International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 5, Sep-Oct-2026, ISSN (Online): 2395-566X

Controlling the Pitch Angle of a Variable Wind Speed on a Wind Turbine using Fuzzy-Logic

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Abstract- One of the problems associated with wind energy is fluctuations in wind speed, which cause unstable and inefficient operation of variable-speed wind turbines, especially above the rated operating range where blade pitch control is necessary to adjust aerodynamic power and maintain generator speed within the rated range. This study investigates the effect of a Fuzzy Logic Controller (FLC) on pitch-angle regulation compared with the dynamic performance of a proportional-integral (PI) controller. The same wind turbine model, generator reference speed, wind-speed profile, and operating conditions were used for both controllers. The proposed Mamdani-type FLC is based on generator-speed error and its rate of change, using scaling, saturation, fuzzification, rule-based inference, and defuzzification to derive an appropriate pitch-angle command. The FLC adjusts the pitch command according to changing turbine operating conditions, enabling control of the aerodynamic power coefficient, aerodynamic torque, generator speed, and output power under wind-speed disturbances. Controller performance was evaluated using rise time, settling time, percentage overshoot, steady-state error, RMSE, IAE, ISE, ITAE, and ITSE. The FLC increased rise time from 1.7677 s to 3.2920 s, while reducing settling time from 17.2793 s to 5.5018 s and overshoot from 7.662% to 0.880%. Furthermore, the FLC reduced steady-state error, IAE, ITAE, and ITSE by 19.20%, 20.76%, 71.56%, and 61.97%, respectively. The PI controller produced lower RMSE and ISE. Overall, the results showed that FLC-based pitch-angle control provides better damping, disturbance rejection, steady-state accuracy, and long-term tracking performance under variable wind operation, although its initial response is slower than conventional PI control.

Keywords- Variable-speed wind turbine, Pitch angle control, Fuzzy Logic Controller, Proportional-Integral controller, Wind energy conversion system, Generator speed regulation, MATLAB/Simulink.

I. INTRODUCTION

One of the most encouraging renewable energy resources that help to decarbonize the energy sector and build energy sustainability, and to help move toward a cleaner energy generation is wind power system [1]. Today's variable-speed wind turbines can take advantage of wind speeds over the entire range by changing the rotor speed and, if required, the blades of the pitch angle. But the intermittent and stochastic nature of the wind power creates challenges for wind turbine operators. The dynamics of wind speed over time can cause variation in aerodynamic power, variation in rotor speeds, variation in mechanical torque, and added structural loads that can adversely impact energy conversion efficiency, and overall reliability of the wind energy conversion system [2].

The speed of the wind plays a significant role in the functionality of a wind turbine. The operating regions of the turbine, broken down by wind speed, are shown in figure 1. Different control objectives are needed in each region for efficient and safe turbine operation. The crossover from one of these regions to the other is significant because at or near rated operating condition, the control algorithm switches from maximizing aerodynamic power to minimizing the wind power when the turbine is operating at or near rated operating condition.

This study covers the principal operating region (full-load or pitch-control region) of region 3 as shown in figure 1. If the wind's speed is above its rated value, the turbine continues to generate aerodynamic power without control which results in the power produced and rotor speed being greater than the rated value. Hence, the active blade pitch control is added. As can be seen in figure 1, the pitch angle β increases from zero (β > 0), which causes the blades to swing away from the optimum aerodynamic position. This decreases the coefficient of drag and so limits the power and torque that can be taken from the wind. In this area, therefore, the basic aim of pitch control is to keep the output power of the generator and rotor speed as close as possible to their rated values, despite additional wind speed increases or changes. A good pitch control also helps to minimize excessive mechanical loadings and protects critical parts of the turbine [2].

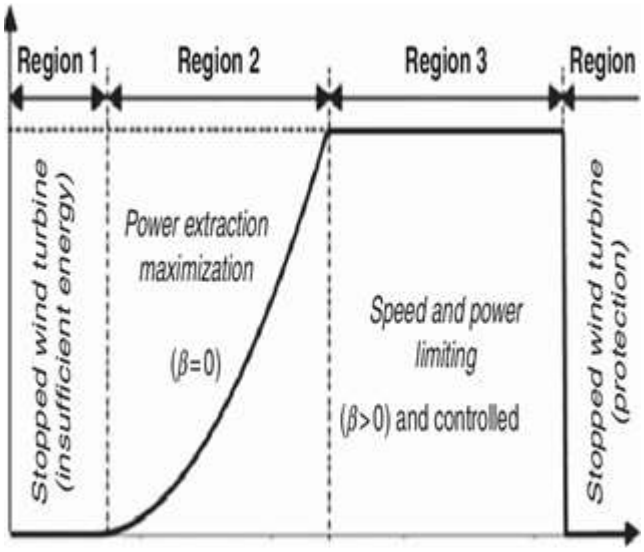

Figure 1. Wind Turbine Operating Regions and Pitch Control Zone

Of these operating regions, region 3 is one of the challenging control problems in which the controller is required to control the turbine even though the aerodynamic conditions continuously change. Pitch angle control is one of the most often used techniques for managing variable speed wind turbines above the rated wind speed [3]. By moving the blades in relation to the wind, the aerodynamic lift and drag forces on the blades can be changed. Consequently, the generator's mechanical power and aerodynamic torque may be regulated. In order to maintain the turbine's rated output, moderate rotor speed, and reduced mechanical stress, proper pitch control is necessary [4].

The traditional proportional-integral (PI) and proportional-integral derivative (PID) controllers have long been used in the pitch control of wind turbines due to their relatively simple structure, easy implementation, and well-known control performance [5]. But, the control performance of traditional controllers is degraded in highly nonlinear and time-varying conditions of the turbine. There are a number of variables that can affect the dynamics of a wind turbine, such as wind speed, the rotor speed, the aerodynamic torque, the pitch angle of the blades, the characteristics of the generator, and the inertia of the turbine. Therefore, a controller designed for a specific wind speed might not be able to maintain the same performance with a higher or lower wind speed, or with varying turbulent wind conditions [5].
Due to the limitations of fixed-parameter controllers, intelligent control techniques are now used for wind turbine pitch control.

Fuzzy Logic Control (FLC) is especially desirable as it is able to express a nonlinear control relationship in terms of linguistic rules instead of relying on a precise mathematical description of the turbine [6]. The fuzzy controller may take into consideration variables like rotor-speed error, power error or change in these variables to provide an appropriate pitch-angle command. The membership-function structure and rule base can be designed appropriately to allow the controller to react in different ways to small, moderate and severe deviations from the desired operating condition.

Fuzzy based control techniques have been proved to be potential solution in enhancing the performance of wind turbine in several studies. Pitch angle control, rotor speed control, power control, and lowering turbine loads under changeable wind have all been accomplished with fuzzy controllers [7]. Other studies have expanded on the fundamental fuzzy technique by employing fuzzy-PI, fuzzy-PID, adaptive fuzzy, and Adaptive Neuro-Fuzzy Inference System (ANFIS) configurations, which improved the robustness and transient performance when operating conditions varied [8].

Despite these developments, there are still a number of research issues that remain. Most previous works focus on the qualitative comparison of the waveforms of generator speed, output power, and pitch angle. While the information in a waveform plot can help give insight into the controller's behavior, using just a visual examination of the plot will not give a strong enough objective basis to decide which controller is more effective than the others. In addition, certain investigations are applied to just one performance attribute (e.g., power regulation or rotor-speed control), but do not examine transient response, steady-state accuracy, tracking error, and controller activity simultaneously [5]. Moreover, the impact of fuzzy membership functions and rule bases, which are the design and tuning of the FLC, are important factors that affect the performance of the FLC in different wind speeds [9].

Thus, a performance-oriented fuzzy pitch angle control strategy that can control the turbine to work near the rated condition and react to the wind variability and turbulence is needed. This type of controller must not only control the output power, but it should also have reasonable rotor speed stability, low steady state error, small overshoot and acceptable transient response. Meanwhile, the pitch-angle movement should be kept to a minimum since unnecessary actuator operation can result in greater mechanical wear and less practical utility of the control system [9].

In light of this, a fuzzy logic controller (FLC)-based pitch angle control technique for a variable-speed wind turbine under varying wind speed conditions is suggested for this study [10]. By adjusting the pitch angle of the blades in response to changes in the turbine's operating conditions, the suggested controller will regulate the aerodynamic power that the rotor absorbs. MATLAB/Simulink is used to model and test the controller for a range of wind speeds. The objectives are to minimize excessive power fluctuations, improve turbine speed stability, maintain the turbine's output power close to its rating value, and get a satisfactory transient response.

This novelty study is based on the application of a structured fuzzy logic pitch controller with focus on quantitative performance evaluation in terms of transient and error. The proposed FLC is assessed with a full range of standard performance measures instead of just relying on graphical interpretation. In order to maintain the turbine functioning under the designated settings, this method provides an objective assessment of the controller's performance under various wind speed conditions [11]. In order to examine the benefits and drawbacks of the fuzzy-based method, the study is also contrasted with the traditional PI control.

Therefore, the main contributions of the study are as follows:

1. Design of a fuzzy logic-based pitch angle controller of a variable speed wind turbine operating under varying wind speed conditions.
2. Designing appropriate fuzzy membership functions and control rules for effective blade pitch-angle control.
3. Implementation and evaluation of the suggested controller in various wind speed operating conditions using MATLAB/Simulink environment.
4. Comparative evaluation of the proposed FLC against conventional PI control based on both transient-response and error-based performance indices.
5. Rise time, settling time, percentage overshoot, steady-state error, RMSE, IAE, ISE, ITAE, and ITSE are all used in the quantitative evaluation of controller performance.
6. Assessment of the ability of the proposed controller to maintain stable turbine operation, regulate output power, and reduce undesirable response characteristics under variable wind conditions.

II. LITERATURE REVIEW

Pitch angle control is a crucial control mechanism to manage the aerodynamic power and rotational speed of a variable speed wind turbine when the wind speed exceeds the rated operating speed. A system that can most effectively use a broad range of wind speeds is called a variable speed wind energy conversion system.

If the wind power produced exceeds the turbine's nameplate rating, however, the rotor may spin too fast, the generator may generate more power than it is supposed to, the mechanical torque output may exceed allowable limits, and the loading on the rotor blades may exceed the turbine's design limits. Pitch angle control has thus been used to control the aerodynamic performance of the turbine and ensure that it runs safely within the desired operating range [12]. The power in the wind that is extracted aerodynamically by a wind turbine can be written as:

$$P_m = \frac{1}{2}\rho A C_p(\lambda, \beta) V_w^3 \quad (1)$$

Where Pm is the mechanical power extracted from the wind, (ρ-rho) is the air density, (A) is the turbine rotor swept area, (Cp) is the power coefficient, (λ, lambda) is the tip-speed ratio, (β-beta) is the blade pitch angle and (Vw) is the wind speed. This relationship shows that wind speed has a significant impact on the turbine's aerodynamic power. Pitch angle can be utilized to control the aerodynamic power supplied to the generator since it directly influences (Cp).

The main objective is often to harvest as much energy as feasible when wind speeds are lower than the rating. However, the goal is to control the wind's speed and power rather than producing as much energy as possible when the wind speed exceeds the rated speed.

The higher the pitch angle the closer the blades move towards the feathered position which decreases the aerodynamic power coefficient. Thus, the pitch control can effectively stop over-acceleration of the rotor and keep the turbine running near its nominal operating point [13].

The pitch control methods used in wind turbines have evolved from linear methods to nonlinear, intelligent, adaptive and hybrid controllers. Figure 2 shows the commonly used pitch angle control methods [12].

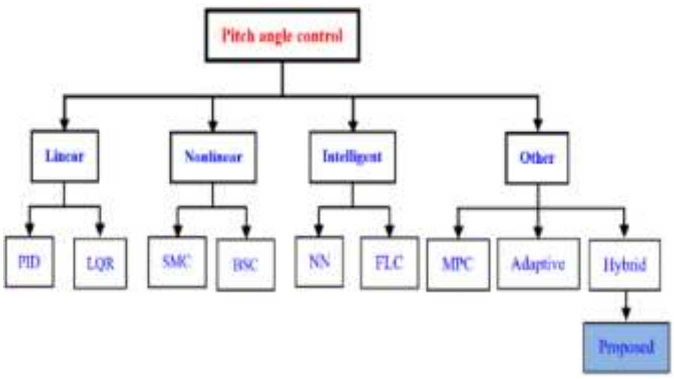

Figure 2. Classification of wind turbine pitch angle control strategies.

Conventional PI Control for Wind Turbine Pitch Regulation

Pitch control of wind turbines has made substantial use of the proportional-integral controller, a common conventional controller in industrial control applications [14]. A PI controller produces a control signal that is based on the current tracking error and the total accumulated error. The control law for it can be represented as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau) d\tau \qquad (2)$$

Where u(t) is controller output signal at time t (control action sent to the actuator), e(t) is tracking error at time t, defined as setpoint minus process variable $e(t) = r(t) - y(t)$, K_p is proportional gain coefficient, K_i is integral gain coefficient (frequently written as $K_i = \frac{K_p}{T_i}$, where T_i is the reset time/integral time constant) and τ is dummy integration variable representing time past from 0 up to the current time t.

The difference between the measured and reference generator speeds can be used to establish the error for pitch angle regulation given as:

$$e(t) = \omega_{ref}(t) - \omega_g(t) \qquad (3)$$

Where e(t) is generator speed tracking error signal at time t ("rad/s" or "rpm"), $\omega_{ref}(t)$ is reference (desired) generator rotational speed at time t ("rad/s" or "rpm") and $\omega_g(t)$ is actual measured generator rotational speed at time t ("rad/s" or "rpm").

The proportional portion gives an instant reaction to the speed error changes, and the integral portion helps to eliminate the steady-state error. The relatively simple structure of PI control makes it suitable for implementation in MATLAB/Simulink and practical wind energy conversion system.

However, the performance of a fixed gain PI controller is subject to changes in wind speed and turbine operating conditions. The wind speed, rotor speed, pitch angle and tip-speed ratio affect the nonlinear aerodynamic characteristics of the wind turbine.

Thus, a gain that works well at one operating point may not be optimal at another operating point [15].

Control of Wind Turbine Pitch with Fuzzy Logic

Fuzzy Logic Control is a smart control technique which can describe a set of nonlinear control relations with linguistic variables and a set of predesigned rules. An FLC can also use qualitative knowledge about the behaviour of the system to be controlled by using fuzzy rules, while traditional controllers require detailed knowledge about the controlled plant in the form of mathematical models.

The processes of fuzzification, rule inference, and defuzzification make up a standard fuzzy pitch controller. The control input is usually a variable that includes both the system error's measure and its rate of change. In this research, generator-speed error and the error rate are used to find an appropriate pitch command.

The generator-speed error is expressed as

$$e(k) = \omega_{ref}(k) - \omega_g(k) \qquad (4)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (5)$$

Where k is discrete sampling time instant (t=k·T_s, where T_s is the sampling period), e(k) is discrete generator speed tracking error at sample k, ω_"ref" (k) is reference (desired) generator speed at sample k, ω_g (k) is measured generator speed at sample k, Δe(k) is change in error (error derivative approximation) between consecutive sampling instants k-1 and k and e(k-1) is generator speed error recorded at the previous sample k-1.

The two variables are processed by the fuzzy controller to determine the required change in pitch command. The general operation of the FLC can therefore be represented in figure 3.

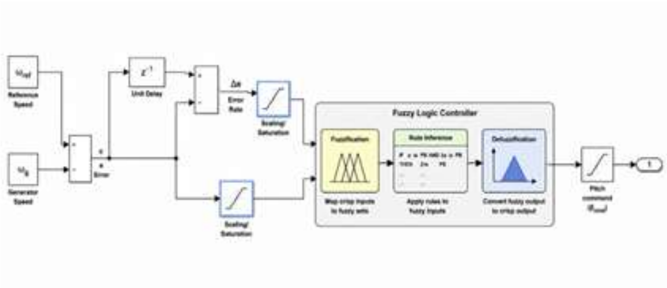

Figure 3: General operation of FLC

Negative Big (NB), Negative Medium (NM), Negative Small (NS), Zero (ZE), Positive Small (PS), Positive Medium (PM), and Positive Big (PB) are the groups into which the linguistic variables can be divided. The membership functions and rule base allow the controller to react to different speed deviations, of different magnitudes and directions.

For instance, the controller can reduce aerodynamic torque by increasing the pitch angle of the blades if the generator speed is significantly higher than the reference value.

On the other hand, if the generator speed drops below the desired level, controller can decrease the pitch angle to allow more aerodynamic energy to be captured.

The pitch actuator normally has physical limitations. The restrictions are the maximum and minimum allowed pitch angle and rate of change in blade angle. Therefore, for a realistic controller, both pitch-angle and pitch-rate constraints need to be taken into account.

Figure 4 depicts the fundamental architecture of a fuzzy pitch control system.

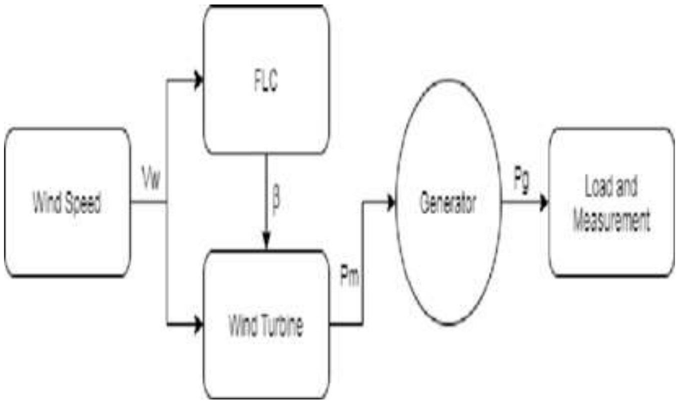

Figure 4. Fuzzy logic-based wind turbine pitch control architecture.

The use of these constraints is significant since an unrealistic controller may generate very fast pitch movement which cannot be generated by pitch actuator. Mechanical wear can also be increased with too much activity of the actuator, and the practical reliability of the wind turbine is reduced.

In recent years, intelligent control techniques have become an increasing subject of study for the wind turbine application due to its capability of dealing with the nonlinearity and uncertainty. Power regulation, rotor-speed regulation, load reduction and pitch control problems are among those that have been solved using fuzzy logic, neural networks, adaptive fuzzy systems and hybrid fuzzy controllers [16].

Previous research on fuzzy pitch controller has shown that the transient response, power regulation, and turbine-load characteristics can be improved under varying wind conditions [17]. Fuzzy controller has also been used in conjunction with the conventional PI or PID controller to develop a hybrid fuzzy-PI controller, and fuzzy – PID controller. This type of methods try to merge the simplicity of classical control and the nonlinear decision-making power of fuzzy logic.

Distinction of PI and Fuzzy Logic Control

Conventional PI control and FLC are important to compare, since the two controllers are different types of controllers used for wind turbine pitch control.

Fixed proportional and integral gains, which react to the speed mistake, are the foundation of the PI controller. Its simplicity, minimal processing requirements, and ease of implementation are its primary advantages. However, when the operating conditions differ significantly from the fixed gains, it might not be able to function at its best.

The FLC operates, on the other hand, with a nonlinear rule-based decision making. Based on the magnitude and direction of the generator-speed error and the rate of change of the error, the controller is able to adjust the pitch command. This makes the FLC potentially more appropriate for systems with nonlinear and uncertain operating conditions.

Rise time (tr), settling time (ts), percentage overshoot (Mp), and steady-state error (ess) are the transient response indices that have been taken into consideration.

Root mean square error (RMSE), integral absolute error (IAE), integral squared error (ISE), integral time absolute error (ITAE), and integral time squared error (ITSE) are the indices that are based on errors.

III. RELATED WORKS AND RESEARCH GAPS

Conventional, fuzzy-based, adaptive and hybrid techniques for wind turbine pitch-angle regulation have been investigated in several studies.

The pitch control of wind turbines has widely used conventional PI and PID controllers due to their simple design and easy implementation [14].

In particular, the PI control is effective at keeping the generator speed close to the reference, thanks to the integral term that helps to correct persistent steady-state deviations. However, when wind conditions change significantly, the fixed controller gains may no longer be able to achieve the desired performance.

Previous investigations have reported the potential of fuzzy-based controllers for generator-speed regulation and power control under changing wind conditions [18].

Hybrid approaches, including fuzzy-PI and fuzzy-PID controllers, have also been developed to combine conventional and intelligent control characteristics. Reported studies involving fuzzy-PI and fuzzy-PID techniques have indicated improvements in transient behaviour, power regulation, and turbine-load characteristics [19].

Under turbulent conditions, changes in aerodynamic torque can produce corresponding fluctuations in rotor speed and generator power. Consequently, recent investigations of intelligent pitch-control techniques have increasingly considered variable and turbulent wind profiles [17].

Previous research has validated the feasibility of fuzzy control for wind turbine applications, but many investigations are only based on the generator-speed, power and the pitch-angle waveforms for performance evaluation.
Based on the studies reviewed, several research gaps can be identified.

First, although conventional PI controllers remain attractive because of their simplicity, fixed controller parameters may not provide optimum performance across a wide range of variable wind conditions. Second, although FLC has demonstrated considerable potential for nonlinear wind turbine control, its effectiveness depends on appropriate selection of membership functions, scaling factors, saturation limits, and fuzzy rules. Third, most of the existing studies are based on individual objectives such as the regulation of power, the rotor-speed control, or the reduction of load, without a comprehensive comparison based on the transient and the cumulative error measures. Fourth, the waveform-based assessment alone does not offer sufficient quantitative evidence to evaluate relative controller performance.

Hence, a systematic comparison of conventional PI and fuzzy logic pitch control based on a common turbine model, same reference speed, similar wind-speed conditions, same simulation duration and same performance criteria is required in MATLAB/Simulink.

IV. METHODOLOGY

The Proposed methodology comprises five main steps; wind turbine modeling, reference-speed generation, development of the PI controller, development of the FLC and comparative performance evaluation. The two controllers are implemented on the same model of a wind turbine with variable speed and under the same operating conditions. This setup makes sure that any difference observed in the simulation results is mainly due to the control strategy and not due to difference in turbine parameters or disturbances.

The whole simulation is developed on MATLAB/Simulink to reproduce the dynamic behavior of a variable speed wind energy conversion system by the interconnection of the wind turbine, generator, pitch actuator and controllers.
Figure 5 illustrates the general process, while table 1 displays the simulation parameters used in this stud

Table 1. Parameters of the Proposed System

Parameters	Values
Power coefficient, Cp	0.48
Lambda, λ	8.1
Constants, C1 to C6	0.51763,116,0.4, 5, 21, 0.006795
Nominal output power (MW)	1.5
Base Power (MVA)	1.6667
Max. power at base wind speed (pu)	0.73
Base rotational speed (pu)	1.2
Wind Speed (m/s)	12
Air density (ρ	1.225
Radius blade R(m)	40

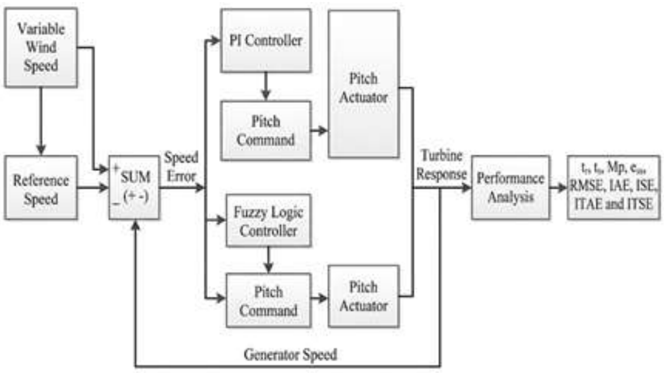

Figure 5. Wind Turbine Pitch Control Architecture

Variable-Speed Wind Turbine Model

The wind turbine with variable speed converts the kinetic energy of wind into the mechanical energy, which is converted into the electrical energy by the generator. Power that can be extracted from the wind aerodynamically is given by:

$$P_t = \frac{1}{2}\rho A C_p(\lambda,\beta) v_\omega^{\ 3} \qquad (6)$$

where Pt = aerodynamic power captured by the turbine (W), ρ = air density (kg/m3), A = swept area of turbine blades (m2), Cp = power coefficient, λ = tip-speed ratio, β = blade pitch angle and v_(ω)= wind speed (m/s). The swept area is given by:

$$A = \pi R^2 \qquad (7)$$

Where R is the turbine blade radius.
The tip-speed ratio is defined as:

$$\lambda = \frac{\omega_t R}{v_\omega} \qquad (8)$$

where the angular speed of the turbine rotor is represented by ω_t
The aerodynamic torque is obtained from

$$T_t = \frac{P_t}{\omega_t} \qquad (9)$$

or equivalently,

$$T_t = \frac{1}{2}\rho\pi R^3 \frac{C_p(\lambda,\beta)}{\lambda} v_\omega^{\ 2} \qquad (10)$$

The link between wind speed, rotor speed, pitch angle, and extracted aerodynamic power is established by these equations.

The turbine blades' aerodynamic orientation with respect to the incoming wind is determined by the pitch angle, or β. It has a huge impact on the power coefficient which impacts the aerodynamic power and torque of the turbine.

In the region below the rated wind speed, the turbine typically seeks to capture the maximum wind energy. The pitch controller controls the blade pitch angle to limit the aerodynamic power and prevent the generator from rotating too fast when the wind speed approaches or exceeds the rated operating region.

The control objective of the proposed system is therefore to generate an appropriate pitch-angle command from the generator-speed tracking error. The control relationship can be represented as:

$$\beta = f(e, \dot{e}) \qquad (11)$$

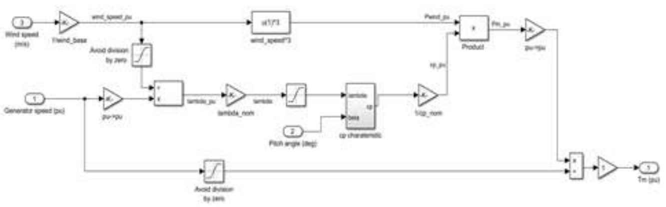

Figure 6. Variable Wind Turbine Subsystem Model

Conventional PI Pitch-Angle Controller Model

The conventional PI controller is implemented as the benchmark control strategy against which the proposed FLC is evaluated.

The continuous-time PI controller is expressed as

$$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau \qquad (12)$$

where e(t) is the generator-speed tracking error, u(t) is the controller output, Kp is the proportional gain, and Ki is the integral gain.

While the integral component accumulates the mistake over time and lowers steady-state tracking error, the proportional component responds to the speed error instantly.

Thus, the pitch-angle command is generated by the PI controller in accordance with equation (29):

$$\beta_{PI}(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau \qquad (13)$$

subject to the pitch actuator limits.

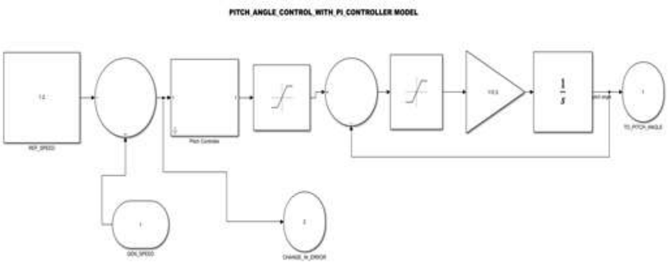

Figure 7. Pitch Angle Control with PI Controller Subsystem

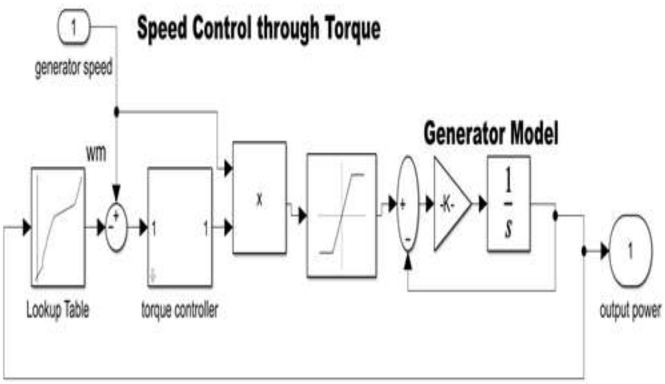

Figure 8. Generator Speed of a Variable Wind Turbine Subsystem

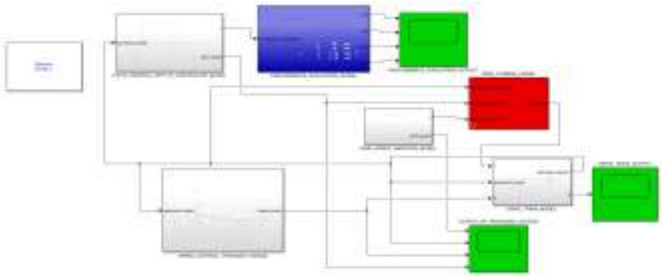

Figure 9. Complete Model for Controlling Pitch Angle in a Variable Wind Turbine using a PI Controller

Proposed Fuzzy Logic Pitch-Angle Controller

A Mamdani-type fuzzy logic controller is used in the suggested control approach to calculate the pitch-angle command based on the generator-speed error and its rate of change.

Unlike the conventional PI controller, the FLC does not depend directly on a mathematical linear relationship between the error and control action. Instead, it uses linguistic rules to determine the appropriate pitch response.
Figure 10 illustrates the four main steps of the FLC.

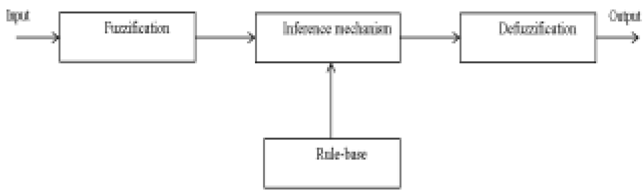

Figure 10. Schematic Diagram of the fuzzy logic controller

1. Fuzzification
2. Rule evaluation/inference mechanism
3. Defuzzification
4. Rule-base

Two input variables are used:
Input 1: Speed Error

$$e = \omega_{ref} - \omega_g \qquad (14)$$

The difference between the intended and actual generator speed is represented by the error.
Input 2: Change in Error

$$\dot{e} = \frac{de}{dt} \quad (15)$$

The error-rate signal provides information about the direction and speed of the response.

Both FLC inputs are normalized to the universe of discourse: [-0.5,0.5]

This normalization ensures compatibility between the controller input signals and the defined membership functions. Because the FLC input universe is defined as [-0.5,0.5], scaling gains are introduced before the fuzzy inference system.
The scaled error is given by $e_f = K_e e$
while the scaled error rate is $\dot{e}_f = K_{de}\dot{e}$
Where Ke = error scaling gain and Kde = error-rate scaling gain.

Saturation limits are then applied: $-0.5 \le e_f \le 0.5$ and $-0.5 \le \dot{e}_f \le 0.5$

This prevents the fuzzy inference system from receiving values outside its defined operating range. The final FLC output is subsequently scaled by an output gain: β=K_u u_f, where Ku is the output scaling gain and is the defuzzified fuzzy output.

FLC is characterized by five linguistic membership functions for each input and output. PS-Positive Small, PB-Positive Big, ZE-Zero, NS-Negative Small and NB-Negative Big. The input membership functions are in the normalized range of [-0.5, 0.5].

The linguistic variables are represented by either trapezoidal or triangular membership functions. The membership function rules for the suggested controller are shown in the table below.

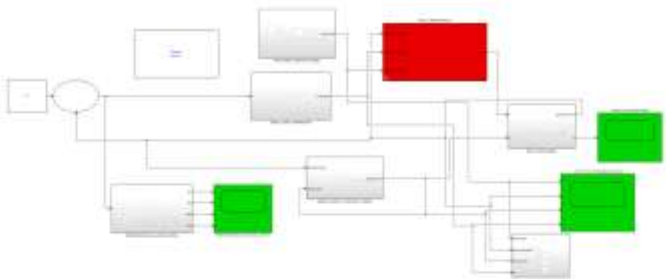

Figure 11. Complete Model for Controlling Pitch Angle in a Variable Wind Turbine using a Fuzzy Logic Controller (FLC)

Table 2. Membership Rules

Error / Error Rate	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PB
PB	ZE	PS	PB	PB	PB

V. SIMULATION RESULTS ANALYSIS OF PROPOSED SYSTEM

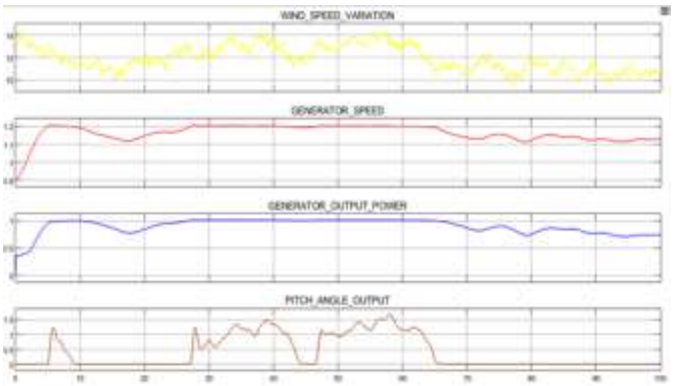

Figure 12. Output Results of System with PI Controller

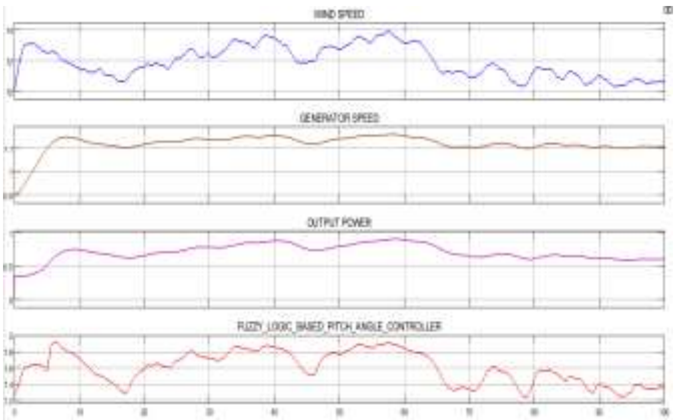

Figure 13. Output Results of System with Fuzzy Logic Controller (FLC)

Figures 12 and 13 present the dynamic responses of the variable-speed wind turbine under conventional PI and Fuzzy Logic Controller (FLC) strategies, respectively, using the same variable wind-speed profile of approximately 10-15 m/s. The results demonstrate that both controllers regulate generator speed and output power despite continuous aerodynamic disturbances.

The PI controller has faster initial response as it takes 1.7677 s to reach the rise time as compared to 3.2920 s of FLC. But the generator speed controlled by PI has more oscillations and a much longer settling time of 17.2793 s, higher overshoot of 7.662%, and larger steady-state error of 0.078782. The controller pitch-angle response also exhibits relatively sharp changes during wind-speed transitions, which implies more aggressive control action. In contrast, FLC gives much better damping and transient stability. Its settling time is reduced to 5.5018 s which is about 68.16% improvement over PI and the overshoot is decreased by about 88.51% to 0.880%. The FLC also has a lower steady state error of 0.063659. Its pitch angle response varies continuously as the operating conditions change. This demonstrates the nonlinear decision-making ability of fuzzy control.

The error-based indices also confirm that the FLC gives lower IAE (1.369917 versus 1.728832), ITAE (4.522756 versus 15.905242), and ITSE (0.566354 versus 1.489202). However, the lower RMSE and ISE of PI indicate that the FLC does not dominate PI in all metrics. Overall, the results demonstrate that the proposed FLC provides superior settling characteristics, overshoot reduction, steady-state accuracy, and cumulative error performance, although at the expense of a slower initial response.

Quantitative Analysis of Controller Performance

Table 3 present the numerical performance indices which provide a more objective comparison than waveform inspection alone.

Table 3. Performance Numerical Indices of Proposed System

Performance Index	PI	FLC	Percentage Improvement (%) of FLC relative to PI
Rise Time (s)	1.7677	3.2920	86.23% slower
Settling Time (s)	17.2793	5.5018	68.16% improvement
Overshoot (%)	7.662	0.880	88.51% reduction
Steady-State Error	0.078782	0.063659	19.20% reduction
RMSE	0.108078	0.161270	49.22% higher
IAE	1.728832	1.369917	20.76% improvement
ISE	0.233613	0.260078	11.33% higher
ITAE	15.905242	4.522756	71.56% improvement
ITSE	1.489202	0.566354	61.97% improvement

The performance characteristics of the comparative controllers of the proposed system are shown in figures 14 through 17.

Figure 14. Steady State and Tracking Error of Proposed Controllers

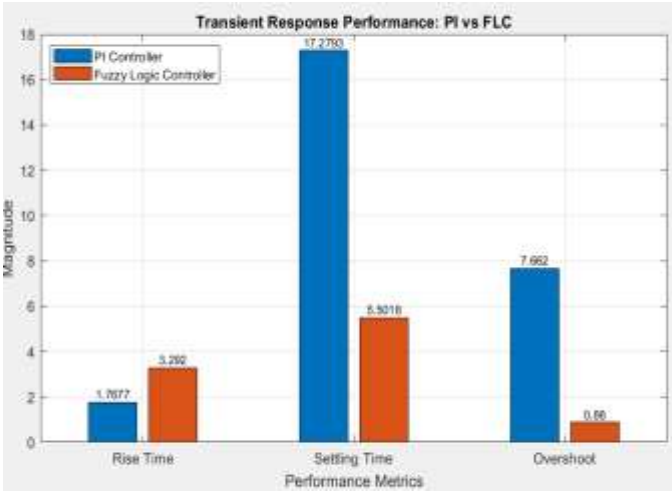

Figure 15. Transient Response Performance of proposed Controllers

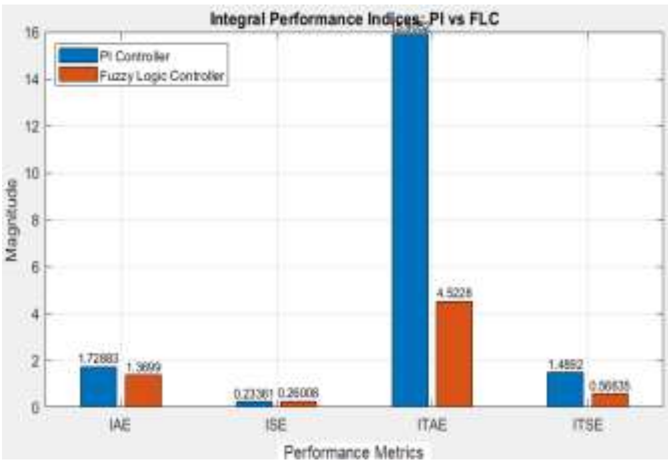

Figure 16. Integral Performance Indices of Proposed Controllers

International Journal of Scientific Research & Engineering Trends
Volume 12, Issue 5, Sep-Oct-2026, ISSN (Online): 2395-566X

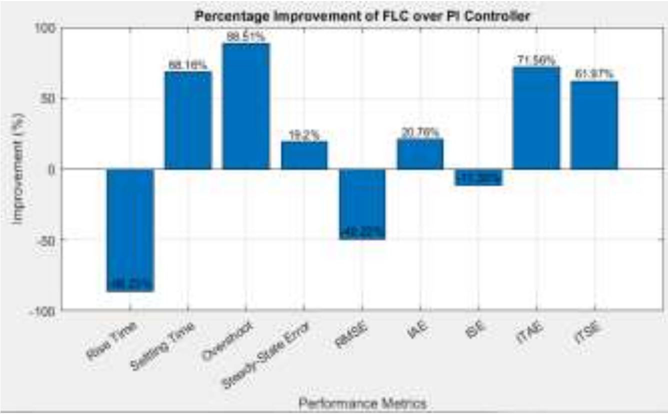

Figure 17. Percentage Improvement of Proposed Controllers

The comparison of the performance of the conventional PI and the proposed Fuzzy Logic Controller (FLC) for the control of pitch angle of variable speed wind turbines is presented in Table 3 and figures 14-17. From Figure 14 it is observed that the FLC has less steady state error i.e. 0.063659 as compared to 0.078782 for PI which is improved by 19.20%. But its RMSE (0.161270) is higher than PI (0.108078), which shows that PI has a better overall RMS tracking accuracy.

The FLC has a slower rise time of 3.2920 s, similar to Figure 15, while the PI controller has a faster rise time of 1.7677 s. However, FLC decreases the overshoot from 7.662% to 0.880% (88.51%) but improves the settling time significantly by reducing it from 17.2793 s to 5.5018 s (68.16%).

The superiority of the FLC in terms of the accumulated error performance is further verified in Figure 16 with the reductions of IAE, ITAE and ITSE being 20.76%, 71.56% and 61.97% respectively. Conversely, PI has lower ISE by 11.33%.

Overall, Fig. 17 shows that FLC provides better damping, long-term tracking and disturbance rejection, while PI provides faster initial response and lower RMSE and ISE. Thus, the FLC provides a more balanced and robust pitch-control performance under variable wind conditions.

VI. CONCLUSION

This study examined the pitch-angle control of a variable-speed wind turbine under varying wind-speed conditions using a suggested Mamdani-type fuzzy logic controller and a traditional PI controller.

Both controllers were implemented on the same wind turbine model and under the same operating conditions, which allows an objective comparison of their performance using transient-response and cumulative-error indices.

The results of the simulation show that the two controllers exhibit different control behaviors. The initial response of the PI controller is faster, with a rise time of 1.7677 s, compared to the FLC with a rise time of 3.2920 s. However, the faster response is associated with larger overshoot and longer transient behavior. The FLC decreased the settling time from 17.2793 s to 5.5018 s, an improvement of 68.16%, and decreased the overshoot from 7.662% to 0.880%, a reduction of 88.51%.

The FLC also had a lower steady state error of 0.063659 as compared to 0.078782 for PI which is a reduction of 19.20%. Its IAE, ITAE, and ITSE values were also lower than those of PI, demonstrating improved cumulative and long-term error suppression. In particular, the reductions in ITAE and ITSE indicate that the FLC was more effective in suppressing persistent generator-speed deviations and restoring the turbine operating condition following wind disturbances.

Nevertheless, the results show that the FLC does not outperform PI in every performance criterion. PI achieved lower RMSE and ISE values, indicating better performance according to these particular error measures. This finding is important because it demonstrates that controller superiority should not be established using a single performance index.

Overall, the proposed FLC provides a more balanced performance for variable-wind turbine pitch control, particularly in terms of damping, settling behaviour, overshoot reduction, steady-state regulation, long-term tracking, and disturbance rejection.

The study therefore demonstrates the potential of fuzzy logic as an effective intelligent alternative to fixed-gain PI control for variable-speed wind turbine pitch regulation.

Future research could concentrate on optimizing the fuzzy rule base, incorporating actuator constraints, adaptively tuning fuzzy membership functions and scaling factors, and comparing with more sophisticated adaptive, neuro-fuzzy, model-predictive, or hybrid control methods under more general turbulent-wind scenarios.

Interest of Conflict

Regarding the publishing of this paper, the authors state that they have no conflicts of interest.

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