Comparison of Fuzzy Logic and ANFIS-Based Pitch Control for Wind Turbines in High Wind Speed Region

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***Abstract* — In grid-connected wind energy systems, maintaining the generated power at a level consistent with grid demand plays a crucial role in ensuring stable operation, particularly under high wind speed conditions. This study focuses on Region 3, where the wind speed exceeds the rated value, and the control objective is to limit the turbine output power to an appropriate level in order to protect equipment and maintain power quality. To achieve this objective, the paper proposes the application of two intelligent control methods, namely the Fuzzy Logic Controller (FLC) and the Adaptive Neuro-Fuzzy Inference System (ANFIS), to regulate the turbine blade pitch angle. These two approaches are developed and evaluated independently to compare their effectiveness in maintaining stable power output under nonlinear and fluctuating wind conditions. The system model is developed and simulated using the MATLAB/Simulink platform to validate the effectiveness of the proposed control strategies. The results demonstrate that intelligent control methods can significantly improve power stability, reduce oscillations, limit mechanical stress, and enhance the lifespan of the equipment. Therefore, this study provides valuable insights for selecting appropriate control strategies for wind turbine operation under high wind speed conditions.**

Keywords- Wind Energy Conversion System, Pitch Angle Control, Fuzzy Logic Controller, ANFIS, Grid-Connected Wind Turbine

I. INTRODUCTION

In recent years, wind energy has emerged as a key alternative to fossil fuels, but its large-scale integration still faces challenges [1]. Wind variability causes power fluctuations that affect grid stability, while high wind speeds can lead to turbine overloading and damage.

To address these issues, advanced control strategies are required. In wind energy systems, control methods are typically designed based on turbine operating regions. This work targets Region 3, where the turbine operates under high wind speeds. In this region, pitch angle control plays a crucial role in limiting excess power and reducing mechanical stress, though controller design remains challenging due to system nonlinearities and uncertainties.

Therefore, this study proposes the use of a Fuzzy Logic Controller (FLC) and an Adaptive Neuro-Fuzzy Inference System (ANFIS) for pitch angle control. The FLC handles system uncertainties without requiring an accurate mathematical model, while ANFIS improves control performance through data-driven learning. A comparative analysis is conducted to evaluate their effectiveness in maintaining stable power output and enhancing system reliability under Region 3 operating conditions.

II. System Structure

A. Overall System Structure

A grid-integrated wind energy system based on a permanent magnet synchronous generator typically includes several main components: a wind turbine, the PMSG unit, a generator-side power converter, a grid-side converter, and associated control mechanisms [2]:

- The wind turbine extracts kinetic energy from the airflow and converts it into rotational torque.
- The PMSG transforms the mechanical rotation into AC electrical power.
- To ensure grid compatibility, the generated electrical power must be conditioned using a power conversion system.
  - The generator-side converter functions as an AC-to-DC rectifier and employs a Maximum Power Point Tracking (MPPT) technique to control rotor speed, thereby maximizing energy capture from the turbine
  - The grid-side converter acts as a DC-to-AC inverter, ensuring synchronization with the grid voltage, regulating the DC-link voltage, and managing both active and reactive power exchange.
- The two converters are interconnected via a DC-link capacitor, which acts as an intermediate energy storage component to compensate for short-term power variations.

B. Wind Turbine Characteristics

Wind turbine converts wind energy into mechanical power. It can operate at a fixed rotational speed while using pitch angle control to regulate the extracted power to a desired level.

The available wind power can be calculated using the following expression [3, 4]:

$$P_{wind} = \frac{1}{2} \times \rho \times A \times V_w^3 \tag{1}$$

Where: A represents the swept area of the blades, ρ denotes air density, and V_w indicates wind speed.

The mechanical output power of the wind turbine can be expressed as:

$$P_{tur} = 0.5 \times \rho \times A \times V_w^3 \times C_p(\lambda, \beta) \tag{2}$$

Where C_p denotes the power coefficient of the turbine.

Tip speed ratio:

$$\lambda = \frac{r \times w_{tur}}{V_w} \tag{3}$$

Where: w_{tur} represents the turbine's angular velocity, expressed in radians per second (rad/s).

Equation (3) defines the relationship between the tangential velocity at the blade tip and the wind speed.

The coefficient $C_p(\lambda, \beta)$ is a nonlinear steady-state function that characterizes the aerodynamic behavior of the wind turbine.The mathematical expression for the power coefficient C_p is defined as:

$$C_p(\lambda, \beta) = C_1 \left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right) e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \tag{4}$$

Typically, the power coefficient C_p is assumed to be around 0.47, indicating that only a fraction of the wind energy can be converted into useful mechanical power. The maximum power extraction occurs when the pitch angle β is equal to zero.

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III. System Modeling

A. Modeling of the PMSG.

In this paper, we develop the electrical mathematical model of the PMSG in the dq reference frame based on the differential equations of the stator currents as follows [5, 6]:

$$\frac{di_{ds}}{dt} = \frac{1}{L_d}\left(V_{ds} + \omega_e L_q i_{qs} - R_s i_{ds}\right) \tag{5}$$

$$\frac{di_{qs}}{dt} = \frac{1}{L_q}\left(V_{qs} - \omega_e L_d i_{ds} - \omega_e y_r - R_s i_{qs}\right) \tag{6}$$

where:

- R_s is the stator winding resistance; y_r is the rotor flux.
- L_d, L_q are the stator inductances along the d-axis and q-axis, respectively.
- i_{ds}, i_{qs} are the stator current components in the dq reference frame.
- ω_e is the electrical angular speed.
- V_{ds}, V_{qs} are the stator voltage components in the dq reference frame.

The electromagnetic torque of the PMSG can be expressed in terms of current and flux components in the dq reference frame as [4]:

$$T_e = \frac{3}{2}\rho\left(i_{qs} y_{ds} - i_{ds} y_{qs}\right) \tag{7}$$

By substituting the flux components, the above expression can be rewritten as:

$$T_e = \frac{3}{2}\rho\left(i_{qs} y_r + \left(L_d - L_q\right) i_{ds} i_{qs}\right) \tag{8}$$

where T_e denotes the electromagnetic torque and ρ is the number of pole pairs of the generator.

In addition to the electromagnetic model, the system dynamics are also described by the torque balance equation, representing the relationship between electromagnetic torque and mechanical torque as follows:

$$T_e - T_m = \frac{j}{p}\frac{d\omega}{dt} \tag{9}$$

B. Power Converter Model

The full-scale power converter is an essential power electronic component. Its primary function is to convert the energy generated by the generator into a form suitable for grid connection. The typical structure consists of two converters connected via a DC-link to ensure stable energy exchange. As a result, the system can effectively control power.

1) Machine-Side Converter Control (MSC)

The generator torque depends on two current components, i_{sd} and i_{sq}. Based on the mathematical model of the MSC, the control equations can be expressed as follows [5]:

$$L_d \frac{di_{sd}}{dt} + R_s i_{sd} = u_d \tag{10}$$

$$L_q \frac{di_{sq}}{dt} + R_s i_{sq} = u_q \tag{11}$$

These two expressions correspond to two decoupled first-order SISO systems, allowing independent control of i_{sd} and i_{sq} to track their reference values i_{sdref} and i_{sqref}.

For the control of i_{sd}, $(K_d(s))$ processes the error e_d to generate the control signal u_d. Similarly, $(K_q(s))$ processes the error e_q to produce the control signal u_q. The controllers are defined as follows:

$$K_d(s) = \frac{L_d s + R_s}{\tau_i s} \quad (12)$$

$$K_q(s) = \frac{L_q s + R_s}{\tau_i s} \quad (13)$$

From the control signals u_d and u_q, the stator voltage components V_{sd} and V_{sq} can be calculated based on the following relationships:

$$u_d = L_q \omega_r i_{sq} + V_{sd} \quad (14)$$

$$u_q = -L_d \omega_r i_{sd} - l_m \omega_r + V_{sq} \quad (15)$$

These voltages are then normalized with respect to the DC-link voltage to generate modulation signals for the converter. Specifically, by dividing by $V_{DC}/2$, the control signals in the d–q axes of the MSC are obtained as:

$$m_{d\_MSC} = (u_d - L_q \omega_r i_{sq}) \times \frac{2}{V_{DC}} \quad (16)$$

$$m_{q\_MSC} = (u_q + L_d \omega_r i_{sd} + l_m \omega_r) \times \frac{2}{V_{DC}} \quad (17)$$

2) Grid-Side Converter Control (GSC)

To achieve these goals, the converter is controlled using modulation signals defined in the dq reference frame. The control inputs m_d and m_q are derived from the voltage control signals u_d and u_q, as expressed in [7]:

$$m_d = \frac{2}{V_{DC}} \left(u_d - L\omega_0 i_q + V_{sd}\right) \quad (18)$$

$$m_q = \frac{2}{V_{DC}} \left(u_q + L\omega_0 i_d + V_{sq}\right) \quad (19)$$

These modulation signals are then applied to the converter to generate the output voltages. Based on the AC-side dynamic model, the grid currents in the dq frame are obtained as follows:

$$i_d = \frac{L\omega_0 i_q + V_{td} - V_{sd}}{Ls + R + r_{on}} \quad (20)$$

$$i_q = \frac{-L\omega_0 i_d + V_{tq} - V_{sq}}{Ls + R + r_{on}} \quad (21)$$

The control signals u_d and u_q in (17) and (18) are generated by two independent PI controllers. One controller regulates the d-axis current error $i_{sdref} - i_{sd}$, while the other controls the q-axis current error $i_{sqref} - i_{sq}$.

The reference currents are determined based on the desired active and reactive power:

$$i_{sdref}(t) = \frac{2}{3V_{sd}} P_{sref}(t) \quad (22)$$

$$i_{sqref}(t) = -\frac{2}{3V_{sd}} Q_{sref}(t) \quad (23)$$

In practice, the active power reference P_{sref} is generated by the DC-link voltage controller, while the reactive power reference Q_{sref} is often set to zero to ensure unity power factor operation.

DC-Voltage Power Port control model [7]:

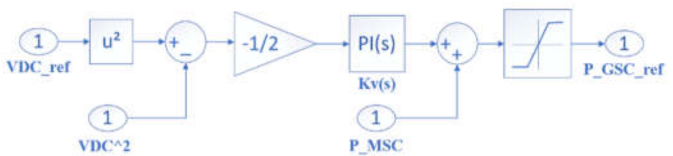

Figure 1. DC-Voltage Power Port control model

The DC-link voltage controller plays a key role in stabilizing the system. It generates the reference active power required to maintain the DC voltage at its desired value.

To synchronize the converter with the grid, a phase-locked loop (PLL) is employed. It provides the phase angle used for dq transformation. The grid voltage components in the dq frame are expressed as:

$$V_{sd} = \widehat{V}_s \cos(\omega_0 t + \theta_0 - \rho) \quad (24)$$

$$V_{sq} = \widehat{V}_s \sin(\omega_0 t + \theta_0 - \rho) \quad (25)$$

With ρ being the phase angle in the rotating reference frame and designed so that $\rho(t) = \omega_0 t + \theta_0$. The control objective is to regulate V_{sq} to zero, ensuring proper alignment between the rotating reference frame and the grid voltage.

The injected active and reactive powers can be calculated using the dq components of voltage and current:

$$P_s(t) = \frac{3}{2}\left[V_{sd}(t) i_d(t) + V_{sq}(t) i_q(t)\right] \quad (26)$$

$$Q_s(t) = \frac{3}{2}\left[-V_{sd}(t) i_q(t) + V_{sq}(t) i_d(t)\right] \quad (27)$$

These equations highlight that active and reactive power can be independently controlled through the d-axis and q-axis currents, respectively.

IV. CONTROLLER DESIGN

Each operating region (mode) of a wind turbine influences the power control strategy in wind energy systems. In practice, only Region 2 (medium wind speed) and Region 3 (high wind speed) require active control. In contrast, in Region 1, no control is needed due to insufficient wind energy, while in Region 4, the turbine is shut down to ensure system safety [8].

When the wind speed exceeds the rated value V_{nom} to the cut-out speed V_{out}, the control objective is no longer to maximize power extraction but to maintain the output power at the required level (if $P_{nc} < P_{dm}$) or at the rated value [9]. This ensures turbine safety and stable grid operation. Under these conditions, adjusting the blade pitch angle plays a crucial role in limiting power and reducing mechanical stress on the system [9, 10].

To enhance control performance in nonlinear and highly variable wind conditions, this study proposes the use of intelligent control methods, specifically Fuzzy Logic and Adaptive Neuro-Fuzzy Inference System, to determine appropriate control signals. This approach enables the system to respond flexibly to changing wind conditions while improving operational reliability [10,11].

A. Fuzzy Logic Controller

1) Introduction

The Fuzzy Logic Controller (FLC) is a control method based on fuzzy reasoning that does not require an accurate mathematical model of the system.

Structure of a Fuzzy Controller:

- Fuzzification: Converts crisp input values (feedback signals from the system output) into fuzzy values.
- Rule Base: A set of control rules constructed based on experience and expert knowledge.
- Inference Mechanism: Processes the control rules to generate an appropriate control action.
- Defuzzification: Converts the inferred fuzzy output into a crisp value to be used as the control signal.

2) Fuzzy Logic Controller for Pitch Angle

In Region 3 (high wind speed), the system does not continuously operate at maximum power point tracking. Instead, it follows a demanded power level to improve energy utilization efficiency, reduce the risk of overload, and extend equipment lifetime. Specifically, when the required power is lower than the rated value, the turbine operates accordingly at that level. Conversely, if the demanded power exceeds the rated limit, the system adjusts the output power to remain around the rated value, thereby ensuring safe operation of the entire system. To achieve the desired operating condition, a Fuzzy Logic Controller (FLC) is employed to flexibly regulate the blade pitch angle.

The structure of the FLC is described as follows: the input variables include the power error ΔP and the change in power error $\delta(\Delta P)$, while the output variable is the change in pitch angle $\delta\beta$. These quantities are defined as [12]:

$$\Delta P(k) = e = P_t(k) - P_{nom}(k) \tag{28}$$

$$\delta\big(\Delta P(k)\big) = de = \Delta P(k) - \Delta P(k-1) \tag{29}$$

The pitch angle is then updated according to:

$$\beta(k) = \beta(k-1) + \delta\beta(k) \tag{30}$$

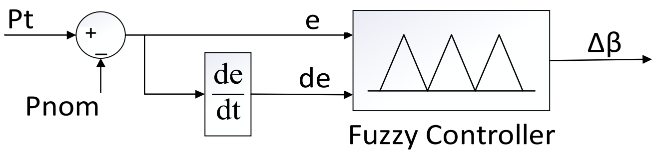

Figure 2. Block diagram of the pitch angle control system using a Fuzzy controller

In the fuzzy logic system developed in this study, each variable is represented by linguistic terms: Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS), and Positive Big (PB).

TABLE I. FUZZY RULE BASE FOR PITCH ANGLE CONTROL

e \ de	NB	NS	ZE	PS	PB
NB	NB	NB	NS	NS	ZE
NS	NB	NS	NS	ZE	ZE
ZE	NS	NS	ZE	PS	PS
PS	ZE	ZE	PS	PS	PB
PB	ZE	PS	PS	PB	PB

B. ANFIS

1) Introduction

To improve pitch angle control under highly variable and nonlinear wind conditions, the Adaptive Neuro-Fuzzy Inference System (ANFIS) is proposed. Compared to the conventional FLC, ANFIS combines: the ability to represent nonlinear relationships between power error, its rate of change, and wind speed with the pitch angle through fuzzy rules, the learning and adaptation capability of neural networks [13, 14].

As a result, ANFIS can automatically tune the parameters of membership functions and the rule base, allowing for a more accurate modeling of the nonlinear relationship between system states and control signals.

In Region 3, ANFIS is applied to regulate the pitch angle to maintain the generated power at the rated level or according to grid demand by learning the nonlinear relationship between system states and control signals.

2) Control Structure Description

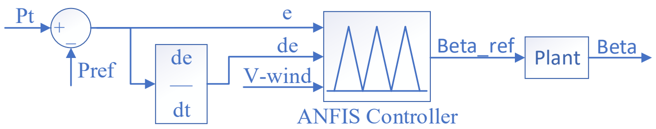

Figure 3. Block diagram of the pitch angle control system using an ANFIS controller

In Region 3, the controller adjusts the pitch angle to ensure the generated power tracks the reference value. The proposed ANFIS-based system integrates wind speed V_{wind} as a third input alongside the power error e and its rate of change de.This modification transforms the controller from a purely reactive mechanism into a Hybrid Feedback-Feedforward architecture.

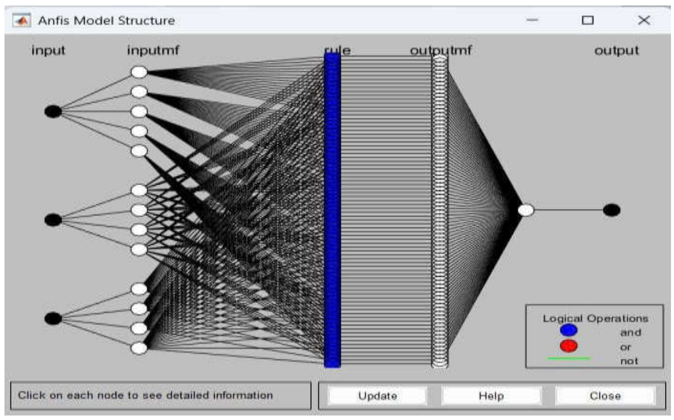

Figure 4. Structure of the ANFIS controller

Unlike previous studies that rely solely on e and de, including V_{wind} allows the controller to distinguish between different operating states: in many scenarios, even if the error conditions are identical, the system requires a completely different pitch angle to maintain stability under different wind speeds due to the third-order nonlinearity of wind power $P \propto V_{wind}^3$. By "looking ahead" and instantly recognizing the energy intensity of the incoming airflow, the controller can proactively adjust the pitch angle rather than reacting after a power overshoot has occurred.

The input variables are defined:

- Power error: $e(t) = P(t) - P_{ref}(t)$
- Rate of change of error: $\dot{e}(t) = de(t)/dt$
- Wind speed: $V_{vent}(t)$
- The output of the controller is: $\beta_{ref}(t)$

The input variables are partitioned:

- Power error e: consists of 5 input neurons
- Error derivative de: consists of 4 input neurons
- Wind speed V**:** consists of 4 input neurons

The total number of rules in the system is: 5×4×4=80.

In this study, the membership functions are chosen as Gaussian membership functions (gaussmf), characterized by smooth and continuous distributions, which help improve the training process of the ANFIS model.

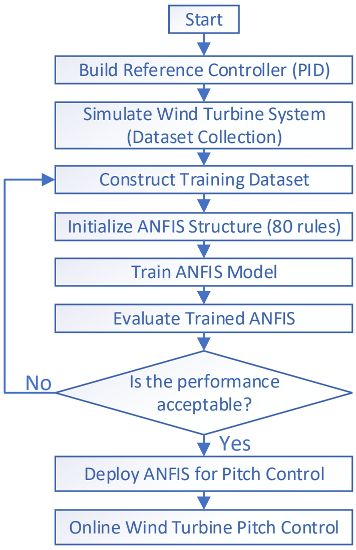

Figure 5. Procedure for developing the ANFIS controller [15]

This process enables ANFIS to learn directly from the behavior of the reference controller, thereby constructing an adaptive controller capable of effectively handling the nonlinearities and variations of the wind turbine system.

3) Anfis Training Data Generation

The training dataset for the ANFIS controller is designed to focus on Region III (high wind speed), specifically within the range of 13.5–20 m/s. A large dataset consisting of 12,000 samples is generated to ensure a high-density mapping of the nonlinear control surface. The wind speed range is divided into four sub-regions, each associated with a dedicated PI controller tuned for its corresponding operating condition. For each sub-region, 3,000 samples are collected, resulting in a total of 12,000 data points. Each sample includes the input–output pair (e, de, V_{wind}, β), where the sampling time is set to 0.01 s to capture the system dynamics with sufficient resolution. A hybrid learning algorithm is then applied to this dataset to optimize the parameters of the 80 fuzzy rules in the ANFIS structure. This approach enables the ANFIS controller to perform smooth interpolation across the entire operating range, effectively eliminating abrupt transitions between operating regions and significantly reducing overshoot.

V. Simulation and Results

A. Basic Simulation Setup

To evaluate the dynamic performance and robustness of the proposed control strategies for a 5 MW PMSG-based wind turbine system, a detailed simulation model was developed in the MATLAB/Simulink environment.

1) Wind Speed Variation Scenario:

The input wind speed is modeled as a step function to examine the system's response to sudden changes in aerodynamic torque. The wind profile is defined over a 3-second interval: **0s – 0.5s:** Wind speed starts at a baseline value of 14 m/s; **0.5s – 1.0s:** Wind speed abruptly increases to 16 m/s; **1.0s – 2.0s:** Wind speed decreases and stabilizes at 15 m/s; **2.0s – 2.4s:** A strong gust raises the wind speed to 17 m/s, pushing the system deep into the pitch control region; **2.4s – 3.0s:** Wind speed stabilizes at 16.5 m/s.

All wind speed values in this scenario are above the rated wind speed threshold (12 m/s), ensuring that the pitch control and power regulation mechanisms remain continuously active.

2) Parameters and Monitoring Objectives

The main signals monitored in the simulation are:

- P_{msc}: Electromagnetic power generated by the permanent magnet synchronous generator (PMSG).
- P_{gsc}: Active power delivered to the grid via the grid-side converter (GSC).
- ω_m: Generator angular speed.

B. FUZZY And ANFIS

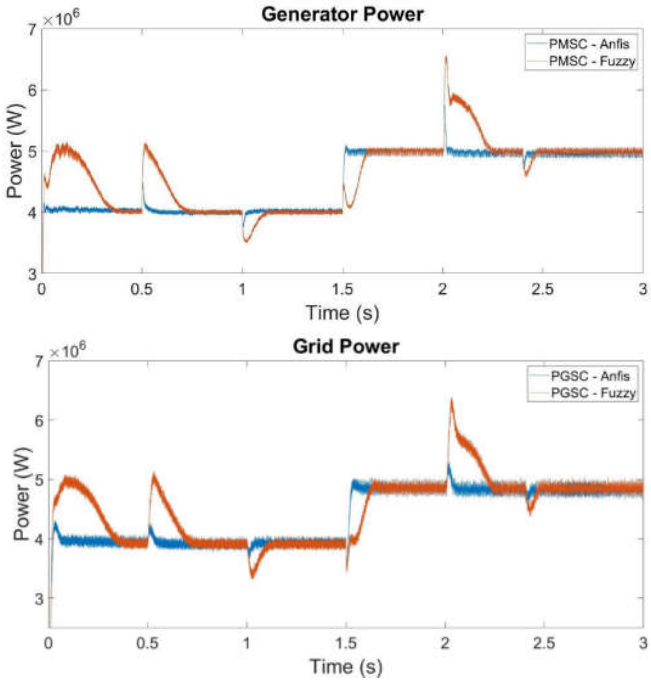

Figure 6. Comparison of generator power and grid power

At t = 2.0 s, when wind speed rises from 15 to 17 m/s, the PMSC power fluctuates significantly. The FUZZY controller produces a large overshoot (~30%) and settles in about 0.3 s to 5×10^6 W. In contrast, the ANFIS controller shows only ~1% overshoot with a much faster response (~0.05 s). A similar trend appears on the PGSC side. The FUZZY controller results in ~24% overshoot and ~0.25 s settling time, whereas ANFIS reduces overshoot to ~12% and shortens settling time to ~0.08 s. Overall, ANFIS enhances both PMSC power stability and PGSC power exchange with the grid, leading to reduced oscillations, faster dynamics, and improved reliability of the wind turbine system under sudden wind variations.

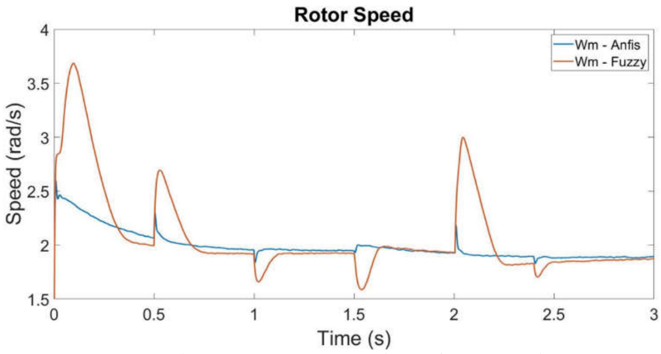

Figure 7. Comparison of rotor speed

From Figure 7, wind speed changes at t = 2.0 s cause noticeable rotor speed fluctuations. The FUZZY controller produces a large overshoot (~50%), peaking at about 3.0 rad/s versus the 2.0 rad/s steady state, with a settling time of ~0.25 s. In contrast, the ANFIS controller shows only ~5% overshoot (≈2.1 rad/s) and a much faster settling time of ~0.05 s.

These results show that ANFIS provides better rotor speed stability, reduces mechanical oscillations, and improves disturbance rejection. As a result, it enhances overall performance, lowers mechanical stress on the drive system, and increases the reliability of the wind turbine during operation..

DISCUSSION

The proposed controllers achieve fast and stable power regulation under varying wind conditions. In Region 3, the ANFIS controller maintains output power close to the reference while significantly reducing speed and power oscillations compared to the conventional Fuzzy approach.

ANFIS exhibits improved dynamic performance, including faster tracking, reduced overshoot, and better handling of nonlinearities through its data-driven learning capability. Incorporating wind speed as an additional input enhances adaptability to environmental variations, especially in high wind regions, thereby improving control accuracy and robustness. Moreover, Reduced rotor speed fluctuations lower mechanical stress, improving reliability and extending turbine lifespan. Overall, the proposed method ensures stable power and safe operation of grid-connected wind energy systems.

The proposed controllers demonstrate fast and stable power regulation under varying wind conditions. In Region 3, the ANFIS controller maintains the output power close to the reference value while significantly reducing speed and power oscillations compared to the conventional Fuzzy approach.

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