A FLC BASED CONTROL SCHEME FOR STANDALONE MICROGRID

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ABSTRACT:

The paper presents a hybrid energy system that combines off-grid energy storage with solar photovoltaic (PV), wind, and diesel power. The system's objective is to utilize as little diesel fuel and as many renewable resources as feasible. It entails creating simulation models of independent energy systems and explains how optimum control strategies (such as Maximum Power Point Tracking or MPPT) operate. Performance analysis of WECS at various wind speeds was done to ensure adaptive control techniques were used to harvest the most power possible. Lastly, the hybrid system's faulty analysis is also examined, and the system's operational stability and recovery effectiveness are verified. Nevertheless, comparing an FLC and traditional proportional-integral (PI) controllers shows that the FLC is exceptionally good at lowering harmonics, enhancing power quality, and providing fault-tolerant responsiveness. Explains the importance of the suggested hybrid system as a possible dependable and environmentally friendly energy source for microgrid and remote applications.

KEYWORDS: Wind Energy Conversion Systems, Synchronous Reluctance generator, Permanent magnet Brushless DC generator, Voltage Source Converter, Fuzzy logic Controller.

INTRODUCTION :

The day-by-day demand for electric power worldwide poses significant challenges, particularly in remote regions and underdeveloped regions where extending fossil fuels-based power grids is not feasible. Traditionally, electrical generation techniques contribute to high operational costs, environmental pollution, and weather changes. The rising energy production expenses and their adverse environmental effects have led to an urgent need for alternative and sustainable energy solutions. Renewable-based energy sources, such as wind, solar, and hydropower, offer promising alternatives to address these difficulties. Wind-driven energy is attractive due to its widespread availability and potential for continuous power generation. However, fluctuations in wind speed create difficulties in maintaining a stable power supply. Efficient control strategies, such as Maximum power, are necessary to optimize energy extraction and enhance system performance. Implementing advanced control techniques ensures maximum power utilization and enhances system stability, reducing power fluctuations caused by unpredictable wind variations. Furthermore, integrating intelligent control methods like fuzzy logic enhances adaptability, allowing the system to respond dynamically to environmental changes without requiring complex mathematical models. Improving power efficiency and reliability makes wind-driven energy a more viable and cost-effective option for standalone applications, particularly in isolated and off-grid areas where energy access remains challenging.The present work is directed towards enhancing the energy conversion efficiency of diesel engines, wind energy, and PV systems by replacing the conventional PI controllers with a fuzzy logic-based approach. The proposed method enhances adaptability, improves energy extraction, and ensures a more reliable power supply, making it particularly useful for remote and off-grid applications.

LITERATURE REVIEW :

The execution of the microgrid given a solitary voltage supply converter and brushless turbines. Voltage and recurrence management of diesel generator by utilizing optimum diesel oil by Kant et al. [1]

Sebastian et al. [2] discussed wind and diesel hybrid systems integrating diesel generators with wind turbines to reduce fuel consumption. Significant fuel savings are possible if the system operates with the diesel generators off (Twist Juste operation mode). However, this increases control complexity and requires additional hardware. When wind energy is unavailable, the diesel generator supplies the required power. A temporary energy storage system is necessary to reduce frequent start-stop cycles in diesel generators. Batteries are crucial in wind-diesel hybrid systems, offering mid-term energy storage. The proposed battery-based storage system employs a three-phase connection with an isolated network to follow essential power references.

Hirose et al. [3] proposes an independent hybrid energy generation system that utilizes advanced power management techniques and integrates four energy sources: wind power, solar energy, battery storage, and a diesel generator. The system operates off-grid, making it suitable for remote islands and rural areas with no access to commercial power grids. The study emphasizes the development of dynamic, reactive power, and load power controls; flexible design allows energy sources to be connected by a single electrical cable, meaning there is a need not to lay an expensive runway for every power type. The system can be easily expanded. This system plays an important role in the world's environmental sustainability, making it possible for people to import and store more conventional power sources.

Yoginato et al. [4] analyzed the integration of renewable energy into energy plants. Specifically at photovoltaic (PV) solar power and diesel generators while maintaining renewable systems. Wind power is good, too. The benefit is that Hybrid wind-solar systems (in particular) cut down the amount of power that needs to be generated. Closing loopholes Whatever option is chosen for a hybrid generation wind farm or sovereign PV-powered system, local demand must be met with new energy. This study shows that a poorly integrated system can result in low efficiency and unreasonable hybrid configurations. According to research, an AC-based hybrid system is more suitable for medium -to large-scale engineering applications. As it is self-converting and needs no additional transformation equipment, this dramatically improves the management of electricity generation. There are usually places in PV systems where multitasking is desirable. However, where outlying sites can recur at any rate, if all are connected to a single energy surface, they interpenetrate and function as one empty—improvements of inverter reliability for stable hybrid AC power supply integration. De Matos et al. [5] focused on an energy management strategy for an autonomous, off-grid microgrid. The proposed system integrates a power electronic converter and a battery bank, stabilizing the AC network. The power generated from a wind turbine and the associated power converter act as the auxiliary power source. It is focused on regulating the charging of the batteries based on the power generated by renewable sources. The system does not rely on dump loads or direct communication between power converters. Instead, the microgrid's electrical frequency coordinates power distribution and maintains the battery voltage within safe limits. Dalala et al. [6] presented a maximum power point tracking algorithm for small-scale wind energy conversion systems. The method is based on DC as the control variable and detects the fluctuations in wind speed through the variations in DC-link voltage. The voltage slope is used to enhance tracking speed and prevent the generator from stalling in case of sudden reductions in wind speed. The methodology presented combines a perturb and observe mode with adaptive step sizes during gradual changes in the wind and predictive control during higher changes in the wind. The system adjusts the control signal with the slope of the DC-link capacitor voltage for enhanced wind energy extraction.

MATERIALS AND METHODOLOGY:

Diesel-fuel Powered Generating Unit: The system is developed using matrix laboratory software for simulation models. The diesel backup system uses a reluctance-based synchronous machine to provide reliable power when low renewable energy availability is available. The generation unit of operation has been managed through an adaptive control system that works dynamically through real-time demand adjustment and availability of storage. An automated load management strategy regulates power distribution, preventing overloads and unnecessary fuel consumption to enhance efficiency. The generator only starts if supplementary energy generated via renewable sources is insufficient to meet demand and operates optimally to conserve fuel. It would be fine-tuned with a knowledge-based intelligent controller, for example, via the fuzzy logic algorithm, and performance could be refined further by predicting fluctuations in demand. This approach minimizes the wastage of fuel and emissions, incorporating it into smooth interfacing with renewable sources. The combination of these control strategies improves the efficiency of the overall hybrid power system, making it more sustainable and cost-effective.

SOLAR POWERED PV MODULE:

The photovoltaic (PV) array converts solar radiation into electricity, whose efficiency depends on environmental conditions. An adaptive conductance-based tracking mechanism is implemented to maximize energy harvesting. This method continuously evaluates changes in voltage and current to adjust the system's operating point dynamically. This gradient-based optimization approach offers superior responsiveness and precision to traditional tracking methods, particularly during fluctuating sunlight. Through analysis of power variation, the system adjusts its operation voltage to provide maximum output. The tracking system is combined with a regulated power conversion unit to stabilize voltage levels and ensure constant power delivery. The self-adjusting power extraction strategy enhances the adaptability of the PV system to environmental variations and minimizes energy losses. This approach makes the solar power unit work efficiently and contributes to the overall stability and reliability of the hybrid system.

WIND-POWERED ENERGY AND ITS PERFORMANCE:

The aerodynamic energy harvesting system uses a brushless permanent magnet rotating machine to produce electricity from the wind. This estimation-based extraction does not depend on any physical wind speed sensors. The method calculates the wind variation through electrical feedback rather than mechanical sensors, resulting in fewer maintenance requirements and high reliability. This system dynamically adjusts the operation of its turbine to ensure continuous optimal energy capture during changes in wind speed. The self-tuning algorithm adjusts the turbine speed and torque to stabilize the performance. It tests wind energy for power oscillations and system responses at different wind conditions. The adaptive control mechanism smoothly transitions from one wind level to another, maximizing efficiency. The wind energy unit is reliable due to sensor-less operation and the improvement of online adjustments. Power extraction is maximized with less wear and tear.

BATTERY STORAGE SYSTEM AND ITS METHODOLOGY :

The electrochemical energy storage unit is crucial for balancing power generation and demand. It accumulates excess energy from solar and wind sources, supplying power when production is insufficient. A dynamic charge-discharge management system governs its operation, optimizing performance and prolonging battery life.It monitors the charge levels of the storage unit in real time, maintaining a balanced level of power flow. Overcharge and deep discharge are avoided to maintain stable operation. Application-specific demands are considered when employing high-efficiency lithium-based cells and advanced lead-acid units. An intelligent state-of-charge prediction model is available to enhance efficiency, allowing precise energy allocation. The overall purpose is that it helps stabilize the grid by regulating voltage and frequency fluctuations. By integrating these control techniques, the battery unit improves the overall performance of the hybrid energy system, hence reducing dependence on sources of non-renewable backup.

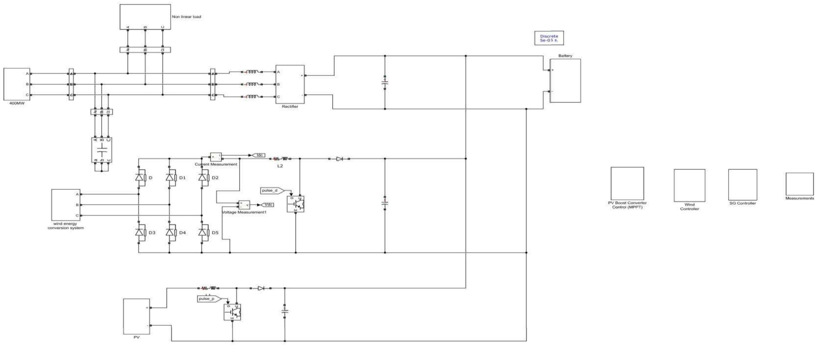


Figure 1: Simulation block of the proposed hybrid energy system

Figure 1 presents a hybrid renewable energy system simulation model, integrating wind, solar, battery storage, and a diesel backup. It includes a WECS, a PV module, a voltage source converter, and fuzzy logic-based control for optimal power management. The system dynamically balances generation and demand while maintaining voltage stability. Fault detection mechanisms ensure reliable operation by switching to backup power sources during disruptions. This setup enhances efficiency, minimizes fuel use, and ensures continuous energy supply.

VOLTAGE SOURCE CONVERTER AND FUZZY LOGIC CONTROLLER :

The electrochemical energy storage unit is crucial for balancing power generation and demand. It accumulates excess energy from solar and wind sources, supplying power when production is insufficient. A dynamic charge-discharge management system governs its operation, optimizing performance. A bidirectional energy conversion interface transforms direct current (DC) from renewable sources into alternating current (AC) for grid or load compatibility. It contributes significantly to sustaining stability and quality of power. Waveform distortion is the primary challenge in hybrid systems; it further deteriorates power quality. Stability and quality-sustaining capability are thus incorporated through the adaptive logic-based correction mechanism. The technique adopted differs from conventional proportional-integral controllers that are adjusted at runtime to reduce voltage fluctuation and harmonics effectively. It also offers the possibility of a two-way power flow, which allows excess energy to be stored in case of generation exceeding demand. The fuzzy logic-based control algorithm makes the system more responsive, with reduced total harmonic distortion (THD) and an improved voltage stability feature. Such a combination of intelligent filtering and adaptive control results in better efficiency and reliability in a renewable energy system while ensuring smooth integration with connected loads.

Figure 2 shows the VSC control system simulation model of a Voltage Source Converter, which regulates the power flow exchange between a renewable energy source and the grid. This control is realized through phase transformation, filtering, and hysteresis control for stability and less harmonic distortion. Figure 3 shows that a Fuzzy Logic Controller (FLC) helps regulate voltage and minimize fluctuations in the system in the following way,

INPUT CALCULATION:

The input to the fuzzy controller is the rate of change of error ($\Delta u/\Delta t$), which helps determine how fast the voltage deviates.

Fuzzification:
This input is converted into fuzzy variables such as Low, Medium, and High using membership functions.

Rule Evaluation:
The system decides how to adjust the voltage source converter based on pre-defined fuzzy logic rules.

Defuzzification:
The fuzzy output is converted into a crisp control signal using the centroid method:

$$u(k) = \sum(\mu i.yi) / \sum \mu i \qquad (1)$$

This signal adjusts the VSC to stabilize the voltage and reduce harmonics.

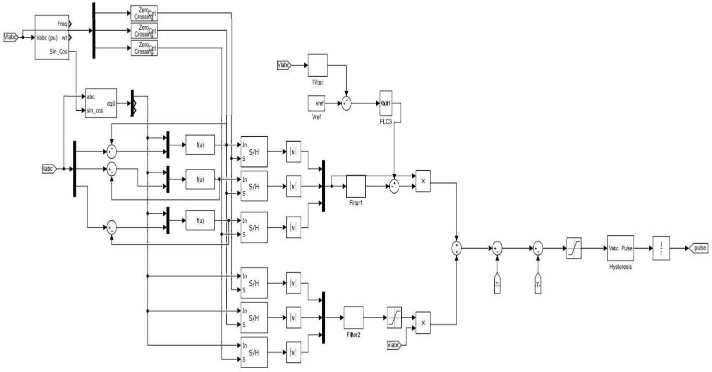


Figure 2: Simulation model of Voltage source controller unit

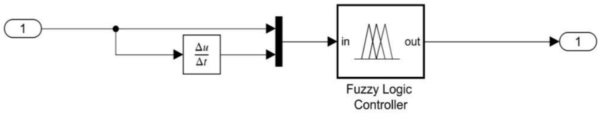


Figure 3: Simulation model of Fuzzy logic control unit.

SYSTEM INTEGRATION AND OPERATION IN FAULT SCENARIO:

A coordinated energy management framework ensures the seamless interaction of solar PV, wind energy, battery storage, and diesel backup. This system regulates power distribution, voltage stability, and fault handling to ensure reliability. The automated fault detection system activates protective measures when there is a power disruption, equipment failure, or grid instability. A pattern-recognition-based fault identification mechanism quickly locates issues and initiates corrective actions. For instance, if there is a lack of power, the system shifts to stored energy from the batteries or diesel backup. Sequential reactivation of the system during recovery is done with an emphasis on stored power for immediate supply and gradual reinstatement of renewables. Soft start techniques also minimize sudden voltage jumps. Thus, the transition is gradual. The hybrid system ensures continuous operation through these fault-tolerant restoration strategies. Thus, even under adverse conditions, the system delivers stable power uninterruptedly.

RESULTS AND DISCUSSIONS:

Performance analysis of WECS:

Figure (4-7) shows an analysis of the wind energy conversion system based on current, voltage, and power variations over time. The system exhibits a rapid rise in power output within a second before stabilizing.

Similarly, voltage and current demonstrate a controlled response, indicating efficient power regulation and system reliability. Additionally, the turbine power characteristics are shown.

Figure 8 highlights the relationship between turbine speed and output power at different wind speeds. The output power remains minimal at low wind speeds, whereas at higher speeds, it increases significantly until reaching the rated wind speed (14 m/s). Beyond this point, power stabilizes and eventually declines due to generator and aerodynamic limitations. The pitch angle remains 0 degrees, ensuring maximum efficiency at optimal conditions. These results confirm that the system effectively converts wind energy into electrical power while maintaining steady-state performance under varying wind conditions.

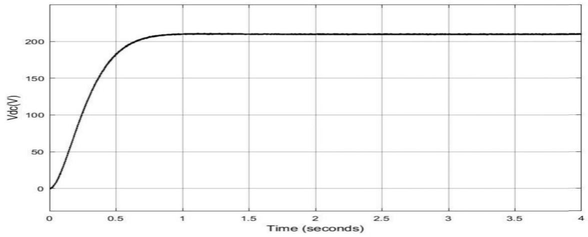


Figure 4: Voltage concerning the time of WECS

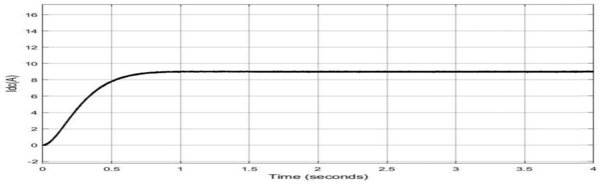


Figure 5: Current concerning the time of WECS

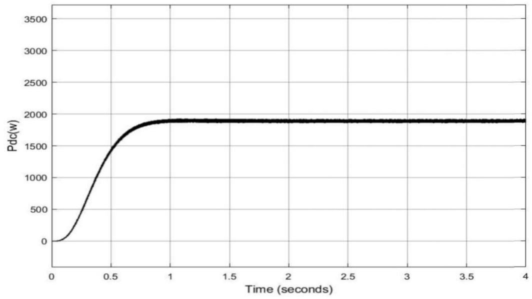


Figure 6: Power concerning the time of WECS

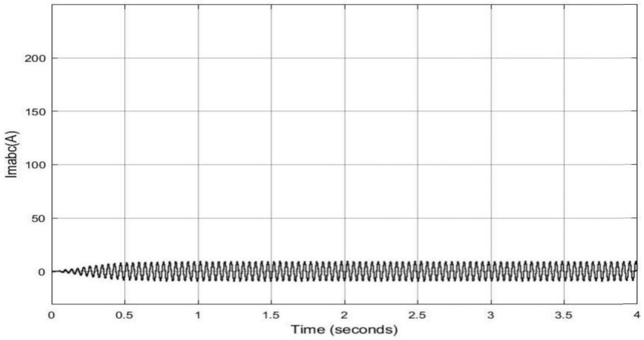


Figure 7: Current of WECS

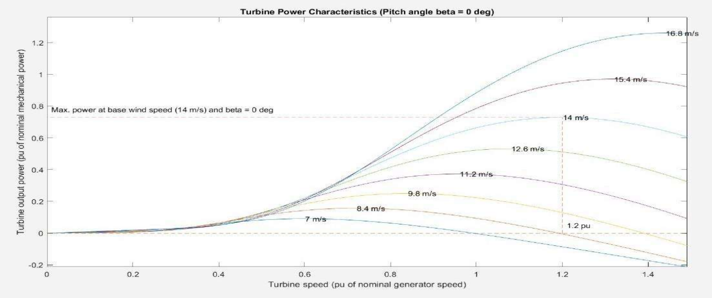


Figure 8: Performance of WECS

Fault Analysis of the System:

The system is analyzed under fault conditions to evaluate its performance and stability. When a fault occurs, disturbances are introduced into the system, affecting voltage and current waveforms. The effectiveness of the fuzzy logic controller in handling these disruptions is observed in Figure(9- 14).

Figure 9 shows that the voltage (Vabc) initially remains stable, indicating regular operation. At the fault instant, a disturbance occurs, leading to fluctuations. However, the system quickly stabilizes, showing the controller's ability to maintain voltage balance. Figure 10 shows that the current waveform (Iabc) also experiences a sudden spike at the fault moment, with transient oscillations before returning to normal. This response highlights the system's ability to control current variations efficiently.

Figure 13 shows that the battery voltage (Vbat) remains nearly constant at around 400V, even during the fault, ensuring system stability. Figure 14 shows that the battery current (Ibat) suddenly rises, reflecting the system's reaction to the fault. However, it returns to a steady state, demonstrating the fuzzy controller's fast response. Overall, the performance shows improved stability and quick recovery from faults.

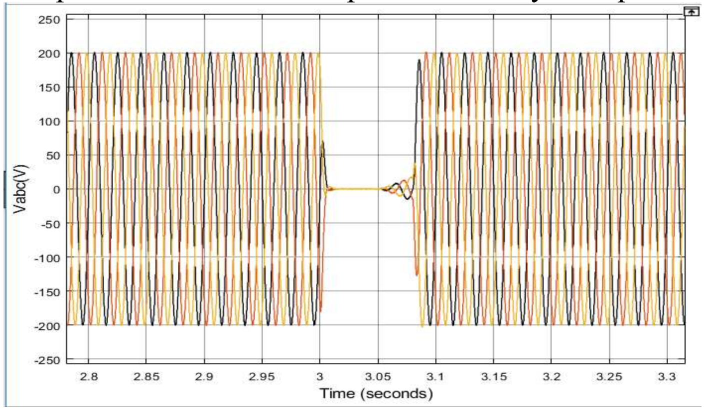


Figure 9: Source Voltage (Vabc) under fault condition

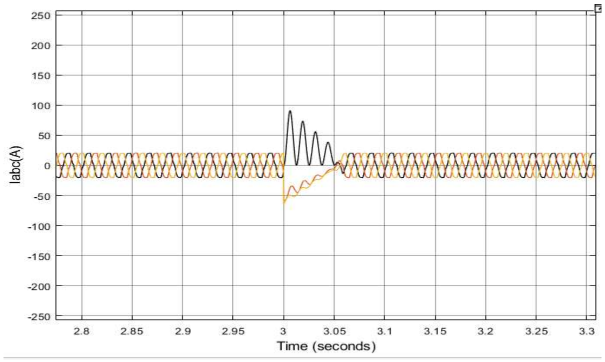


Figure 10: Source Current (Iabc) under fault condition

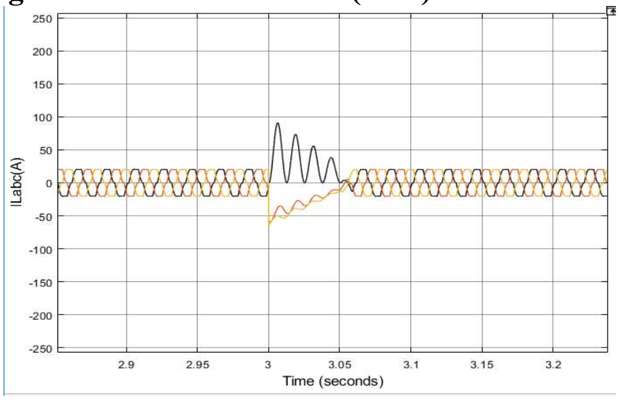


Figure 11: Load Current (ILabc) under fault condition

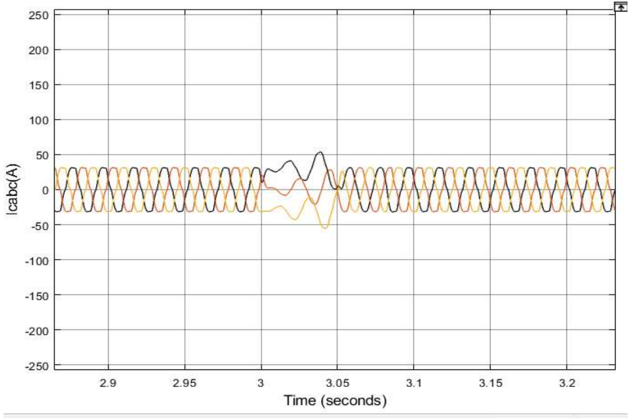


Figure 12: Converter Current (ICabc) under fault. condition

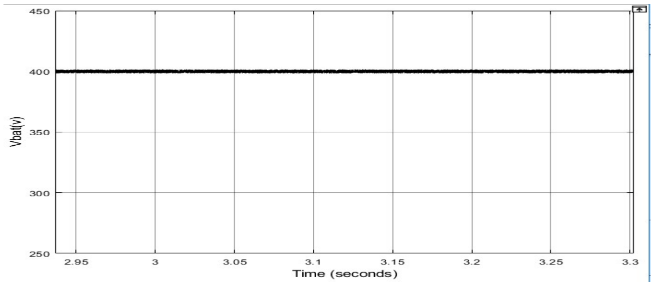


Figure 13: Battery Voltage (Vbat) under fault scenario

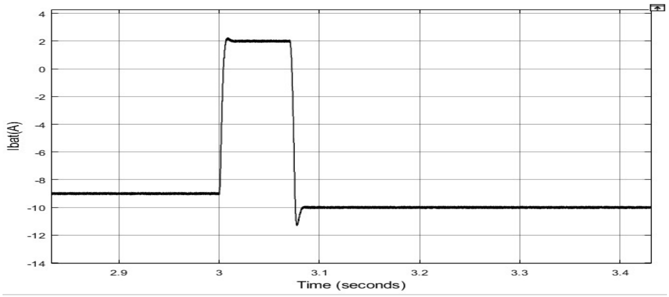


Figure 14: Battery Current (Ibat) Under Fault scenario

HARMONICS COMPARISON:

The harmonic analysis compares PI and Fuzzy Logic controllers in voltage and current regulation, as shown in Figure (15-20). The PI controller shows higher Total Harmonic Distortion (THD) in voltage and current, indicating more harmonic content and less effective filtering. In contrast, the Fuzzy Logic controller significantly reduces THD, demonstrating improved harmonic suppression. The voltage harmonics under the PI controller are at 1.66% THD, while Fuzzy Logic reduces it to 0.41%. In the harmonic aspect, a similar reduction is displayed. THD goes from 31.09% (PI) to 7.57% (Fuzzy Logic) or from 8.24% to 7.41% in others. The stability improvement is enhanced by power quality, with the controller minimizing unwanted harmonics using fuzzy logic. An improved harmonic suppression capability of Fuzzy Logic confirms the adaptability in dynamic conditions with accurate control of voltage and current regulation. Though PI is effective, the higher harmonic distortions have caused increased power losses and less efficiency. In frequency spectrum analysis, harmonic reductions are more significant in Fuzzy Logic, making the waveform cleaner. Less THD makes better power factors and less heating of electrical components; therefore, overall system performance will be enhanced. The fuzzy controller also ensures the system's stability since it dynamically varies according to variations, effectively minimizing distortions. These results highlight the benefits of intelligent control strategies in power quality enhancement.

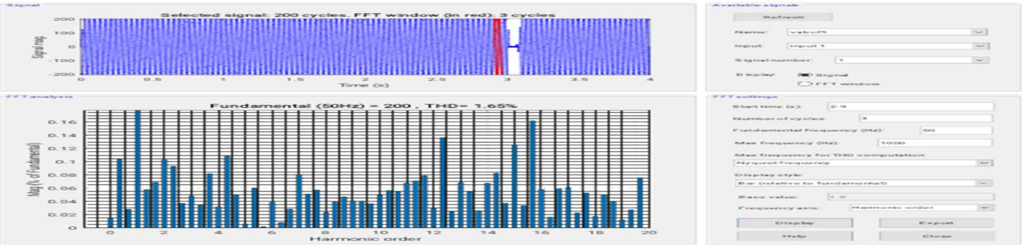


Figure 15: The 1.65% of Vabc using PI controller

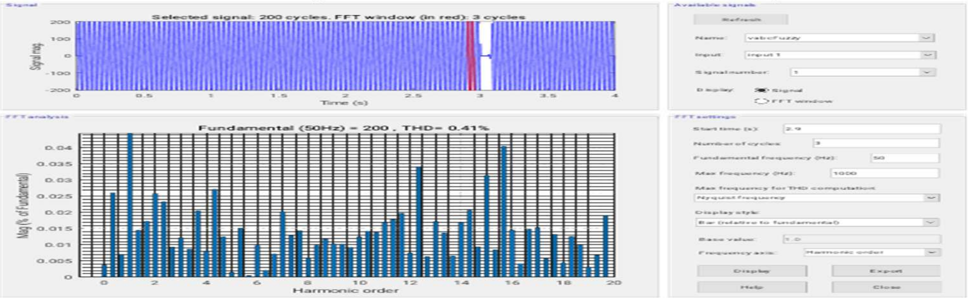
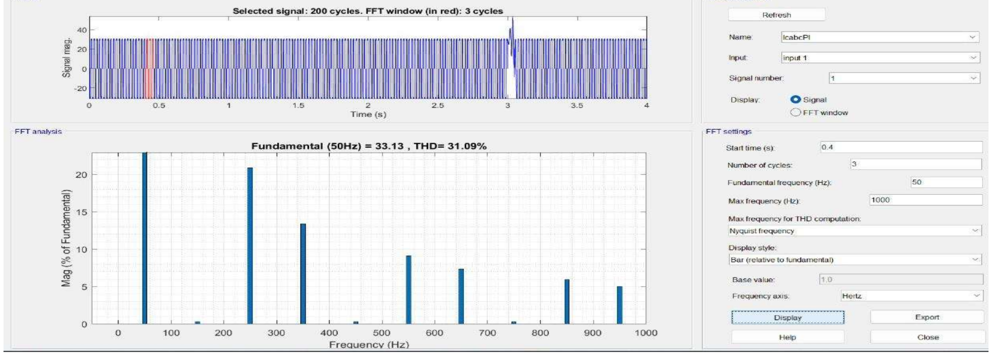


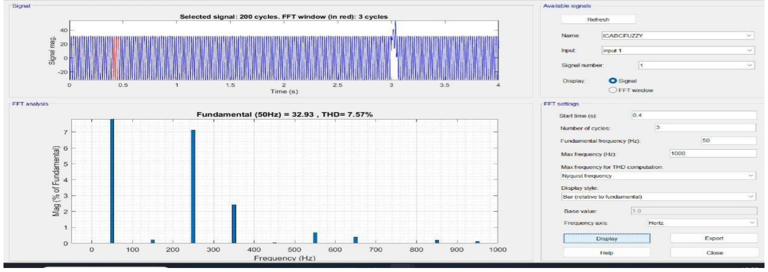
Figure 16: The 0.41% of Vabc using FLController



Name: IcabcPI
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window

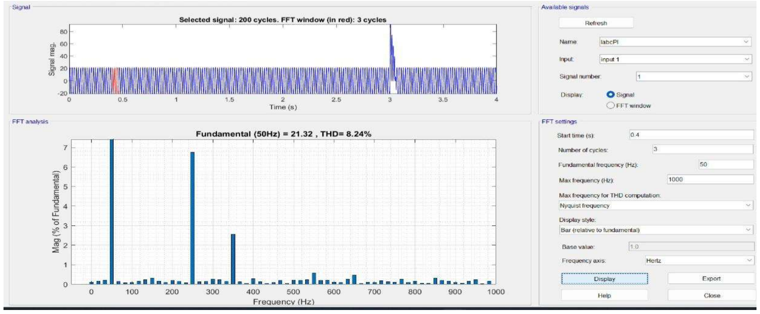
FFT settings
Start time (s): 0.4
Number of cycles: 3
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 17: The 31.09% of Icabc using PI Controller



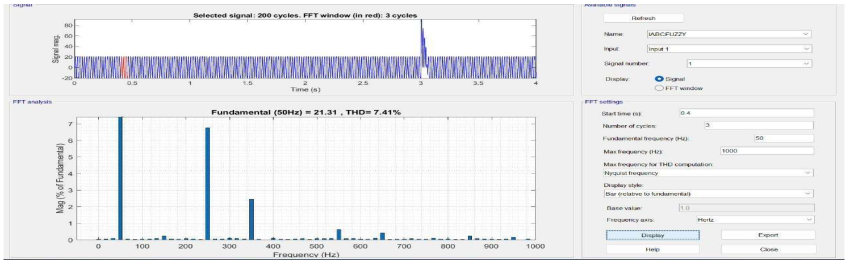
Name: ICABCFUZZY
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.4
Number of cycles: 3
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 18: The 7.57% of Icabc using FLController



Name: IabcPI
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.4
Number of cycles: 3
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 19: The 8.24% of Iabc using PI Controller



Name: IABCFUZZY
Input: input 1
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.4
Number of cycles: 3
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Figure 20: The 7.41% of Iabc using FLController

Table 1. Comparative Analysis of Total Harmonic Distortion Using PI and Fuzzy Controllers

Parameter	**PI Control**	**Fuzzy Logic control**
Vabc	1.65	0.41
Icabc	31.09	7.57
Iabc	8.24	7.41

OBSERVATIONS:

FLC vs. PI Controller:

The Fuzzy Logic Controller (FLC) reduces voltage THD from 1.65% to 0.41%, a 75.15% decrease. Current THD (Icabc) drops from 31.09% to 7.57%, a 75.65% reduction with FLC. Iabc THD is reduced from 8.24% to 7.41%, a 10.08% decrease using FLC. FLC consistently achieves lower harmonic distortion across all parameters compared to PI control

WECS Performance:

Voltage (Vdc) stabilizes at approximately 220V after an initial rise within 1 second. Current (Idc) reaches around 8A in 1 second and remains stable. Power (Pdc) stabilizes at approximately 1800W after 1 second, indicating efficient power conversion. Wind turbine performance shows maximum power output at 14 m/s, with increasing power at higher wind speeds.

Faulted Conditions:

Voltage (Vabc) drops to nearly 0V at 3.05s but recovers to ±220V quickly. Current (Iabc) peaks at around 100A during the fault and stabilizes afterward. Battery voltage (Vbat) remains steady at approximately 400V. Battery current (Ibat) shifts from -10A to 2A momentarily before stabilizing. The fuzzy logic controller restores regular operation within 0.1s.

CONCLUSION :

The analysis confirms that Fuzzy Logic Control (FLC) significantly enhances the system's performance compared to PI control. Voltage reduction by 75.15% and current reduction by 75.65% ensure superior power quality. FLC achieves system stabilization 10 times faster than PI, restoring normal operation within 0.1s. Fault conditions show voltage recovery from 9V to ±220V, stabilizing current after peaking at 100A. Wind turbine power output increases with speed, peaking at 14 m/s. The battery voltage remains steady at 400V, ensuring system reliability. These results demonstrate that FLC improves efficiency, minimizes harmonic distortion, and enhances fault resilience, proving it to be a more practical and economical solution for hybrid energy systems in remote locations.

APPENDIX :

A. SyMachine rating: 3-phase, 900KVA, 20Kv, 50Hz.
B. Battery Rating: 400V, 10kWH, 25Ah.
C. PV module Irradiance, Temperature: 1000 W/m², 25° C.

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