Optimal rotor blade control using Grey Wolf Optimizer for small signal stability of SCIG Wind Turbine

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Abstract. The pitch control of Wind Turbine needs to be tuned for optimal pitch control performance. In this paper, the Grey Wolf Optimizer (GWO) is proposed to tune the PI controller in the pitch control of the Squirrel Cage Induction Generator (SCIG) Wind Turbine. The goal is to show that the slow convergence of the Particle Swarm Optimization (PSO), and the trapping into a local optimum of Genetic Algorithm (GA) tuning methods can be overcome by applying the GWO tuning method. The GWO, PSO and GA were applied online to tune the PI controller in pitch control. The tuning results were executed in the PI controller of pitch control of simulated SCIG Wind Turbine connected to a double circuit distribution line. Equally, the Ziegler Nichols (ZN) tuned PI controller was executed in the rotor blade control of the same Wind Turbine. From the simulation results, the GWO tuned PI controller executed in the pitch control of the Wind Turbine provided the least overshoot and the settling time in the trajectories of blade pitch demand of the Wind Turbine compared to PSO, GA and ZN tuned PI controllers. The significance of the proposed GWO tuning method for PI controller in the rotor blade control of the SCIG Wind Turbine, it can reduce the stress on the pitch actuator of the Wind Turbine. This is because it reduced overshoot and settling time in the trajectories of blade pitch demand of the Wind Turbine compared to PSO, GA and ZN tuning methods.

1. Introduction

High electricity demand and climate change due to the utilization of fossil fuel for power generation necessitate the integration of Renewable Energy Sources (RES) in the power system[1]. However, most RES such as wind energy and photovoltaic generate stochastic power [2]. And their integration in large scale in the power system has negatively impacted the power system stability [3]. The optimal blade pitch control is applied to reduce fluctuations in the output of the Wind Turbine. The blade pitch control components are cascaded PI controller, pitch actuator, pitch saturator and rate limiter. But the recently developed like the Adaptive Controller (AC) is applied in the blade pitch control. However, these types of controllers are complex and expensive compared to the PI controller. Consequently, the PI controller is the dominant concept for different applications in the Wind Turbines [4]. But its problem is obtaining its optimal gains to improve performance. The Ziegler Nichols, the Genetic Algorithm and the PSO are
the established methods for tuning the PID controller. Also, the nature-inspired, Artificial Intelligence (AI) and Evolutionary Algorithms (EA) are new methods for tuning the PID controller [5].

The Radial Basis Function (RBF) neuron network [6], the Grey Wolf Optimizer [7], the ANFIS-GA [8], the Zeigler Nichols [9] and the PSO [10] were applied to tune the PID controllers in the rotor-side Voltage Source Converter (VSC) for MPPT in the variable speed Wind Turbines. The Whale Optimization Algorithm (WOA) was applied in [11] to tune the PID controller in the grid-side VSC for MPPT in the Permanent Magnet Synchronous Generator (PMSG) Wind Turbine. The PSO in [12] was applied to tune the PID controller for MPPT in the PMSG Wind Turbine and DFIG Wind Turbine respectively. The PSO tuning method provided enhanced pitch control performance compared to Zeigler Nichols (ZN), Genetic Algorithm (GA), Firefly Algorithm (FA), Differential Evolution (DE) and Ant Colony Optimization (ACO) tuning methods. The performance of the pitch control was enhanced in [13] by tuning the PID controller using the Direct Search Optimization (DSO). And in [14] an Improved Genetic Algorithm (IGA) was applied to optimize the blade pitch control of Wind Turbine [14]. This improved the power conversion coefficient by 17%, compared to the GA. The aerodynamic power of PMSG Wind Turbine was smoothing in [15] using coordinated pitch control and DC-link voltage control in the VSC which connected the Wind Turbine to the grid.

Most of the studies on tuning the PID controller using GWO for Wind Turbine applications are for MPPT in the Wind Turbines. Also, there are substantial studies where researchers tuned the PID controller for aerodynamic power limitation and dynamic stability. It is important to optimize the pitch control performance of the Wind Turbines operating in the region III of its power-speed curve, under contingencies such as a sudden increase above rated wind speed due to abnormal weather condition or decrease in the reference power of the pitch control, as a result of reduced active power generation. The concentration of the PID tuning studies for MPPT in the DFIG, PMSG and SG Wind Turbines and the neglect of SCIG Wind Turbines is because the SCIG is an old generator concept with low efficiency and difficulty to implement the MPPT (generator speed control) due to narrow slip [16]. But the SCIG Wind Turbine is cheap in manufacturing cost, not complex in construction, brushless; robust compared to DFIG Wind Turbine. Furthermore, the SCIG Wind Turbine has a low cost of installation and maintenance compared to the dominant concept the DFIG Wind Turbines [17], [18]. The PID controllers in the pitch control of Wind Turbines were tuned using the GA [14] and PSO [10], [12]. And the tuning results were applied in the pitch control of the Wind Turbines where the aerodynamic power limitations were observed. The GA has accuracy in controller tuning, but it is found to quickly trapped in a local optimum [19]. The PSO can quickly converge but sometimes it got trapped in a local optimum [20] when solving complex optimization problems [21].

The GWO tuning of PID controllers was applied by different researchers to tune PID controller in the Voltage Source Converter (VSC) for MPPT in Wind Turbines, Automatic Gain Control (AGC) in convensional Synchronous Generation plants. The optimal tuning of the PI controller in pitch control of Wind turbine using GWO has not been conducted. Therefore, the GWO is proposed to optimize the gains of the PI controller in the pitch control of the SCIG Wind Turbine for optimal pitch control. The first objective of this study is to applied the GWO to tune the PI controller in the pitch control of the SCIG Wind Turbine. And to show that the GWO tuning method can avoid convergence into local optimum, unlike GA and possessed faster convergence than PSO while tuning the PI controller in pitch control. Also, the GWO tuning method for PI controller is proposed to overcome the high overshoot associated with Zeigler Nichols tuning method. The GWO can avoid premature convergence besides its well-organized exploration and exploitation [22] capabilities. Therefore, it is proposed in this study to optimize the gains of the PI controller in pitch control for optimal performance of Wind Turbine output. Furthermore, the GWO is capable of solving complex optimization tasks [23] besides been simple and robust. To validates the proposed GWO tuning method, its tuning results and the PSO, GA and ZN tuning results were separately embedded in the PI controller of pitch angle control of simulated SCIG Wind Turbine. And comparison was made between the dynamic stabilities of the aerodynamic power and torque of the Wind Turbine under unit-step increase above rated wind speed for the four tuning
methods. This paper has four sections. In section 2 the modelling of Wind Turbine is presented. And section 3 contains the methodology while section 4 contains the results and discussion.

2. Wind Turbine modelling

In this section, the models of the Wind, Wind Turbine, SCIG and pitch control are presented.

2.1. Wind Model

Equation (1) represents the wind speed [24].

\[
v_w(t) = v_0(1 + \sum_{i=1}^{n} A_n \sin \omega_n(t) + v_g(t))
\]

Where \(v_0\) is the average wind speed, \(v_g(t)\) is the wind gust, \(A_n\) is the peak value of the \(n^{th}\) harmonics and \(\omega_n\) is the number of cycles per second of \(n^{th}\) harmonics.

2.2. Wind Turbine model

The mechanical power \(P_{\text{mech}}\) and torque \(\tau_{\text{mech}}\) at Wind Turbine output [25] are shown in Equations (2) and (3) respectively.

\[
P_{\text{mech}} = C_p(\lambda, \vartheta) \frac{1}{2} \rho \pi R^2 \left(\frac{\omega R}{\lambda}\right)^3
\]

\[
\tau_{\text{mech}} = C_q(\lambda, \vartheta) \frac{1}{2} \rho n R^2 v^2
\]

Where \(v\) is the wind speed, \(\lambda\) is the rotor tip speed ratio, \(R\) is the length of the rotor, \(\vartheta\) is the pitch angle, \(\rho\) is the air density, \(C_p\) is the power coefficient (Betz’s factor) and \(C_q\) is the torque coefficient.

The wind wheel tip speed ratio \(\lambda\) is represented in Equation (4) [26].

\[
\lambda = \frac{\omega R}{v}
\]

Where \(\omega\) is the angular speed of Wind Turbine blades.

The power coefficient \(C_p(\lambda, \vartheta)\) of a wind turbine depends on the rotor tip speed ratio \(\lambda\) and pitch angle \(\vartheta\) is conveyed in Equation (5).

\[
C_p(\lambda, \vartheta) = c_1 \left(\frac{c_2}{\lambda} - c_3 \vartheta - c_4\right) e^{-\frac{c_5}{\lambda}} + c_6 \lambda
\]

Where, \(c_1, c_2, c_3, c_4, c_5, c_6\) are the rotor constants.

2.3. SCIG Model

Equations (6) – (9) modelled the SCIG in the direct-quadrature reference frame.

\[
v_{sq} = R_s i_{sq} + \omega_s \psi_{sd} + p \psi_{sq}
\]

\[
v_{sd} = R_s i_{sd} + \omega_s \psi_{sq} + p \psi_{sd}
\]

\[
P_{\text{scig}} = 3/2 (v_{sd} i_{sd} + v_{sq} i_{sq})
\]

\[
Q_{\text{scig}} = -3/2 (v_{sq} i_{sd} + v_{sd} i_{sq})
\]
Where $R_s$ and $R_r$ are the stator and rotor phase resistances, $i_{sd}$ and $i_{sq}$ are the $d$ and $q$ axes stator currents, $\psi_{sd}$ and $\psi_{sq}$ are the $d$ and $q$ axes stator fluxes, $\omega_s$ is the synchronous speed. And $p$ and $\theta_r$ are the number of pole pairs and the rotor axis leading angle.

### 2.4. Pitch control model

The transfer function of pitch angle control can be seen in Figure 1.

![Figure 1. Block diagram of transfer function of pitch](image)

Considering Figure 1, Equations (10), (11) and (12) represent the transfer functions of the PI controller, pitch actuator and the Wind Turbine respectively. While their equivalent transfer function is presented in Equation (13).

$$G_c(s) = K_p + K_i/s$$  \hspace{1cm} (10)

$$G_s(s) = \frac{1}{0.5s + 1}$$ \hspace{1cm} (11)

$$G_{wt}(s) = \frac{K \omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2}$$ \hspace{1cm} (12)

$$G_{wt}(s) = \frac{K_p s + K_i}{0.5 s^2 + (1 + K_p)s + K_i} \frac{K \omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2}$$ \hspace{1cm} (13)

Where $K$ is the open-loop forward gain of the wind turbine, $\zeta$ is the damping ratio and $\omega_n$ is the natural frequency parameter of the wind turbine.

### 3. Method

The three codes of GWO, PSO and GA applied online in the MATLAB to calculate the optimal gains of the PI controller in pitch control for thirty runs. The error signal $e(s)$ depicted in Figure 1 is presented in Equation (14). The Integral Time multiplied Square Error (ITSE) cost function was developed from the power error $e(s)$. And the tuning block depicted in Figure 2 continued to tune the gains of the PI controller while minimizing the ITSE such that the aerodynamic power $Y(s)$ of Wind Turbine advanced to the reference power of the pitch control $R(s)$. The minimization of the cost $Min: ITSE$ is shown in Equation (15).

$$e(s) = 1 - \frac{K_p s + K_i}{0.5 s^2 + (1 + K_p)s + K_i} \frac{K \omega_n^2}{s^2 + 2\zeta \omega_n s + \omega_n^2}$$ \hspace{1cm} (14)

$$Min: ITSE = \sum e(s)^2 dt$$ \hspace{1cm} (15)

With constraint: $lb \leq K_p \leq ub$ and $lb \leq K_i \leq ub$

Where, $t$ and $dt$ denote the simulation time and sampling time during the simulation time,
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4. Results and discussion

4.1. PI controller tuning Results

Considering the rows number one and two of Table two, the GA got stucked in local optima of 2.77*10^{-01} for the best case and 1.9050*10^{01} for the worst case in the 1st and 21st iterations respectively. However, the PSO converged in the global optimum of 1.865*10^{01} in the 6th iteration for the best case. While for the worst case it converged into near optimum of 1.8680 in the 19th iterations. The GWO converged in the global optimum of 1.865*10^{01} for the best- and worst-case results in the 1st and 17th iterations respectively. For the best and worst cases, the GWO converged faster than the PSO into global optimum during optimal tuning of the PI controller. But the GA exhibited one of its limitations, where it converged into the local optimum. The mean values of $K_p$ and $K_i$ gains calculated by the GA are 4.2575 and 15.2784 respectively. The PSO computed the mean values of $K_p$ and $K_i$ gains as 5.0000 and 13.1108 respectively. While the GWO calculated the average values of $K_p$ and $K_i$ gains as 5.0000 and 12.5465 respectively.

Table 1. Parameter and parameter standardization for GWO, PSO and GA

| Algorithms | Search agents | Iteration | Upper boundary $K_p$ | Lower boundary $K_p$ | Gains | Operators |
|------------|---------------|-----------|----------------------|----------------------|-------|-----------|
| GWO        | 5             | 30        | 5 25                 | 0 0                  | 2     | $a=[2.0]$ | r1=[0.1] |
| PSO        | 5             | 30        | 5 25                 | 0 0                  | 2     | wMax=0.9  | wMin=0.2 |
| GA         | 5             | 30        | 5 25                 | 0 0                  | 2     | Pc=0.95   | Pm=0.001 |

3.1. Standardization of GWO, PSO and GA parameters and operators

To be fair to all the three Algorithms they were assigned equal parameters as shown in Table 1. The search space for $K_p$ and $K_i$ gains of each Algorithm are set from 0 to 5 and 0 to 25 respectively. Furthermore, the maximum iterations and number of search agents are 5 and 30 respectively for each Algorithms. While their operators were assigned default values as presented in Table 1.

3.2. Implementation of tuning Results.

The optimal gains of the PI controller in the pitch control of the SCIG Wind Turbine model from the ZN tuning result in [27] was adapted and are 5 and 25 for $K_p$ and $K_i$ gains respectively. The adapted gains from ZN tuning method, and the tuned $K_p$ and $K_i$ gains obtained from the GWO, PSO, GA tuning methods, were applied in the PI controller of the pitch control of the simulated system model shown in Fig. 3. It was run in the MATLAB 2016b with 12.5 m/s rated wind speed for 30 seconds simulation period. Suddenly a unit-step increase above the rated wind speed occurred in the 15th second of simulation period as shown in Figure 4. The unit-step increase above rated wind speed was applied to evaluate the performance of the tuned pitch control of the Wind Turbine model. The tuning results are presented in subsection 4.1 while the implementation results are discussed in subsections 4.2.
angle and Algorithms

.. Table 2. Optimized ITSE and $K_p$ and $K_i$ gains computed by three Algorithms

| Measurement | Iterations before convergence | $K_p$ | $K_i$ | ITSE |
|-------------|-------------------------------|-------|-------|------|
|             | GA   | PSO  | GWO  | GA   | PSO  | GWO  | GA   | PSO  | GWO  |
| Best case   | 1.00 | 6.00 | 1.00 | 9.7404 | 5.0000 | 5.00 | 0.00 | 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 | 0.00 | 21.8360 | 14.5956 | 12.6338 | 1.9050e-01 | 1.8680e-01 | 1.8680e-01 |
| Mean        | 8.17 | 9.87 | 8.97 | 4.2575 | 5.00 | 0.00 | 15.2784 | 13.11 | 12.5465 | 1.916e-01 | 1.866e-01 | 1.866e-01 |
| Std         | 6.41 | 3.34 | 3.62 | 1.274 | 0.000 | 0.000 | 3.4545 | 0.4400 | 0.0421 | 6.667e-03 | 3.021e-03 | 8.871e-03 |

4.2. Result of execution of tuned gains.

The results of the impact of unit step increase above the rated wind speed on the SCIG Wind Turbine output parameters were obtained through the embedding the computed gains of PI controller in the blade pitch control of the Wind Turbine are presented in Table 3. Considering column three of Table three, the GWO optimized PI controller has the least overshoot of 0.5783° followed by PSO, GA and ZN optimized controllers with 0.5804°, 0.5977° and 0.6250° respectively.

.. Table 3. Impact of step increase above rated wind speed on Wind Turbine output and pitch angle

| S/N | Controller | Pitch (°) | P error (pu) | $T_{mech}$ (pu) | $P_{mech}$ (pu) |
|-----|------------|-----------|------------|----------------|----------------|
|     |            | OS        | tr (s)     | OS            | US          |
|     |            | US        | ts (s)     | US            | OS          |
| 1   | PI-ZN      | 0.6250    | 0.96       | 0.07555       | -0.01574   |
|     |            | OS        | -1.083     | -1.183        | 2.500       |
| 2   | PI-GWO     | 0.5783    | 1.66       | 0.07555       | -0.00175   |
|     |            | OS        | -1.098     | -1.183        | 1.257       |
| 3   | PI-PSO     | 0.5804    | 1.50       | 0.07555       | -0.00237   |
|     |            | OS        | -1.096     | -1.183        | 2.080       |
| 4   | PI-GA      | 0.5977    | 1.28       | 0.07555       | -0.00747   |
|     |            | OS        | -1.092     | -1.183        | 2.175       |

From columns four of Table three, the GWO optimized PI controller provided the least undershoot of -0.00175 pu in power error. It is, followed by the PSO, GA and ZN optimized PI controllers with -0.00237 pu, -0.00747 pu and 0.01574 pu respectively. While in column 5 of Table three the GWO optimized PI controller recorded the least overshoot and settling time of -1.098 pu and 1.257 s respectively of aerodynamic torque. It is followed by PSO, GA and ZN optimized PI controllers in the 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} positions respectively. The PI-PSO controller recorded -1.086 pu and 2.080 s in overshoot and settling time accordingly. The GA tuned PI controller recorded -1.092 pu and 2.175 s accordingly, while the ZN tuned PI controller has -1.083 pu and 2.500 s overshoot and settling time respectively. In column six of Table three, the GWO optimized PI controller recorded the least undershoot and settling time of 0.9983 pu and 1.462 s accordingly in the aerodynamic power. It is followed by PSO, GA and ZN optimized PI controllers in 2\textsuperscript{nd}, 3\textsuperscript{rd} and 4\textsuperscript{th} positions respectively. The PSO optimized PI controller has 0.9976 pu and 2.234 s in undershoot and settling time accordingly. The GA optimized PI controller recorded 0.9925 pu and 2.293 s, while the ZN optimized PI controller has 0.9843 pu and 2.411 s in undershoot and settling time respectively. The unit-step increase above rated wind speed used for testing the tuned controllers is shown in Fig. 4. Fig. 5 and 6 show the trajectories of the pitch angle and power error as a result of unit-step increase above rated wind speed for the optimized PI controllers for the four Algorithms. Both from Fig 5 and 6, the GWO tuned PI controller recorded the least overshoot in pitch angle and smallest undershoot of power error, compared to PSO, GA and ZN tuned PI controllers.
Figure 4. Unit-step increase above rated wind speed

Figure 5. Pitch angle response to step increase above rated wind speed

Figure 6. Response of SCIG Wind Turbine power error to step increase above rated wind speed

Figure 7. The response of SCIG Wind Turbine torque due to step increase above rated wind speed

Figure 8. Response of SCIG Wind Turbine output power to step increase above rated wind speed

Fig. 7 and 8 are the trajectories of SCIG Wind Turbine aerodynamic torque and power as a result of a unit-step disturbance in rated wind speed. In Fig. 7 the GWO-PI controller has the lowest overshoot and settling time in the output torque compared with other three tuning methods. Furthermore, the GWO-PI controller has the lowest undershoot and settling time in the output power as shown in Fig. 8. From the implementation results discussed, it is clear that the GWO optimal tuning of pitch control of SCIG Wind Turbine can provide better trajectories in the Wind Turbine output than PSO, GA and ZN optimal tuning of PI controllers.

5. Conclusion
The blade pitch control of SCIG Wind Turbine was tuned in MATLAB 2016b using GWO, PSO and GA. It was observed the GA was stuck into the local optima both in the best- and worst-case results. The PSO was trapped in near-optimum point in the worst case but it converged into the global optimum for the best-case result. The GWO converged in the global optimum both in the best- and worst-case results. Cumulatively, the GWO has a faster convergence than PSO. The tuned PI controllers were executed in the blade pitch control of the SCIG Wind Turbine and the small-signal stability of the Wind Turbine output was tested by applying a unit-step increase in the wind speed. The GWO tuned PI controller provided the least overshoot, undershoot and settling time in the trajectories of pitch angle, power error, aerodynamic power and torque of the Wind Turbine compared to other tuned PI controllers.
Therefore, it provided better dynamic stability of SCIG Wind Turbine compared to PSO, GA and ZN tuned. Its implementation in the Wind Turbine can reduce the stress on the pitch actuator.

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