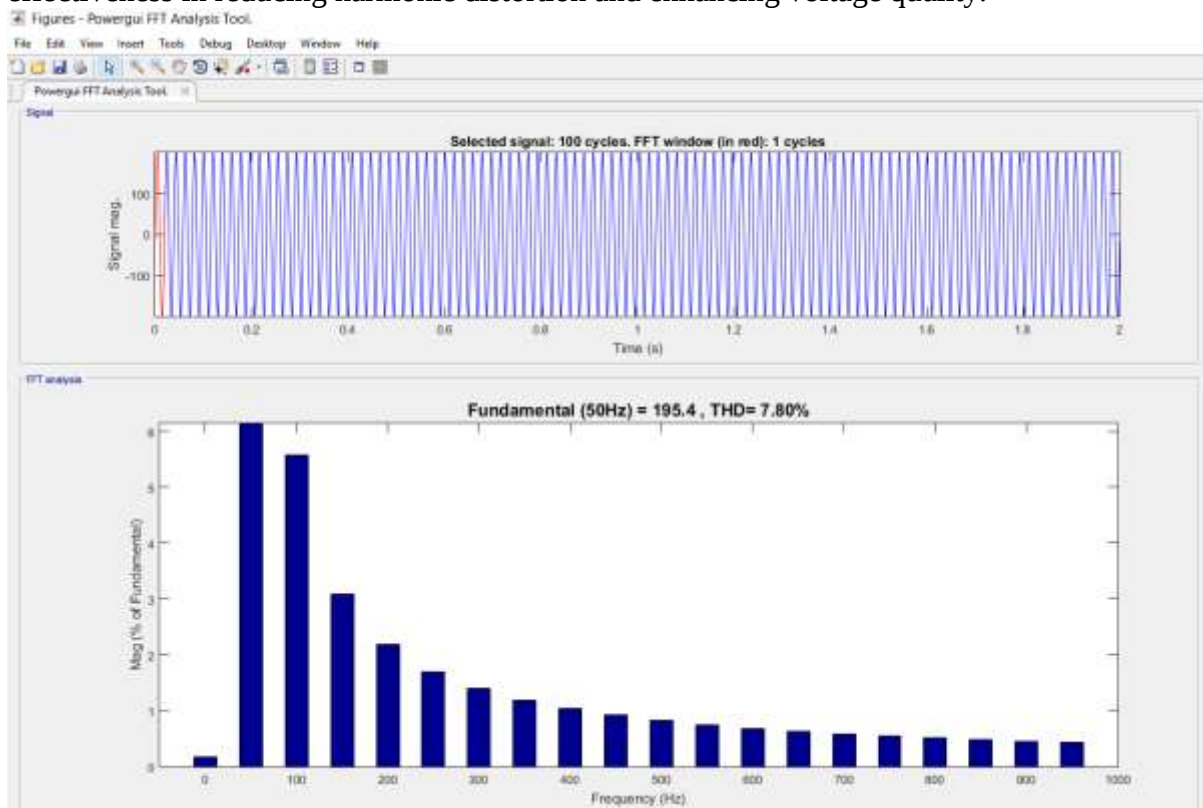


Fig 9: THD for Three-phase Generated Current

"Fig 9 shows the Total Harmonic Distortion (THD) for the three-phase generated current, illustrating the level of harmonic content in the current waveform. The use of fuzzy logic

control results in significantly lower THD compared to traditional methods, highlighting its effectiveness in reducing harmonic distortion and improving power quality."

CONCLUSION

In conclusion, this paper demonstrates the significant advantages of using a Fuzzy Logic Controller (FLC) in hybrid solar-wind renewable energy systems. By addressing the challenges of nonlinearity, dynamic environmental conditions, and suboptimal power quality, the FLC provides an adaptive and intelligent control solution that improves system performance. The proposed approach ensures optimal power tracking, enhances voltage regulation, and reduces Total Harmonic Distortion (THD) compared to traditional Carrier PWM and SVPWM techniques. Simulation results highlight the FLC's ability to deliver faster response times, greater stability, and efficient energy distribution, showcasing its potential to enhance the reliability and efficiency of hybrid renewable energy systems. This study underscores the role of fuzzy logic-based control systems in advancing the capabilities of renewable energy integration.

REFERENCES

1. Wang, Q.; Luo, K.; Wu, C.; Tan, J.; He, R.; Ye, S.; Fan, J. Inter-farm cluster interaction of the operational and planned offshore wind power base. *J. Clean. Prod.* **2023**, 396, 136529. [[Google Scholar](#)] [[CrossRef](#)]
2. Ye, S.; Wang, Q.; Mu, Y.; Luo, K.; Fan, J. Loads and fatigue characteristics assessment of wind farm based on dynamic wake meandering model. *Renew. Energy* **2024**, 236, 121419. [[Google Scholar](#)] [[CrossRef](#)]
3. Zhang, X.; Wang, Q.; Ye, S.; Luo, K.; Fan, J. Efficient layout optimization of offshore wind farm based on load surrogate model and genetic algorithm. *Energy* **2024**, 309, 133106. [[Google Scholar](#)] [[CrossRef](#)]
4. Behara, R.K.; Saha, A.K. Analysis of Wind Characteristics for Grid-Tied Wind Turbine Generator Using Incremental Generative Adversarial Network Model. *IEEE Access* **2024**, 12, 38315–38334. [[Google Scholar](#)] [[CrossRef](#)]
5. Kumar, R.; Mishra, S.K.; Mohanta, D.K. An integrated development environment based situational awareness for operational reliability evaluation in wind energy systems incorporating uncertainties. *Electr. Power Syst. Res.* **2024**, 233, 110467. [[Google Scholar](#)] [[CrossRef](#)]
6. Akhtar, I.; Altamimi, A.; Khan, Z.A.; Alojaiman, B.; Alghassab, M.; Kirmani, S. Reliability Analysis and Economic Prospect of Wind Energy Sources Incorporated Microgrid System for Smart Buildings Environment. *IEEE Access* **2023**, 11, 62013–62027. [[Google Scholar](#)] [[CrossRef](#)]
7. Lohr, C.; Peterssen, F.; Schlemminger, M.; Bensmann, A.; Niepelt, R.; Brendel, R.; Hanke-Rauschenbach, R. Multi-criteria energy system analysis of onshore wind power distribution in climate-neutral Germany. *Energy Rep.* **2024**, 12, 1905–1920. [[Google Scholar](#)] [[CrossRef](#)]
8. Neshat, M.; Sergiienko, N.Y.; Nezhad, M.M.; da Silva, L.S.; Amini, E.; Marsooli, R.; Garcia, D.A.; Mirjalili, S. Enhancing the performance of hybrid wave-wind energy systems through a fast and adaptive chaotic multi-objective swarm optimisation method. *Appl. Energy* **2024**, 362, 122955. [[Google Scholar](#)] [[CrossRef](#)]
9. Rasool, S.; Muttaqi, K.M.; Sutanto, D. A Novel Configuration of a Hybrid Offshore Wind-Wave Energy Conversion System and Its Controls for a Remote Area Power Supply. *IEEE Trans. Ind. Appl.* **2022**, 58, 7805–7817. [[Google Scholar](#)] [[CrossRef](#)]
10. Majout, B.; Bossoufi, B.; Karim, M.; Skruch, P.; Mobayen, S.; El Mourabit, Y.; Laggoun, Z.E.Z. Artificial neural network-based direct power control to enhance the performance of a PMSG-wind energy conversion system under real wind speed and parameter uncertainties: An experimental validation. *Energy Rep.* **2024**, 11, 4356–4378. [[Google Scholar](#)] [[CrossRef](#)]
11. Maafa, A.; Abdelghani, Y.; Mellah, H.; Smail, H.; Sahraoui, H. Optimization of the Powers Exchanged between a Cascaded Doubly Fed Induction Generator and the Grid

- with a Matrix Converter. Eurasia Proc. Sci. Technol. Eng. Math. **2023**, 26, 700–709. [[Google Scholar](#)] [[CrossRef](#)]
12. Milles, A.; Merabet, E.; Benbouhenni, H.; Debdouche, N.; Colak, I. Robust control technique for wind turbine system with interval type-2 fuzzy strategy on a dual star induction generator. Energy Rep. **2024**, 11, 2715–2736. [[Google Scholar](#)] [[CrossRef](#)]
 13. Hossain, M.A.; Chakraborty, R.K.; Elsayah, S.; Gray, E.; Ryan, M.J. Predicting Wind Power Generation Using Hybrid Deep Learning with Optimization. IEEE Trans. Appl. Supercond. **2021**, 31, 06013055. [[Google Scholar](#)] [[CrossRef](#)]
 14. Kushwaha, A.; Gopal, M.; Singh, B. Q-Learning based Maximum Power Extraction for Wind Energy Conversion System with Variable Wind Speed. IEEE Trans. Energy Convers. **2020**, 35, 1160–1170. [[Google Scholar](#)] [[CrossRef](#)]
 15. Li, Y.; Yin, P.-K.; Chen, F.-B. Prediction of wind load power spectrum on high-rise buildings by various machine-learning algorithms. Structures **2024**, 67, 107015. [[Google Scholar](#)] [[CrossRef](#)]
 16. Maafa, A.; Mellah, H.; Ghedamsi, K.; Aouzellag, D. Improvement of Sliding Mode Control Strategy Founded on Cascaded Doubly Fed Induction Generator Powered by a Matrix Converter. Eng. Technol. Appl. Sci. Res. **2022**, 12, 9217–9223. [[Google Scholar](#)] [[CrossRef](#)]
 17. Li, N.; He, F.; Ma, W.; Wang, R.; Zhang, X. Wind Power Prediction of Kernel Extreme Learning Machine Based on Differential Evolution Algorithm and Cross Validation Algorithm. IEEE Access **2020**, 8, 68874–68882. [[Google Scholar](#)] [[CrossRef](#)]
 18. Dineshkumar, C.; Jeong, J.H.; Joo, Y.H. Observer-based fuzzy control for fractional order PMSG wind turbine systems with adaptive quantized-mechanism. Commun. Nonlinear Sci. Numer. Simul. **2024**, 136, 108087. [[Google Scholar](#)] [[CrossRef](#)]
 19. Benbouhenni, H.; Bizon, N.; Mosaad, M.I.; Colak, I.; Djilali, A.B.; Gasmi, H. Enhancement of the power quality of DFIG-based dual-rotor wind turbine systems using fractional order fuzzy controller. Expert Syst. Appl. **2024**, 238, 121695. [[Google Scholar](#)] [[CrossRef](#)]
 20. Wadawa, B.; Errami, Y.; Obbadi, A.; Sahnoun, S. Robustification of the H_∞ controller combined with fuzzy logic and PI&PID-Fd for hybrid control of Wind Energy Conversion System Connected to the Power Grid Based on DFIG. Energy Rep. **2021**, 7, 7539–7571. [[Google Scholar](#)]