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Optimal Tuning of PI Controllers for Doubly-Fed Induction Generator-Based Wind Energy Conversion System using Grey Wolf Optimizer

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ABSTRACT
This paper introduces modelling and simulation of Doubly-Fed Induction Generator (DFIG) of Wind Energy Conversion System (WECS). Two Pulse Width Modulation (PWM) converters have been connected back to back from the rotor terminals to the utility grid via a dc-link. Vector control system typically controlled by a set of PI controllers, which have an important effect on the performance of system dynamics. This paper presents an optimally tuned PI controllers design of a DFIG wind energy system connected to grid using Particle Swarm Optimization (PSO), and Grey Wolf Optimizer (GWO). PSO and GWO used to optimize PI controller parameters of both Grid side converter (GSC), and Rotor side converter (RSC) to improve the dynamic operation of the DFIG wind energy system under a variable speed condition.
Keywords-Doubly fed induction generator (DFIG), wind energy conversion system (WECS), Rotor side converter (RSC), Grid side converter (GSC), Particle Swarm Optimization (PSO), Grey Wolf Optimizer (GWO).

I. INTRODUCTION

Wind energy has attracted huge attention caused by several advantages. The concern about the environmental pollution and the probable energy predicament has led to increase the interest of researchers. So a great effort has been done to find pollution less and sustainable ways to generate from renewable electrical energy. Among several sources of renewable energy, wind power generation has been the important source in the power production [1]. Recently, The Doubly Induction Generator (DFIG) is widely accepted because it has the advantages of converter ratings reduction for power conversion and a high efficiency of power extraction due to the variable speed operation. In addition it is widely used in the development of distributed renewable energy sources [2],[3].

In DFIG, the generator is connected to the grid via stator, and the rotor is connected to the grid via AC/DC/AC Converter. With the advanced power electronic techniques, an AC/DC/AC Converter, which comprises of a dc link and two bidirectional converters. This converter acts as an optimal operation tracking between generator and the grid [4-7]. Field Oriented Control (FOC) is applied to both Rotor Side Converter (RSC) and Grid Side Converters (GSC) to get the desirable requirements of the control system [8-10]. Generally, FOC has been presented based on DFIG mathematical model. In order to operate in both sub-synchronous and super-synchronous speed modes it is possible to control the rotor using a controlled converters to ensure effective operation [8].

Field orientated control is used to optimize the energy conversion and keep the terminal voltage constant for variable speed. It is based on proportional, integral controllers (PI controllers) which controls the active and reactive powers that the DFIG exchanges with the electrical grid. The aim of the field-orientated control is to maximize the extracted power from the wind [7,11-14].

Recently, several modern control techniques such as variable structure control, adaptive control and intelligent control have been studied competently to control nonlinear components of power systems. However, these control techniques have few real applications possibly due to their difficult structures or the lack of certainty in their stability. Therefore, PI controllers are still the most regularly used control techniques in power systems. Because of their simple structures, and that is obvious in control of wind turbines equipped with DFIGs. Unfortunately, tuning PI controllers is wearisome and might be tough to tune the gains of PI controller properly due to the nonlinearity and the high complexity of the system [1]. However, the online tuning of these parameters are difficult due to the nonlinearity and the high complexity of the system [15]. “Differential evolution (DE) is a population-based method and generally considered as a parallel stochastic direct search optimizer. Which is very simple, precise, fast as well as robust algorithm" [16-18]. The DE solves optimization problems with multi-modal objective and non-linear functions. Lately, intelligent optimization algorithms such genetic algorithm (GA) and particle swarm optimization (PSO) have been effectively used as optimization tools in several applications. This including the online tuning of the controller parameters. "Particle Swarm Optimization (PSO) is an evolutionary computation optimization technique (a search method based on a natural system) developed by Kennedy and Eberhart" [19-22].

In this paper, a proper fitness functions is suggested and it is used to measure the performance of the proposed controllers. PSO is used to determine the optimal gains for the PI controllers to both the grid-side converter and the rotor-side converter of the DFIG. For comparison of the performance of the system dynamics while Appling PSO procedures to design gains of the controller. Results are compared with those obtained using Grey Wolf Optimizer (GWO). A complete simulation model is developed using MATLAB Simulink under variable speed conditions. Simulation results show that the proposed optimization technique is capable of finding the optimal parameters of the PI controllers. Therefore, it develops the dynamic performance of the WECS over a wide range of operating conditions.

II. WIND ENERGY CONVERSION SYSTEM

The DFIG based WECS (wind energy convertor system) basically consists of generator, wind turbine with drive train system, Rotor Side Converter (RSC), Grid Side Converter (GSC), DC-link capacitor, pitch controller, coupling transformer, and control system as shown in Figure 1.

The DFIG is a wound-rotor induction generator with the stator terminals connected directly to the grid and the rotor terminals to the mains via a partially rated variable frequency AC/DC/AC converter. It only needs to handle (25-30 %) of the total power to accomplish full control of the generator. The functional principle of this variable speed generator is the combination of DFIG and four-quadrant ac/dc/ac VFC (variable frequency converter equipped with IGBTs. The AC/DC/AC converter system is made of a RSC and a GSC connected back-to-back by a capacitor in the DC-link. The rotor current is controlled by RSC to vary the electro-magnetic torque and machine excitation. Since the power converter operates in bi-directional power mode, the DFIG can operate either in sub synchronous or in super-synchronous operational mode. The general structure of control the DFIG-based WECS having two levels of control. The highest level is the WECS optimization where the speed of the wind turbine is set in such a way that optimum wind power can be captured. This control level is mechanical system control. The lower level control being the electrical system control, i.e. torque and reactive power control. The mechanical control system is slower than the electrical control system. The power converter consists of two converters, the Rotor Side Converter (RSC) and the Grid Side Converter (GSC), which are controlled independently of each other. The RSC controls the active and reactive power by controlling the rotor current components. The GSC controls the DC link voltage and DFIG terminal voltage or power factor of the overall DFIG system by controlling amount of reactive power exchanged with the power grid. Grid side always feeds active power to the grid whereas active power is fed into or out of the rotor depending on the operating condition of the drive. In super-synchronous speed, power flows from the rotor via the converter to the grid, whereas it flows in the opposite direction in sub-synchronous speed of the drive. The wind turbine aerodynamic characteristics are used to estimate the shaft power and torque. Which is an input to the DFIG model. The three phase voltages and currents are an input to active and reactive power calculation model to calculate active and reactive power Pg and Qg output from DFIG.

Reactive power Qgis compared with Qg_ref. The error signal is fed to PI-controller to generate iqr_ref. Rotational speed is an input to the aerodynamic model to determine the torque command. The torque command is the input of the torque regulator model, which used to determine the reference value of the direct axis current of the rotor side converter (RSC), idr_ref. The reference currents of direct and quadrature axis of rotor are fed to the current regulator of RSC to determine the direct and quadrature reference values of RSC, vdr_ref, and vqr_ref respectively. Sinusoidal pulse width modulation (SPWM) model uses vdr_ref, and vqr_ref to generate a suitable switching pattern for the RSC. The grid side controller is used to control the DC-link voltage, Vdc by comparing the measured value of Vdc with Vdc_ref and the error signal is used to generate ids_ref. In addition, iqs_refcan be generated from comparing the grid reactive power Qg with Qg_ref to improve the reactive power control. The pitch angle controller compares the rotational speed with the rated speed. The error signal is fed to PI-controller and compensates this signal with another one comes from the comparison of the rated power and the measured power to determine the value of β, which is required to the wind turbine (WT) model.

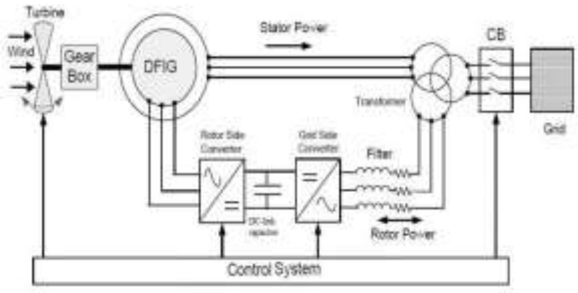

Figure 1:Components of DFIG-based WECS

III. Modeling of the PSO-PI controller

In this subsection, the PSO-PI controller is proposed. The method of tuning the parameters of PI controller by the Particle Swarm Optimization (PSO) is briefly reviewed. In the PSO algorithm, a population of particles is put into the d-dimensional search space with randomly chosen velocities and positions knowing their best values so far (pbest) and the position in the d-dimensional space. The velocity of each particle is adjusted according to its own flying experience and the other particles flying experience as the following [15, 16]:

$$v_i^{k+1} = \omega v_i^k + c_1 rand_{1i}\left(pbest_i - s_i^k\right) + c_2 rand_{2i}\left(gpest - s_i^k\right) \quad (1)$$

Where, $v_i^k$is the current velocity of particle i at iteration k,v_i^{k+1} is the updated velocity of particle i,$\omega$is the inertia weight. c_1, c_2 are two acceleration positive PSO constants,s_i^k is the current position of particle i at iteration k,$rand_{1i}$,$rand_{2i}$ are random numbers between 0 and 1, $pbest_i$ is the best position of particle i, and gbest is the global best position of the group so far.

The new position s_i^{k+1}can be modified using the present positions_i^k and updated velocityv_i^{k+1}.

$$s_i^{k+1} = s_i^k + v_i^{k+1} \quad (2)$$

The positive constants $c_1$and c_2 are usually set between 0.5 to 2 [7].The inertia weight $\omega$is set as a decreasing linear function with the iteration number from 0.9 to 0.2[3, 17].This large value of inertia weight at the beginning enhances the PSO global searching ability, while, the small inertia weight near the end of the run improves its local search ability.

The fitness function value is calculated for each particle. If the value is better than the current pbest of the particle, the pbest value is replaced by the current value. If the best value of pbest is better than the current gbest, the gbestis replaced by the best value and the particle number with the best value is stored. The operation is continued until the current iteration number reaches the predetermined maximum iteration number.

The PSO algorithm has been run for many independent trials with different settings until the solutions are very close to each other. According to the trials, the PSO parameters are summarized in Table 1.

Table 1: PSO parameters

Population size	15
Number of generations	20
Acceleration Constant c_1	0.5
Acceleration Constantc_2	1.5
Initial inertia weight w_{max}	0.9
Final inertia weight w_{min}	0.2

IV. Modeling of the GWO-PI controller

This section reviews the main steps of grey wolf optimizer (GWO) to tune the PI controller. GWO is a new population based algorithm which is introduced in [18]. GWO algorithm inspired by grey wolves. The method mimicked the social hierarchy and hunting behavior of grey wolves. For simulating the leadership hierarchy in GWO algorithm, four groups are defined: alpha, beta, delta, and omega.

The three main steps of hunting, searching for prey, encircling prey, and attacking prey, are simulated.

This algorithm requires a number of parameters to be set, which is:

- initialize alpha, beta, and delta,
- Number of search agents,
- Maximum number of iterations,
- Number of sites selected for neighborhood search (out of n visited sites) and the stopping criterion.

The main steps of grey wolf hunting are as follows:

- Tracking, chasing, and approaching the prey.
- Pursuing, encircling, and harassing the prey until it stops moving.
- Attack towards the prey.

For modeling the social hierarchy of wolves until designing GWO, the fittest solution considered as the alpha (). Accordingly, the second and third best solutions are beta ( ) and delta () respectively. The rest of the candidate solutions are considered to be omega (). The x wolves follow these three wolves. For modeling encircling behavior, some equations are considered:

$$\vec{D} = \left|\vec{C}\cdot\vec{X_p}(t) - \vec{X}(t)\right| \quad (3)$$

$$\vec{X}(t+1) = \vec{X_p}(t) + \vec{A}\cdot\vec{D} \quad (4)$$

Where t indicates the current iteration, $\vec{A}$ and $\vec{C}$are coefficient vectors,$\vec{X_p}$ is the position vector of the prey, and $\vec{X}$ indicates the position vector of a grey wolf. The vectors $\vec{A}$ and $\vec{C}$are calculated as follows:

$$\vec{A} = 2\vec{a}\cdot\vec{r}1 - \vec{a} \quad (5)$$

$$\vec{C} = 2\cdot\vec{r_2} \quad (6)$$

Where components of are linearly decreased from two to zero over the course of iterations and r1, r2 are random vectors in [0, 1].

The first three best solutions obtained so far and oblige the other search agents (including the omegas) to update their positions according to the position of the best search agents. The following formulas are proposed in this regard.

$$\vec{D_\alpha} = |\vec{C_1}\cdot\vec{X_\alpha} - \vec{X}|, \vec{D_\beta} = |\vec{C_2}\cdot\vec{X_\beta} - \vec{X}|, \vec{D_\delta} = |\vec{C_2}\cdot\vec{X_\delta} - \vec{X}| \quad (7)$$

$$\vec{X_1} = \vec{X_\alpha} + \vec{A_1}\cdot(\vec{D_\alpha}), \vec{X_2} = \vec{X_\beta} + \vec{A_2}\cdot(\vec{D_\beta}), \vec{X_3} = \vec{X_\delta} + \vec{A_3}\cdot(\vec{D_\delta}) \quad (8)$$

$$\vec{X}(t+1) = \vec{X_1} + \vec{X_2} + \vec{X_3}/_3 \quad (9)$$

It can be observed that the final position would be in a random place within a circle, which is defined by the positions of alpha, beta, and delta in the search space. In other words, alpha, beta, and delta estimate the position of the prey and other wolves updates their positions randomly around the prey [18-20].
The flow chart of the GWO algorithm is presented in Figure 2.

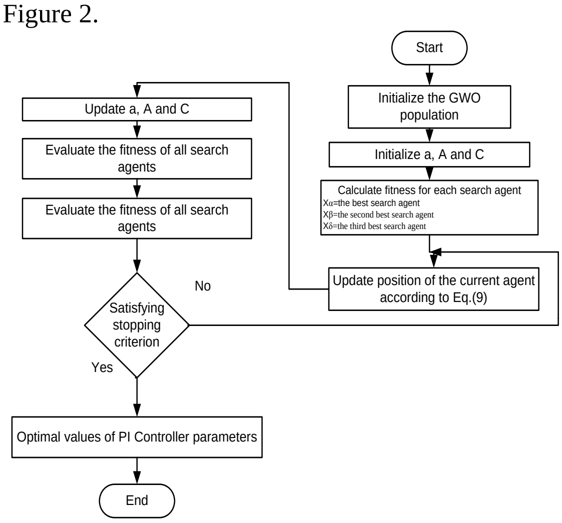

Figure 2. Flow chart of the proposed GWO algorithm.

V. PI CONTROLLER AND FITNESS FUNCTION MODELING

The tuning of PI parameters is related to the characters of the system. Thus, the properly tuned PI parameters are needed to approach the required performance. The transfer function of a PI controller is usually given by [1]:

$$G_c(s) = K_p + \frac{K_i}{s} \quad (9)$$

Where, K_p, and K_i denotes the proportional gain, and integral gain respectively.

In this paper, the strategies of PSO and GWO are implemented for the optimum search of the controller parameters. These parameters for DC link voltage of GSC, reactive power control of RSC and current regulation of both RSC and GSC of the DFIG according to the criteria of performance index.

The optimization problem is formulated in the form of objective function for timing of RSC and GSC controller parameters to get better response of the system. The objective function based on the relationship of the system performance. When analyzing a set point response, criteria used to describe how well the process responds to the change include the maximum overshoot ratio, rise time, settling time, and steady state error. The objective function with integral time weighted squared error (ITWSE) combines the time weighting with the exaggerated punishment for larger error.

$$ITWSE = \int_0^\infty [c_1(t(Vdc_e)^2) + c_2(t(I\_gsc_e)^2) + c_3(t(I\_rsc_e)^2) + c_4(t(Q_e)^2)] \quad (10)$$

Where, Vdc_e is the DC link voltage error, I_gsc_e is the GSC current regulation error, I_rsc_e is the RSC current regulation error, Q_e is the RSC reactive power error, c_1:c_4 are positive constants (weighting factors), their values are chosen according to prioritizing their importance.

There are four PI controllers. The PI controller gains as initial values then tuned by PSO, and GWO tuning method illustrated in

Table 2.

Table 2: PI Controller Parameters

PI controller	*Optimization methods*	*DC-link Voltage gains*	Rotor-side converter current regulator gains	Grid-side converter current regulator gains	*Reactive power gains*
Kp	*Initial*	8	0.6	0.83	1
	PSO	2.3178	7.1385	2.3903	9.0163
	GWO	3.1423	2.8905	3.8717	6.9023
Ki	*Initial*	400	8	5	0.05
	PSO	475.0610	2.9554	4.6289	2.5490
	GWO	103.8970	4.5244	10	5.6390

VI. SIMULATION RESULTS

In order to investigate the performance of controller stated earlier, a Wind Energy Conversion System is developed in MATLAB/SIMULINK, and simulated under various wind speed conditions. Step change in wind speed is simulated in Figure 3, the wind speed starts at 7 m/s, at 3 s, the wind speed suddenly changing at 11 m/s, at 6 s, the wind speed drops to 9 m/s to test the performance of the system.
Figure 4 presents the active power without and with optimized PI resulting of the control systems. It is observed that at wind speed equals 7 m/s, the power

reaches a certain value. When the wind speed upturns from 7m/s to 11 m/s, the active power follows the increase of the wind speed. When the wind speed falls to 9 m/s, the active power output also decreases,thatis because the active power is regulated by the controller of RSC and will track the maximum power.

Figure 5 shows the reactive power without and with optimized PI versus time. As a unity power factor is required by the system, the reactive power must kept at zero. From the curve shown in Figure 5, it can be observed that no matter what the wind speed is, the reactive power retains zero.

Figure 6 Shows the DC-Link voltage without and with optimized PI versus time, which illustrates that the GSC controller will endeavor to keep the DC-link voltage as constant as possible under several wind speed conditions.

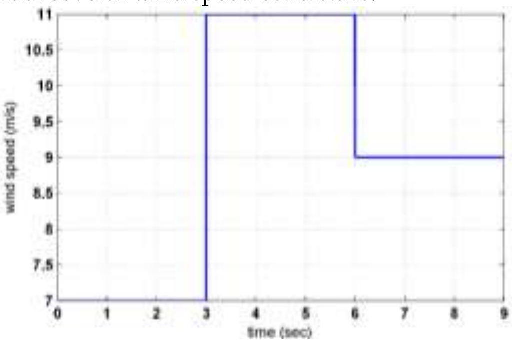

Figure 3: Wind speed

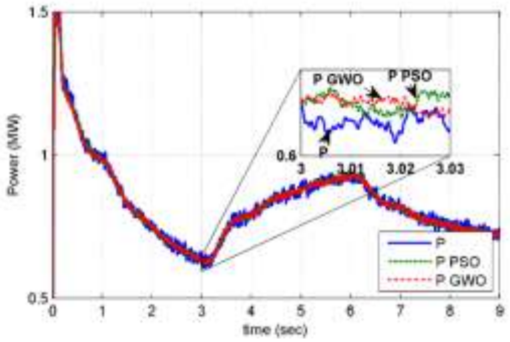

Figure 4: Active power curve

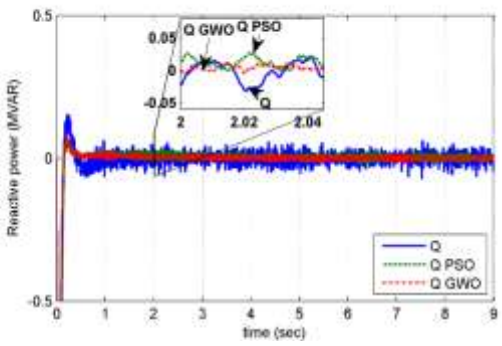

Figure 5: Reactive power curve

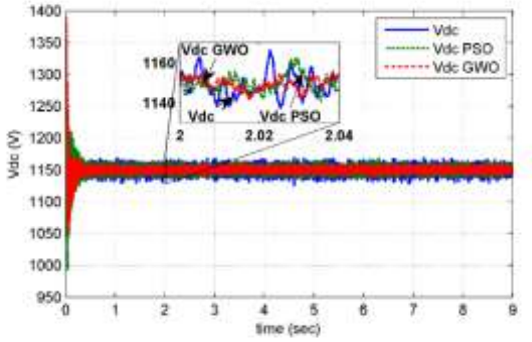

Figure 6: DC-link voltage profile

Comparison between different control techniques for the active, reactive power and the DC-link voltage of the DFIG based on GSC and RSC control under variable wind speed conditions are illustrated in Table 3.

Table 3: Comparison between different PI controllers without optimization and tuned by PSO, and GWO

Response	*Optimization methods*	*Power*	*Reactive power*	*DC-link Voltage*
Value of fitness function	*PSO*	165463.2		
	GWO	1157.714		
Rising time(sec)	*Initial*	1.49E-05	1.14E-06	4.46E-05
	PSO	0.000871	0.000196	9.42E-05
	GWO	0.00158	3.83E-07	8.25E-05
Overshoot percentage	*Initial*	124.3081	12111.4	13.2803
	PSO	118.7671	3129.662	18.5198
	GWO	127.6676	34946.28	20.6168
Settling time (sec)	*Initial*	8.3653	8.7899	8.9996
	PSO	7.9653	0.20093	8.9986
	GWO	8.1555	0.25349	8.9981
Steady state error	*Initial*	-731629	0.016141	0.002478
	PSO	-723253	-0.00169	0.00181
	GWO	-715215	0.005411	-0.00195

VII. CONCLUSION

Control of active and reactive powers is achieved by RSC through direct and quadrature axes currents. DC-link voltage is controlled via GSC through direct and quadrature axes currents, respectively. This paper presents an Optimal PI controllers design of a DFIG. A Grey Wolf Optimizer (GWO) technique is presented. The GWO-PI controller results are compared to that obtained by the Particle Swarm Optimization (PSO) to explain the merits of each one. Both PSO and GWO are used to optimize the control parameters of both the RSC and GSC to improve the transient operation of the DFIG wind energy system under a variable speed conditions. The proposed Grey Wolf Optimization algorithm (GWO) has been proven more efficient in seeking for the global optimum PI parameters with respect to the desired performance indices. Therefore, the GWO algorithm offers a new optimization tool for tuning PI controller.

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