PITCH ANGLE CONTROL FOR VARIABLE SPEED WIND TURBINES WITH DOUBLY FED INDUCTION GENERATORS

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Abstract: *In this paper, we focus mainly on controlling the aerodynamic power collected by the turbine. The goal is to limit this power when the wind speed becomes too high. We demonstrate the importance and influence of the pitch angle on the performance of a variable speed wind turbines based on Doubly Fed Induction Generator (DFIG).This ingenious device uses the pitch variation primarily as a means of power control which increases with the cube of the wind speed. The effectiveness of the proposed control strategy is evaluated by simulation results.*

Key words: *Variable-speed wind turbine, DFIG (Doubly Fed Induction Generator), Pitch control.*

1. Introduction

Electrical energy is one of the most important factors in daily life of human beings as well; the global consumption is increasing by the multiplicity of business areas and daily needs using electricity. Much of this energy comes from fossil fuels causing environmental problems.

From this fact and following the search for sustainable development, mastery and development of renewable energy have become one of the important topics discussed and conveyed in congresses, conferences and research labs ect. , especially wind energy has evolved tremendously over the past two decades [2].

The need for control of wind turbines back to their origins of Use. The main purpose was the limitation of the power and speed to protect the turbines from strong winds [8]. Nowadays, wind turbines have become in size and larger power, control specifications more demanding and more sophisticated regulatory mechanisms. Moreover, it was expected that control systems not only keep the turbine in its safe operating area, but also improve the efficiency and quality of energy conversion which requires more accurate modelling and demanding and different control techniques for each range of wind speeds, low, medium or high.

Controlling a variable speed wind generator is divided into two parts: the mechanical control through the setting angle of the blades and the machine controller via electric power electronics. Currently, the strategies are designed to extract maximum power from the wind. This power is extracted when the turbine operates at maximum power coefficient. Using the strategy MPPT (Maximum Power Point Tracking) which automatically adjusts the specific rate at its optimum value, so as to obtain maximum power coefficient [1], [2], [3]. But, in the case of high winds, it is necessary to degrade a portion of the kinetic power not to damage the turbine and also the electrical machine. The speed limit is obtained with the control of the setting angle.

When the wind speed becomes too great, the pitch angle increases to decrease the speed of the turbine and limit the power generated at nominal power (P_n). [2] [4],[7]. The control of the turbine aims then to maximize the power extracted from the wind when the wind speed is less than its nominal value and to limit the electrical power when the wind speed exceeds the nominal value [10].

In this study, we present a strategy to control the pitch angle of a variable speed wind turbine based on double-fed induction generator (DFIG) of 1.5MW. The overall pattern of a string conversion of wind energy connected to the grid is described in Fig. 1. The stator is connected to the network, the rotor being connected to the latter by means of a cascade rectifier and inverter phase three-level structure NPC

2. Modelisation of the wind turbine

2.1 Model of the turbine

The recoverable energy wind across the surface S swept by the blades of a wind turbine is given by the relation [7]:

$$P_v = \frac{1}{2}\rho S v^3 \quad (1)$$

ρ , ***v***: Density and wind speed.

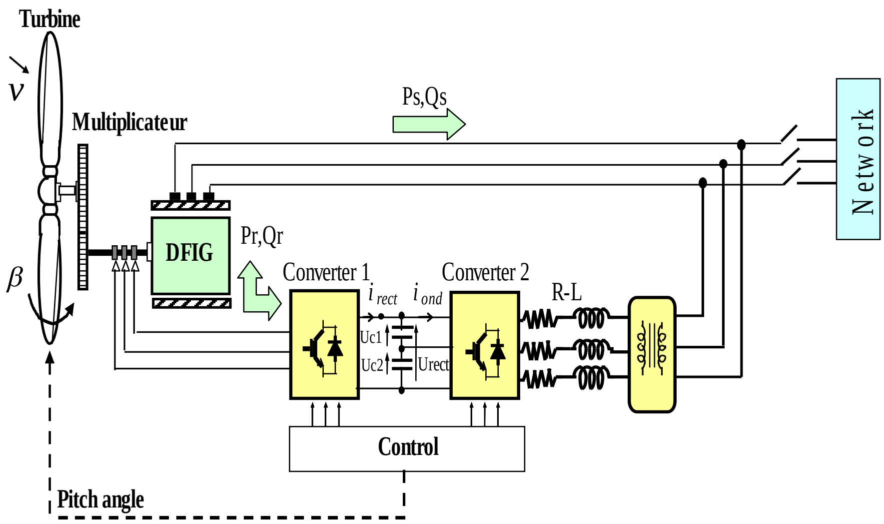


Fig. 1. Schematic representation of DFIG-based wind turbine

The aerodynamic performance of horizontal axis wind turbine is expressed by the power coefficient C_p is written as follows:

$$P_t = C_p(\lambda,\beta)P_v = \frac{1}{2}\rho S C_p(\lambda,\beta).v^3 \qquad (2)$$

The theoretical maximum value of this coefficient called Betz limit is 16/27. It is variable and depends on the characteristic of the turbine and wind speed. It is often represented by the ratio of the speed **λ** which is defined by the expression: **λ=R Ω_t/v.** Or **Ω_t** is the mechanical speed of the turbine (rad /s^{-1}).

It is possible to define the coefficient **C_p** by a mathematical approximation for a 1.5MW wind turbine [11]:

$$C_p(\lambda,\beta) = (0.5 - 0.00167(\beta-2))\sin[\frac{\pi(\lambda+0.1)}{18.5-0.3(\beta-2)}] \qquad (3)$$
$$-0.00184(\lambda-3)(\beta-2)$$

On Fig. 2 is represented this coefficient in function of λ and for different values of pitch angle β of the blades. This curve is characterized by the optimal point (λ_{opt}=9, $C_{p\text{-}max}$=0.5, β=2°) corresponding to the maximum power coefficient C_p and therefore the maximum mechanical power recovered.

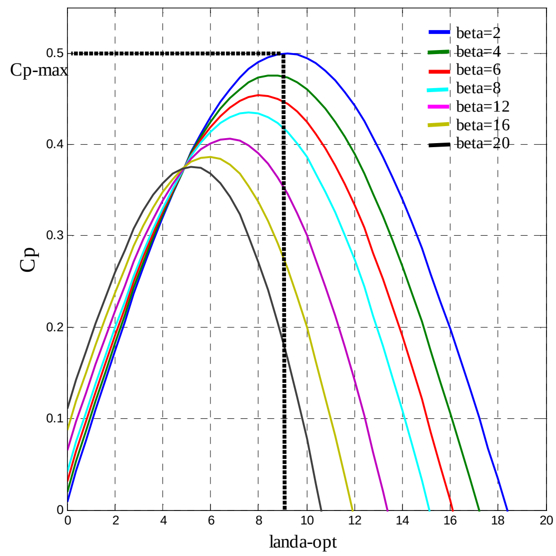


Fig. 2. The Representation of Cp as a function of λ for different values of β

The relation (2) permits the deduction the characteristic that binds to a given wind speed, the power of the turbine as a function of its speed of rotation for β=2° Fig. 3.

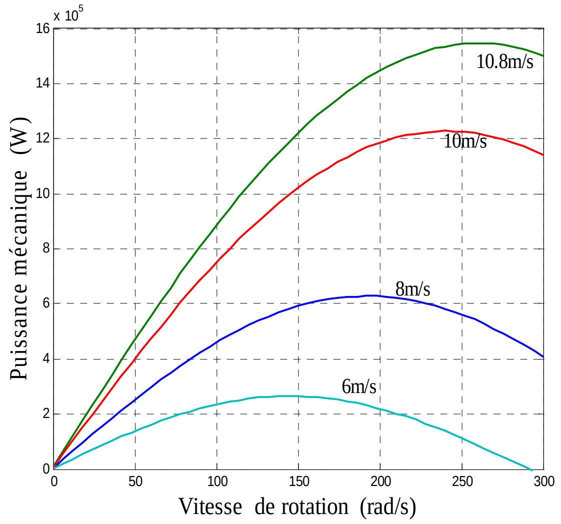


Fig. 3. Wind Power as a function of speed rotation for different wind speeds

Knowing the speed of the turbine Ω_t, the aerodynamic torque is directly determined by:

$$T_{aer} = \frac{P_{aero}}{\Omega_t} = \frac{1}{2\Omega_t} C_p(\lambda).\rho\pi R^2 v^3 \qquad (4)$$

The multiplier adapts the slow speed of the blades to the fast speed of the machine by the multiplication ratio G. This element defines the mechanical torque and speed of the machine as follows:

$$T_g = \frac{T_{aero}}{G} \qquad (5)$$

$$\Omega_{mec} = G\Omega_t$$

The fundamental equation of dynamics determines the evolution of the mechanical speed of the generator. The simplified model of this equation is given by:

$$J\frac{d\Omega_{mec}}{dt} = \frac{J}{P}\frac{d\omega_{mec}}{dt} = T_{mec} = T_g - T_{em} - f\Omega_{mec} \qquad (6)$$

Where J is the total inertia that appears on the shaft of the generator, T_{em} electromagnetic torque, P the number of pairs of poles, ω_{mec} electrical angular speed of the rotor and f is a coefficient of viscous friction.
Fig. 4 can define a physical model of the turbine having as inputs the pitch of the blades, wind speed and electromagnetic torque provided by the generator.

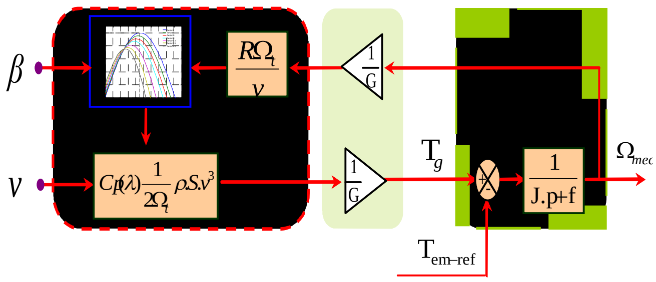


Fig. 4. Block diagram of the model of the turbine

Fig. 5 shows the four areas of operation of a wind turbine incorporating a DFIG, according to [1], [9] of which two are in the range of wind turbine production:

Area **2**: Correspond to low wind speeds; the power available in this area is less than the rated power of the turbine. The objective in this area is to extract maximum power from the wind by applying a technical MPPT (MPPT Maximum Power Point Tracking).
Area **3**: Corresponds to strong winds, the goal in this area is to limit the power produced at a value equal to the rated power of the wind to avoid overload. This is done by acting on the blade pitch angle, is the pitch control. The blades are facing into the wind at low speed for high speeds they bow to degrade the power coefficient. They reach the feathered position at maximum speed.
In both zones, the wind speed is below a limit (v_{max}) of the wind stop determined for safety reasons

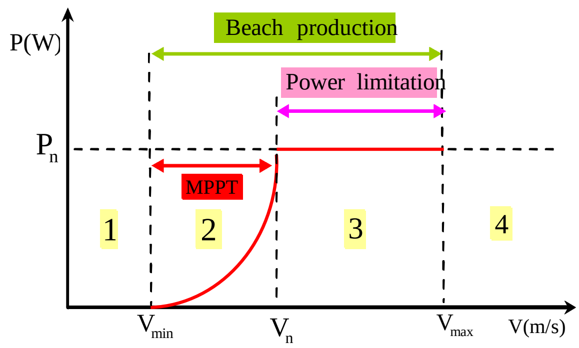
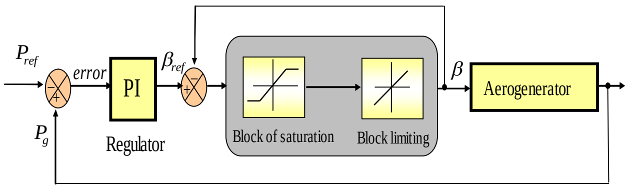


Fig. 5. Areas of operation with control of the pitch angle (pitch control)

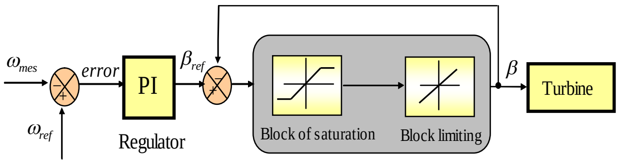
2.1.1 Pitch angle control

Two techniques for generation of the reference angle β_{ref} [5]. Fig. 6:
- Fig. 6(a)**:** The generated power P_g, is compared with the reference power P_{ref}, the error in them, and sent to the PI controller that generates the reference value of the angle β_{ref}.
- Fig 6(b): the speed of the turbine ω_{mes}, compared with the reference speed ω_{ref}, the error in them, and sent to the PI controller that generates the reference value of the angle $\beta_{ref.}$

In the rest of our work the pitch angle generates by the electric power. account held the efforts suffered by the blades, the change in pitch angle must be limited to about 12°/s during normal operation and 20°/s for cases of emergency imposed by the limiter block [5]. The saturation block imposes upper and lower limits on a signal, in our case in the setting angle limit of 0° to 90 °.



-a- by the electric power



-b- by the turbine speed

Fig. 6. Generation of the Pitch angle

2.2 The DFIG modelling and control

The electric and magnetic relations governing the operation of the DFIG from [8] are:

$$\begin{cases} v_{ds} = R_s.i_{ds} + \dfrac{d\phi_{ds}}{dt} - \omega_s.\phi_{qs} \\ v_{qs} = R_s.i_{qs} + \dfrac{d\phi_{qs}}{dt} + \omega_s\phi_{ds} \\ v_{dr} = R_r.i_{dr} + \dfrac{d\phi_{dr}}{dt} - \omega_r\phi_{qr} \\ v_{qr} = R_r.i_{qr} + \dfrac{d\phi_{qr}}{dt} + \omega_r\phi_{dr} \end{cases} \quad (7)$$

$$T_{em} = -P\frac{M}{L_s}(\Phi_{qs}i_{dr} - \Phi_{ds}i_{qr})$$

$$\begin{cases} \phi_{ds} = L_s.i_{ds} + M.i_{dr} \\ \phi_{qs} = L_s.i_{qs} + M.i_{qr} \\ \phi_{dr} = L_r.i_{dr} + M.i_{ds} \\ \phi_{qr} = L_r.i_{qr} + M.i_{qs} \end{cases} \quad (8)$$

The stator active and reactive power rotor are defined by:

$$\begin{cases} P_s = v_{ds}i_{ds} + v_{qs}i_{qs} \\ Q_s = v_{qs}i_{ds} - v_{ds}i_{qs} \end{cases}, \begin{cases} P_r = v_{dr}i_{dr} + v_{qr}i_{qr} \\ Q_r = v_{qr}i_{dr} - v_{dr}i_{qr} \end{cases} \quad (9)$$

By choosing a reference two-phase (d, q) related to the rotating stator field and aligning the stator flux vector Φ_s with the axis, we can write $\Phi_{ds} = \Phi_s$ and $\Phi_{qs}=0$ [9].

Then the torque is simplified as indicated below:

$$T_{em} = -P\frac{M}{L_s}\phi_s i_{qr} \quad (10)$$

The electromagnetic torque and power depend only on the current active rotororique axis q. neglecting the stator resistance machines for medium and high power we have: $v_{ds}=0$, $v_{qs}= v_s$ Thus, the rotor currents are related to the stator active and reactive power as follows:

$$\begin{cases} P_s = -v_s\dfrac{M}{L_s}i_{qr} \\ Q_s = \dfrac{v_s\Phi_s}{L_s} - \dfrac{v_sM}{L_s}i_{dr} \end{cases} \quad (11)$$

Regulation of the rotor currents can control the exchange of power between the stator and the network. Equation (12) gives the expression of tensions rotor according to the rotor currents.

$$\begin{cases} v_{dr} = R_ri_{dr} + (L_r - \dfrac{M^2}{L_s})\dfrac{di_{dr}}{dt} - g\omega_s(L_r - \dfrac{M^2}{L_s})i_{qr}; \\ v_{qr} = R_ri_{qr} + (L_r - \dfrac{M^2}{L_s})\dfrac{di_{qr}}{dt} + g\omega_s(L_r - \dfrac{M^2}{L_s})i_{dr} + g\omega_s\dfrac{Mv_s}{\omega_sL_s}. \end{cases} \quad (12)$$

3. Simulation Results

Fig. 7 shows the profile of the wind that has been applied to the wind turbine varies below and above its rated speed 11.8m/s. This variation can observe the operation of the wind in both areas of operation (2 and 3), or we are interested in Area 3.

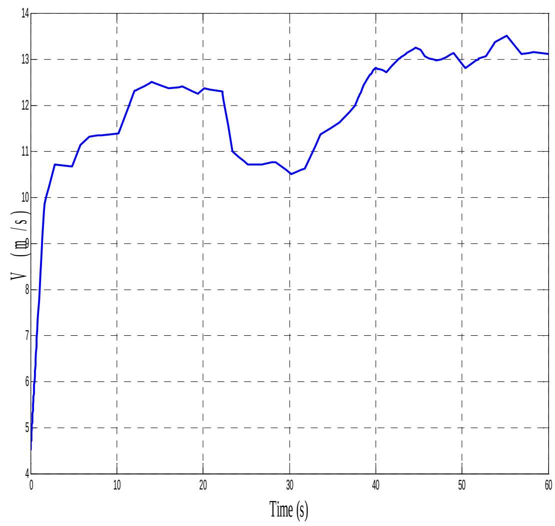


Fig. 7. The wind profil

Fig. 8 shows the time of starting the wind the pitch angle β is set at a value of 0° to a power variation ranging from 0 to about 1.6MW (Fig. 9). Then, this angle varies vertically to reach such values so as to maintain constant power, in a time which varies depending on the speed of the selected pitch angle (12°/s).

The setting angle comes into play and goes from 0° to 24° in near 2s [11.9s , 13.9s] the influence of this passage see this on the electrical power generated, exceeded 9% of the power beyond the set point (nominal power) Fig. 9.

At the 24s, the pitch angle β, returns to 0° which implies that at that moment the wind speed dropped beyond the wind speed that produces the nominal power at 0°, therefore, the pitch system is deactivated, and resumes the regulation has the 38s .

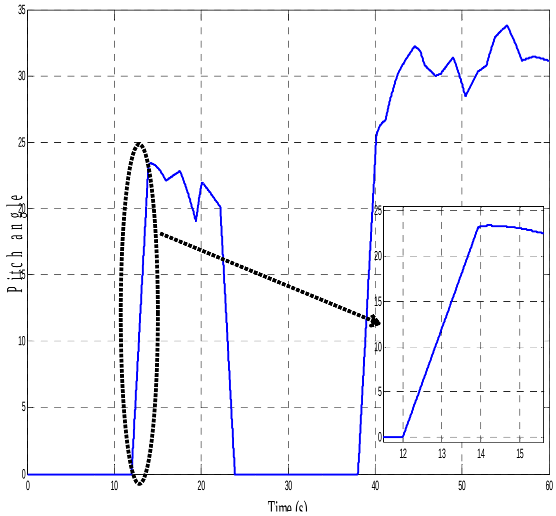


Fig. 8. Pitch angle (variable speed 12°/s)

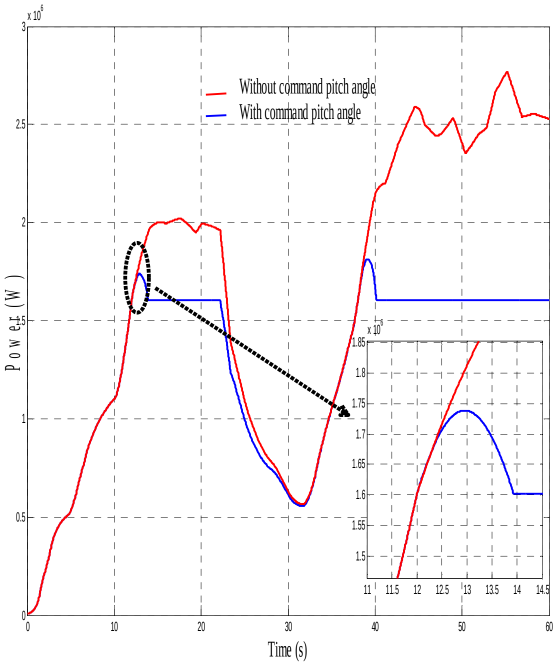


Fig. 9. Electric power generated

Fig. 10 and Fig.11 shows the simulation results for a speed variation of the pitch angle of 20°/s. At boot time the wind the pitch angle β pass 0° to 24° in 1.3s near [11.9s, 13.2s] (Fig.10), a significant improvement compared to the previous configuration of 12°/s which is 2s [11.9s, 13.9s], (Fig. 8). Rest, this configuration is used only in emergencies where the blades positioned doits feathered beings (90°) in a very short period of time.

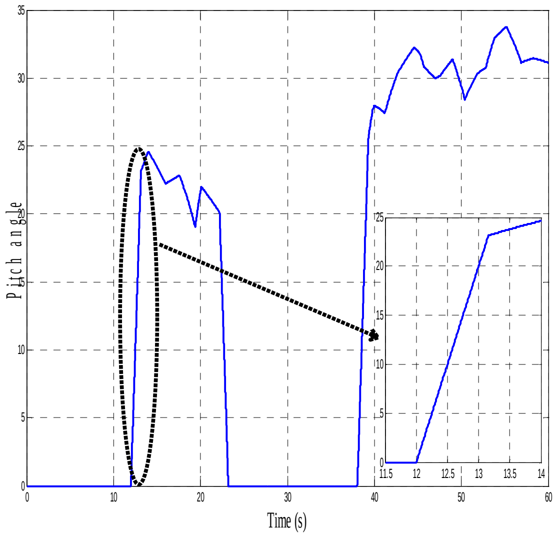


Fig. 10. Pitch angle (variable speed 20°/s)

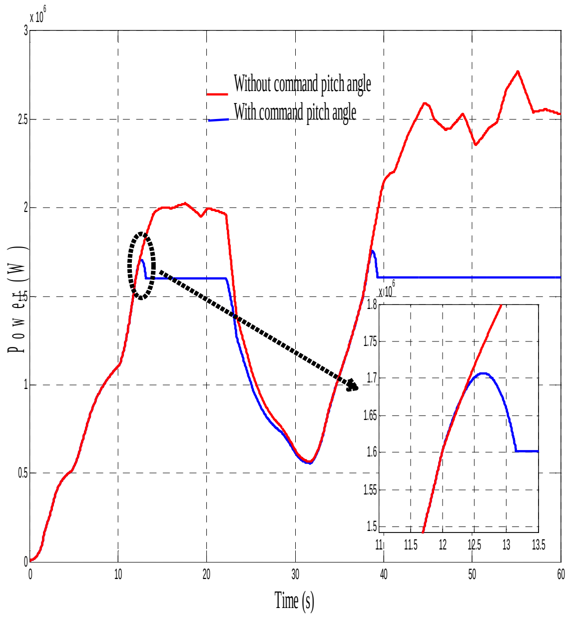


Fig. 11. Electric power generated

Fig. 11 shows the effect of pitch angle β of 20°/s on the electrical power generated. At 20°/s the effect on the power curve is remarkable, and clearly shows that the power is fully stabilized in less time and overtaking 6%. Therefore, the speed pitch angle plays a primordial role in the quality and reliability of power, but it is limited by the efforts that can withstand the pales.

Fig. 13 shows the simulation results of the power or the laws of physics are neglected, or the speed of the pitch angle will be sized in an exaggerated manner, to see the difference between the realities of things.
Speed pitch angle β set to a value excessive at 600°/s, the pitch angle changes from 0 ° angle to another in a fraction of second Fig.12, the result is probably perfect. Note that no overtaking (0%) beyond the reference power.

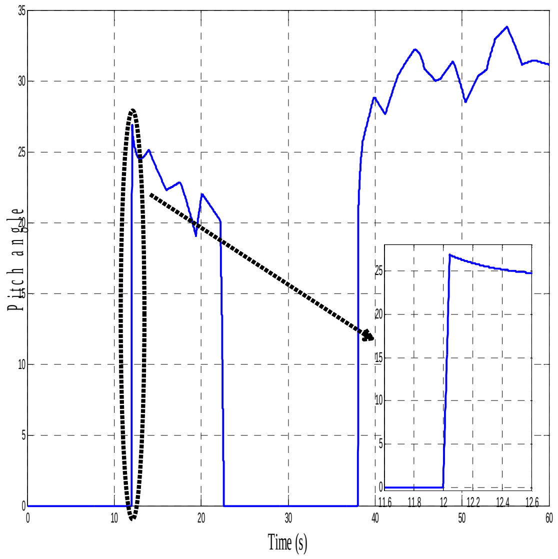


Fig. 12. Pitch angle (variable speed 600°/s)

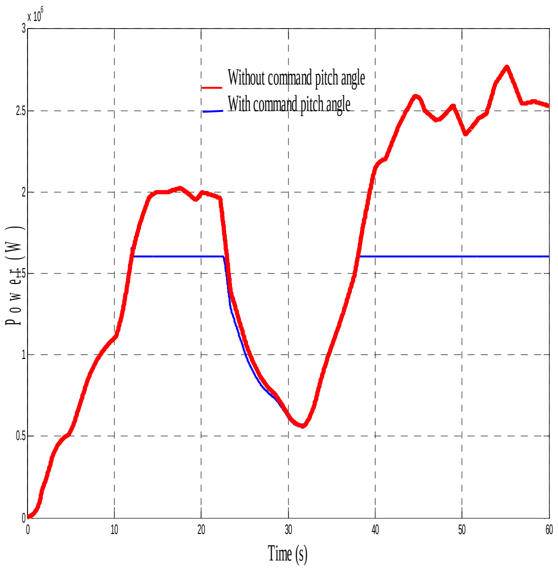


Fig. 13. Electric power generated

In order to see the behavior of the chain with the wind system of orientation of the pales, we applied the same wind profile of 60 seconds.

It appears that the pitch angle β affects the various magnitudes: the power coefficient C_p, the relative speed, power generation and mechanical rotor speed. Figures 14, 15, 16 and 17.

Fig. 17 and Fig. 18 shows that the active and reactive power following their references, the intervention of blade pitch system that comes into play between times 13s and 22s and 40s and 60s, causing a limitation of active power, with a mere passing related to the speed of rotation of the blades was set at 12°/s and remarkable. The reactive power set point is maintained at zero to ensure a unity power factor stator side. The ripples on the powers are due to the presence of the PWM inverter.

The variation in amplitude of the stator currents follows the variation in active power delivered to the network Fig.19. Currents limited to its nominal value imposed by the system of orientation of the blades, In Fig. 20 watches that the amplitude of rotor currents equal the stator currents by cons in the frequency varies with the slip. At time t=13s to 22s, and t=39s to 60s, we note that the current is constant in amplitude and frequency, caused by the intervention of the pitch angle β.

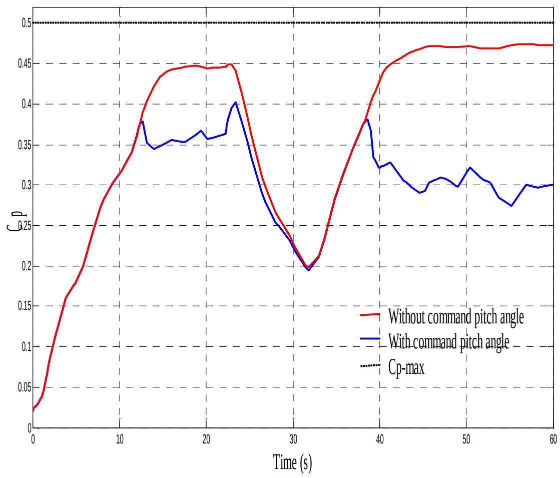


Fig. 14. Power coefficient

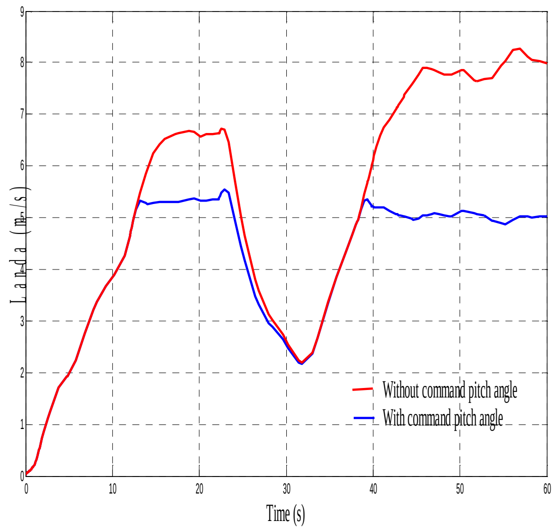


Fig. 15. The relative speed λ

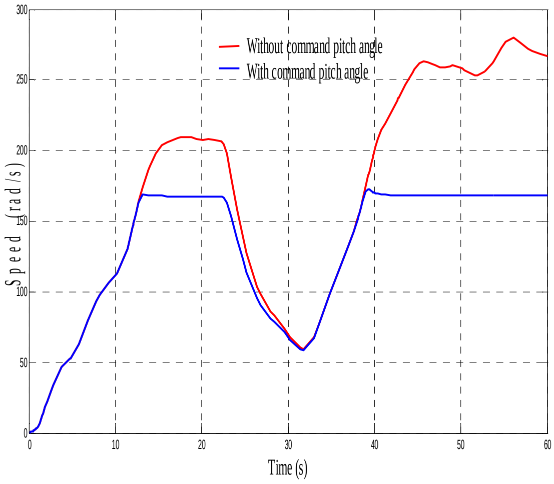


Fig. 16. The speed

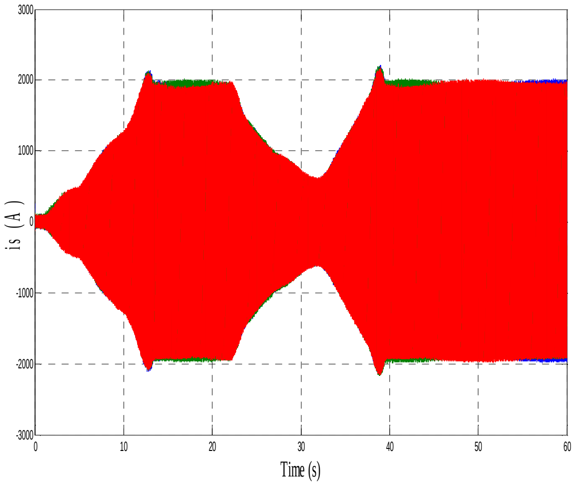


Fig. 19. Stator current

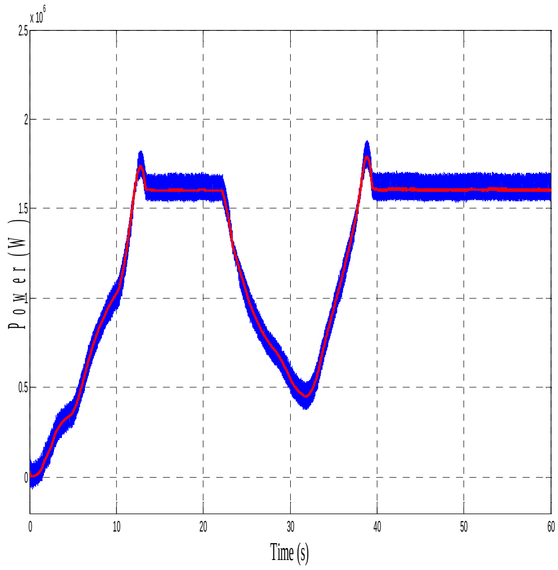


Fig. 17. The active power of the DFIG

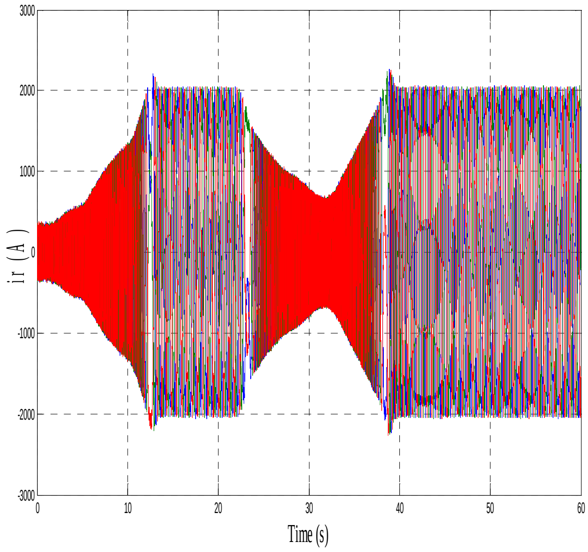


Fig. 20. Rotor current

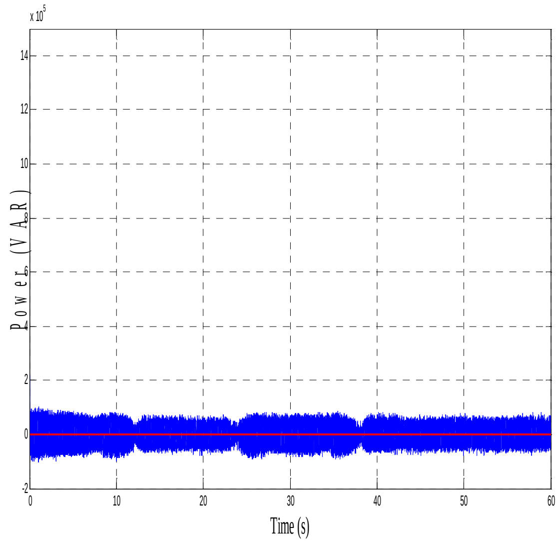


Fig. 18. The reactive power of the DFIG

Conclusion

In this paper, the study was done to Bute see the behavior of the chain of wind turbine with the orientation system of the pales (pitch control),the simulations showed clearly the interest of the operation of this system. For a wind which gives a power greater than the nominal of the turbine, the wind turbine equipped with this system pitch allows to lower the excess power to keep it constant to ensure the continuity of the production of electrical energy, which provides a more level economic performance and commercial. So the orientation of the pales, it is a protection system that reacts to the wind without cutoff action, all ensuring continuity of service.

References

1. Merabet A.,Thongam J.,Gu J.: *Torque and Pitch Angle Control for Variable Speed Wind Turbines in All Operating Regimes*. 2011 IEEE.

2. Mansour M., Mansouri M.N., Mimouni M.F.: *Study of Performance of a Variable-Speed Wind Turbine with Pitch Control Based on a Permanent Magnet*. 8th International Multi-Conference on Systems, Signals & Devices, IEEE-2011.

3. Hamzaoui I., Bouchafaa F., Hadjammar A., Talha A.: *Improvement of the performances MPPT system of wind generation*. Saudi international Electronics, Communications and photonics Conference (CIECPC' 11), 23-26 April, 2011.

4. Isaac I.A., Cabrera D., Pizarro H., Giraldo D., Gonzalez J.W., Biechl H.: *Fuzzy Logic Based Parameter Estimator for Variable Speed Wind Generators PI Pitch Control*. 2010- IEEE.

5. Zhang J., Cheng M., Chen Z., Fu X.: *Pitch Angle Control for Variable Speed Wind Turbines.* DRPT 2008 6-9 April, 2008 Nanjing China.

6. Uehara A., Pratap A.,Goya T., Senjyu T., Yona A., Urasaki N.,Funabashi T.: *A Coordinated Control Method to Smooth Wind Power Fluctuations of a PMSG-Based WECS.* IEEE TRANSACTIONS ON ENERGY CONVERSION, Vol. 26, No. 2, June 2011.

7. Wenjing Z., Hongze XU.: *Active Disturbance Rejection Based Pitch Control of Variable Speed Wind Turbine*. Proceedings of the 30th Chinese Control Conference, 22-24 July 2011, Yantai, China.

8. Ben Elghali S.E.: *Modélisation et Commande d'une Hydrolienne Equipée d'une Génératrice Asynchrone Double Alimentation.* JCGE'08 LYON, 16-17 décembre 2008.

9. Boukhezzar B., Lupu L., Siguerdidjane H., Hand M.: *Multivariable control strategy for variable speed, variable pitch wind turbines.* Elsevier, Journal Renewable Energy 32 (2007) 1273-1287.

10. ABU-TABAK N.: *Stabilité dynamique des systèmes électriques multi machines: modélisation, commande, observation et simulation*. Thèse de Doctorat, Ecole Centrale de Lyon, France, Novembre 2008.

11. EI Aimani S.: *Modélisation de différentes technologies d'éoliennes intégrées dans un réseau de moyenne tension*. Thèse de Doctorat, Ecole Centrale de Lille, 2004.