ISSN 2229-5518

Optimum Identification of Induction Generator Parameters in Wind Energy System based on Particle Swarm Optimization

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Abstract— Electric power generation using non-traditional sources of energy such as wind energy became one of the techniques that attracted much attention worldwide. The induction generator is used in the exploitation of this energy and converts it into electrical energy because of the advantages that distinguish it from other types of generators. In this paper, an optimal identification of induction generator parameters is proposed. Particle Swarm Optimization technique (PSO) is used to identify the main parameters of the induction generator in cases of wind speed change, load change and fault cases. The simulation results obtained indicate that the particle swarm optimization is suitable for controlling and optimization the voltage, frequency and generated power. The simulation programming is implemented using MATLAB.

Index Terms— Wind Energy (WE), Induction Generator (IG), Doubly Fed Induction Generator (DFIG), Particle Swarm Optimization (PSO).

1 Introduction

Wind energy has proven to be a potential clean, free and renewable source for generation of electricity with minimal environmental impact [1].

In recent years, wind energy has become one of the most important and promising sources of renewable energy, which demands additional transmission capacity and better means of maintaining system reliability. The evolution of technology related to wind systems industry led to the development of a generation of variable speed wind turbines that present many advantages compared with the fixed speed wind turbines. These wind energy conversion systems are connected to the grid through Voltage Source Converters (VSC) to make variable speed operation possible [2, 3]. In this paper, proposed a variable speed wind generation system based on Doubly Fed Induction Generator (DFIG) with introduces the operation and control of a system and describes the effect of electrical parameters of the Double Fed Induction Generator (DFIG) for operation within power system in order to perform stability and turbine control to maximize the power generated with the lowest impact on the grid voltage and frequency during normal operation and under several disturbances, such as a transmission line earth fault. The proposed methods consider wind turbines based on induction generator and a grid-connected converter with constant or variable speed wind turbines. The proposed work is performed within the multiple technologies design tool MATLAB/Simulink.

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The performance of DFIG under different operating conditions is investigated and Artificial Intelligence (AI) controllers are proposed to enhance the performance of induction generator parameters in wind energy system during different disturbances conditions. The purpose of the control system is to manage the safe, automatic operation of the turbine, within a framework of optimizing generated power.

2 Mathematical Model of DFIG

A doubly fed induction machine is basically a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through a converter. The AC/DC/AC Converter is divided to two components: the rotor side converter (RSC) and the grid side converter (GSC) as shown in Figure (1).

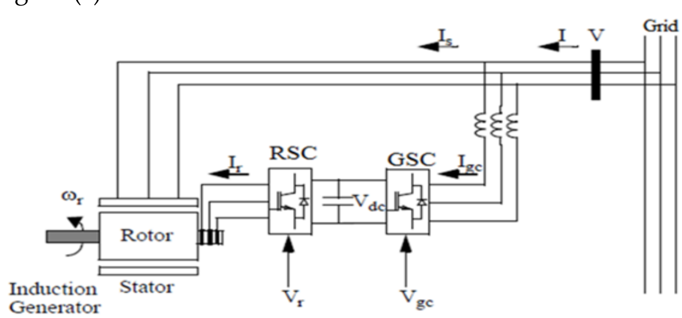

Fig. 1. Rotor Side and Grid Side Converters control system

For a doubly fed induction machine, as shown in Figures (2) and (3) the Concordia and Park transformation's application to the traditional a, b, c model allows to write a dynamic model in a d-q reference frame as follows [4, 5, 6]:

$$V_{ds} = R_s I_{ds} + \frac{d}{d_t}\psi_{ds} - \omega_s \psi_{qs} \quad (1)$$

$$V_{qs} = R_s I_{qs} + \frac{d}{d_t}\psi_{qs} + \omega_s \psi_{ds} \quad (2)$$

$$V_{dr} = R_r I_{dr} + \frac{d}{d_t}\psi_{dr} - (\omega_s - \omega_r)\psi_{qr} \quad (3)$$

$$V_{qr} = R_r I_{qr} + \frac{d}{d_t}\psi_{qr} + (\omega_s - \omega_r)\psi_{dr} \quad (4)$$

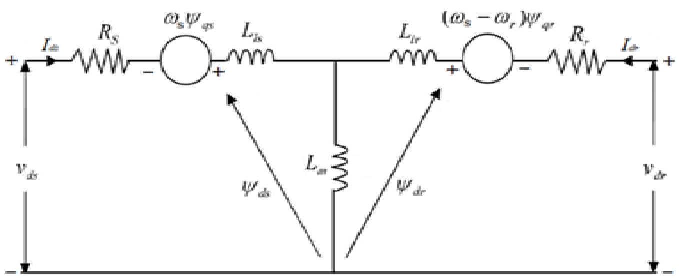

Fig. 2. Dynamic d axis circuit

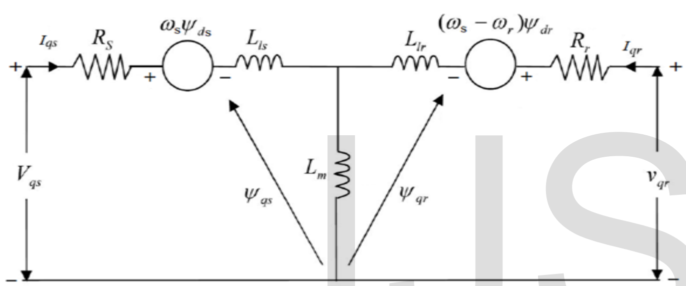

Fig. 3. Dynamic q axis circuit

Where $V_{ds}, V_{qs}, V_{dr}, V_{qr}$ are the q and d-axis stator and rotor voltages, respectively. $I_{ds}, I_{qs}, I_{dr}, I_{qr}$ are the q and d-axis stator and rotor currents, respectively. $\psi_{ds}, \psi_{qs}, \psi_{dr}, \psi_{qr}$ are the q and d-axis stator and rotor fluxes, respectively. ω_s is the angular velocity of the synchronously rotating reference frame. ω_r is rotor angular velocity, R_s and R_r are the stator and rotor resistances, respectively. The stator and rotor fluxes can be expressed:

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr} \quad (5)$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr} \quad (6)$$

$$\psi_{dr} = L_r I_{dr} + L_m I_{ds} \quad (7)$$

$$\psi_{qr} = L_r I_{qr} + L_m I_{qs} \quad (8)$$

Where L_s, L_r, and L_m are the stator, rotor, and mutual inductances, respectively, with and: being the self-inductance of stator and being the self-inductance of rotor.

The mechanical and electromagnetic torques is expressed with the following equations:

$$T_m = T_e + J\frac{d\omega}{dt} + f\omega \quad (9)$$

$$T_e = -P\frac{L_m}{L_s}(\psi_{qs} I_{dr} - \psi_{ds} I_{qr}) \quad (10)$$

The active and reactive powers at the stator are defined as:

$$P_S = v_{ds} I_{ds} + v_{qs} I_{qs} \quad (11)$$

$$Q_S = v_{qs} I_{ds} - v_{ds} I_{qs} \quad (12)$$

Also the active and reactive powers at the rotor:

$$P_r = v_{dr} I_{dr} + v_{qr} I_{qr} \quad (13)$$

$$Q_r = v_{qr} I_{dr} - v_{dr} I_{qr} \quad (14)$$

3 Wind Farm DFIG Model Description

9-MW wind farm turbine with the parameters values of DFIG used as shown in Appendix connected to a 33kV distribution system exports power to a 132-kV grid through a 30-km, 33kV feeder. A 2300V, 2-MVA plant consisting of a motor load (1.68 MW induction motor at 0.93 PF) and of a 500-kW resistive load is connected at bus B400 as shown in Figure (4).

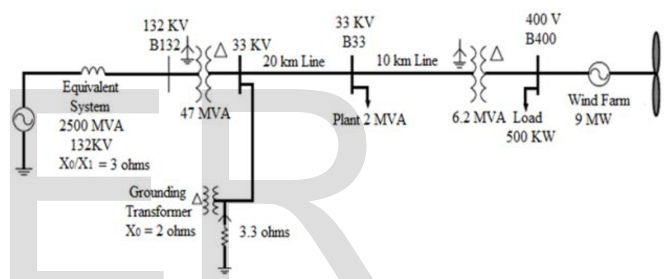

Fig. 4. Single-line diagram of the wind farm connected to a distribution system

4 PI Controller:

The PI controller has been widely used in industry due to simple implementation, low coast and the ability to apply in a wide range of application. It also improves the dynamic response of the system as well as reduces or eliminates the steady state error and the error sensibility. This is achieved by providing a proportional gain (K_p) for the error input term with an integral component correction (K_i) [7].

5 Particle Swarm Optimization (PSO)

The Particle Swarm Optimization (PSO) algorithm is a population-based stochastic optimization technique developed by Eberhart and Kennedy in 1995. It is inspired by the natural animal social behavior such as bird flocking and fish schooling. It has been found to be robust in solving continuous nonlinear optimization problems. PSO becomes a focus these days due to its simplicity and ease to implement [7].

A modified PSO was introduced in 1998 to improve the performance of the original PSO. A new parameter called inertia weight is added [8].

ISSN 2229-5518

In PSO, each single solution is a "bird" in the search space; this is referred to as a "particle". The swarm is modeled as particles in a multidimensional space, which have positions and velocities. These particles have two essential capabilities: their memory of their own best position and knowledge of the global best. Members of a swarm communicate good positions to each other and adjust their own position and velocity based on good positions [8]. The particles are updated according to the following equations [7, 8]:

$$v(k+1)_{i,j} = w.v(k)_{i,j} + c_1 r_1 \left(gbest - x(k)_{i,j}\right) + c_2 r_2 (pbest - x(k)_{i,j} \quad (15)$$

$$x(k+1)_{i,j} = x(k)_{i,j} + v(k+1)_{i,j} \quad (16)$$

Where

v_{ij} : Velocity of particle i and dimension j.
$x_{i,j}$: Position of particle i and dimension j.
c_1, c_2 : Known as acceleration constants.
w : Inertia weight factor.
r_1, r_2 : Random numbers between 0 and 1.
Pbest : Best position of a specific particle.
Gbest : Best particle of the group.

The PSO algorithm is implemented in the following iterative procedure to search for the optimal solution [7].

1) Initialize a population of particles with random positions and velocities of N dimensions in the problem space.

2) Define a fitness measure function to evaluate the performance of each particle.

3) Compare each particle's present position (xi) with its (xpbest) based on the fitness evaluation. If the current position xi is better than (xpbest), then set (xpbest = xi).

4) If (xpbest) is updated, then compare each particle's (xpbest) with the swarm best position (xgbest) based on the fitness evaluation. If (xpbest) is better than (xgbest), then set (xgbest = xpbest).

5) At iteration k, a new velocity for each particle is updated by equation (15).

6) For each particle, change its position according to the equation (16).

7) Repeat steps (2)-(6) until a criterion, usually a sufficiently good fitness or a maximum number of iterations is achieved. The final value of (xgbest) is regarded as the optimal solution of the problem.

The PSO tuning algorithm for gains can be illustrated with flow chart as shown in Figure (5).

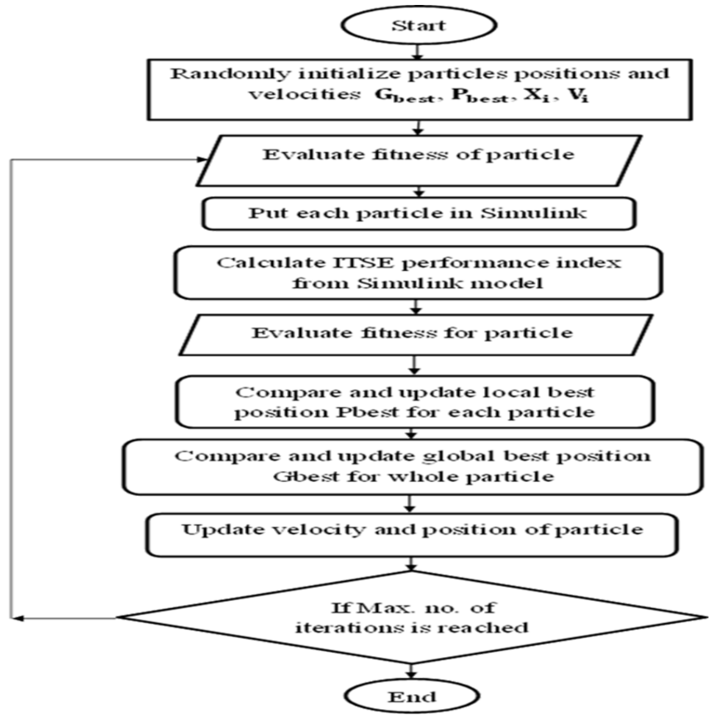

Fig. 5. Flow chart of PSO algorithm

6 Performance of PSO-PI Controller

In most intelligent optimization algorithms, there are commonly performance criteria such as: Integrated Absolute Error (IAE), the Integrated of Square Error (ISE), and Integrated of Time Weight Square Error (ITSE). That can be evaluated analytically in frequency domain. These performance criteria are including the overshoot, rise time, setting time and steady-state error. In addition, it has been indicated the optimization, and robust of the drive system [8]. The performance criterion formulas are as follows:

$$\text{Integral Square Error (ISE)} = \int_0^\infty e^2(t).\,dt \quad (17)$$

$$\text{Integral Absolute Error (IAE)} = \int_0^\infty |e(t)|.\,dt \quad (18)$$

$$\text{Integral Time Square Error (ITSE)} = \int_0^\infty t.\,e^2(t).\,dt \quad (19)$$

In this paper the (ITSE) time domain criterion is used as a Fitness Function for evaluating the PI controller performance. A set of good controller parameters K_p and K_i can yield a good step response that will result in performance criteria minimization [7, 8].

7 PI-PSO Controller:

The conventional PI controller is normally used due to its simple structure, and the ability to apply for a wide range of dynamic control system. Many traditional tuning methods were used for tuning gains of PI controller such as trial and error tuning method. In some cases, this method doesn't assure good tuning results and tends to produce a steady state error and an overshoot. In order to improve the capabilities of the traditional PI parameter tuning techniques, several intelligent techniques have been suggested to improve the PI tuning such as PSO technique. The simulation of the complete model with PI controller is shown in Figure (6).

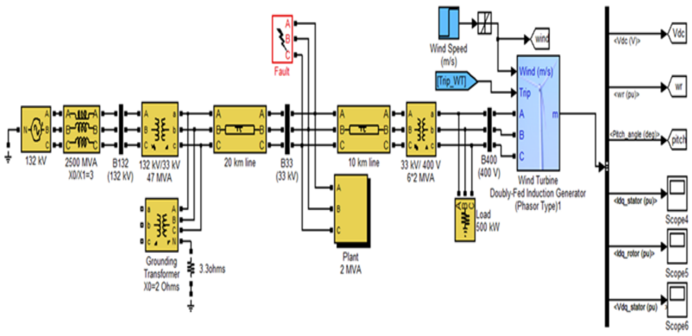

Fig. 6. Doubly fed induction generator model

The parameters of PSO algorithm that achieved better solution are illustrated in Table (1).

Table (1): Parameters of PSO algorithm for tuning gains of PI controller

Swarm size (Number of birds)	8
Number of iterations	10
Cognitive coefficient (C1)	1.2
Social coefficient (C2)	1.2
Inertia weight (w)	0.8

There are four PI controllers. The PI controller gains tuned by classical trial and error method and then result obtained with PSO tuning method illustrated in Table (2).

Table (2) PSO PI Controller Parameters

PI Controller	voltage regulator gains		Power regulator gains		Rotor-side converter current regulator gains		Grid-side converter current regulator gains	
PI Parameters	K_{p1}	K_{i1}	K_{p2}	K_{i2}	K_{p3}	K_{i3}	K_{p4}	K_{i4}
Initial design	1.25	300	1	100	0.3	8	1	100
PSO design	1.65	192.14	1.49	109.80	0.56	51.28	0.86	5.10

8 Simulation Results of DFIG with Different Controllers

A comparison between different controllers for the active power of the DFIG based on GSC and RSC control with different conditions is explained as follows:

Case 1: Turbine response to a change in wind speed:

Figure (7) show the generated active power starts increasing smoothly (together with the turbine speed) to reach its rated value of 9MW in approximately 14s with three type of control; PI controller tuned by trial and error, optimal PI-controller gains tuned by PSO method and ANN controller with gains tuned by PSO method is shown below.

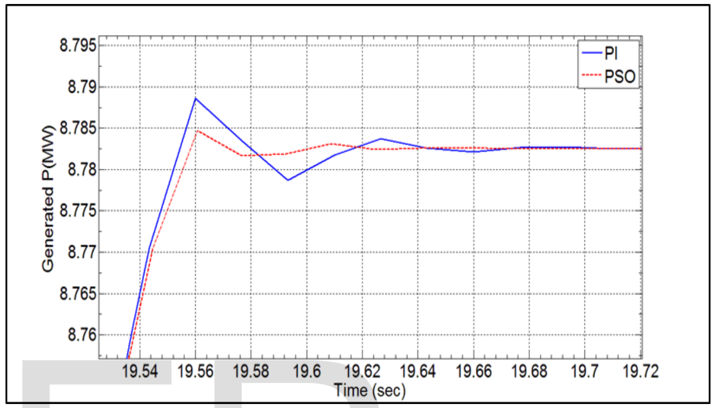

Fig. 7. Active power of wind turbine

A comparison between different controllers for the active power of the DFIG based on GSC and RSC control under change of wind conditions are illustrated in Table (3).

Table (3) DFIG responses of change in wind speed

Wind speed (m/s)	Initial value		Final value
	8		14
Rated value of Active Power in Wind Turbine (MW)			8.7825
Active Power in Wind Turbine (MW)	Over shoot	under shoot	Settling time (sec) 5%
PI controller	8.7900	8.778	19.60
PSO controller	8.7847	8.781	19.55

Case 2: Simulation of single phase-to-ground fault.

In this case, single phase-to-ground fault occurring on the 33 kV line.

The settling times and the maximum overshoots of the voltage variation curves are measured with transient response analysis as shown in Figure (8), in order to determine the performances of the proposed system. 5% band of unit step change is for determining the settling times.

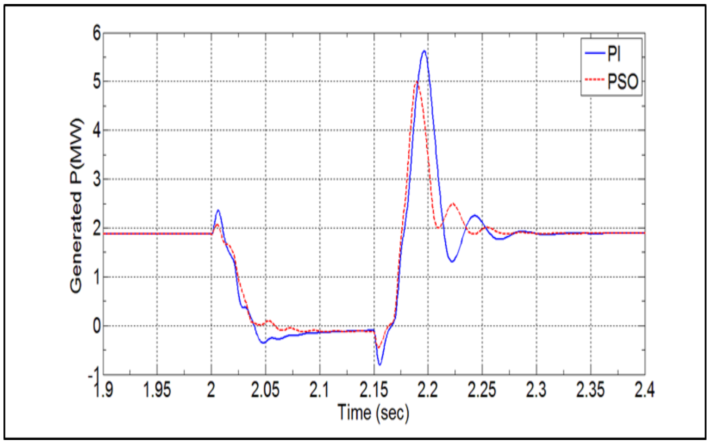

Figure (8) Active power of wind turbine at bus B400

The results of the transient response analysis are illustrated in Table (4) to comparison between different controllers for the active power of the DFIG based on GSC and RSC control.

Table (4) DFIG responses of a single phase-to-ground

Wind speed (m/s)			8	
Rated value of Active Power in Wind Turbine (MW)			1.94	
Active Power in Wind Turbine (MW)	over shoot	Percent ratio (other/ANN) *100	under shoot	Settling time (sec) 5%
PI controller	5.625	113.75%	-0.810	2.275
PSO controller	4.992	100.95%	-0.450	2.235

Case 3: Simulation of a sudden voltage drop in the 132KV system.

There are certain advantages of using PSO controller when comparing with PI controller of DFIG. There are smaller overshoots, which gives a faster response, i.e. the system retakes the regimen in lesser time; and smaller oscillatory behavior. The PSO system that estimates the control parameters of the generator showed satisfactory characteristics as was verified in the presented results. It was demonstrated that the reference signals for the grid side and rotor side converters of the DFIG can be obtained using control systems based on PSO. These can show the superiority of the proposed PSO control of DFIG with the referred advantages.

Figure (9) show the response of Double Fed Induction Generator (DFIG) for two controllers.

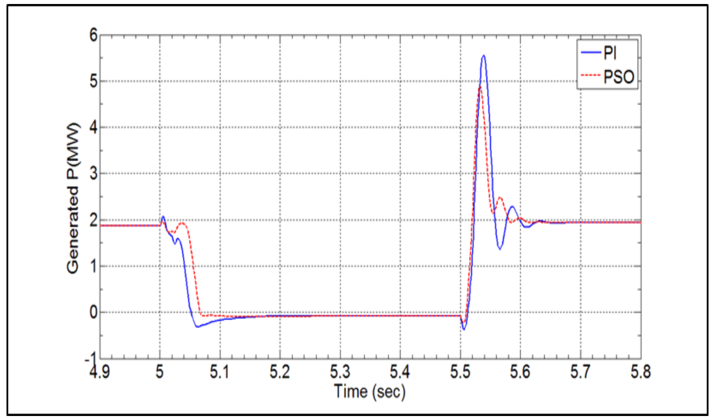

Figure (9) Active power of wind turbine at bus B400

Table (5) illustrates a comparison between different controllers for this case.

Table (5) DFIG responses of voltage drop on the 132 KV system

Wind speed (m/s)			8	
Rated value of Active Power in Wind Turbine (MW)			1.94	
Active Power in Wind Turbine (MW)	over shoot	Percent ratio (other/ANN)*100	under shoot	Settling time (sec) 5%
PI controller	5.56	115.59%	-0.382	5.617
PSO controller	4.88	101.46%	-0.226	5.604

9 Conclusion

In case of steady state, all of PI based on trial and error controllers and PSO have a good performance with steady state error.

When a fault is applied after a specified time, the PI controller with gains tuned by trial and error method shows steady state parameters error which is proportional with the applied load. In case of light load, the DFIG is not too affected, but in the case of higher load such as fault applied to the DFIG the situation is different by higher values of steady state error. The active power response has an oscillation and overshoot in addition to higher value of ripples.

In case of PI controllers with gains tuned by PSO show an improvement in performance in terms of reducing steady state error, maximum overshoot and minimum undershoot of the power response with less oscillation and the ripples is reduced. On the other hand, there is nearly zero steady state power error with smooth power performance in the PSO controller for wide speed range.

The final simulation results of the proposed controller for DFIG show the superiority of the PSO versus PI controller, which improves the time specification of the response in term of reducing steady state error, overshoot, smoother response and requires less time to reach steady state which makes this controller more robust to the variation in load and wide range of power other than the rest controllers.

The PSO controller designed for DFIG has been connected to a variable speed wind Turbine. The grid-side and rotor-side converters reference voltages are optimization PI parameters. The comparative study between the two controllers shows that PSO is very effective on the stabilization of the system. The Processing becomes simpler as computational complexity is reduced.

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Appendix A

Parameters of Doubly Fed Induction Generator.

Table (A) Parameters of Doubly Fed Induction Generator

Pairs of poles (P)	3
Rated Output Power (MW)	9MW (6*1.5)
Rated Voltage V(L-L) (V)	400
Frequency (HZ)	50
Stator winding resistance (R_s) (pu)	0.00706
Stator leakage inductance (L_s) (pu)	0.171
Rotor winding resistance (R_r) (pu)	0.005
Rotor leakage inductance (L_r) (pu)	0.156
Magnetizing inductance (L_m) (pu)	2.9
Rated wind speed at point C (m/s)	12
Power at point C (pu/mechanical power)	0.73
Cut-in speed (m/s)	4
Cut-out speed (m/s)	25
Maximum pitch angle (deg.)	45
Maximum rate of change of pitch angle (deg./s)	2
Nominal DC bus voltage (V)	1200
DC bus capacitor (F)	6*10000e-6
Inertia constant (Kgm2)	5.04