International Journal of
Science and Engineering Investigations
vol. 2, issue 19, August 2013
ISSN: 2251-8843

Optimization of Direct Power Control in Doubly-Fed Induction Machine (DFIM) using PSO Algorithm

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Abstract- Doubly-fed induction generators (DFIG) are widely used in wind power plants due to several advantages such as partial rating converter, the ability of decoupled active and reactive power control, etc. This paper discusses modeling and control of doubly-fed induction generator using direct power control method. Direct power control method is based on active and reactive power control that can be controlled independently. This method has better dynamic rather than other methods. In this paper the model of doubly-fed induction machine has been expressed with some relations. We have used an intelligent optimization method named PSO for optimization of control parameters at the PI controller used in this control system. PSO methods avoid the shortcoming of premature convergence and can obtain a solution with better computation efficiency. Simulation results based on this method has been compared with the results based on trial and error method. Evaluation and comparison between these methods shows that when using PSO method, the stator active and reactive power ripple can be reduced than the trial and error method. Improvement in the harmonics of the input and output currents of the machine would be one of the other results of using this method.

Keywords- Direct Power Control (DPC), Doubly-Fed Induction Generator (DFIG), Particle Swarm Optimization Algorithm (PSO), Total Harmonic Distortion (THD)

I. INTRODUCTION

Nowadays the use of renewable energy sources for electricity production has increased significantly. Efficiency and performance of power plants such as wind power plants and pumped storage power plants can be significantly improved by using variable speed machines that doubly-fed induction machines provide this possibility. Use of doubly fed induction machines in this plants that are improved with advances in power electronics devices lead to increased and higher controllability[1].

Although still a few of variable speed units are equipped with cycloconverter but now the use of back-to-back AC/DC/AC converters are common. Important advantages of using inverter instead of cycloconverter is that there would be no need to reactive power compensator in grid side, better ability to control the plant in case of network errors and no need for starter to set up power plant. The system with AC/DC/AC converter includes an AC/DC rectifier set connected to power grid by a transformer and a DC/AC dihedral inverter set that is directly connected to rotor windings of DFIM. This kind of converters can transfer energy in both directions [2], [3], [4].

This paper attempts to provide an appropriate method based on PSO algorithm for optimal control of active and reactive power in doubly-fed induction machine. PSO intelligent optimization method is one of optimization methods with fast convergence and high search ability [5]. The PI controller has been used in control system of doubly fed induction machines. Systems that are controlled usually have time delays and high degrees, there for proper and precise tuning of controller coefficients is very important in design of PI controller. In this paper, the PSO method is used to adjust these coefficients. Fig.1 shows connection of doubly fed induction machine to power grid by a back to back converter.

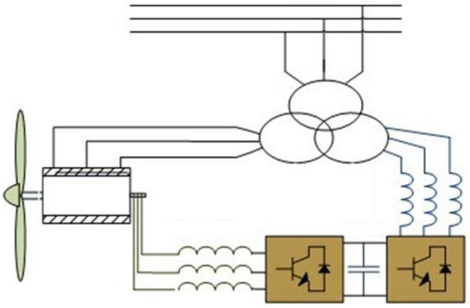

Figure 1. Block diagram of DFIG connected to power grid

In this paper at the first, model of doubly fed induction machine and its relations is expressed. Then, the principles of direct power control will be presented. Then, the particle swarm optimization PSO algorithm is investigated. This intelligent optimization method is used for setting parameters of the PI controller in the control system and at the end simulation results and optimum coefficients calculated by PSO intelligent method is presented.

II. DOUBLY-FED INDUCTION MACHINE MODEL

Assuming linear magnetic circuit, DFIM can be modeled by flux and voltage relations in the d-q reference frame as follows [6]:

$$V_{sd} = R_s i_{sd} + \frac{d\psi_{sd}}{dt} - \varpi_s \varphi_{sq} \tag{1}$$

$$V_{sq} = R_s i_{sq} + \frac{d\psi_{sq}}{dt} + \varpi_s \varphi_{sd} \tag{2}$$

$$V_{rd} = R_r i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_s - \varpi)\psi_{rq} \tag{3}$$

$$V_{rq} = R_r i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_s - \varpi)\psi_{rd} \tag{4}$$

$$\psi_{sd} = L_s i_{sd} + L_m i_{rq} \tag{5}$$

$$\psi_{sq} = L_s i_{sq} + L_m i_{rd} \tag{6}$$

$$\psi_{rd} = L_s i_{rd} + L_m i_{sd} \tag{7}$$

$$\psi_{sq} = L_r i_{rq} + L_m i_{sq} \tag{8}$$

At the above relations i_{sd} ، i_{sq} ، i_{rd} and i_{rq} are respectively d and q components of stator and rotor currents. Also ψ_{sd} ، ψ_{sq} ، ψ_{rd} and ψ_{rq} are respectively d and q components of stator and rotor fluxes. R_s and R_r are stator and rotor resistances. Also L_s and L_s are self-inductances of stator and rotor and are obtained from the following relations:

$$L_s = L_{ls} + L_m \tag{9}$$

$$L_r = L_{lr} + L_m \tag{10}$$

At the other hand, active and reactive power of stator can also be expressed by the following relations:

$$P_s = \frac{3}{2}\left(v_{sd} i_{sd} - v_{sq} i_{sq}\right) \tag{11}$$

$$Q_s = \frac{3}{2}\left(v_{sq} i_{sd} - v_{sd} i_{sq}\right) \tag{12}$$

III. DIRECT POWER CONTROL METHOD

Since the relations 11 and 12 don't provide the information necessary to investigation of direct power control, so these relations are modified in terms of stator and rotor fluxes [7],[8]:

$$P_s = \frac{3}{2}\frac{L_m}{\sigma L_s L_r}\varpi_s \left|\psi_s\right|\left|\psi_r\right|\sin\delta \tag{13}$$

$$P_s = \frac{3}{2}\frac{L_m}{\sigma L_s L_r}\varpi_s \left[\frac{L_h}{L_r}\left|\psi_s\right| - \left|\psi_r\right|\cos\delta\right] \tag{14}$$

The above relations indicate that the active and reactive power of stator vary with changes in relative angle between rotor and stator flux vectors and their amplitudes.

Since the amplitude of the stator flux is constant, stator active and reactive power only depend on angle between stator and rotor flux vectors δ and amplitude of rotor flux. Since the stator flux vector rotates with a constant speed, each of the eight voltage vectors in dihedral converter creates a new angle δ. So by evaluation of $\left|\psi_r\right|\cos\delta$ and $\left|\psi_r\right|\sin\delta$ variations of active and reactive power can be reduced.

Fig.2 shows impact of voltage vector v_6. It can be seen that vectors $\left|\psi_r\right|\cos\delta$ and $\left|\psi_r\right|\sin\delta$ are increased. According to the relations 13 and 14 it increases the active power and decreases the reactive power (when the machine operates at sub synchronous speed) [6], [7].

It is clear that considering to the sector which rotor flux vector is in it, voltage vectors will have different effects on active and reactive power. Similar analysis can be performed in different sectors and effect of voltage vectors generated by the inverter on the active and reactive power of stator can be seen and thereby switching table of direct power control method in generator mode and sub synchronous speed will be as follows[7].

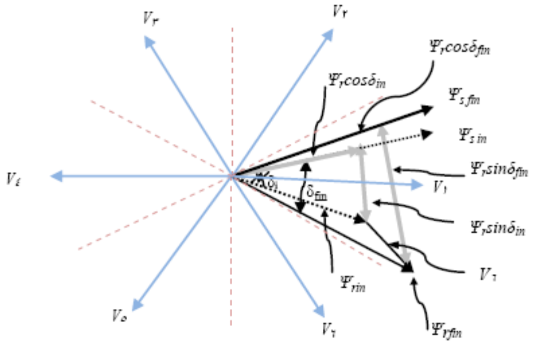

Figure 2. Impact of inverter output vectors on the stator active and reactive power

Fig. 3 shows block diagram of direct power control method for a doubly-fed induction machine.

As it can be seen, reference values of active and reactive power have been compared with calculated values and have been applied to hysteresis controllers. Output of the hysteresis comparators with rotor flux position (the sector number which rotor flux is located there) are applied to switching table as an input.

Appropriate voltage vector is determined by this table and pulses Sa, Sb and Sc are applied to IGBTs of dihedral Voltage source converter [7], [8].

TABLE I.SWITCHING TABLE OF DIRECT POWER CONTROL METHOD IN GENERATOR MODE

E_P		1	0	-1	1	0	-1
E_Q		1			-1		
Sector Number	1	V_3	V_7	V_5	V_2	V_0	V_6
	2	V_4	V_0	V_6	V_3	V_7	V_1
	3	V_5	V_7	V_1	V_4	V_0	V_2
	4	V_6	V_0	V_2	V_5	V_7	V_3
	5	V_1	V_7	V_3	V_6	V_0	V_4
	6	V_2	V_0	V_4	V_1	V_7	V_5

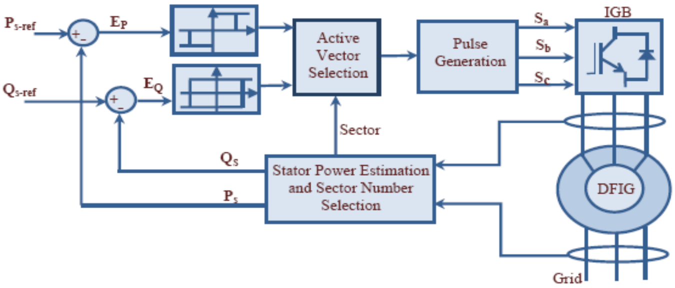

Figure 3. DPC block diagram in doubly-fed induction machine

IV. INTRODUCTION OF PSO METHOD

PSO (Particle Swarm Optimization) method that presented in 1995 by Kennedy and Elberhart is one of optimization techniques and it is an evolutionary computational approach. The PSO comes from behavior of fish and birds during gathering [9], [10]. In this method, the search process can be summarized as follows [11]:

First step) Initialization: at this stage, a specific situation is considered for each member of particles group.

Second step) Evaluation: this stage calculates appropriate value of every particle.

Third step) checking the stop criteria: if one of the stopping criteria is satisfied, the algorithm stops, otherwise it goes to step four. Stopping criteria will be met when the finest particle in comparison with other particles has been found.

Fourth step) Update velocities and positions: at this stage, new position of each particle is checked after changing the particle's position. This new position is compared with previous particle's positions and also compared with the other particle's positions and finest position will be selected. Flowchart of PSO algorithm is shown in fig.4 [12].

In this algorithm, each particle can acquire information from other particles. In PSO method every particle moves with a certain velocity in search space and this velocity is determined by previous velocity, personal experience and collective experience of the particle [9].

Velocity and position of each particle can be determined according to the following relations [5], [9]:

$$V_i^{(t+1)} = w * V_i^{(t)} + C_1 * r_1 \left(X_{i,best}^{(t)} - X_i^{(t)} \right) + C_2 * r_2 \left(X_{g,best}^{(t)} - X_i^{(t)} \right) \quad (15)$$

$$X_i^{(t+1)} = X_i^{(t)} + V_i^{(t)} \quad (16)$$

At this relations x_i and v_i are respectively position of particle *i* and velocity of particle *i*. $x_{i,best}$ is the best position that particle *i* has experienced and x_{gbest} is position of the best particle among all particles. *w*, c_1 and c_2 are respectively inertia coefficient, personal learning coefficient and collective learning coefficient. r_1 and r_2 are random numbers at range of (0,1). This algorithm is a stochastic algorithm that coefficients r_1 and r_2 increase search power of algorithm.

According to above relations, velocity of *i*th particle is determined with vector sum of previous velocity of the particle, personal experience of the particle and collective experience of the particle.

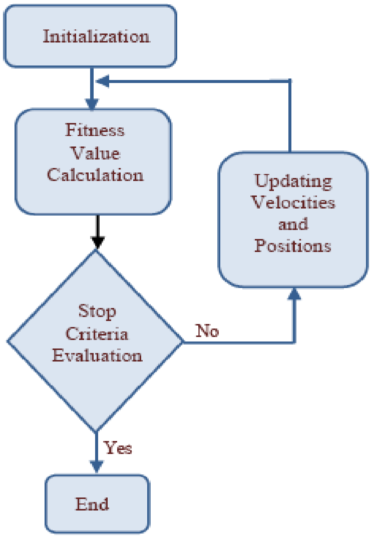

Figure 4. Flowchart of PSO algorithm

V. INTRODUCTION OF PROPOSED MODEL

At this research, general simulated model consists of a doubly-fed induction machine that it's stator is connected directly to the power grid and it's rotor is connected to power grid through a back-to-back dihedral converter.

Also voltage source converter (VSC) is composed of grid side converter and machine side converter and they are connected together by a dc link capacitor. In fact, dc voltage created by a rectifier set is applied to the inverter set. At this model direct power control methods have been used to control the machine. There are two control systems for grid side converter and rotor side converter.

Sinusoidal bandwidth modulations (PWM) have been used in control system of grid side converter. In order to implement PWM method, proportional-integral (PI) controllers are used.

Figure 5 shows the block diagram of grid side converter control system briefly. As it can be observed ther are three PI controllers.

To improve performance of the control system, PI controller coefficients must be adjusted. In this section, two following methods are used to adjust the coefficients:

1- Trial and error method

2- PSO intelligent optimization method

Output results for these two different techniques are presented and compared with together in the next section.

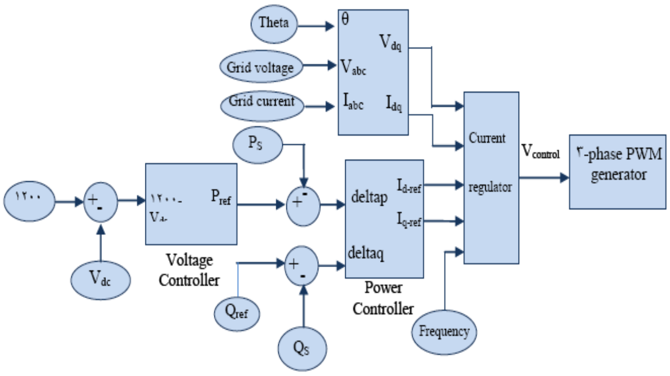

Figure 5. Block diagram of grid side converter control system

VI. SIMULATION RESULTS

Characteristics of doubly-fed induction machine that is modeled in MATLAB software is presented in table 2. Effective voltage of network is 11 kv and also dc link voltage is 1200 volts. Parameters used in PSO setting are presented in table 3.

As mentioned in the previous section, PI controller coefficients have been adjusted using trial and error method and PSO method that these values are presented in table 4.

TABLE II. ELECTRICAL SPECIFICATIONS OF DFIM

Nominal Power	2 (MVA)
Nominal Voltage	690 (V)
Nominal Frequency	50 (Hz)
Stator Resistance	0.0108 (P.U)
Self-Inductance of Stator	0.102 (P.U)
Rotor Resistance	0.0121 (P.U)
Self-Inductance of Rotor	0.11 (P.U)
Mutual Inductance	3.362 (P.U)
Polepaires	2

TABLE III. PSO SETTING SPECIFICATIONS

Number of Iterations	Population Number	Inertia Coefficient	Insider Learning Coefficient	Collective Learning Coefficient
30	20	0.7298	1.4962	1.4962

TABLE IV. COMPARISON OF PROPORTIONAL-INTEGRAL CONTROLLER COEFFICIENTS

Method / Controllers coefficients		Trial and Error	PSO
Voltage controller	K_P	0.002	0.0031
	K_I	0.5	0.59
Power controller	K_P	5	7.12
	K_I	500	503.65
Current regulator	K_P	5	6.79
	K_I	500	473.2

Figures 6 and 7 show the stator active and reactive power when using trial and error method to adjust the coefficients.

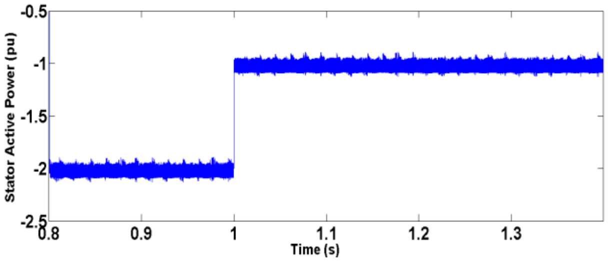

Figure 6. Variations of stator active power in trial and error method

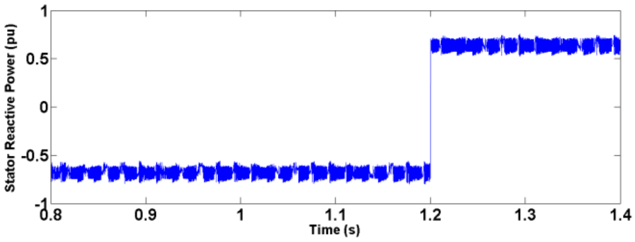

Figure 7. Variations of stator reactive power in trial and error method

As it can be seen when we change reference active power in the time 1 second, output active power is increased to -1 per unit. Also when we change reference reactive power in the time 1.2 second, output reactive power is increased to 0.6 per unit. It is observed that change of active power doesn't effect on reactive power and vice versa. This feature is one of the important benefits of direct power control method.

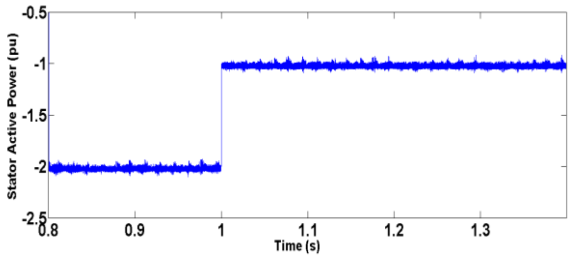

Figure 8. Variations of stator active power in the method based on PSO

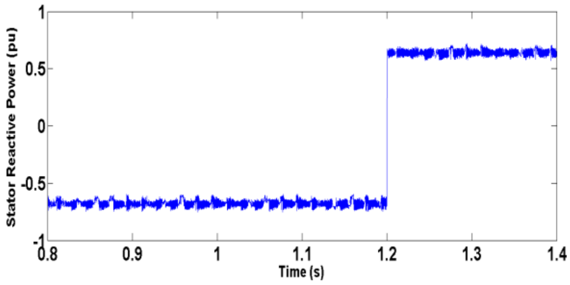

Figure 9. Variations of stator reactive power in the method based on PSO

Figures 8 and 9 shows the active and reactive power of stator when using PSO method to adjust the coefficients.

As it can be seen, ripples or variations of active and reactive power are reduced when using PSO method. Percentage of improvement in output power ripple is presented in table 5.

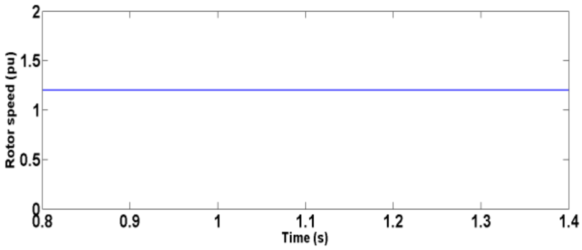

Figure 10. Variations of rotor speed in DFIM

Figures 10 and 11 indicate diagrams of rotor speed in doubly-fed induction generator and DC voltage applied to inverter respectively.

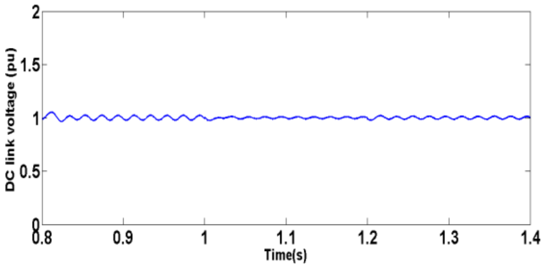

Figure 11. Diagram of DC link voltage applied to inverter

Figures 12 and 13 also show the stator and rotor three phase current variations in the control method based on PSO. Frequency of stator current is constant and equal to grid frequency

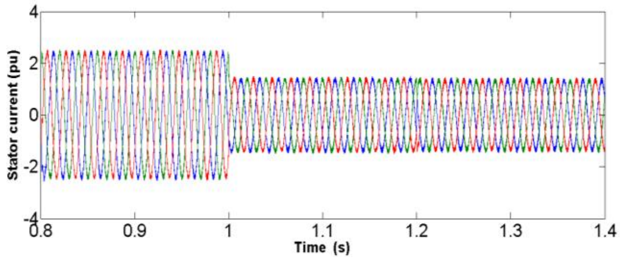

Figure 12. Stator current variations

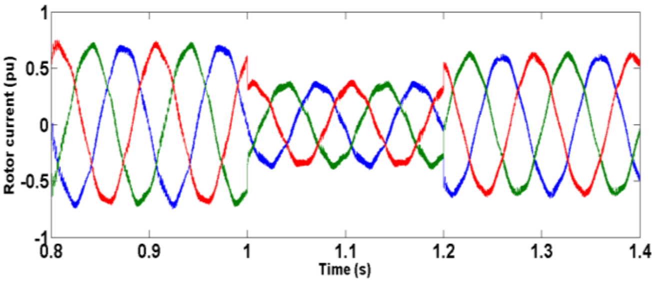

Figure 13. Rotor current variations

Total harmonic distortion for stator and rotor currents in both methods is shown in figures 14-17. By evaluation of total harmonic distortion (THD) for stator and rotor currents in both methods this result is obtained that THD is reduced in method based on PSO than method based on trial and error. That indicates increase in output power quality and reduction in output current ripple.

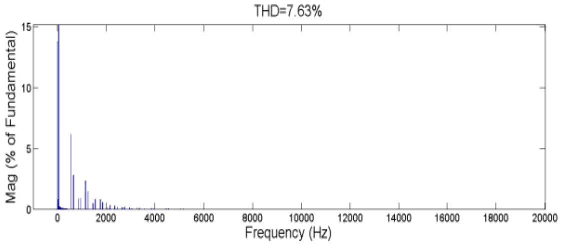

Figure 14. THD for stator current in method based on trial and error

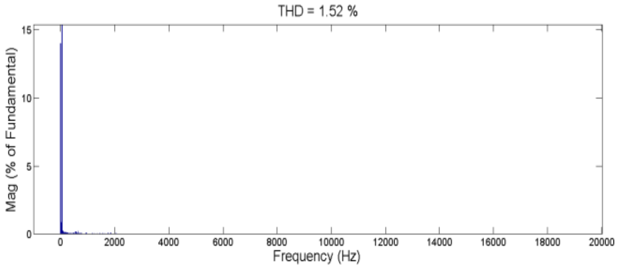

Figure 15. THD for stator current in method based on PSO

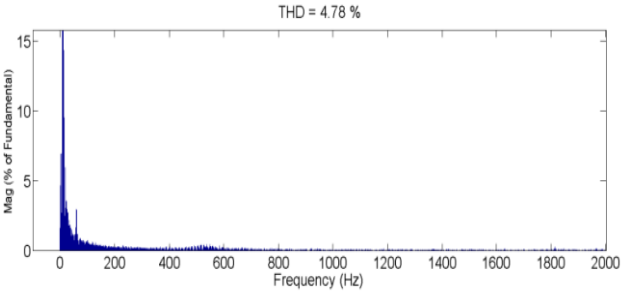

Figure 16. THD for rotor current in method based on trial and error

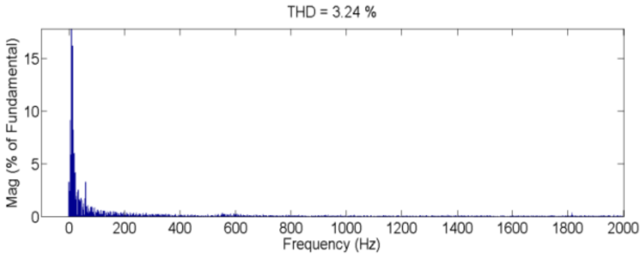

Figure 17. THD for rotor current in method based on PSO

Table 5 indicates exact comparison between stator active and reactive power ripples and also THD values.

TABLE V.
COMPARISON OF THD VALUES AND PERCENTAGE OF ACTIVE AND REACTIVE POWER RIPPLES IN METHODS BASED ON TRIAL AND ERROR AND PSO

Method Parameter	Trial and Error	PSO
Stator Current THD	7.63 %	1.52 %
Rotor Current THD	4.78 %	3.24 %
Ripple of Active Power	1.895 %	0.803 %
Ripple of Reactive Power	1.71 %	0.89 %

VII. CONCLUSION

In this paper, a doubly-fed induction generator has been modeled with a back-to-back converter via MATLAB software. Direct power control (DPC) method is used to control machine. Since the control coefficients k_i and k_p in PI controller used in PWM technique have to be adjusted, both methods based on PSO and based on trial and error was used for this purpose and results of these two methods were compared.

Comparison of results shows that when using intelligent methods such as PSO to adjust PI coefficients, harmonic amount (THD) is reduced that it reflect improvement in quality of output power. Also in this case, the stator active and reactive power fluctuations are reduced. Due to importance of the power quality in the system, it is necessary to produce constant active and reactive power from a DFIG. The results show the PSO method is a useful technique to improve DFIG’s output power.

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