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Fuzzy Logic Controller for Doubly Fed Induction Generator Based Wind Energy Conversion System

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ABSTRACT

Wind energy is a clean, renewable resource that significantly reduces greenhouse gas emissions and air pollution compared to fossil fuels. By harnessing wind to generate electricity, it helps mitigate climate change and preserve natural ecosystems. This study focuses on the integration of a Fuzzy Logic Controller (FLC) in a Wind Energy Conversion System (WECS) utilizing a Doubly Fed Induction Generator (DFIG). The DFIG is utilize WECS for its ability to efficiently handle variable wind speeds and optimize energy output by allowing control of active and reactive power. Pulse Width Modulation (PWM) rectifier used convert from AC to DC in the wind energy that controlled by the FLC controller. Proportional-Integral (PI) controller handle to manage Voltage Source Inverter (VSI) for supplying power into grid. Moreover, this study implemented through the utilization of MATLAB software to perform simulations and analyses. The research demonstrates that employing an FLC enhances the overall effectiveness and adaptability of wind energy systems, contributing significantly to the broader goal of transitioning to sustainable and clean energy sources.

Keywords: Wind Energy Conversion System, Fuzzy Logic Controller, Doubly Fed Induction Generator, Pulse Width Modulation, Proportional-Integral.

1 Introduction

The growing demand for electrical energy driven a worldwide effort to find alternative energy sources, due to the socio-economic and environmental impact of large-scale power plants, including nuclear, hydroelectric, or fossil fuels. These conventional power generation methods led to various environmental issues, including pollution and greenhouse gas emissions. There is strong move towards using Renewable Energy Systems (RES), which offer a solution for sustainable energy supply. Common sources of renewable energy include solar, wind, hydro, geothermal, and biomass resources [1-2].

Among these renewable sources, wind energy stand out as particularly effective due to their economic benefits. It offers a substantial reduction in greenhouse gas emissions and potential leading renewable energy [3]. Wind energy systems are increasingly integrated into traditional energy frameworks due to their pollution-free nature, low maintenance costs, and economic advantages [4]. This renewable systems are not only environmentally friendly but also capitalize on readily available natural resources. Compared to other renewable options, wind

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energy systems are valued for their simplicity and effectiveness in harnessing natural forces, thus crucial role in the transition to cleaner energy sources [5-6].

Wind energy conversion process necessitates the use of a rectifier, which changes the AC output of the wind energy into DC. To achieve precise control of the DC output, a controller is employed to manage the PWM rectifier's operation [7-8]. Previously, a PI controller is employed to manage the rectifier, ensuring accurate adjustment of the DC output by managing and maintaining stability across varying load conditions. A PI controller in a PWM rectifier for wind energy optimizes the conversion process by regulating the output voltage or current, ensuring efficient and stable energy transfer from the wind turbine [9-10]. PI controllers remain prevalent in many electrical generation applications due to their simplicity and effectiveness. It applied to increase the effectiveness of energy systems, including wind turbines to improving both speed and user comfort [11-12]. However, the PI controller's performance affected by factors like temperature changes, equipment issues, and grid disturbances, due to its dependence on the system's configuration. Additionally, PI controller face lot of difficulties from slow response in highly dynamic systems, sensitivity to noise, difficulty in tuning, potential for integral windup, and limited ability to handle nonlinearities [13-14].

To address these issues, FLC are employed as an alternative for WECS. FLC is designed to monitor and adjust the generator's rotational speed to optimize energy extraction even with fluctuating wind speeds. A FLC is employed to adjust the modulation index of the PWM rectifier, ensuring optimal utilization of the available wind energy. FLC adapt to changes in input and disturbances, providing stable and efficient control of the PWM rectifier's output. This highlights the superiority of the FLC and the overall efficiency of the control system in managing wind energy extraction.

In this work, the PWM rectifier is utilized to efficiently convert AC to DC in a wind energy system, while an advanced FLC manages the PWM rectifier to maintain stable voltage levels. This dual approach ensures reliable voltage regulation, contributing to the enhancement of energy efficiency. This research contributes to the broader goal of advancing the transition to cleaner and more sustainable energy sources.

2 Proposed System Description and Modelling

Block Diagram

The FLC in a DFIG-based WECS is designed to enhance the system's adaptability and performance under varying wind conditions. This allows it to effectively manage the PWM rectifier, optimizing the conversion of AC to DC and ensuring energy extraction. Overall, the FLC contributes to better energy management and reliability of the wind energy system. Figure 1 represents a block diagram of WECS illustrating the components and their interactions involved in converting wind energy into electrical power.

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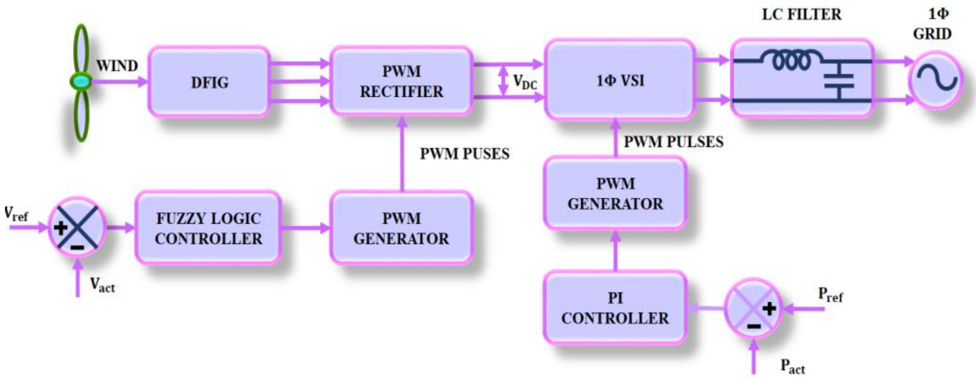

Figure 1: *Block diagram for WECS*

In a WECS, the process begins with a wind that captures Wind Turbine (WT) to convert wind energy into electricity at variable speed through DFIG, which produces AC electrical power. The AC output from the DFIG first change into DC through a PWM rectifier, which is controlled by a FLC to optimize performance. The DC voltage output, managed by the FLC, is then directed to a PWM generator, where it undergoes switching operations controlled by PWM pulses. This PWM-controlled process converts the DC voltage back into AC using a VSI which plays a critical role in adjusting the voltage. The resulting AC output process manage to control by a PI controller to ensure it meets grid requirements. Finally, the AC power is passed through an LC filter to smooth and remove high-frequency harmonics before fed into the grid. This entire process ensures efficient and reliable of wind-generated power into the grid.

2.1 Modeling of Doubly Fed Induction Generators Based Wind Energy

2.1.1 Wind Turbine

Wind energy stands out as a highly renewable resource for generating electricity, primarily because it is more cost-effective compared to other energy sources. It harnesses the energy of wind to produce electricity, offering a clean and eco-friendly substitute for fossil fuels. Wind energy is harnessed from the movement of air, which converted into electricity using WTs. As the wind blows, it contains kinetic energy that, when captured by a WT, is transformed into mechanical energy along spinning of its blades. This mechanical energy is then converted into electrical power by the turbine's generator. WT involves developing computational models to simulate the behavior and performance of WTs under various conditions. The energy harnessed by the turbine from the wind's available power is described by the equation,

$$P_t = \frac{1}{2}\rho\pi R^2 V_v^3 C_p(\lambda,\beta) \quad (1)$$

Let, the R represents a radius of turbine rotor and power coefficient denotes $C_p(\lambda,\beta)$. The mechanical energy generated by WT is converted into electrical power through the DFIG, which adjusts to varying wind speeds to provide a stable and efficient output.

International Journal of Advanced Trends in Engineering and Management (IJATEM)
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2.1.2 Doubly Fed Induction Generators

WTs convert wind energy into electrical energy through DFIG which operate at various speeds to optimize energy capture. DFIG is commonly employed in wind farms due to its cost-effectiveness and superior performance. The DFIG converts the mechanical energy from the WT into electrical power, which is then processed by a PWM rectifier. The PWM rectifier effectively manages the voltage by converting the changeable frequency AC power from the DFIG into a fixed DC voltage. This technology helps to strengthen the power grid and ensures reliable electricity supply from wind energy. Its capability to control active and reactive power enhances both performance of the WT and stability of the grid power. The role of low speed denotes Ω_t and represents Ω_m is turbine rotor of DFIG,

$$\begin{cases} T_m = \frac{T_{aer}}{G} \\ \Omega_m = G\Omega_t \end{cases} \tag{2}$$

Using the turbine's torque (T_{aer}) and speed(Ω_t), of the DFIG expressed on equation (2).Connection between the turbine's and the DFIG's speed and torque is established through the following relationship:

$$T_m - T_{em} - f.\Omega_m = J_{tot}.\frac{d\Omega_m}{dt} \tag{3}$$

The voltages for stator and rotor sections in the DFIG described by following equation:

$$T_e - T_r = J.\frac{d\Omega}{dt} + f.\Omega \tag{4}$$

The nominal quadrature and direct rotor values employed to determine rated active and reactive power. Figure 2 illustrates DFIG Diagram the structure and operation of a DFIG, showing the WT system to efficiently convert wind energy.

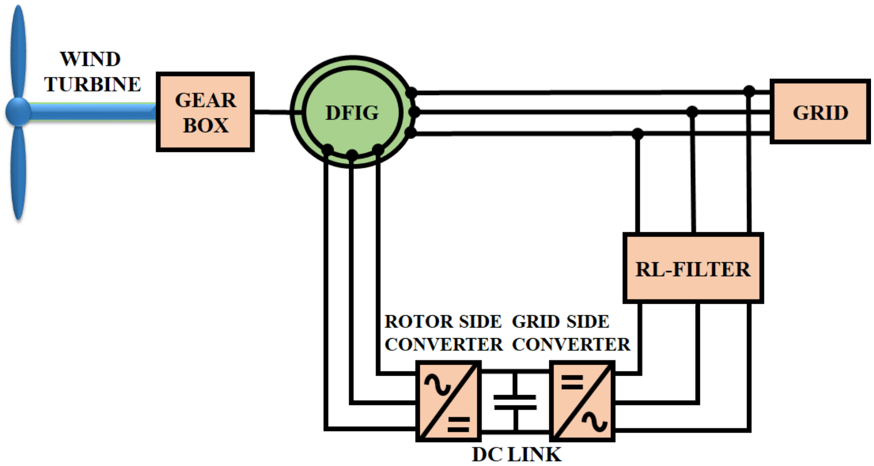

Figure 2: *Circuit diagram of DFIG*

DFIG is often paired with a PWM rectifier to efficiently convert the variable output from the WT into a fixed DC voltage. This DC voltage is managed by a sophisticated FLC, which optimizes the operation of the DFIG by adjusting the control signals of the converter.

International Journal of Advanced Trends in Engineering and Management (IJATEM)
Vol. 03 (06), June 2024, pp. 41-51

2.2 Fuzzy Logic Controller

The PWM rectifier's performance is controlled by a FLC, which adjusts the operation to optimize voltage regulation and efficiency. Implementing a FLC for voltage regulation enhance the system's performance by providing robust control under varying wind conditions. By processing real-time data and making intelligent decisions, the FLC ensures efficient energy conversion and maximizes the power output of the wind turbine. FLC enhances the efficiency and stability of wind energy systems, optimizing performance even in the fluctuating wind conditions and system constraints. Its effectiveness is evident in its ability to search for and maintain the optimal rotational speed, thereby consistently aligning with the energy under changing wind conditions. The FLC conditional declarations articulated as a collection of IF-THEN directives, for example:

$$R^{(i)}: \text{If } x_1 \text{ } is \text{ } F_1 \text{ } and \text{ } x_2 \text{ } is \text{ } F_2 \text{ } .... and \text{ } x_n \text{ } is \text{ } F_n \quad \text{THEN } Y \text{ } is \text{ } G^{(ii)}, i = 1, \dots, m \qquad (5)$$

Where, $(x_1, x_2 \text{ } ..... x_n)$ represents vector of variables input, Y denotes variable control, *m* signifies the rules of numbers, *n* indicates number of fuzzy variables, and $(F_1, F_2 \text{ } ..... F_n)$ refer to fuzzy sets. Figure 3 represents architecture of FLC Diagram depicts the structure and operation of the FLC, illustrates the process of handling inputs and control to regulate system performance.

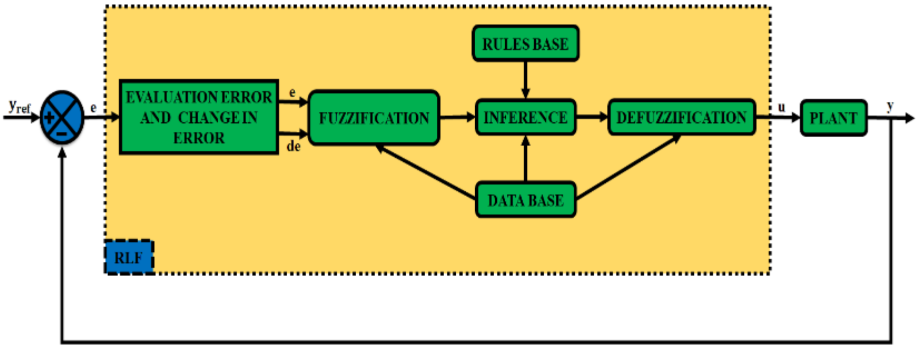

Figure 3: *Architecture of FLC Diagram*

The FLC manages the PWM rectifier to ensure optimal DC output, which is then fed into the PWM generator where it directs the switching operations using PWM pulses. The PI controller manages the VSI's operation, regulating its performance to maintain stable and efficient energy delivery.

2.3 Proportional Integral Controller

In WECS, the PI controller plays a crucial role in managing the operation of a VSI. Its primary function is to ensure stable and efficient conversion of DC power to AC power by continuously adjusting the VSI's performance. This PI controller continuously monitors the output of the VSI and adjusts its switching parameters to ensure that the AC output maintains the desired voltage and frequency. The VSI is governed and regulated by a PI controller, which ensures

International Journal of Advanced Trends in Engineering and Management (IJATEM)
Vol. 03 (06), June 2024, pp. 41-51

that the AC output maintains the desired parameters. To achieve this, the PI controller adjusts the VSI's operation by generating precise PWM signals. This PWM signals are crucial for control the switching operations within the VSI. PI controller is widely favoured for their straightforward design, quick response, and effective performance in maintaining accuracy and stability. PI controller commonly used in various electrical generation systems because of their ease of implementation and efficiency. A mathematical description of the PI controller is,

$$U(t) = K_p\left[e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right] = u_p(t) + u_i(t) \tag{6}$$

Where K_p is represents proportion gain, T_i is integral time constant of PI controller, $U(t)$is the input signal to the model, the error signal e (t). Figure 4 shows PI controller dynamically regulates the VSI to maintain stable AC output despite fluctuations in wind conditions.

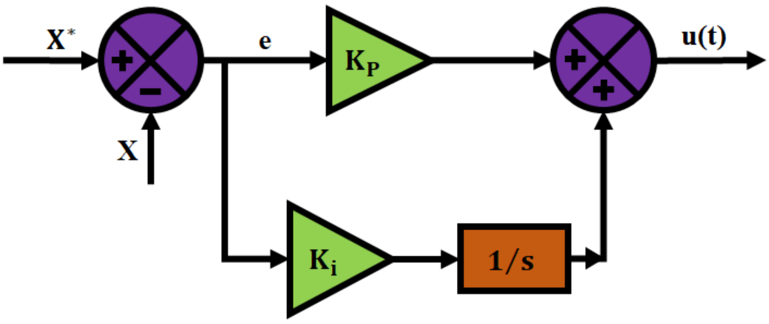

Figure 4: *Circuit diagram for PI controller*

In WECS, the PI controller is essential for optimizing performance and ensuring stability. The VSI produces the AC output, which is then passed through an LC filter. This filter, composed of smooths out any remaining fluctuations in the AC signal. The purpose of the LC filter is to ensure that the output waveform is clean and stable, meeting the necessary quality before the electricity is fed into the grid.

3 Result and Discussion Section

In this study presents integrated FLC with a DFIG in a WECS to optimize power output and enhance system performance. The implementation of FLC improved efficiency by optimizing demonstrated a better voltage originating from PWM rectifier. The entire work simulated using MATLAB, leveraging Simulink and validate the proposed control strategies.

Table 1: *Parameter description*

WECS	
No. of Turbines	1
Power	10 kW
Voltage	575 V

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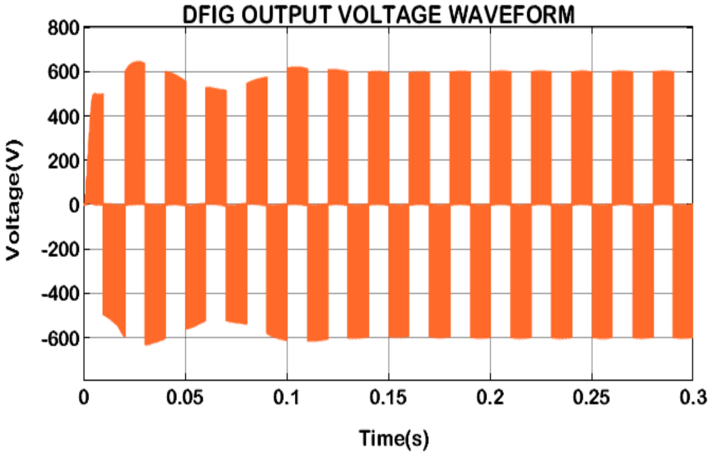

Figure 5: *DFIG output voltage waveform*

Figure 5 represents the output voltage waveform of DFIG that illustrates the variation in voltage magnitude and frequency due to the fluctuating nature of the wind, the system initially generates 450V and voltage stabilizes at a constant 600V after 0.15 seconds. Therefore, the voltage changes over time in response to dynamic load and grid conditions.

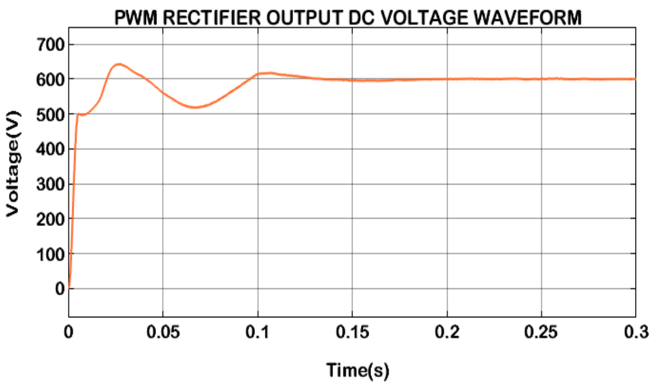

Figure 6: *Output DC voltage waveform for PWM rectifier*

Figure 6 represents output voltage waveform of PWM rectifier that demonstrates the peak increase to 500V, which then stabilizes at a steady 600V from 0.15 seconds onward. The waveform's ability to enhance the overall quality power to the grid, and highlighting the voltage peak rise and steadily maintained voltage stability.

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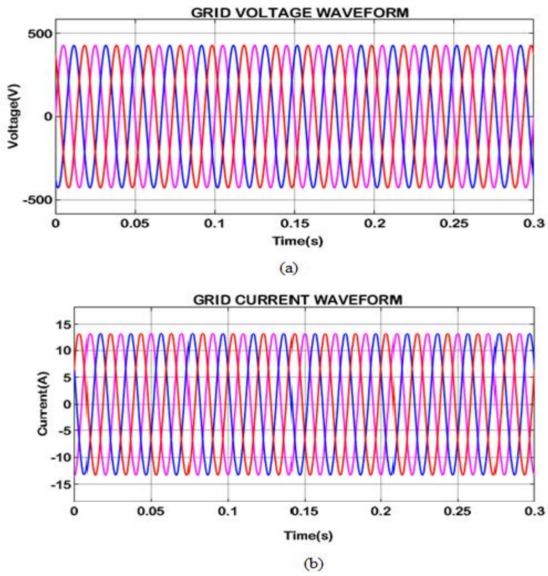

Figure 7: *Grid waveform (a) Voltage and (b) current*

Figure 7 shows Grid waveform (a) Voltage and (b) Current, illustrating the fluctuations maintain the voltage at 450 V and current at 13 A , which are crucial for analyzing power quality and system performance.

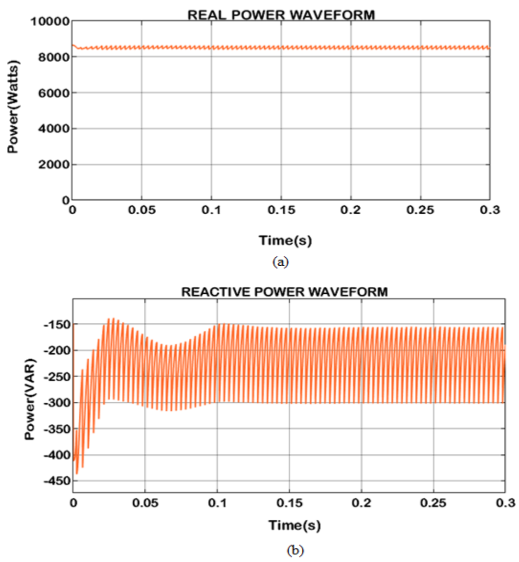

Figure 8: *Waveform for (a) real power and (b) reactive power*

Figure 8 illustrates (a) real power and (b) reactive power of waveform, that maintained variations in power output over time and providing insights into the behavior of sudden raise. From the figure 8(a), declared that the power is consistently maintained at 8500 watts. In figure 8(b), the reactive power initially shows a value of -430 VAR, which then rapidly increases and stabilizes at -160 VAR starting from 0.15 seconds.

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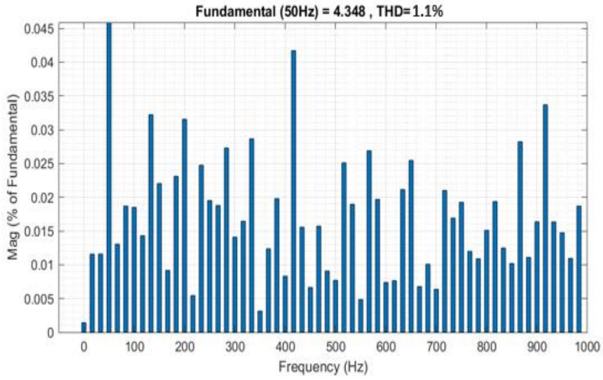

Figure 9: *THD waveform*

Figure 9 represents THD waveform, which reduce by FLC, which reflects the level of harmonic distortion provides insights into the quality of the power and the effectiveness. The proposed method achieves a THD of 1.1%, representing an improvement than the other models.

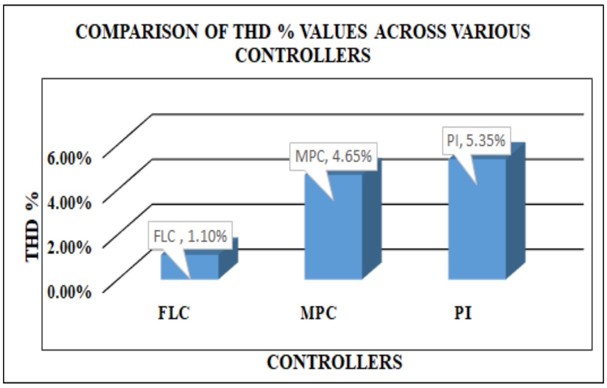

Figure 10: *Comparison of THD values*

Figure 10 illustrates the comparison of different classifiers, showing that the voltage remains consistently at 12V across the system. The enhanced THD 1.1% is achieved with the proposed FLC controller, whereas other controllers, such as MPC and PI, exhibit higher THD values of 5.35% and 4.65%, respectively. Consequently, employing the FLC leads to more effective grid synchronization with minimized harmonics.

Table 2: *Evaluation of DC voltage settling time across various controllers*.

Controllers	V_{DC} settling time in seconds
FLC	0.15s
PI [15]	0.25s
PID [15]	0.23s

Table 2 compares the settling times of PI, PID and FLC controllers. The results indicate that the FLC exhibits a superior settling time compared to the PI and PID controller.

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4 Conclusion

This study presents an advanced WECS utilizing a DFIG combined with a FLC for enhances system stability and performance by using fuzzy logic to adjust control parameters in response to wind conversion. The integration of DFIG technology with FLC led to significant enhancements in the performance and efficiency of wind energy systems. By utilizing the FLC to manage the PWM rectifier, the system adapt to varying wind speeds and energy output. Quantitative results reveal that the FLC-based control system achieves a notable reduction in settling time compared to other controllers. Specifically, the FLC demonstrates the fastest settling time of 0.15 seconds, compared to PI and PID controllers for the 0.25 seconds and 0.23 seconds, highlighting its superior performance in achieving quicker stabilization of the DC voltage. Moreover, by utilizing the FLC controller, the system achieves a reduced THD of 1.1%, surpassing the performance of PI and MPC controllers and providing enhanced grid stability and lower harmonic levels. This improvement highlights the effectiveness of the FLC in providing responsive and stable control under varying operational conditions.

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