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Pitch Angle Modulation of the Horizontal and Vertical Axes Wind Turbine Using Fuzzy Logic Control

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Abstract: The aim of this research work is to modulate the pitch angle of both types of wind turbines based on fuzzy logic control (FLC), as changes in the pitch angle have various functions in horizontal and vertical axis wind turbines. For HAWT, pitch angle control is applied to shield the electrical components of the turbine when the wind speed exceeds the rated speed without shutting down the turbine. FLC is used to control the angular velocity using two inputs and one output with three membership functions for both inputs and output. In VAWT, pitch angle control is applied to boost the performance of the turbine and its self-starting torque. FLC utilizes two inputs and one output with five membership functions for both inputs and output. For both turbine types, FLC produces a control signal that drives the actuator to achieve the desired pitch angle. The dynamics of HAWT and VAWT are simulated by the MATLAB/Simulink to demonstrate the influence of pitch controls on their dynamics. For HAWT, the FLC control has successfully maintained the angular speed of the rotor. The values of tip speed ratio and coefficient of performance are reduced in order to maintain the rotor angular velocity at its rated value. On the other hand, the results showed that the torque produced by the VAWT individual blade has improved with the pitch angle control. In addition, using FLC to control the pitch angle gives enhanced output and higher C_p at low tip speed ratios. Gain schedule PI controller is also used in both HAWT and VAWT for comparative study.

Keywords: HAWT; VAWT; pitch control; FLC; darrieus turbine

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1. Introduction

Electricity derived from renewable energy sources may provide a constructive contribution to the reduction of environmental emissions since fossil fuels remain the most common energy source to generate electricity. There are many pollutants produced by the burning of fossil fuels, such as Carbon Monoxide, Carbon Dioxide, Nitrogen Oxides, etc. Those emissions should be reduced to keep life on our planet. Moreover, fossil fuels will be fully consumed over time [1]. Therefore, the interest in alternative renewable energy sources such as wind energy has increased. Wind turbines are generally known as a horizontal axis wind turbine (HAWT) or a vertical axis wind turbine (VAWT) based on the direction of the axis of rotation. Although HAWT is more common because it is more efficient, VAWT has many other advantages [2]. The VAWT does not need a yaw control since it can collect wind from any direction. Since the generator is mounted on the ground, a VAWT needs less maintenance cost and produces less noise than a HAWT. In addition, one more significant benefit of VAWT is that it has improved performance in areas where the flow is turbulent. Therefore, it can be used in urban areas [3].

The purpose of wind turbine control is to bring down the cost of electricity production in order to make them more competitive. HAWT operations usually employ two kinds of control. The first type is used when the speed of the wind is greater than the cut-in speed and less than the rated wind speed. In this district, the generator torque control and maximum power point tracking (MPPT) strategy is used. The aim of this control is to

maximize extracted power by assisting the turbine in running at an optimal tip speed ratio. As the wind speed increases, the controller sets the rotor angular speed to maintain the optimal tip speed ratio. This is accomplished by regulating the torque of the generator [2]. The second type of control is used when the speed of the wind is greater than its rated value and less than the cut-out speed. This control aims to prevent the turbine's electrical components from overloading. The control accomplished its objective by keeping the rotor's angular speed constant (rated angular speed). This can be realized by modifying the pitch angle. The HAWT's pitch angle control is known as collective pitch control, where the same control action is taken for each blade [2–6]. Zhou and Liu [7] used PI/PD controllers to regulate the pitch angle for 2 MW HAWT to limit the generated power. MATLAB/SIMULINK was used to simulate and test the control system for the 2 MW turbine. In [8], Hwas and Katebi used a PI controller to regulate the pitch angle for a 5 MW HAWT to regulate the rotor speed. The controller error was the difference between the rated speed of the rotor and the actual speed of the rotor. The simulation was implemented using MATLAB/SIMULINK. Abbas and Abdulsada [9] used PID control to regulate the pitch angle for the HAWT to maintain the angular velocity near a reference value. Again, a PID regulator was used to control the pitch angle for a 20 kW HAWT using the difference between the angular speed of the rotor and its rated value as an error signal [10]. A collective adaptive pitch regulator was developed for a variable speed HAWT to regulate generator angular speed at the rated power region. Adaptive pitch control was proposed because it is suitable for difficult-to-model applications such as wind turbines [11].

On the other hand, VAWTs are divided into two types: Darrieus and Savonius. The Savonius VAWT depends on aerodynamic drag force to generate mechanical power, whereas the Darrieus VAWT depends on aerodynamic lift force to generate rotating torque [12]. Generally, the low efficiency of VAWT is caused by the continuous change in blade angle of attack as a result of the continuous change in azimuth position. The Savonius type has a lower efficiency than the Darrieus type, but it has better starting torque at low wind speed. Researchers, therefore, wanted to improve the efficiency of the Savonius type. Khader [12] has come up with an innovative concept to increase VAWT efficiency by utilizing gears and timing belts to support turbine blades facing the wind. The researcher used a wind tunnel to check the model validity and proved that the mechanical mechanism improved the turbine efficiency. Khader and Nada [13] used a crank mechanism to improve the efficiency of the Savonius wind turbines without requiring additional power. Khader et al. [14] improved the blade structure by manufacturing it using a composite material with Zinc–oxide (ZnO) nanoparticles for the Savonius VAWT. Five different ZnO volume percentages were used to conclude the effect of blade structure on vibration and turbine performance.

Darrieus turbines, which have a low starting torque, are the second type of VAWT. Pitch control was proposed by the researchers as a way to improve turbine starting torque and efficiency and eliminate the negative torque produced by the turbine at some azimuth positions. Mechanical mechanisms and algorithm techniques were used by researchers to control the pitch angle, while traditional control systems were used by a few researchers. Lazauskas [15] used a mechanical mechanism to modify the pitch angle of the VAWT blades. The sinusoidal pitch was applied to boost the turbine self-start. The H-type VAWT has a simpler structure than the HAWT since the blade cross-section consists of one airfoil, but it has more complicated aerodynamic characteristics. Komass [16] investigated the effect of pitch angle change on the H-type VAWT efficiency to get the higher value of the ratio between lift to drag coefficients and the higher individual blade torque at all azimuth positions as well. The investigation was made using a MATLAB environment. Liu et al. [17] made a force analysis for fixed and variable pitch angle H-type VAWT and proved that changing the pitch angle could enhance the turbine efficiency and its self-starting torque. A 2D CFD and genetic algorithm was used in [18] to automatically optimize the VAWT pitch angle, and it was concluded that optimizing pitch angle could enhance the self-starting torque of the turbine and its efficiency. Abdalrahman et al. [19] designed a pitch angle

regulator based on Multi-Layer Perceptron Artificial Neural Networks (MLP-ANN) for an H-type VAWT to enhance its performance. In order to investigate the pitch angle controller efficiency, a PID control was applied to the MLP-ANN, and a 2D CFD model was generated to obtain an optimum pitch angle. An experimental study has been conducted for VAWT to evaluate the effect of turbine solidity (σ) on turbine power coefficient (C_p) [20]. The experiment was conducted using a suction wind tunnel. The experiment was carried out at two different turbine solidities (σ = 0.26 and 0.34). The authors inferred that the higher solidity VAWT resulted in a higher C_p. Although most experimental studies investigate the effect of VAWT solidity and blade number on the efficiency of the turbine, Guo et al. [21] created 2D CFD to study the influence of adjusting pitch angle on the efficiency of the turbine. They concluded that modulation of the pitch angle significantly increases the C_p.

Based on the foregoing, there is a scarcity of using modern soft computing techniques to control the pitch angle for the H-type VAWT. A novel pitch control technique based on FLC for the H-type VAWT is proposed. The aim of this control is to adjust the pitch angle in order to maintain the angle of attack of the blade at its optimum value to enhance the performance of the turbine. In addition, pitch angle control for an HAWT was implemented to keep the rotor angular speed at its rated value. The objective of preserving the rotor angular speed is to secure the electric components of the turbine. Mathematical models for both types of turbines were simulated by MATLAB/SIMULINK in order to compare the effectiveness of pitch control on the performance of both types. The rest of the paper is organized as follows: Section 2 describes the mathematical modeling for VAWT and HAWT, as well as the pitch control strategies used for both types. The findings of the simulation and the effect of pitch regulation on the performance of both types are presented in Section 3. Conclusions are summarized found in Section 4.

2. Mathematical Models and Pitch Angle Control Strategies

2.1. Mathematical Model of H-Type VAWT

The continuous variation of the angle of attack reduces the efficiency of the turbine. Therefore, a new pitch angle control technique based on FLC is suggested to enhance its performance by setting the angle of attack at its optimum value. A simple aerodynamic model of the H-type VAWT is used to implement the suggested control. This section, therefore, introduces the mathematical H-type VAWT model and the FLC technique as well. It is worth mentioning that there are multi-aerodynamic models were developed to predict H-type VAWT performance. They are blade-element momentum (BEM), finite volume method (FVM) and vortex models. In this paper, blade-element momentum (BEM) is used because it gives a reasonably accurate prediction of turbine performance without a high computing cost.

2.1.1. Forces and Velocities of the Air Flow

The wind speed at the rotor plane can be expressed as follows [22]:

$$V_a = V_w * (1 - a) \tag{1}$$

where a denotes the axial induction factor, which determines the reduction in wind speed at the rotor plane.

$$a = \frac{N * c}{2 * \pi * R} * \frac{R * \omega_r}{V_w} * \sin\theta \tag{2}$$

Figure 1 shows the velocities and forces acting on the wind turbine blade airfoil. Tangential and normal air flow velocities can be obtained by:

$$V_n = V_a * \sin\theta \tag{3}$$

$$V_t = R * \omega_r + V_a * \cos\theta \tag{4}$$

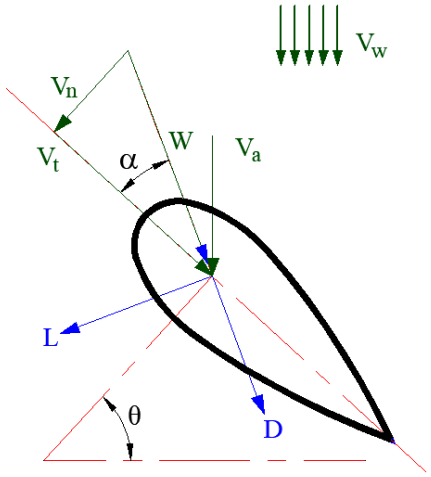


Figure 1. Forces and velocities of the blade flow.

As illustrated from the figure, the attack angle α is the angle formed by the relative velocity and the chord length and can be written as follows:

$$\alpha = \tan^{-1}(\frac{V_n}{V_t})$$

$$\alpha = \tan^{-1}\frac{V_a * \sin\theta}{R * \omega_r + V_a * \cos\theta} \quad (5)$$

Equation (5) gives the attack angle for a fixed pitch turbine, while for a variable pitch turbine, the following equation gives the angle of attack as:

$$\alpha = \tan^{-1}\frac{V_a * \sin\theta}{R * \omega_r + V_a * \cos\theta} - \beta \quad (6)$$

The tangential force (F_t) is responsible for generating the rotating torque. A typical wind turbine blade is facing two aerodynamic forces, lift force (L) and drag force (D), as illustrated in Figure 1. Wind turbines can be classified based on the aerodynamic force responsible for generating power. There are two types of wind turbines based on this classification: lift type and drag type. The H-type VAWT is a lift-type wind turbine. In this type, it is important to increase the lift force to increase the turbine efficiency. For more clarification, the H-type VAWT rotating torque is produced from F_t, which is the difference between L and D and can be written as [16,17]:

$$F_t = 0.5 * C_t * \rho * c * H * W^2 \quad (7)$$

where,

$$C_t = C_l * \sin\alpha - C_d * \cos\alpha \quad (8)$$

Once C_t is obtained, F_t can be calculated easily, and the individual blade generated torque can be calculated from Equation (9).

$$T_r = F_t * R \quad (9)$$

In this paper, NACA 0018 airfoil is used in the simulation. The values of C_l and C_d were extracted from Xfoil and Qblade software [23,24]. The H-type VAWT specifications used in the simulation are shown in Table 1.

Table 1. VAWT specifications.

Turbine radius (m)	3
Turbine height (m)	5
No. of blades	3
Airfoil	NACA0018

2.1.2. Pitch Angle Control Strategy

Figure 2 illustrates the suggested new control strategy construction for the H-type VAWT. It shows an individual blade pitch angle control implementation for each blade. It is worth noting that the increase in the tangential coefficient would result in an increase in the tangential force, leading to an increase in the rotating torque and improving turbine efficiency. The tangential coefficient is related to the angle of attack and the type of the airfoil at the same operating conditions. Therefore, changing the attack angle by varying the pitch angle can increase the tangential coefficient for the same airfoil and at the same operating conditions.

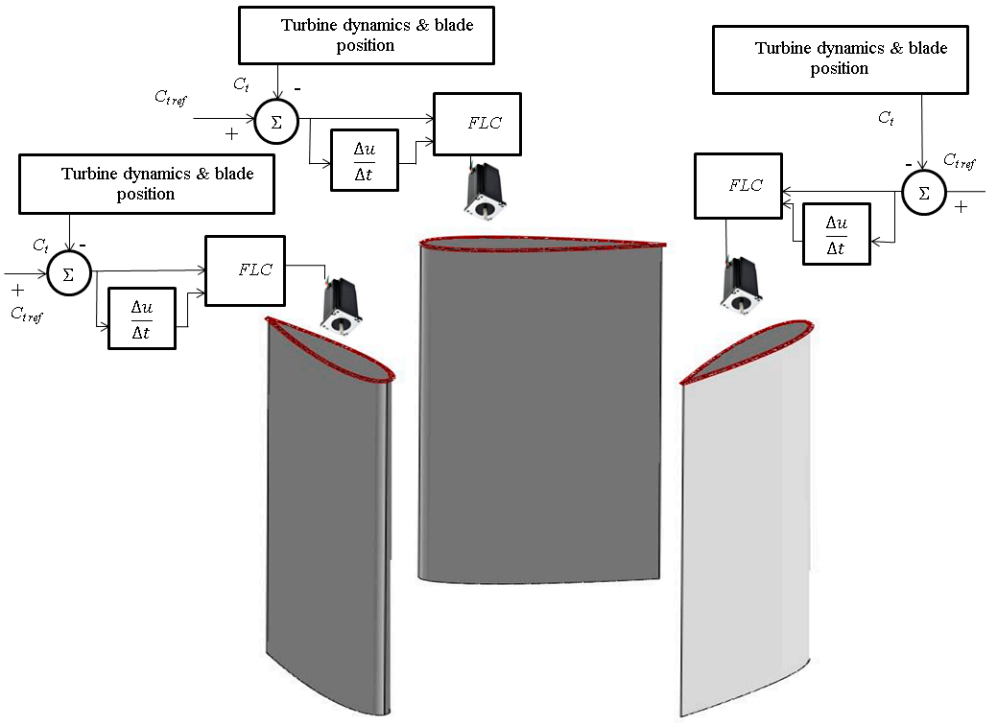


Figure 2. The individual pitch angle control system for each blade.

The aim of the proposed regulation for pitch angles in this analysis is to maintain a constant attack angle at all azimuth positions, thus creating a higher tangential coefficient. The suggested control strategy is shown in Figure 3 at different azimuth positions. It depicts the pitch angle that the control should achieve in order to preserve the optimum effective angle of attack at different azimuth positions. The control actuator used in this paper is a stepper motor, and its transfer function is given by the equation below:

$$\frac{\beta}{\beta_d} = \frac{1}{\tau s + 1} \tag{10}$$

where τ is the time constant depending on the actuator type.

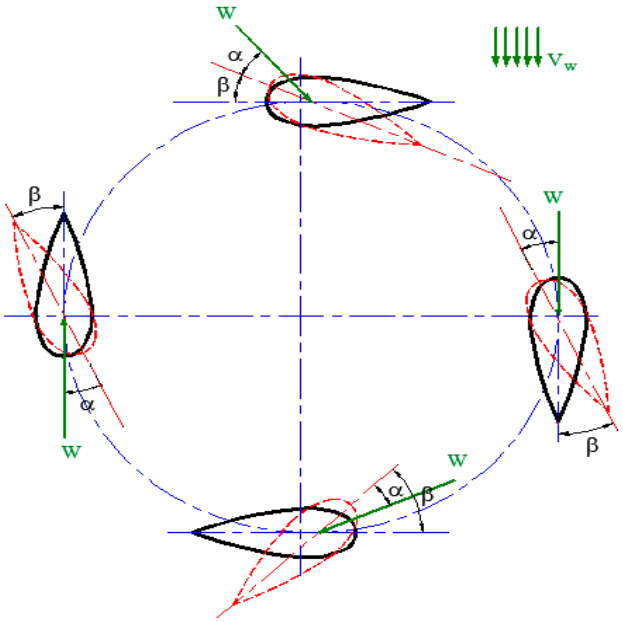


Figure 3. The angle of attack and pitch angle at different azimuth positions.

Figure 4 describes the steps of a typical fuzzy controller. First, fuzzification converts the crisp input into fuzzy input. Secondly, the combination between the inference mechanism and the rule-base gives a fuzzy output. Finally, defuzzification converts the fuzzy output into the crisp output [25]. Figure 5 represents the simulation model of the individual blade pitch angle with FLC of the mathematical model presented in Section 2.1.

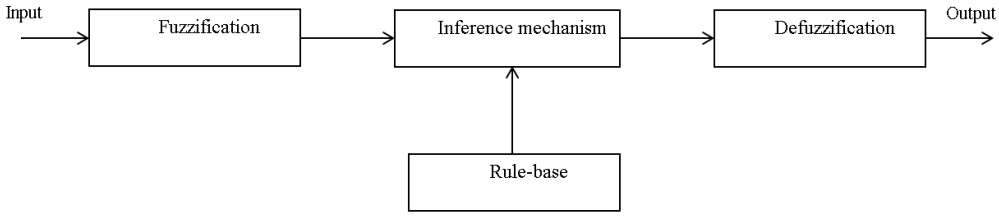


Figure 4. The structure of the fuzzy logic controller.

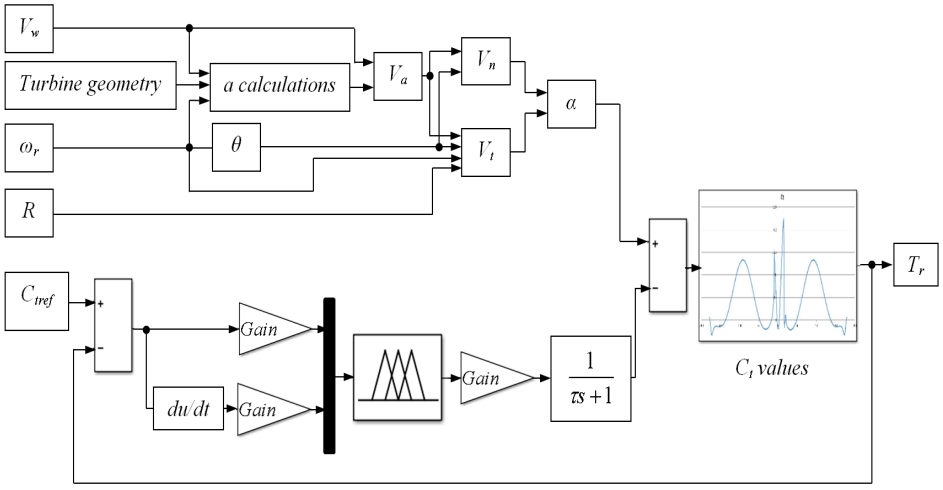


Figure 5. Simulation model of the individual blade pitch angle control with fuzzy logic controller.

A Multi-Inputs Single-Output (MISO) FLC is used to generate the control single to drive the actuator in order to obtain the optimal effective angle of attack at all azimuth

positions. The first input is the error between the reference tangential coefficient and its actual value, and the second is the error change rate. The output is the desired pitch angle.
Input (1): $e = C_{tref} - C_t$
Input (2): $\frac{de}{dt}$
Output: β_d

Inputs and output of the membership functions are illustrated in Figure 6. Five membership functions are used for both the two inputs and the output. The linguistic terms used are presented in Table 2.

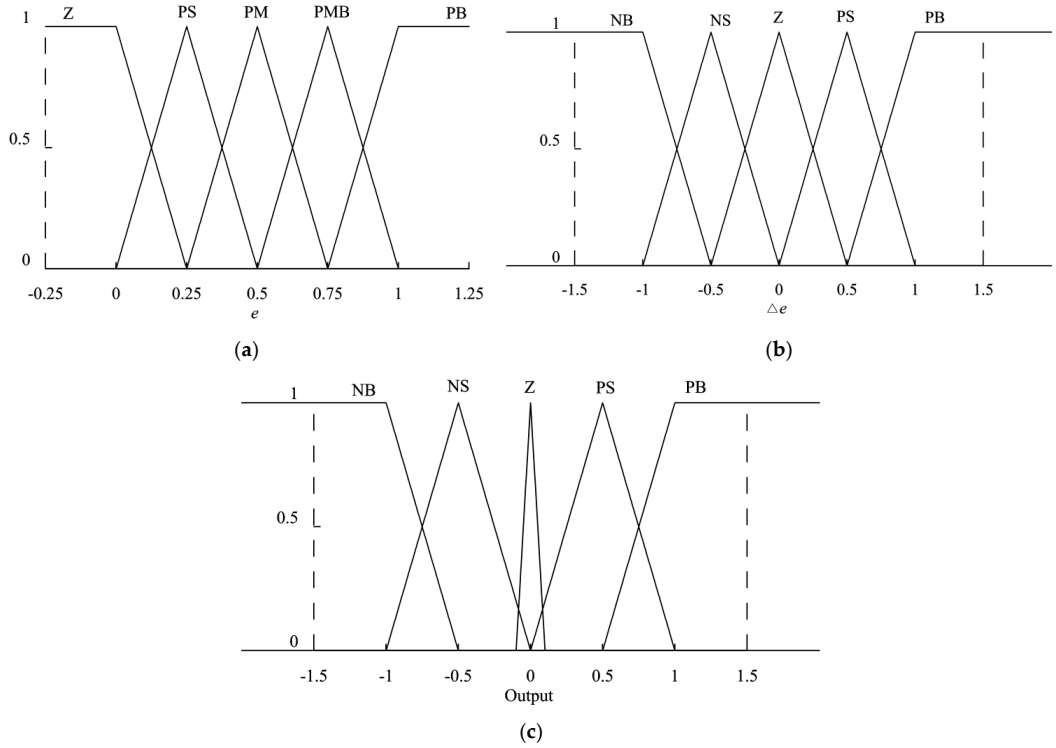


Figure 6. VAWT pitch control membership functions: (**a**) first input membership functions; (**b**) second input membership functions and (**c**) Output membership functions.

Table 2. VAWT pitch control linguistic terms.

NB	negative big
NS	negative small
Z	zero
PS	positive small
PM	positive medium
PBM	positive medium big
PB	positive big

Based on expert expertise and numerous simulations conducted in this analysis, 25 rules for pitch control using the fuzzy logic controller were created, as shown in Table 3. For VAWT individual blade pitch control, the following statements explain the different configurations of AOA and C_t:

- The statement "error is zero" represents a situation where the AOA is at its optimal value and blade tangential coefficient equals its higher value.
- The statement "error is small positive" represents a situation where the value of C_t is positive but lower than the set point.
- The statement "error is positive medium big" represents a situation where the value of C_t is negative.

- The statement "error is positive big" represents the situation where the value of C_t is near its lowest value.
- The statement "error is small positive and change-in-error is negative big" represents a situation in which the value of AOA is greater than its optimal value and increasing.
- The statement "error is positive medium big and change-in-error is negative small" represents a situation where C_t has a negative value. Therefore, the value of AOA should be increased by the control system.
- The statement "error is zero and change-in-error is negative big" represents a situation where the value of AOA is at its optimal value but getting higher.
- The statement "error is positive big and change-in-error is Zero" represents a situation where the C_t is at its lowest value and the AOA should be increased to achieve its optimal value.

Table 3. The rule base of the FLC.

Δ Error	**Error**				
	Z	**PS**	**PM**	**PMB**	**PB**
NB	NB	NS	Z	NB	NB
NS	NS	Z	PS	NB	NB
Z	Z	PS	PB	NS	NB
PS	PS	PB	PB	Z	NS
PB	PB	PB	PB	PS	Z

The output scaling factor was used to generate an actual output signal for the control actuator. In order to assess the scaling factor, several simulation trials were carried out.

2.2. Mathematical Model of HAWT

2.2.1. Aerodynamic Subsystem

The available wind power is proportional to the swept area of the turbine, wind speed, and air density, as seen in the equation below.

$$P_a = 0.5 * \rho * A * V_w^3$$

P_m is the amount of power that can be generated from a wind turbine and is given as follows:

$$P_m = 0.5 * \rho * A * V_w^3 * C_p \tag{11}$$

It is noteworthy that C_p, which is determined by the tip speed ratio and pitch angle, is a measure of the turbine efficiency. Therefore, in the region where the wind speed is less than the rated wind speed, it is important to increase the value of C_p. On the other hand, where the wind speed exceeds the rating value, it might be important to reduce the value of C_p. The value of C_p can be written as follows [9,26,27]:

$$C_p = (0.44 - 0.0167 * \beta) * \sin(\pi * \frac{\lambda - 3}{15 - 0.3 * \beta}) - 0.00184 - (\lambda - 3) * \beta \tag{12}$$

$$\lambda = \frac{\omega_r * R}{V_w} \tag{13}$$

2.2.2. Mechanical Subsystem

There are two commonly used models for wind turbines. The first is the one-mass model, while the second is the two-mass model. In this article, the one-mass model was considered in order to simplify the mathematical model. In this case, the equation of motion can be written as follows [4]:

$$J_t * \dot{\omega}_r = T_a - T_g \tag{14}$$

When the turbine runs in a region where the air speed exceeds its rated value, the power produced should be limited to the rated value. Assume that the generator torque is maintained at a constant value; the angular speed of the rotor should be regulated to regulate the power output. The regulation of the angular velocity of the rotor can be carried out by means of pitch angle control. The dynamics of a wind turbine are linearized around a specific operating point for simplicity [9]. The linearized equation can be obtained as below:

$$J_t * \Delta\dot{\omega}_r = \gamma * \Delta\omega_r + \zeta * \Delta V_w + \delta * \Delta\beta \tag{15}$$

where,

$$\gamma = \left.\frac{\partial T_a}{\partial \omega_r}\right|_{op}, \ \zeta = \left.\frac{\partial T_a}{\partial V_w}\right|_{op} \text{ and } \delta = \left.\frac{\partial T_a}{\partial \beta}\right|_{op}$$

The Laplace transformation for both sides of Equation (15) gives:

$$\Delta\omega_r = \left(\frac{\zeta}{J_t} * \Delta V_w + \frac{\delta}{J_t} * \Delta\beta\right) * \frac{1}{s - \frac{\gamma}{J_t}} \tag{16}$$

The HAWT specifications used in this analysis are given by the National Renewable Energy Laboratory (NREL) and are listed in Table 4 [28].

Table 4. NREL 5 MW wind turbine specifications.

Rating	5 MW
No. of blades	3 Blades
Blade length	63 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm

2.2.3. Pitch Angle Control Strategy

For the HAWT, Figure 7 gives the relationship between turbine output power and wind speed. There are four zones, as seen in the diagram. The wind speed in region (1) is lower than the cut-in speed ($V_{cut\text{-}in}$), so the wind speed is inadequate to generate output electricity. In region (2), the wind speed is greater than $V_{cut\text{-}in}$ and lower than the rated speed. The turbine control in this area aims to increase the produced power. In region (3), the wind speed is higher than the rated value and lower than the cut-out speed ($V_{cut\text{-}out}$). Hence, the control's goal is to control the rotor angular velocity by regulating the pitch angle. Finally, in region (4), the wind speed is higher than $V_{cut\text{-}out}$, where the turbine is switched off. Typical HAWTs operate in two main regions, regions (2) and (3).

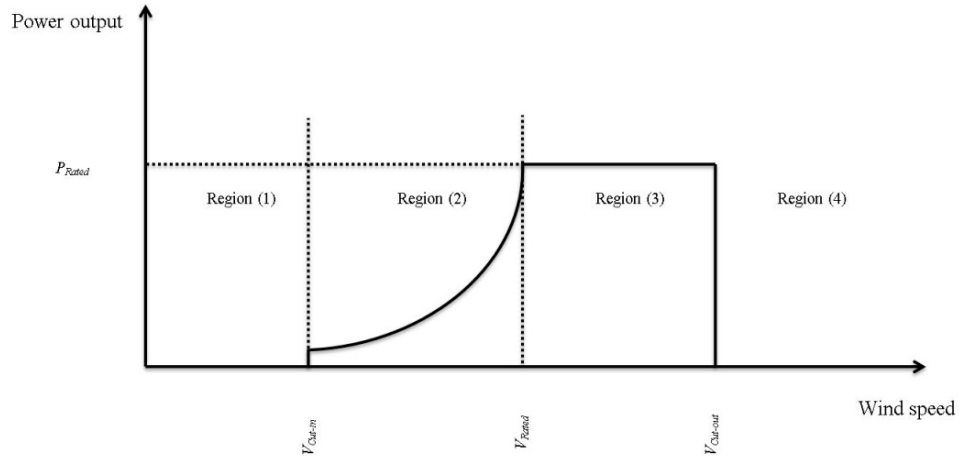


Figure 7. Working regions of the wind turbine.

In the pitch control technique, the actuator whose transfer function is given by Equation (10) is used to change the pitch angle by turning the blade around its longitudinal axis, as shown in Figure 8. The simulation representation of the collective pitch angle with FLC of the mathematical model presented in Section 2.2 is shown in Figure 9.

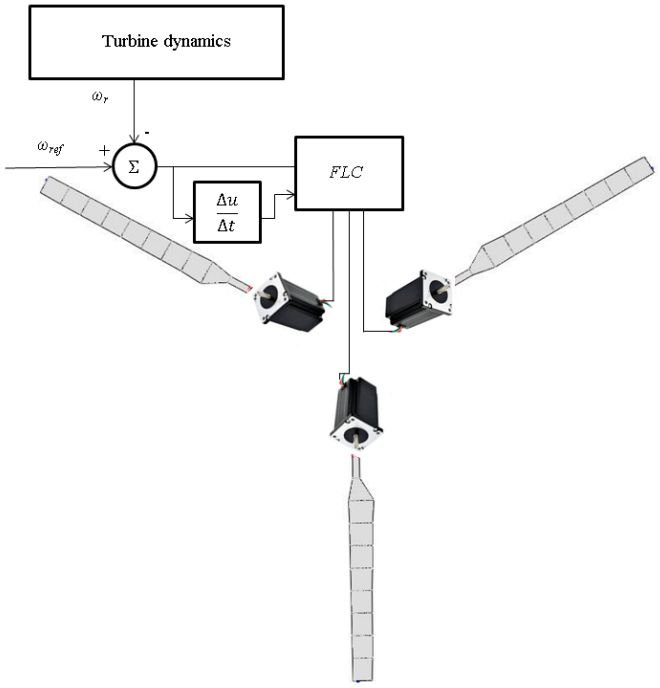


Figure 8. Simulation model of HAWT collective pitch control with fuzzy logic controller.

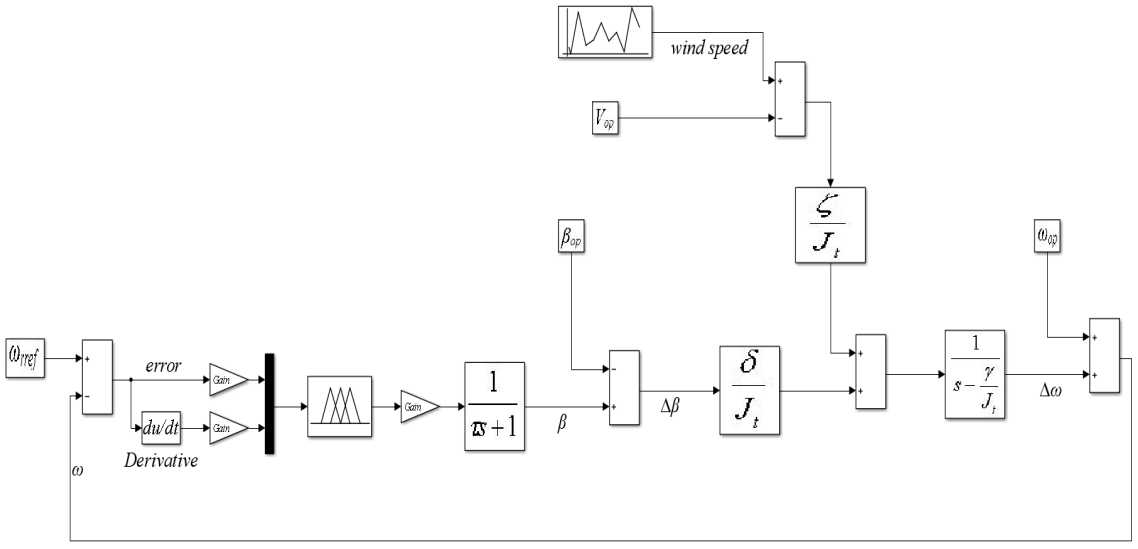


Figure 9. Simulation model of the pitch angle control with fuzzy logic controller for HAWT.

To maintain the rotor's angular speed at its rated value even though the wind speed increases, a Multi-Input Single-Output (MISO) fuzzy logic controller is used to regulate the pitch angle. The error between the reference rotor speed and its actual value and the rate of change of the error are the inputs, while the output is the desired pitch angle.
Input (1): $e = \omega_{rref} - \omega_r$
Input (2): $\frac{d}{dt}e$
Output: β_d

Three membership functions are used for the inputs and the output and they are illustrated in Figure 10. Table 5 lists the linguistic terms that are used. The nine base rules listed in Table 6 are stated based on expert knowledge that explains the different configurations of the rotor angular velocity as follows:

- The statement "error is positive and change-in-error is negative" represents the situation where the rotor speed is lower than the set point and getting higher.
- The statement "error is negative and change-in-error is negative" represents the situation where the rotor speed is higher than the set point and getting higher.

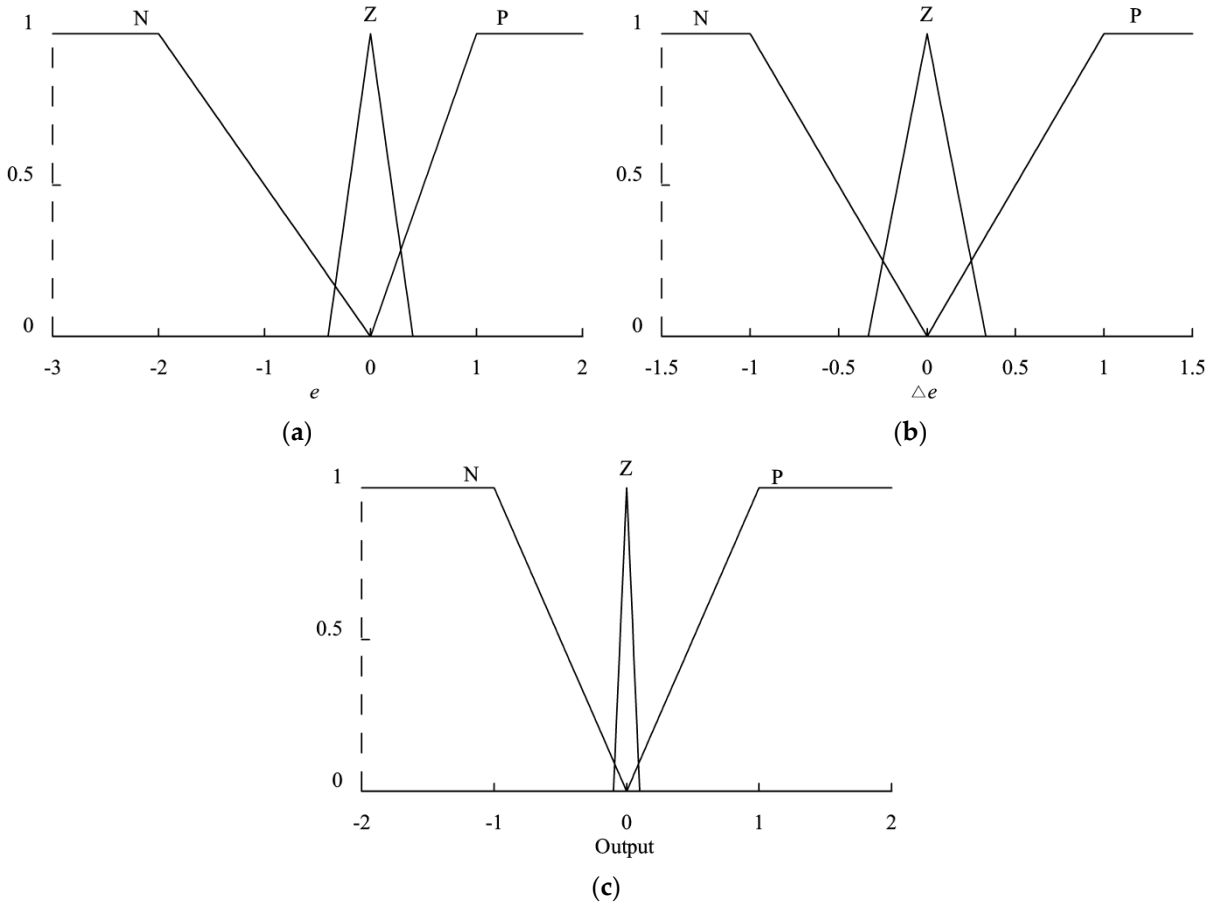


Figure 10. HAWT pitch control membership functions: (**a**) First input membership functions; (**b**) Second input membership functions and (**c**) Output membership functions.

Table 5. HAWT pitch control Linguistic terms.

N	Negative
Z	Zero
P	Positive

Table 6. The rule base of the FLC.

Δ Error	**Error**		
	N	**Z**	**P**
N	N	N	Z
Z	N	Z	P
P	Z	P	P

To produce an actual output signal to the control actuator, the output scaling factor was used. Several simulation trials were conducted to determine the scaling factor.

3. Simulation Results and Discussion

3.1. H-Type VAWT

The H-type VAWT mathematical model presented in Section 2.1 was simulated using MATLAB/SIMULINK at three different tip speed ratios to evaluate the performance of the wind turbine with and without the aid of pitch regulation. In the simulation, the wind speed was set to be equal to 3 m/s, and the results are seen in Figures 11–13. In these figures, the sub-figures (a) illustrate the association between the azimuth angle and the angle of attack in the cases of (i) AOA without control, (ii) AOA with control, and (iii) the controlled pitch angle. Sub-figures (b) display the relationship between tangential coefficient and azimuth position in both cases with and without control. Finally, sub-figures (c) represent the association between individual blade generated torque and azimuth position with FLC, gain scheduled PI controllers and without control.

The finding shows that the FLC controls the attack angle and maintains its optimal value (sub-figures (a)). Consequently, the tangential coefficient stays constant at its optimum value, as seen in sub-figures (b). As a result, the individual blade torque indicates better output due to the pitch control, as is apparent from the sub-figures (c). In the absence of FLC, negative values of the blade torque occur at the tip speed ratios provided in the analysis at several azimuth positions. On the contrary, the torque produced by the blades against every azimuth location is always positive with the present FLC. However, the gain scheduled PI controller achieved almost the same results as FLC providing that the input speed is constant during one cycle.

Figure 14 shows the relationship between tip speed ratios and C_p with and without pitch control. The figure demonstrates a quantitative comparison between controlled pitch turbine and fixed pitch turbine performance. Figure 14 reveals that the fixed pitch turbine has low values of C_p at low tip speed ratios while using FLC to control the pitch angle gives improved output and higher C_p at low tip speed ratios.

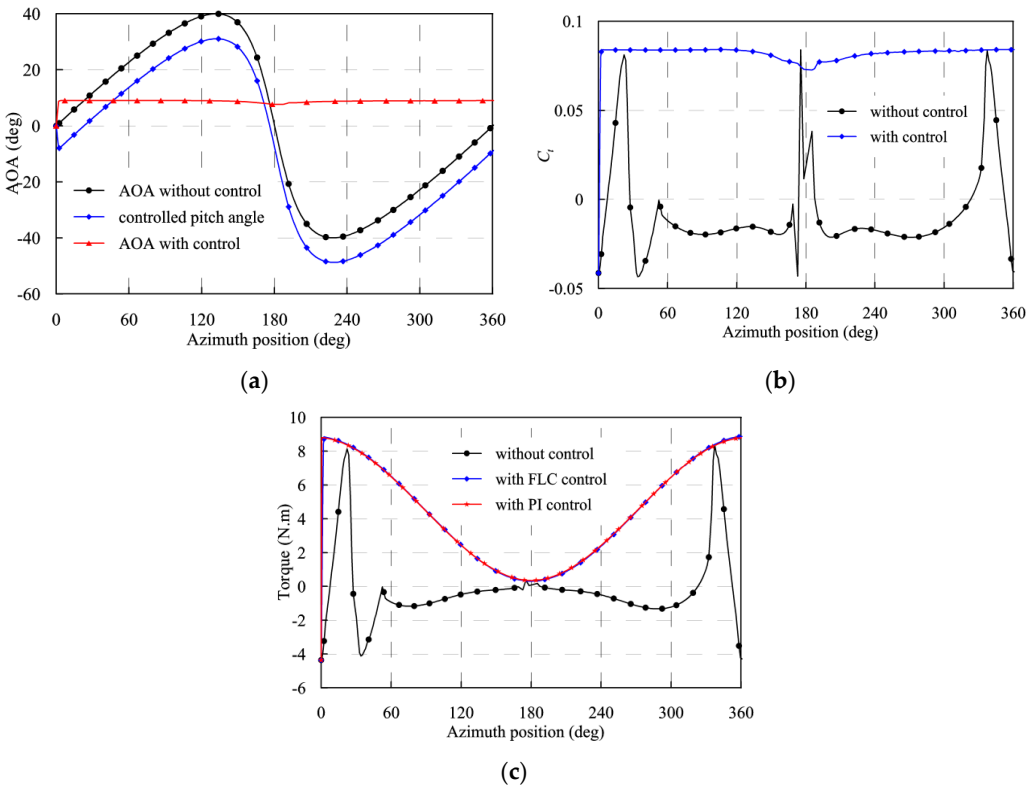


Figure 11. H-type VAWT simulation results at tip speed ratio = 1.5: (**a**) The relation between AOA and azimuth position; (**b**) the relation between tangential coefficient and azimuth position; and (**c**) the relation between blade torque and azimuth position.

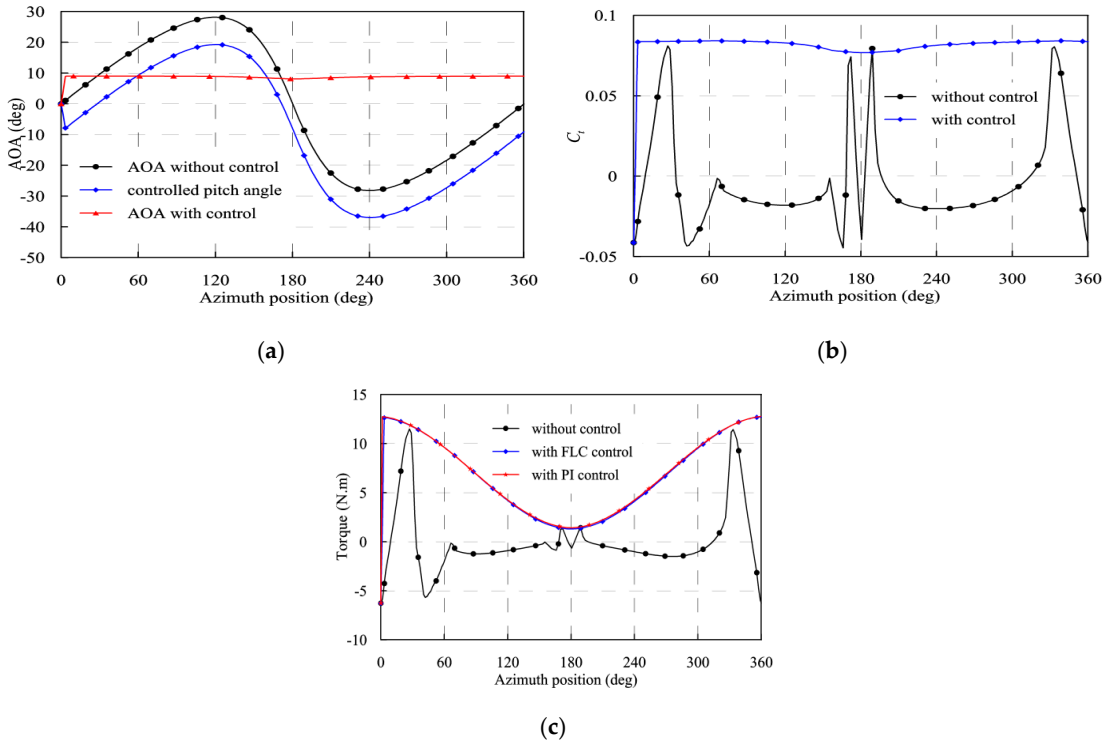


Figure 12. H-type VAWT simulation results at tip speed ratio = 2: (**a**) The relation between AOA and azimuth position; (**b**) the relation between tangential coefficient and azimuth position; and (**c**) the relation between blade torque and azimuth position.

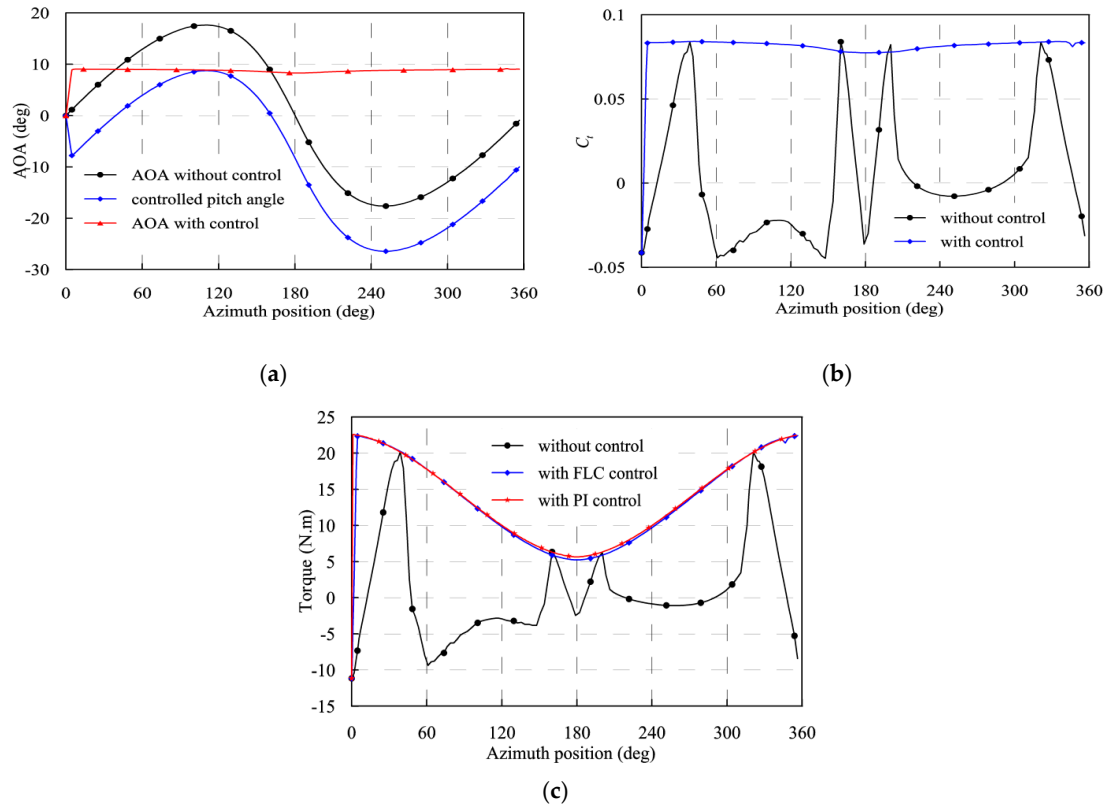


Figure 13. H-type VAWT simulation results at tip speed ratio = 3: (**a**) The relation between AOA and azimuth position; (**b**) the relation between tangential coefficient and azimuth position; and (**c**) the relation between blade torque and azimuth position.

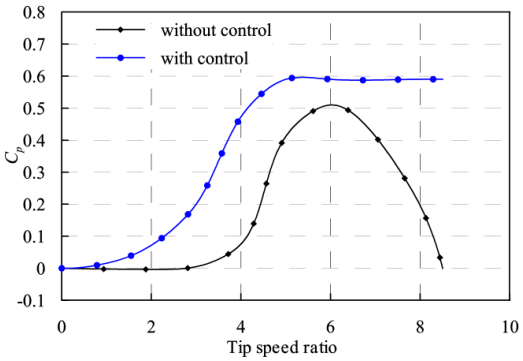


Figure 14. C_p at different tip speed ratios.

3.2. HAWT

The mathematical model presented in Section 2.2 was computed using MATLAB/SIMULINK. For HAWT, pitch control has been employed to limit the rotor angular speed to its rated value. First, the simulation was performed for wind speeds higher than the rated value and lower than the cut-out speed (V_w = 12–25 m/s) to test the control system and to get the pitch angle needed at any of those speeds to maintain the rotor angular speed at its rated value. Second, the simulation was performed considering the wind speed as random noise with low variation since higher variation values would be non-realistic in real life. Finally, a simulation was conducted with a sudden increase in wind speed to evaluate the FLC's effectiveness. The results are shown in Figure 15: (a) shows the input wind speed; (b) shows the difference between controlled pitch angle using the FLC and uncontrolled pitch angle; (c) presents a comparison between controlled with FLC; gain schedule PI controllers and uncontrolled rotor angular velocity; (d) compares between controlled and uncontrolled tip speed ratios; (e) depicts the coefficient of performance with and without pitch control; and finally, (f) represents the controlled pitch angles needed at different wind speeds; (g) represents the wind speed variation with a sudden increase; (h) compares controlled and uncontrolled angular speed with a sudden rise in wind speed.

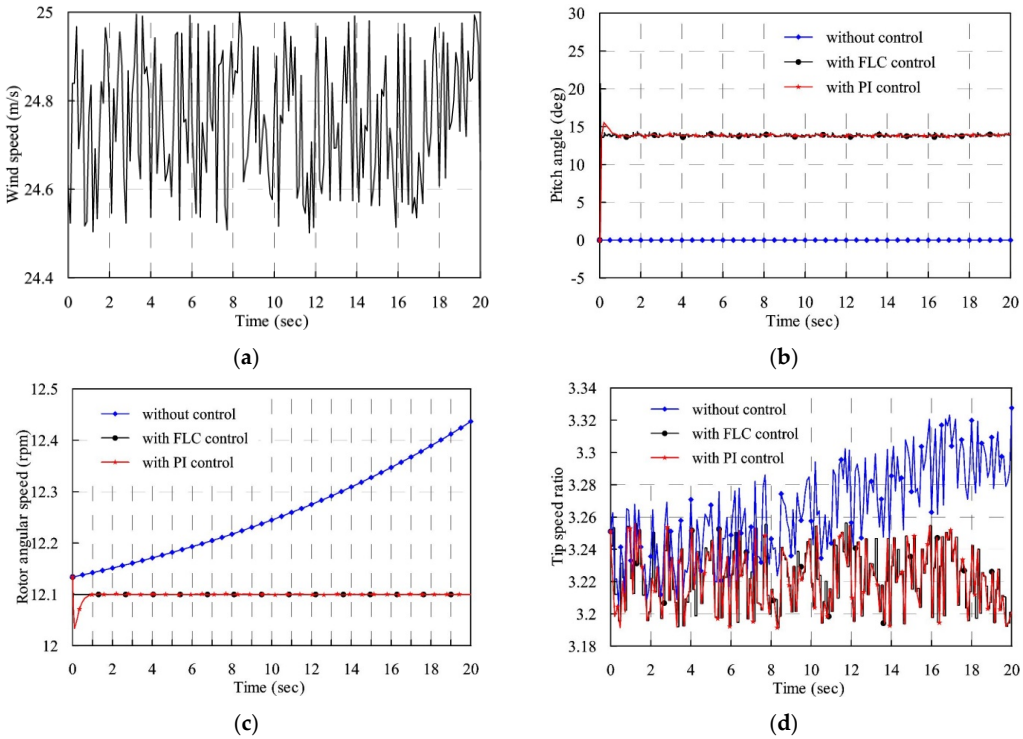


Figure 15. *Cont.*

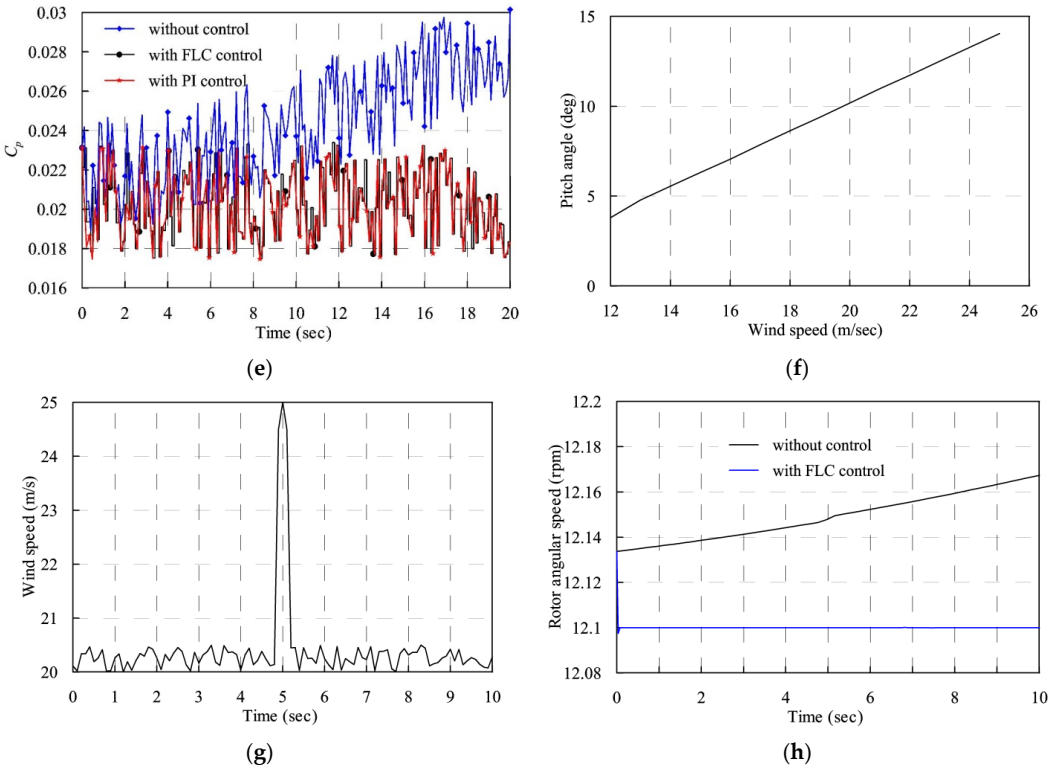


Figure 15. HAWT simulation results: (**a**) wind speed as input; (**b**) the pitch angle; (**c**) rotor angular speed with and without pitch control; (**d**) tip speed ratio; (**e**) power coefficient;(**f**) the relation between wind speed and needed pitch angles; (**g**) wind speed time history with sudden increase and (**h**) rotor angular speed with sudden rise in wind speed.

The pitch control was used to control the angular velocity of the HAWT. Figure 15b,c depict how adjusting the pitch angle keeps the rotor angular velocity at its rated value of 12.1 rpm in the case of FLC. In addition, the rotor angular speed settles at 0.018 s. The gain schedule PI controller, on the other hand, provides acceptable performance but with a longer settling time when compared with FLC. It is clear that the proposed FLC has better performance anyway due to the robust behavior in the presence of turbulent wind speed and model uncertainties. As a result, the values of tip speed ratio and coefficient of performance are reduced, as seen in Figure 15d,e, respectively, where the power coefficient C_p is reduced by 6.5 percent when compared to its values without pitch control. In order to maintain the rotor angular velocity at its value, the FLC increases the pitch angle with rising wind speed, as seen from Figure 15f. Figure 15h proved that FLC could maintain the angular speed at its rated value even with a high sudden increase in wind speed variation.

4. Conclusions

FLC was used to control the pitch angle of HAWT and VAWT to investigate the influence of pitch regulation on the power coefficient in both types. Each turbine type was mathematically modeled, and the simulation was carried out using MATLAB/SIMULINK. In addition, the gain schedule PI controller is presented for the sake of comparison.

In the H-type VAWT, the pitch regulation aimed to regulate the AOA to hold it at its optimum value to improve the torque output at low wind speed and low tip speed ratios. The desired AOA for the NACA 0018 airfoil was 9 degrees, which ensured higher values of C_t. The results showed that using pitch control can significantly increase the torque produced by individual blades. It is worth noting that in the absence of pitch modulation, there are positions where the individual blade-induced torque is negative. Using FLC for pitch regulation resulted in positive individual blade output torque at all azimuth positions. In the case of the gain scheduled PI controller, almost the same results are obtained as with FLC providing that the input speed is constant during one cycle.

FLC was also used in HAWT pitch angle control in order to keep the rotor angular velocity at its rated value. The system with FLC showed a lower settling time of rotor angular speed against the wind speed variations when compared to the gain scheduled PI controller. With pitch control, the power coefficient C_p is reduced when compared to its values without pitch control. Nonetheless, preserving the rotor angular speed secures the electric components of the turbine.

For future work, the performance of the VAWT with the proposed pitch control strategy can be compared with the hybrid VAWT system, which includes Darrieus and Savonius units. In addition, an experimental validation can be conducted to evaluate the effectiveness of the proposed control technique.

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Nomenclature

A	Swept area
a	Axial induction factor
c	Length of the chord
C_d	Coefficient of drag
C_l	Coefficient of lift
C_p	Coefficient of power
C_t	Tangential coefficient
F_t	Tangential force
H	VAWT blade length
J_t	The equivalent for the rotor and generator
N	Blades number
R	Radius of rotor
T_a	Aerodynamic torque
T_g	Generator torque
T_r	VAWT blade generated torque
V_a	Induction velocity
V_n	Normal velocity
V_t	Tangential velocity
V_w	Free stream velocity
W	Relative velocity
α	Attack angle
β	Pitch angle
β_d	Desired pitch angle
θ	Angle of azimuth
λ	Tip speed ratio
ρ	Air density
τ	Actuator time constant
ω_r	Rotor angular velocity

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