Full Length Research Paper

Optimal PI Pitch Control of Doubly-Fed Induction Generator Wind Turbine for Enhancing Dynamic Stability Using Grey Wolf Optimizer

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ABSTRACT: The nonlinear relationship between the wind turbine power coefficient, tip speed ratio, and pitch angle makes tuning the Proportional Integral (PI) controller in the Wind Turbine pitch control for optimal control performance a difficult task. The Grey Wolf Optimizer (GWO) is proposed in this paper to tune the PI controller in pitch control of the Double-Fed Induction Generator (DFIG) Wind Turbine (WT) by minimizing power error. The goal is to create a GWO tuned PI pitch control that outperforms Particle Swarm Optimization (PSO) and Genetic Algorithm tuned PI-based pitch controls on the DFIG Wind Turbine. The tuning of the PI controller in pitch control was formulated as a cost function minimization with bounded gains as constraints. In MATLAB, the GWO, PSO, and GA codes were run separately to minimize the cost function while computing the optimal controller gains. The computed PI gains and the Zeigler Nichols (ZN) baseline gains were loaded

into the PI controller of the DFIG-based pitch control of WTs connected to the double-circuit distribution line. The GWO was discovered to converge faster than the PSO, whereas the GA was trapped in a local optimum. Furthermore, simulation tests demonstrated that the GWO-based tuning improved the dynamic stability of WT output when compared to its counterpart algorithms. When compared to the PSO, GA, and ZN algorithms, the GWO algorithm provides a faster settling time in the step response of the pitch angle, which can reduce stress on the pitch actuator.

Keywords: Optimal tuning of PI pitch controller; Grey Wolf Optimizer; Enhancing Dynamic Stability; Double-Fed Induction Generator Wind Turbine

INTRODUCTION

The increased demand for electricity as a result of population growth and the issue of climate change necessitates the incorporation of Renewable Energy Sources (RES) into the power system (Razavi et al., 2019). Wind Turbine (WT) output power generation, on the other hand, is stochastic (Pathak et al., 2015). As a result, their widespread incorporation into the power system has had a negative impact on power system stability (El-Bidairi et al., 2020), power quality, and protection schemes (Razavi et al., 2019). These factors compel researchers to employ various pitch control strategies to limit the aerodynamic power of WT and reduce the intermittency of their outputs. Pitch control is a control strategy used to limit aerodynamic power to rated power and reduce loading on WT

components. Pitch control based on Adaptive Control (AC), Model Predictive Control (MPC), Sliding Mode Control, Fuzzy Logic Control (FLC), and Programmable Logic Control (PLC) has recently been used to limit aerodynamic power, reduce component loading, and limit intermittency in WT outputs. However, when compared to recently developed controllers, the PI controller is more versatile in pitch control because it is simple to operate, has low-cost maintenance, and is easy to build (Osman et al., 2015). The performance of the above-mentioned control strategies is dependent on an accurate model of the WT. Because the WT model is highly nonlinear due to its complex structure, obtaining an accurate model of it is difficult. Soft control strategies, such as optimal tuning of WT pitch control, are preferable to hard control strategies

(Nguyen and Naidu, 2015).

Literature review

Trial and error and Zeigler Nichols are the traditional methods of tuning the PID controller. Recently nature-inspired artificial Intelligence (AI) and Evolutionary Algorithms are applied for tuning the PID controller (Pathak and Gaur, 2019). The Radial Basis Function (RBF), Neuron Network (NN) (Pathak and Gaur, 2019), Grey Wolf Optimizer (Sinha and Chandel, 2015), the ANFIS-GA (Chao and Weixing, 2006), Zeigler Nichols (Abdul-Adheem, 2009) and PSO (Zhang et al., 2015) are applied to tune the PID controllers in the rotor-side Voltage Source Converter (VSC) for implementing the MPPT in the variable speed Wind Turbines.

The Whale Optimization Algorithm (WOA) was used to tune the PID controllers in the grid-side VSC for MPPT in the Permanent Magnet Synchronous Generator (PMSG) Wind Turbine by Choi et al. (Choi et al., 2015). The indirect Field Oriented controls in VSCs are used to achieve MPPT, generator active and reactive power control, DC-link voltage control, and reactive power exchange control through indirect rotor speed control and generator torque control. In Civelek et al. (2016), the authors reorganized the GA mutation and crossover rates and used the Improved Genetic Algorithm (IGA) to compute the PID controller gains in the pitch control of the WT. The implementation of the IGA tuned PID controller in the pitch control of the WT increased the wind power conversion efficiency by 17% compared to the GA tuned PID controller. The gains of the PID controller in the pitch control of Synchronous Generator Wind Turbine were tuned in Ebrahim et al. (2012) using the PSO. The wind gust and step change in reference torque were applied to test the performance of the tuned controller. The PSO tuned controller provided better dynamic stability in the WT output trajectories compared to the GA tuned PID controller.

Problem statement

There are many studies on tuning the PID controller in the pitch control of Wind Turbines for limiting the aerodynamic power, reducing loading and enhancing dynamic stability in the Wind Turbines. Direct Search Optimization (DSO), GA and MFO are applied in Ebrahim et al. (2012), Gao and Gao, (2016), Zheng et al. (2020) and Ebrahim et al. (2018) respectively to tune the PI controller in the pitch control of WT operating in region III. The GA is accepted for its precision in tuning, however, it can provide a sub-optimal solution (Sinha and Chandel, 2015). Therefore, tuning the PI controller in the pitch control using GA doesn't provide optimal control performance. The PSO has inadequate convergence (Wang and Li, 2019) and it is stuck in a

local optimum (Abdul-Adheem, 2015) while solving complex optimization problems such as tuning the PI controller for controlling highly nonlinear WT. This is due to the limitation in its convergence characteristic, which consequently hampers its particles to effectively fly in the search space (Zhang et al., 2015). Similarly, the PI controller in the pitch control tuned by PSO cannot provide optimal control performance due to its limitations. Many Researchers applied the GWO to tune the PID controllers in the vector controls of VSCs for MPPT in the WTs, to mitigate oscillations in the power system frequency using Automatic Gain Control (AGC) of convectional Synchronous Generators for power generation, which provided promising results.

The pitch angle control is not considered by these Researchers. Therefore, in this study, the GWO is proposed to tune the PI controller in the pitch control for aerodynamic power limitation in the DFIG based WT operating from rated to cut-out wind speeds because of its strength in tuning the PI controllers in vector controls of VSCs for MPPT in the WT and reactive power exchange control with the grid.

The objective of proposing the GWO is to optimally tune the PI controller in pitch control of WT which provide less overshoot compared to Zeigler Nichols; avoid sub-optimal solution associated with GA, and the fast convergence compared to PSO.

This can provide optimal pitch control performance in Wind Turbines. What motivates the proposal of the GWO for tuning the PI controller is its well-organized exploration and exploitation capabilities (Yang et al., 2017) and it can avoid the local optimum. Furthermore, its robustness and simplicity make it ideal for solving intricate optimization problems (Choi et al., 2016).

Wind turbine modelling

The Wind Turbine components are interconnected (Muhando et al., 2010) as shown in (Figure 1) and the models are shown.

Modelling the Wind

Equation (1) was obtained from (Costea et al., 2015) and it represents the wind speed model.

$$v_w(t) = v_0 + \sum A_n \sin \omega_n(t) + v_g(t) \quad (1)$$

where v_0 ; $v_g(t)$; A_n ; and ω_n are the mean wind speed, the wind gust, the amplitude of n^{th} harmonics and the frequency of n^{th} harmonics respectively.

Modelling of wind turbine

Equations (2) and (3) portray the models of the aerodynamic power P_{mech} and torque τ_{mech} of the WT

Figure 1: Interconnection of wind turbine components.

respectively (Burakov and Shishlakov, 2017), (Ou et al., 2017).

$$P_{mech} = C_p(\lambda, \beta) \frac{1}{2} \rho \pi R^2 \left(\frac{\omega R}{\lambda} \right)^3 \quad (2)$$

$$\tau_{mech} = C_q(\lambda, \beta) \frac{1}{2} \rho \pi R^3 v^2 \quad (3)$$

Where C is the power coefficient of WT also fame as Betz's constant and C_q is torque coefficients. The other variables i.e. v, λ, R, ρ and β are the wind speed, the rotor tip speed ratio, the rotor length, air density (kg/m^3) and the pitch angle respectively.

The blade tip speed ratio (λ) set to maximize the power coefficients is represented as (Bektache and Boukhezzer, 2018).

$$\lambda = \frac{\omega R}{v} \quad (4)$$

where ω is the rotor angular velocity (rad/sec) of the turbine.

The below equations represent the optimal aerodynamic power and angular acceleration of the rotor respectively (Burakov and Shishlakov, 2017).

$$P_{MPPT} = K_{opt} \cdot \omega^3 \quad (5)$$

where K_{opt} is optimal gain constant and J_m is the inertia moment of the WT.

$$K_{opt} = C_{p_max}(\lambda, \beta) \frac{1}{2} \rho \pi R^2 \frac{R^3}{\lambda^2} \quad (6)$$

$$\dot{\omega} = \frac{(\tau_{wt} - \tau_r)}{J_m} \quad (7)$$

The relationship between WT power coefficient $C_p(\lambda, \beta)$, rotor tip speed ratio (λ) and pitch angle (β) are non-linear which is expressed as:

$$C_p(\lambda, \beta) = c_1 \left(c_2 \frac{1}{\lambda_i} - c_3 \beta - c_4 \right) e^{-\lambda_i} + c_6 \lambda \quad (8)$$

where the values of coefficients $c_1, c_2, c_3, c_4, c_5, c_6$ depend on the rotor of the WT.

Figure 2 shows the power-wind speed curve of variable pitch variable speed WT operation (Colombo et al. 2020). From zero to cut-in wind speed the WT is parked. But from cut-in to below-rated wind speed the WT is operating at below-rated power. The vector control using Power Electronic Converter is applied to variable-speed Wind Turbines to implement MPPT from cut-in to below-rated wind speed, while the pitch controller is applied to limit the aerodynamic power to rated power from above rated to cut-out speed Wind Turbines. This would reduce loading and prevent the Wind Turbine components from being damaged.

Mass shaft modelling

In the understudied research, the two-mass model is used to model the drivetrain due to the linkage between the electrical and mechanical subsystem of WT (Rogdakis et al., 2012). The dynamics of the rotor and the generator obtained from (Rogdakis et al., 2012) are expressed below.

$$J_m \frac{d\omega_m}{dt} = T_m - T_g - D_m \omega_m \quad (9)$$

$$J_g \frac{d\omega_g}{dt} = T_g - T_e - D_g \omega_g \quad (10)$$

Figure 2. Wind turbine power-wind speed curve.

$$\frac{d\theta_s}{dt} = \omega_0(\omega_m - \omega_g) \quad (11)$$

Where J_m and J_g are moments of inertia of the rotor and the generator accordingly. T_m , T_g and T_e are rotor torque, generator torque and electromagnetic torque respectively. ω_m , ω_g and ω_0 are the rotor, generator and synchronous angular speeds where D_m and D_g are the rotor and generator damping coefficients.

Pitch actuator modelling

The pitch actuator turns the three blades of the WT along their longitudinal axis to limit the aerodynamic power of the rotor at high wind speed to a rated speed (Baburajan, 2018). In this understudied paper, the first order pitch actuator is obtained from (Duong et al., 2014) and mathematically expressed as (Kim et al., 2019).

$$T_\beta * d\beta / dt = (\beta_{ref} - \beta_{actual}) \quad (12)$$

where β_{actual} , β_{ref} and T_β are the pitch actuator output angle, reference input angle from the pitch controller and time constant.

DFIG Modelling

The Doubly Fed Induction Generator or slip-ring generator is modelled using a direct and quadrature rotating frame. Its direct and quadrature axes stator voltages, stator active and reactive power are presented in equations (13) - (16). Its electromagnetic torque is presented in equation (17).

$$v_{sd} = R_s i_{sd} + L_s (di_{sd}/dt) - \omega_e L_{sq} i_{sq} \quad (13)$$

$$v_{sq} = R_s i_{sq} + L_s (di_{sq}/dt) + \omega_e L_{sd} i_{sd} \quad (14)$$

$$P_s = v_{sd} \cdot i_{sd} + v_{sq} \cdot i_{sq} \quad (15)$$

$$Q_s = v_{sq} \cdot i_{sd} - v_{sd} \cdot i_{sq} \quad (16)$$

$$T_e = pL(i_{rd}i_{sq} - i_{rq}i_{sd}) \quad (17)$$

where v_{sd} and v_{sq} are the d and q axes stator voltages, R_s is the stator resistance, i_{sd} and i_{sq} are the d and q axes stator currents, L_{sd} and L_{sq} are the d and q axes stator inductances, ω_e is the electrical speed, p is the number of pole pairs and L_r is the mutual inductance between stator and rotor, i_{rd} and i_{rq} are the d and q axes rotor currents.

PI controller Modelling

In this study, the GWO is proposed to tune the gains of the PI controller in the pitch control of the WT. The function of the controller is to regulate pitch angle based on the power error e between the reference power P_n from the generator of the Wind Turbine and the aerodynamic power P_{mech} . Equation (18) expressed the regulation of the pitch angle β_{ref} by the PI controller in pitch control (Habibi et al. 2018).

$$\beta_{ref}^\circ(t) = K_p * e + K_i * \int_0^t e(\tau) d\tau \quad (18)$$

where β_{ref}° is the reference pitch angle, t is the control timing, $d\tau$ is sampling time, K_p and K_i are the Proportional and Integral gains of the controller.

Proposed approach

The performance of a PI-based pitch angle controller depends on the controller structure and type of cost function applied for its design (Padhy et al., 2017). Also, it depends on the type of optimization Algorithm applied to determine the gains of the controller. In this study, the GWO is proposed to tune the PI controller in the pitch control for aerodynamic power limitation in high wind speed.

Figure 3. Block diagram for GWO-PI based pitch control structure.

Design of GWO-PI controller

The control objective of the Wind Turbine operating in the power limitation region is to adjust the blade pitch angle so that the aerodynamic power of the blade is limited to rated power using control law expressed by equation (19).

$$\beta_{bld}(t) = K_p^2(P_{nom} - P_{mech}) + K_i^2 \int_{t_0}^t (P_{nom} - P_{mech})dt \quad (19)$$

Where, K_p^2 and K_i^2 are proportional and integral gains of the PI controller in the power control loop of the pitch control. While P_{mech} and P_{nom} are Wind Turbine aerodynamic power and nominal power respectively.

Formulation of the transfer function of pitch control

Figure 3 is a block diagram for tuning the PI controller in the pitch control. The PI controller is cascaded with the pitch actuator and the WT. The major benefit of the PI controller is its application. The PI controller gains are crucial for solving instability and it can be of constant values or can be fine-tuned adaptively using online self-tuning (Arfeen et al., 2019). The GWO tuning block in (Figure 3) continues to tune the gains of the PI controller while minimizing the power error between the aerodynamic power P_{mech} and the generator nominal power P_n at the input of the PI controller of the pitch control. The power error $e(t)$ at the input of the PI controller is presented in equation (20). The PI controller provides the reference pitch angle β_{ref} as presented in equation (21). The β_{ref} is the input to the pitch actuator which provides β_{actual} , the required adjustment of pitch angle to the rotor blades.

$$e(t) = P_n - P_{mech} \quad (20)$$

$$\beta_{ref}(t) = K * e + K * \int e(\tau) d\tau \quad (21)$$

$$T\beta * d\beta/dt = (\beta_{ref} - \beta_{actual}) \quad (22)$$

The first step in the proposed GWO method of tuning the PI controller in the pitch control of WT is to formulate the equivalent transfer function of the cascaded PI controller,

the pitch actuator and the WT in the closed-loop of pitch control shown in (Figure 3). The transfer functions of the PI controller and pitch actuator presented in equations (23) and (24) were obtained through Laplace transformation of equations (21) and (22) respectively. The WT is presented in equation (25) as a second-order transfer function. Since those transfer functions are for serially connected components in (Figure 3), their equivalent transfer function is as presented in equation (26).

$$G_c(s) = K_p + K_i/s \quad (23)$$

$$G_s(s) = \frac{1}{T_p * s + 1} \quad (24)$$

$$G_{wt}(s) = \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (25)$$

$$G_{wt}(s) = \left(\frac{K_p s + K_i}{T_p * s^2 + (1 + K_p)s + K_i} \right) \frac{K\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \quad (26)$$

where K is the open-loop forward gain of the WT, ζ is its damping ratio and ω_n is the natural frequency parameter of the second-order WT.

In this study, the pitch-actuator adapted is a first-order, and its transfer function is expressed in the given equation. The time constant T_β is equal to 0.5 seconds, obtained by substituting the values of β_{ref} and $d\beta/dt$ from the WT parameters in (Table 3) into equation (12).

Developing of ITSE cost function

The cost function is based on the power error (s) between the nominal power P_n and the aerodynamic power P_{mech} at the input of the PI controller in the pitch control is shown in (Figure 3) and is given in equation (20). The Laplace Transform of the error (s) signal in the s -plane is outlined in equation (27). Then the Integral Time multiplied Square Error (ITSE) cost function was developed from the error (t). The cost function was applied to tune the gains of the PI controller in the pitch control. Tuning of PI controller is done using the GWO, PSO, GA and ZN is aim at

minimizing the ITSE cost function, enhancing the controller performance specifications namely reduced overshoot, undershoot, rising time, settling time. The PI controllers are good to use to achieve an offset response (Arfeen et al., 2020). The tuning is modelled using equation (28) as minimization of a single objective function *Min: ITSE*.

$$e(s) = 1 - \left(\frac{K_p s + K_i}{T_p s^2 + (1 + K_p)s + K_i} \right) \frac{K \omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2} \quad (27)$$

$$ITSE = \int_{-\infty}^{+\infty} (t \cdot e(t))^2 dt \quad (28)$$

subject to bounded constraint:

$$lb \leq K_p \leq ub, \& \quad b \leq K_i \leq ub \quad (29)$$

$$\text{where } 0^\circ \leq \beta^\circ \leq 90^\circ \quad (30)$$

and :

$$d\beta^\circ/dt = 0.6^\circ/s \quad (31)$$

where t is the simulation time, dt is the sampling time and β° represent the pitch angle.

The bounded constraint for tuning the PI controller are the upper and lower bounds of Proportional and Integral gains of the controller and the pitch angle as presented in Equations (29) and (30).

Minimization of the cost function using the GWO, PSO and GA optimizers

The PI controller tuning with its constraints is simulated in MATLAB and is run using the GWO, PSO and GA to minimize the cost function ITSE while the optimal gains of the PI controller are determined by the three algorithms. The tuning is depicted in (Figure 3) by GWO/PSO/GA tuning block continued to adjust the gains of the controller by minimizing the cost function ITSE, such that the aerodynamic power P_{mech} approach the reference power P_n of the pitch control.

Optimization techniques

The GWO algorithm is considered in this study to overcome the limitations of the established optimization techniques the PSO and GA. The modelling of the three techniques is presented as follows:

Grey wolf optimizer

The Grey Wolf Optimizer (GWO) was developed by Mirjalili et al. in 2014 which systematically mimics the leadership and prey hunting behaviour of grey wolves. It is a population-based algorithm and it can be applied to

optimize different objective functions (Arfeen et al., 2020). The wolves have hierarchy leadership as shown in (Figure 4). Generally, grey wolves lived in a group of 5 –10. There are four types of grey wolf α , β , δ and ω used in simulating the hierarchy of leadership. Wolves are the main leader responsible for making the decisions, wolves assist them whereas wolf dominates all the rest of the wolves. The next wolves in the leadership hierarchy are the β wolves, followed by the δ wolves, and the ω wolves are the lowest in social leadership.

Hunting prey

While hunting the grey wolves identify the position of the prey X and enclosed it. The locations in the search space for the best three solutions to K_p and K_i gains of the PI controller are identified and enclosed by the search agents as expressed in equations 32 -34.

$$\vec{D}_{\alpha,\beta,\delta} = |\vec{C}_{1,2,3} \vec{X}_{\alpha,\beta,\delta} - \vec{X}| \quad (32)$$

$$\vec{X}_{1,2,3} = \vec{X}_{\alpha,\beta,\delta} - \vec{A}_{1,2,3} \cdot (\vec{D}_{\alpha,\beta,\delta}) \quad (33)$$

$$X(t+1) = \frac{X_1 + X_2 + X_3}{3} \quad (34)$$

The best positions of α , β , and δ wolves are represented by equations 32-33, while equation 34 represents the updating of positions of the wolves with the best positions from α , β , and δ wolves (Han et al., 2018).

Encircling of prey

The encircling of prey by the grey wolves is modelled in the given equations:

$$\vec{D} = |\vec{C} \cdot \vec{X}_{pi} - \vec{X}_t| \quad (35)$$

$$\vec{X}_{t+1} = \vec{X}_{pi} - \vec{A} \cdot \vec{D} \quad (36)$$

where $\vec{X}_{pi}$ and $\vec{X}$ are the prey and grey wolf positions respectively.

Attacking of prey

The given equations expressed the variable vectors A and C (Mirjalili et al., 2016) respectively. When A is greater than 1 or less than -1, the wolves leave the candidate solution and search for a better one. Otherwise, they encircled and approached the optimal values of the PI controller.

$$\vec{A} = 2 \cdot a \cdot r_1 - 1 \quad (37)$$

Figure 4: Social leadership hierarchy of wolves in GWO.

$$\vec{C} = 2 \cdot r_2 \quad (38)$$

When the wolves are very close to the prey, this is equivalent to varying the operator a from 2 to 0, while the vector $\vec{A}$ is reduced to a . The operators r_1, r_2 lie between 0 and 1.

Particle swarm optimization modelling

The Particle Swarm Optimization (PSO) is one of the swarm population-based algorithms (Shi and Eberhart, 1998) developed by Eberhart and Kennedy in 1995. It mimics the dynamic movement of social insects, the social behaviour of flocking of birds (Manusov et al., 2019), or the schooling of fishes (Chao et al., 2006). The PSO imitates the natural selection and searching methods applied by the aforementioned social creatures (Dashti et al., 2010). In this paper, 5 particles were applied to tune the PI controller and each represents a candidate solution of the optimal gains of the controller. To run the PSO the numbers of its particles, their positions, and velocities must be initialized. While running its particles update their positions and velocities as presented in equations 39 and 40 as they moved in the search space (Panda and Padhy, 2008).

$$\vec{V}^{t+1} = w\vec{V}^t + c_1 * r_1 * (P_{best,i} - \vec{X}^t) + c_2 * r_2 * (G_{best} - \vec{X}^t) \quad (39)$$

$$\vec{X}^{t+1} = \vec{X}^t + \vec{V}^{t+1} \quad (40)$$

The inertial weight w of PSO usually has a value in the range of 0.9 to 0.4 and it determines its stability. The cognitive coefficient c_1 and the social factor c_2 are

operators chosen from 0 to 2. The random numbers r_1 and r_2 are selected from 0 to 1, facilitating the PSO to carry out the random search. Furthermore, the $P_{best,i}$ is the individuals' solutions, while G_{best} is the global attained by the search agents (Cherkaoui et al., 2019).

Genetic algorithm modelling

The Genetic Algorithm (GA) is a dynamic search technique that imitates the genetic mechanism and the biological evolution of genes. It is applied to solve complex control problems (Keshta et al., 2017). It is a particular class of evolutionary algorithms that use techniques inspired by evolutionary biologists such as hereditary, mutation, selection and recombination.

To run the GA, five chromosomes of constant lengths were applied as candidate solutions to the PI optimal gains. The objective function Min:(ITSE) was used to rank the fitness of each chromosome (Garroussi et al., 2020), before the GA operators namely selection, crossover, and mutation were executed. During iterations, the operators are executed on the parents in the population to produce offspring for a new population (Hocine and Djamel, 2019). The initialization, evaluation of the fitness of each chromosome, producing offspring using crossover and mutation (Chao et al., 2006) are the four steps to be followed in running the GA to tune the PI controller. Steps two and three are repeatedly implemented during iterations (generations) until the best optimal gains of the controller are computed by the GA.

Parameter setting for GWO, PSO and GA algorithms

Table 1 contains the selected parameters and operators of algorithms used in tuning the PI controller. The tuning of the controller is ended when either the GA, PSO, GWO

Table 1: Set parameters and operators used in running the three algorithms.

Optimizer	No of Search agents	Max Iteration	Upper bound		Lower bound		No of Variable	Operators		
			K_p	K_i	K_p	K_i				
GWO	15	30	5	25	0	0	2	$a = (2 \ 0)$	$r1 = (0 \ 1)$	$r2 = (0 \ 1)$
PSO	15	30	5	25	0	0	2	$w_max = 0.9$	$w_min = 0.2$	$r1 = (0 \ 1)$
GA	15	30	5	25	0	0	2	$c1 = 2$	$c2 = 2$	$r2 = (0 \ 1)$
								$Pc = 0.95$	$Pm = 0.001$	$Er = 0.2$

Figure 5: 3 MW DFIG based WT system model connected to distribution lines.

running time, stall time limit, fitness limit, stall generation, function tolerance, constraint tolerance or the maximum number of generations are reached. The upper and lower bounds of K_p and K_i gains for each algorithm are set from 0 to 5 and 0 to 25 respectively. Also, the numbers of search agents and the maximum number of iterations for each Algorithm are set to 15 and 30 respectively. The operators were set to default values for each algorithm.

Description of the wind turbine system model

Figure 5 consists of a 3 MW DFIG based WT coupled to a 10-kilometre length 22.9 kV single line connected to a 22.9 kV double circuit distribution line of 100 km length through a 690 V/22.9 kV 4 MW step-up transformer. The half-scale power electronic Converter in the 3 MW/575 V DFIG was used to couple the DFIG based Wind Turbine to a coupling transformer of 575 V/22.9 kV 4 MVA. The parameters of the half-scale power electronic Converter is presented in (Tables 3 and 4). The high voltage side of the coupling

transformer is connected to the 1 km distribution line. The second end of the 1 km line is connected to one end of the 10 km double distribution line through the PCC bus. The other ends of the double circuit line are connected to a 154 kV/60 Hertz generator through a 22.9 kV/154 kV 30 MVA step-up transformer. A 500 KW load was connected at PCC. The parameters of the DFIG based WT and the distribution network of Figure 5 are presented in (Table 2).

Development of the Simulink model of GWO-PI pitch control structure

The Simulink model of the pitch angle control of the DFIG WT of (Figure 5) is shown in Figure 6. This model is different from the rotor torque model. The mechanical power P_{mech} is to track the nominal electrical power of the generator P_n .

It consists of the PI controller cascaded with the pitch actuator, the pitch angle rate limiter, the pitch saturation and WT as shown in (Figure 6).

Table 2: DFIG wind turbine and distribution network parameters

DFIG WT parameters			Distribution network parameters		
Parameters	Value	Unit	Parameters	Value	Unit
Rated power	3	MW	Rated voltage	154	kV
Rated speed	12.5	m/s	Rated frequency	60	Hz
Cut-in speed	4	m/s	Tx-1 rating	22.9/154/30	kV/kV/MVA
Cut out speed	20	m/s	Tx-2 rating	575/22.9/4	kV/kV/MVA
Roto speed	5-16	rpm	Load	500	kW
Rotor radius	50	m	Line-1	1x10	km
Rate of change of pitch angle	0.6	°/s	Line-2	1x10	km
$\alpha\beta^{\circ}_{min} \leq \beta, \leq \beta^{\circ}_{max}$	0°-90°	°	Line-3	1x1	km
β°_{ref}	0.3	°			
Rated V/Freq	575/60	V/Hz			
R_s/R_r	0.00706/0.00500	Ω/Ω			
$L1s/L1r$	0.17100/0.15600	Henry			
L_m	2.90000	Henry			
H	5.04000	s			
F	0.01000	pu			
p	3	Pole pairs			

Table 3: DFIG voltage source converter parameters.

Converters Parameters			Converter Control (VAR Regulation)		
Parameters	Value	Unit	Parameters	Value	Unit
P_{max}	0.5	pu	Q_{ref}	0	pu
L_{grid}	0.15	pu	I_{q_ref}	0	pu
R_{grid}	0.15/100	pus	K_p/K_i (Reactive power)	0.05/5	-
II	0	pu	K_p/K_i (Active power)	1/100	-
Ph_I_l	90	°	K_p/K_i (Vdc link)	0.002/0.050	-
V_{dc} link	1200	V	K_p/K_i (Grid side)	1/100	-
C_{dc} link	0.01	F	K_p/K_i (Rotor side)	0.3/8	-
			$d/dt (Q_{ref})_{max}$	100	pu
			$d/dt (P_{ref})_{max}$	1	pu
			$d/dt (I_{conveter})_{max}$	200	Pu/s

Table 4: Data for three Phase pi -section 10 km or 1 km Line.

Parameter	Values	Parameters.	Values
Frequency	60 Hz	Positive-sequence L1	0.9337e-3 H/km
Positive-sequence R1	0.01273 Ω /km	Zero-sequence L0	4.1264e-3 H/km
Zero-sequence R0	0.3864 Ω /km	Positive-sequence C1	12.74e-9 F/km
Line section length	10 km or 1 km	Zero-sequence C0	7.751e-9 F/km

The proposed GWO algorithm tuned the gains of the PI controller while minimizing the power error between the mechanical power P_{mech} and the generator nominal power n at the input of the PI controller.

Deployment of tuned gains in pitch control of Wind Turbine with wind perturbation

The next step involves implementing the optimal gains of the PI controller obtained from the GWO, PSO, GA and ZN

tuning methods in the PI controller of the pitch control of the 3- MW DFIG based WT system model. The K_p and K_i gains obtained from the ZN tuning method (5 and 25 respectively) implemented in the PI controller of the pitch control of the DFIG based WT system model in (Duong et al., 2014). The optimal gains from the GWO, PSO, GA and ZN tuning methods, were also implemented in the pitch control of the simulated 3- MW WT system model shown in (Figure 5 and Table 4). The tuned PI controllers implemented in the pitch control of the DFIG WT were tested using small perturbations. The objective is to

Table 5: Minimized ITSE and tuned K_p and K_i gains using GWO, PSO, and GA.

Parameters	Iterations before convergence			$ITSE = \int_{-\infty}^{+\infty} (t \cdot e(t))^2 dt$, for 30 trails								
	GA	PSO	GWO	K_p			K_i			ITSE		
				GA	PSO	GWO	GA	PSO	GWO	GA	PSO	GWO
Best case	1.00	6.00	1.00	9.7404	5.0000	5.00	16.5917	12.5943	12.5138	2.779e-01	1.865e-01	1.865e-01
Worst case	21.00	19.00	17.00	4.0736	5.0000	5.00	21.8360	14.5956	12.6338	1.9050e-01	1.8680e-01	1.865e-01
Mean	8.17	9.87	8.97	4.2575	5.00	5.00	15.2784	13.1108	12.5465	1.916e-01	1.866e-01	1.865e-01
Std	6.41	3.34	3.62	1.274	0.000	0.00	3.4545	0.4400	0.0421	6.667e-03	3.021e-10	8.871e-07

Figure 6: Simulink model of GWO-PI based pitch control structure.

enhance the dynamic stability of the WT output power and torque during small perturbation using the GWO tuned PI controller compared with PSO, GA and ZN tuned PI controllers.

RESULTS AND DISCUSSION

From the best and worst fitness in rows 2 and 3 of (Table 5), the GA was trapped into local optima of 2.77×10^{-01} and 1.9050×10^{-01} in the 1st and 21st iterations respectively. The PSO converged in the global optimum of 1.865×10^{-01} in the 6th for the best fitness, while for the worst fitness it converged into near optimum of 1.8680 in the 19th iterations. Conversely, the GWO tuning process converged in the global optimum of 1.865×10^{-01} in the best and worst fitness in the 1st and 17th iterations respectively. The GWO shows its superiority in faster convergence than the PSO into global optimum for the best and worst fitness. Moreover, GWO is better than the GA which exhibited one of its limitations, which is convergence into local optimum. The average values of K_p and K_i gains computed by the GA are 4.2575 and 15.2784 respectively. The PSO computed the average values of K_p and K_i gains of 5.000 and 13.1108 respectively, while the GWO computed them as 5.0000 and 12.5465

A case study I: Application of 10% decrease in reference power

The DFIG based WT in the system model of (Figure 5) is

operating at rated wind speed with reactive power control to zero ($\cos\phi = 1$). The Parameters of the DFIG based WT and the Voltage Source Converters utilized are presented in (Tables 3 and 4) respectively. The K_p and K_i gains obtained from the Zeigler Nichols tuning method for PI controller which is also known as the 'Reaction Curve' method was adopted from Duong et al., 2014. The gains are 5 and 25 respectively. The reported gains from the ZN tuning method, as well as the optimal K_p and K_i gains obtained from the GWO, PSO, GA tuning methods, were implemented in the PI controller of the pitch control of the DFIG based WT. The simulated WT model was run in MATLAB with a 12.5 m/s rated wind speed shown in (Figure 7) for 30 seconds simulation period. The generator nominal power was decreased by 10% in the 15th second of the 30 seconds simulation period as shown in (Figure 8). The decrease in the reference period was applied to study the dynamic response of the DFIG based WT output with ZN, GA, PSO and GWO tuned PI controllers implemented in its pitch control.

Result of implementation of tuned PI controllers in the pitch control of DFIG based WT

For the second case study, the dynamic results of the DFIG based WT output for tuned PI controllers implemented in the pitch angle control of the WT are presented in (Table 6). Column 2 of (Table 6) contains the overshoot (OS), rise time (t_r) and the settling time (t_s) recorded for the pitch angle. The GWO-PI controller has the lowest overshoot of 0.6977° followed by the PSO-PI,

Table 6: Result of 10% decrease of pitch control reference power on the DFIG based WT output

Controller	Pitch angle (°)			Power error (per-unit)			P_t (per-unit)			τ_m (per-unit)		
	OS (°)	t_r (s)	t_s (s)	US (pu)	t_f (s)	t_s (s)	US	t_f (s)	t_s (s)	OS	t_r (s)	t_s (s)
GWO-PI	0.6977	1.4200	3.760	-0.002054	0.1020	2.264	-0.1020	1.642	3.372	0.1108	1.4300	2.9300
PSO-PI	0.7001	1.4520	3.884	-0.002780	0.1050	3.172	-0.1028	1.701	3.491	0.1134	1.5800	3.3300
GA-PI	0.7273	1.3200	4.370	-0.008828	0.0998	4.325	-0.1088	1.553	3.668	0.1202	1.3500	4.0300
ZN-PI	0.7538	0.9890	4.230	-0.018070	0.0980	4.050	-0.1180	1.000	3.550	0.1299	0.9800	3.4000

Figure 7: Rated wind speed. **Figure 8:** Decrease in generator nominal power of pitch control.

GA-PI and ZN-PI controllers with 0.7001° , 0.7273° and 0.7538° overshoot in the pitch angle respectively. Moreover, the GWO-PI controller has the smallest settling time of the pitch angle overshoot in 3.760 s, while the PSO-PI, ZN-PI and GA-PI controllers have 3.884 seconds, 4.230 seconds and 4.370 seconds of settling time respectively. From these results, it can be seen that the GWO-PI controller provided the low overshoot, low undershoot and the smallest settling time in step response of pitch angle of the DFIG based WT compared to PSO, GA and ZN PI controllers. Column 4 in (Table 6) contains the result of the impact of a 10% decrease in reference power of pitch angle control on the DFIG based WT aerodynamic power. The GWO-PI controller recorded the least undershoot and settling time of -0.1020 per unit and 3.3720 seconds respectively in the step response of the aerodynamic power. It is followed by PSO-PI, GA-PI and ZN-PI controllers in the second, third and fourth positions

respectively with -0.1028 per unit, -0.1088 per unit and -0.1180 per unit in undershoot of mechanical power. The PSO-PI, ZN-PI and GA-PI controllers recorded 3.491 seconds, 3.550 seconds and 3.668 seconds of settling time of the undershoot in mechanical power respectively. However, the ZN-PI, GA-PI, GWO-PI and PSO-PI controllers have 1.000 seconds, 1.553 seconds, 1.642 and 1.701 seconds respectively to attain the undershoot of the mechanical power. For the DFIG based WT mechanical torque, the result is presented in column 5 of (Table 6), where the GWO-PI controller recorded the least overshoot and settling time of 0.1108 per unit and 2.9300 seconds of the mechanical torque respectively. It is followed by PSO-PI, GA-PI and ZN-PI controllers with 0.1134 per unit, 0.1202 per unit and 0.1299 per unit of overshoot in the second, third and fourth positions respectively. The PSO-PI, ZN-PI and GA-PI controllers recorded 3.3300 seconds, 3.4000 seconds and 4.0300 seconds of settling time of the

Figure 9: Five unit-step increases above 12.5 m/s rated wind speed applied to DFIG based WT.

Figure 10: Step-response of the pitch to consecutive unit-step increase above the rated wind speed.

Figure 11: Step-response of DFIG mech power to consecutive unit steps above the rated wind speed.

DFIG based WT overshoots in the mechanical torque. However, the ZN-PI controller is faster in attaining the overshoot of the mechanical torque in 0.9800 seconds. It is trailed by the GA-PI, GWO-PI and PSO-PI controllers with 1.3500 seconds, 1.4300 seconds and 1.5800 seconds of rising time in attaining the overshoot. From the implementation results of tuned PI controllers in the pitch control of DFIG based WT, it can be seen the GWO tuned PI controller has shown its superiority over the PSO, GA and ZN tuned controllers in providing dynamic stability in the WT output.

Result of case study II: Application of consecutive unit-step increased above rated wind speed

Figure 9 is the five consecutive unit-step above rated wind speed applied to test the GWO-PI, PSO-PI, GA-PI and ZN-PI controllers implemented in the pitch angle control of the DFIG based WT. The DFIG based WT was operating in region III when the five-consecutive unit-step increases in the wind speed occurred, therefore the pitch control made adjustments in the pitch angle as shown in (Figures 10 and 11) to limit the mechanical power and torque to rated

Figure 12: Step-response of DFIG mech torque to consecutive unit-steps above the rated wind speed.

Figure 13: Step-response of DFIG power coupling coefficient to five consecutive unit-steps above the rated wind speed.

values shown in (Figure 12). While Figure 13 is the step response of the power coupling coefficient of the WT. The PI tuned GWO controller provided the least overshoot, undershoot and settling time in the step-responses of the pitch angle, mechanical power and torque of the WT compared to PSO-PI, GA-PI and ZN-PI controllers.

Conclusion

The PI controller in the pitch control of the DFIG Wind Turbine was successfully tuned using GWO, PSO and GA in the MATLAB environment. The proposed GWO-based tuning for the PI controller in pitch control of Wind Turbine provided the least cost function compared to PSO and GA; avoiding sub-optimal solution associated with GA, and the fast convergence compared PSO. The GWO, PSO, GA and ZN tuning results were implemented in the PI

controller of pitch angle control of the DFIG based WT and simulation tests were conducted where the Grey wolf algorithm outperformed other algorithms due to its smooth transition between local and global optima finds best in pitch control of DFIG Wind Turbine. It provided the least overshoot, undershoot, settling time in the Wind Turbine aerodynamic power, mechanical torque, pitch angle trajectories. This has provided optimal pitch control performance in DFIG Wind Turbines compared to PSO, GA and ZN algorithms. Many Researchers applied the GWO to tune the PID controllers in the vector controls of VSCs for MPPT in the WTs, to mitigate oscillations in the power system frequency using Automatic Gain Control (AGC) of convectional Synchronous Generators for power generation, which provided promising results. The novelty of this study is the proposed GWO-based method for PI controller tuning in pitch control of wind turbine which has not been conducted by the Researchers.

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Conflict of interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

REFERENCES

- Abdul-Adheem, W. R. (2019). "An enhanced particle swarm optimization algorithm," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 6, pp. 4904–4907, 2019, doi: 10.11591/ijece.v9i6.pp4904-4907.
- Arfeen, Z. A., Sheikh, U. U., Azam, M. K., Hassan, R., Shehzad, H. M. F., Ashraf, S., Abdullah, P., Aziz, L. (2020). A comprehensive review of modern trends in optimization techniques applied to hybrid microgrid systems. *Concurrency and Computation: Practice and Experience*. Volume 33, Issue 10
- Arfeen, Z. A., Khairuddin, A. B., Larik, R. M., and Saeed, M. S. (2019). "Control of distributed generation systems for microgrid applications: A technological review," *Int. Trans. Electr. Energy Syst.*, vol. 29, no. 9, pp. 1–26, 2019, doi: 10.1002/2050-7038.12072.
- Baburajan, S. (2018). "Improving the efficiency of a wind turbine system using a Fuzzy-PID controller," in *2018 Advances in Science and Engineering Technology International Conferences, ASET 2018*, 2018, pp. 1–5, doi: 10.1109/ICASET.2018.8376776.
- Bektache A., and Boukhezzar, B. (2018). "Nonlinear predictive control of a DFIG-based wind turbine for power capture optimization," *Int. J. Electr. Power Energy Syst.*, vol. 101, pp. 92–102, 2018, doi: 10.1016/j.ijepes.2018.03.012.
- Burakov, M., and Shishlakov, V. (2017). "Genetic algorithm optimization for pitch angle control of variable speed wind turbines," in *12th International Scientific-Technical Conference on Electromechanics and Robotics "Zavalishin's Readings," 2017*, Pp. 1–6, doi: 10.1109/ICSET.2017.8376776.
- Chao, O. and Weixing, L. (2006). "Comparison between PSO and GA for parameters optimization of PID controller," in *Proceedings of the 2006 IEEE International Conference on Mechatronics and Automation*, 2006, pp. 2471–2475.
- Cherkaoui, N., Belfqih, A., El Mariami, F., Boukherouaa, J., and Berdai, A. (2019). "Optimal location and reactive power injection of wind farms and SVC's units using voltage indices and PSO," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 5, pp. 3407–3414, 2019, doi: 10.11591/ijece.v9i5.pp3407-3414.
- Choi, J. W., Heo, S. Y., and Kim, M. K. (2016). "Hybrid operation strategy of wind energy storage system for power grid frequency regulation," *IET Gener. Transm. Distrib.*, vol. 10, no. 3, pp. 736–749, 2016, doi: 10.1049/iet-gtd.2015.0149.
- Civelek, Z., Çam, E., Lüy, M., and Mamur, H. (2016). "Proportional-integral-derivative parameter optimization of blade pitch controller in wind turbines by a new intelligent genetic algorithm," *IET Renew. Power Gener.*, vol. 10, no. 8, pp. 1220–1228, 2016, doi: 10.1049/iet-rpg.2016.0029.
- Colombo, L., Corradini, M. L., Ippoliti, G., and Orlando, G. (2020). "Pitch angle control of a wind turbine operating above the rated wind speed: A sliding mode control approach," *ISA Trans.*, vol. 96, pp. 95–102, 2020, doi: 10.1016/j.isatra.2019.07.002.
- Costea, M., Vladu, E., and Károly, T. (2015). "Wind turbine modelling in MatLab Simulink," *SSRN*, pp. 113–120, 2015, doi: http://protmed.uoradea.ro/facultate/publicatii/natural_resources/2011/papers/16.%20Costea%20Monica.pdf.
- Dashti, M., Shojaaee, K., Seyedkashi, S. M. H., and Behnam, M. (2010). "Tuning of digital PID controller using particle swarm optimization," in *Proceedings of the 29th Chinese Control Conference, CCC'10*, 2010, pp. 3383–3389.
- Duong, M. Q., Grimaccia, F., Leva, S., Mussetta, M., and Ogliari, E. (2014). "Pitch angle control using hybrid controller for all operating regions of SCIG wind turbine system," *Renew. Energy*, vol. 70, pp. 197–203, 2014, doi: 10.1016/j.renene.2014.03.072.
- Ebrahim, M. A., Becherif, M., and Abdelaziz, A. Y. (2018). "Dynamic performance enhancement for wind energy conversion system using Moth-Flame Optimization based blade pitch controller," *Sustain. Energy Technol. Assessments*, vol. 27, no. April, pp. 206–212, 2018, doi: 10.1016/j.seia.2018.04.001.
- Ebrahim, M. A., El-Metwall, K. A., Bendary, F. M., and Mansour, W. M. (2012). "Optimization of
- El-Bidairi, K. S., Nguyen, H. D., Mahmoud, T. S. S., Jayasinghe, D. G., and Guerrero, J. M. (2020). "Optimal sizing of Battery Energy Storage Systems for dynamic frequency control in an islanded microgrid: A case study of Flinders Island, Australia," *Energy*, vol. 195, pp. 1–25, 2020, doi: 10.1016/j.energy.2020.117059.
- Gao, R. and Gao, Z. (2016). "Pitch control for wind turbine systems using optimization, estimation and compensation," *Renew. Energy*, vol. 91, pp. 501–515, 2016, doi: 10.1016/j.renene.2016.05.011.
- Garroussi, Z., Ellaia, R., Talbi, E. G., and Lucas, J. Y. (2020). "A hybrid non-dominated sorting genetic algorithm for a multi-objective demand-side management problem in a smart building," *Int. J. Electr. Comput. Eng.*, vol. 10, no. 1, pp. 559–574, 2020, doi: 10.11591/ijece.v10i1.pp559-574.
- Habibi, H., Rahimi Nohooji, H., and Howard, I. (2018). "Adaptive PID control of wind turbines for power regulation with unknown control direction and actuator faults," *IEEE Access*, vol. 6, pp. 37464–37479, 2018, doi: 10.1109/ACCESS.2018.2853090.
- Han, T., Wang, X., Liang, Y., Wei, Z., and Cai, Y. (2018). "A novel grey Wolf optimizer with random walk strategies for constrained engineering design," *2018 ACM Int. Conf. Proceeding Ser.*, pp. 1–6, 2018, doi: 10.1145/3148453.3306270.
- Hocine, S. and Djamel, L. (2019). "Optimal number and location of UPFC devices to enhance voltage profile and minimizing losses in electrical power systems," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 5, pp. 3981–3992, 2019, doi: 10.11591/ijece.v9i5.pp3981-3992.
- Keshta, H., Ali, A., Saied, E., and Bendary, F. (2017). "Comparative performance of wind energy conversion system (WECS) with PI controller using heuristic optimization algorithms," in *24th International Conference & Exhibition on Electricity Distribution (CIRED)*, 2017, pp. 549–553, doi: 10.1049/oap-cired.2017.0097.
- Kim, K., Kim, H. G., Song, Y., and Paek, I. (2019). "Design and simulation of an LQR-PI control algorithm for medium wind turbine," *Energies*, vol. 12, no. 11, pp. 1–18, 2019, doi: 10.3390/en12110001.
- Manusov, V. Z., Matrenin, P. V., and Khasanzoda, N. (2019). "Swarm algorithms in dynamic optimization problem of reactive power compensation units' control," *Int. J. Electr. Comput. Eng.*, vol. 9, no. 5, pp. 3967–3974, 2019, doi: 10.11591/ijece.v9i5.pp3967-3974.
- Mirjalili, S., Mirjalili, S. M., and Lewis, A. W. O. (2014). "Grey Wolf Optimizer," *Adv. Eng. Softw.*, vol. 69, pp. 46–61, 2014, doi: 10.1016/j.advengsoft.2013.12.007.
- Mirjalili, S., Saremi, S., Mirjalili, S. M., and Coelho, D. S. (2016). "Multi-objective grey wolf optimizer: A novel algorithm for multi-criterion optimization," *Expert Syst. Appl.*, vol. 47, pp. 106–119, 2016, doi: 10.1016/j.eswa.2015.10.039.
- Muhando, E. B., Senjyu, T., Omene, E., Funabashi, T., and Kim, C. H. (2010). "Modelling-based approach for digital control design for nonlinear WECS in the power system," *Wind Energy*, vol. 13, pp. 52–57, 2010, [Online]. Available: https://www.researchgate.net/publication/311773574_Evolution_of_Wind_Turbine_Control_Systems/figures?lo=1&utm_source=google&utm_medium=organic&fullTextFileContent=10.1016/j.weneng.2010.01.002
- Osman, A. A., El-wakeel, A. S., Kamel, A., and Seoudy, H. M. (2015). "Optimal Tuning of PI Controllers for Doubly-Fed Induction Generator-Based Wind Energy Conversion System using Grey Wolf Optimizer," *J. Eng. Res. Appl.*, vol. 5, no. 11, pp. 81–87, 2015.
- Ou, T., Lu, K., and Huang, C. (2017). "Improvement of Transient Stability

- in a Hybrid Power MultiSystem Using a Designed NIDC," *energies Artic.*, vol. 10, no. 4, pp. 1–16, 2017, doi:
- Padhy, S., Panda, S., and Mahapatra, S. (2017). "A modified GWO technique based cascade PI-PD controller for AGC of power systems in presence of Plug-in Electric Vehicles," *Eng. Sci. Technol. an Int. J.*, vol. 20, no. 2, pp. 427–442, 2017, doi: 10.1016/j.jestch.2017.03.004.
- Panda S., and Padhy, N. P.(2008). "Comparison of particle swarm optimization and genetic algorithm for FACTS-based controller design," *Appl. Soft Comput. J.*, vol. 8, no. 4, pp. 1418–1427, 2008, doi: 10.1016/j.asoc.2007.10.009.
- Pathak, A. K., Sharma, M. P., and Bundeale, M. (2015). "A critical review of voltage and reactive power management of wind farms," *Renew. Sustain. Energy Rev.*, vol. 51, pp. 460–471, 2015, doi: 10.1016/j.rser.2015.06.015.
- Pathak, D., and Gaur, P.(2019). "A fractional order fuzzy-proportional-integral-derivative based pitch angle controller for a direct-drive wind energy system," *Comput. Electr. Eng.*, vol. 78, pp. 420–436, 2019, doi: <https://doi.org/10.1016/j.compeleceng.2019.07.021>.
- Ebrahim, M. El-Metawali, K.A., Bendary, F.M. and Masour, F.M.,(2012). "Proportional-Integral-Differential Controller for Wind Power Plant Using Particle Swarm Optimization Technique," *Int. J. Electr. Power Eng.*, vol. 6, no. 1, pp. 32–37, 2012, doi:
- Razavi, S. E., Rahimi, E., Javadi, M. S., Nezhad, A. E., Lotfi, M., Shafie-khah, M., and João P. S. C. (2019). Impact of distributed generation on protection and voltage regulation of distribution systems: A review," *Renew. Sustain. Energy Rev.*, vol. 105, Pp. 157–167, 2019, doi: 10.1016/j.rser.2019.01.050.
- Rogdakis, G., Garcia-Valle, R., and Arana, I. (2012). "Transient model validation of fixed-speed induction generator using wind farm measurements," *IEEE Trans. Power Syst.*, vol. 27, no. 1, pp. 564–571, 2012, doi: 10.1109/TPWRS.2011.2168832.
- Shi, Y. and Eberhart, R. (1998). "Modified particle swarm optimizer," in *1998 Proceedings of the IEEE Conference on Evolutionary Computation, ICEC*, 1998, pp. 69–73, doi:
- Sinha, S. and Chandel, S. S. (2015). "Review of recent trends in optimization techniques for solar photovoltaic-wind based hybrid energy systems," *Renew. Sustain. Energy Rev.*, vol. 50, pp. 755–769, 2015, doi: 10.1016/j.rser.2015.05.040.
- vol. 13, no. 6, pp. 543–557, 2010, doi: 10.1002/we.376.
- Wang J. S. and Li, S. X. (2019). "An Improved Grey Wolf Optimizer Based on Differential Evolution and Elimination Mechanism," *Sci. Rep.*, vol. 9, no. 1, pp. 1–21, 2019, doi: 10.1038/s41598019-43546-3.
- Yang, B., Zhang, X., Yu, T., Shu, H., and Fang, Z. (2017). "Grouped grey wolf optimizer for maximum power point tracking of doubly-fed induction generator based wind turbine," *Energy Convers. Manag.*, vol. 133, pp. 427–443, 2017, doi: 10.1016/j.enconman.2016.10.062.
- Zhang, Y., Wang, S., and Ji, G. (2015). "A Comprehensive Survey on Particle Swarm Optimization Algorithm and Its Applications," *Math. Probl. Eng.*, vol. 2015, pp. 1–39, 2015, doi: <http://dx.doi.org/10.1155/2015/931256>.
- Zheng, S.G., Chang, C.K., and Pan, J.-S. (2020). "Double Fuzzy Pitch Controller of Wind Turbine Designed by Genetic Algorithm," in *2020 International Automatic Control Conference (CACS)*, 2020, pp. 1–5, doi: 10.1109/cacs50047.2020.9289749.