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Control of Variable Speed Wind Turbines: Comparing 1DoF Closed-Loop, PID, and Modified PID Controllers

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ABSTRACT

Effective control strategies are necessary for enhancing wind turbine efficiency and lifespan. The purpose of this paper is to control the rotational speed of a wind turbine by adjusting the pitch angle of the blades. Initially, a one-degree-of-freedom closed-loop controller is designed based on the complementary sensitivity function, followed by a PID and a modified PID controller. Finally, their performance in tracking the desired rotational speed of the wind turbine, which includes step and sinusoidal signals, is compared. The 1DOF controller introduced oscillation, while the PID controller eliminated oscillation but exhibited steady-state error. To preserve the advantages of the PID controller and eliminate steady-state error, an integrator term (1/s) has been added to the controller. Consequently, the modified PID controller has been designed. The results of the modified PID controller show no steady-state error or peak overshoot percentage for step inputs. While, the PID and the one-degree-of-freedom closed-loop controller in tracking the step reference input result in steady-state errors of 1.464% and 0.497% and peak overshoot percentages of 23.688% and 84.389%, respectively. During the implementation of the one-degree-of-freedom closed-loop controller, significant oscillations occur while tracking the desired input. The oscillations occurring in the rotor speed can lead to increased fatigue in various wind turbine components, which is an undesirable outcome. However, no oscillations are observed in rotor speed with the PID and modified PID controllers. Finally, according to the obtained results, the modified PID controller demonstrates superior performance compared to the other controllers in tracking the desired rotor speed.

Keywords: Wind Turbine, Rotational Speed, Step Tracking, Modified PID Controller

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1- Introduction

Nowadays, considering the increasing human demand for energy, and the presence of limited energy resources, the utilization of renewable energy sources has gained significant importance. Consequently, given the economic and environmental implications, many countries prefer to generate electricity from renewable energy sources like wind. The wind energy industry has experienced rapid growth due to the cost-effective and environmentally friendly nature of wind energy compared to various other energy resources [1]. As a result, wind energy stands out as a prominent and evolving source among other renewable energy alternatives [2].

There are significant drawbacks in the development of effective control strategies to establish an energy management system with sufficient system stability and reliability [3]. Hence, control strategies need to be effective to improve the performance of wind energy conversion systems. Therefore, the investigation and control of the dynamic behavior of wind turbines to enhance their performance have received significant attention. Wind turbines convert the kinetic energy of wind into electrical energy. In wind turbines, control systems play a vital role in increasing efficiency, adjusting power output, and prolonging turbine lifespan, contributing to overall cost reduction. For instance, pitch control, a common control strategy, adjusts turbine blade angles to align with incoming wind, optimizing energy capture. This enables the turbine to maintain consistent power output under varying wind conditions [4], preventing wear from turbulence. This adaptive measure significantly extends the turbine's lifespan, as adjusting pitch is commonly used to mitigate turbulent wind impact [5]. Additionally, the oscillations occurring in rotor speed or output power can result in increased fatigue in various components of wind turbines [6]. Thus, the design of an appropriate controller is highly important.

Wind turbines can be classified based on the type of generator, whether the speed is fixed or variable, the orientation of the turbine axis (horizontal or vertical), and also the power control system [7]. In this study, a variable-speed horizontal axis wind turbine is investigated. Modern wind turbine systems are now commonly designed as variable-speed turbines to enhance their operational efficiency [8]. Variable-speed wind turbines offer several advantages, including better energy capture efficiency and reduced mechanical stress on the turbine components [9].

The disadvantages of fixed-speed wind turbines have been investigated in prior studies [9,10]. For instance, these turbines commonly employ simpler control mechanisms, leading to a reduced range of options for optimizing performance under diverse operating conditions. In addition, under conditions of fixed-speed operation, the maximum value of performance coefficient and consequently the maximum output power can only be attained at a particular wind speed [6].

However, in previous studies, control of both fixed-speed and variable-speed wind turbines has been conducted using various methods. For variable-speed wind turbines, approaches such as digital robust control [11,12] and fuzzy control methods [13-17] have been studied. For example, X. Zhang et al. [16] demonstrated that using a fuzzy controller yields smoother outputs and superior anti-interference properties compared to a PID controller. Additionally, R. F. Nayeh et al. [18] investigated multivariable robust control methods, comparing sliding mode control and H_∞ robust control. Their findings indicated that the sliding mode controller exhibits improved transient response, reduced tracking error, and faster settling time compared to H_∞.

Other approaches include nonlinear and adaptive algorithm [19, 20] that enable achieving smooth and asymptotic rotor speed tracking, adaptive fractional order non-singular fast terminal sliding mode control [21], and various first-order or high-order sliding mode control approaches [22]. Notably, adaptive robust control strategies have been developed to manage inherent nonlinearities and external disturbances in wind turbine systems [23]. Furthermore, studies have delved into fractional order PID controllers to enhance the stability of generated power [24] and Linear Quadratic Gaussian Control (LQG) [25].

Furthermore, a comparison has been made between linear and nonlinear models for the control of variable-speed wind turbines [26, 27]. Additionally, comparative analyses have been performed between a fuzzy controller and PI controller [28], as well as between a fuzzy controller and a PID controller [16] in variable-speed wind turbines. Additionally, some studies have been conducted on the concepts and various methods of wind turbine control [29-32]. It should be noted that in most of these studies, linear controllers are typically applied within the vicinity of the operating regions within the nonlinear system due to linearization operations. Additionally, in numerous instances, it is commonly assumed that the parameters vary at a slower rate compared to the dynamics of the wind turbine system [6].

This study focuses on modeling the wind turbine as a system with a single degree of freedom. In this model, the rotational speed of the wind turbine is controlled by adjusting the pitch angle of the blades in the constant torque of the generator. The studied wind turbine is a variable-speed turbine with a horizontal axis and three blades. Initially, a one-degree-of-freedom closed-loop controller is designed based on the complementary sensitivity function. Subsequently, a PID controller and a modified PID controller are designed. Finally, the performance of the three controllers in tracking the desired rotational speed of the wind turbine, which includes step and sinusoidal signals, is compared. As demonstrated in the following, the steady-state error, peak overshoot percentage, and the oscillations occurring during the tracking of the desired input are measured for the three mentioned designed controllers and compared with each other. In this comparison, one of the controllers shows superior performance, exhibiting lower steady-state error, reduced peak overshoot percentage, and no oscillations compared to the others. The details of these aspects are thoroughly examined in the subsequent sections.

2- Wind Turbine Dynamic Model

The mechanical energy of the wind turbine, obtained from the kinetic energy of the wind, is converted to electrical energy through the generator. A gearbox acts as a connection between the turbine and the electrical generator, enabling amplification of the output speed and a simultaneous reduction in torque. The schematic of a wind turbine system along with its generator is shown in Figure 1.

The aerodynamic torque, denoted as T_a, is the torque exerted on the blades and is defined by the following non-linear function [6]:

$$T_a = \frac{1}{2\lambda}\,\rho\,\pi\,C_p\,(\lambda\,,\beta)\;R^3\;V^2 \tag{1}$$

where ρ is the air density, R is the rotor radius, V is the wind speed, β represents the pitch angle of the blades and λ represents the tip speed ratio, defined as the ratio of the blade tip speed to the wind speed, and it is defined by Eq. (2).

$$\lambda = \frac{R\,\omega_r}{V} \tag{2}$$

Where ω_r represents the rotor speed and $C_p(\lambda,\beta)$ is the power coefficient, which is a non-linear function of the tip speed ratio and the pitch angle of the blades. The determination of $C_p(\lambda,\beta)$ is achieved through curve fitting methods using experimental data, and in this study, Eq. (3) is utilized [6].

$$C_p\,(\lambda\,,\beta) = 0.73\left(\frac{151}{\lambda^*} - 0.58\,\beta - 0.002\,\beta^{2.14} - 13.2\right)e^{-\frac{18.4}{\lambda^*}} \tag{3}$$
$$\frac{1}{\lambda^*} = \frac{1}{\lambda - 0.02\beta} - \frac{0.003}{\beta^3 + 1}$$

The equations of motion for the wind turbine-generator system are obtained as follows [6]:

$$\begin{cases} T_a - T = J_r\,\ddot{\theta}_r + C_r\dot{\theta}_r + K_r\theta_r \\ T_p - T_e = J_g\,\ddot{\theta}_g + C_g\dot{\theta}_g + K_g\theta_g \\ T_p\dot{\theta}_g = T\dot{\theta}_r \end{cases} \tag{4}$$

In which J, C, and K represent the moment of inertia, damping coefficient, and torsional stiffness of the shaft, respectively. Furthermore, g and r correspond to the generator and rotor, respectively.

Additionally, the gear ratio γ is defined as $\gamma = \frac{\omega_g}{\omega_r}$. By substituting this expression into Eq. (4), the single-degree-of-freedom model for the wind turbine-generator system, as presented in [6], can be obtained as Eq. (5).

$$J_t\,\ddot{\theta}_r + C_t\dot{\theta}_r + K_t\theta_r = T_a - T_g \tag{5}$$

Where

$$\begin{aligned} J_t &= J_r + \gamma^2 J_g \\ C_t &= C_r + \gamma^2 C_g \\ K_t &= K_r + \gamma^2 K_g \\ T_g &= \gamma T_e \end{aligned} \tag{6}$$

The schematic of the single-degree-of-freedom model for the wind turbine-generator system is shown in Figure 2.

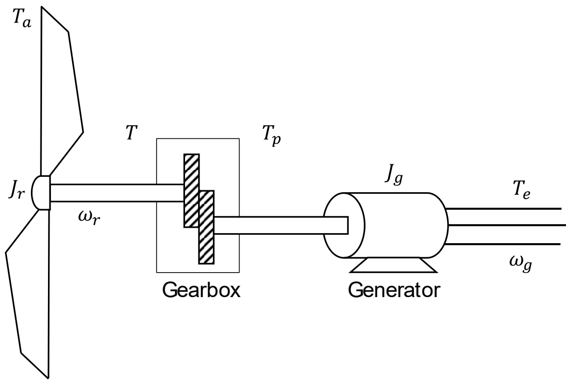

Fig. 1 Schematic of a wind turbine system along with its generator

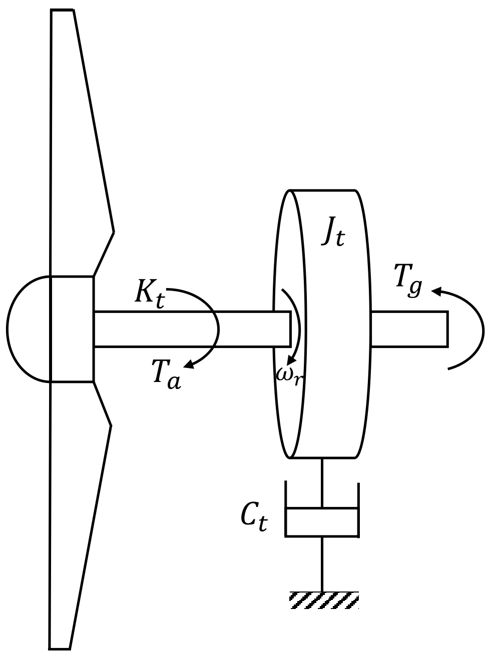

Fig. 2 Equivalent single-degree-of-freedom model of the system

As shown in Eq. (5), there are two control input parameters: the pitch angle of the blades, which impacts the aerodynamic torque on the blade, and the torque of the generator. In many previous studies, the generator torque is assumed to be constant [19, 33]. In this study as well, only the pitch angle of the blades is considered as the control input, while the generator torque is assumed to be constant. Therefore, the generator torque is taken to be its nominal value denoted as $\overline{T}_g$ [6]. Consequently, the control input u is defined as $u = T_a - \overline{T}_g$, as presented in [6].

The purpose of this research is to control the rotational speed of the wind turbine, denoted as ω_r (where $\omega_r = \dot{\theta}$). The transfer function of the system is derived by substituting $\dot{\theta}_r = \omega_r$ into Eq. (5) and transforming both sides of the equation into the Laplace domain, as expressed in Eq. (7).

$$P(s) = \frac{\omega_r(s)}{U(s)} = \frac{s}{J_t s^2 + C_t s + K_t} \tag{7}$$

3- Simulation of the Dynamic Model

The dynamic model is simulated in MATLAB, using the nominal parameter values of a real turbine, as provided in Table 1. The simulation aims to control the rotational speed of the wind turbine (ω_r) for two desired rotor speeds (ω_d), including a step signal (ω_d=2) and a sinusoidal signal (ω_d= 2 + 0.5 sin (πt/100)), as illustrated in Figure 3. The simulation results are also presented for a constant wind profile V=10 m/s [6].

Table 1 Nominal parameter values of the wind turbine system [19]

Parameter	Value
J_t	16 $(Kg.m^2)$
C_t	52 $(N.s/m)$
K_t	52 (N/m)
ω_r	2 (Rad/s)
R	19 (m)
$\overline{T}_g$	50 $(KN.m)$
ρ	1.31 (Kg/m^3)
γ	37.5

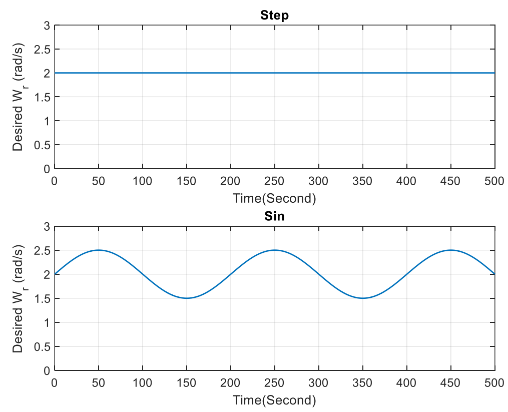

Fig. 3 Desired targets for the rotational speed of the wind turbine, comprising step and sinusoidal signals

3-1- Verification of the Simulation Code

To verify the simulation results, a modified PID controller, as introduced in section 4-3, is applied, and the system is subjected to a step input of 2.5. The rotor speed response is then compared with the corresponding result from [6]. As shown in Figure 4, the two responses are in excellent agreement, confirming the accuracy of the implementation.

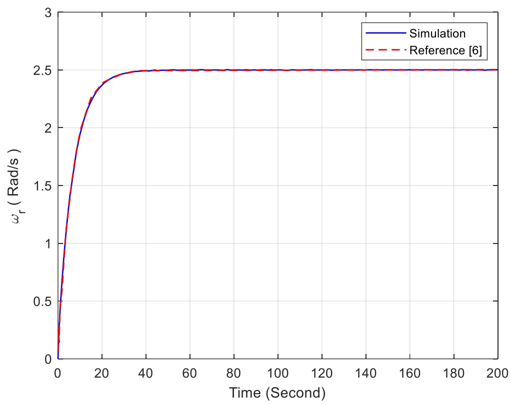

Fig. 4 Comparison of rotor speed response between the present simulation and reference [6] under a step input of 2.5

4- Design of Controllers

In this section, first, a 1DOF closed-loop controller is designed based on the complementary sensitivity function. Then, a PID controller and a modified PID controller are designed.

4-1- Design of the 1DOF closed-loop controller

The 1DOF closed-loop controller is designed based on the complementary sensitivity function (T), which considering the presence of a non-minimum phase zero at the origin, is formulated as Eq. (8).

$$T = \frac{800s}{s^2 + 803s + 4} \tag{8}$$

Finally, based on the formulation of T in Eq. (8), the controller is designed according to Eq. (9).

$$F(s) = \frac{12800s^2 + 41600s + 41600}{s^2 + 3s + 4} \tag{9}$$

Considering that there is no integrator ($\frac{1}{s}$) in the dynamic system and the designed controller, the steady-state error of the system never reaches zero. Therefore, to eliminate the steady-state error, an integral term is introduced into the controller, leading to the design of the 1DOF closed-loop controller as depicted in Eq. (10).

$$F(s) = \frac{12800s^2 + 41600s + 41600}{s^3 + 3s^2 + 4s} \tag{10}$$

4-2- Design of the PID controller

In this section, a PID controller is designed. To obtain the initial coefficients of the PID controller, the general form of Eq. (11) is utilized.

$$G_c(s) = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{11}$$

Where

$$K_c = K\left(1 + \frac{T_2}{T_1}\right), \qquad T_i = T_1 + T_2, \qquad T_d = \frac{T_1 T_2}{T_1 + T_2} \tag{12}$$

The system's Bode plot is illustrated in Figure 5. Based on the determined system's crossover frequency, the initial coefficients are calculated as follows:

$$T_2 = 0.034s, \qquad T_1 = 1s, \qquad K = 0.941 \tag{13}$$

The initially calculated coefficients result in a significant steady-state error into the system. To reduce the steady-state error, the coefficients are adjusted through MATLAB. Ultimately, the PID controller is designed according to Eq. (14).

$$G_c(s) = 100\left(2 + \frac{1}{0.0286s} + 0.01s\right) \tag{14}$$

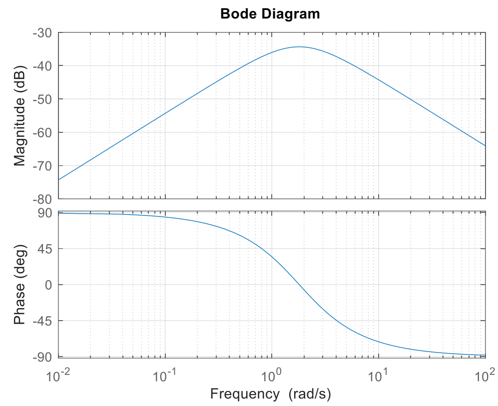

Fig. 5 Bode diagram of the system

4-3- Design of the modified PID controller

In this section, a modified PID controller is designed. As mentioned in section 4-2, the general form of Eq. (11) is used to design the PID controller and is rewritten in the form of Eq. (15).

$$K(s) = \frac{\xi s^2 + \eta s + \delta}{s} \tag{15}$$

Where

$$\xi = k_c T_d, \qquad \eta = k_c, \qquad \delta = \frac{k_c}{T_i} \tag{16}$$

In the design of the controller in the form of Eq. (15), the steady-state error in tracking a step input is always non-zero. Only when neglecting the torsional stiffness of the turbine shaft ($K_t \approx 0$), it is possible to eliminate the steady-state error [6]. However, this assumption is unrealistic and incorrect. Therefore, to eliminate the steady-state error in the presence of torsional stiffness ($K_t \neq 0$), an integrator ($\frac{1}{s}$) should be added to Eq. (15), resulting in the modified PID controller given in Eq. (17) [6].

$$K(s) = \frac{\xi s^2 + \eta s + \delta}{s^2} \tag{17}$$

Where the optimal gain values of the modified PID controller are adopted from [6] as follows:

$$\xi = 4.1, \qquad \eta = 10.2, \qquad \delta = 7.9 \tag{18}$$

The block diagrams of the control system for the wind turbine are illustrated in Figure 6.

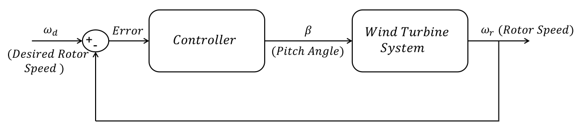

Fig. 6 Block diagrams of the control system for the wind turbine

5- Results and discussion

The system response (ω_r) for the step and sinusoidal reference inputs using the designed 1DOF closed-loop controller as described in section 4.1, considering the integration term (Eq. (10)), is shown in Figure 7. Additionally, to evaluate the steady-state error, Figure 8 illustrates the error corresponding to the step and sinusoidal inputs.

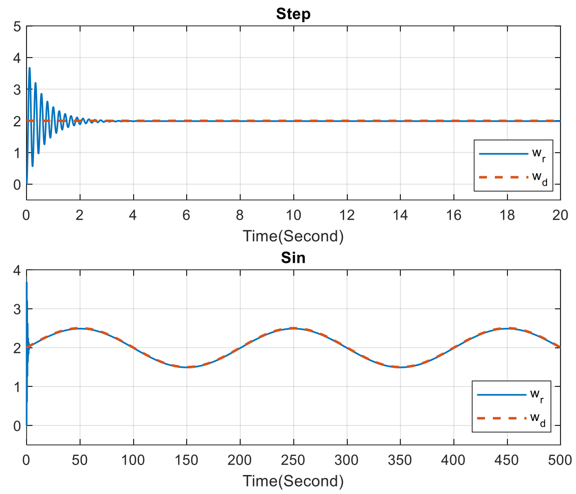

Fig. 7 ω_r and ω_d for step and sinusoidal inputs with 1DOF closed-loop controller

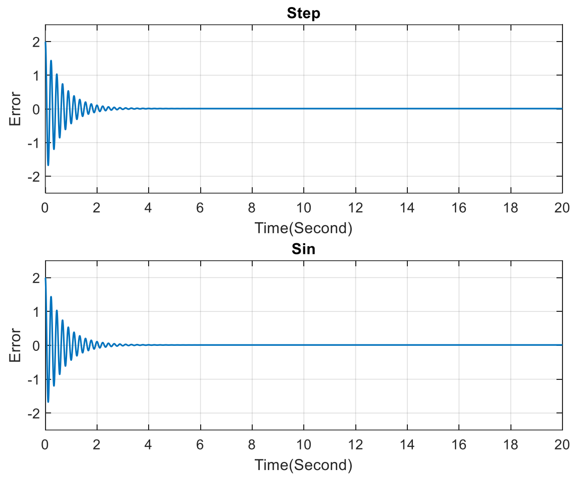

Fig. 8 Error for step and sinusoidal inputs with 1DOF closed-loop controller

Based on the system response shown in Figure 7, the designed 1DOF closed loop controller (Eq. (10)) exhibits acceptable performance in tracking the reference speed, including step and sinusoidal signals. The mentioned controller has a steady-state error of 0.497%, a peak overshoot percentage of 38.9%, and a settling time of approximately 2.5 seconds in tracking the step input. As evident from the system response plot, when using this controller, in addition to the high peak overshoot percentage, the system experiences significant oscillations during the desired input tracking. These oscillations in rotor speed can lead to increased fatigue in various wind turbine components, which is undesirable.

The system response for the step and sinusoidal reference inputs using the designed PID controller in section 4.2. (Eq. (14)) is shown in Figure 9. Additionally, Figure 10 illustrates the steady-state error corresponding to the step and sinusoidal inputs.

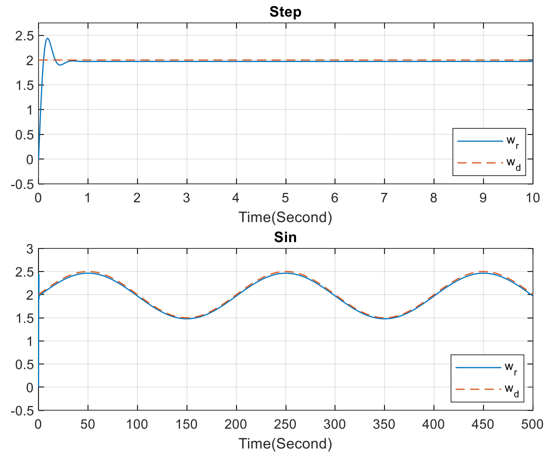

Fig. 9 ω_r and ω_d for step and sinusoidal inputs with PID controller

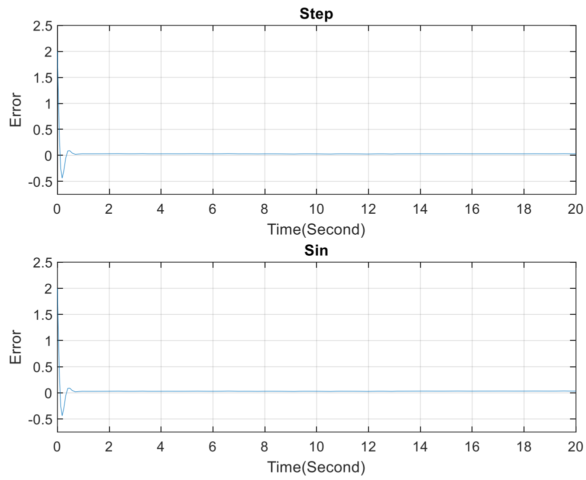

Fig. 10 Error for step and sinusoidal inputs with PID controller

Considering the absence of an integrator in the dynamic system and the designed PID controller in Eq. (14), the steady-state error in response to a step input is always non-zero. As shown in the error plot in Figure 10, the error value is close to zero but not eliminated. Consequently, as also depicted in the system response in Figure 9, the designed PID controller in Eq. (14) exhibits a small amount of error in tracking both step and sinusoidal reference speed. The designed PID controller achieves a steady-state error of 0.464%, a peak overshoot percentage of 23.688%, and a settling time of approximately 0.5 seconds in tracking the step input. Based on the system response plot, the PID controller demonstrates an acceptable peak overshoot percentage and eliminates oscillations during desired input tracking.

The system response for the step and sinusoidal reference inputs using the modified PID controller in Eq. (17) is shown in Figure 11. Additionally, to examine the steady-state error, the error for the step and sinusoidal inputs for the modified PID controller are presented in Figure 12.

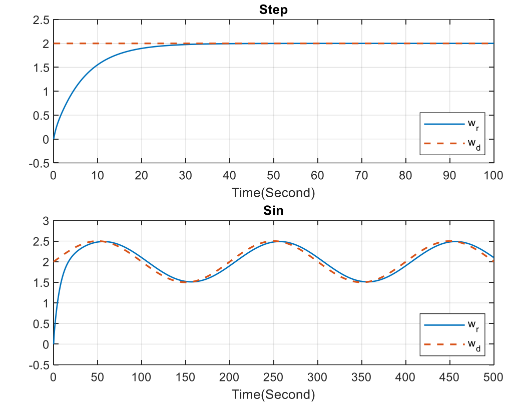

Fig. 11 ω_r and ω_d for step and sinusoidal inputs with modified PID controller

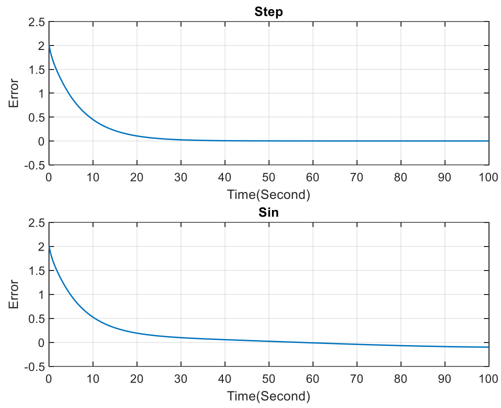

Fig. 12 Error for step and sinusoidal inputs with modified PID controller

Based on the system response shown in Figure 11, the modified PID controller designed in section 4.3. (Eq. (17)) accurately tracks the reference speed without any significant overshoot. Additionally, the steady-state error for the step input is completely eliminated. As shown in the system response plot, no oscillations are observed during the tracking of the desired input. Furthermore, the settling time is approximately 25 seconds, which is notably longer than that of the previously designed controllers in this study.
To compare the performance of the three designed controllers, the steady-state error, peak overshoot percentage, and settling time for the step input are presented in Table 2, Table 3, and Table 4, respectively.

Table 2 Percentage of steady-state error for step input

Controller	Steady-State Error (%)
1 DOF Controller	0.497
PID Controller	1.464
Modified PID Controller	0

Table 3 Peak overshoot percentage for step input

Controller	Peak Overshoot (%)
1 DOF Controller	84.389
PID Controller	23.688
Modified PID Controller	0

Table 4 Settling time for step input

Controller	Settling Time (s)
1 DOF Controller	2.35
PID Controller	0.5
Modified PID Controller	25

Based on the values of the steady-state error and peak overshoot percentage presented in Table 2 and Table 3, the modified PID controller demonstrates significantly better performance in tracking the reference input among the three controllers. However, its longer settling time compared to the other two controllers can be considered a disadvantage in its design.

The PID controller exhibits lower overshoot, shorter settling time, and higher steady-state error compared to the 1DOF closed-loop controller. While the 1DOF closed-loop controller causes significant oscillations in the wind turbine's rotor speed, which are undesirable, the PID controller eliminates such oscillations. Therefore, the PID controller ultimately offers better performance than the 1DOF closed-loop controller in tracking the reference input.

6- Conclusion

In this research, a variable-speed horizontal-axis wind turbine with three blades was investigated. The wind turbine-generator system was modeled as a single-degree-of-freedom system, and the rotational speed of the wind turbine shaft was controlled by adjusting the pitch angle of the blades at a constant generator torque. Initially, a 1DOF closed-loop controller was designed based on the complementary sensitivity function, followed by the design of a PID controller and a modified PID controller. Finally, the performance of the three controllers in tracking the desired speed of the wind turbine shaft, including step and sinusoidal signals, was examined.
The results demonstrate that the modified PID controller exhibits superior performance in tracking the reference input compared to the other two controllers. This is evident from its zero steady-state error and peak overshoot percentage for the step input. Additionally, in the implementation of the modified PID controller, no oscillations are observed in the wind turbine rotor speed.
Furthermore, the results indicate that the PID controller has a higher steady-state error compared to the 1DOF closed-loop controller. Since the PID controller does not include an integrator term, the steady-state error never reaches zero. However, in the implementation of the PID controller, the peak overshoot percentage and settling time are significantly lower compared to the 1DOF closed-loop controller. Additionally, while the 1DOF controller introduces significant oscillations in the wind turbine rotor speed, the PID controller effectively eliminates these oscillations. Therefore, the PID controller exhibits superior performance compared to the 1DOF closed-loop controller in tracking the reference input.
The 1DOF controller resulted in significant oscillations in the system's response. Although the PID controller successfully mitigated these oscillations, a persistent steady-state error remained. To overcome this limitation, an integrator term $(\frac{1}{s})$ was incorporated into the PID controller, resulting in the modified PID controller. This controller not only eliminates oscillations, similar to the PID controller, but also eradicates steady-state error. Thus, it inherits the advantages of the PID controller, presenting a control solution free from both oscillations and steady-state errors. This enhancement marks a significant stride towards achieving a more efficient control strategy for wind turbine speed regulation.

Ethics Approval:
The scientific content of this article is the result of the authors' research and has not been published in any Iranian or international journal.
Conflict of Interest:
The authors declare that they have no conflicts of interest to this work.

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