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Active and Reactive Power Control of a DFIG Using a Combination of VSC with PSO

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Abstract: Nowadays, application of renewable energies has taken a rapid trend. Wind energy is among those mostly used for this purpose. Doubly Fed Induction Generators (DFIG) are widely used in wind power plants due to several advantages such as partial rating converter, capability of decoupled active and reactive power control, etc. Application of a suitable control strategy is of great importance in wind power plants. In this paper, the parameters of a hybrid controller are calculated using Particle Swarm Optimization (PSO) subjected to satisfying the required criteria in output active and reactive powers of a DFIG. In the proposed system Direct Power Controller (DPC), Variable Structure Controller (VSC) and Space Vector Modulation (SVM) have been applied to the converters. Simulation results show the validity of the proposed control approach.

Key words: Active power · DFIG · PSO · Reactive Power · SVM · VSC

INTRODUCTION

Wind energy has attracted great attention due to several advantages such as low pollution, being relatively endless and being free. This has been the motivation for developing new methods for its production, control and optimization. It is predicted that the total annual capacity of it will be increased by a factor of 25% and the operation expenses will be decreased about 20 to 40% [1].

Wind turbines can be divided into two categories, nominated as fixed speed and variable speed turbines. The generator is connected directly to the grid in fixed speed turbines while there is a power electronic device in variable speed ones. Variable speed turbines have several advantages such as lower mechanical stress and audible noise, lower power fluctuations and the ease of active and reactive power control. Moreover, using these turbines results in increasing the energy efficiency [2].

Recently, the overall aim of most of the wind energy conversion systems (WECS) has been to provide a constant frequency output voltage from a VSC. This has given rise to the term Variable Speed Constant Frequency (VSCF). ADFIG can supply power at constant voltage and frequency while its rotor speed varies. This provides more flexibility in power conversion and also better stability in

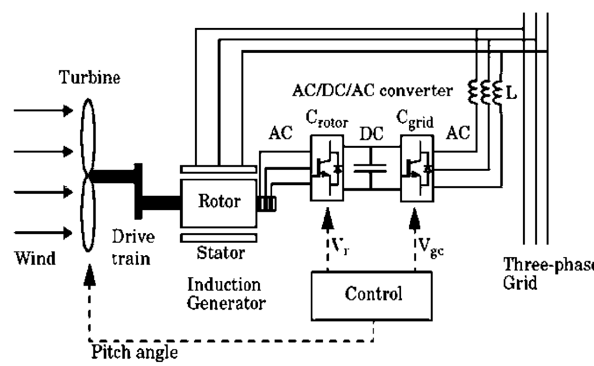

Fig. 1: Wind turbine and DFIG system [2]

frequency and voltage control in the power systems to which such generators are connected. A DFIG consists of a wound rotor induction generator (WRIG) with the stator windings directly connected to the three-phase grid and the rotor windings connected to a back-to-back partial scale (20-30% rating) power converter as shown in Fig. 1 [2].

Such an arrangement provides flexibility of operation in sub-synchronous and super-synchronous speeds both in generating and motoring modes. The power converter needs only be rated for a fraction of the total output power, the fraction depending on the allowable sub- and

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super-synchronous speed range. This results in lower converter cost and reduced power loss [3].

The magnitude and direction of rotor power should be controlled in order to have constant voltage at constant frequency. Various schemes have been proposed for the control of DFIGs which can be generally put into two categories:

- Schemes that either neglect the nonlinear nature of the equations of the machine or try to take it into account by simple feed forward compensation [4-13].
- Schemes incorporating nonlinear control methods such as input-output linearization, back-stepping, sliding mode control, etc [14-21].

It is rational to expect the second schemes to have better performance in terms of steady state error, decoupling between quantities such as stator active-reactive power and the speed of tracking power commands. Therefore, a nonlinear control method has been chosen in this paper to take advantage of the mentioned properties.

In [22], a control method has been applied using a rotating reference frame fixed on the gap flux of the generator and can control active and reactive powers independently and stably. The characteristics of the control system have been proved by experiment. Reference [23] has applied a vector control method to DFIG. This enables the decoupling between active and reactive powers as well as between torque and power factor. An optimal control strategy for the two converters is developed. This strategy aims to minimize the electrical losses which results in optimizing the system overall efficiency. This scheme is based on the splitting of the reactive power flow in the system and allows having both leading and lagging power factors. In [24], two different control schemes are studied to achieve a decoupled control of the active and the reactive powers. First of all, a classical PI controller designed by means of the pole placement technique is investigated. Secondly, a predictive-integral controller is realized. The objective of both control schemes has been set to obtain a deadbeat system. The design of these control systems is developed in discrete time and a comparison of both methods is carried out. In [25], a DPC strategy has been used as an alternative to the vector control method. This method was first used in three-phase PWM rectifiers [26], where the converter switching states were selected from an optimal switching table based on the instantaneous errors between the reference and estimated values of active and reactive power and the angular position of the estimated converter terminal voltage vector. In [25], the required rotor control voltage, which eliminates active and reactive power errors within each fixed time period is directly calculated based on stator flux, rotor position and active and reactive powers and their corresponding errors. No extra power or current control loops are required, simplifying the system design and improving transient performance. Constant converter switching frequency is achieved which eases the design of the power converter as well as the ac harmonic filter.

As the original DPC method results in active power, reactive power and current pulsations in steady state operation, the VSC method is presented in [27], using the principles of an active and reactive power controller known as modified DPC where VSC and SVM are combined to ensure high-performance operation.

Recently, AI and soft computing methods such as fuzzy logic and intelligent optimization algorithms have been used in DFIG wind systems. As tuning the PI controllers in rotor side converters of the DFIG control system is a tedious work and it is difficult to tune the PI gains optimally, an approach to use the PSO algorithm has been proposed in [28] to design the optimal PI controllers for the rotor-side converter of the DFIG. A new time-domain fitness function is defined to measure the performance of the controllers. Fuzzy controllers have also been used for control of DFIG [2, 29].

In this paper, a combination of novel optimization techniques with VSCs is used to extend the other works in control of DFIG systems. It has been tried to enhance the performance of the system using novel methods.

Wind Turbine Characteristics: Based on the wind turbine aerodynamics, the turbine catches only a part of the kinetic energy contained in the wind. The power extracted from a wind turbine is a function of the wind power available, the power curve of the machine and its ability to react to wind variations. The power and torque extracted from the wind can be expressed as: [2]

$$P_{\omega} = \frac{1}{2}\rho C_P(\lambda,\beta)AV_{\omega}^3 \tag{1}$$

$$T_{\omega} = \frac{P_{\omega}}{\omega_r} = \frac{1}{2}\rho C_T(\lambda,\beta)r_m AV_{\omega}^2 \tag{2}$$

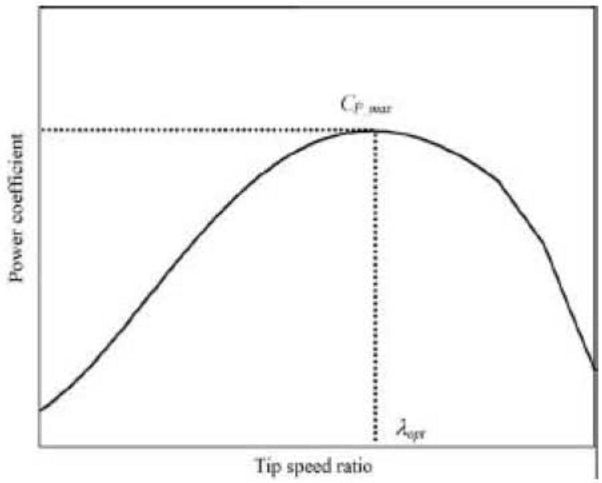

Fig. 2: Power coefficient vs. tip speed ratio [2].

where P_ω is the rotor mechanical power (W), T_ω the turbine torque (N.m), V_ω the wind speed at the center of the rotor (m/s), $A = \pi r_m^2$ the rotor swept area (m^2), ρ the air density (kg/m^3), $\omega_r = \frac{\lambda V_\omega}{r_m}$ the rotor angular velocity (rad/s), r_m the turbine radius (m), C_p the rotor power coefficient, the percentage of the kinetic energy of the incident air mass that is converted to mechanical energy by the rotor (maximum value Betz's limit 59.3%), C_T the torque coefficient, C_P and C_T are non-linear functions with respect to the tip speed ratio and the pitch angle related by the following equation: $C_P(\lambda,\beta) = \lambda C_T(\lambda,\beta)$, β is the pitch angle of rotor blades (degrees). and $\lambda = \frac{\omega_r r_m}{V_\omega}$ is the tip speed ratio, defined as the ratio between blade tip speed and wind speed upstream the rotor. An example of power coefficient C_P versus tip speed ratio is shown in Fig. 2: the maximum power coefficient $C_{P,max}$ corresponds to the optimal tip speed ratio λ_{opt}. Clearly, the turbine speed should be changed with wind speed so that optimum tip speed ratio is maintained. This is called Maximum Power Point Tracking (MPPT).

As an example, the relation of C_P can be considered as following: [29]

$$\begin{cases} C_p(\lambda,\beta) = 0.22(\frac{116}{\lambda} - 0.4\beta - 5)e^{\frac{-12.5}{\lambda}} \\ \lambda = \dfrac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}} \end{cases} \quad (3)$$

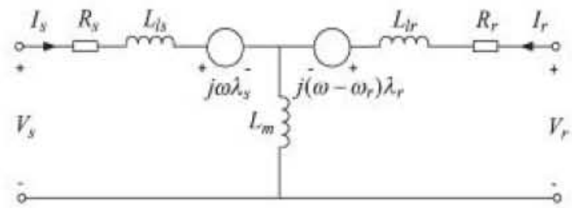

Fig. 3: Equivalent circuit of DFIG in the arbitrary reference frame [8]

Dynamic Equations of DFIG: The d-q model of a DFIG in an arbitrary reference frame is expressed as follows: [27]

$$V_s = R_s I_s + \frac{d\lambda_s}{dt} + j\omega\lambda_s \quad (4)$$

$$V_r = R_r I_r + \frac{d\lambda_r}{dt} + j(\omega - \omega_r)\lambda_r \quad (5)$$

$$\begin{aligned} \lambda_s &= \lambda_{ds} + j\lambda_{qs} \\ \lambda_r &= \lambda_{dr} + j\lambda_{qr} \\ \lambda_{ds} &= L_s I_{ds} + L_m I_{dr} \\ \lambda_{qs} &= L_s I_{qs} + L_m I_{qr} \\ \lambda_{dr} &= L_r I_{dr} + L_m I_{ds} \\ \lambda_{qr} &= L_r I_{qr} + L_m I_{qs} \\ L_s &= L_{ls} + L_m \\ L_r &= L_{lr} + L_m \end{aligned} \quad (6)$$

where I_{ds}, I_{qs}, I_{dr}, I_{qr} and λ_{ds}, λ_{qs}, λ_{dr}, λ_{qr} are the currents and flux linkages of the stator and rotor in the d-axis and q-axis, R_s and R_r are the resistances of the stator and rotor windings and ω_r is the rotor speed. An equivalent circuit is set up by means of the voltage and flux equations in the arbitrary reference frame, as shown in Fig. 3.

The Particle Swarm Optimization: PSO is a population based stochastic optimization technique developed by Eberhart and Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling [30]. It has shown to have suitable performance in various optimization problems [31, 32].

PSO is similar to a GA [2] in that the system is initialized with a population of random solutions.

PSO is unlike GA, however, in that each potential solution is also assigned a randomized velocity and the potential solutions, called particles, are then "flown" through hyperspace. Each particle keeps track of its coordinates in hyperspace which are associated with the best solution (fitness) it has achieved so far

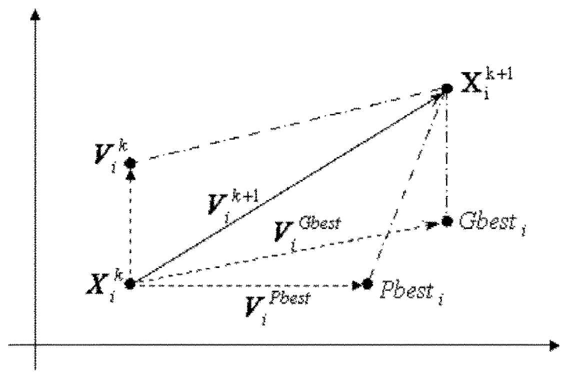

Fig. 4: Velocity and position variation in PSO

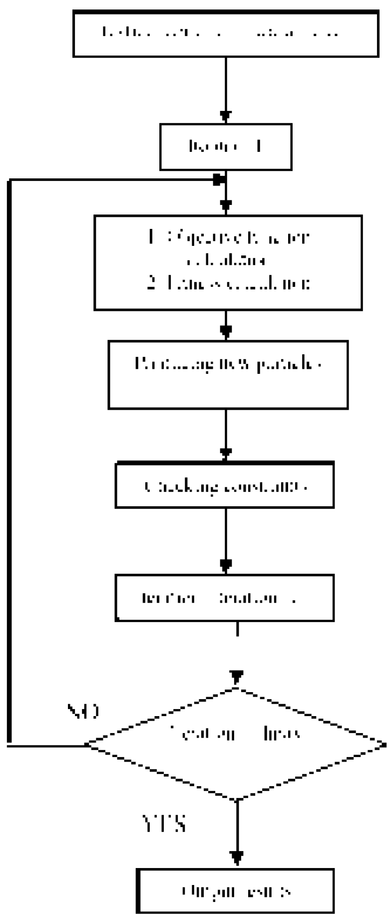

Fig. 5: PSO general flowchart

(The value of that fitness is also stored). This value is called pbest. Another "best" value is also tracked. The "global" version of the PSO keeps track of the overall best value and its location, obtained thus far by any particle in the population; this is called gbest. The velocity and position of each particle is according to the following relation:

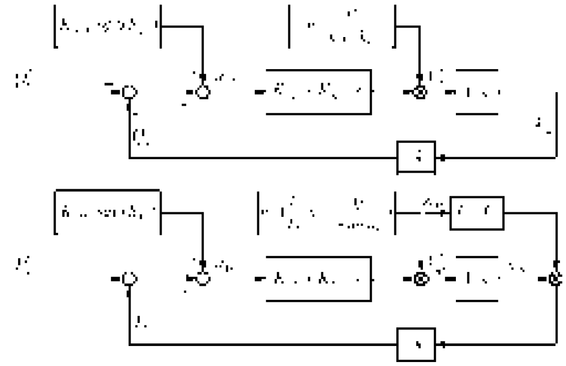

Fig. 6: Variable structure active and reactive power control

$$\vec{v}_i(t+1) = Inertia \times \vec{v}_i(t) + c_1 r_1 (\vec{x}pbest_i - \vec{x}_i) + c_2 r_2 (\vec{x}gbest_i - \vec{x}_i) \quad (7)$$
$$\vec{x}_i(t+1) = \vec{x}_i(t) + \vec{v}_i(t+1)$$

where $\vec{v}_i(t)$ is velocity, "Inertia" is the inertia coefficient of the particle, c_1 and c_2 are acceleration coefficients of the particle and r_1 and r_2 are random numbers. The function of the operators has been shown schematically in Fig. 4.

The flowchart of the PSO algorithm is shown in Fig. 5.

Proposed Control System: In this paper, a combination of the DPC method with VSC and SVM has been considered. The block diagram of the used VSC system has been shown in Fig. 6 [27].

In this system, P_s^* and Q_s^* are reference stator active and reactive powers while K_{IQ}, K_{PP}, K_{IP} are the proportional-integral controller gains.

Parameters from the grid, SVM, DFIG and turbine are fed to the system while the output of the system will be considered as the input to the converters (V_r in this paper). Wind speed has been taken constant for simplicity. This causes some of the time derivative terms to be zero which simplifies the analysis [27].

Simulation Results: Performance of the proposed method is simulated using Matlab/ Simulink® and its effectiveness is investigated. A 5 kW DFIG, whose nominal parameters are reported in Table I, is used.

Initially, the system has been simulated using DPC and VSC without using PSO. The used parameters in this approach are shown in Table II.

Table 1: DFIG Parameters

Stator Resistance (R1)	0.95 Ω	Magnetizing Inductance (Lm)	0.041 H
Stator Inductance (L1)	0.094 H	Pole Pairs	3
Rotor Resistance (R2)	0.45 Ω	Rotor Inertia (J)	0.05 Kg.m^2
Rotor Inductance (L2)	0.022 H	Nominal Torque (N.m)	50 N.m

Table 2: System Parameters Before Optimization

Control Variable	KPQ	KIQ	KPP	KIP
Value	0.4	500	0.45	600

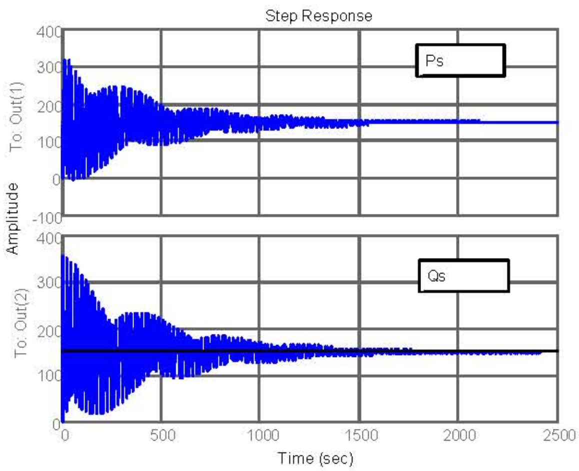

Fig. 7: Stator active and reactive powers for the non-optimal controller

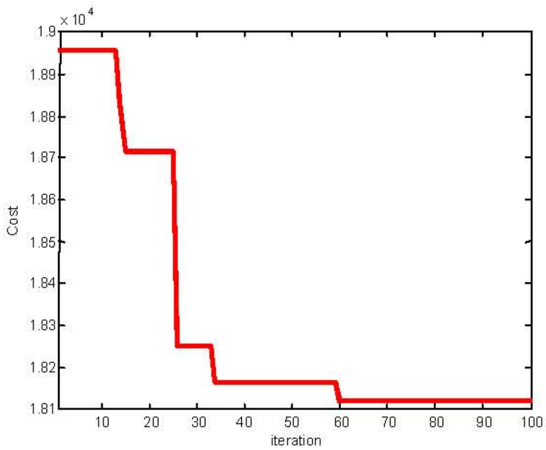

Fig. 8: Cost function (integration of error) variation in successive PSO iterations

Stator active and reactive powers using these parameters are shown in Fig. 7.

In the next stage, optimal controller parameters are calculated using PSO. It is then required to define a fitness function for simulating using PSO. This function is selected based on such criteria as system stability, response speed, response error and overshoot.

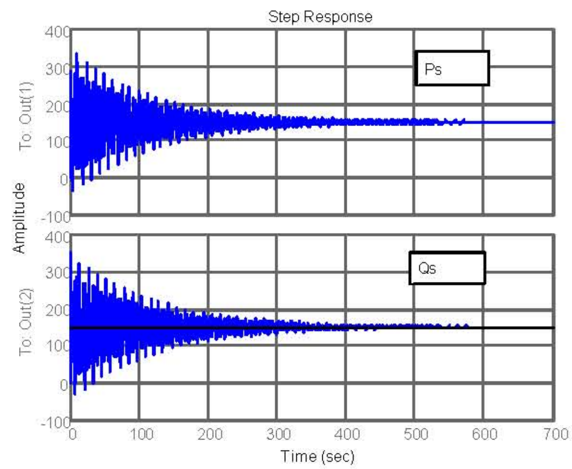

Fig. 9: Stator active and reactive powers for the optimal controller using integral of output error

Here, the time integral of absolute value of output error is selected as the objective function:

$$COST = \int_0^{t_{end}} |(y_o(t) - y^*)|\, dt \quad (8)$$

where $y_o(t)$ is system output at time t and y^* is its reference value. The objective function should minimize this cost. Fig. 8 shows the variation of cost function in successive iterations.

The values of control variables after 100 iterations are shown in Table III:

Using these control parameters, the system has been simulated again where stator active and reactive powers have been depicted in Fig. 9.

At the third stage, the time derivative of output error is also considered in order to remove the startup oscillations present at active and reactive powers.

$$COST = \int_0^{t_{end}} |(y_o(t) - y^*)|\, dt + \int_0^{t_{end}} |\frac{d}{dt}(y_o(t) - y^*)|\, dt \quad (9)$$

Using this cost function for PSO, its variation in successive iterations will be as in Fig. 10.

Table 3: System Parameters after Minimization of Integral of Output Error

Variable Control	KPQ	KIQ	KPP	KIP
Variable Sum	0.8435	400	0.3	800

Table 4: System Parameters after Minimization of Integral plus Derivative of Output Error

Variable Control	KPQ	KIQ	KPP	KIP
VariableSum	0.8435	400	0.3	800

Table 5: Parameters of Pso During Simulation.

Parameter	ParticleNo.	Iteration No.	C1	C2
Value	40	100	1.5	2.5

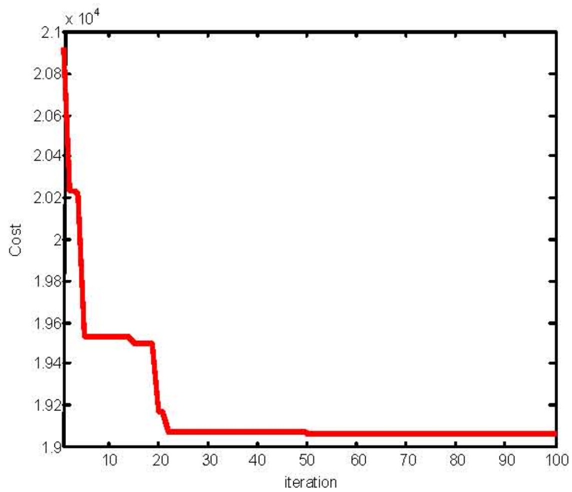

Fig. 10: Cost function (integration plus derivative of error) variation in successive PSO iterations

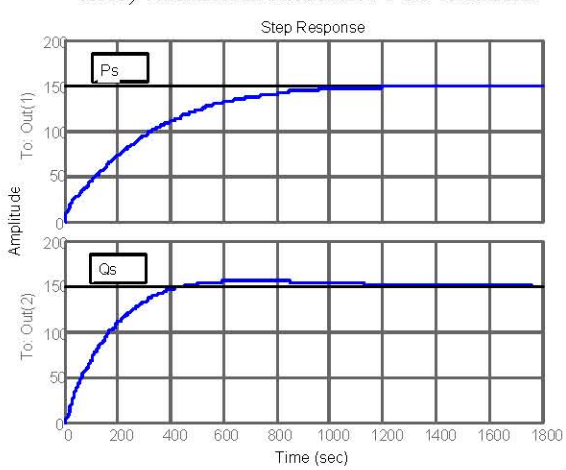

Fig. 11: Stator active and reactive powers for the optimal controller using integral plus derivative of output error

The controller parameters will change to optimal values shown in Table IV.

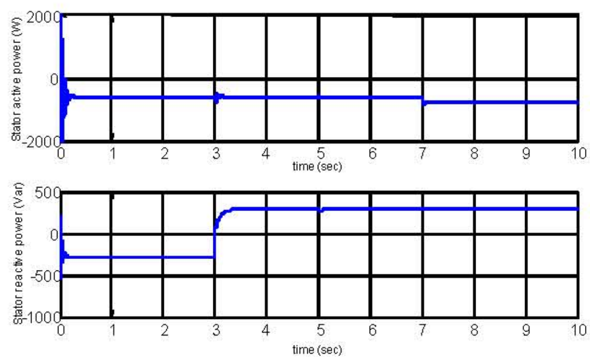

Fig. 12: Stator active and reactive powers

System response using these values will be as shown in Fig 11.

In all of the above simulations, the parameters of PSO have been set as shown in Table V.

The simulated scenario is described in the next paragraph.

The generator is first operating at a speed of 100 elect-rad/s with the reference active and reactive commands equal to -600 Watts and -300 VARs respectively (The minus sign denotes production and the plus sign denotes consumption). At the third second the reactive command changes from -300 VARs to +300 Vars. This process continues till the speed changes to 150 elect-rad/s in the fifth second. Finally, the active power command changes from -600 W to -800 W in the 7^{th} second. Of course, it is worthy to mention that in a wind power plant, neither the active nor the reactive power commands are actually constant. The active power reference is a cubic function of rotor speed while the reactive power reference is usually the output of the loss minimization subsystem.

The waveforms o f active and reactive powers are depicted in Fig. 12. It is seen that there is a good reference power tracking. The rotor d and q

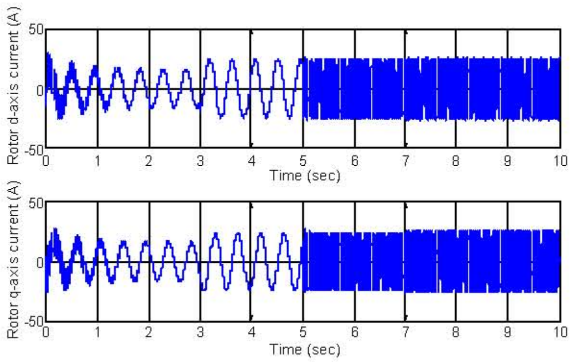

Fig. 13: Rotor d and q-axis currents

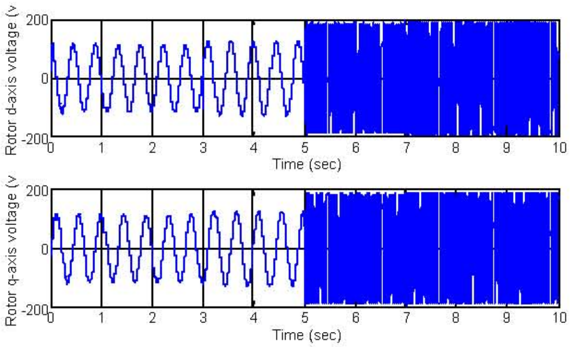

Fig. 14: Rotor d and q-axis voltages

axis current components in the rotor reference frame are shown in Fig. 13 and its voltage components are demonstrated in Fig.14.

CONCLUSION

A combination of variable structure control with particle swarm optimization was used in order to control stator active and reactive powers of a doubly fed induction generator. Parameters of the controller were chosen using the PSO method. Different fitness functions can be considered in order to have the desired output responses in regards to the control criteria. It was shown through simulation results that less oscillations and zero steady state error can be achieved via minimizing the integral and derivative of output error simultaneously.

REFERENCES

1. Ackermann, "Wind Power in Power Systems" John Wiley and Sons, 2005.
2. Calderaro, V., V. Galdi, A. Piccolo and P. Siano, 2008. "A fuzzy controller for maximum energy extraction from variable speed wind power generation systems", Electric Power Systems Res., 78: 1109-1118.
3. Datta, R. and V. Ranganathan, 2002. "Variable-Speed Wind Power Generation Using a Doubly Fed Wound Rotor Induction Machine: A Comparison with Alternative Schemes," IEEE Power Engineering Rev., 22(7): 52-55.
4. Boldea, I., 2005. Variable Speed Generators. CRC Press, pp: 11-22.
5. Leonhard, W., 2001. Control of Electrical Drives, Springer, pp: 400-418.
6. Yamamoto, M. and O. Motoyoshi, 1990. "Active and reactive power control of doubly fed wound rotor induction generator", Power Electronics Specialists Conference, 11: 455-460.
7. Bogalecka, E., 1993. "Power control of a double fed induction generator without speed or position sensor", Fifth European Conference on Power Electronics and Applications, 8: 224-228.
8. Quang, N.P., A. Dittrich and A. Thieme, 1997. "Doubly-fed induction machine as generator: control algorithms with decoupling of torque and power factor", 80(5): 325-335.
9. Xu, Longya and Wei. Cheng, 1995. "Torque and reactive power control of a doubly fed induction machine by position sensorless scheme", IEEE Trans on Industry Applications, 31(3): 636-642.
10. Pena, R., J.C. Clare and G.M. Asher, 1996. "Douvelbly fed induction generator using back-to-back PWM converters and its application to variable-speed wind-energy generation", IEE Proc on. Electric Power Applications, 43(3): 231-241.
11. Hopfensperger, B., D.J. Atkinson and R.A. Lakin, 2000. "Stator-flux-oriented control of a doubly-fed induction machine with and without position encoder", IEE Proc on Power Applications, 147(4): 241-250.
12. Datta, R. and V.T. Ranganathan, 1999. "Decoupled control of active and reactive power for a grid-connected doubly-fed wound rotor induction machine without position sensors", IEEE Industry Applications Conference, 4: 2623- 2630.
13. Azaza, H. and A. Masmoudi, 2000. "Implementation of a dual vector control strategy in a doubly-fed machine drive", European Trans on electrical power, pp: 541-555.
14. Peresada, S., A. Tilli and A. Tonielli, 1998. "Robust active-reactive power control of a doubly-fed induction generator", IECON, 3(31): 1621-1625.
15. Peresada, S., A. Tilli and A. Tonielli, 1999. "Robust output feedback control of a doubly-fed induction machine", IECON, 3: 1348-1354.

16. Peresada, S., A. Tilli and A. Tonielli, 1999. "Dynamic output feedback linearizing control of a doubly-fed induction motor", Proceedings of the IEEE International Symposium on Industrial Electronics, ISIE, 3: 1256-1260.
17. Peresada, S., A. Tilli and A. Tonielli, 2003. "Indirect stator flux-oriented output feedback control of a doubly fed induction machine", IEEE Trans on Control Systems Technol., 11(6): 875-888.
18. Patin, N., A. Nassani, E. Monmasson and J.P. Louis, 2007. "Sliding mode control of a doubly-fed induction generator", European Conference on Power Electronics and Applications, pp: 1-9.
19. Vidal, P., P. David and F. Bonnet, 2008. "Mixed Control Strategy of a Doubly Fed Induction Machine", 90(5): 337-346.
20. Lan, P.N., N.P. Quang and P. Buechner, 2006. "A non-linear control algorithm for improving performance of wind generator using doubly-fed induction generator", Proceeding of European Wind Energy Conference, Feb/March 2006.
21. Li, D.D., 2006. "Decoupled Power Control of Wind Turbine Based on Doubly-Fed Induction Generator", IEEE Conf on Industrial Electronics and Applications, pp: 1-5.
22. Yamamoto, M. and O. Motoyoshi, 1990. "Active and Reactive Power Control for Doubly Fed Wound Rotor Induction Generator", IEEE. TRANS. POWER ELEC, 6(4): 624-629.
23. Rabelo, B. and W. Hofmann, 2001. "Optimal Active and Reactive Power Control with the Doubly-Fed Induction Generator in the MW-Class Wind turbines", in Proc. International Conference on Power Electronics and Drives Systems, Vol. 1, Denpasar, Indonesia, Oct. 22-25, 2001, pp: 53-58.
24. Roncero-Sanchez, P.L., V. Feliu-Batlle and A.G. Cerrada, 2005. "Active and Reactive Power Control for a Wind Generator Connected to the Grid using a Predictive-Integral Control and a PI Control Schemes", European Conference on Power Electronics and Applications,
25. Zhi, D. and L. Xu, 2007. "Direct Power Control of DFIG with Constant Switching Frequency and Improved Transient Performance", IEEE Trans Energy Converse, 22: 1.
26. Noguchi, T., H. Tomiki, S. Kondo and I. Takahashi, 1998. "Direct power control of PWM converter without power-source voltage sensors," IEEE Trans. Ind. Appl., 34(3): 473-479.
27. Chwa, D. and K.B. Lee, 2010. "Variable Structure Control of the Active and Reactive Powers for a DFIG in Wind Turbines", Ieee Trans. Ind Appl., 46: 6.
28. Qiao, W., G.K. Venayagamoorthy and R.G. Harely, 2006. "Design of Optimal PI Controllers for Doubly Fed Induction Generators Driven by Wind Turbines Using Particle Swarm Optimization", 2006 International Joint Conference on Neural Networks Sheraton Vancouver Wall Centre Hotel, Vancouver, BC, Canada, pp: 16-21.
29. Karimi-Davijani, H., A. Sheikholeslami, H. Livani and M. Karimi-Davijani, 2009. "Fuzzy Logic Control of Doubly Fed Induction Generator Wind Turbine", World Applied Sciences J., 6(4): 499-508.
30. Kennedi, J. and R. Eberhart, 1995. "A Discrete Binary of the Particle Swarm Algorithm", in IEEE Int . Conf., 4(2): 1942-1948.
31. Abido, M.A., 2002. "Optimal design of power system stabilizers using particle swarm optimization", IEEE Trans. Energy Conversion, 17: 406-413.
32. Yoshida, H., K. Kawata, Y. Fukuyama and S. Takayama, 2000. "A particle swarm optimization for reactive power and voltage control considering voltage security assessment ", IEEE Trans. Power Syst., 15: 1232-1239.