International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

December 2013 Issue 17 Volume 5 Number 4 Pages 22-27

MODELING AND CONTROL OF REACTIVE POWER OF DFIG BASED WIND TURBINE UNDER SUPER/SUB SYNCHRONOUS OPERATION USING FUZZY LOGIC

O. Rahat [1] **H. Hemati** [2] **J. Barati** [1]

1. Electrical Engineering Department, Ramhormoz Branch, Islamic Azad University, Ramhormoz, Iran
rahat_omid@yahoo.com, tj_barati62@yahoo.com
2. Electrical Engineering Department, Izeh Branch, Islamic Azad University, Izeh, Iran, hosein.hemati@yahoo.com

Abstract- Using wind energy as the most important source of clean electricity generation in many countries is increasing and many wind turbines are under construction or exploiting around the world. One of the problems, which can be observed in the wind turbine is related to the control of reactive power produced or consumed in the wind turbine. Today doubly fed induction generators due to work in both super/sub synchronous mode and other benefits have the highly application among the other types of wind generators in the wind turbines. In this paper, the reactive power control of wind turbine with induction generator, fed from both sides of the stator and rotor using fuzzy logic is presented. Type of controller used in this paper is FLPID and to optimize the controller parameters in different operation modes, the Particle Swarm Optimization (PSO) Algorithm is used. Here, capability of FLPID controller that their parameters in both super and sub-synchronous operations, optimized with PSO algorithm is investigated. The obtained results indicate that the proposed controller can effectively control the reactive power of wind turbine, also can improve transient stability. The simulation performed by MATLAB software.

Keywords: DFIG, Fuzzy Logic, PSO Algorithm, Reactive Power Control, Super Synchronous Operation, Sub Synchronous, Transient Stability, Wind Turbine.

I. INTRODUCTION

According to the limitations in fossil fuels and increasing the human needs to electricity energy, the renewable energy exploitation is rapidly growing. Among the renewable energy, wind energy, is the most accessible and cheapest energy. Therefore, the wind power plants and its technology are growing and expanding [1, 2]. Among the various types of wind power plants, wind power plants with doubly fed induction generator due to its great advantages, especially the ability to exploit in wide range of speed and in super and sub synchronous mode has wide use [3]. With increasing doubly fed induction generators and their connection to the power system, it is clear that these generators participate in the system parameters control, such as reactive power.

In this paper, for having an efficient control on reactive power of wind power plant, fuzzy logic is used and to optimize the controller parameters the PSO algorithm has been used. The main advantage of a fuzzy controller is that, it is not sensitive to change the structure of the system parameters and operation points [4]. In wind power plants due to the atmospheric conditions, power plants operating point is changing constantly and using such controller would be very beneficial. In a wind power plant, there are various controls on power plant parameters such as output active power tracking on maximum power at a certain speed, DC bus voltage, terminals voltage, reactive power and etc. thus, coordinated tuning of the reactive power controller with other controllers is essential.

Due to the operation of the doubly fed induction generator in both under and super synchronous mode, it is necessary that the coordinated tuning is performed in these both modes. In this paper, this coordinated tuning is performed using the PSO algorithm. In this paper, different parts of the power plant and the reactive power control algorithm using the fuzzy logic are presented. The parameters of the controller are coordinated in different operation modes using the PSO algorithm. Finally, the simulated results using Simulink/MATLAB are shown.

II. MODELING THE WIND POWER PLANT

The Wind Turbine and the Doubly-Fed Induction Generator (WTDFIG) are shown in Figure 1. AC/DC/AC Converts is divided into two components, the rotor side converter C_r, and the grid side converter C_g. The capacitor connected in DC side converters, acts as DC voltage source. Three-phase rotor winding is connected to C_r by the slip rings and brushes and three-phase stator winding is directly connected to the network. Taken power by wind turbine is converted into electric power by induction generator, then transmitted to the grid via the stator and rotor. The control system generates the voltage command signals V_r and V_{gc} for C_r and C_g respectively in order to control the power of the wind turbine, the DC bus voltage, and the reactive power at the grid terminals [5, 6].

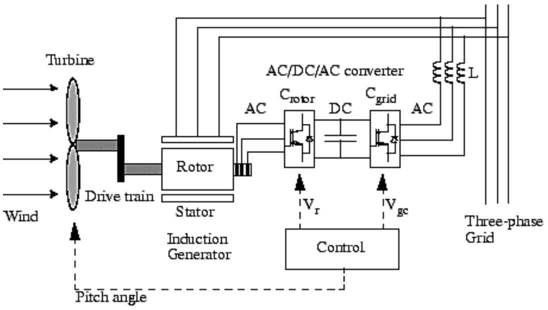

Figure 1. Wind turbine and the doubly-fed induction generator [7]

A. Turbine Model

Mechanical power produced by wind turbines according to the following equation is obtained [8].

$$P_m = \frac{1}{2} P C_P V^3 \tag{1}$$

where, V is wind speed, P is density of air, C_P is aerodynamic wind turbine power factor.

Wind turbine aerodynamic power factor depending on the tip speed ratio and blade angle is changed. Here the following equation is used to calculate C_P in simulations.

$$C_P = (0.44 - 0.0167\beta)\sin\left[\frac{\pi(\lambda-3)}{15-0.3\beta}\right] - \\ -0.00784(\lambda-3)\beta \tag{2}$$

where, β and λ are the angle of the blades and tip speed respectively. The Turbine output torque is obtained using following relation.

$$T_m(\text{pu}) = P_m(\text{pu}) / \omega_r(\text{pu}) \tag{3}$$

B. DFIG Model

The dq model of the doubly fed induction machine is shown in Figure 2.

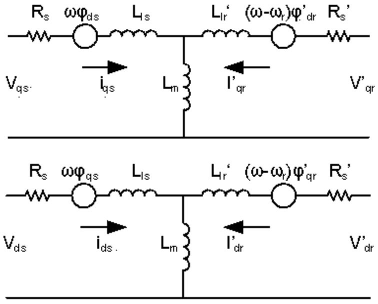

Figure 2. The dq models of doubly fed induction machine

The Equations in dq space and in synchronous field reference frame are as follows [5, 6, 9].

$$v_{ds} = R_s i_{ds} - \omega_b \varphi_{ds} + d\varphi_{qs} / dt \tag{4}$$

$$v_{qs} = R_s i_{qs} - \omega_b \varphi_{ds} + d\varphi_{qs} / dt \tag{5}$$

$$v_{dr} = R_r i_{dr} - (\omega_b - \omega_r)\varphi_{dr} + d\varphi_{qr} / dt \tag{6}$$

$$v_{qr} = R_r i_{qr} + (\omega_b - \omega_r)\varphi_{dr} + d\varphi_{qr} / dt \tag{7}$$

$$\begin{cases} \psi_{qs} = L_{ls} i_{qs} + \psi_{mq} \\ \psi_{ds} = L_{ls} i_{ds} + \psi_{md} \\ \psi_{mq} = L_{mq}(i_{qs} + i_{qr}) \\ \psi_{md} = L_{md}(i_{ds} + i_{dr}) \end{cases} \tag{8}$$

$$\begin{cases} \psi_{qr} = L_{lr} i_{qr} + \psi_{md} \\ \psi_{dr} = L_{lr} i_{dr} + \psi_{md} \end{cases} \tag{9}$$

$$T_e = 1.5 p(\varphi_{ds} i_{qs} - \varphi_{qs} i_{ds}) \tag{10}$$

$$\frac{d}{dt}\omega_m = \frac{1}{2H}(T_e - F\omega_m - T_m) \tag{11}$$

where, v_{ds}, i_{ds}, v_{qs} and i_{qs} are the voltages and currents of d and q axes of stator, v_{dr}, i_{dr}, v_{qr} and i_{qr} are the voltages and currents of d and q axes of rotor, φ_{ds}, φ_{qs}, φ_{dr} and φ_{qr} are flow of d and q axes of the stator and rotor, R_s and R_r are resistances stator and rotor, L_{md} and L_{mq} are the mutual inductance of d and q axes between stator and rotor, L_{ls} and L_{lr} are the stator and rotor leakage inductance.

C. Converters Model

AC/DC/AC Converts is divided into two components as the rotor side converter C_r and the grid side converter C_g. The C_r and C_g are the voltage source converters. The capacitor connected DC side converters acts as DC voltage source. The C_g is used to produce or attract P_g, to regulate DC bus voltage. Rotor side converter is used to control wind turbine power output and reactive power measured at the terminals. The rotor side converter works at slip frequency of machine and the grid side converter works at grid frequency, and both have ability to attract or inject the power. Thus, rotor power is defined as:

$$p_r = p_{dc} + p_g \tag{12}$$

where, p_r, p_{dc} and p_g are the active powers of rotor side converter, DC capacitor, and grid side converter. Which are defined as follows:

$$p_r = v_{dr} i_{dr} + v_{qr} i_{qr} \tag{13}$$

$$p_g = v_{dg} i_{dg} + v_{qg} i_{qg} \tag{14}$$

$$p_{dc} = v_{dc} i_{dc} = c v_{dc} \frac{dv_{dc}}{dt} \tag{15}$$

where, v_{dg}, i_{dg}, v_{qg} and i_{qg} are the voltages and currents of d and q axes of grid side converter v_{dr}, i_{dr}, v_{qr}, and i_{qr} are the voltages and currents of d and q axes of the rotor side converter, v_{dc} and i_{dc} are the voltage and current and C is the capacity of DC capacitor.

Vector control structure of a DFIG based wind turbine is given in Figure 3. In [10], vector control structure of a DFIG based wind turbine was reported using PI regulators for the active and reactive power control. Here, the objective is reactive power control using fuzzy logic instead of PI controller.

III. PROPOSED CONTROL MODEL

The most important advantage of the fuzzy controller is that it is not sensitive to the change of the system parameters and operational points. Therefore, it is a good candidate in the wind turbine controls. Determining membership functions and control rules of the fuzzy control design is based on the trial and error and designer experiences. However, for useful performance of the controller and appropriate output, in this paper, PSO algorithm is used to optimize the controller gains. Figure 4 shows FLPID Controller.

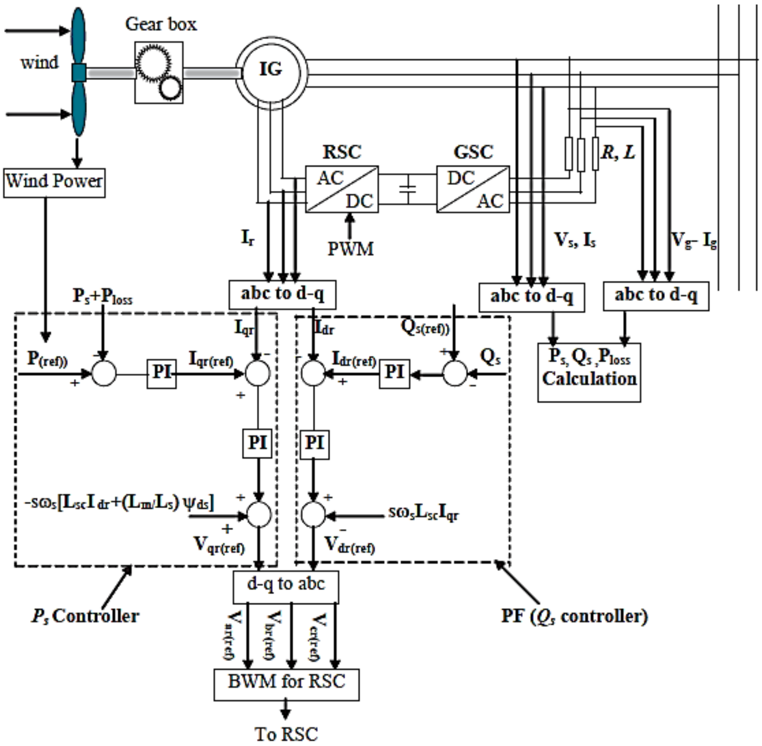

Figure 3. Vector control structure of a DFIG based wind turbine [10]

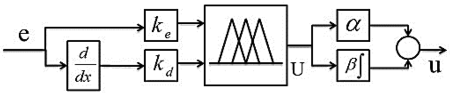

Figure 4. FLPID controller structure

As can be seen, the controller is composed of one fuzzy part and a PI part. Control signal u is expressed as follows:

$$u = \alpha U + \beta \int U dt \tag{16}$$

where, U is the fuzzy logic output and the relationship between input-output variables of fuzzy logic controller is as follows [4]:

$$U = A + PE + DE^* \tag{17}$$

where, $E = k_e e$ and $E^* = k_d e^*$ Therefore, the controller output will be as follows:

$$\begin{aligned} u &= \alpha A + \beta At + \alpha k_e P_e + \beta k_d D_e + \\ &+ \beta k_e P \int e dt + \alpha k_d D_{e^*} \end{aligned} \tag{18}$$

Because of the error derivative in the controller input, this controller would be same a PID controller, that PID gains are as, $\alpha k_e P + \beta k_d D$ is proportional gain, $\beta k_e P$ is Integral gain, and $\alpha k_d D$ is derivative gain. In the controller design, determination of the gains (k_d, k_e, β, α), membership functions and control rules are very important. Generally membership functions and control rules is determined by the trial and error method and designers experience.

As shown in Figure 5, fuzzy controller consists of two membership functions for two inputs and one membership function for output. Each membership function has five triangular sections and two trapezoid sections. Based on two-input and one-output membership functions, control rules are determined. These are shown in Table 1. To obtain optimal controller gain, the PSO algorithm is used.

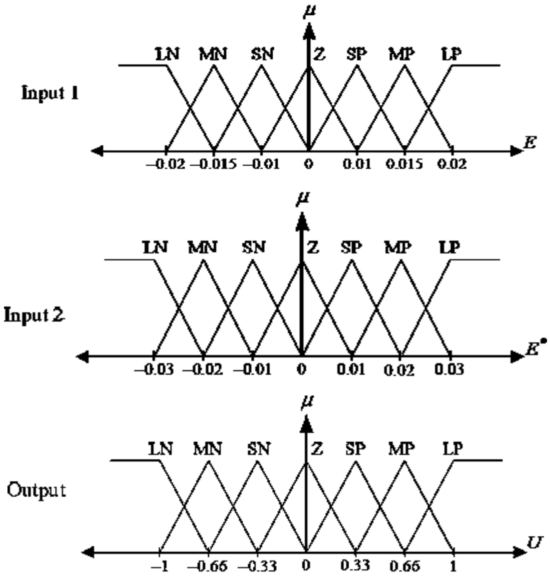

Figure 5. Membership functions of controller

Table 1. Control rules of controller

E	*E**						
	LN	*MN*	*SN*	*Z*	*SP*	*MP*	*LP*
LN	*LP*	*LP*	*LP*	*MP*	*MP*	*SP*	*Z*
MN	*LP*	*MP*	*MP*	*MP*	*SP*	*Z*	*SN*
SN	*LP*	*MP*	*SP*	*SP*	*Z*	*SN*	*MN*
Z	*MP*	*MP*	*SP*	*Z*	*SN*	*MN*	*MN*
SP	*MP*	*SP*	*Z*	*SN*	*SN*	*MN*	*LN*
MP	*SP*	*Z*	*SN*	*MN*	*MN*	*MN*	*LN*
LP	*Z*	*SN*	*MN*	*MN*	*LN*	*LN*	*LN*

IV. PSO ALGURITHM AND OPTIMIZATION

Compared to other optimization methods, many advantages of the PSO algorithm have caused it as a useful engineering tool [11]. In PSO algorithm, initial population consists of n particles that are selected randomly. Each particle in initial population using objective function j is evaluated. Every particle is real value of a k-dimensional vector, k is the number of parameters that we want to optimize them. In this paper $k=4$. Therefore, each optimized parameter is representative of a dimension of the problem space.

Corresponding to each particle, a random velocity is also selected in the initial population. The objective function is calculated at the particles location. Then each particle chooses the movement direction according to its current location and their best previous location and the location of the best particles in the population. All particles choose their direction to move and after their movement, one step of the algorithm is finished. These steps are repeated several times until desired response is achieved. In this method, current position of each particle in problem space by a velocity vector is changed and according following relation is placed in a new position [11].

$$x_{i,k}(t) = v_{i,k} + x_{i,k}(t-1) \tag{19}$$

In each step, velocity vectors are updated based on the places having the best optimized record value for the objective function. Velocity of particle i with dimension k is updated according to following equation [11].

$$v_{i,k} = \begin{bmatrix} w.v_{i,k}(t-1) + c_1 r_1 (x^{*}_{i,k}(t-1) - x_{i,k}(t-1) \\ +c_2 r_2 (x^{**}_{i,k}(t-1) - x_{i,k}(t-1) \end{bmatrix} \tag{20}$$

where, w is a control parameter that is used for controlling the impact of previous velocity on the current velocity. For this coefficient in the basic PSO algorithms, a fixed value and near to one is proposed. The r_2 and r_1 are random numbers with uniform distribution between [0, 1], $x_i^{**}(t)$ is the best position among all the individual best position $x^{*}(t)$, c_1, c_2 are positive constants, in an optimization problem with objective function J and i particle's best positions $x^{*}(t)$ are determined as [11]:

$$j(x_i^{*}(t)) \le j(x_i(\tau)) \quad , \quad \tau \le t \tag{21}$$

$$j(x_i^{**}(t)) \le j(x_i^{*}(t)) \quad , \quad i = 1,2,3,....,n \tag{22}$$

Therefore, the location of every particle in such a population based on the social behavior will change. To optimize the controller parameters, following objective function is selected to obtain the best performance in the transient mode.

$$j = \int_{t=0}^{t=t_{sim}} \left(t\Delta Q\right)^2 dt \tag{23}$$

where, ΔQ is the reactive power changes and t_{sim} is the simulation time. In this relationship, j represent the settling time of controller. Optimization is done in such a way that the j is minimized, such that

$$\begin{cases} \alpha^{\min} \le \alpha \le \alpha^{\max} \\ \beta^{\min} \le \beta \le \beta^{\max} \\ {k_e}^{\min} \le k_e \le {k_e}^{\max} \\ {k_d}^{\min} \le k_d \le {k_d}^{\max} \end{cases} \tag{24}$$

The PSO technique is used to find optimal values of the controller parameters to optimize the above problem. A simple and good description of the PSO algorithm is given in [11]. Optimal values obtained using this method is given in Table 2.

Table 2. Optimal values of controller in sub, normal and super synchronous speed

Operation mode	Parameter			
	α	β	k_e	k_d
6 m/s wind sub synchronous	0.092	0.058	0.351	0.213
7 m/s wind normal operation	0.273	0.134	0.753	0.091
10 m/s wind super synchronous	0.532	0.433	0.634	0.121

V. SIMULATION RESULTS

Test system includes a DFIG based wind turbine with 2 MW power and 690 V output voltages. It is connected to the infinite bus with 20 kV voltage level and 60 Hz frequency via a transformer and a transmission line.

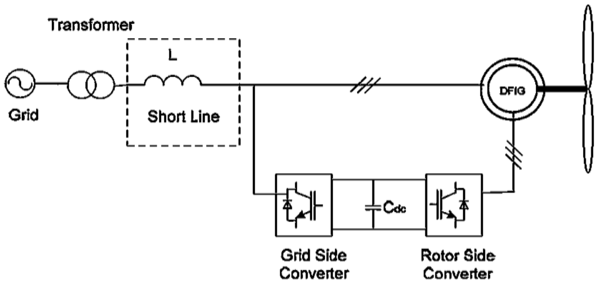

Figure 6. Test system

To check the efficiency of the designed reactive power controller, two different tests perform on a test system using SIMULINK/MATLAB software as follows:

A. Steady State in Generator Normal Operation

In this study, wind speed regarding generator normal operation is considered 7 m/s. The reference power factor is shown in Figure 7 and the corresponding reference reactive power in Figure 8. The reactive power response of the controller is shown in Figure 8 as well. It is seen that the controller follows the reference value very well.

B. Transient State

For investigation of the designed reactive power controller in transient state, two cases is considered as follows B_1. Controller response to changes in wind speed and thus the various modes of the generator operations for the simulation, the controller parameters are set in sub-synchronous mode. Wind speed is considered as Figure 9 and machine works in different modes. To achieve unit power plant power factor, Q_{ref} is considered zero. Control response is shown in Figure 10.

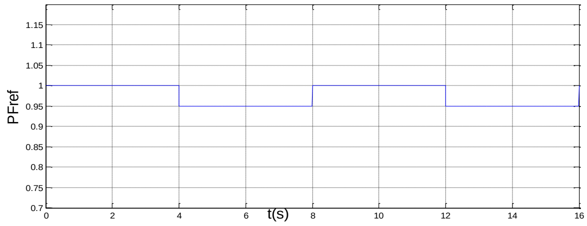

Figure 7. Power factor reference of wind turbine

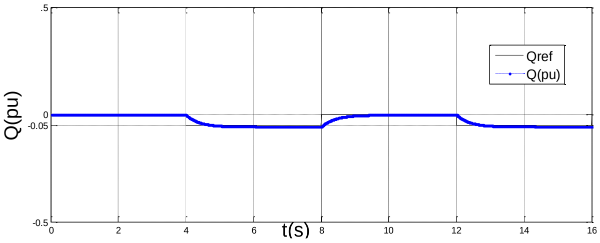

Figure 8. Reactive power control in steady state operation

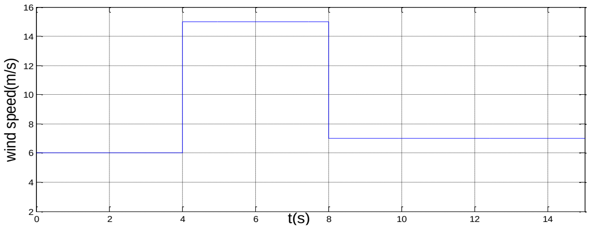

Figure 9. Wind speed changes

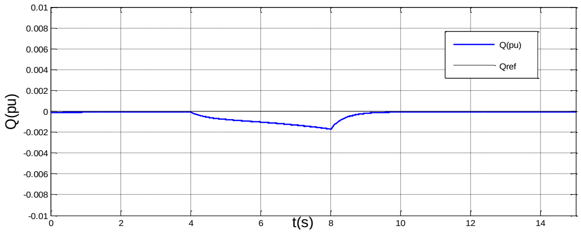

Figure 10. Reactive power control response in transient state operation due to wind speed changes

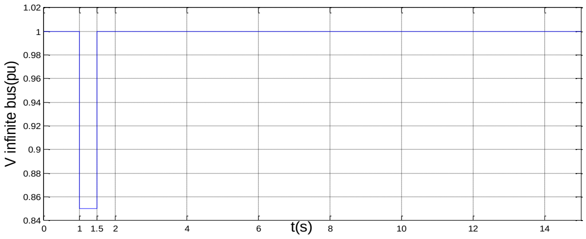

Figure 11. Voltage sag in infinite bus

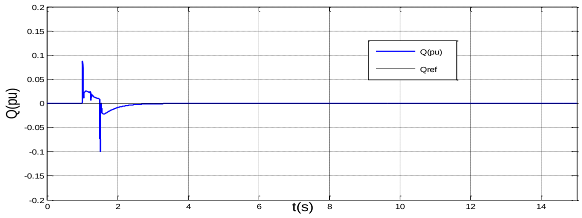

Figure 12. Controller response to 0.15 pu voltage sag in infinite bus at t =1 sec

It is observed that when the tuning of the controllers is done at sub synchronous speed, the system is stable for all modes of operations. The B_2 controller responses to voltage sag in infinite bus. Here we see the controller response to voltage sag in infinite bus. In this simulation, the controller parameter are set in synchronous mode, Q_{ref} = 0 and V_w = 7 m/s. A 0.15 pu voltage drop in the infinite bus lasting for 0.5 sec. is considered, as shown in Figure 11. It is occurred at t =1 sec. Simulation results are shown in Figure 12. The controller response also in this case is satisfied.

VI. CONCLUSIONS

This paper presents the fuzzy reactive power controller for the DFIG system. The purposed controller gives good results in damping the oscillations and improves the system stability of the grid-connected DFIG system. The controller also gives a good result in both steady state and transient state. The tuning of the controllers parameters with PSO algorithm is emphasized to ensure the stable operation under variable wind speed. The super synchronous, normal, and sub synchronous mode of operation of DFIG based wind turbine was investigated. It is observed that when the tuning of the controllers is done at sub synchronous speed, the system is stable for all modes of operations.

ACKNOWLEDGEMENTS

Funding support of this research was provided by the Ramhormoz Branch, Islamic Azad University, Ramhormoz, Khuzestan, Iran. Moreover, this paper was derived from a research project named "Modeling and Control of Reactive Power of DFIG based Wind Turbine under Super/Sub Synchronous Operation Using Combination Fuzzy Logic and PSO Algorithm".

REFERENCES

[1] J. Slootweg, H. Polinder, "Dynamic Modelling of A Wind Turbine with Doubly-Fed Induction Generator", IEEE Power Engineering Society Summer Meeting, Vancouver, BC, Canada, Vol. 1, pp. 644-649, July 2001.

[2] A. Tapia, G. Tapia, J.X. Ostolaza, "Modeling and Control of a Wind Turbine Driven Doubly-Fed Induction Generator", IEEE Transactions on Energy Conversion, Vol. 18, No. 2, pp. 194-204, June 2003.

[3] S. Muller, M. Deicke, R.W. De Doncker, "Doubly-Fed Induction Generator Systems for Wind Turbines", IEEE Industry Applications Magazine, Vol. 8, Issue 3, pp. 26-33, June 2002.

[4] Z.Q. Wu, M. Mizumoto, "PID Type Fuzzy Controller and Parameter Adaptive Method", Fuzzy Set and System, Vol. 78, No. 1, pp. 23-35, February 1996.

[5] V. Akhmatov, "Variable-Speed Wind Turbines with Doubly-Fed Induction Generators", Wind Engineering, Vol. 26, No. 2, pp. 85-108, March 2002.

[6] R. Pena, J.C. Clare, G.M. Asher, "Doubly-Fed Induction Generator Using Back-to-Back PWM Converters and its Application to Variable-Speed Wind-Energy Generation", IEEE, Electrical Power Applications, Vol. 143, No. 3, pp. 231-241, May 1996.

[7] M. Mohammadi, N. Javidtash, M. Parhoodeh, "Stability Enhancement of DFIG Wind Turbines by Parameters Tuning of Shunt Connected Facts Devices Using ITAE index", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 14, Vol. 5, No. 1, pp. 82-88, March 2013.
[8] Gh. Ahrabian, A. Roshan-Milani, A. Lafzi, "Wind Farm Transient Behavior Optimizing by Capacitor Banks", International Journal on Technical and Physical Problems of Engineering (IJTPE), Issue 1, Vol. 1, No. 1, pp. 65-68, December 2009.
[9] N.W. Miller, J.J. Sanchez-Gasca, W.W. Price, R.W. Delmerico, "Dynamic Modeling of GE 1.5 and 3.6 MW Wind Turbine Generators for Stability Simulations", GE Power Systems Energy Consulting, IEEE WTG Modeling Panel, Vol. 143, pp. 1977- 983, July 2003.
[10] X. Yunqi, "A Novel Optimum Power Fuzzy Control Strategy for Doubly-Fed Wind Turbine", The 8th International Conference on Control and Automation, pp. 165-170, Xiamen, China, June 2010.
[11] M.A. Abido, "Optimal Design of Power System Stabilizers Using Particle Swarm Optimization", IEEE Transactions on Energy Conversion, Issue 3, Vol. 17, No. 3, pp. 406-413, September 2002.

BIOGRAPHIES

Omid Rahat was born in Behbahan, Iran, in 1986. He received the B.Sc. and M.Sc. degrees in Power Engineering from Shahid Chamran University, Ahwaz, Iran in 2009 and 2011, respectively. He is currently with Ramhormoz Branch, Islamic Azad University, Ramhormoz, Iran as a Lecturer. His areas of research include power system dynamic stability and control and wind turbines.

Hosein Hemati was born in Izeh, Iran, in 1985. He received the B.Sc. and M.Sc. degrees in Power Engineering from Shahid Chamran University, Ahwaz, Iran in 2005 and 2010, respectively. He is currently with Izeh Branch, Islamic Azad University, Izeh, Iran as a Lecturer. His areas of research include power system dynamic stability and control.

Jamshid Barati was born in Baghmalek, Iran, in 1984. He received the B.Sc. and M.Sc. degrees in Power Engineering from Shahid Chamran University, Ahwaz, Iran in 2006 and 2009, respectively. He is currently with Ramhormoz Branch, Islamic Azad University, Ramhormoz, Iran as a Lecturer. His areas of research include power system dynamic stability and control and FACTS devices.