A Proposed Controller for Pitch Angle of Wind Turbine

NORHAN M. MOUSA[1], YASSER I. EL-SHAER[2], MOHAMED I. ABU EL-SEBAH[3]
[1]Mechatronics and Robotics Engineering Department, Faculty of Engineering,
Egyptian Russian University (ERU),
Cairo 11829,
EGYPT

[2]Mechanical Engineering Department,
Arab Academy for Science and Technology and Maritime Transport (AASTMT),
Smart-Village Branch, Cairo,
EGYPT

[3]Electronics Research Institute,
Cairo,
EGYPT

Abstract: - Wind turbines are complicated non-linear systems with certain random disruptions. The pitch control system is a commonly employed method for regulating the electricity generated by a wind turbine. Many researchers have observed developments in the pitch control field during the last few decades. Traditional PID controllers have the drawback of being slow or imprecise when wind and pitch angles suddenly change. These drawbacks can be solved with artificial intelligent algorithms. However, the algorithms' design and implementation are highly complex. A new pitch-regulated variable-speed control strategy for wind turbines to address their nonlinear properties is presented. To manage the pitch system's control mechanisms with disturbances, this research evolved a mathematical model that illustrates HAWT's pitch angle control system and applied a proposed Simple Optimal Intelligent PID Controller (SOI-PID). Under various operating conditions, the proposed SOI-PID controller was tested with the Traditional PID, Fuzzy Logic Controller (FLC), and Fuzzy-Adaptive-PID controller. For system simulation, the MATLAB/Simulink software was used. According to simulation results, compared to PID, FLC, and Fuzzy-Adaptive-PID controllers, the proposed SOI-PID controller responds faster and has a better rise and settling time. Other benefits of the SOI-PID controller are its simplicity of implementation and design, distinguishing it from other intelligent algorithms.

Key-Words: - Wind Turbine (WT), Pitch angle control, Wind Energy Conversion System (WECS), Modeling, Simulink, PID Controller, Fuzzy Logic Control (FLC), Fuzzy-Adaptive-PID Controller, Simple Optimum PID (SOI-PID).

Received: March 9, 2023. Revised: November 26, 2023. Accepted: December 13, 2023. Published: December 31, 2023.

1 Introduction

Renewable energy is being used more often to produce electricity as a result of issues with pollution from fossil fuels and a shortage of energy sources.

Wind energy is a prominent source of sustainable energy. This energy is constantly available, dispersed, and vastly geographic. In wind turbines, mechanical energy is first transformed from kinetic energy to electrical energy using a wind turbine generator, [1], [2], [3].

Wind energy is highly maneuverable in operation (from a couple of watts to numerous megawatts). In addition to partially satisfying the requirement for electricity, wind energy has additional advantages, such as eliminating the need for fuel for wind turbines, promoting energy diversification and building a sustainable energy system, requiring no water, and causing no environmental pollution, [4].

The wind is wavering and sporadic and does not blow continuously. Wind farms do not generate sustained energy, similar to a fuel plant; half of the electricity produced by the wind turbines is generated during around 15% of their operating duration, [5]. Nowadays, wind turbines represent major significance inside microgrids as energy generation sources. They can be operated at both fixed and variable speeds. Many research studies have been conducted on wind power and wind turbines, [6], [7], [8].

Figure 1 illustrates the structure of WT. The primary components of the WT are the blades, nacelle, main controller, and tower. A power converter, gearbox, generator, and transformer are all housed within the nacelle. The turbine's blade shafts and the generator's blade shafts are joined by the gearbox while wind motion rotates its blades. A transformer sends the Electricity to the grid by the generator, [9].

Non-torque loads are applied as input and output to the wind turbine, mainly on both the generator's and blade's sides. These non-torque loads impact the WT drive train's mechanical loads and stresses, [10].

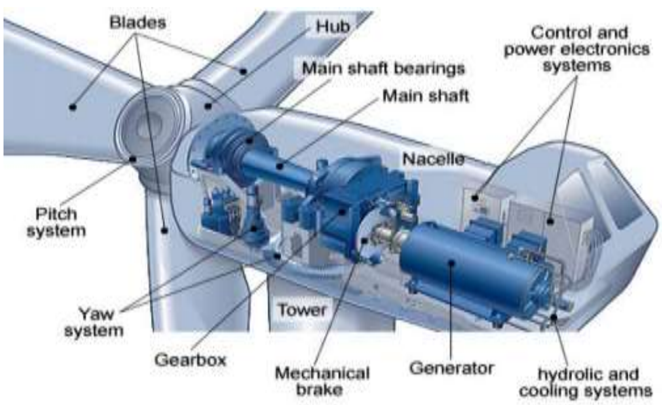

Fig. 1: Wind turbine components, [9]

The utilization of fuzzy logic as a technique of the pitch angle control of variable-speed WT. The FLC's control input variables are the generator's speed and output power, described in [11].

Model prediction controls for load frequency control in microgrids are proposed to coordinate the regulation of pitch angle in WT generators and hybrid plug-in electric automobiles. The simulation outcomes demonstrate that this approach exhibits greater efficacy in adjusting system parameters when compared to PID control, [12].

The efficacy of the standalone incorporated system of renewable energy, comprised of solar photovoltaic cells, WT, and fuel cells, this improvement was attained through the execution of a proportional-integral (PI) controller that is highly effective for the dynamic voltage restorer, leading toward effective utilization of this control methodology. The enhancement of voltage, current, and each source's power waveforms within the system has improved the WT generator's dynamic performance. Furthermore, the system has successfully maintained the continuous performance of all three sources, even under fault situations. This performance was enhanced in a previous study, [13].

For wind energy conversion systems used in DC microgrids, the author suggests the maximum power tracking (MPPT) method. Because of the excitation capacitor in the stator, the induction generator operates in a self-excited state. In addition, a technique has been devised to evaluate the proposed system's efficacy and determine the proportion of duty of a DC-DC converter under (MPPT) conditions. This methodology uses the attributes of wind turbines, the power balance in power converters, the steady-state equivalence for an inductance generator, and the MPPT algorithm's efficacy with its results. The experimental results using simulated values are presented, [14].

The impact of the steadiness of variable wind speed power systems in strong and weak networks utilizing a wind farm accompanied by doubly-feed induction generators (DFIG). The study analyzed the impact of a static series synchronous compensator and power system stabilization (PSS) on the power system's stability using a modified 14-bus IEEE test system introduced in [15].

A paradigm for controlling a wind farm's frequency coupled to conventional units, the wind farm is alerted to power variations through a PID controller. Additionally, the specified frequency control parameters (PID coefficients) are improved by employing the particle swarm optimization (PSO) technique following a multi-objective function to enhance the model's performance; the model is proposed in [16].

The issue relates to regulating the power output of variable-speed WT with flexible shafts. To control the improvement of wind energy absorption by monitoring its desired output power, a dynamic compensation using suitable parameters is devised to handle errors created by the steering filter and unknown control gains; this problem was studied in [17].

Among the most significant difficulties in conversion systems for wind energy is determining how to get the greatest output power of these systems at various wind speeds.

First, this paper will describe a proposed simple optimum (SO-PID) for pitch angle control of variable-speed WT. The results attained by a simple optimum (SO-PID) controller have been compared with those obtained using a fuzzy-adaptive-PID controller, FLC, and PID controller by changing the input by unit step and unit sine wave to determine the fastest response at the output.

This paper will be structured as follows: Section 2 presents a mathematical model of wind turbines. Section 3 introduces a concise summary of the wind turbine's model system. Section 4 describes the pitch angle control (PC) system with a proposed Simplified Optimum PID (SO PID). A PC system simulation and its results are compared with PID, Fuzzy Logic Controller (FLC), and Fuzzy-adaptive-PID control, which are demonstrated in Section 5. Section 6 concludes this study.

2 Mathematical Model of WT

The WT's maximum power extraction is as follows in equ (1).

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

The equation represents the power produced by the wind (P_m) in watts. It involves variables such as density of air (ρ), which is 1.225 (kg/m^3), coefficient of power (C_p), wind velocity (v) in meters per second, and the swept area (A) in square meters.

The coefficient of power, denoting the proportion of power generated by wind energy, can be calculated using two parameters.

$$C_p(\lambda,\beta) = C_1(C_2K - C_3\beta - C_4\beta^x - C_5)e^{-C_6K} \qquad (2)$$

The coefficients ($C1{-}6$) represent the distinctive values for WT. The pitch angle, denoted as (β), is maintained at a minimal value less than the rated wind velocities. It can be modified to safeguard the turbine from potential harm, particularly during higher wind velocities. The parameters (λ) and (K) represent the tip speed ratio and are defined according to equ (3,4).

$$\lambda = \frac{R*\omega}{v} \qquad (3)$$

$$K = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{1+\beta^3} \qquad (4)$$

In equ (3), (ω) represents the rotor angular velocity of WT in radians per second, (R) represents the blade radius in meters, and (v) represents the wind velocity in meters per second.

The power coefficient (C_p) is illustrated in Figure 2 about the tip speed ratio (λ) and the pitch angle (β).

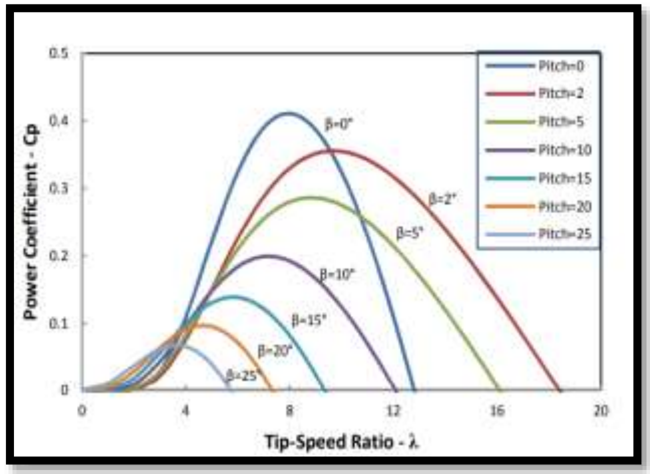

Fig. 2: Curves of C_p in relation to λ and β, [18]

Figure 2 shows that achieving the highest mechanical energy output in response to rapidly changing wind velocity relies on maintaining the coefficient of power at its maximum value. Additionally, achieving the highest possible coefficient of power regardless of the wind velocity is reliant on maintaining the smallest possible pitch angle and an appropriate tip speed ratio. The power coefficient decreases as the pitch angle value increases, which is another characteristic illustrated. This ensures that beyond the rated wind velocities, excessive power can be constrained via pitch angle adjustment. The rotor speed can be modified following the instantaneous wind velocity, as demonstrated in equ (3), to achieve the optimal value of the tip speed ratio. This adjustment constitutes the fundamental MPPT and pace control principle. Thus, by adjusting the pitch angle, it is possible to restrict excessive power beyond the rated wind velocities.

The coefficient of rotor power can be computed as

$$C_p = \frac{P_m}{P} \qquad (5)$$

(rotor blades' mechanical power divided by power of wind)

The highest power output that may be produced by a rotor with the most blades is limited to 59.26% of the overall power accessible from the wind, as stated by the physicist Betz (Betz Limit), [19].

3 Wind Turbines System Model

Wind energy is employed to be a sustainable energy source. The kinetic energy in the wind is proportionate to the square of its speed, whereas the power of the wind is proportionate to the cube of its speed. Consequently, when the velocity of the wind rises, the amount of wind energy will also increase.

The amount of electricity generated from wind energy in (WECS) is influenced by both the wind attributes at the location and the control method used.

3.1 Wind Energy Conversion System (WECS)

The (WECS) is represented by the connection of multiple subsystems as illustrated in Figure 3, where (F_t) refers to the structural force entering the tower; in addition, shaft speed (ω_r), hub torque (T_t), reaction torque (Tg), and power output (P_o) indicate the consumer power as well as the pitch angle (β) and its reference value (βref), [20], [21].

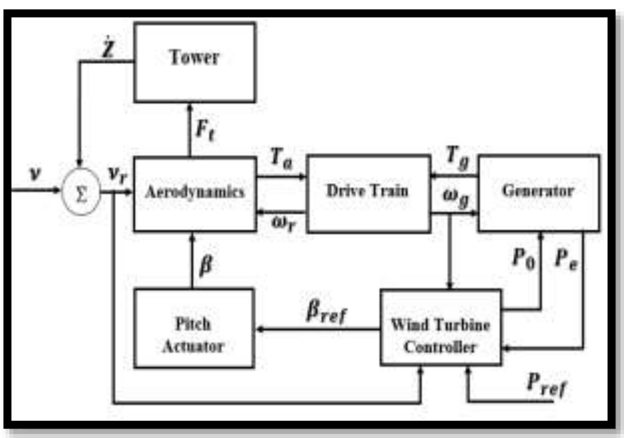

Fig. 3: Block diagram of (WECS)

3.2 Various Wind Speed Work Areas

The torque, power reference, and turbine velocity are all determined by the wind velocity. There are four primary regions in which the turbine operates, each of which is determined by the wind speed. The WT's mechanical power generation is depicted in Figure 4 in terms of wind speed across four different areas.

Every region possesses unique attributes and constraints. Wind speed in Region 1 falls below the cut-in wind speed, thereby failing to provide adequate power to operate the turbine. As a result, zero output power is generated. Region 2 commences when the wind velocity surpasses the cut-in value and continues until the rated wind velocity is reached, which is when the rated output power is generated. Maximizing power extraction is the primary concern in this region. As a result, the pitch angle remains at zero degrees. To prevent turbine excess in Region 3, both the power extraction and rotor speed are restricted to the rated power.

This is accomplished at the turbine level through the implementation of the (PC), which modifies the pitch angle to a predetermined value. In Region 4, wind velocities attain the dangerous threshold of cut-out wind speed; when this occurs, the turbine is deactivated to safeguard against potential mechanical damage.

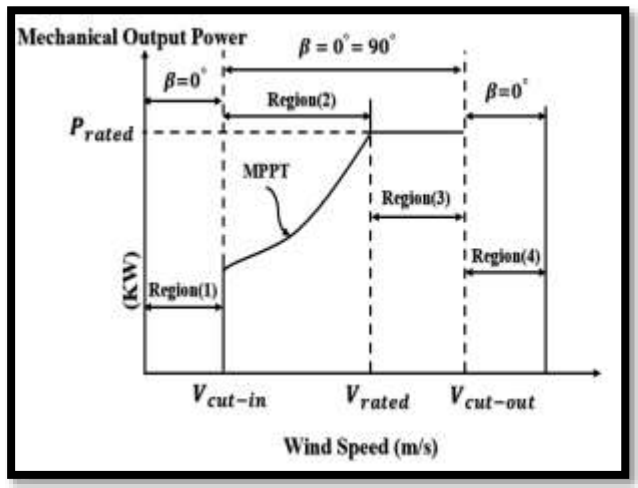

Fig. 4: Operating regions of WT according to wind velocity

3.3 Pitch Actuator Motor Model

The pitch actuator motor model illustrates the dynamic performance between the required pitch demand (β_d) from Pitch control (PC) and the pitch angle measurement (β), [22]. Blades revolve around their linear axes with the help of the pitch actuator. The subsequent equations describe the variation of pitch angle.

$$\frac{d\beta}{dt} = \frac{\beta_d - \beta}{T_\beta} \tag{6}$$

$$\left(T_\beta * \frac{d\beta}{dt}\right) + \beta = \beta_d \tag{7}$$

By utilizing the Laplace transform.

$$T_\beta * S * \beta + \beta = \beta_d \tag{8}$$

$$\beta(T_\beta * S + 1) = \beta_d \tag{9}$$

$$\frac{\beta}{\beta_d} = \frac{1}{(T_\beta * S+1)} \quad (10)$$

Wind turbine parameters are used to derive the time constant and transfer function.

$$T_\beta = \frac{\beta_d - \beta}{\frac{d\beta}{dt}} = 0.3/_{0.6} = 0.5$$

The transfer function that is required is denoted by Equ(11). T_β, the time constant for the pitch actuator, can be specified. Table 1 shows the initial wind turbine parameters, [23].

$$\frac{\beta}{\beta_d} = \frac{1}{(0.5 * S+1)} \quad (11)$$

Table 1. Initial wind turbine parameters

Parameters	Values
Rated generator's power, P_g	1000 Kw
Rated generator's speed, W_g	1500 rpm
Rated rotor's turning speed, W_t	20 rpm
The wind turbine's blade radius, R	35 m
Reference pitch blade angle, β_d	0 to 90 degrees
Pitch angle change rate , $\frac{d\beta}{dt}$	0.6 degrees/s
Coefficient of damping, B	2 N.m/rad/s
Inertia of Drive-Train, J_t	0.75 N.m^2

3.4 Model of a Drive-Train

As shown in Figure 5, the mechanical drive-train model is illustrated, [24]. The mathematical modeling of the drive train is represented by

$$J_T . \frac{d}{dt}(\omega_T) = T_T - (K_s . \delta\theta + B . \delta\omega) \quad (12)$$

$$\frac{d}{dt}(\delta\theta) = \delta\omega \quad (13)$$

By applying Newton's second law,

$$J . \frac{d\omega}{dt} = T - B . \omega \quad (14)$$

By using the Laplace transform,

$$J * S * \omega = T - B . \omega \quad (15)$$

$$\frac{\omega}{T} = \frac{\frac{1}{\beta}}{\left(\frac{J}{\beta}\right) * S+1} \quad (16)$$

$$\frac{\omega}{T} = \frac{0.5}{(0.37 * S+1)} \quad (17)$$

The variable " **ω** " denotes the value obtained from the combination of the generator shaft speed and WT, " **J** " the value obtained from the generator shaft inertia and WT, and " **T** " the value obtained from the generator shaft torque and WT.

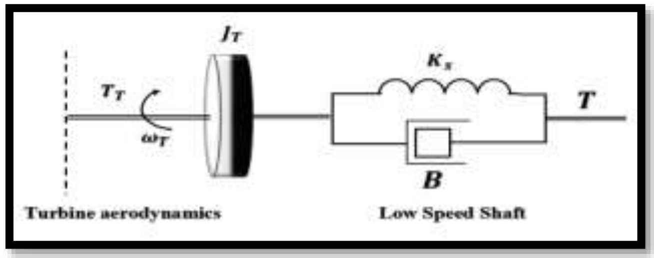

Fig. 5: Two-Mass Model of Drive-Train

A wind turbine model has been constructed utilizing a two-mass model. The gearbox shaft rotates in conjunction with the pitch's rotation. The rotor then begins to rotate according to the gear's ratio due to the gears' rotation. The stator's electrical energy is generated through the rotation of the magnetic field produced by the coil, [24]. Table 2 displays the specifications of the drive train model.

Table 2. The drive-train model's specifications

Parameters	Description	Parameters	Description
J_T	WT's Inertia(Kg/m^2)	ω_T	WT's speed shaft(rad/s)
J_g	Generator's Inertia(Kg. m^2)	ω_g	Generator's speed shaft (rad/s)
K_s	Coefficient of Stiffness(N.m/rad)	θ_T	WT's shaft angle(rad/s)
B	Coefficient of Damper(N.m/rad/s)	θ_g	Generator's shaft angle(rad/s)
T_T	WT's Torque(N.m)	$1: n_{gear}$	Gear Ratio
T_g	Electromechanical generator's Torque(N.m)		

An analysis of the mathematical model of the wind turbine was conducted using the MATLAB Simulink software. Peak overshoot and comparatively slow response are characteristics of the traditional PID controller when the input is a unit step.

This paper proposed a simple optimum (SO-PID) controller for this application to attain the fastest response.

4 Pitch Control with a Proposed Simplified Optimum Intelligent (SOI) Controller

To ascertain the coefficient of the optimal PID controller, the proposed design formula for simple optimum SO-PID utilizes the process transfer function. Figure 6 shows a typical second-order system featuring a controller that is inferred from the optimal response, which is determined by the transfer function of the process, [25], [26], [27], [28].

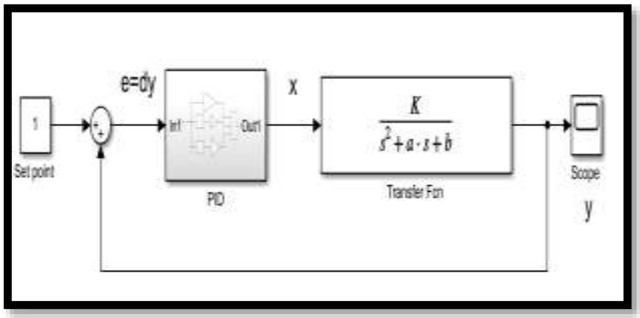

Fig. 6: closed-loop system with PID controller

The controller is represented by the following equations:

The process transfer function

$$\frac{y}{x} = \frac{k}{a.s^2+b.s+c} \tag{18}$$

$$y(a.s^2 + b.s + c) = k.x \tag{19}$$

$$a.\frac{d^2y}{dt^2} + b.\frac{dy}{dx} + c.y = k.x \tag{20}$$

Substituting

$$\frac{dy}{dt} = \frac{\Delta y}{T} \tag{21}$$

$$a\frac{dy}{dx}\left(\frac{\Delta y}{T}\right) + b\frac{\Delta y}{T} + c\int \Delta y\, dt = kx \tag{22}$$

$$a\frac{dy}{dt}\left(\frac{e}{T}\right) + b\frac{e}{T} + c\int e\, dt = kx \tag{23}$$

$$x = \frac{b}{kT}e + \frac{c}{kt}\int e\, dt + \frac{a}{kT}\frac{dy}{dt}(e) \tag{24}$$

Matching the Equation (24)'s coefficient to equation (25), which it corresponds to.

$$x = K_p e + K_i \int e\, dt + K_d \frac{dy}{dx}(e) \tag{25}$$

The controller constant

$$K_p = \frac{b}{kT} \tag{26}$$

$$K_i = \frac{c}{kT} \tag{27}$$

$$K_d = \frac{a}{kT} \tag{28}$$

In which T represents the sampling time of the control program or a multiple of that time.

The pitch control contains two transfer functions of the pitch actuator model, and the drive-train model can be simplified in the manner depicted in the subsequent block diagram (Figure 7).

Simplifying the block diagram of (PC), it contains the model of pitch actuator and drive train model in one block in second order to calculate coefficients of SO PID, as shown in Figure 8.

The transfer function that is required is denoted by Equation (29)

$$G(s) = \frac{0.5}{0.185.s^2+1.12.s+1.5} \tag{29}$$

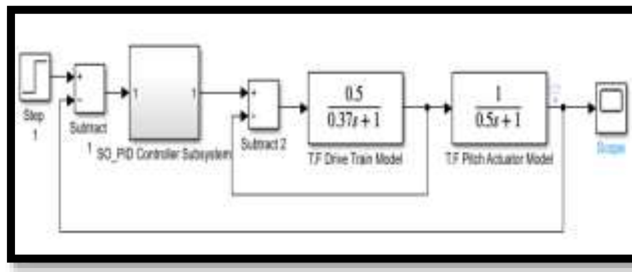

Fig. 7: Proposed SO PID controller in Pitch Control

T equal to half of the sampling time can accelerate the response, which is equal to 0.0001 sec

$$K_p = \frac{1.12}{0.5 * 0.0001} = 22400$$

$$K_i = \frac{1.5}{0.5} = 3$$

$$K_d = \frac{0.185}{0.5 * 0.0001} = 3700$$

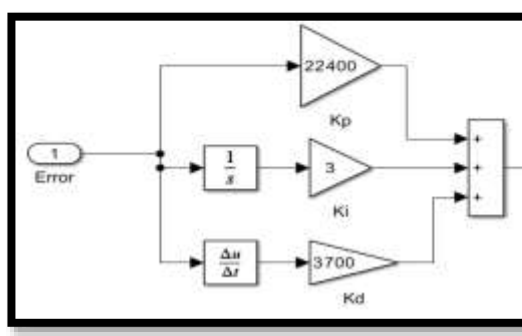

Fig. 8: SO PID controller Coefficients

The MDOF controller comprises two controllers, one intended for fine-tuning and the other for accommodating a wide range of errors. The multi-degree of freedom controller (MDOF) is generated through the combination of two controllers, where the weights of the controllers differ based on the error at each value of the controller input. The MDOF controller underwent a two-step design process. The first step is to devise two distinct controllers, one of which is intended for fine-tuning and the other for a wide range of large errors. The outputs of both controllers are combined in the second step to generate the final output under the assumption that the error and controller weights follow a linear relationship. The composition formula that is being proposed is denoted in per-unit values as follows:

Controller output = Output1*(Error) + Output2*(1−Error)

where O/P1 is denoted to the controller output for a wide-range controller (using large T in the design formula) and O/P2 is denoted to the controller output for the fine-tuning controller (using large T in the design formula).

The two controllers were incorporated into the system, each assigned with adaptive weights: one for the error (e) and the other for (1–e). This phenomenon results in a good tracking reaction. A simplified adaptive weighting is accomplished by adjusting the PID controller gains to these values. Assuming a linear relationship between the controller weights and the error per unit value, adaptive weights are applied to the designed controller outputs prior to addition, [29].

The two controllers were developed to function as an intelligent Proportional-Integral-Derivative (PID) controller through the process of modifying the controller constants. The PID controller equations were modified by replacing the controller constants with the following values.

This substitution makes it possible to create an intelligent PID controller, as shown in Figure 9.

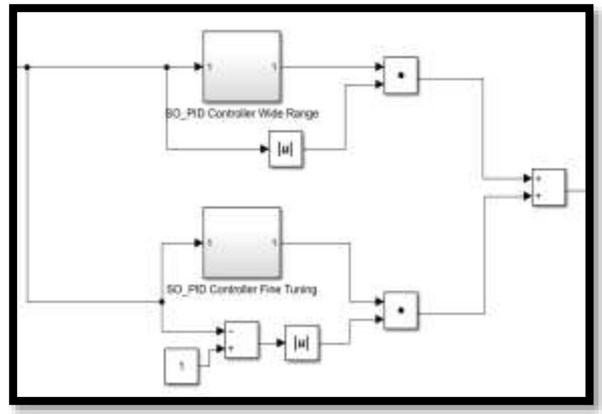

Fig. 9: Simple optimum intelligent PID (SOI PID) controller block diagram

5 Simulation Results

The pitch angle of a WT system refers to the angle at which a turbine blade's rotor or propeller is set about the axis of rotation. Pitch angle controlling is a common technique utilized to modify the aerodynamic torque of wind turbines. Pitch angles can substantially impact the output of a turbine and the power curve. This section evaluates the performance of four distinct types of controllers utilized for regulating the angle of the wind turbine blade, [30].

5.1 The Execution of a Traditional PID Controller

By changing the values of the control parameters until the desired output is close to the optimal level, PID tu ning is performed on the plant. Figure 10 displays the step response of the (PC). The figure shows less rise time, a greater peak overshoot, and more settling time excess with the PID controller.

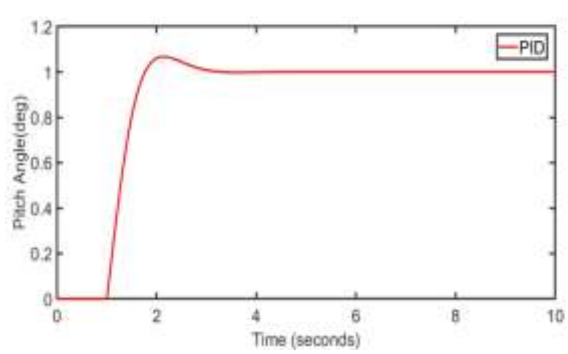

Fig. 10: Pitch control with PID, unit step

5.2 The Execution of a Fuzzy Logic Controller (FLC)

In fuzzy logic, rules are represented as linguistic variables derived from human experience.
By submitting to these rules and implementing this logic in power systems, superior outcomes can be obtained compared to traditional controllers. Because of this, several researchers have discussed using fuzzy logic in the power system, [31], [32], [33], [34], [35], [36], [37].

Figure 11 illustrates the Simulink model of the pitch control (PC) system, which incorporates a fuzzy logic controller. Figure 12 illustrates the unit step response of the (PC) pitch control with FLC. It observed more settling time and more rise time with the FLC in comparison to the traditional PID controller, with no overshoot.

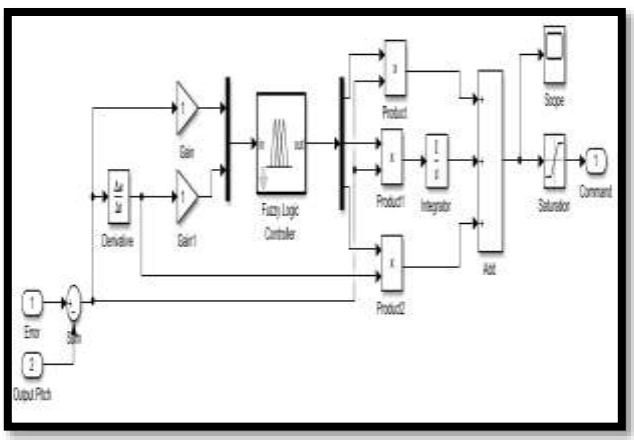

Fig. 11: Simulink diagram of Pitch control with FLC

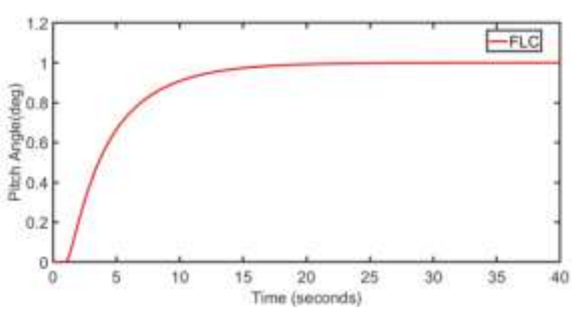

Fig. 12: Pitch control with FLC, unit step

5.3 The Execution of Fuzzy-Adaptive-PID Control

Adaptive Fuzzy PID can significantly enhance the performance of FLC systems. The parameters in fuzzy logic control are fixed. Therefore, it is unsuitable for applications involving a wide range of operating conditions. Fuzzy-adaptive-PID is necessary to optimize control performance and adapt to changes in operating conditions. The pitch system's fuzzy-adaptive-PID control block is seen in Figure 13.

Here, the fuzzy logic controller modifies the three PID control parameters (Kp, Ki, and Kd) based on the pitch's error (e) and changes in the pitch's error (ec) values. As indicated below, the three PID controller parameters must be changed in response to changes in pitch deviation and the present pitch deviation.

$$K_p = K_{p(present)} + \Delta K_{p(fuzzy)}, \quad (30)$$

$$K_i = K_{i(present)} + \Delta K_{i(fuzzy)}, \quad (31)$$

$$K_d = K_{d(present)} + \Delta K_{d(fuzzy)} \quad (32)$$

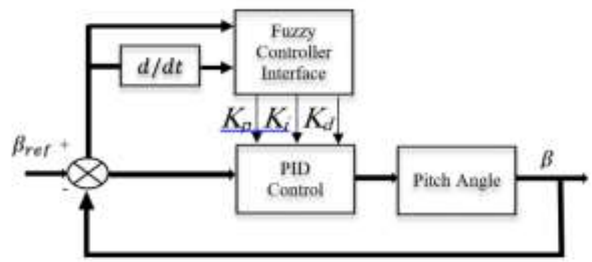

Fig. 13: Block of Fuzzy-Adaptive-PID control

The control coefficients have been altered based on the fuzzy inputs. Changes in blade angle and its derivative constitute the system inputs. The PID coefficients and the coefficients derived from the fuzzy are combined to generate the new PID controller parameters. Currently, the system is adjusted by comparing the feedback of the output to the present angle.

Figure 14 illustrates the Simulink model of the pitch control (PC) system for a WT, which incorporates a fuzzy-adaptive-PID controller. Illustrated in Figure 15 is the unit step response of the (PC) for a WT with Fuzzy-Adaptive-PID.

No overshoot was observed, and the settling time was significantly reduced to 5.23 seconds in comparison to fuzzy logic controllers. In comparison to a traditional PID controller, the efficiency in terms of rise time is not enhanced with 2.55 seconds.

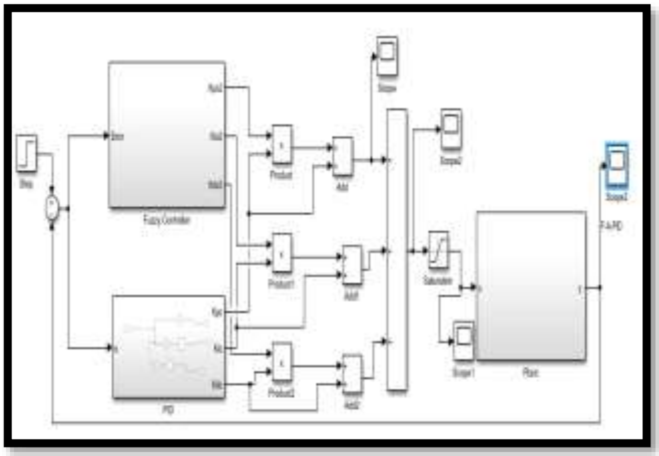

Fig. 14: Simulink of (PC) with Fuzzy-Adaptive-PID

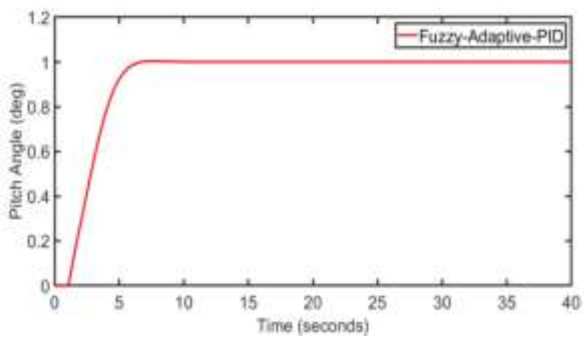

Fig.15: Pitch control with Fuzzy-Adaptive-PID, unit step

5.4 The Execution of a Proposed Simple Optimum (SO-PID) Controller

A robust controller must meet specified requirements in terms of design, implementation, and performance. Simplified design & adaptation techniques are preferred for the controller, which entails simple process modeling (traditional control) or input-output testing (modern control). The design must be accomplished through the implementation of a simple algorithm and the execution of a fast algorithm. The selection of the controller is determined by its ability to provide system stability and achieve optimal system responsiveness. A simplified manner was used to develop a proposed intelligent controller. The (SO-PID) controller is characterized by its simple design and implementation while also delivering excellent performance. The results of the suggested controller demonstrate that an optimal response can be attained using a simple optimal PID controller. Figure 16 illustrates the unit step response of pitch angle with (SO-PID). The response is done with the lowest rise time of 1.22 seconds and settling time of 2.11 seconds with no overshoot.

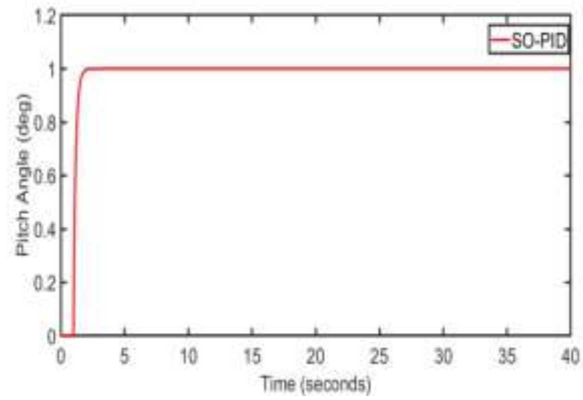

Fig. 16: Pitch control with (SO-PID), unit step

Figure 17 shows the performance of the (PC) when distributed with unit step input. It can be seen from the figure that the slowest performance is performed by FLC, with a settling time of 17.5 sec and a rise time of 4.5 sec. The PID controller, although it has a rise time of 1.367 sec and a settling time of 3.21 sec, has an overshoot of 8%.

The proposed (SO-PID) controller can be seen as a superior controller. A comparison between the four controllers is presented in Table 3.

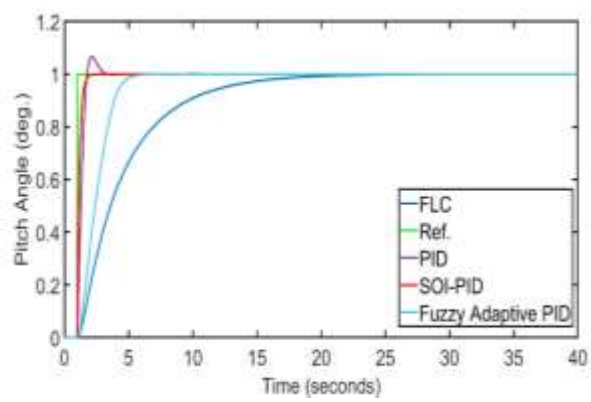

Fig. 17: Pitch control behavior with various controller, unit step

Table 3. Comparison response of various controller

Time Domain	PID	FLC	Fuzzy-Adaptive-PID	SO-PID
Rise Time (sec)	1.367	4.59	2.55	1.22
Settling Time (sec)	3.21	20	5.23	2
Peak Overshoot	8%	0	0	0

The PC system employs the sine wave function as a reference value for the pitch angle. Figure 18 illustrates the outcomes of the simulation for the output. In this instance, we evaluated the controllers using different inputs. It is evident from Figure 10 that the system generated the best response with (SO-PID).

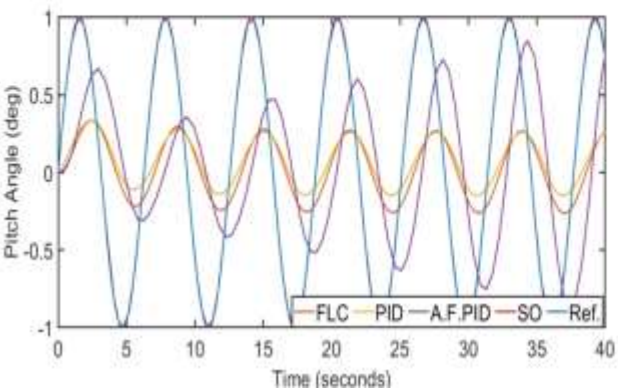

Fig. 18: Pitch control response with unit sine wave

When the system is subjected to parameter variation at running, the PID controller must adapt the controller constant. Using two Simple Optimum controllers (SO-PID) with an MDOF controller concept, one of them with slow-response (using large T in the design formula) as a fine-tuning controller, and the other with fast-response (using small T in the design formula) as a wide range controller. The resultant controller is a Simplified Optimum Intelligent PID (SOI PID) controller. The different controller's responses are compared when the system is subjected to sudden parameter variation. The SOI PID controller is unaffected by the parameter variation; it still achieves the best response; whatever parameters are changed. This proves this controller is robust, as shown in Figure 19.

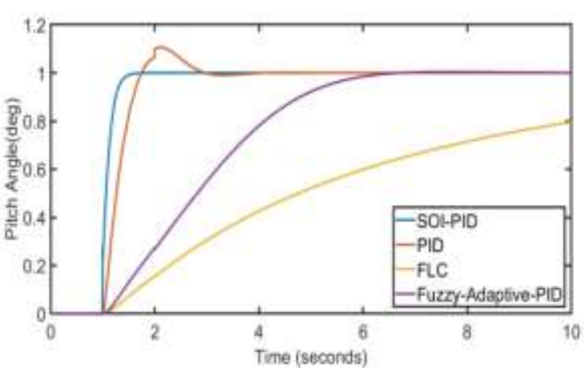

Fig. 19: Parameters variation with (SOI-PID), unit step

6 Conclusion

A new pitch-regulated variable-speed control strategy is proposed for wind turbines with a simple, optimum intelligent PID (SOI-PID) controller to address their nonlinear properties. To control the pitch system with disturbances, Under diverse operational circumstances, four controllers are implemented. These controllers are the PID, FLC, Fuzzy-Adaptive-PID, and the proposed (SOI-PID) controller in terms of time domain specifications with unit step and unit sine wave. The configuration of the system has been simulated using the MATLAB-SIMULINK package. Following the theoretical results, The conclusions listed below can be derived:

a- The PID controller exhibits oscillations with a peak overshoot of 8%, resulting in detrimental effects on the performance of the system despite generating a response with a shorter rise time.

b- Fuzzy logic controllers are suggested as a means to suppress these oscillations. This controller suppresses oscillations effectively and generates a steady response; however, its rise and settling times are lengthier.

c- By implementing fuzzy logic concepts to tune the PID gains, this design successfully mitigates steady-state error, as demonstrated by the substantial reduction in settling time to 5.23 seconds when compared to fuzzy logic controllers. There is no discernible improvement in the rise time efficacy when compared to a traditional PID controller by 2.55 seconds.

d- A proposed SO-PID controller achieves a faster rising time of 1.22 seconds, a quick settling time of 2 sec, and stability with no overshoot. The analysis proves that a proposed (SO-PID) controller gives a faster response for unit step and unit sine wave input. This method is significantly superior for implementing pitch system control and ensuring the output power stability of WT.
A proposed SOI-PID achieves the SO PID response in addition to robust performance under parameter variations.

e- In future work, the authors tend to verify the proposed work experimentally, apply Artificial Intelligence Neural Networks on (PC) of wind turbines, and check its performance with the simple optimum intelligent (SOI-PID) controller.

References:

[1] G. Shahgholian, "A Brief Review on Microgrids Operation, Applications, Modeling, and Control", *International Trans. on Electrical Energy Systems*, vol. 31, no. 6, Article 12885, 2021.

[2] Xie. Feng, Aly.A. M., "Structural Control and Vibration Issues in Wind Turbines: A Review ", *Engineering Structures*, Vol. 210, Article 110087, May 2020.

[3] E. Hosseini, G. Shahgholian, "Partial- or full-power production in WECS: A survey of control and structural strategies", *European Power Electronics and Drives*, vol. 27, no. 3, pp. 125-142, Dec. 2017.

[4] H. Zuo, K. Bi, H. Hao, "A state-of-the-art review on the vibration mitigation of wind turbines", *Renewable and Sustainable Energy Reviews*, Vol. 121, Article 109710, April 2020.

[5] E. Hosseini, G. Shahgholian, "Different types of pitch angle control strategies used in wind turbine system applications", *Journal of Renewable Energy and Environment*, vol. 4, no. 1, pp. 20-35, Winter 2017.

[6] O. Feizollahzade, "Investigate and improve the reliability of small size wind energy conversion systems connected to the network", *International Journal of Smart Electrical Engineering*, vol. 9, no. 2, pp. 69-77, 2020.

[7] E. Mohammadi, R. Rasoulinejad, G. Moschopoulos, "Using a supercapacitor to mitigate battery microcycles due to wind shear and tower shadow effects in wind-diesel microgrids", *IEEE Trans. on Smart Grid*, vol. 11, no. 5, pp. 3677-3689, Sept. 2020.

[8] J.E. Sierra-García, M. Santos, "Improving wind turbine pitch control by effective wind neuro-estimators", *IEEE Access*, vol. 9, pp. 10413-10425, 2021.

[9] P. Tchakoua, R. Wamkey, M. Ouhrouche, F. Slaoui-Hasnaoui, T.A. Tameghe, G. Ekemba, Wind turbine condition 32 monitoring: State-of-the-art review, new trends, and future challenges, *Energies*, 7 (2014) 2595–2630

[10] J. Antonelli, "Reduced order modeling of wind turbines in Matlab for grid integration and control studies"1-2, 2012, Gotland University, Sweden. [Online]. https://www.diva-portal.org/smash/get/diva2:617775/FULLTEXT01.pdf (Accessed Date: January 25, 2024).

[11] T.L. Van, T.H. Nguyen, D. Lee, "Advanced pitch angle control based on fuzzy logic for variable-speed wind turbine systems", *IEEE Trans. on Energy Conversion*, vol. 30, no. 2, pp. 578-587, June 2015.

[12] J. Pahasa, I. Ngamroo, "Coordinated control of wind turbine blade pitch angle and PHEVs using MPCs for load frequency control of microgrid", *IEEE Systems Journal*, vol. 10, no. 1, pp. 97-105, March 2016.

[13] M. O. A. El-Raouf, M. I. Mosaad, M. A. Al-Ahmar, A. l. Mallawany, F. M. El Bendary, "Optimal PI controller of DVR to enhance the performance of hybrid power system feeding a remote area in Egypt", *Sustainable Cities and Society*, vol. 47, Article Number: 101469, May 2019.

[14] V. Nayanar, N. Kumaresan, N. Ammasai-Gounden, "A single-sensor-based MPPT controller for wind-driven induction generators supplying dc microgrid", *IEEE Trans. on Power Electronics*, vol. 31, no. 2, pp. 1161-1172, Feb. 2016.

[15] J. Bhukya, V. Mahajan, "Optimization of damping controller for PSS and SSSC to improve stability of the interconnected system with DFIG based wind farm", *International Journal of Electrical Power and Energy Systems*, vol. 108, pp. 314-335, June 2019.

[16] V. Gholamrezaie, M.G. Dozein, H. Monsef, B. Wu, "An optimal frequency control method through a dynamic load frequency control (LFC) model incorporating wind farms", *IEEE Systems Journal*, vol. 12, no. 1, pp. 392-401, March 2018.

[17] M. Huang, L. Tao, Z. Hu, "Command filter adaptive power capture control based on fuzzy rules emulated networks for variable speed wind turbines with flexible shaft", *IEEE Access*, vol. 9, pp. 91377-91386, April 2021.

[18] Priya, G. J.," Modelling and performance analysis of grid-connected PMSG based wind turbine.", *International Journal of Advanced Research in Electrical, Electronics and Instrumentation Engineering*, 3(2), pp 155-165, 2014

[19] Karakaya, A., Karakaş, E., "Simulation, Modeling and Application of Small Power Wind Energy Conversion System, *Karaelmas Science and Engineering Journal*, pp 377-386, 2016.

[20] Ramadan, H.S. Optimal fractional order PI control applicability for enhanced dynamic behavior of on-grid solar PV systems. *International Journal of Hydrogen Energy,* 2017, 42, 4017-4031.

[21] S. A. Hamoodi, F. I. Hameed, and A. N. Hamoodi, "Pitch angle control of wind turbine using adaptive fuzzy-PID controller," *EAI Endorsed Trans. Energy Web*, vol. 7, no. 28, pp. e15–e15, 2020.

[22] R.R. Londero, C.M. Affonso, J.P.A. Vieira, "Effects of operational limits of DFIG wind turbines on long-term voltage stability studies", *Electric Power Systems Research*, v, pp. 134–140, Jan. 2017.

[23] X. Tang, M. Yin, C. Shen, Y. Xu, Z.Y. Dong, Y. Zou, "Active power control of wind turbine generators via coordinated rotor speed and pitch angle regulation", *IEEE Trans. on Sustainable Energy*, vol. 10, no. 2, pp. 822-832, April 2019.

[24] A. Jafari, G. Shahgholian, "Analysis and simulation of a sliding mode controller for the mechanical part of a doubly-fed induction generator-based wind turbine", *IET Generation, Transmission and Distribution*, vol. 11, no. 10, pp. 2677-2688, July 2017.

[25] Mohamed I. Abu Al-Sebah, "PMSM position control with a SUI PID controller", *Journal of power electronics*, vol. 10, no.2. pp.171-175, Mar.2010.

[26] El-Khatib, Mohamed Fawzy; SHAABAN, S.; EL-SEBAH, Mohamed I. Abu. "A proposed advanced maximum power point tracking control for a photovoltaic-solar pump system", *Solar Energy*, 158: 321-331, 2017.

[27] Mohamed I. Abu Al-Sebah, "Simplified intelligent Universal PID Controller", *International Journal of Engineering Research*, vol No.5, Issue no.1, pp. 11-15, Jan 2016.

[28] H. Ghorbani, R. Kardehi Moghaddam, S. Razavi, "Regulating the output voltage of buck-boost converters using general type2 fuzzy controller", *Signal Processing and Renewable Energy*, vol. 4, no. 2, pp. 37-51, 2020.

[29] Yasser Mohammed Safan, Sameh Shaaban, Mohamed I. Abu El-Sebah, "Hybrid Control of a Solar Tracking System Using MDOF-SUI PID Controller", *International conference on sensors, networks, smart and emerging*, Beirut, Lebanon, Sep.2017.

[30] M. Abbasi, M. Nafar, M. Simab, "Management and control of microgrids connected to a three-phase network with the approach of activating current limitation under unbalanced errors using the fuzzy intelligent method with the presence of battery, wind, photovoltaic and diesel sources", *Journal of Intelligent Procedures in Electrical Technology*, vol. 13, no. 49, pp. 59-71, June 2022.

[31] S. Baburajan and A. Ismail, "Pitch Control of Wind Turbine through PID, Fuzzy and Adaptive Fuzzy-PID controllers, ", *International Research Journal of Engineering and Technology (IRJET)*, Vol. 4, no. 9, 2017.

[32] M. Rahmani, F. Faghihi, H. Moradi-Cheshmeh-Beigi, S. Hosseini, "Frequency control of islanded microgrids based on fuzzy cooperative and influence of STATCOM on frequency of microgrids", *Journal of Renewable Energy and Environment*, vol. 5, no. 4, pp. 27-33, 2018

[33] H. Moradi CheshmehBeigi, A. Mohamadi, "Torque ripple minimization in srm based on advanced torque sharing function modified by genetic algorithm combined with fuzzy PSO", *International Journal of Industrial Electronics Control and Optimization*, vol. 1, no. 1, pp. 71-80, Spring 2018.

[34] R. Zamani, M. Siahi, A. Ramezani, "Robust type-2 fuzzy control for glucose-level regulation in type-i diabetic patients", *International Journal of Smart Electrical Engineering*, vol. 10, no. 2, pp. 87-94, 2021.

[35] H. Habibi, H. Rahimi Nohooji, I. Howard, "Adaptive PID control of wind turbines for power regulation with unknown control direction and actuator faults", *IEEE Access*, vol. 6, pp. 37464-37479, 2018.

[36] H. Ren, B. Hou, G. Zhou, L. Shen, C. Wei, Q. Li, "Variable pitch active disturbance rejection control of wind turbines based on bp neural network PID", *IEEE Access*, vol. 8, pp. 71782-71797, 2020.

[37] R. Shahedi, K. Sabahi, M. Tayana, A. Hajizadeh, "Self-tuning fuzzy PID controller for load frequency control in ac micro-grid with considering of input delay", *Journal of Intelligent Procedures in Electrical Technology*, vol. 9, no. 35, pp. 19-26, December 2019.

Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.