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Backstepping Controller for a Variable Wind Speed Energy Conversion System Based on a DFIG

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Abstract**—**In this paper we present a contribution for the modeling and control of wind energy conversion system based on a Doubly Fed Induction Generator (DFIG). Since the wind speed is random the system has to produce an optimal electrical power to the Network and ensures important strength and stability. In this work, the Backstepping controller is used to control the generator via two converter witch placed a DC bus capacitor and connected to the grid by a Filter R-L, in order to optimize capture wind energy. All is simulated and presented under MATLAB/Simulink Software to show performance and robustness of the proposed controller.

Keywords**—**Wind turbine, doubly fed induction generator, MPPT control, backstepping controller, power converter.

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I. Introduction

THE development and exploitation of renewable energies has greatly evolved in recent decades. Among these energy sources, there is wind power, which produces electrical energy from the kinetic energy of the wind. This source of energy has been the subject of several researches in electrical and electromechanical engineering in order to optimize and improve the quality of energy produced. Currently, most recent wind turbines are based on variable speed generators to better exploit the wind resources for different value of wind speed, the most used in wind farms is the DFIG, the stator of the machine is connected directly to the grid while the rotor is connected to the grid via a back-to-back power converter which placed a DC Bus Capacitor (Fig. 1) [1]-[3], this structure has many advantages, allows a variable speed operation around asynchronous machine. The power converters used are sized to pass a fraction of the total power of the system, which allows the reduction of losses in power electronics components [4]-[6].

The aim of this study is to control the whole system by the nonlinear Backstepping approach associate to Lypunov function in order to ensure stability system and maximize the power extracted from the generator-DFIG against variable-speed large wind. To control the rotor side converter (RSC), the voltages references are obtained by the rotor currents control loop, this control loop gets its reference from the Maximum power point tracking algorithm used to maximize the power generated from the wind. As for the grid side converter (GSC), its voltages references are provided from the filter currents control loop, the performance and robustness of this controller are tested in terms of reference tracking and analyzed by simulation results in MATLAB/SIMULINK environment.

This article is organized as follows, in Section I a brief introduction, the modeling of the wind turbine energy and the principle of maximum power point tracking (MPPT) are presented in Section II. In Section III we describe the mathematical development of the Backstepping controller used in the control of the generator, thereafter we present the simulation results and their interpretations, and then we finish by a conclusion.

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II. Modelling of the Wind Turbine Energy System

A. Modelling of the Wind Turbine

Wind turbines transform the kinetic energy of the wind to the electrical energy. The aerodynamic power P_{aer} available on the rotor depends on the power coefficient C_p is written as [4]-[7]:

$$P_{aer} = C_p(\lambda.\beta).\frac{\rho.S.v^3}{2} \quad (1)$$

where: ρ : Air density (ρ =1.22 kg/m3), S : Circular surface swept by the turbine, v : Wind speed, C_p : Power coefficient, λ : Tip Speed Ratio (TSR), β : Pitch angle of the blade.

The TSR λ is defined as:

$$\lambda = \frac{R.\Omega_t}{v} \quad (2)$$

The expression $C_p(\lambda.\beta)$ defines the aerodynamic efficiency of the wind turbine it can be expressed as follows [5]:

$$C_p(\lambda.\beta) = 0.5176(\frac{116}{\lambda_i} - 0.4\beta - 5)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \quad (3)$$

$$\lambda_i = \frac{1}{\lambda + 0.008.\beta} - \frac{0.035}{\beta^3 + 1} \quad (4)$$

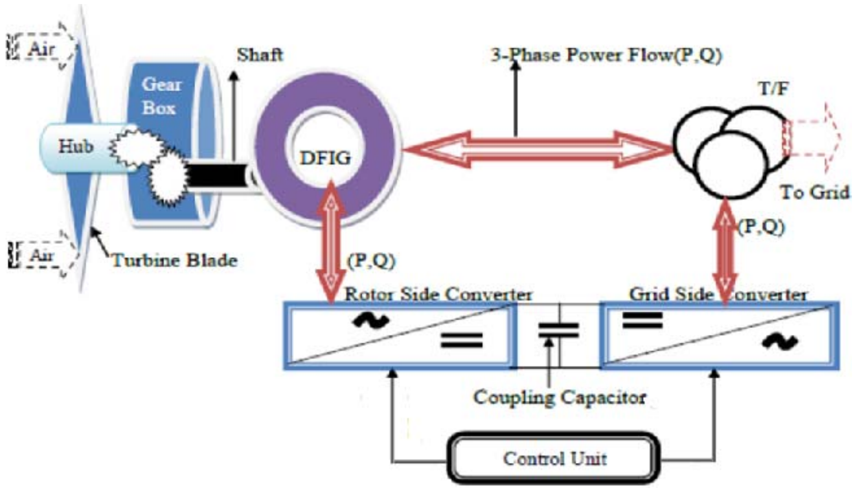

Fig. 1 Wind Energy Conversion System

The characteristics of Aerodynamic power Coefficient $C_p(\lambda.\beta)$ depending of λ for different values of β is presented in the Fig. 2.

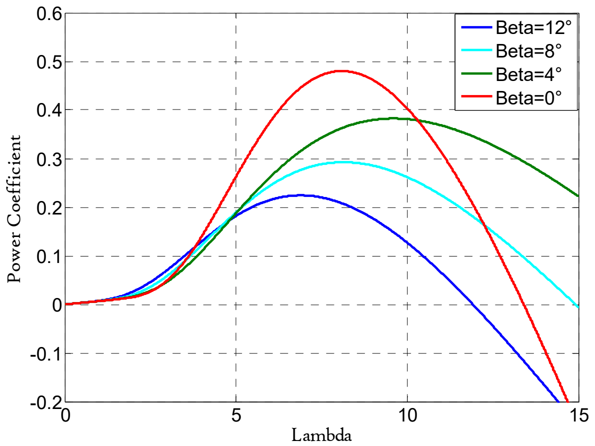

Fig. 2 The characteristics of $C_p(\lambda.\beta)$ depending of λ for different values of β

The fundamental equation of dynamics makes it possible to determine the evolution of the mechanical speed from the total mechanical torque applied to the rotor [4]:

$$J\frac{d\Omega_{mec}}{dt} = T_{mec} = T_g - T_{em} - C_f.\Omega_{mec} \quad (5)$$

where: J : The Total inertia, Ω_{mec} : The Mechanical speed, T_g : The generator torque, T_{em} : The electromagnetic torque, $C_f.\Omega_{mec}$: The torque of viscous friction.

B. Extraction of Maximum Power (MPPT Control)

The aim of this control is to optimize the capture wind energy by tracking the optimal speed, to extract the maximum of the power produced from the wind turbine; we must always adjust the mechanical speed of the DFIG to the wind speed [8]. By setting β and λ respectively to their optimal values which corresponds to the maximum power coefficient $C_{p\max}$ the wind turbine system will produce optimum electrical power [4]. According to (2) it can be possible to deduce in real time the estimate value of the wind speed:

$$v_{est} = \frac{R.\Omega_t}{\lambda_{opt}} \quad (6)$$

The electromagnetic torque extracted from the MPPT Control should be applied to the DFIG in order to run the generator at its optimal speed [8]. The expression of the reference electromagnetic torque as a function of the mechanical rotor speed is expressed as [9]:

$$T_{em\ ref} = \frac{1}{2}C_{p\max}(\lambda.\beta).\frac{\rho.\pi.R^5}{(G.\lambda_{opt})^3}\Omega_{mec}^{\ 2} \quad (7)$$

C. Modelling of the DFIG

In this work, we chose a park reference (d-q) linked to the rotating field. Assuming that the flux stator is oriented along the axis d of the rotating reference frame and is constant, and the stator resistance R_s is neglected for high and medium power [3]. The mathematical model of the DFIG in the Park reference (d-q) is given by the following equations [10], [11]:

$$\begin{cases} V_{sd} = R_s.I_{sd} + \frac{d\phi_{sd}}{dt} - \phi_{sq}.\omega_s = 0 \\ V_{sq} = R_s.I_{sq} + \frac{d\phi_{sq}}{dt} + \phi_{sd}.\omega_s = \phi s.\ \omega_s \\ V_{rd} = R_r.I_{rd} + \frac{d\phi_{rd}}{dt} - \phi_{rq}.\omega_r \\ V_{rq} = R_r.I_{rq} + \frac{d\phi_{rq}}{dt} + \phi_{rd}.\omega_r \end{cases} \quad (8)$$

The stator and rotor flux can be described as:

$$\begin{cases} \phi_{sd} = L_s.I_{sd} + L_m.I_{rd} = \phi_s \\ \phi_{sq} = L_s.I_{sq} + L_m.I_{rq} = 0 \\ \phi_{rd} = L_s.I_{rd} + L_m.I_{sd} \\ \phi_{rq} = L_r.I_{rq} + L_m.I_{sq} \end{cases} \quad (9)$$

where ω_s is the pulsation of the currents stator and ω_r is the pulsation of the currents rotor, p is the number of the pole pairs of the DFIG. $R_s; R_r$ are the stator and rotor resistance, $L_{s.}; L_r$ are the cyclic stator and rotor inductance, and L_m is the mutual inductance.

The expressions for the active and reactive powers of the stator, and the electromagnetic torque are written as follows [4]-[9]:

$$P_s = -\frac{V_s.L_m}{L_s}.I_{rq} \quad (10)$$

$$Q_s = \frac{V_s.\phi s}{L_s} - \frac{V_s.L_m}{L_s}.I_{rd} \quad (11)$$

$$T_{em} = -\frac{3}{2}.p.\frac{L_m}{L_s}.\varphi s.I_{rq} \quad (12)$$

D. Modelling of the Filter Rf-Lf

The GSC is connected to the Network via a Filter $R_f\ L_f$, in a reference Park frame d-q the voltage Vs is oriented along the axis q, this implies V_{sd} =0 [3], [4], so the expressions of the mathematical model of the filters is giving by:

$$\begin{cases} 0 = L_f \frac{dI_{fd}}{dt} + R_f.I_{fd} + I_{fq}.L_f.\omega_s + V_{fd} \\ V_{sq} = L_f \frac{dI_{fq}}{dt} + R_f.I_{fq} - I_{fd}.L_f.\omega_s + V_{fq} \\ P_f = V_{sq}.I_{fq} \\ Q_f = V_{sq}.I_{fd} \end{cases} \quad (13)$$

III. Backstepping Controller

The Backstepping approach is a recursive control design for stabilizing highly nonlinear dynamic systems [12]. The principle of the Backstepping controller approach is the use of a virtual control to decompose a complex nonlinear design problem into various simpler design steps. The stability and performance of the system are achieved by using a Lyapunov function which is used to drive the virtual control [10].

A. Control of the Rotor Side Converter (RSC)

To extract the maximum power generated it is necessary to provide the adequate and the necessary electromagnetic torque which is used to vary the mechanical speed of the DFIG for different value of wind speed [3]. According to (14) and (15) we deduce that V_{rd} and V_{rq} are the components of the rotor voltages to impose on the machine in order to obtain the desired rotor currents. From (12) we deduce that the rotor current I_{rq} can control the electromagnetic torque:

$$I_{rq\,ref} = -\frac{2}{3}.\frac{L_s}{p.L_m.\varphi_s} \quad (14)$$

According to (7), the expression of the rotor current reference I_{rqref} becomes:

$$I_{rq\,ref} = \frac{1}{3}.\frac{L_s}{p.L_m.\varphi_s}.C_{p\max}(\lambda.\beta).\frac{\rho.\pi.R^5}{(G.\lambda_{opt})^3}\Omega_{mec}^{\ 2} \quad (15)$$

From (11) we deduce that the rotor current I_{rdref} can control the stator reactive power:

$$I_{rd\,ref} = \frac{\varphi_s}{L_m} - \frac{L_s}{V_s.L_m}.Q_s \quad (16)$$

According to (8) and (9) the model of the system can be written as:

$$\begin{cases} \frac{dI_{rd}}{dt} = -b.I_{rd} + \omega_r.I_{rq} + a.V_{rd} \\ \frac{dI_{rq}}{dt} = -b.I_{rq} - \omega_r.I_{rd} - c.\phi s.\omega_r + a.V_{rq} \end{cases} \quad (17)$$

where:

$$\left\{ \sigma = 1 - \frac{L_m^{\ 2}}{L_s.L_r}; a = 1 - \frac{1}{\sigma.L_r}; b = a.R_r; c = a.\frac{L_m}{L_s} \right.$$

The currents rotor tracking errors e_2 and e_3 are defined by:

$$\begin{cases} e_1 = I_{rdref} - I_{rd} \\ e_2 = I_{rqref} - I_{rq} \end{cases} \quad (18)$$

The derivative of equation errors variables gives:

$$\begin{cases} \dot{e}_1 = \dot{I}_{rdref} - \dot{I}_{rd} \\ \dot{e}_2 = \dot{I}_{rqref} - \dot{I}_{rq} \end{cases} \quad (19)$$

Using (13), (20) and (22), we get:

$$\begin{cases} \dot{e}_1 = \dot{I}_{rdref} - (-b.I_{rd} + \omega_r.I_{rq} + a.V_{rd}) \\ \dot{e}_2 = \dot{I}_{rqref} - (-b.I_{rq} - \omega_r.I_{rd} - c.\phi s.\omega_r + a.V_{rq}) \end{cases} \quad (20)$$

In order to reduce the tracking error, we use a new Lyapunov candidate function, such that [5]:

$$v_1 = \frac{1}{2}e_1^2 + \frac{1}{2}e_2^2 \quad (21)$$

Using (20) and (21), the derivative of the Lyapunov function becomes:

$$\dot{v}_1 = e_1.\dot{e}_1 + e_2.\dot{e}_2 \quad (22)$$

$$\dot{v}_1 = -k_1.e_1^2 - k_2.e_2^2 + e_1.\left(k_1.e_1 + \dot{I}_{rdref} + b.I_{rd} - \omega_r.I_{rq} - a.V_{rd}\right) + e_2.\left(k_2.e_2 + \dot{I}_{rdref} + b.I_{rq} + \omega_r.I_{rd} + c.\phi s.\omega_r - a.V_{rq}\right) \quad (23)$$

In order to ensure a good and stable tracking the derivatives of the Lyapunov function should be negative $\dot{v}_1 \le 0$ and k_1, k_2 positives parameters [13], [14]. From (23) the expressions of the control variables voltages V_{rd} and V_{rq} are given by:

$$\begin{cases} V_{rdref} = \dfrac{\dot{I}_{rdref} + b.I_{rd} - \omega_r.I_{rq} + k_1.e_1}{a} \\ V_{rqref} = \dfrac{\dot{I}_{rqref} + b.I_{rq} + \omega_r.I_{rd} + c.\phi s.\omega_r + k_2.e_2}{a} \end{cases} \quad (24)$$

B. Control of the GSC

In order to supply the rotor side converter and realize a robust variable speed control, we need to rectifier interfacing the grid, so the DC Bus voltage must be maintain to a constant value, the aim of the control of the GSC is to ensures a good regulation of the DC bus voltage U_{dc} and have a unity power in the grid side [4].

The expression of the electrical currents of the Filter becomes:

$$\begin{cases} \dfrac{dI_{fd}}{dt} = \dfrac{1}{L_f}\left(-V_{fd} - R_f.I_{fd} + \omega_s.I_{fq}\right) \\ \dfrac{dI_{fq}}{dt} = \dfrac{1}{L_f}\left(V_{sq} - V_{fq} - R_f.I_{fq} - \omega_s.I_{fd}\right) \end{cases} \quad (25)$$

As shown in (14) the active power P_f can be controlled by I_{fq} and the reactive power Q_f can be controlled by I_{fd}.

The currents tracking errors e_3 and e_4 are defined by:

$$\begin{cases} e_3 = I_{fdref} - I_{fd} \\ e_4 = I_{fqref} - I_{fq} \end{cases} \quad (26)$$

The derivatives of the errors give:

$$\begin{cases} \dot{e}_3 = \dot{I}_{fdref} - \dot{I}_{fd} \\ \dot{e}_4 = \dot{I}_{fqref} - \dot{I}_{fq} \end{cases} \quad (27)$$

Using (25) and (27) the derivatives of the errors variables becomes

$$\begin{cases} \dot{e}_3 = \dot{I}_{fdref} - \left(-\dfrac{V_{fd}}{L_f} - \dfrac{R_f.I_{fd}}{L_f} + \omega_s.I_{fq}\right) \\ \dot{e}_4 = \dot{I}_{fqref} - \left(\dfrac{V_{sq}}{L_f} - \dfrac{V_{fq}}{L_f} - \dfrac{R_f.I_{fq}}{L_f} + \omega_s.I_{fd}\right) \end{cases} \quad (28)$$

To reduce the tracking error, we chose the following Lyapunov function [13]:

$$v_2 = \frac{1}{2}e_3^2 + \frac{1}{2}e_4^2 \quad (29)$$

The derivative of the Lyapunov function is given by

$$\dot{v}_2 = e_3.\dot{e}_3 + e_4.\dot{e}_4 \quad (30)$$

Replacing the derivative of the errors by using (28) and (30), the expression of the derivative of the Lyapunov function becomes:

$$\dot{v}_2 = -k_3.e_3^2 - k_4.e_4^2 + e_3.\left(k_3.e_3 + \dot{I}_{fdref} - \left(-\frac{V_{fd}}{L_f} - \frac{R_f.I_{fd}}{L_f} + \omega_s.I_{fq}\right)\right) + e_4.\left(k_4.e_4 + \dot{I}_{fqref} - \left(\frac{V_{sq}}{L_f} - \frac{V_{fq}}{L_f} - \frac{R_f.I_{fq}}{L_f} + \omega_s.I_{fd}\right)\right) \quad (31)$$

In order to ensure a good and stable control the derivatives of the Lyapunov function should be negative so we chose k_3 and k_4 positives [13]. The expressions of the control variable V_{fd} and V_{fq} to impose on the GSC are expressed as following equations:

$$\begin{cases} V_{fd} = -L_f(\dot{I}_{fdref} + \frac{R_f}{L_f}.I_{fd} - \omega_s.I_{fq} + k_3.e_3) \\ V_{fq} = -L_f(\dot{I}_{fqref} + \frac{R_f}{L_f}.I_{fq} + \omega_s.I_{fd} - \frac{V_{sq}}{L_f} + k_4.e_4) \end{cases} \quad (32)$$

That ensure $\dot{v}_2 \leq 0$. The performance and the stability the of the system are giving by a good choice of k_3 and k_4.

C. Dc Bus Voltage Control:

In power terms and by neglecting the converter losses, the DC bus equation can be written as following expressions [15]:

$$\begin{cases} W_{dc} = \int P_{dc}.\mathrm{dt} = \frac{1}{2}.C.U_{dc}^{\ 2} \\ \frac{dU_{dc}^{\ 2}}{dt} = \frac{2}{C}.(P_f - P_r) \end{cases} \quad (33)$$

where W_{dc} and P_{dc} are the energy and the power in the DC-Bus Capacitor.

$$\begin{cases} P_f = P_{dc} + P_r \\ P_{dc} = U_{dc}.\, \mathrm{I}_{dc} \end{cases} \quad (34)$$

According (34) it is possible to control the power P_{dc} in the DC-Bus By adjusting the power P_f to control the Dc voltage [13]. We can used PI controller (Fig. 3).

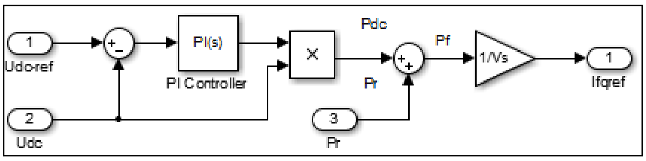

Fig. 3 Control loop of DC bus Voltage Block in SIMULINK

IV. Simulation Results

The global model of the wind system using a DFIG was simulated in MATLAB/SIMULINK. The parameters of the system are given in the appendix. To improve the robustness and the performance of the Backstepping controller we apply a random wind profile which varies between 7 m/s and 11 m/s presented in Fig. 4.

The profile of the mechanical rotor speed of the machine which is driven in rotation by wind is presented in Fig. 5. Mechanical rotor speed varies in the same shape as the wind speed, in order to extract the maximum of the electrical power for different value of wind speed [4], it varies between 1000 rpm and 1600 rpm, the parameters of the DFIG are given in the appendix.

Fig. 6 shows that the rotor currents Irq which controls the electromagnetic torque of the DFIG perfectly follows it reference. From Fig. 7 it can be seen that the stator active power is negative Ps<0 which means that the network is a receiver of the energy produced by the generator. Ps varies between -100KW and -600KW, against this variation the power coefficient *Cp* kept at its maximum value Cp=0.48 (From Fig. 8) which confirm the robustness of the MPPT controller.

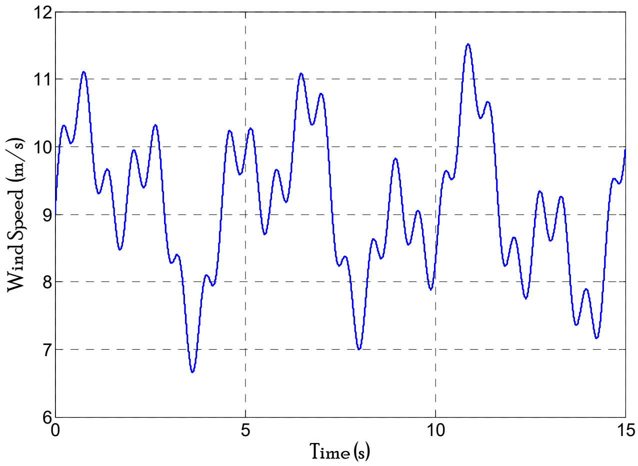

Fig. 4 Wind Speed Profile

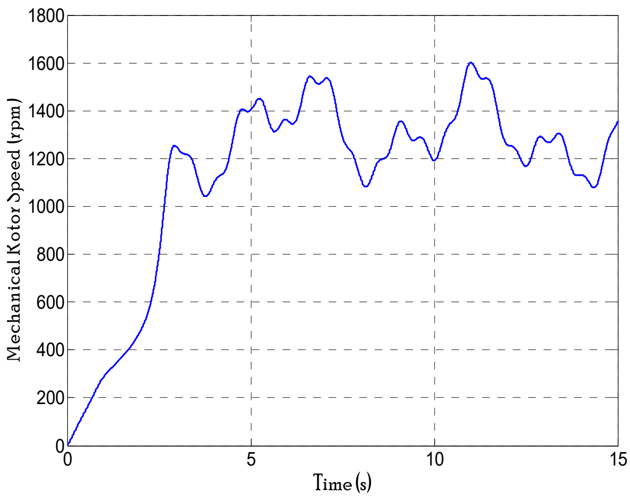

Fig. 5 The Mechanical Rotor Speed (rpm)

The DC bus voltage reference is kept at a constant value U_{dc-ref} =900V, from Fig. 9 we can see that DC voltage U_{dc} follows this constant; Fig. 10 presents active power grid side. Scanning the simulation results, it can be concluded that MPPT control and Backstepping approach are efficient and robust.

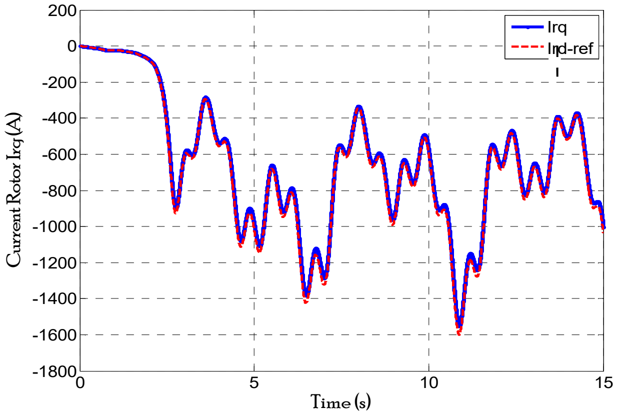

Fig. 6 Current rotor Irq and its reference

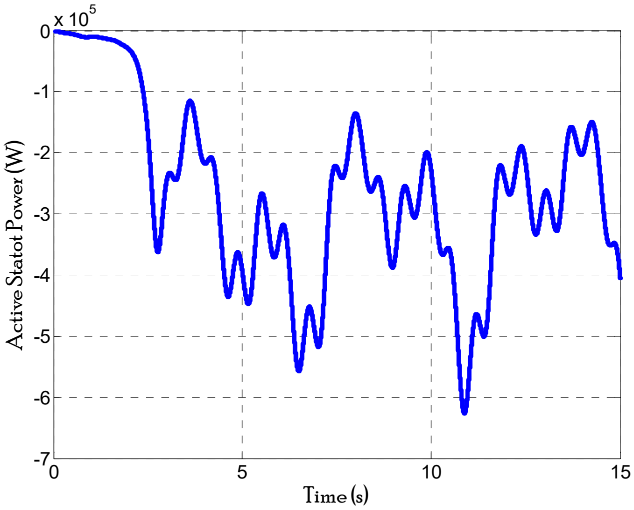

Fig. 7 Active Stator Power (W)

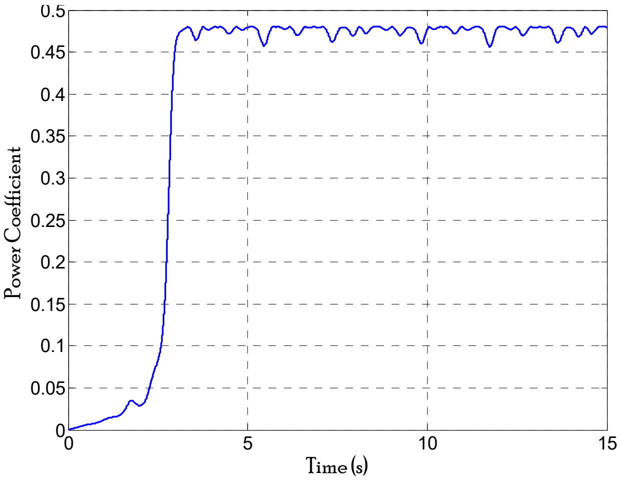

Fig. 8 Power Coefficient Cp

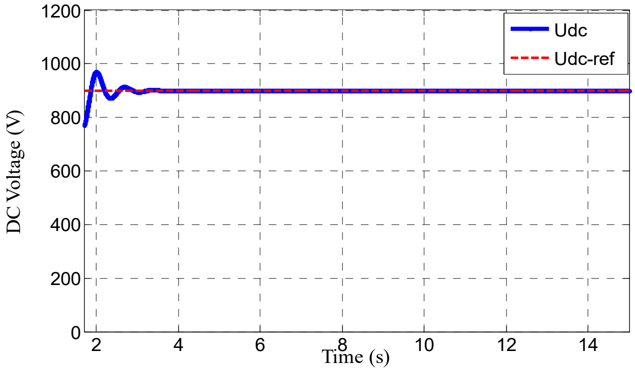

Fig. 9 DC Voltage and its Reference

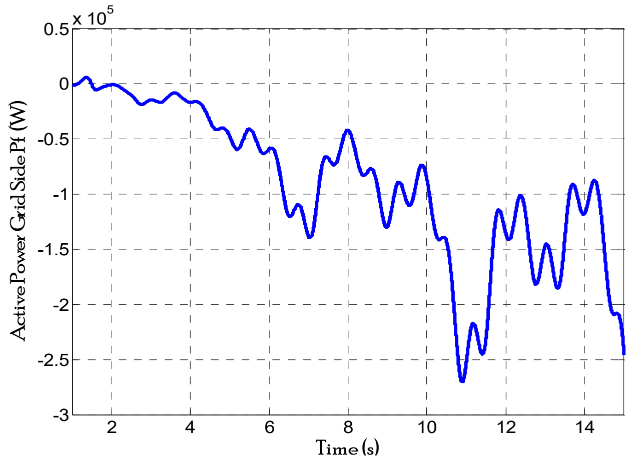

Fig. 10 Active Power Grid Side (W)

V. Conclusion

The work presented in this paper was devoted to control of a DFIG applied in a wind energy conversion system, after modeling the wind turbine and the DFIG in the d-q axis, we have established a vector control of the machine based in the flux oriented in order to relies a decoupling between direct and quadrature currents, then we have applied the Nonlinear Backstepping approach to control the two converter the RSC and the GSC in order to maximize capture wind energy. The simulation results show that the Nonlinear Backstepping controller is efficient and is a good approach for controlling the machine, it make possible to have an optimal operation of the electrical generation system and ensure some important strength and stability against variable wind speed.

Appendix

TABLE I
PARAMETER OF DFIG

Denotation	Numerical value of parameter
Rated Power	$P = 660KW$
Nominal Frequency	$f = 50\ Hz$
Number of pole pair	$p = 2$
Stator Resistance	R_s=0.0146 Ω
Rotor Resistance	R_r=0.0238 Ω
Stator Inductance	L_s=0.0306 H
Rotor Inductance	L_r=0.0303 H
Mutual Inductance	L_m=0.0299 H

TABLE II
PARAMETER OF WIND TURBINE

Denotation	Numerical value of parameter
Radius of the Turbine	$R = 21.165m$
Gain Multiplier	$G = 39$
Inertia Total Moment	$J = 28kg.\mathrm{m}^2$
Coefficient of Viscous Friction	$C_f = 0.01m / s$
Optimal Tip Speed Ratio	$\lambda_{opt} = 8.1$
Maximal Power Coefficient:	$C_{p\max} = 0.48$

TABLE III
PARAMETERS OF FILTER RL & DC-BUS

Symbol	Value
Lf	*3 mH*
Rf	*0.4Ω*
C	*2.2 mF*

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