Optimized fuzzy PI controller for variable speed wind turbine using DE algorithm

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Article Info

ABSTRACT

To design an optimal fuzzy proportional-integral (PI) controller for the variable speed wind turbine systems, a new differential evolution (DE) algorithm approach is developed in this paper. We have investigated a fuzzy PI controller, in which fuzzy rules are applied to adapt the parameters of the PI controller founded on the error and its first-time derivative. The fuzzy PI controller's inputs and outputs are tuned using the DE optimization method. The superiority of the suggested (DE fuzzy PI) controller has been proved by comparing the results with (fuzzy PI) and only the PI controller applied to the wind turbine system. In comparison to a fuzzy controller with parameters selected by a human operator, the numerical validation results of the suggested approach (DE fuzzy PI) have shown good performance in terms of robustness, pursuit, and response time.

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1. INTRODUCTION

The fastest production energy source is Wind energy is a clean, renewable energy source that has been used for centuries. Wind turbine systems generate electricity for utilities, homeowners, and remote villages [1]. A considerable investment was made in the scientific field has been made in the development and enhancement of wind turbines. These wind systems could serve as an innovative and cost-effective replacement for many energy sources [2].

Variable speed wind turbines are becoming more prevalent than conventional fixed-speed turbines [3]. This type of system is characterized by its capacity to increase energy recovery, decrease disturbance, and enhance the quality of the energy produced [4]. It can also alter the shaft speed as the wind speed varies. Power systems are incorporating wind energy more and more, the analysis of the stability of wind turbine systems is becoming a significant problem for planners and for operators of power systems.

Due to the variable-speed wind turbine system's (VS-WTS) increased complexity and nonlinearity, an effective and convenient control mechanism is required [5]. However, it is challenging to guarantee effective stability and effective control performance when utilizing linear and classical control methods; Alternatively, recent technological improvements have produced intelligent controls for nonlinear, complex systems ,using a variety of techniques, which include optimal feedback control [6], dynamic control founded on nonlinear prediction models [7], control using T-S systems [8], wide-area fuzzy controller with time delay [9], and sliding mode control by using type-2 fuzzy system [10].

To improve the system's performance and efficiency by employing traditional controls such as the PID controllers. It's all about finding the right balance. Some programs will accept an overrun to speed up stabilization time; therefore, it all depends on the requirements. Each of the parameters (KP, KI, and KD) has an effect on the system's response. KP and KI must be reduced in aim to reduce the static error. If KP or KI declines or KD increases, the overshoot is lowered. If KP or KI increases or KD drops, the rising time lowers [11]. However, implementing this standard type of control (PID) provides several challenges in assuring robust performance due to the numerous issues in the wind turbine system (WTS), such as uncertainties, nonlinearity of the WTS, parameter change, and unidentified disturbances [12].

The main goal of this research is to create an enhanced intelligent technique based on the fuzzification of a PI controller (FLC-PI) and optimization techniques using the DE algorithm to optimize the inputs and outputs of the fuzzy controller. The goal of this technique is to develop a reliable a powerful and effective controller for rotor speed tracking to ensure maximizing wind energy capture. Fuzzy logic has been shown to be a powerful control tool. It enables the creation of an intelligent controller using linguistic rules without knowledge of the plant's mathematical model. The use of fuzzy logic to establish PI controllers considered as an effective approach that surpasses traditional PI, particularly in the presence of uncertainties, because fuzzy logic does not require a formal model and may include expert knowledge and experience to achieve an intelligent control [13]. Many studies have shown that by adjusting the controller's parameters, The fuzzy logic controller can manage any operating point changes, but there is no explicit mathematical method for selecting the right fuzzy parameters, such as the membership function, input-output scaling factors, and the rules [14]. These settings are chosen using the trial technique, which means they are not ideal and have an effect on the fuzzy logic controller's performance. Many optimization methods, such as the genetic algorithm [15] and particle swarm optimization [16], have been integrated with the fuzzy logic controller. The DE technique is widely used in scientific and professional domains for tackling the bulk of optimization issues [17]. This algorithm employs real number coding as part of its stochastic population-based search strategy. It is a straightforward, dependable, and strong technique for global optimization. In this study, the fuzzy PI controller's input and output parameters are optimally tuned applying the differential evolution algorithm (DE), which improves system performance and significantly decreases tracking errors.

In the face of uncertainties and variations in the parameters, the efficiency of the suggested approach (DE-fuzzy-PI) is confirmed and compared to the fuzzy PI and the traditional PI. The simulation results demonstrated that the suggested technique is robust and superior, as a result, oscillations were dampened more effectively, and the relevant data were tracked accurately and quickly. The following is how the paper is structured. Section 2 gives a description of the mathematical model of a WTS, section 3 presents the proposed (DE-fuzzy-PI) control approach, and section 4 offers simulations to show the effects of the suggested approaches. Section 5 has the conclusion.

2. THE MATHEMATICAL MODEL OF WTS

The following [12], [18] the aerodynamic power that the WTS is capable of producing:

$$P_\upsilon = \frac{1}{2}\rho A v^3 \tag{1}$$

where ρ is the density of air (kg/m3), $A = \pi R^2$ and v is the speed of wind system (m/s). The following equation [19] represents the power that the rotor is able to capture:

$$P_a = C_p(\lambda, \beta)P_\upsilon \tag{2}$$

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

where, C_p is the power performance coefficient, and λ indicates the tip speed ratio.

The aerodynamic torque is produced when the aerodynamic power is transformed into mechanical power, as seen in [4]:

$$T_a = \frac{1}{2}\rho \pi R^3 v^2 \frac{C_p(\lambda, \beta)}{\lambda} \tag{4}$$

A general model that may be used for wind turbines is the two-mass model given in Figure 1.
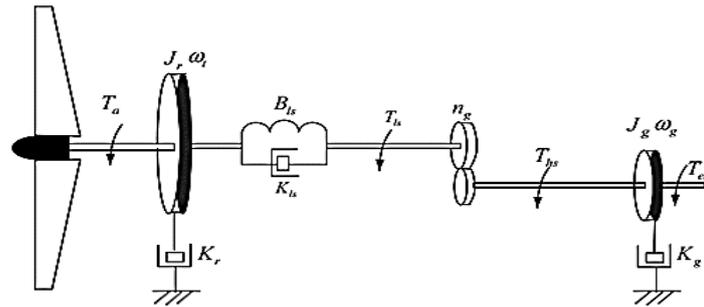
Figure 1. The two-mass WTS model [20]

We may use the following to represent the WTS:

$$
\begin{bmatrix} \dot{\omega}_t \\ \dot{\omega}_g \\ \dot{T}_{ls} \end{bmatrix} = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{32} & c_{33} \end{bmatrix} \begin{bmatrix} \omega_t \\ \omega_g \\ T_{ls} \end{bmatrix} + \begin{bmatrix} b_{11} \\ b_{21} \\ b_{31} \end{bmatrix} T_a + \begin{bmatrix} b_{12} \\ b_{22} \\ b_{32} \end{bmatrix} T_{em}
\tag{5}
$$

where:

$$
c_{11} = -\frac{K_r}{J_r}; \ c_{12} = 0; \ c_{13} = -\frac{1}{J_r}; \ c_{21} = 0; c_{22} = -\frac{K_g}{J_g}; \ c_{23} = \frac{1}{n_g J_g}; \ c_{31} = \left(B_{ls} - \frac{K_{ls} K_r}{J_r} \right)
$$

$$
c_{32} = \frac{1}{n_g}\left(\frac{K_{ls} K_g}{J_g} - B_{ls} \right); c_{33} = -K_{ls}\left(\frac{J_r + n_g^2 J_g}{n_g^2 J_g J_r} \right); b_{11} = \frac{1}{J_r}; \ b_{12} = 0; \ b_{22} = -\frac{1}{J_g}; \ b_{31} = \frac{K_{ls}}{J_r};
$$

$$
b_{21} = 0; \ b_{32} = \frac{K_{ls}}{n_g J_g}
$$

we define $x_1 = \omega_t, x_2 = \dot{\omega}_t, x_3 = \omega_g$, and $u = T_{em}$, the set of equations in (6) may be reformulated in the state space as follows [12]:

$$
\begin{cases}
\dot{x}_1 = x_2 \\
\dot{x}_2 = f(x,t) + g(x,t).u + \xi(x,t) \\
\dot{x}_3 = c_{22}x_3 + \frac{c_{23}}{c_{13}}(x_2 - c_{11}x_1 - b_{11}T_a) + b_{22}u(x,t) \\
y = x_1
\end{cases}
\tag{6}
$$

where $\underline{x} = [x_1, x_2, x_3]^T \epsilon R^3$ is the system's state vector, which is supposed to be measured, $u \epsilon R$ and $y \epsilon R$ are respectively input of system, the output of system, and $f(x,t), g(x,t)$ are the system's nominal form provided by (7) and (8):

$$
f(x,t) = x_1(c_{11}^2 + c_{13}c_{31}) + T_{ls}(c_{11}c_{13} + c_{13}c_{33}) + T_a(c_{11}b_{11} + c_{13}b_{31}) + b_{11}\dot{T_a}
\tag{7}
$$

$$
g(x,t) = c_{13}b_{32}
\tag{8}
$$

ξtx, t) are the external disturbances and the uncertainties.

3. PROPOSED CONTROLLER DESING
3.1. PI controller for variable speed wind turbine system (PI-VS-WTS)
The designed controller's main objectives are to minimize errors, get the elimination of oscillations, and keep track of the desired rotor speed ω_{topt}. Let's define tracking errors as follows:

$$
e(x,t) = \omega_t(x,t) - \omega_{topt}(x,t)
\tag{9}
$$

in terms of the error, the conventional PI controller is given by [9]:

$$U_{PI}(x,t) = K_P e(x,t) + K_I \int e(x,t)dt \qquad (10)$$

K_P, K_I represent the classical value of proportional gain, and integral gain. The (11) presents the structure of the traditional control:

$$u(x,t) = u_{eq}(x,t) + u_{PI}(x,t) \qquad (11)$$

The traditional PI or PID controllers are frequently ineffective and unsatisfactory, especially when higher level operations involve a temporal delay, or the systems have considerable uncertainty [12]. The usage of the Fuzzy logic System (FLS) was proposed in this study to increase the performance and the robustness of the classical PI controller and to adapt any adjustments to system parameters or operational conditions.

3.2. Fuzzy PI controller for variable speed wind turbine system (fuzzy PI-VS-WTS)

The wind turbine system's (WTS) rotor speed oscillations can be damped using fuzzy logic based on PI Controller. The input signal could be the error of the generator's rotor speed deviation e(t) and its derivative $\dot{e}(t)$. Disturbances in a wind turbine system led to electromechanical oscillations. To keep the system stable, these oscillations must be adequately dampened. The Fuzzy PI Controller's output signal is employed as an additional input $U_{Fuzzy-PI}$ in the VS-WTS control law. The two signals' input ranges $\{e(t), \Delta e(t)\}$ are from [-0.01, 0.01] are given in Figure 2.
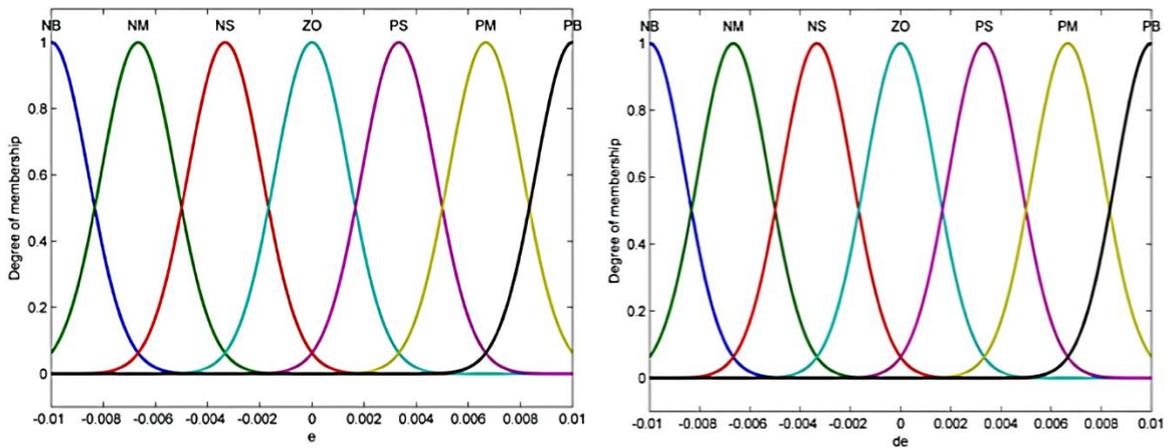
Figure 2. Membership functions for input parameters

The input of fuzzy variables is created for the rule base [21]:

$$\{e(t), \Delta e(t)\} = \{NB, NM, NS, Z, PS, PM, PB\}$$

The fuzzy logic controller based on PI replaces the traditional PI controller in this article. The fuzzy logic toolbox in the MATLAB software is used to create the FLC. For the output and the two inputs $U_{fuzzy-PI}$, the Gaussian membership function is employed. For the controller's best performance, a total of 49 rule bases are built, as given in Table 1.

Table 1. The fuzzy controller's rule set [22]

e \ de	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NB	NM	NM	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NM	NS	Z	PS	PM	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PM	PM	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

The $\theta_{1,..,}\theta_n$ represent the centroids of M membership functions which are allocated to the controller output $U_{Fuzzy-PI}$. Thus, the controller's output for M rules is [23]:

$$U_{Fuzzy-PI} = K_{out}\frac{\sum_{i=1}^{M}\beta_i\theta_i}{\sum_{i=1}^{M}\beta_i} = K_{out}\theta^T\xi \tag{12}$$

where $\xi = [\xi_1, \xi_2, ..., \xi_M]$; $\xi_i = \frac{\beta_i}{\sum_{i=1}^{M}\beta_i}$ and $\theta^T = [\theta_1 ... \theta_M]$; β_i is the degree of activation of each ith rule. Fuzzy sets can effectively cope with model uncertainties, but choosing appropriate membership function parameters is difficult. The DE algorithm is employed in this paper to identify the best settings for the fuzzy system's membership functions.

3.3. Differential evolution algorithm

The differential evolution algorithm (DE) is one of the simplest and most efficient evolutionary algorithms. Storn and Price first proposed the notion in 1997 [17]. This technique belongs to the class of stochastic meta-heuristic global optimization methods, and it is distinguished by its ease of use, resilience, and fast convergence, making it an ideal tool for solving challenging problems. Starting with a randomly generated initial population, the algorithm's (DE) goal is to enhance it through an evolutionary loop that is separated into three basic operations: selection, mutation, and crossing.

3.3.1. Initialization

By assigning each variable a random value, the population of solution candidates is created at the first stage of the optimization DE algorithm. These values, which must lie within the user-specified According to the problem's nature, lower and upper limits for the control variables can be generated as (13) [24]:

$$x_{i,j,0} = x_{i,min} + rand_j(0,1) \times (x_{j,max} - x_{i,min}) \tag{13}$$

3.3.2. Mutation

A mutation operator is in charge of adding new parameters to the population. To accomplish so, the mutation operator disrupts a random vector to produce mutant vectors $V_{i,G}$. $X_{r_i^1}$ unlike the two vectors $(X_{r_i^2}$ and $X_{r_i^3})$ according to the (14), a random selection made from the population:

$$V_{i,G} = X_{r1^i,G} + F.(X_{r2^i,G} - X_{r3^i,G}) \tag{14}$$

The mutation factor F is defined in the interval [0 1] and is used to adjust the size of the differential variation $(X_{r2^i,G} - X_{r3^i,G})$ to improve convergence.

3.3.3. Crossover

Build a test individual $U_{j,i,G}$ using the crossover operator out of a combination of a mutant $V_{j,i,G}$ and a target individual $X_{j,i,G}$ in accordance with probability distributions. To increase population diversity, the crossover operator is utilized, while also preventing the population from converging to a local minimum. This is accomplished by following the steps outlined in the equation [25]:

$$U_{j,i,G} = \begin{cases} V_{j,i,G} & if\ rand_j \leq CR\ or\ j = j_{rand} \\ X_{j,i,G} & if\ rand_j > CR\ or\ j \neq j_{rand} \end{cases} \tag{15}$$

CR is the crossover probability and $rand_j \in [0,1]$ is the jth random number index.

3.3.4. Selection

By comparing mainly, the values of the two competitors' objective functions, the selection operator enables you to choose the most suitable individual for the population of the following generation from the target individual $X_{i,G}$ and the test individual $U_{i,G}$. The selection process is described in the following manner:

$$X_{i,G+1} = \begin{cases} U_{i,G} & if\ J(U_{i,G}) < J(X_{i,G}) \\ X_{i,G} & otherwiswe \end{cases} \tag{16}$$

$J(X)$ is the objective function to be minimized and $i \in [1, N_p]$. The flowchart in Figure 3 depicts the several stages of the differential evolution algorithm.
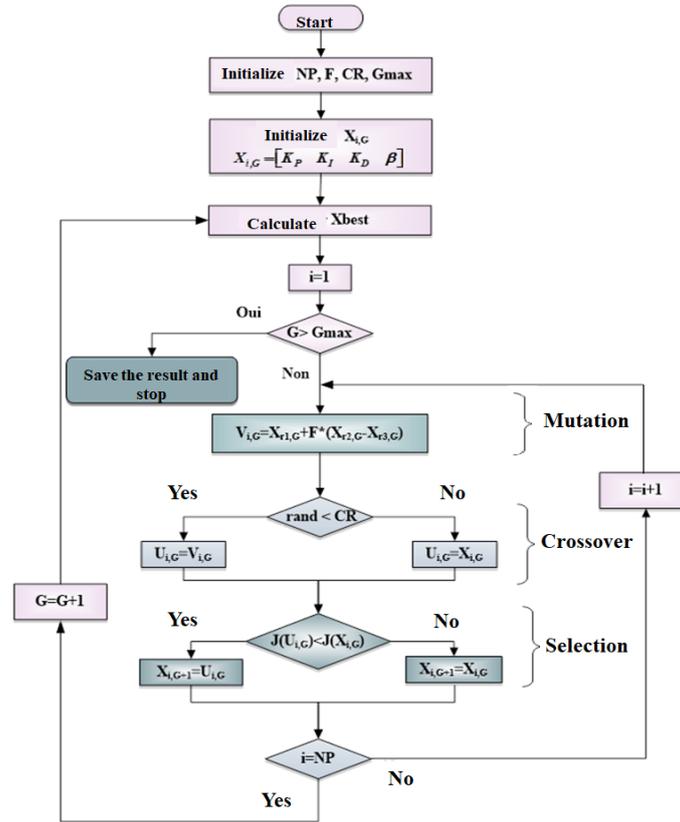
Figure 3. Flow chart of the differential evolution algorithm

3.4. Design of proposed optimized fuzzy PI controller by differential evolution algorithm (DE fuzzy PI)

This paper's key contribution is to use the differential evolution method (DE) to optimize the fuzzy PI controller's scaling factor parameters, which improves system performance and considerably lowers tracking errors. Finally, we obtain the proposed control's structure (DE-fuzzy-PI), which is given by (17):

$$u(x,t) = u_{eq}(x,t) + u_{DE-Fuzzy-PI}(x,t) \qquad (17)$$

$$u(x,t) = -\frac{F(x,t)}{G(x,t)} + U_{DE-Fuzzy-PI}(x,t) \qquad (18)$$

where $F(x,t)$ and $G(x,t)$ are the nominal representation of the system WTS. The two inputs (the error and its derivative) and the output of the optimized fuzzy logic control based on PI controller, which is shown in Figure 4. The suggested design process optimizes the fuzzy PI controller's kin1, kin2, and k out input-output scaling factors. The membership functions in this instance are unchanged over a single universe of discourse in the range [-1, 1].
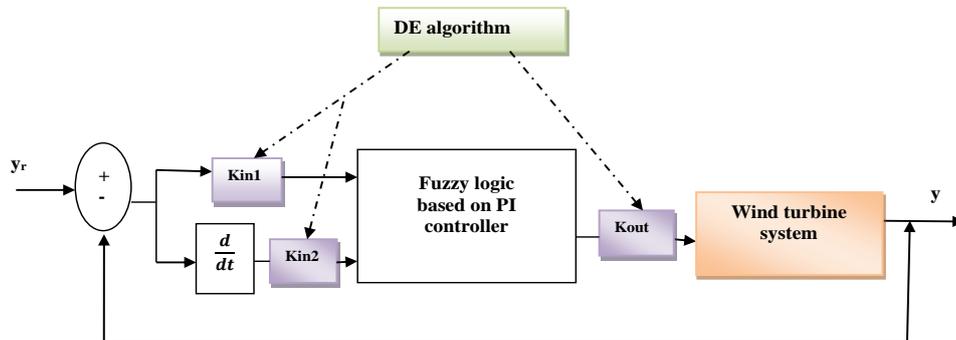
Figure 4. DE-Fuzzy-PI controller block diagram for WTS

4. RESULTS AND DISCUSSION

The system under study is simulated by the MATLAB software presented in Figure 4 to prove the efficacy of the proposed controllers in this work. This essay chooses one type of wind turbine from the two-mass model. Table 2 [26] lists the wind turbines specifications. To verify the effectiveness and resilience of the created and suggested approach (DE-fuzzy-PI), simulation experiments in MATLAB software are suggested. We take into account the electromagnetic torque with a 2000 N.m continuous disturbance. Table 3 lists the differential evolution algorithm's parameters that were employed in this study.

<table>
<tr><th colspan="4">Table 2. Parameters of VS of WTS</th></tr>
<tr><th>Parameters</th><th>Value</th><th>Parameters</th><th>Value</th></tr>
<tr><td>R</td><td>$21.65\ m$</td><td>B_{ls}</td><td>$2.691 \times 10^5\ N.m/rad$</td></tr>
<tr><td>ρ</td><td>$1.29\ kg/m^3$</td><td>K_r</td><td>$27.36\ N.m/rad/s$</td></tr>
<tr><td>J_r</td><td>$34.4\ kg.m^2$</td><td>K_g</td><td>$0.2\ N.m/rad/s$</td></tr>
<tr><td>K_{ls}</td><td>$9500\ N.m/rad/s$</td><td>n_g</td><td>43.165</td></tr>
</table>

<table>
<tr><th colspan="2">Table 3. Factors of the DE algorithm</th></tr>
<tr><th>Parameters</th><th>Value</th></tr>
<tr><td>NP</td><td>30</td></tr>
<tr><td>CR</td><td>0.8</td></tr>
<tr><td>F</td><td>0.6</td></tr>
<tr><td>G</td><td>30</td></tr>
<tr><td>D</td><td>3</td></tr>
</table>

- Scenario 1

The first scenario's application of the wind speed profile with variations given in Figure 5. Based on Figures 6, 7, and 8, it can be noticed that the optimized fuzzy PI by the DE algorithm gives better performance compared to the fuzzy PI and PI controller, the proposed approach leads to efficient performance compared to the other controllers. The effectiveness and robustness of the suggested controller device (DE-fuzzy-PI) can therefore be inferred from this simulation's results. The outcomes show that this clever controller is able to reduce tracking errors and eliminating oscillations. The wind turbine's rotor speed can be intelligently controlled in order to produce better results and faster response times when compared to other controllers.
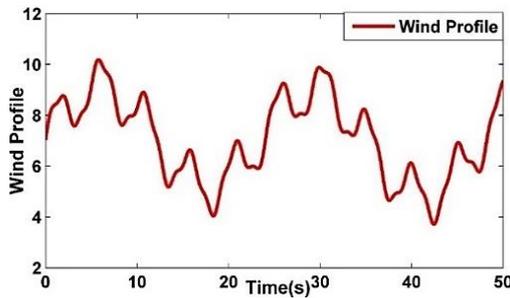
Figure 5. Profile of wind speed
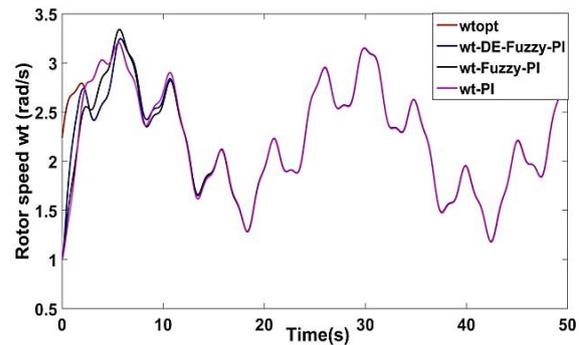
Figure 6. Rotor speed's reaction
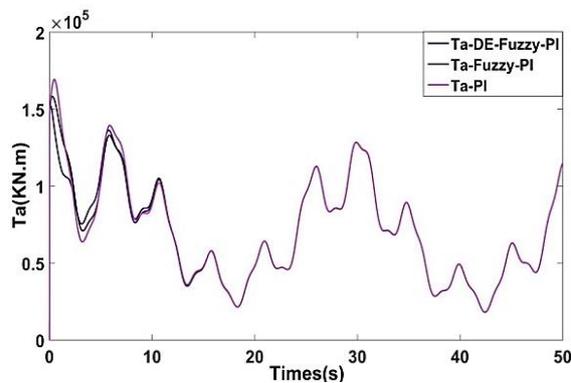
Figure 7. The reaction of aerodynamic torque
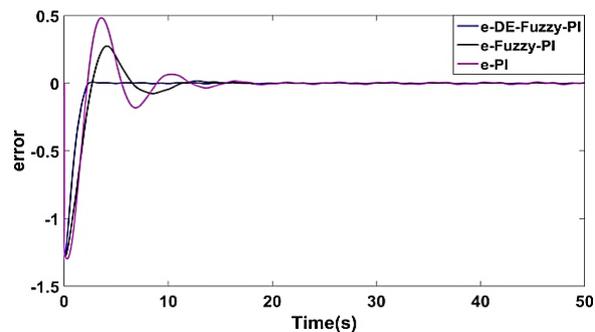
Figure 8. Tracking error comparison

- Scenario 2

The profile of wind speed with substantial variance used in this situation after 20 seconds given in Figure 9. With the elimination of steady-state oscillations at the speed level of the rotor and the aerodynamic torque, the results obtained given in Figures 10, 11 and 12 show flawless static and dynamic performance, better tracking of the regulated setpoint (speed), and a preferable response time supplied by the DE-Fuzzy PI controller. In addition, the error converges to zero after 3 seconds, meaning that oscillations are fully dampened in comparison to the other two control strategies (fuzzy PI and PI), or oscillations are still present and the error converges to zero after 15 seconds.
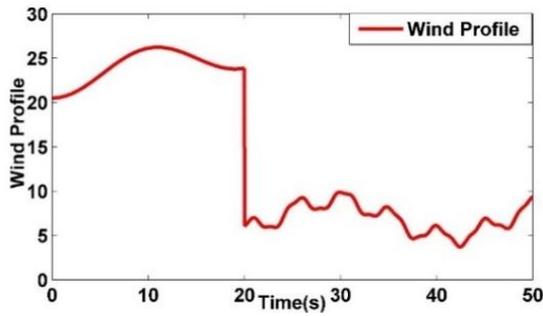
Figure 9. Profile of wind speed
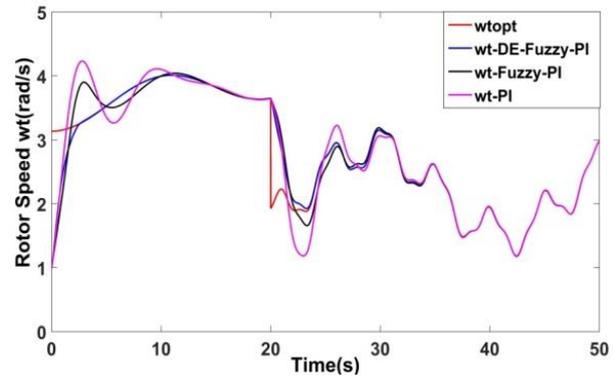
Figure 10. Rotor speed's reaction
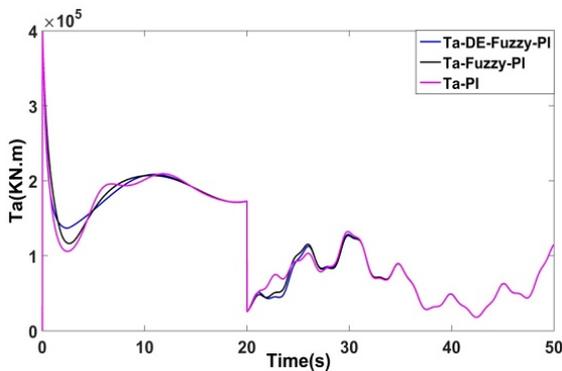
Figure 11. The reaction of aerodynamic torque
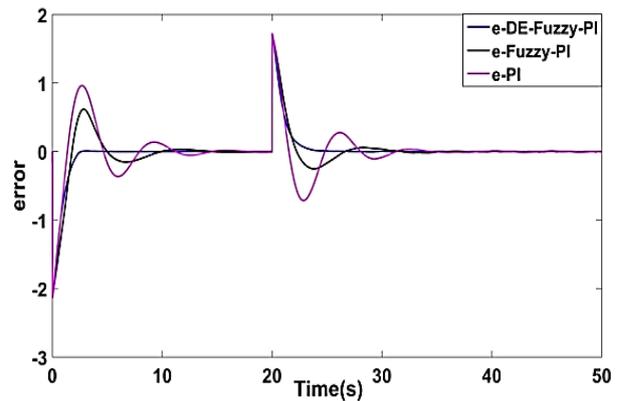
Figure 12. Tracking error comparison

The effectiveness and reliability of the suggested controller (DE-fuzzy-PI) can be seen from this simulation instance, and the results show that it is able to minimize tracking errors and remove oscillations when compared to other controllers. The suggested controller performs admirably when it comes to removing disturbances and pursuing the appropriate rotational speed. Even when the wind profile is changed, the suggested controller (DE-fuzzy-PI) swiftly converges to the ideal state with reduced oscillation. The response's output of (DE-fuzzy-PI) reaches the appropriate values more quickly than other controllers (fuzzy-PI), according to all of these figures (PI). As a result, the simulation results demonstrate that the described approach enables response time minimization with satisfactory convergence despite fluctuations in wind speed.

5.   CONCLUSION

In the aim of maximizing the energy produced by the wind and enhancing the stability of the WTS, the optimized fuzzy PI controller for a VS-WTS is introduced and applied in this work. The method entails applying the DE algorithm to optimally tune the scaling factors of a fuzzy PI controller. The three approaches (DE-fuzzy-P), (fuzzy-PI), and (PI) were compared in order to show that the proposed method (DE-fuzzy-PI) offered the greatest performance. Regarding robustness in the face of change in the system's parameters, as

well as in regards of pursuing the desired values, since it guarantees a very high performance for speed. The new method DE-fuzzy-PI gives a quicker response than normal PI, and simulation results show that it can achieve the optimal tracking results with the least amount of tracking error and oscillations.

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