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Power control of a wind energy based on a DFIG by sliding mode approach and pitch angle optimal control by genetic algorithm

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ABSTRACT

Purpose: In this paper, a regulate of a variable wind energy conversion system, based on a doubly fed induction generator DFIG is proposed, the system we considered is controlled to generate maximum energy while minimizing loads. In low to medium wind speeds, the generator and the power converter control the wind turbine to capture maximum energy from the wind, in the high-wind-speed regions, the wind turbine is controlled to maintain the aerodynamic power produced by the wind turbine. Generator torque and Pitch angle are controlled simultaneously to maximize energy capture.

Design/methodology/approach: Two methods for adjusting the aerodynamic power have been studied: For generator load control, The DFIG control structure contains rotor currents and stator powers loops where PI controllers are used. This control could be obtained by applying a DFIG active and reactive power decoupling strategy based on stator flux orientation method, Another controller based on a sliding mode theory is adopted to maximize the extracted power has been used , both of which are employed to regulate the operation of the DFIG. For the pitch control, a nonlinear controller based on artificial intelligence techniques: genetic algorithms, to regulate the blade pitch angle and rotate speed of the wind turbine system.

Findings: Proposed DFIG and pitch control algorithms provide good static and dynamic performances. Validity the strategies proposed was analyzed by simulations.

Originality/value: The intelligent controller is proposed to blade pitch position control above the rated wind speed in this paper; Genetic Algorithm based controller gave better results. Simulated wind turbine parameters are obtained from a real turbine and generating system. Hence, proposed controllers can be easily adapted to real time applications and operated with real wind turbines. Compared simulation results validate the proposed method in the paper is an effective method.

Keywords: DFIG; Sliding mode; Pitch angle; Genetic algorithms

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ANALYSIS AND MODELLING

1. Introduction

The main control objective is energy capture maximization by tracking the changes in wind speed and consequently maintaining optimum aerodynamic efficiency, Wind energy has evolved into an attractive energy source for electric utilities. It not only plays an important role in reducing environment pollution and changing country energy structure, but also promotes the sustainable development of economy, energy and society. The Double-fed induction generator (DFIG) and Pitch angle torque are controlled simultaneously to maximize energy capture. With this objective, the control system of DFIG wind turbine has been performed by three controllers:

- active power regulation of DFIG using sliding-mode control,
- reactive power regulation of DFIG using sliding-mode control
- pitch angle optimal control by genetic algorithm.

For The double-fed induction generator (DFIG) have attracted much attention in the variable speed wind energy applications due to their robustness, flexibility, effective and cheap implementation [1-6], doubly-fed induction machine DFIG is an electrical three-phase asynchronous machine with wound rotor accessible for control. The main purpose of this paper is to present the complete modeling and simulation analysis and performance comparison of wind turbine driven doubly-fed induction generator by using both the classical PI and Sliding Mode Controller.

The essential idea of sliding mode control is to enforce sliding-mode in a predefined sliding surface of the system state space. Once the state of system reaches the sliding surface, the structure of the controller is adaptively changed to slide the state of system along the sliding surface. Hence, the system response depends only on the predefined sliding surface and is insensitive to variations of system parameters and external disturbances. Interest in this regulate approach has emerged due to its potential to eliminate the effects of parameter variations with minimum complexity of implementation [7]. Our Sliding Mode Control strategy was adopted to control both the active and reactive power, and achieve the maximum wind energy capturing.

For the pitch control [8,9], a nonlinear controller based on artificial intelligence techniques: genetic algorithms [10,11], to regulate the blade pitch angle and rotate speed of the wind turbine system, Genetic algorithm is an evolution method based on natural selection theory and biological genetics. The algorithm simulates reproduction, intercross, and aberrance in the processing of natural selection and natural inheritance.

According to the natural rule "the survival of the fittest" [12] it uses genetic operators to select intercross and mutation until the optimal results are gained. Genetic algorithm provides a new way for the design of the optimal controller. The simulation results show that this strategy has fast dynamic response, good robustness and low dependence on the model parameters

2. Model of wind turbine

The model characteristics for the DFIG based wind turbine are presented in Figure 1. First, the turbine model is introduced concentrating the attention to the existing relationship between the wind speed and the amount of wind power that can be captured by this device. In second part the power coefficient characteristic as a function of the tip speed ratio and various values of the blade pitch angle is explained.

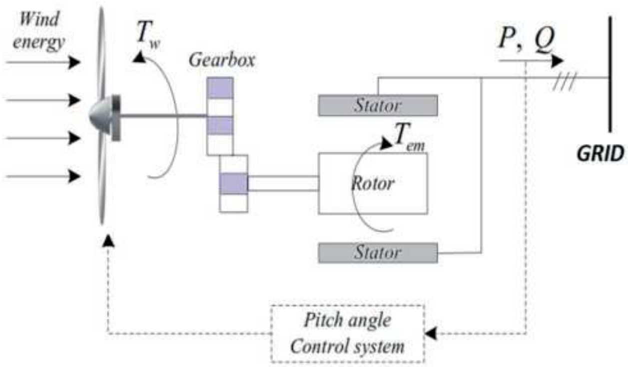

Fig. 1. The Doubly Fed Induction Generator based wind turbine

2.1. Model of DFIG

Figure 2 shows the equivalent circuit of a DFIG, expressed in space vector form in the stationary reference frame.

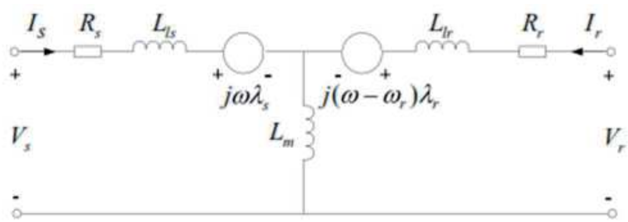

Fig. 2. Equivalent circuit of a DFIG referred to the stationary reference frame

The stator and rotor voltage equations and flux components are given below [13]:

$$\begin{cases} V_{ds} = R_S I_{ds} + \frac{d\varphi_{ds}}{dt} - \dot{\theta}_s \varphi_{qs} \\ V_{qs} = R_S I_{ds} + \frac{d\varphi_{ds}}{dt} - \dot{\theta}_s \varphi_{qs} \\ V_{dr} = R_r I_{dr} + \frac{d\varphi_{dr}}{dt} - \dot{\theta}_r \varphi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d\varphi_{qr}}{dt} - \dot{\theta}_r \varphi_{dr} \end{cases} \tag{1}$$

The stator and Rotor flux equation:

$$\begin{cases} \varphi_{ds} = L_S I_{ds} + M I_{dr} \\ \varphi_{qs} = L_S I_{qs} + M I_{qr} \\ \varphi_{dr} = L_S I_{dr} + M I_{ds} \\ \varphi_{qs} = L_S I_{qs} + M I_{qr} \end{cases} \tag{2}$$

The electromechanical equation is expressed by:

$$T_e = T_r + f\Omega + J\frac{d\Omega}{dt} \tag{3}$$

2.2. Model of turbine

The mechanical power transferred from the wind to the aerodynamic rotor is given in by:

$$P_a = \frac{1}{2}\rho\pi R^2 C_p\,(\lambda, \beta)\, v^3 \tag{4}$$

where ρ is the air density, R is the Radius of wind turbine; v is the wind speed and the power coefficient C_p. The power coefficient is a non-linear function depending on the tip speed ratio λ and β blade pitch angle $C_p = C_p(\lambda,\beta)$.

λ is defined as :

$$\lambda = \frac{\Omega_t * R}{V_{wind}} \tag{5}$$

where Ω_t the rotation speed of the rotor, V_{wind} wind speed.

The produced torque, T_t of the turbine can be found from:

$$T_t = \frac{P_a}{\Omega_t} \tag{6}$$

C_p value is calculated using a generic equation proposed in [14] given by:

$$C_p\,(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3.\beta - c_4\right)e^{-\frac{c_5}{\lambda_i}} + c_6.\Lambda \tag{7}$$

where: $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{1+\beta^3}$

The characteristic of power coefficient versus tip speed is shown in Figure 3. Under certain values of the wind power can be regulated by adjusting either tip speed ratio or pitch angle.

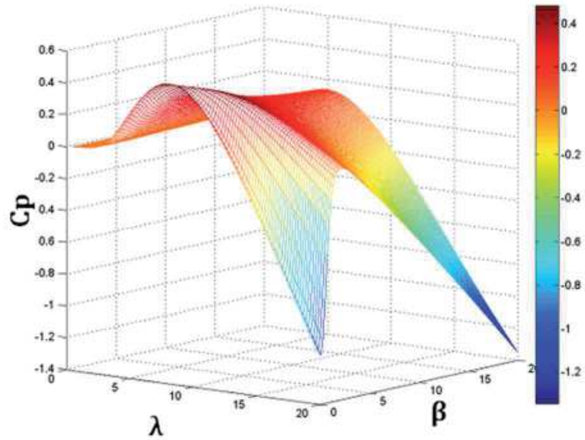

Fig. 3. Power coefficient as a function of the tip-speed ratio and pitch angle

3. Regulate strategy of system of DFIG wind turbine

3.1. Control of DFIG

The vector control strategy

In an aim to decouple the torque and the flux, the stator flux vector will be aligned with the d-axis. So, by neglecting the stator resistance and assuming that the stator flux $\varphi_{ds} = \varphi_s$ is maintained constant, we then have [15-17]:

$$\begin{aligned} V_{ds} &= 0 \\ V_{qs} &= V_s \approx \omega_s \varphi_{ds} \\ \varphi_{ds} &= \varphi_s = L_S I_{ds} + M I_{dr} \\ \varphi_{qs} &= 0 = L_S I_{qs} + M I_{qr} \end{aligned} \tag{8}$$

With this relation, the statoric active and reactive power, the rotoric fluxes and voltages can be written versus rotoric currents as:

$$\begin{cases} Ps = V_{ds} I_{ds} + V_{qs} I_{qs} = V_s \frac{L_m}{L_s} I_{qr} \\ Qs = V_{qs} I_{ds} - V_{ds} I_{qs} = -V_s \frac{L_m}{L_s} I_{dr} + \frac{{V_s}^2}{\omega_s L_s} \end{cases} \tag{9}$$

and:

$$\begin{cases} V_{dr} = R_r I_{dr} + \left(L_r - \frac{{L_m}^2}{L_s}\right)\frac{dI_{dr}}{dt} - g\omega_s\left(L_r - \frac{{L_m}^2}{L_s}\right)I_{qr} \\ V_{qr} = R_r I_{qr} + \left(L_r - \frac{{L_m}^2}{L_s}\right)\frac{dI_{qr}}{dt} - g\omega_s\left(L_r - \frac{{L_m}^2}{L_s}\right)I_{dr} + g\frac{L_m}{L_s}V_s \end{cases} \quad (10)$$

The sliding mode strategy

Generality

Sliding mode control is a robust technique for the regulation of nonlinear systems. It is a particular operation mode of variable structure control systems. Its concept consists in moving the state trajectory of the system to a predetermined surface called sliding surface and maintaining it around this latter with an appropriate logic commutation [18]. In general, for a system defined by the state equation (11), for a vector u of dimension m, we must choose m surfaces. In general, for a system defined by the state equation (11), for a vector u of dimension m, we must choose m surfaces.

$$\dot{x} = f(x) + g(x).u \quad (11)$$

with $x \in R^n$ and $u \in R^m$

Concerning the surface form, [19] propose the following form:

$$h(x) = \left(\frac{d}{dt} + \delta\right)^{\alpha-1}.e(x) \quad (12)$$

e(x): The error between the variable and its reference, δ: Positive constant indicating the desired control bandwidth, α: Relative degree, equal to the number of times to derive the output to appear the command.

When the regulate system operates in variable structure sliding mode, the switching (commutation low) always respects the condition: h(x) =0.

Therefore, the derivative versus time should also always be zero, i.e. $\dot{h(x)} = 0$, In order to respect this condition all times, the magnitude of command should take a well determined value, designated by the equivalent control u_{eq}. And in a way to lead the evolution trajectory of the system to *h=0*, the system must be submitted to the attraction of this surface. This will be done by the attractive control u_a determined by the condition of attractiveness $h(x).\dot{h(x)} < 0$ .This command defines the dynamic behaviour of the system during the trajectory convergence mode to the sliding surface. It is equal to zero once the sliding mode is achieved. The simplest solution is to choose u_a with the relay shape: $u_a = -k.sign[h(x)]$, with: k>0.

Thus, the necessary low control to bring back the variable we want control to the selected surface, respecting both existence and attractiveness conditions, is given by equation 13.

$$u = u_{eq} + u_a \quad (13)$$

In the proposed control strategy for DFIG based Wind turbine, rotor voltage components I_{qr} ,I_{dr} assumed as the system inputs and the stator active and reactive power *Ps*, *Qs* considered as the system outputs. The control objective is to capture maximum wind energy, considering wind speed as a disturbance, by tracking estimation of *Ps* and *Qs* in each instant. In other word, the aim of the purposed control is to capture the maximum disturbance power and the system operating points are determined by the disturbance.

The sliding mode control

The DFIG system is linearizable from an input-output linearization perspective [20], therefore the relative degree of the outputs should be well-defined. According to the wind turbine model the system outputs are defined and sliding surface, $h(t)$ and $\dot{h(t)}$, as follow:

$$\begin{cases} h_1(P) = (P_s^{ref} - P_s) \\ h_2(Q) = (Q_s^{ref} - Q_s) \end{cases} \quad (14)$$

and

$$\begin{cases} \dot{h_1}(P) = (\dot{P}_s^{ref} - V_s\frac{L_m}{L_s}\dot{I}_{qr}) \\ \dot{h_2}(Q) = (\dot{Q}_s^{ref} + V_s\frac{L_m}{L_s}\dot{I}_{dr}) \end{cases} \quad (15)$$

Differentiating results in instantaneous variations of stator active and reactive powers as:

$$\begin{cases} \dot{h_1}(P) = (\dot{P}_s^{ref} + V_s\frac{L_m}{\sigma L_s L_r}(V_{qr} - \mathbf{R_r I_{qr}})) \\ \dot{h_2}(Q) = (\dot{Q}_s^{ref} + V_s\frac{L_m}{\sigma L_s L_r}(V_{dr} - \mathbf{R_r I_{dr}})) \end{cases} \quad (16)$$

We consider that:

$$\begin{cases} V_{qr} = V_{qr}^{eq} + V_{qr}^{n} \\ V_{dr} = V_{dr}^{eq} + V_{dr}^{n} \end{cases} \quad (17)$$

$$\begin{cases} \dot{h_1}(P) = (\dot{P}_s^{ref} + V_s\frac{L_m}{\sigma L_s L_r}(V_{qr}^{eq} + V_{qr}^{n} - \mathbf{R_r I_{qr}})) \\ \dot{h_2}(Q) = (\dot{Q}_s^{ref} + V_s\frac{L_m}{\sigma L_s L_r}(V_{dr}^{eq} + V_{dr}^{n} - \mathbf{R_r I_{dr}})) \end{cases} \quad (18)$$

To ensure the attractiveness condition $h(x).\dot{h(x)} < 0$, *h(x)* is chosen, So, the active and reactive power command of DFIG are:

$$\begin{cases} \dot{h_1}(P) = -V_s \dfrac{L_m}{\sigma L_s L_r} V_{qr}^n \\ \dot{h_2}(Q) = -V_s \dfrac{L_m}{\sigma L_s L_r} V_{dr}^n \end{cases} \tag{19}$$

where k_1 and k_2 are positive constants, sign(h) is the signum function.

$$\begin{cases} V_{qr}^{eq} = k_1 . V_{dr}^n . \mathrm{sign}\big(h_1(P)\big) \\ V_{dr}^{eq} = k_2 . V_{qr}^n . \mathrm{sign}\big(h_2(Q)\big) \end{cases} \tag{20}$$

with $k_1 . V_{qr}^n > 0$ & $k_2 . V_{dr}^n > 0$

$$\begin{cases} V_{qr}^{lim} = V_{qr}^{MAX} . \mathrm{sat}\big(h_1(P)\big) \\ V_{dr}^{lim} = V_{dr}^{MAX} . \mathrm{sat}\big(h_2(Q)\big) \end{cases} \tag{21}$$

3.2. Control pitch angle

Genetic Algorithm (GA) works on the theory of Darvin's theory of evolution and the survival-of-the fittest [21]. Genetic algorithms guide the search through the solution space by using natural selection and genetic operators, such as crossover, mutation and the selection. A flow-chart of the GA algorithm optimization is given in Figure 4.

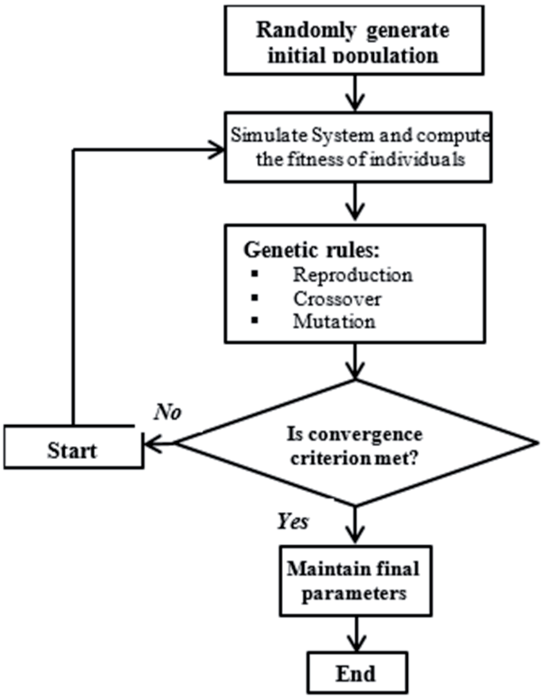

Fig. 4. Flow-chart of the GA algorithm optimization

The proposed Genetic algorithm regulatory approach can be better explained by considering the turbine power curves shown in Figure 5.

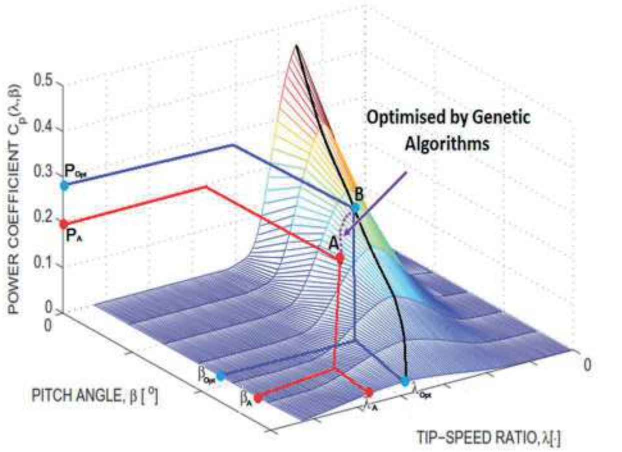

Fig. 5. The block diagram of the blade angle control system

Assuming that the wind turbine operates initially at point A, the genetic algorithm controller measured λ_A speed ratio and β_A angle pitch, turbine power P_a can derive the corresponding optimum operating point B, giving the desired rotor speed reference λ_{Opt} and send a control signal for new β_{Opt}. Therefore, the generator speed will be regulated in order to reach the speed Ω_A and β allowing the extraction of the maximum power P_{Opt} from the turbine [14].

4. Simulation results

Simulations of the proposed regulate strategy for a DFIG based wind power generation systems were carried out, using MATLAB/Simulink. Scheme of the studied device is shown in Figure 6.

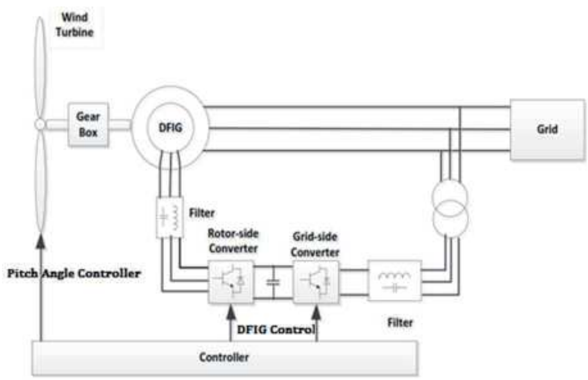

Fig. 6. Scheme of the studied device

4.1. The active and reactive power regulation of DFIG using sliding-mode control

The machine is first tested as in ideal conditions mode. Different step inputs for an active and a reactive power were applied and we observed the response obtained with both the vector control and the Sliding Mode control, results are presented in Figure 7.

a)

b)

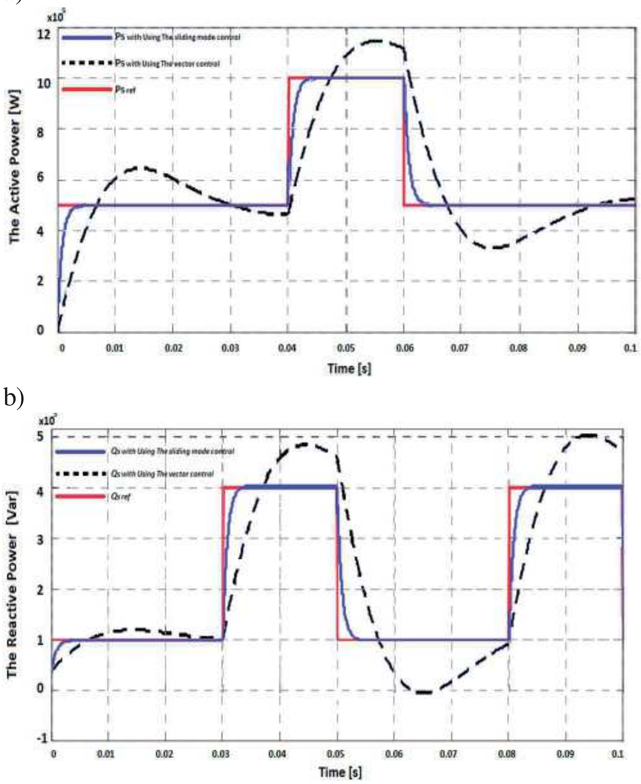

Fig. 7. The response of a) active and b) reactive power with both the vector control and the sliding mode control

This test shows clearly that in the case of the classical vector control regulator, the time response is strongly altered whereas in the case of the proposed regulator sliding mode control it is almost! Unaltered. Thus, we can conclude from these results that the regulator sliding mode control is more powerful than the classical one.

4.2. Pitch angle optimal regulate by genetic algorithm

In Genetic Algorithm-based control, output power and rotor speed reach the rated value quickly.

When wind speed is increased above the rated speed, Figure 8a, the pitch controller prevents the turbine from overloading and does not allow power generation above the system's rated power. This situation continues when the wind speed is increased again at 14 m/s. Power generation λ also change as shown in Figure 8b.

The blade pitch angle is increased so that turbine blades is braked and slowed down as seen in Figures 8a-c.

a)

b)

c)

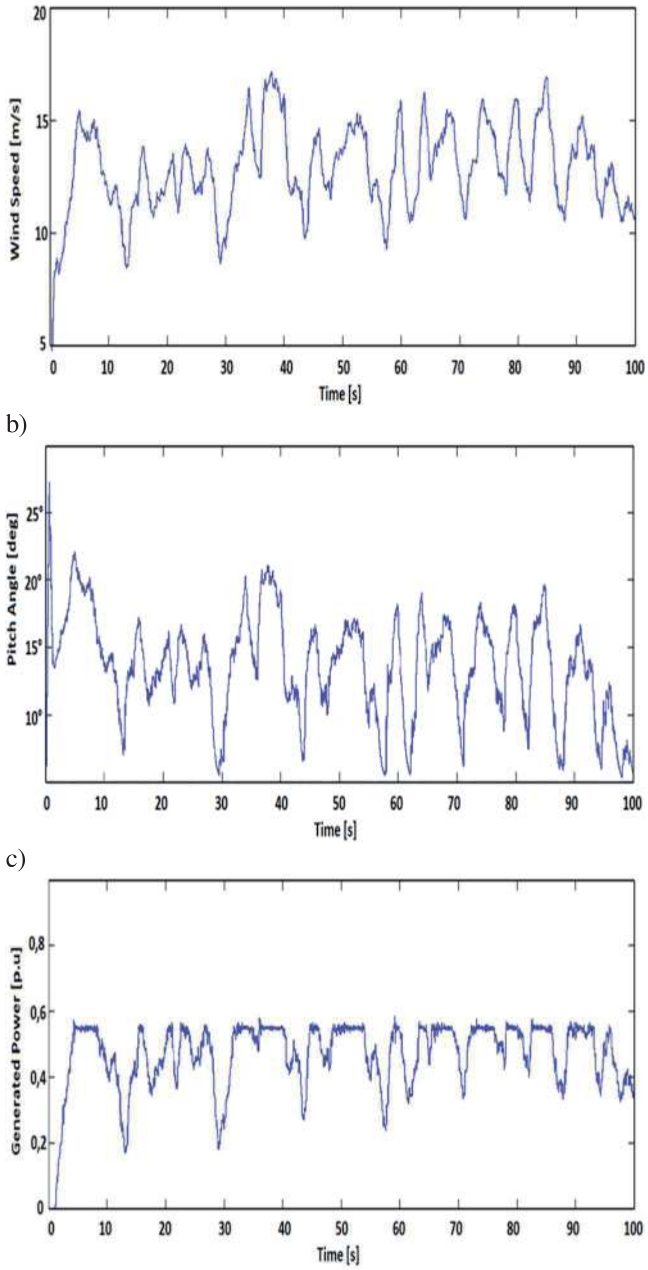

Fig. 8. a) Wind speed, b) pitch angle β, c) generated power

The performance coefficient, tip speed ratio and pitch angle were changed according to the trained Genetic Algorithm controller outputs.

5. Conclusions

Frequency and power regulate in large wind power plants have a great importance due to variable and uncontrollable wind speeds.

In this study, adaptation of pitch controllers to variable conditions and their suitability for controlling the over wind speeds are investigated.

Two controllers are proposed:

1. The paper adopted stator voltage orientation vector control strategy in DFIG (parameters of DFIG – Table 1) and studied the principle of DFIG; According to the mathematical model of DFIG, the paper proposes a higher-order sliding mode controller for the model.
2. The intelligent controller is proposed to blade pitch position control above the rated wind speed in this paper; Genetic Algorithm based controller gave better results. Simulated wind turbine parameters are obtained from a real turbine and generating system (Tab. 2). Hence, proposed controllers can be easily adapted to real time applications and operated with real wind turbines. Compared simulation results validate the proposed method in the paper is an effective method.

Table 1.
Parameters of DFIG

Symbol	Value
Pole Pairs P	2
Rated Power Pm	1.5 MW
Stator resistance Rs	0.012 Ω
Rotor resistance Rr	0.021 Ω
Stator inductance Ls	0.0137 H
Rotor inductance Lr	0.0136 H
Mutual inductance Lm	0.0135 H

Table 2.
Parameters of turbine

Symbol	Value
Gain multiplier	90
Radius of the wind R	35.25 m
Stator resistance Rs	1.22 Kg /m^3

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