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BACKSTEPPING ADAPTIVE CONTROL OF DFIG-GENERATORS FOR WIND TURBINES VARIABLE-SPEED

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ABSTRACT

In this paper, we present a new contribution for control of wind turbine energy conversion system. A new observer Backstepping control of DFIG-Generators for Wind Turbines Variable-Speed is developed.
A new control technique for wind systems is presented. This control scheme is based on an adaptive pole placement control strategy integrated to a Backstepping control scheme. The overall stability of the system is shown using Lyapunov technique. The performance and robustness are analyzed and compared by simulation using Matlab / Simulink software.
Keywords: *Wind-Turbine, Double-Fed asynchronous generator (DFIG), MPPT, Adaptive Control Backstepping, Matlab / Simulink*

1. INTRODUCTION

Due to the need to their enormous energy and the growing scarcity of raw materials, Emerging countries are forced to rely on renewable energy.

Wind energy is one of the oldest energy sources used by humans, and nowadays, has become a recognized solution for the production of energy, in addition to other renewable energy sources.

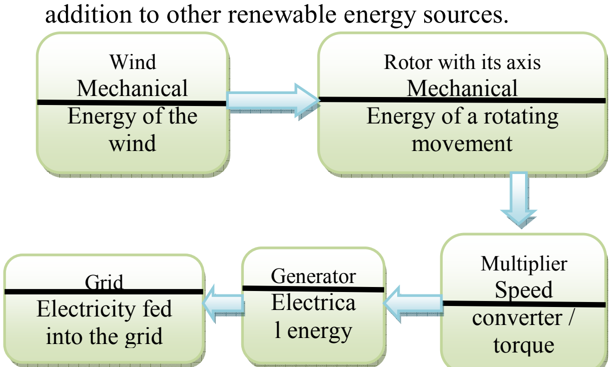

Fig.1: Energy Transformation

Although each wind turbine is optimized for local conditions, there are two fundamental designs: fixed speed wind turbine and variable speed wind turbine, while the majority of wind turbines use constant speed, the number of variable speed wind turbines is increasing.

The operation of a wind turbine DFIG at a variable speed can be realized by the following steps:
The sliding power of the machine is fed into the grid, and then it's supplied from the network in the armature, which allows the operation of the machine in the dual mode operations of the machine generator and motor.

The frequency generated by the converter is superposed to the rotating field of the armature. The assigned superposed frequency remains constant, regardless of the armature speed. The speed range is determined by the frequency which feeds the armature. However, with such a design, the regulation remains to be introduced.

A particular advantage of this design is the ability to separate the regulation of the active and the reactive power [1-2].

Moreover, only one third of the nominal power of the generator flows through the circuit of the armature and thus the frequency converter.

"The variable speed" has become the mostly used system in modern wind turbine. Depending on wind speed and generator power, the blade angle can be optimally adjusted by the adjustment mechanism from a partial to full load. Such a system is called a variable valve control. The generators mounted in such a wind turbine are

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coupled via an additional component rather than being linked to the network.

In addition to other renewable energy sources, wind energy has become a trusted solution for the production of energy. While the majority of wind turbines are fixed speed, the number of variable speed wind turbines is increasing [3]. It has been shown that the *Doubly-Fed Asynchronous Generator* (*DFIG*) with Backstepping control is a machine that has excellent performance and is commonly used in the wind turbine industry [4]. There are several reasons for using a Doubly-Fed Asynchronous Generator (DFIG) for a variable speed wind turbine , such as reducing the exhaustion on mechanical parts, noise reduction as well as the possibility of control of active and reactive power.

The Backstepping approach offers a choice of design tools for accommodation of the nonlinearities uncertainties and allows to avoid wasteful cancellations. However, the none adaptive backstepping approach is able to keep almost all the robustness properties of the mismatched uncertainties. The none adaptive backstepping is a rigorous design procedure and methodology for nonlinear feedback control. The principal idea of this approach is to recursively design controllers for the machine torque, the uncertainty of the subsystems and the feedback signals towards the control input. thz difference between this approch and the the approach of the conventional feedback linearization is its ability to avoid cancellation of useful nonlinearities in pursuing the objectives of stabilization and tracking

A nonlinear Backstepping control design scheme is developed in order to control the speed of DFIG that has specific model knowledge. The asymptotic stability of the resulting closed loop system is guaranteed upon the use of the Lyapunov stability theorem.

Due to the complexity of the diversity of the electric control devices of the machines, it is difficult to define a general structure for such systems. However, if we consider the elements most commonly encountered in these systems, it is possible to define a general structure of an electric control device of machines which is show in *Fig.2*:

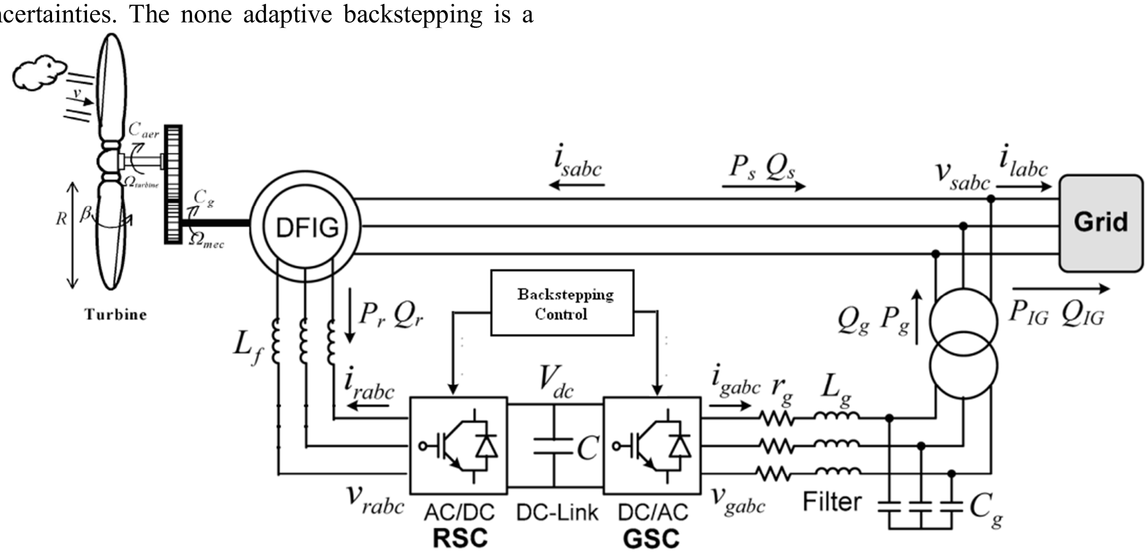

Fig.2: Architecture Of The Control

2. WIND-TURBINE MODEL

The model of the turbine is built from the following system of equations: [7-8]:

$$P_{incident} = \frac{1}{2}.\rho.S.v^3 \tag{1}$$

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

$$\lambda = \frac{\Omega_t.R}{v} \tag{3}$$

$$C_p^{\max}(\lambda,\beta) = \frac{16}{27} \approx 0.593 \tag{4}$$

$$C_p(\lambda,\beta) = c_1\left(c_2.\frac{1}{A} - c_3.\beta - c_4\right).e^{-c_5\frac{1}{A}} + c_6.\lambda \tag{5}$$

$$\frac{1}{A} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{1+\beta^3} \tag{6}$$

$$C_{al} = \frac{P_{eol}}{\Omega_t} = \frac{1}{2}.\rho.S.C_p(\lambda,\beta).v^3.\frac{1}{\Omega_t} \tag{7}$$

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$$J = \frac{J_{tur}}{G^2} + J_g \tag{8}$$

$$J\frac{d\Omega_{mec}}{dt} = C_{mec} = C_{ar} - C_{em} - f.\Omega_{mec} \tag{9}$$

S : the area swept by the pales of the turbine [m^2]
ρ : the density of the air ($\rho = 1.225 kg/m^3$ at atmospheric pressure).
v : wind speed [m/s].
$Cp\ (\lambda, \beta)$: the power coefficient.
λ : the specific speed
β: the angle of orientation of the blades
$P_{extracted}$: the power extracted of the turbine.
Ω_t : Rotational speed of the turbine
C_{al} : Torque on the slow axis (turbine side)
J_{tur} : turbine inertia
J_g : inertia of the generator.
Ω_{mec} : Mechanical speed of DFIG
C_{ar} : Aerodynamic torque on the fast axis of the turbine
$c_1 = 0.5872,\ c_2 = 116,\ c_3 = 0.4,\ c_4 = 5,\ c_5 = 21,\ c_6 = 0.0085$

The six coefficients c_1, c_2, c_3, c_4, c_5 are modified for maximum Cp equal to 0.564 for $\beta = 0°$.

The *Fig.2* shows the evolution of the power coefficient as a function of λ for different values of β. A coefficient of maximum power of Cp=0.564 is obtained for a speed ratio λ which is (3) (λopt). Fixing β and λ respectively to their optimal values, the wind system provides optimal power.

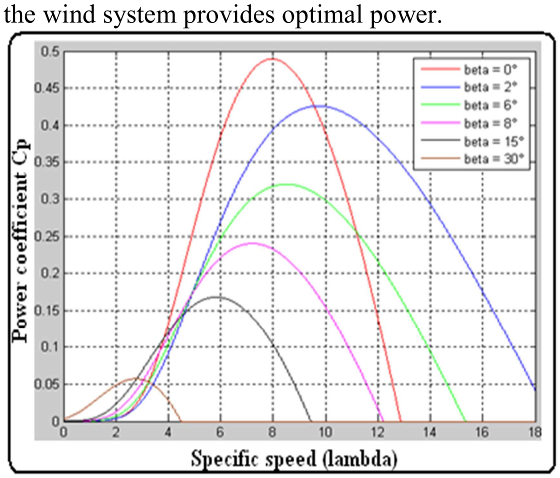

Fig.3: Power Coefficient As A Function Of Λ And Β

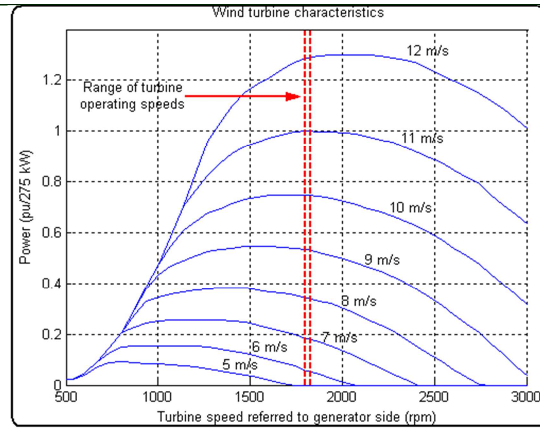

Fig.4: Wind-Turbine DFIG Characteristics

The above equations are used to prepare the block diagram of the model of turbine (Fig.4).

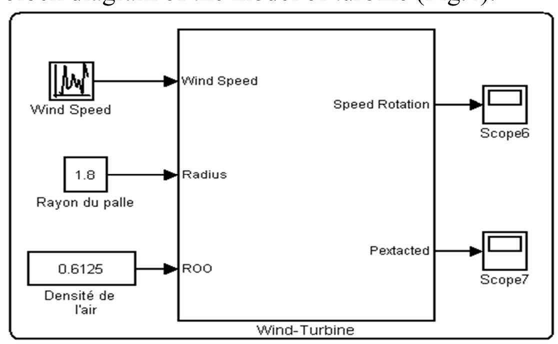

Fig.5: Wind-Turbine Model

In order to capture the maximum power of the incident energy of the wind-turbine, we must continuously adjust the rotational speed of the wind turbine. The optimal mechanical turbine speed corresponds to λopt and β = 0°. The speed of the DFIG is used as a reference value for a proportional-integral type of a controller (PI phase advance). The latter determines the control set point which is the electromagnetic torque that should be applied to the machine to run the generator at its optimal speed.

The "Pitch Control" is a technique that mechanically adjusts the blade pitch angle to shift the curve of the power coefficient of the turbine [5-6].

The “Pitch control” technique can be quite expensive and it is generally used for wind turbines and high average power. However, for our model, we decided to use the "Stall Control" technique, which is a passive technique that allows a natural aerodynamic stall (loss of lift when the wind speed becomes more important). The regulation of the speed of rotation of the pitch angle of the turbine’s blades is produced due to the increase of the generated speed by 30% from the normal speed, if not, β is equal to zero. The synthesis of the PI

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controller requires knowledge of the transfer function of our system which can be difficult to realize due to the power of coefficient. A simple proportional correction (P) is obtained after the realization of a first test. Note that β may vary from 0 ° to 90 ° which characterize the saturation.

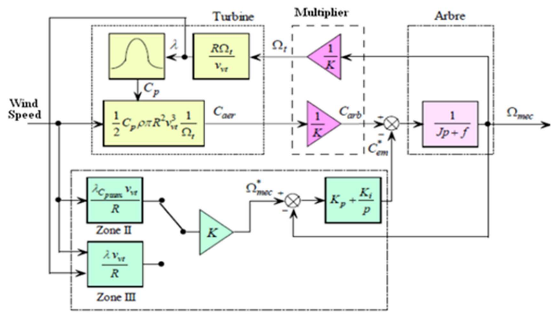

Fig.6: Block Diagram With Control Of The Speed

3. DFIG MODEL SYSTEM

The Power equations in the d-q reference DFIG can be written as follows [13-14]:

$$\begin{cases} v_{ds} = R_s.i_{ds} + \dfrac{d}{dt}\phi_{ds} - \omega_s.\phi_{qs} \\ v_{qs} = R_s.i_{qs} + \dfrac{d}{dt}\phi_{qs} + \omega_s.\phi_{ds} \\ v_{dr} = R_r.i_{dr} + \dfrac{d}{dt}\phi_{dr} - \omega_s.\phi_{qr} \\ v_{qr} = R_r.i_{qr} + \dfrac{d}{dt}\phi_{qr} + \omega_r.\phi_{dr} \end{cases} \tag{10}$$

With:

$$\omega_r = \omega_s - P.\Omega$$

$$\begin{cases} \phi_{ds} = L_s.i_{ds} + M.i_{dr} \\ \phi_{qs} = L_s.i_{qs} + M.i_{qr} \\ \phi_{dr} = L_r.i_{dr} + M.i_{ds} \\ \phi_{qr} = L_r.i_{qr} + M.i_{qs} \end{cases} \tag{11}$$

$$L_s = l_s - M_s, \qquad L_r = l_r - M_r$$

L_s, L_r: Cyclic inductances of stator and rotor phase;
l_s, l_r : Inductances of stator and rotor phase;
M_s, M_r : Mutual inductances between stator and rotor phases respectively;
M: Maximum mutual inductance between stator and rotor stage (the axes of the two phases coincide).

The expression of the electromagnetic torque of the DFIG depending on flow and stator currents can be written as follows:

$$C_{em} = P(\phi_{ds}.i_{qs} - \phi_{qs}.i_{ds}) \tag{12}$$

With P: number of pole pairs of the DFIG.

The active and reactive powers stator and rotor of the DFIG are written as follows [7-12]:

$$\begin{cases} P_s = v_{ds}.i_{ds} + v_{qs}.i_{qs} \\ Q_s = v_{qs}.i_{ds} - v_{ds}.i_{qs} \\ P_r = v_{dr}.i_{dr} + v_{qr}.i_{qr} \\ Q_r = v_{qr}.i_{dr} - v_{dr}.i_{qr} \end{cases} \tag{13}$$

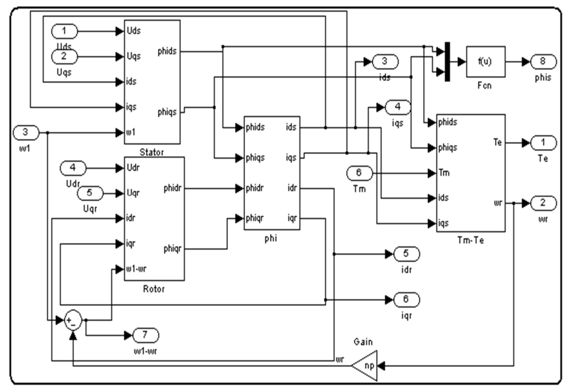

Fig.7: DFIG Model For Wind-Turbine

4. BACKSTEPPING CONTROLLER APPLIED TO DFIG GENERATOR

The adaptive Backstepping control approach is a control technique that can efficiently linearize a nonlinear system as DFIG in the presence of uncertainties. Unlike other information linearization techniques, adaptive Backstepping has the flexibility to keep useful nonlinearity intact during stabilization. The essence of Backstepping is to stabilize the state of the virtual control. Therefore, it generates a corresponding error variable that can be stabilized by carefully selecting the appropriate control inputs. These inputs can be determined from the analysis of Lyapunov stability

From the equation (10) it is clear that the dynamic model of the DFIG is highly non-linear due to the coupling between the speed and the electric currents. According to the vector control principle, the direct axis current i_d is always forced to equal zero in order to orient all the linkage flux in the d axis and achieve maximum torque per ampere.

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$$\frac{d\varphi_{rd}}{dt}=V_{rd}+\left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sd}-\left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rd}+\omega_r.\varphi_{rq}$$
$$\frac{d\varphi_{rq}}{dt}=V_{rq}+\left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sq}-\left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rq}-\omega_r.\varphi_{rd} \quad (14)$$
$$\frac{d\varphi_{sd}}{dt}=V_{sd}+\left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rd}-\left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sd}+\omega_s.\varphi_{sq}$$
$$\frac{d\varphi_{sq}}{dt}=V_{sq}+\left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rq}-\left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sq}-\omega_s.\varphi_{sqd}$$

It is obvious that the dynamic model is highly nonlinear due to the coupling between the velocity and magnetic flux. Thus, the study of stability of the system is characterized by:

$[X]=[\varphi_{rd} \quad \varphi_{rq} \quad \varphi_{sd} \quad \varphi_{sq} \quad \Omega]^T$: The state vector (the flux and speed are measurable).

$[U]=[V_{rd} \quad V_{rq} \quad V_{sd} \quad V_{sq}]^T$: The control variable (voltage stator and rotor).

The Lyapunov function is divided into two steps, one for the control of the speed and the other for the control of the flux.

4.1. Backstepping Controller speed.

The first step of the Backstepping control is defined Lag error of the state variable by the following calculation [15-16]:

$$e_\Omega=\Omega_{ref}-\Omega \quad (15)$$

Its derivative gives:

$$\dot{e}_\Omega=\frac{de_\Omega}{dt}=\dot{\Omega}_{ref}-\dot{\Omega} \quad (16)$$

With:

$$\dot{\Omega}=\left(\frac{P(1-\sigma)}{J.\sigma.M}\right)(\varphi_{rd}.\varphi_{sq}-\varphi_{rq}.\varphi_{sd})-\frac{f}{J}\Omega-\frac{C_r}{J} \quad (17)$$

One finds:

$$\dot{e}_\Omega=\dot{\Omega}_{ref}-\left(\frac{P(1-\sigma)}{J.\sigma.M}\right)(\varphi_{rd}.\varphi_{sq}-\varphi_{rq}.\varphi_{sd})-\frac{f}{J}\Omega-\frac{C_r}{J} \quad (18)$$

With the application the principles of rotor flux orientation:

$$\begin{cases}\varphi_{sd}=0\\ \varphi_{rq}=0\end{cases}$$

It results in the following expression:

$$\dot{e}_\Omega=\dot{\Omega}_{ref}-\left(\frac{P(1-\sigma)}{J.\sigma.M}\right)(\varphi_{rd}.\varphi_{sq})+\frac{f}{J}\Omega+\frac{C_r}{J} \quad (19)$$

Subsequently we define the Lyapunov function from the form:

$$V_1=\frac{1}{2}e_\Omega{}^2 \quad (20)$$

Its derivative gives:

$$\dot{V}_1=e_\Omega\dot{e}_\Omega$$
$$\dot{V}_1=e_\Omega(\dot{\Omega}_{ref}-\left(\frac{P(1-\sigma)}{J.\sigma.M}\right)(\varphi_{rd}.\varphi_{sq})+\frac{f}{J}\Omega+\frac{C_r}{J}) \quad (21)$$

, to ensure the stability of the sub system, using the Backstepping design method we need to turn the equation (19) more negative, and consider the flux φ_{rd}, φ_{sq} as virtual inputs of our system (12), thus, we define the following equations:

$$\begin{cases}\varphi_{rd\_ref}=\varphi_r\\ \varphi_{sq\_ref}=\dfrac{1}{\left(\dfrac{P(1-\sigma)}{J.\sigma.M}\right)\varphi_{rd\_ref}}\left(K_\Omega e_\Omega+\dfrac{f}{J}\Omega+\dfrac{C_r}{J}\right)\end{cases} \quad (22)$$

With K_Ω this is a positive constant.

We substitute equation (20) in the derivative of the Lyapunov function equation V_1 (19) and assuming that Ω_{ref} is constant we have the negativity of the function as:

$$\dot{V}_1=-K_\Omega e_\Omega{}^2\le 0 \quad (23)$$

Whence the asymptotic stability of the origin of the equation system (12)

4.2. Backstepping Controller flux

The objective of the section is the elimination the flux regulators by calculating the command voltages, for this we define the following errors:

$$\begin{cases}e_1=\varphi_{rd\_ref}-\varphi_{rd}\\ e_2=\varphi_{rq\_ref}-\varphi_{rq}\\ e_3=\varphi_{sd\_ref}-\varphi_{sd}\\ e_4=\varphi_{sq\_ref}-\varphi_{sq}\end{cases} \quad (24)$$

Its derivative is:

$$\begin{cases}\dot{e}_1=\dot{\varphi}_{rd\_ref}-\dot{\varphi}_{rd}\\ \dot{e}_2=\dot{\varphi}_{rq\_ref}-\dot{\varphi}_{rq}\\ \dot{e}_3=\dot{\varphi}_{sd\_ref}-\dot{\varphi}_{sd}\\ \dot{e}_4=\dot{\varphi}_{sq\_ref}-\dot{\varphi}_{sq}\end{cases} \quad (25)$$

The results of the derivative of equation (32) are:

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$$\begin{cases} \dot{e}_1 = \dot{\varphi}_r - V_{rd} - \left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sd} + \left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rd} - \omega_r.\varphi_{rq} \\ \dot{e}_2 = -V_{rq} - \left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sq} + \left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rq} + \omega_r.\varphi_{rd} \\ \dot{e}_3 = -V_{sd} - \left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rd} + \left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sd} - \omega_s.\varphi_{sq} \\ \dot{e}_4 = \dot{\varphi}_s - V_{sq} - \left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rq} + \left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sq} + \omega_s.\varphi_{sd} \end{cases} \quad (26)$$

The laws of real machine control are V_{sd}, V_{sq}, V_{rd} and V_{rq} appear in equation (33), then to analyze the stability of this system, we define a new Lyapunov function final V_2 given by the following form:

$$V_2 = \frac{1}{2}\left(e_\Omega{}^2 + e_1{}^2 + e_2{}^2 + e_3{}^2 + e_3{}^2\right) \quad (27)$$

The result of the derivative of equation (24) is:

$$\begin{aligned} \dot{V}_2 &= -K_\Omega e_\Omega - K_1 e_1 - K_2 e_2 - K_3 e_3 - K_4 e_4 \\ &+ e_\Omega\left(K_\Omega e_\Omega - \left(\frac{P(1-\sigma)}{J.\sigma M}\right)(\varphi_r.\varphi_s) + \frac{f}{J}\Omega + \frac{C_r}{J}\right) \\ &+ e_1\left(K_1 e_1 + \dot{\varphi}_r - V_{rd} - \left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sd} + \left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rd} - \omega_r.\varphi_{rq}\right) \\ &+ e_2\left(K_2 e_2 - V_{rq} - \left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sq} + \left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rq} + \omega_r.\varphi_{rd}\right) \\ &+ e_3\left(K_3 e_3 - V_{sd} - \left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rd} + \left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sd} - \omega_s.\varphi_{sq}\right) \\ &+ e_4\left(K_4 e_4 + \dot{\varphi}_s - V_{sq} - \left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rq} + \left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sq} + \omega_s.\varphi_{sd}\right) \end{aligned} \quad (28)$$

With K_1, K_2, K_3 and K_4 are positive constants.

Extracted from equation (25) expressions the controls voltages V_{sd}, V_{sq}, V_{rq} and V_{rd} as following:

$$\begin{cases} V_{rd} = \left(K_1 e_1 + \dot{\varphi}_r - \left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sd} + \left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rd} - \omega_r.\varphi_{rq}\right) \\ V_{rq} = e_2\left(K_2 e_2 - \left(\frac{R_r.M}{\sigma.L_s.L_r}\right)\varphi_{sq} + \left(\frac{R_r}{\sigma.L_r}\right)\varphi_{rq} + \omega_r.\varphi_{rd}\right) \\ V_{sd} = e_3\left(K_3 e_3 - \left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rd} + \left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sd} - \omega_s.\varphi_{sq}\right) \\ V_{sq} = e_4\left(K_4 e_4 + \dot{\varphi}_s - \left(\frac{R_s.M}{\sigma.L_s.L_r}\right)\varphi_{rq} + \left(\frac{R_s}{\sigma.L_s}\right)\varphi_{sq} + \omega_s.\varphi_{sd}\right) \end{cases} \quad (29)$$

This equation (26) implies the negativity of the following Lyapunov function V_2:

$$V_2 = -K_\Omega e_\Omega - K_1 e_1 - K_2 e_2 - K_3 e_3 - K_4 e_4 \leq 0 \quad (30)$$

4.3. Estimation and observation of parameters DFIG

In the previous equations, the control laws are developed under the assumption that the machine parameters are known and invariants. This assumption is not always true, because, the stator and rotor resistance are varied with temperature, also for the coefficient cyclic inductance of the stator and the rotor. The adaptive Backstepping control takes account of these parametric variations, and there are estimated by other parameter same as the one shown in the equation (17), as we do not know the exact value of the load torque C_r; it will be replaced by its estimated value $\hat{C}_r$.

$$\hat{\varphi}_{rd\_ref} = \frac{1}{\left(\frac{P(1-\hat{\sigma})}{J.\hat{\sigma}.M}\right).\varphi_{sd\_ref}}\left(K_\Omega e_\Omega + \frac{f}{J}\Omega + \frac{\hat{C}_r}{J}\right) \quad (31)$$

From this relation (31), we deduce the dynamics of the speed error as follows:

$$\dot{e}_\Omega = \left(\frac{P(1-\hat{\sigma})}{J.\hat{\sigma}.M}\right)(\varphi_{rd}.\varphi_{sq}) + \frac{f}{J}\Omega + \frac{\hat{C}_r}{J} \quad (32)$$

For simplicity the equation (30) we write:

$$\hat{a}_1 = \left(\frac{P(1-\hat{\sigma})}{J.\hat{\sigma}.M}\right)$$

The equation becomes:

$$\dot{e}_\Omega = -\hat{a}_1(\varphi_{rd}.\varphi_{sq}) + \frac{f}{J}\Omega + \frac{\hat{C}_r}{J} \quad (33)$$

The new results estimated the parameters of the equation (26) are written:

$$V_2 = \frac{1}{2}\left(\begin{aligned} &e_\Omega{}^2 + e_1{}^2 + e_2{}^2 + e_3{}^2 + e_4{}^2 \\ &+ \frac{\tilde{C}_r{}^2}{\gamma_1} + \frac{\tilde{a}_1^2}{\gamma_2} + \frac{\tilde{a}_2{}^2}{\gamma_3} + \frac{\tilde{a}_3{}^2}{\gamma_4} + \frac{\tilde{a}_4{}^2}{\gamma_5} \end{aligned}\right) \quad (34)$$

The derivative of V_2 is:

$$\dot{V}_2 = \left(\begin{aligned} &e_\Omega\dot{e}_\Omega + e_1\dot{e}_1 + e_2\dot{e}_2 + e_3\dot{e}_3 + e_4\dot{e}_4 \\ &+ \frac{\tilde{C}_r\dot{\tilde{C}}_r}{\gamma_1} + \frac{\tilde{a}_1\dot{\tilde{a}}_1}{\gamma_2} + \frac{\tilde{a}_2\dot{\tilde{a}}_2}{\gamma_3} + \frac{\tilde{a}_3\dot{\tilde{a}}_3}{\gamma_4} + \frac{\tilde{a}_4\dot{\tilde{a}}_4}{\gamma_5} + \frac{\tilde{a}_5\dot{\tilde{a}}_5}{\gamma_5} \end{aligned}\right) \quad (35)$$

Finally, the control laws are now developed as follows:

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$$\begin{cases} V_{rd} = \left(K_1 e_1 + \dot{\varphi}_r - \hat{a}_2 \varphi_{sd} + \hat{a}_3 \varphi_{rd} - \omega_r . \varphi_{rq}\right) \\ V_{rq} = e_2\left(K_2 e_2 - \hat{a}_2 \varphi_{sq} + \hat{a}_3 \varphi_{rq} + \omega_r . \varphi_{rd}\right) \\ V_{sd} = e_3\left(K_3 e_3 - \hat{a}_4 \varphi_{rd} + \hat{a}_5 \varphi_{sd} - \omega_s . \varphi_{sq}\right) \\ V_{sq} = e_4\left(K_4 e_4 + \dot{\varphi}_s - \hat{a}_4 \varphi_{rq} + \hat{a}_5 \varphi_{sq} + \omega_s . \varphi_{sd}\right) \end{cases} \quad (36)$$

With this calculation, the expression (36) becomes:

$$V_2 = -K_\Omega e_\Omega - K_1 e_1 - K_2 e_2 - K_3 e_3 - K_4 e_4 \leq 0 \quad (37)$$

So the system is globally asymptotically stable in the presence of parametric uncertainties and variables [18].

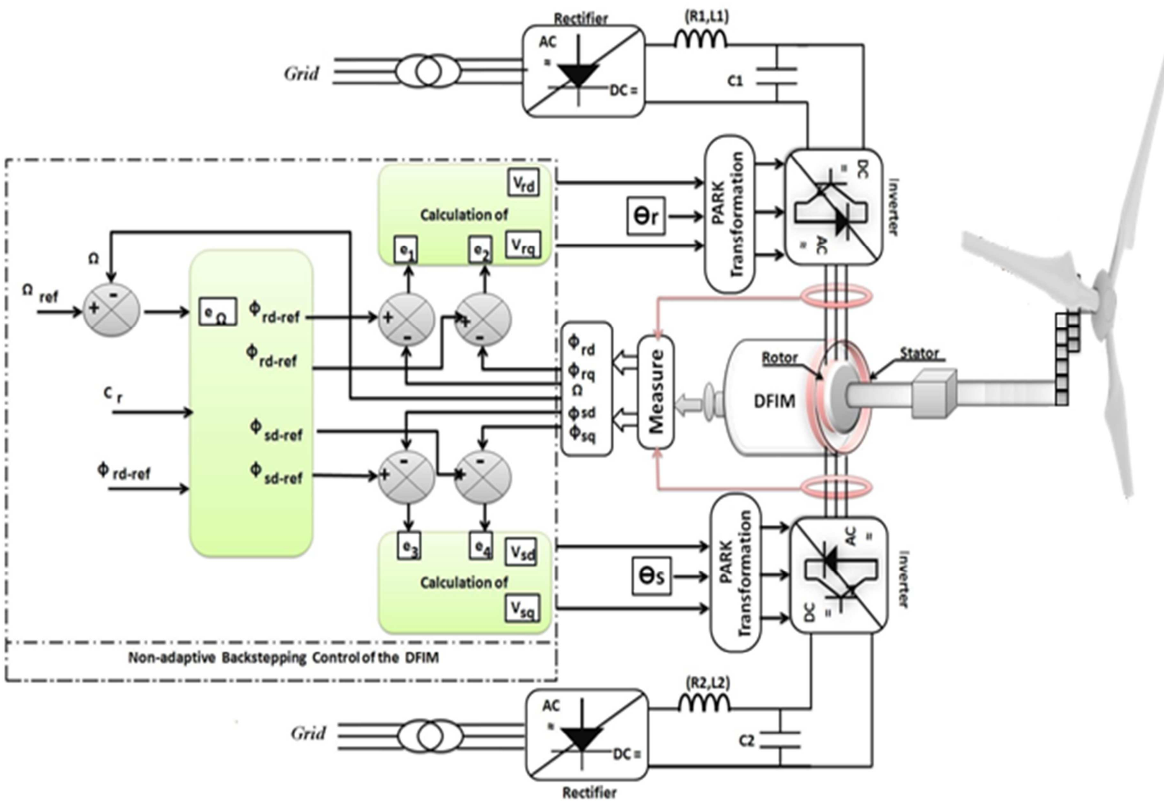

Fig.8: Backstepping Control Structure For Wind-Turbine System

5. RESULTS & SIMULATIONS

The simulation results are given by a system with the following parameters:

TABLE I. *Parameters Of Wind Power System*

Parameters of the turbine	
Diameter of blade	R=35.25 m
Gain multiplier	G=16
Inertia of the turbine	J=0.3125 Kg.m2
Coefficient of viscosity	f=0.00673 m.s-1
Parameters of the DFIG	
stator resistance	Rs=0.455
rotor resistance	Rr=0.62
stator inductance	Ls=0.084H
rotor inductance	Lr=0.081H
Mutual inductance	Msr=0.078H
Number of poles	P=2

5.1. DFIG-Generator Performances

The following results are obtained by choosing the following values:

- ✓ Gains of the control law: $k_\Omega = 0.15$, $k_d = 0.01$, $k_q = 0.01$.
- ✓ Adaptation gains: $\gamma_1 = 0.15$, $\gamma_2 = 0.01$, $\gamma_3 = 0.015$.

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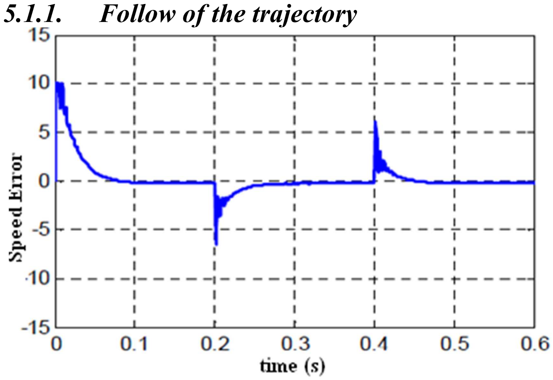
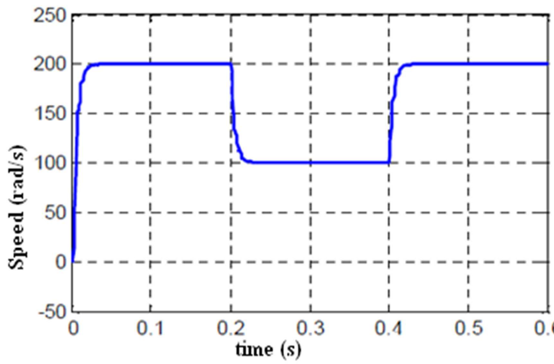
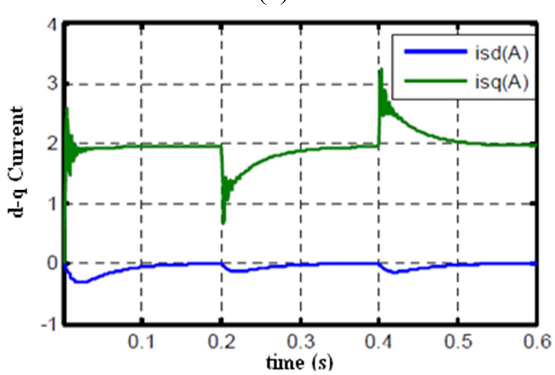
5.1.1. Follow of the trajectory



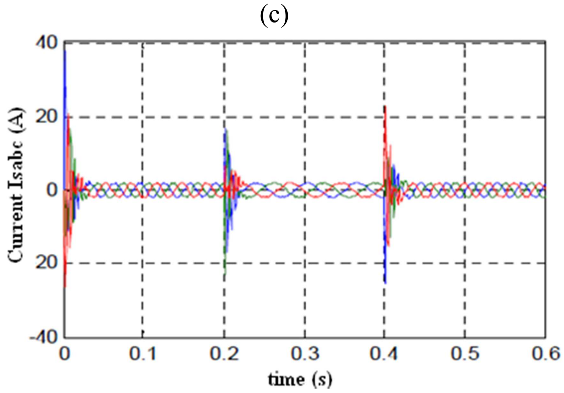
(a)



(b)



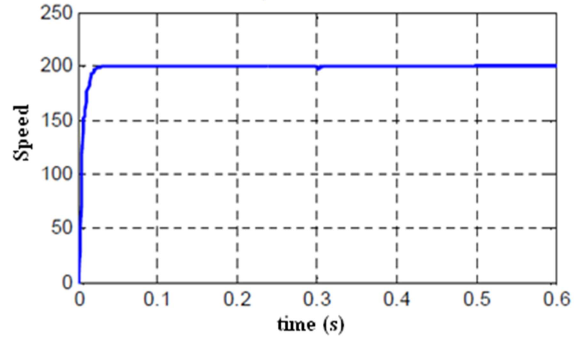
(c)



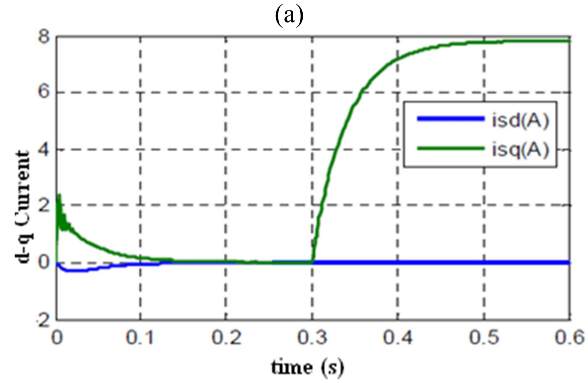
(d)

Fig.9: Test Performance Of The Adaptive Controller For Trajectory Tracking, (A) Speed Response Trajectory (B) Error Speed Response (C) D-Q Axis Current Without Uncertainties (D) Abc Axis Current

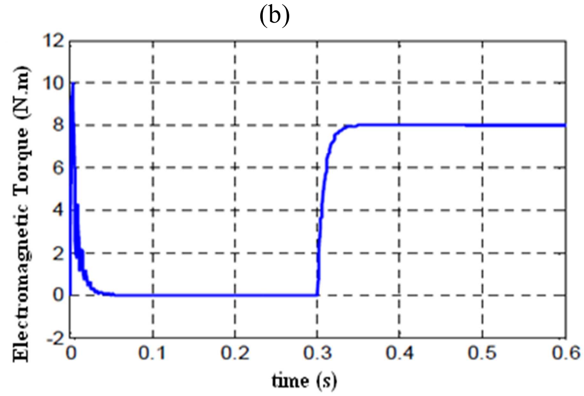
5.1.2. Disturbance rejection



(a)



(b)



(c)

Fig.10: Test performance of the adaptive controller for rejecting disturbance torque load applied at t = 0.3s. (a)Speed response trajectory (b) d-q axis current without uncertainties (c) Electromagnetic Torque

5.2. Wind-turbine performances

By using the reduced model, we applied a wind profile closer to the real one. The random wind was filtered depending on the slow dynamics of the system studied. The objective is to see the degree of power and efficiency of the maximum continuing speed provided by the controller Backstepping.

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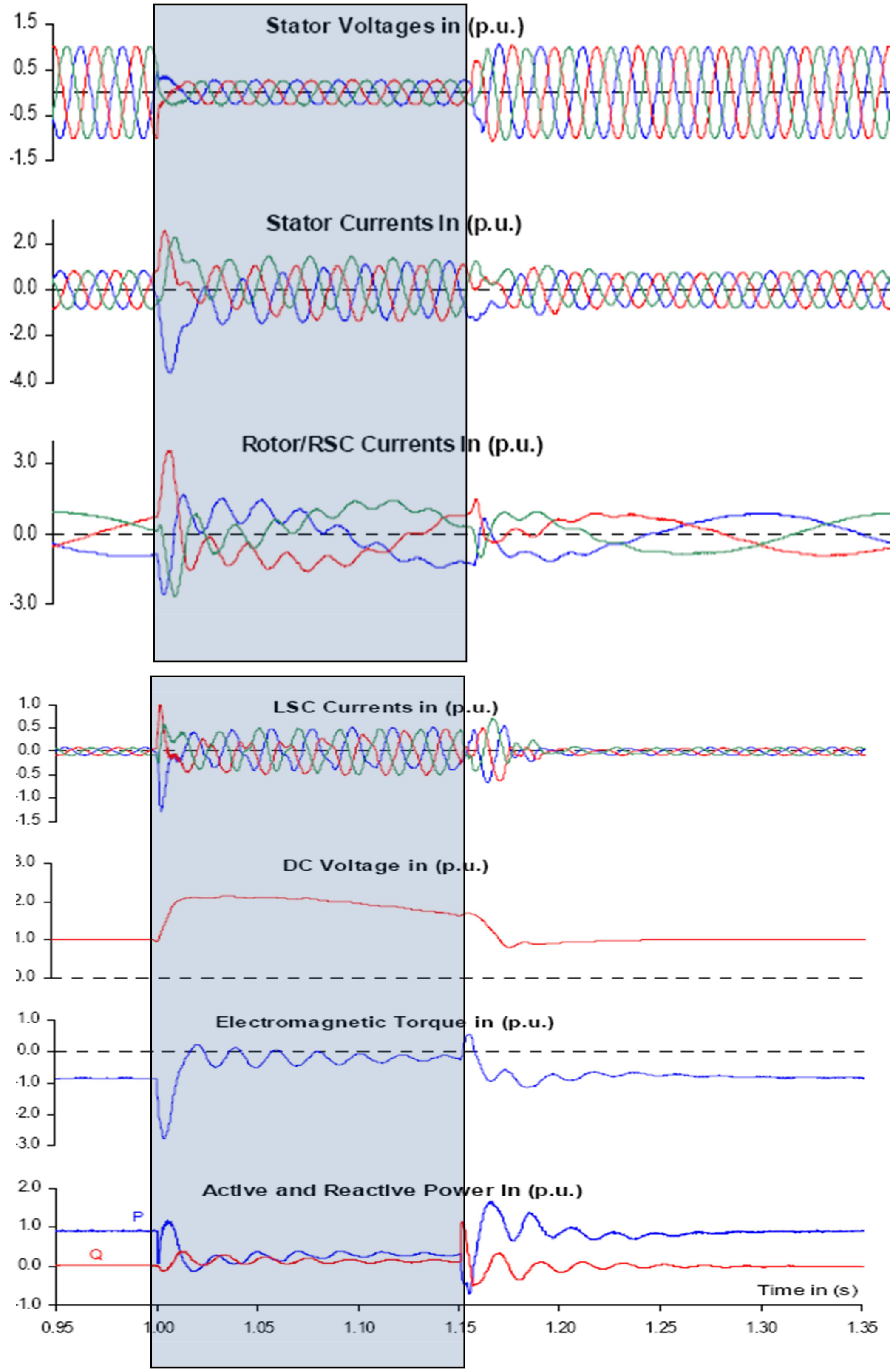

Fig.11: Simulation Results For Backstepping Command Without Protection

6. CONCLUSION

This work developed a new control strategy for electric machines applied to a variable speed wind turbine system. The Backstepping control provides an improved robustness and a great enhancement and stability of systems performance. The results obtained in this study show the validation of the proposed model.

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