Modern Applied Science; Vol. 10, No. 8; 2016
ISSN 1913-1844 E-ISSN 1913-1852
Published by Canadian Center of Science and Education

Simulation and Control of Doubly Fed Induction Generator (DFIG) Used in Wind Turbines by Using Genetic Algorithm

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Received: March 8, 2016 Accepted: April 1, 2016 Online Published: April 26, 2016

doi:10.5539/mas.v10n8p1 URL: http://dx.doi.org/10.5539/mas.v10n8p1

Abstract

Wind energy is one of the extraordinary sources of renewable energy due to its clean character and free availability. With increase in wind power penetration, the wind farms are directly influencing the power systems. The majority of wind farms are using variable speed wind turbines equipped with doubly fed induction generators (DFIG) due to their advantages over other wind turbine generators (WTGs). Therefore, the analysis of wind power dynamics with the DFIG wind turbines has become a very important research issue, especially during transient faults. In this article, a controller is provided to control the active and reactive power of a wind system equipped with doubly fed induction generator. The generator is connected to the grid by a back to back converter that gets benefit from control system known as single periodic controller. Grid and generator side converters respectively control the generator speed and reactive power using proposed controller. In order to increase the accuracy of controller, we optimized its PI parameters using genetic optimization algorithm. Finally, simulation results conducted by the MATLAB software are shown. The results of simulation gained through this system, show the capability of proposed controller under error conditions for controlling active and reactive power and also elimination of harmonics caused by non-linear load.

Keywords: doubly fed induced generator, control system, PI parameters, genetic algorithms

1. Introduction

Due to the diversity of human needs in relation to energy and inability of direct use of many primary energy resources, humankind would change and transform these energies to desired type of energy such as electric energy. Electric energy is produced mainly by fossil fuels. The fossil fuels in addition to their limited life, are associated with environmental problems. Hence, use of renewable sources such as wind has been proposed. (Moghadas Tafreshi, 2011).Increase in use of renewable energy is due to their compatibility with environment, availability and low costs. (Gautam, Vittal, Harbour, 2009) The use of wind energy in many countries is growing. In current situation regarding the economic feasibility of wind energy compared with other resources of new energies, getting benefit from wind energy is widespread and Iran is not an exception.

After rising oil prices in 1973, advanced industrial countries were forced to consider energy problems more seriously, and this was the beginning of long-term programs in the field of energy saving and optimization. In other words, the use of renewable energy sources, especially wind energy, was the agenda of these countries. One of the main problems that should be considered in use of wind turbines, is their control. In general, control of wind turbines is two main axis, which includes:

1. The maximum absorbable wind mechanical power from wind turbine for different values of wind speed would be different. So the maximum absorbable wind mechanical power at every moment should be determined.

2. Turbine generator should be controlled so that can track and produce the maximum mentioned power at any moment. Wind turbine systems equipped with double-fed induction generator have the following advantages: As a result of constant frequency of network and adjusting the electric frequency of rotor, control of mechanical speed and absorbance of maximum power of the wind turbine is possible. Hereby, depreciation of mechanical devices is reduced.

Generally, a wind turbine can be equipped with three phase generator. Nowadays, need for creating a flow electrical compatible with network is possible by frequency converter connected to the network. Even if flows

are in two alternate forms of variable frequency or direct flow (DC).

Common used generators in wind turbines are as follows:

1. Synchronous Generator
2. Asynchronous Generator

Usage of induction generators (Asynchronous Generator) in wind energy conversion systems is increasing, that it is because of low cost, strength and low needs to their maintenance (Chen, Hsu, 2006). The most important advantages of these generators are their sustainability, simple mechanical structure and mass production with lower price. In recent years, wind turbines with double nutrition (DFIG) are highly regarded by manufacturers. Their variable speed makes this ability that turbine can operate work at maximum efficiency in wider range of wind blowing (Gautam, Vittal,, Harbour, 2009). Other advantage of DFIG is absorption of wind fluctuations by changing the rotor speed rotation and the lack of their transmission to the grid. Control unit of a wind system is considered as the most important part of a system to get the best efficiency. Many different methods have also been proposed which along with their advantages, there were disadvantages as well.

Among the important ways, we can mention Pulse width modulation method (PWN) that is a linear control method. There are other methods such as Programmed PWM and SPWM which are sub-branch of PWM (Kazmierkowski, 2002). The Current mode control method has been used that is a common applicable method in pneumatic control systems. Other control methods, such as SVM, $MRAS$ are used also, of course, their applications are less than PWM(Forchetti, Garcia, Valla, 2002; Cardenas, Pena, Clare, Asher, Proboste, 2008) . Another method is fuzzy Control System is based on fuzzy logic. This type of control, approaching the human reasoning that makes use of the tolerance, uncertainty, imprecision, and fuzziness in the decision-making process, manages to offer a very satisfactory performance, without the need of a detailed mathematical model of the system, just by incorporating the experts' knowledge into fuzzy rules. In addition, it has inherent abilities to deal with imprecise or noisy data; thus, it is able to extend its control capability even to those operating conditions where linear control techniques fail (i.e., large parameter variations). This system has four main parts. First, using input membership functions, inputs are fuzzified, then, based on rule bases and inference system, outputs are produced, and finally the fuzzy outputs are defuzzified and applied to the main control system. Error of inputs from their references and error deviations in any time interval are chosen as inputs.

In this article in section 2, wind system model using the double-fed induction generator is provided, in section 2-1 a wind turbine is described. In Section 2.2 wind turbine model is discussed. In Section 2-3 model of doubly fed induction generator is described. In section 3 controller is explained and in section 4 simulation results conducted by the MATLAB software are shown. Finally at final section, the result of proposed method is revealed.

2. Wind Turbine Model Using DFIG

2.1 Wind Turbine

As shown in Figure 1, the structure of a wind turbine is designed to connect DFIG stator directly to its rotor circuit by a back-to-back converter (ADC generator and grid side converter) with sliding rings to the grid. There is a capacitor between two converters which is called DC link. This capacitor is used as energy storage and also to keep the voltage variations (ripple voltage) fixed. Under normal operation, DFIG through the grid side converter can control active and reactive power needed in the system independently (Yanhua, ZhangZhao,, Ma, 2011; Lesan., Tarymrady, 2002) This application is performed by control method which is called Single periodic control (Lock, da Silva, Elbuluk, Jacobina, 2009; Femia, Fortunato, 2008)

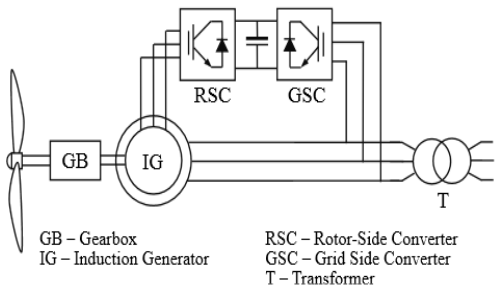


Figure 1. DFIG connected to the back to back converter

2.2 Wind Turbine Model

In order to fully understand the performance of Wind Turbines, a mathematical model is expressed below based on some assumptions.

In this Model, equations of wind turbine are as follows:

$$P_m = \frac{1}{2} p_{air} A C_p(\lambda)(\frac{R}{\lambda})^3 \omega_r^3 \tag{1}$$

$$\lambda = \frac{\omega_m R}{V_{wind}} \tag{2}$$

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - c_3\beta - c_4\beta^{c_s} - c_6\right) \exp\left(\frac{c_7}{\lambda_i}\right) \tag{3}$$

$$\lambda_i = \left[\left(\frac{1}{\lambda + c_8\beta}\right) - \left(\frac{c_9}{\beta^3+1}\right)\right]^{-1} \tag{4}$$

P_m is the mechanical power of turbine, ρ_{air} Air density, V_{wind} wind speed, ω_m rotational speed of turbine, β blade angle of wind turbine, R the radius of turbine. Power coefficient curve $C_p(\lambda,\beta)$, for a certain speed and λ. Characteristic is noticeable. As well as constants coefficient C 1 up to C 2 given by the manufacturer. $C_p(\lambda,\beta)$ Should not extend more than its limitation $C_p^{\max} = 0.59$ which is called Betz. This coefficient is used for continuous operation of the turbine .(Gautam., Vittal, Harbour, 2009) In this article, we assume that the turbine blade angle is constant ($\beta = 0$).

2.3 Doubly Fed Induction Generator Model

The dynamic model of voltage and stator flux in induction generator (asynchronous reference) is expressed by equations (5) - (8):

$$v_s = R_s i_s + \frac{d\varphi_s}{dt} + j\omega_s\varphi_s \tag{5}$$

$$v_r = R_r i_r + \frac{d\varphi_r}{dt} + j\omega_{slip}\varphi_r \tag{6}$$

$$\varphi_s = L_s i_s + L_m i_r \tag{7}$$

$$\varphi_r = L_s i_r + L_m i_s \tag{8}$$

where $L_S=L_{1s}+L_m$ and $L_r=L_{1r}+L_m$ are and $\omega_{slip} = \omega_s - \omega_r$ is frequency slip.

3. Control Model

3.1 Genetic Algorithm

Genetic algorithm in each repetition (iteration) works with a set of questions. The population in each repetition of algorithm is called generation. For production of new generation, usually three genetic operators known as presence, crossover and mutation are used. The mutation operator is between the answers to make diversity. The crossover operator for making concentration lies in two answers that are selected as parents. Selection of parents and crossover is done with different methods. These operators will evolve new generations over the previous generation. To assess the answers, the fitness value is assigned to each answer that for one objective matter, different values can be defined as equal to the objective function value at that point and for multi-objective problems depending on the type of algorithm. After repetition of this process several times and over some generations, the algorithm converges to a specific region of the answer space. There are several single objective genetic algorithms to solve problems. In general, the implementation of GA is as follows:

First step: creating the first generation of chromosomes.

Second stage: Assessing the fitness of each initial chromosome.

Third step: Creating new chromosomes by applying the genetic operators like crossover, mutation and reproduction of existing chromosomes.

Fourth step: Evaluating the fitness of new generation of chromosomes.

Fifth Step: If the stop condition is established, stop is done and the best chromosome should be displayed. Otherwise, the third stage is done.

3.2 Single Periodic Controller

As shown in Figure 2 (Chen, Smedley, 2008) at first the difference between measured value (generator speed to control the input active power from turbine and generator terminal voltage in order to control grid reactive power) and control reference enters into a PI controller in order to make the average value of the error. By command of control system to the inverter, capability of control is gained in the grid. In this paper, PI controller is added to this system.

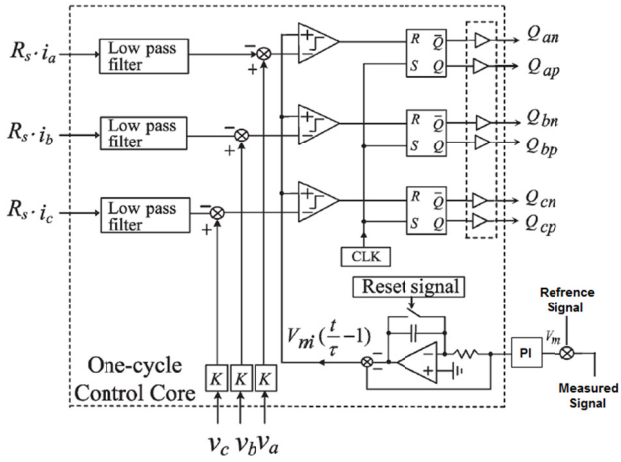


Figure 2. Single control circuit in three-phase system

The most important task of generator side converter would be control of DFIG rotor speed which is done by a single periodic controller. First, The generator rotor speed (ω_r) is measured and compared with the reference speed. According to the equation (9) the generator speed has direct relation to the output active power of the turbine.

$$P_m = \frac{1}{2}\rho_{air} A C_p(\lambda)\left(\frac{R}{\lambda}\right)^3 \omega_r^3 \tag{9}$$

In the above equation $C_P(\lambda)$ is Power coefficient that represents the ratio of conversion of kinetic energy into mechanical energy by the turbine. λ is speed ratio of the blade tip dependent on angle of the turbine blade for turbines with curve control ability. A is a swept surface by the blade. By controlling the generator speed in reference value (according to the characteristic of wind power output to the speed of the generator), required power of network can be received from the wind turbine.

PI Output would enter in an integrator and forms the equation $V_m\left(1-\frac{d_{an}}{K_1}\right)$ which is a triangular wave form. On the other hand, sample the ($R_s I_{ph}$) from network transmission line voltage and two equations are compared with each other by a comparator.

$$\begin{cases} R_s I_a = V_m\left(1-\frac{d_{an}}{K_1}\right) \\ R_s I_b = V_m\left(1-\frac{d_{bn}}{K_1}\right) \\ R_s I_c = \left(1-\frac{d_{cn}}{K_1}\right) \end{cases} \quad (10)$$

When two equations are equal to each other (measured value reach to the reference value) cause flip-flop to reset and finally the state of flip-flop output will be changed. In the above equation for better convergence we put K 1 = 0.5.

The most important task of side generator converter is control of required reactive power network. It is done by controlling the voltage of terminal generator, and command to the grid side converter. Bus side voltage of generator is sampled. By controlling mentioned voltage, the reactive power exchange to the grid is also controlled.

4. Simulation Results

4.1 Optimizing the parameters of PI Controller

This section aims to provide the simulation results of the proposed control strategy (single periodic control by using the PI controller) for wind turbine equipped with double-fed induction generator supported by Matlab / Simulink software. Figure 3 shows a single-phase system of a wind farm connected to the power network.

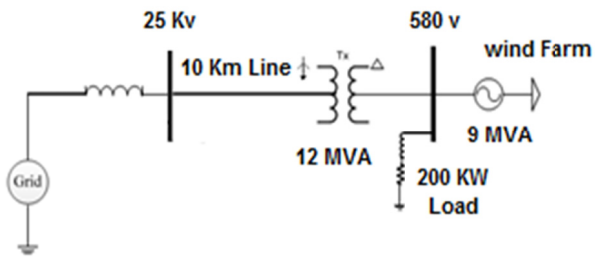


Figure 3. One-phase Schematic of a wind farm

As seen in Figure 3, a simulated system consisting of a wind farm with 9 one megabit turbines that are connected to a 25 kV distribution network is shown. Preliminary specifications of the generator and transmission line are given in the appendix. Some amount of produced power by turbines reaches to existent load in the network, means a 200KW load in the bus arrives to 580 volt and the remaining power produced through a 25KV feeder in length of 10 Km is transmitted to a source with constant voltage (infinity bus bar). The role of this source is to supply the necessary power of consumers in case of decrease in production of turbines. Parameters of induction machine and transmission line are shown in Table 1.

Table 1. Parameters of induction machine and transmission line

580(v)	Rated voltage
10(MVA)	Rated power
60(Hz)	Network frequency
0.92	Power coefficient
1200(rpm)	Rated speed
0.0072(H)	R_s
0.172(H)	L_{ls}
0.055(Ω)	R'_r
0.157(H)	L'_{Lr}
3(H)	Lm
5.03(kg.m^2)	J
30(km)	Line length

In order to achieve the optimum response by controller, the genetic optimization algorithm for optimizing parameters of PI existing in One-time control circuit is proposed. The used algorithm is called a genetic algorithm. In this simulation the defined target that should be optimized, is the voltage recovery time to the primary mode after the changes. Parameters K_p And K_i, are optimum variable algorithms that can be obtained by objective factor (the minimum voltage recovery time). Respectively in Table 2 optimum parameters for PI controller in the system are shown.

Table 2. Optimized PI parameters

Parameters	K_p	K_I
Under error condition	0.055	0.29

4.2 Wind Speed Pattern

In this model, the entered wind speed into the wind turbine is given in equation (11) .

$$v_w = v_0 + \sum_{i=0}^{n} A_i \cos(\omega_i t + \varphi_i) \tag{11}$$

In the above equation $A_1 = 0.06$, $\varphi_1 = 0$ and $\omega_1 = \pi$. We consider the wind speed in fluctuation simulation and in wind speed base v0 = 11. under the equation (12) fluctuations of wind speed within the speed base 12m / s Continues till entering the turbine and then power output can also be obtained. According to equation (12) cubic wind speed has a direct relation to obtained power from the wind turbine. So received optimum from wind can be stated as below:

$$P_{m-opt} = \frac{1}{2}\rho_{air} A C_p^{\max} \pi R^2 \frac{\omega_{r-opt}^3}{\lambda_{opt}} \; P_{m-opt} = \frac{1}{2}\rho_{air} A C_p^{\max} \pi R^2 \frac{\omega_{r-opt}^3}{\lambda_{opt}}$$

In the above equation $C_p^{\max}$ is the maximum power coefficient and λ_{opt} the optimum ratio of blade tip speed to wind speed that their values are obtained in continue.

According to equation (12) and considering the fixed angle of wind turbine blades $(\beta = 0)$ and due to constant $\lambda_{opt} = 8$ and R=1m then $_p^{\max} = 0.49$ is obtained.

4-3 controlling the output active power of turbine

Output active power of the wind turbine and input to the generator according to equation (12) only depend on changes of optimal speed of generator $(\omega_r^3 - opt)$. Thus, by controlling the speed of generator at desired amount then output power can be also controlled. In this paper, the Maximum power point tracking of wind (MPPT) is used. By assuming an approximate fixed value for wind speed, we also can keep the generator speed and output power of the turbine in a fixed value by a single periodic controller. As a result, this power for

approximate wind speed would be 12 meters per second and by speed of generator $\omega_r = 1.2$ Per unit, according to the characteristics of output power of wind to the defined speed of generator shown in Figure 4, 97/5 MW can be obtained. According to the nominal power output of the wind turbine $(p_{rate} = 8MW)$, it is 74/0 per unit.

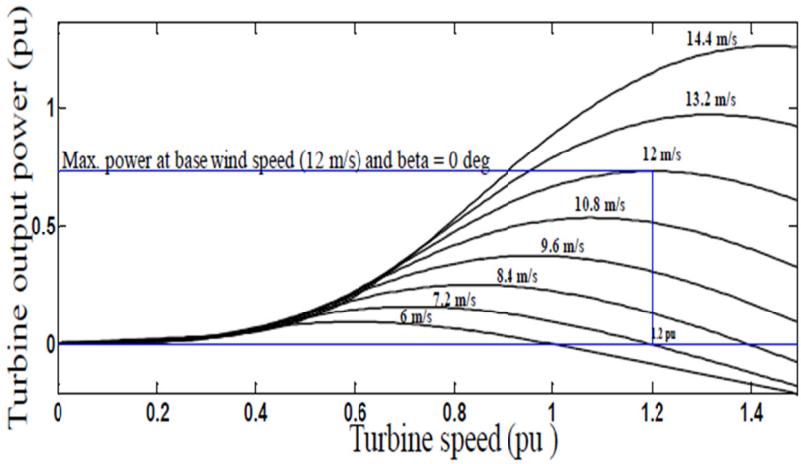


Figure 4. Characteristic of turbine output power related to turbine speed

A graph of the wind speed is presented in Figure 5. As the result of this wind speed , mechanical torque Tm is shown in Figure 6 and the generator rotor speed is shown in Figure 7.

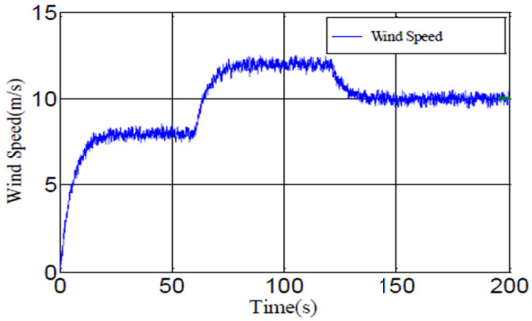


Figure 5. Wind Speed Chart

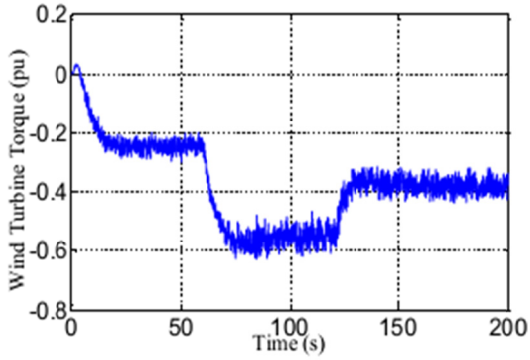


Figure 6. Wind turbine torque

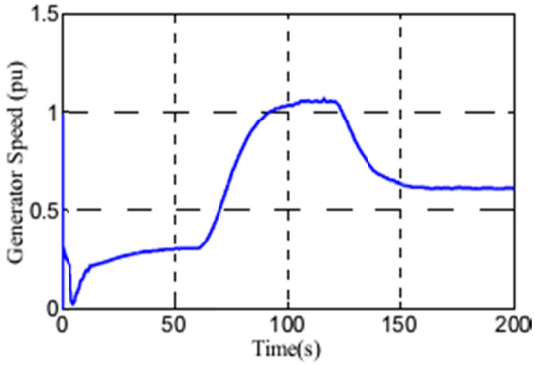


Figure 7. Rotor speed

The generator rotor speed is a factor that directly affects the output power of the wind turbine. So its control and stability in a certain amount is always an important purpose of wind systems. This is done by converter and by a single periodic controller then can fix the speed in a required amount which is about 15/1 per unit in this simulation. Figure 8 shows the steady state of controlled rotor speed by a single periodic method.

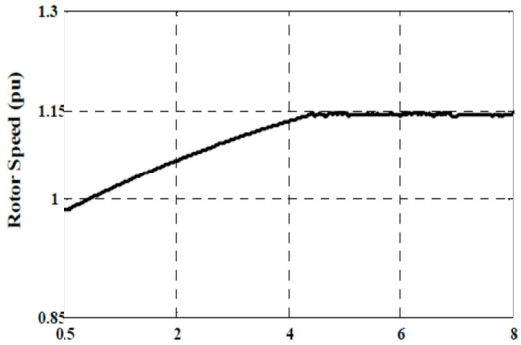


Figure 8. Controlled rotor speed with a single periodic controller

As shown in this diagram, the speed of the generator will reach a value of 1 per unit after 6.0 seconds (to the nominal value). After some times about 4.5 seconds will reach to the appointed value means 1.15 per unit (of nominal value to higher than nominal value) and is fixed in the same range with slight fluctuation due to changes in arrival wind speed.

4.3.2 Control of Active Power by Means of Single Periodic Controller

According to the operation time of generator, rotor can operate in either power absorber or producer, in super-synchronous mode, rotor is the power producer and in low-synchronous mode rotor can act as power absorber, Chart of active and reactive power of rotor is provided in Figure 9 and 10. Controlled Active power by controller is shown in Figure 11.

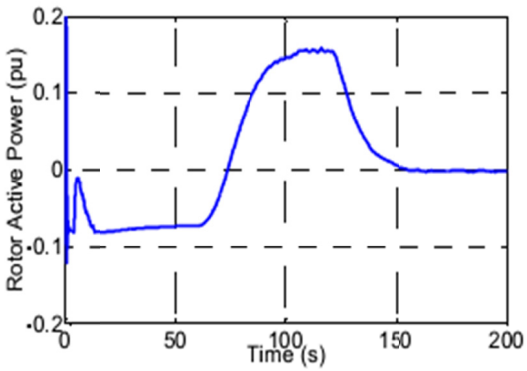


Figure 9. waveform of rotor active power

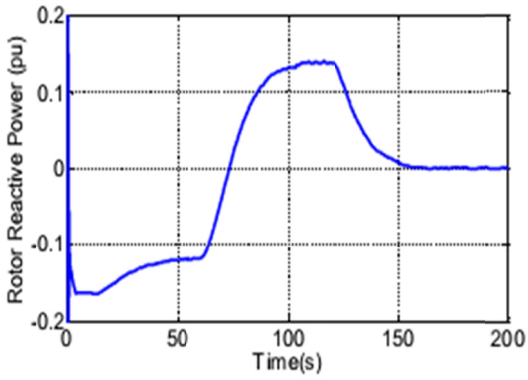


Figure 10. The waveform of rotor reactive power

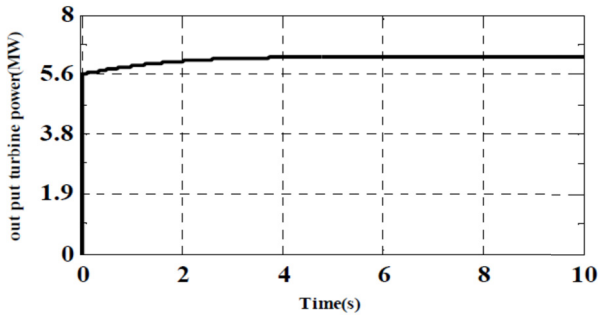


Figure 11. Output Active power of wind turbine

Since the stator voltage is connected to the grid voltage, therefore its value is constant, frame of synchronous has been considered so that the voltage D Stator is equal to zero and the voltage Q stator is equal to the network voltage (1 per unit), in figures 12 and 13 amounts of Q and D voltage and Stator current are displayed.

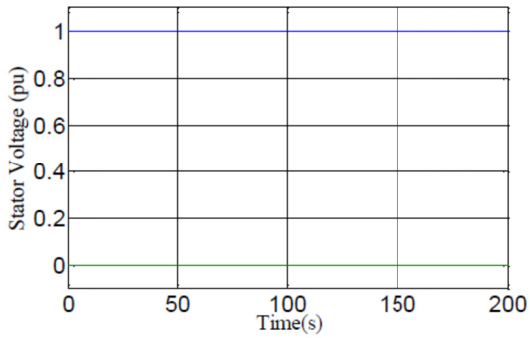


Figure 12. q, d components, stator voltage

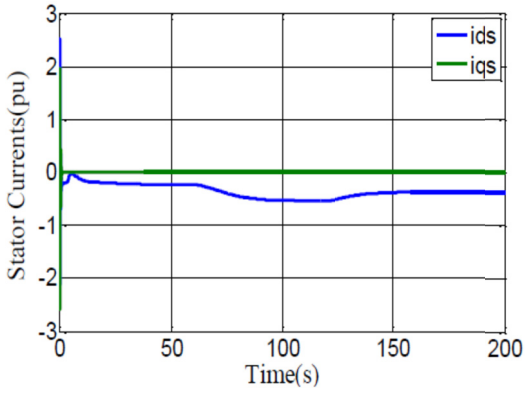


Figure13. q , d components, stator current

Control of generator output power emanating from the changes in wind speed is done by applying voltage to rotor, hence the chart of voltage and applied current to the rotor which are the results of a single periodic control are shown in figures 14 and 15.

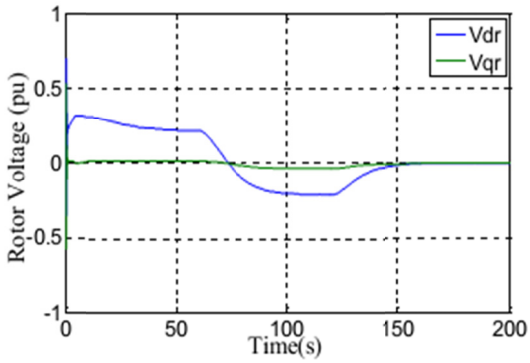


Figure 14. q, d Rotor voltage

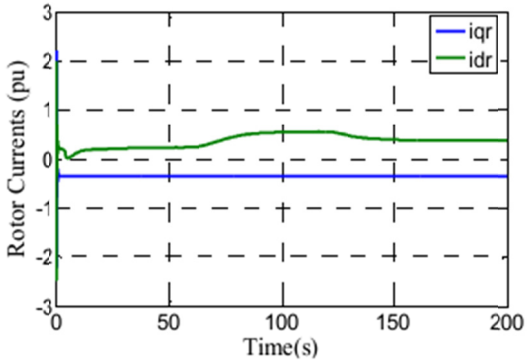


Figure 15. q, d Rotor current

4.4 THD Evaluation of Stator Current Wave Form

Figures 16 and 17 show waveform of stator frequency current spectrum with its THD calculation. In fact in order to check the quality of produced power, assessment of THD value of stator current is represented and as it can be seen, THD has low quantity of 1.13 which according to the proposed standards in, this amount is acceptable, also the waveform of stator current has good quality. This waveform is as a result of implementation of single periodic control method.

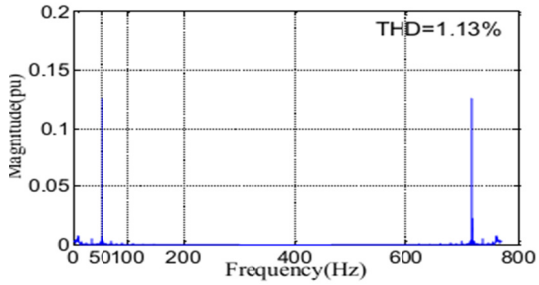


Figure 16. Waveform of three-phase stator current

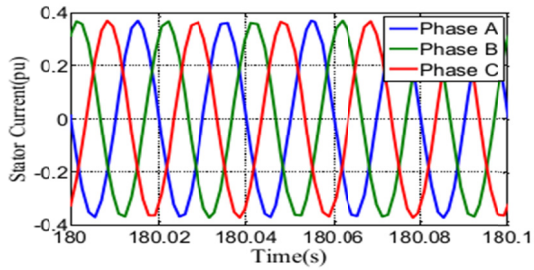


Figure 17. THD value of Stator current

DC link voltage is shown in Figure 18. As it mentioned before, its value should be a constant value so that output voltage of rotor side converter can be controlled and consequently grid side converter should keep this voltage fixed.

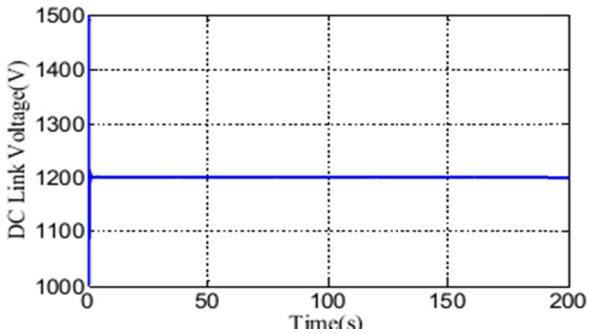


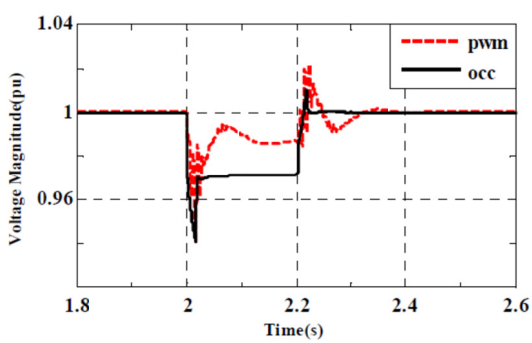
Figure 18. DC link voltage

4.5 Error Condition

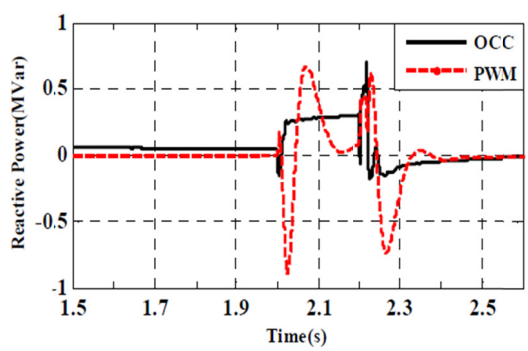
In figure (19) operation of controller under three-phase error is shown. We enter a three-phase error at the beginning of 25 kV transmission line. At first, after 2 seconds, an error happens and lasts for 0.2 seconds (about 12 cycles) and then during 2.2 seconds removed from the grid. When the three-phase error happens on grid, then a sudden drop will happen in generator voltage. At this time, the proposed controller is operated to restore the voltage at its original value. If the duration of voltage drop on the bus side of generator takes too long then can damage and separate the wind turbine.

For better understanding of capabilities in the proposed controller, figure 19 shows the comparison between operation of single periodic controller and PWM controller which indicates the priority of single periodic controller to the PWM controller.

By analyzing Figure 19, we can conclude that voltage rate of bus side generator and exchanged reactive power to the grid are less volatile in a single periodic control. In other words, stability during error and recovery speed of voltage after fault correction in single periodic is more than PMW method. Also produced fluctuations will be damped faster in the optimum value.



(A)



(B)

Figure 19. Performance of controller during three-phase error (A) bus voltage (B) reactive power

5. Conclusion

In this paper, in order to control the existing converters in a pneumatic system equipped with doubly fed induction generator, we used a single periodic control method. The input power to the generator is controlled by controlling the generator speed and we also control the reactive power by controlling the bus voltage under error condition in the grid using a single periodic controller. Genetic optimization algorithm is used in order to achieve optimal parameters of PI controller.

The results of this control method show its capability for controlling the active and reactive power and also elimination of harmonics caused by non-linear load. Finally, by comparing the single periodic method with common and famous PWM method, the accuracy and speed of the proposed single periodic method is specified.

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