Global Journal of Computer Sciences: Theory and Research

Volume 7, Issue 2, (2017) 77-91

www.gjcs.eu

Modelling and control of wind turbine doubly fed induction generator with MATLAB simulink

Merabet Leila*, Laboratory of Electromechanical Systems, Department of Electrotechnical, Badji Mokhtar University, P. O. BOX 12, Annaba 23000, Algeria.

Mekki Mounira, Department of Electrotechnical, Larbi Ben M'Hidi, University Oum el Bouaghi, P. O. BOX 04000, Algeria.

Ourici Amel, Department of Electrotechnical, Badji Mokhtar University, P. O. BOX 12, Annaba 23000, Algeria.

Saad Salah, Laboratory of Electromechanical Systems, Department of Electromechanical, Badji Mokhtar University, BP 12, Annaba 23000, Algeria.

Suggested Citation:

Leila, M., Mounira, M., Amel, O. & Salah, S. (2017). Modelling and control of wind turbine doubly fed induction generator with MATLAB Simulink. *Global Journal of Computer Sciences: Theory and Research. 7*(2), 77-91.

Received April 9, 2017; revised June 29, 2017; accepted August 21, 2017.

Selection and peer review under responsibility of Prof. Dr. Dogan Ibrahim, Near East University, North Cyprus.

Abstract

This paper describes the modelling and control system of a wind turbine, using a doubly fed induction generator. This configuration makes the wind turbine suitable for variable speed wind energy application. The power captured by the wind turbine is converted into electrical power by the induction generator, and it is transmitted to the grid by the stator and the rotor windings. The control system generates voltage command signals for rotor converter and grid converter, respectively, in order to control the power of the wind turbine. Reactive power exchanged with the network through the converters is set to 0 VAr. The control strategy has been developed using MATLAB/Simulink. The simulation results are presented and discussed in the conclusions.

Keywords: Wind energy, doubly fed induction generator, grid power, modelling, control.

* ADDRESS FOR CORRESPONDENCE: **Merabet Leila,** Laboratory of Electromechanical Systems, Department of Electrotechnical, Badji Mokhtar University, BP 12, Annaba 23000, Algeria. *E-mail address*: lei_elt@yahoo.fr / Tel.: +0-0669912295

1. Introduction

Recently, wind energy has become the most promising of renewable energy sources and has expanded rapidly throughout the world. With the advancement of aerodynamic designs, wind turbines that can capture several megawatts of power are available. When such wind energy conversion systems (WECSs) are integrated to the grid, they produce a substantial amount of power, which can supplement the base power generated by thermal, nuclear or hydro power plants.

A WECS can vary in size from several megawatts to a few hundred kilowatts. The largest series production units today are specified to deliver 1.5-MW output power. It is anticipated that in the near future, the power rating of wind turbines will increase further, especially in offshore applications. For example, the prototype of a Nordex N80 with a rated power of 2.5 MW was installed in March 2000 near Aachen. The choice of the generator and converter system was determined by the size of the WECS. Among electrical rotating machines, induction machines are of special importance due to their simplicity and robustness. In comparison with alternative schemes, the doubly fed induction machine for variable speed constant frequency generation systems is nowadays an established technology. Other solutions based on direct-driven permanent magnet synchronous machines are proposed on the market.

There exists a large range of possible wind turbine configurations. Most commonly, wind turbines are of two major categories: 'fixed speed turbines' and 'variable speed turbines'. There is a wide range of topologies classified into these groups. A comparison and discussion of a few concepts can be found in [1–5].

The most commonly used concepts are fixed speed wind turbines equipped with asynchronous or induction generators directly connected to the grid. One of the oldest and simplest concepts was first used in Denmark, and therefore known as the 'Danish concept'.

Variable speed turbines with induction or synchronous generator, directly or indirectly connected to the grid have become more and more important in recent years. Possibilities such as mechanical load reduction and more efficient energy production, due to intelligent control strategies, make these concepts a beneficial economic solution. Furthermore, these types are better grid-compliant compared to fixed speed turbines. The possibility to independently control the speed decoupled from the grid gives the possibility to decouple frequencies resulting from wind fluctuations from the grid, which reduces flicker contribution. The converter integrated in a variable speed wind turbines gives the possibility to actively control the power output of the wind turbine, which is increasingly important for integration of wind turbines into the grid [6, 7].

The fixed speed wind turbine is a self-controlled concept. With increasing wind speed, the laminar wind current flow around the fixed blade profile breaks and the turbine loses the possibility to obtain energy from the wind and stalls. The squirrel cage induction generator, which transforms the obtained mechanical energy into electrical energy, is directly connected to the grid. The speed of the generator may differ from the grid frequency due to the slip variation of the generator, which is up to 1%.

The variable speed wind turbine is usually equipped with a pitch control, where the blade can be turned to increase or decrease lift forces on the blade profile and, thereby, continuously control energy absorption from the wind. The active pitch control is designed to optimize the power obtained from the wind by changing the rotation speed of the rotor and the pitch angle, and therefore gain an optimum current flow around the blade. This achieved variable speed range at the turbine shaft or generator axes is different from the fixed frequency of the power system by 50 or 60 Hz. A direct coupling of a synchronous generator to the grid is therefore not possible, and a squirrel cage induction machine is too small in speed variation possibilities (<1%), which would limit power production only in a synchronism of the shaft speed and grid frequency. To enable efficient power production at a huge range of different wind speeds, the mechanical speed has to be decoupled from the grid frequencies. One method to decouple the two systems is to use a full-scale power converter between the generator and the grid. This may give a speed variation of up to 120%. The success of this concept has been limited over many years due to technical development in the area of power electronics and the associated costs. Another way to connect a variable speed wind turbine to the grid is to use a doubly fed induction generator (DFIG). Wind turbines equipped with DFIG have become more and more common in the recent years. They combine the advantages of pitch control with efficient transmission of power to the grid and the possibility of dynamic control of active and reactive power. Wind turbine technology benefits from developments in the area of drive control. Essential progress in the dynamical control of machines brought the introduction of field-oriented control by Blaschke. In the following years until today, research to improve the principle has been done [8–12].

In a system with DFIG, the converter is placed to feed into the rotor of the machine while the stator is directly connected to the grid. Through the converter, it is possible to control the supply, or extract the energy to the rotor of the induction machine.

Thus, the machine can be controlled to run between sub-synchronous speed and over synchronous speed (speed higher than synchronous speed). Usually, a variation from −40% to +30% of synchronous speed is chosen. The total speed variation is between 60% and 70%. Under these conditions, the power converter has a size of 30, or a maximum of 40 of the rated power, which is beneficial both economically and technically.

The WECS configuration used in this work is a DFIG with converters cascade and a capacity energy storage system in the dc link.

This paper is structured as follows. First, we illustrate the importance of a wind turbine system, with different configurations existing for fixed, variable speed and several progresses in control. In Section 2, we describe the configuration proposed in this paper. Section 3 is devoted to modelling the wind turbine. Section 4 presents the modelling of the DFIG system. The detailed control strategy is discussed in Section 5. Section 6 presents and discusses the simulation and results, followed by the conclusions in Section 7.

2. Operating Principle of the Wind Turbine DFIG System

The wind turbine and DFIG are represented in Figure 1. Two cascaded voltage source converters (VSCs) make the transfer. The first is linked to the network called the grid converter (C_{grid}), which operates as a rectifier and the second is called the rotor converter (C_{rotor}), which operates as an inverter connected to the rotor of the generator.

The rotor windings are powered via bidirectional PWM VSCs by slip rings and brushes. The converters use forced-commutated power electronic devices (IGBTs) to generate an AC voltage from a DC voltage source assured by a capacitor on the DC side. The rotor converter is connected to the grid via a coupling inductor L. The conversion of the mechanical power captured by the wind turbine in electrical power is done by the induction generator and it is carried out to the grid by stator and rotor winding.

Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generators.

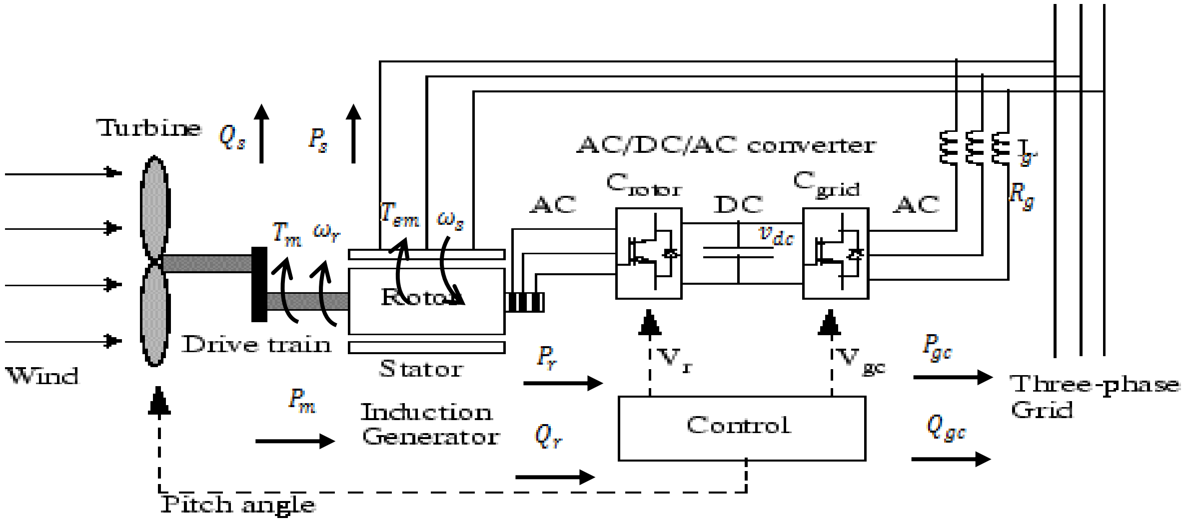


Figure 1. The wind turbine and the doubly fed induction generator system

3. Wind Turbine Model

A 1.5-MW wind turbine uses a DFIG that consists of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 60-Hz grid, while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting the maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind.

The aerodynamic model of a wind turbine is determined by its power speed characteristics [3]. The friction factor and the inertia of the turbine must be combined with those of the generator associated to the turbine. For a horizontal axis wind turbine, the mechanical power output P_m (w) that a turbine can produce is given as

$$P_m = \frac{1}{2}\rho A C_p(\lambda,\beta) v^3 \tag{1}$$

where ρ is the air density (in kg/m^3), v is the wind speed (in m/s), A is the turbine swept area (m^2) and C_p is the power coefficient, which is a function of both tip speed ratio λ and blade pitch angle β (in degrees). In this work, the C_P equation is approximated using a non-linear function according to [3]

$$C_p(\lambda,\beta) = 0{,}517 - \left(\frac{116}{\lambda_i} - 0{,}4\beta - 5\right)e^{-\frac{21}{\lambda_i}} + 0{,}0068\lambda \tag{2}$$

which is

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0{,}08\beta} - \frac{0{,}035}{\beta^3 + 1} \tag{3}$$

The tip speed ratio λ is

$$\lambda = \frac{\Omega R}{v} \tag{4}$$

where Ω is the angular velocity of wind turbine and *R* is the blade radius. In this paper, we consider the pitch angle β equal to 0° (in this case, the power coefficient is the maximum) (see Figure 2(a)).

The turbine power characteristics are in Figure 2(b). At wind speed equal to 12 m/s, the turbine output power per unit of nominal mechanical power is equal to 0.73 for 1.2 turbine speed in per unit of nominal generator speed turbine speed.

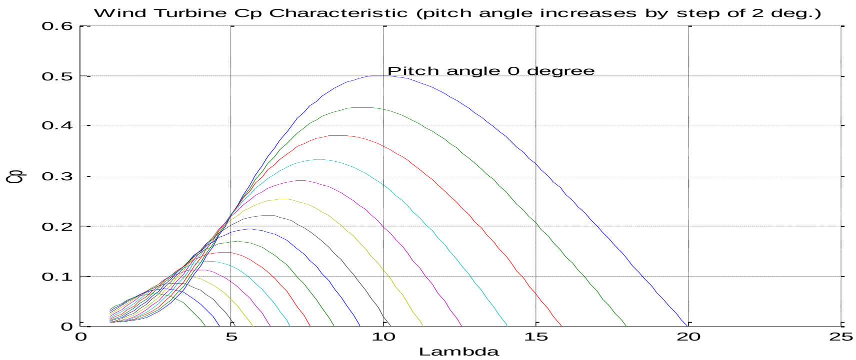
In the per unit system, we have

$$P_m = k_p C_{p-pu} v^3 wind - pu \tag{5}$$

$$c_p - p_u = \frac{C_p}{C_{p-max}} \tag{6}$$

$$v_{wind} - p_u = \frac{v_{wind}}{v_{mean}} \tag{7}$$

with v_{mean} as the mean value of the expected wind speed in metre per second and k_p (less than or equal to 1) as the power gain for $C_{p-pu} = 1$ pu and $v_{wind-pu} = 1$ pu.



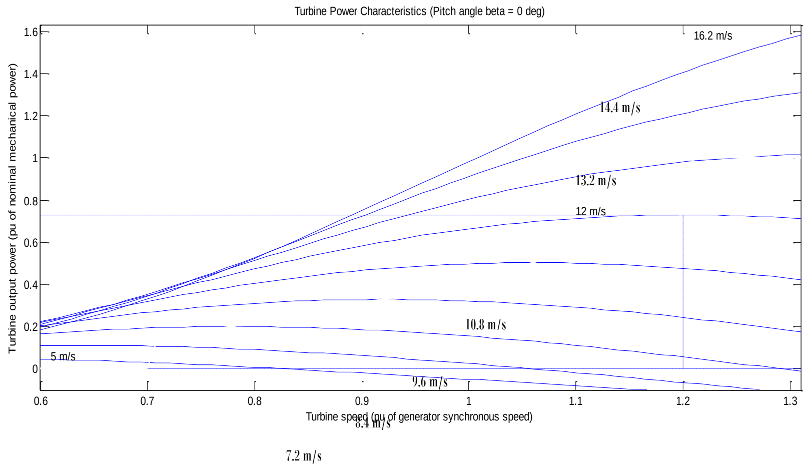


Figure 2. (a) Wind turbine power coefficient characteristics. (b) Turbine power characteristics

Figure 3. Wind turbine model

4. Modelling of DFIG

The DFIG model is based on the following assumptions. The equations are derived in the synchronous reference frame using direct (d) and quadrature (q) axis representation.

The stator voltages are given as

$$\begin{cases} V_{ds} = R_s I_{ds} + \dfrac{d\phi_{ds}}{dt} - \phi_{qs}\omega_s \\ V_{qs} = R_s I_{qs} + \dfrac{d\phi_{qs}}{dt} + \phi_{ds}\omega_s \end{cases} \tag{8}$$

The rotor voltages are

$$\begin{cases} V_{dr} = R_r I_{dr} + \dfrac{d\phi_{dr}}{dt} - \phi_{qr}\left(\omega_s - \omega_r\right) \\ V_{qr} = R_r I_{qr} + \dfrac{d\phi_{qr}}{dt} + \phi_{dr}\left(\omega_s - \omega_r\right) \end{cases} \tag{9}$$

where the flux linkages are expressed as

$$\begin{cases} \phi_{ds} = L_s I_{ds} + M I_{dr} \\ \phi_{qs} = L_s I_{qs} + M I_{qr} \\ \phi_{dr} = L_r I_{dr} + M I_{ds} \\ \phi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \tag{10}$$

The developed electromagnetic torque is

$$T_{em} = \frac{3}{2} PM (I_{qs} I_{dr} - I_{ds} I_{qr}) \tag{11}$$

To obtain an independent control of the powers produced from the wind system, we achieve a decoupled control of active and reactive power by the stator flux orientation. Controls of the electromagnetic torque and stator reactive power will be obtained by controlling the dq-axe rotor currents of the DFIG.

The stator field rotates in steady state at the synchronous speed. This field is symbolised by the stator flux vector, which gives a visual idea of the phase and flux amplitude. By choosing the two-phase *d*, *q* related to rotating stator field, and placing the stator flux vector on the *d*-axis [13–15], we can write

$$\begin{cases} \phi_{qs} = 0 \\ \phi_{ds} = \phi_s \end{cases} \tag{12}$$

This choice is not random but is justified by the fact that the machine is often coupled with a powerful network voltage and constant frequency, which leads to finding the stator flux of the machine. Neglecting the resistance of the stator windings is the often accepted hypothesis for high power machines: The systems of Eqs. (8) and (10) can be simplified as follows:

$$\begin{cases} V_{ds} = 0 \\ V_{qs} = V_s = \phi_s \omega_s \end{cases} \tag{13}$$

$$\begin{cases} \phi_s = L_s I_{ds} + M I_{dr} \\ 0 = L_s I_{qs} + M I_{qr} \\ \phi_{dr} = L_r I_{dr} + M I_{ds} \\ \phi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \tag{14}$$

The stator active and reactive power in the orthogonal coordinate system can be written as

$$\begin{cases} P_s = \frac{3}{2}(V_{ds} I_{ds} + V_{qs} I_{qs}) \\ Q_s = \frac{3}{2}(V_{qs} I_{ds} - V_{ds} I_{qs}) \end{cases} \tag{15}$$

Under the assumption of a stator flux oriented, this system of equations can be simplified as

$$\begin{cases} P_s = \frac{3}{2} V_s I_{qs} \\ Q_s = \frac{3}{2} V_s I_{ds} \end{cases} \tag{16}$$

The stator currents can be derived in the following form:

$$\begin{cases} I_{ds} = \dfrac{\phi_s - M I_{dr}}{L_s} \\ I_{qs} = \dfrac{M}{L_s} I_{qr} \end{cases} \tag{17}$$

By introducing these expressions in Eq. (6), the rotor voltages are equal to

$$\begin{cases} V_{dr} = R_r I_{dr} + \sigma L_r \dfrac{dI_{dr}}{dt} - \omega_s g \sigma L_r I_{qr} \\ V_{qr} = R_r I_{qr} + \sigma L_r \dfrac{dI_{qr}}{dt} + \omega_s g \sigma L_r I_{dr} + g \dfrac{M}{L_s} V_s \end{cases} \tag{18}$$

where σ is the dispersion coefficient between the two axes *d* and *q*, and *g* is the slip

The rotor side converter is a two-level inverter, which controls the active and reactive powers generated by the stator of the DFIG.

5. Modelling of DFIG

5.1. Model Description

Decoupled control of active and reactive powers based on vector control is used. The control strategy provides the pitch angle, the command signals $v_{rc-control}$ and $v_{gc-control}$ for rotor converter and grid converter, respectively, in order to control the active and reactive powers at the grid terminals.

The mechanical power and the stator electric power are given as

$$p_m = T_m \omega_r \tag{19}$$

$$p_s = T_{em} \omega_s \tag{20}$$

The mechanical equation is

$$j \frac{d\omega_r}{dt} = T_m - T_{em} \tag{21}$$

In steady state at fixed speed without power losses in generator, we have

$$p_r = -s p_s \tag{22}$$

where *s* is the slip of the generator

$$s = \frac{\omega_{s-}\omega_r}{\omega_s} \tag{23}$$

From Eq. (22), we can deduce that the electrical rotor power is a fraction of electrical stator power. is negative for speed generator lower than synchronous speed (sub-synchronous speed operation) and positive for speed generator greater than synchronous speed (super-synchronous speed operation).

The rotor converter C_{rotor} and the grid converter C_{grid} are used to control the active powers flow p_r and p_{gc} in order to keep the DC voltage constant.

In addition, the rotor converter and the grid converter attribute directly in production or absorption of reactive power at the grid.

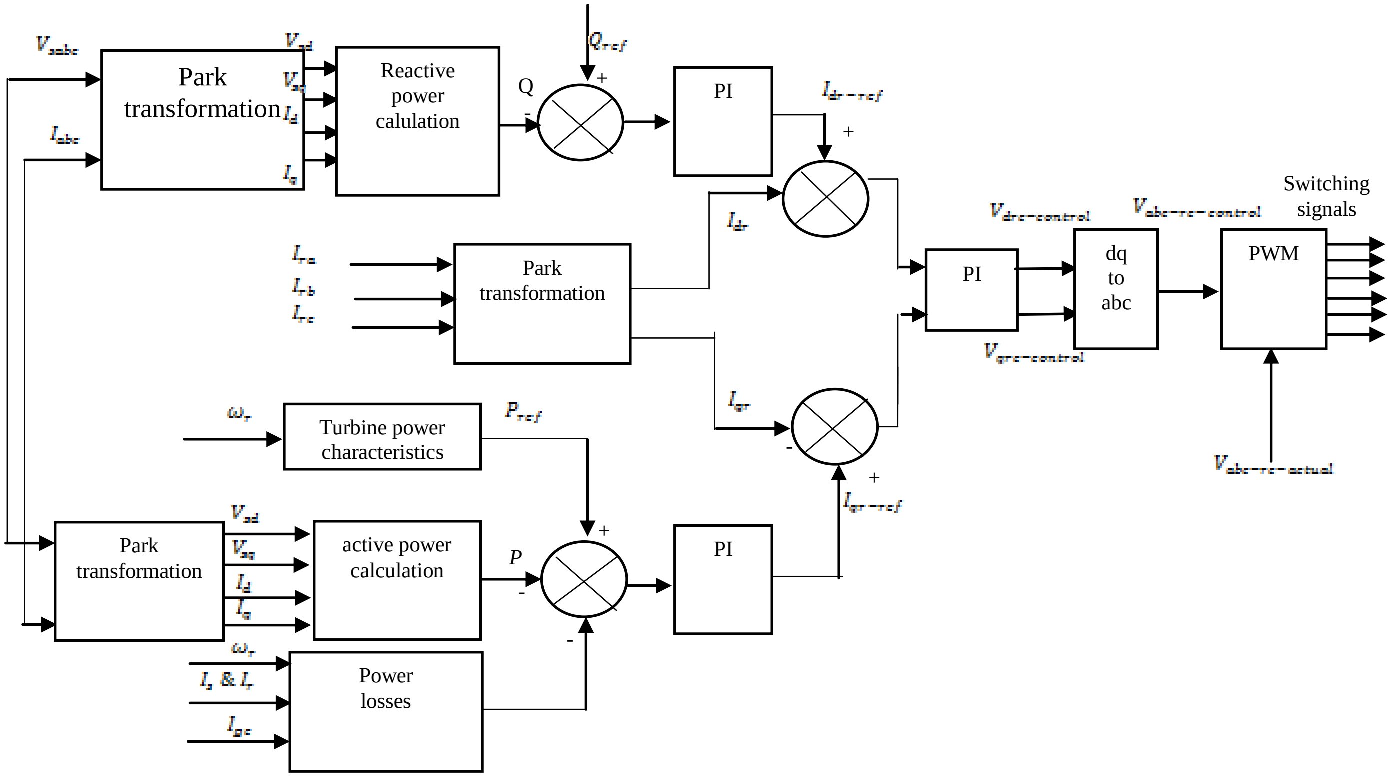


Figure 4. Rotor-side converter control system for reactive power control

The reactive power at grid (see Figure 1) is controlled by the reactive current flowing in the rotor converter C_{rotor}. The reactive power control loop is illustrated in Figure 4.

The reactive power at the grid is given as

$$Q = \frac{3}{2}(V_q I_d - V_d I_q) \tag{24}$$

The grid voltage and the grid current vectors are expressed as

$$\begin{cases} V = V_s = V_{sd} + jV_{sq} \\ I = I_s + I_{gc} = I_d + jI_q \end{cases} \tag{25}$$

It is controlled by adjusting the direct current component delivered by the rotor converter. A proportional-integral (PI) regulator is used to regulate the direct I_{dr} component current to its reference value. The output of this regulator is the direct voltage control $V_{\text{drc-control}}$ generated by the rotor converter.

The active power measured at the grid terminals of the wind turbine is given as

$$P = \frac{3}{2}(V_d I_d + V_q I_q) \tag{26}$$

It is added to the power losses, which represent the Joule effect losses in rotor, stator and grid converter winding and power friction given as

$$P_{\text{losses}} = R_r I_r^2 + R_s I_s^2 + R_g\ I_{\text{gc}+}^2 \omega_r T_{\text{friction}} \tag{27}$$

$$\text{with} \begin{cases} I_r = \sqrt{i_{\text{dr}}^2 + i_{\text{qr}}^2} \\ I_s = \sqrt{i_{\text{ds}}^2 + i_{\text{qs}}^2} \\ I_{\text{gc}} = \sqrt{i_{\text{dgc}}^2 + i_{\text{qgc}}^2} \end{cases} \tag{28}$$

R_g is the resistance of grid-side converter coupling inductor to the grid and T_{friction} is the friction torque of the generator.

These powers are subtracted from the reference power obtained from the tracking turbine power characteristic. In order to reduce the power error to zero, a PI regulator is used. The output of this regulator is the reference rotor current $i_{\text{qr-ref}}$, which produces the electromagnetic torque T_{em}. The error produced between the actual i_{qr} component and the reference $i_{\text{qr-ref}}$ component is reduced to zero by a PI regulator. The output of this current regulator is $V_{\text{qgc-control}}$, the quadratic voltage control generated by the rotor converter. The rotor voltages control are converted from *d–q* axis to the *abc* axis and compared to the actual voltages rotor in order to generate the PWM switching signals to the IGBTs constitute the rotor converter.

Then we can deduce that the active power at the grid is regulated with the quadratic current component generated by the rotor converter. Hence, this control loop allows obtaining a decoupled control of active and reactive power at the grid.

5.2. Model Description

The converter C_{grid} generates the grid voltage signals to the IGBTs, constituting the grid converter in order to regulate the voltage of the DC bus capacitor and control the production and absorption of reactive power at the grid. The control system is illustrated in Figure 5. An outer regulation loop regulates the DC voltage regulator at the DC bus bar capacitor. The output of the DC voltage regulator is the reference current $i_{dgc\text{-}ref}$. This current is compared to the actual direct current generated by the grid converter i_{dgc} in order to control active power flow.

A PI regulator is introduced to the inner current regulation loop which controls the reactive power absorption or production via the quadratic current generated by the grid converter i_{qgc}.

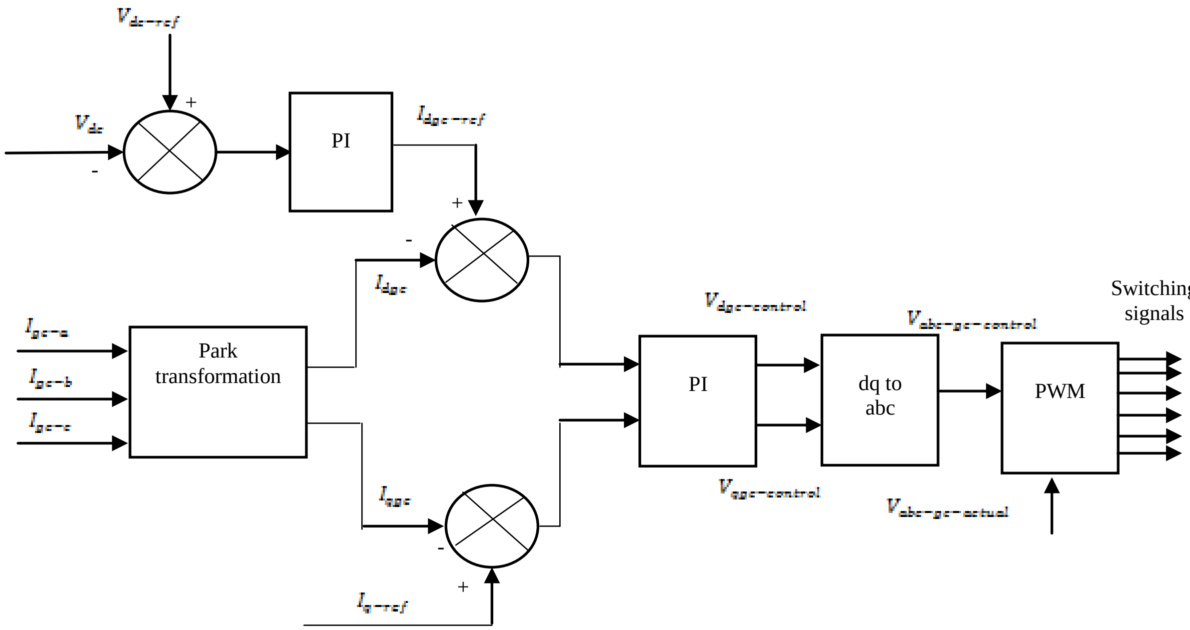


Figure 5. Grid-side converter control system

The output of this current regulator is $V_{dgc\text{-}control}$ and $V_{qgc\text{-}control}$. The grid voltages control are converted from d-q axis to the abc axis and compared with the actual voltages grid converter in order to generate the PWM switching signals to the IGBTs that constitute the grid converter.

5.3. Rotor Speed Control

The control system uses a torque controller in order to maintain the speed at 1.2 pu. A PI regulator is introduced to achieve this goal (see Figure 6).

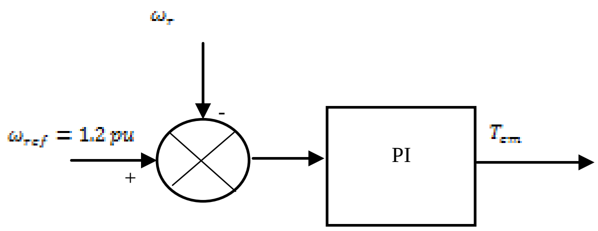


Figure 6. Rotor speed control system

5.4. Pitch Angle Control System

A PI controller is used to control the blade pitch angle in order to limit the electric output power to the nominal mechanical power. The pitch angle is maintained constant at zero degree when the measured electric output power is under its nominal value. When it increases above its nominal value, the PI controller increases the pitch angle to keep the measured power to its nominal value. The pitch angle β is proportional to the speed deviation. The control system is illustrated in Figure 7.

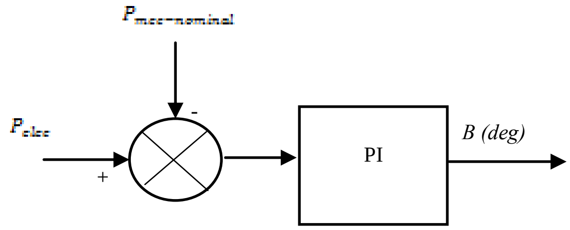


Figure 7. Pitch control system

6. Simulation Results

The simulations were performed using MATLAB/Simulink software. In order to validate the control approach discussed in this paper, we present an operating point when the wind speed is constant equal to 15 m/s. For this simulation, we consider the parameters of generator, converters (Table 1), turbine (Table 2) and control parameters in Table 3.

Table 1. Generator and converters parameters

Parameter	Value
Stator resistor per phase	4 mΩ
Rotor resistor per phase	3 mΩ
Inductance of the stator winding	120 mH
Inductance of the rotor winding	50 mH
Mutual inductance	12,12 mH
Number of pole pairs	3
Inertia	114 kg. m^2
Rated power	1.5 MW
Grid voltage	575 V
Grid frequency	60 Hz
Nominal DC bus voltage	1150 V
Grid-side coupling inductor	0.1 Ω , 0.6 mH
DC bus capacitor	10000 µF
Frequency of the grid-side PWM carrier	2700 Hz
Frequency of the rotor-side PWM carrier	1620 Hz

Table 2. Turbine parameters

Parameter	Value
Number of blade	3
Wind speed	15 m/s
Gearbox ratio	100
Blade radius	40 m
$C_{p-\max}$	0.5
λ	10

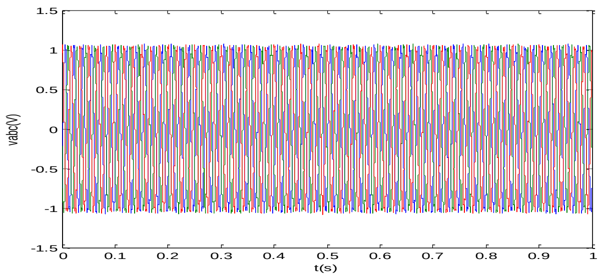
Table 3. Control parameters

Parameter	k_p	k_I
DC bus voltage regulator	0.002	0.05
Current regulator (grid-side converter)	1	100
Current regulator (rotor-side converter)	0.3	8
Active power regulator	1	100
Reactive power regulator	0.05	5
Rotor speed regulator	3	0.6
Pitch angle regulator	3	30

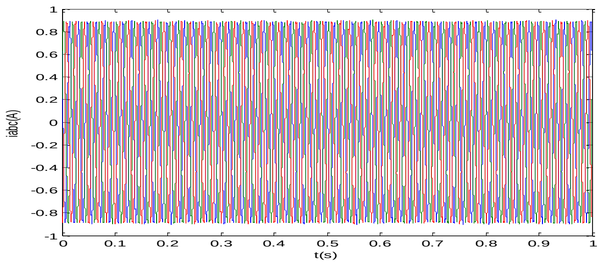
The reference of the DC bus voltage denoted $v_{\text{dc-ref}}$ is set at 1150 V. The reference value of reactive power (Q_{ref}) exchanged with the network through the converters is set to (0 VAr), which guarantees a power factor close to unity. The switching frequency of the power switches of the grid converter and rotor converter is set to 5 kHz.

Figures 8(a) and 8(b) show the three phase voltages and currents at the grid. We also observe in Figure 8(c) that the DC bus voltage is well regulated to 1150 V. Figures 8(d) and 8(e) show the active and reactive power. Note that the DFIG wind system produces 1.5 MW. The turbine output power is 1 pu of its rated power, and the reactive power is controlled to 0 Var.

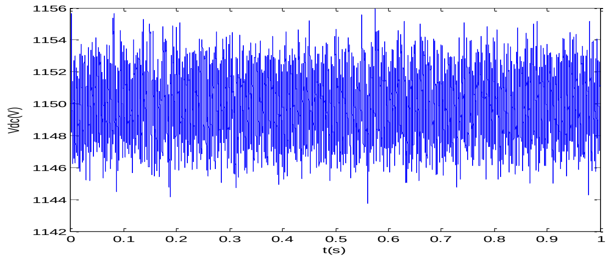
In this paper, the wind speed is maintained constant at 15 m/s. The control system uses a torque controller in order to maintain the speed at 1.2 pu (see Figure 8(f)).The pitch angle is 8.7° as shown in Figure 8(g).



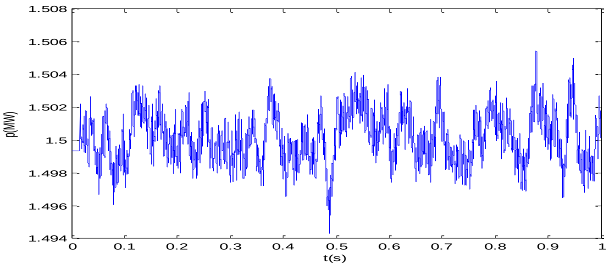
(a)



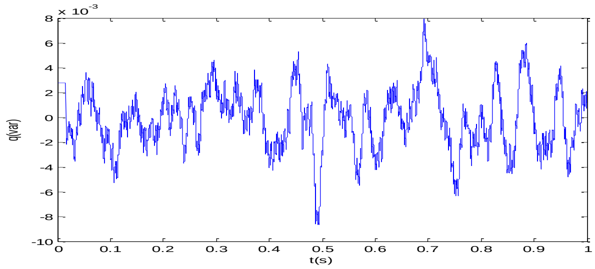
(b)



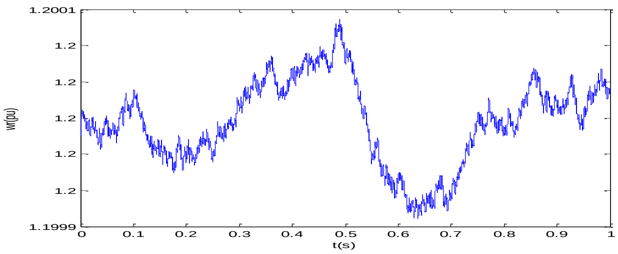
(c)



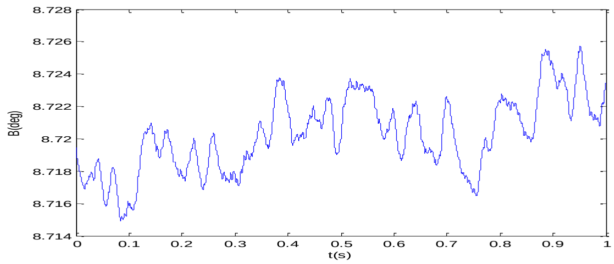
(d)



(e)



(f)



(g)

Figure 8. Simulation results. (a) Three-phase voltages (pu) at the grid. (b) Three-phase currents (pu) at the grid. (c) DC bus voltage. (d) Active power in the grid. (e) Reactive power in the grid. (f) Rotor speed (pu) of DFIG. (g) Pitch angle

7. Conclusion

This paper has addressed the modelling and control of a wind system based on a DFIG. First, we explained why this wind system is most used now, including the economy realized through the design of static converters implemented.

Then we discussed the modelling of various components of the wind system. The aerodynamic and mechanical models of the turbine have been developed. Then, in order to establish different controllers for two converters, we developed models of DFIG. The controls of C_{grid} and C_{rotor} were detailed to provide independent control of active and reactive power while ensuring optimal operation of the turbine.

To validate the model and control of the global wind system, we performed simulation for an operating point at constant wind speed. The results showed that the active and reactive power of the wind system based on DFIG could be controlled independently while ensuring optimal active power supplied to the grid.

References

[1] L. H. Hansen, "Generator concepts and their progress," presented at Seminar on Control Concepts of Wind Turbines, Aalborg University, Aalborg, Denmark, Oct. 2000.

[2] J. H. S. Hansen *et al.*, *Sensorless control of a double fed Induction generator for wind turbine applications*. Aalborg, Denmark: Aalborg University, 1998.

[3] S. Heier, *Grid integraton of wind energy conversion systems*. Wiley, 1998. ISBN 0-471-97143-X.

[4] W. Hofmann and A. Thieme, "Control of a double-fed induction generator for wind-power plants," in: *PCIM'98*, Nürnberg, Germany, May 1998.

[5] W. Xueguang *et al.*, "Application of models of the wind energy conversion system to wind power dynamic analysis," in: *Proceedings of the International Conference on Power System Technology*, 1998.

[6] V. Akhmatov, "*Analysis of dynamic behavior of electric power systems with large amount of wind power*," PhD Thesis, Ørsted DTU, Denmark, April 2003.

[7] S. M. Bolik, "Grid requirements challenges for wind turbines," in: *Proceedings 4th International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms*, Billund, Denmark, October 2003.

[8] W. Hofmann and B. Rabelo, "Optimal active and reactive power control with the double-fed induction generator in the MW-class wind-turbines," in: *PEDS´01*.

[9] W. Leonard, *Control of electrical drives.* New York: Springer Verlag, 1996. ISBN 3-540-59380-2.

[10] L. Morel *et al.*, "Double-fed induction machine: converter optimisation and field oriented control without position sensor," *IEE Proc. Electr. Pow. Appl*., vol. 145, issue 4, pp. 360–368, 1998.

[11] D. W. Novotny and T. A. Lipo, *Vector control and dynamics of AC drives*. Oxford: Clarendon Press, 1996. ISBN 0-19-856439-2.

[12] U. Rädel *et al.*, "Sensorless field-oriented control of a slipring induction generator for a 2.5 MW wind power plant from Nordex Energy GmbH," in: *EPE* 2001.

[13] Y. Lei *et al.*, "Modeling of the wind turbine with a doubly-fed induction generator for grid integration studies," *IEEE Trans. Energy Convers.*, vol. 21, issue 1, pp. 257–264, March 2006.

[14] A. Tapia *et al.*, "Modeling and control of a wind turbine driven doubly fed induction generator," *IEEE Trans. Energy Convers.*, vol. 18, issue 2, pp. 194–204, 2003.

[15] S. Li and T. A. Haskew, "Analysis of decoupled d-q vector control in DFIG back-to-back PWM converter," in: *Power Engineering Society General Meeting, IEEE*, 2007, pp. 1–7.