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Backstepping Adaptive Control of DFIG-Generators for Variable-Speed Wind Turbines

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ABSTRACT

In this paper, we present a nonlinear robust control of active and reactive power by the use of the technique Backstepping a double-fed asynchronous generator (DFIG) system incorporated in a wind. The power transfer between the stator and the network is carried out by acting on the rotor via a bidirectional signal converter.

Initially, a control strategy of the MPPT asynchronous double fed generator is presented. Thereafter, 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 based Matlab / Simulink software.

Indexing terms/Keywords

FPGA, Indirect Sliding Mode Control; Permanent Magnet Synchronous Machine (PMSM); Power System Control, Systems Generator; Reusability; PWM.

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1. INTRODUCTION

Today, wind energy has become a viable solution for the production of energy, in addition to other renewable energy sources. While the majority of wind turbines are fixed speed, the number of variable speed wind turbines is increasing [1]. 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 [2-3]. There are many reasons for using an Doubly-Fed Asynchronous Generator (DFIG) for wind turbine a variable speed , such as reducing efforts on mechanical parts, noise reduction and the possibility of control of active power and reactive.

The wind system using DFIG generator and a "back-to-back" converter that connects the rotor of the generator and the network has many advantages. One advantage of this structure is that the power converters used are dimensioned to pass a fraction of the total system power [5-6]. This allows reducing losses in the power electronics components. The performances and power generation depends not only on the DFIG generator, but also the manner in which the two parts of "back-to-back" converter are controlled.

The power converter machine side is called "Rotor Side Converter" (RSC) and the converter Grid-side power is called "Grid Side Converter" (GSC). The RSC converter controls the active power and reactive power produced by the machine. As the GSC converter, it controls the DC bus voltage and power factor network side.

The not adaptive backstepping approach offers a choice of design tools for accommodation of uncertainties nonlinearities. And can avoid wasteful cancellations. However, the not adaptive backstepping approach is capable of keeping almost all the robustness properties of the mismatched uncertainties. The not adaptive backstepping is a rigorous and procedure design methodology for nonlinear feedback control. The principal idea of this approach is to recursively design controllers for machine torque constant uncertainty subsystems in the structure and ''step back'' the feedback signals towards the control input. This approach is different from the approach of the conventional feedback linearization in that it can avoid cancellation of useful nonlinearities in pursuing the objectives of stabilization and tracking. A nonlinear backstepping control design scheme is developed for the speed tracking control of DFIG that has exact model knowledge. The asymptotic stability of the resulting closed loop system is guaranteed according to Lyapunov stability theorem.

The adaptive backstepping design offers a choice of design tools for accommodation of uncertainties nonlinearities. And can avoid wasteful cancellations. In addition, the adaptive backstepping approach [12] is capable of keeping almost all the robustness properties of the mismatched uncertainties. The adaptive backstepping is a systematic and recursive design methodology for nonlinear feedback control.

The Backstepping control is a systematic and recursive design methodology for nonlinear feedback control. Appling those design methods, control objectives such as position, velocity can be achieved.

A nonlinear backstepping control design scheme is developed for the speed tracking control of DFIG that has exact model knowledge. The asymptotic stability of the resulting closed loop system is guaranteed according to Lyapunov stability theorem.

In this paper, we present a technique to control two power converters which is based on the backstepping control. We analyze their dynamic performances by simulations in Matlab/Simulink environment. We start by modeling of the wind turbine, and then a tracking technique operating point at maximum power point tracking (MPPT) will be presented. Thereafter, we present a model of the DFIG in the dq reference, and the general principle of control of both power converters which is based on backstepping technique.

Considering the complexity of the diversity of the electric control devices of the machines, it is difficult to define with universal manner a general structure for such systems. However, by having a reflexion compared to 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.1*:

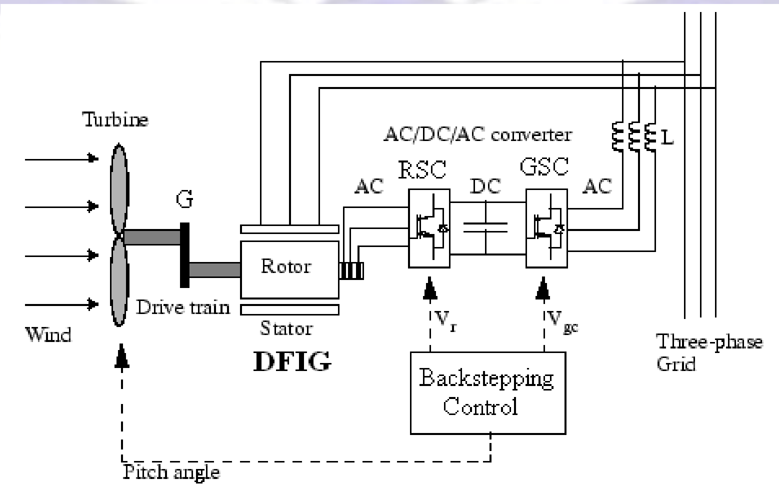

Fig.1: Architecture of the Control

2. MODELLING OF THE WIND-TURBINE

By applying the theory of momentum and Bernoulli's theorem, we can determine the incident power (theoretical power) due to wind [7-8]:

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

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*]

In wind energy system due to various losses, available on the power extracted from the turbine rotor, is lower than the incident power. The power extracted is expressed by [9]:

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

Cp (λ, β) is called the power coefficient, which expresses the aerodynamic efficiency of the turbine. It depends on the ratio λ, which represents the ratio between the speed at the end of the blades and the wind speed and the angle of orientation of the blades β. The ratio λ can be expressed by the following relation [9-10]:

$$\lambda = \frac{\Omega_t.R}{v} \quad (3)$$

The maximum power coefficient Cp was determined by Albert Betz (1920) as follows [11]:

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

The power factor is intrinsic to the constitution of the wind-turbine and depends on the profiles of the blades. We can model the power coefficient with a single equation that depends on the speed ratio λ and pitch angle β for the blade [12]:

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

$c_1 = 0.5872$, $c_2 = 116$, $c_3 = 0.4$, $c_4 = 5$, $c_5 = 21$, $c_6 = 0.0085$

The six coefficients c_1, c_2, c_3, c_4, c_5 are modified for maximum Cp equal to 0.498 for $\beta = 0°$.

With A which depends on λ and β:

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

The *Fig.2* shows the curves of the power coefficient as a function of λ for different values of β. A coefficient of maximum power of 0.498 is obtained for a speed ratio λ which is 8 (λopt). Fixing β and λ respectively to their optimal values, the wind system provides optimal power.

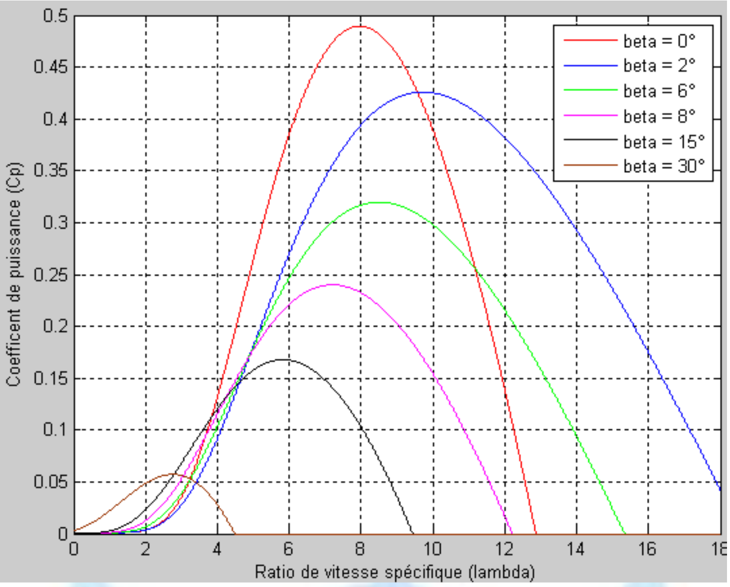

Fig.2: Power coefficient as a function of λ and β

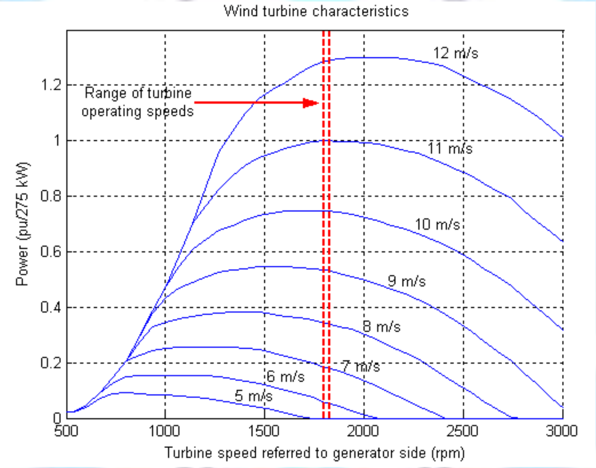

Fig.3: Wind-turbine DFIG characteristics

The aerodynamic torque on the slow axis can be expressed by Equation 7: [10]

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

Ω_t : Rotational speed of the turbine

C_{al} : Torque on the slow axis (turbine side)

The mechanical speed is related to the speed of rotation of the turbine by the coefficient of the multiplier. The torque on the slow axis is connected to the torque on the fast axis (generator side) by the multiplier coefficient.

The total inertia J is formed of the reduced inertia of the turbine and the fast axis of the inertia J of the generator g [10]:

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

J_{tur} : turbine inertia

J_g : inertia of the generator.

To determine the evolution of the mechanical speed from C_{mec} total torque applied to the rotor of the DFIG, we apply the fundamental equation of dynamics:

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

Ω_{mec} : Mechanical speed of DFIG

C_{ar} : Aerodynamic torque on the fast axis of the turbine

C_{em} : Electromagnetic torque

f : Friction.

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

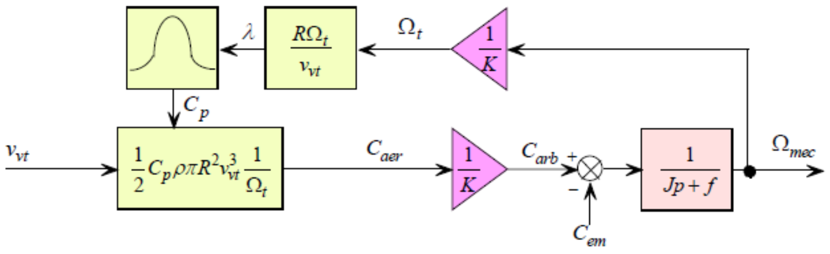

Fig.4: Wind-turbine model

3. EXTRACTION OF MAXIMUM POWER

In order to capture the maximum power of the incident energy of the wind-turbine, must continuously adjust the rotational speed of the wind turbine. The optimal mechanical turbine speed corresponds has λopt and β = 0°. The speed of the DFIG is used as a reference value for a controller proportional-integral type (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 torque thus determined by the controller is used as a reference torque of the turbine model (Fig.5). The system of variation of the angle of orientation of the blades (variation of the angle of incidence) to change the ratio between the lift and drag. To extract the maximum power (and maintain constant), the adjusted angle of incidence of the blades to the wind 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 [13].

However, it is quite expensive and is generally used for wind turbines and high average power. For our model, 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). La régulation de la vitesse de rotation de l'angle de pas des pales de la turbine se produit lorsque la vitesse de la génératrice est supérieure à 30% de sa vitesse nominale. Otherwise, β is zero. The synthesis of the PI controller requires knowledge of the transfer function of our system. This is especially difficult because of the power coefficient. A simple proportional correction (P) is obtained after testing. Note that β may vary from 0 ° to 90 ° characterized by saturation.

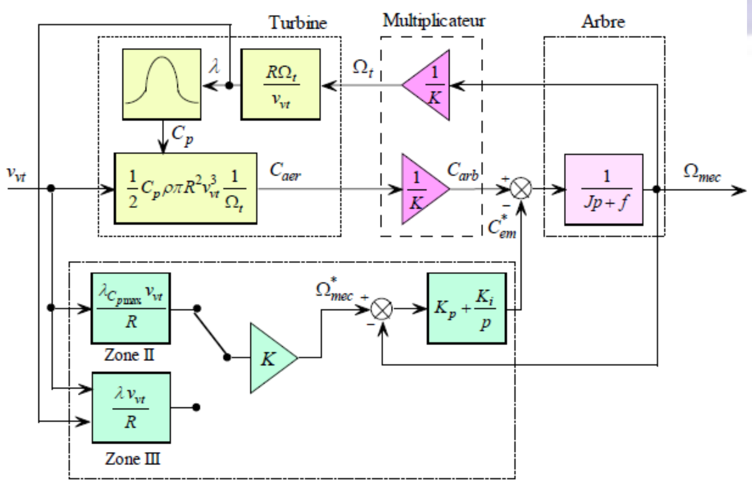

Fig.5: Block diagram with control of the speed

4. DFIG MODEL SYSTEM

The Power equations in the dq reference DFIG can be written [10-14]:

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

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 [10-14]:

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

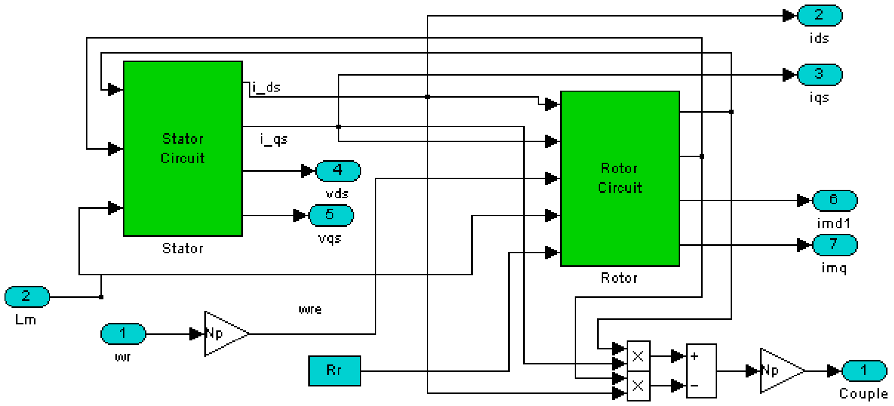

Fig.6: DFIG Model for wind-turbine

5. BACKSTEPPING ADAPTATIVE CONTROLLER APPLIED TO DFIG GENERATOR

The Adaptive Backstepping Control is a control technique that can effectively linearize a nonlinear system such as the DFIG in the presence of uncertainties. Unlike other feedback linearization techniques, adaptive backstepping has the flexibility of keeping useful non linearity's intact during stabilization. The essence of backstepping is the stabilization of a virtual control state. Hence, it generates a corresponding error variable which can be stabilized by carefully selecting proper control inputs. These inputs can be determined from Lyapunov stability analysis.

From (10), it is obvious that the dynamic model of PMSM is highly nonlinear because of the coupling between the speed and the electrical currents. According to the vector control principle, the direct axis current i_d is always forced to be zero in order to orient all the linkage flux in the d axis and achieve maximum torque per ampere.

$$\begin{aligned} \frac{di_{sd}}{dt} &= -\frac{r_s}{L_{sd}}.i_{sd} + \frac{L_{sq}}{L_{sd}} p\Omega i_{sq} + \frac{V_{sd}}{L_{sd}} \\ \frac{di_{sq}}{dt} &= -\frac{r_s}{L_{sq}}.i_{sq} - \frac{L_{sd}}{L_{sq}} p\Omega i_{sd} - \frac{\Phi_f}{L_{sq}} p\Omega + \frac{V_{sq}}{L_{sq}} \\ \frac{d\Omega}{dt} &= \frac{3p}{2J}(\Phi_f i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}) - \frac{f}{J}\Omega + \frac{C_r}{J} \end{aligned} \tag{14}$$

The vector $[x] = [x_1 \quad x_2 \quad x_3]^T = [i_{sd} \quad i_{sq} \quad \Omega]^T$ choice as state vector is justified by the fact that currents and speed are measurable and that the control of the instantaneous torque can be done comfortable via the currents i_{sd} and/or i_{sq}. And stator voltages as control variables $u = [V_{sd} \quad V_{sq}]^T$.

The main objective of the backstepping control is to regulate the speed of the machine to its reference value Ω_{ref} whatever external disturbances.

It is assumed that the engine parameters are known and invariant.

By choosing $[i_{sd} \quad i_{sq} \quad \Omega]^T$ as variable states and equation (14) the mathematical model of the machine. The objective is to regulate the speed to its reference value.

5.1. Backstepping speed Controller

We begin by defining the tracking errors:

$$e_\Omega = \Omega_{ref} - \Omega \tag{15}$$

The derivative of (15) is:

$$\dot{e}_\Omega = \frac{de_\Omega}{dt} = \dot{\Omega}_{ref} - \dot{\Omega} = \dot{\Omega}_{ref} - \frac{1}{J}\left[\frac{3p}{2}(\Phi_f i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}) - f\Omega - C_r\right] \tag{16}$$

We define the following quadratic function:

$$V_1 = \frac{1}{2} e_\Omega^2 \tag{17}$$

Its derivative along the solution of (17), is given by:

$$\dot{V}_1 = e_\Omega \dot{e}_\Omega = e_\Omega \left(\dot{\Omega}_{ref} - \frac{1}{J}\left[\frac{3p}{2}(\Phi_f i_{sq} + (L_{sd} - L_{sq}) i_{sd} i_{sq}) - f\Omega - C_r \right] \right) \tag{18}$$

Using the backstepping design method, we consider the d-q axes currents components i_{sd} and i_{sq} as our virtual control elements and specify its desired behavior, which are called stabilizing function in the backstepping design terminology as follows:

$$\begin{cases} i_{sdref} = 0 \\ i_{sqref} = \dfrac{2}{3p\Phi_f}(f\Omega + C_r + J.k_\Omega.e_\Omega) \end{cases} \tag{19}$$

Where k_Ω is a positive constant

Substituting (19) in (18) the derivative of V_1:

$$\dot{V}_1 = -k_\Omega e_\Omega^2 \le 0 \tag{20}$$

5.2. Backstepping Current controller

We have the asymptotic stability of the origin of the system (14). We defined:

$$\begin{cases} e_d = i_{sdref} - i_{sd} \qquad with \quad i_{sdref} = 0 \\ e_q = i_{sqref} - i_{sq} \end{cases} \tag{21}$$

Their dynamics can be written:

$$\begin{aligned} \dot{e}_d &= \dot{i}_{sdref} - \dot{i}_{sd} = \frac{r_s}{L_{sd}}.i_{sd} - \frac{L_{sq}}{L_{sd}} p\Omega i_{sq} - \frac{V_{sd}}{L_{sd}} \\ \dot{e}_q &= \dot{i}_{sqref} - \dot{i}_{sq} = \frac{2}{3p\Phi_f}(f\Omega + C_r + J.k_\Omega.e_\Omega) + \frac{r_s}{L_{sq}}.i_{sq} + \frac{L_{sd}}{L_{sq}} p\Omega i_{sd} + \frac{p\Phi_f}{L_{sq}}\Omega - \frac{V_{sd}}{L_{sd}} \end{aligned} \tag{22}$$

To analyze the stability of this system we propose the following Lyapunov function:

$$V_2 = \frac{1}{2}(e_\Omega^2 + e_d^2 + e_q^2) \tag{23}$$

Its derivative along the trajectories (20), (21) and (22) is:

$$\dot{V}_2 = \frac{1}{2}(e_\Omega \dot{e}_\Omega + e_d \dot{e}_d + e_q \dot{e}_q)$$

$$= -k_\Omega e_\Omega^2 - k_d e_d^2 - k_q e_q^2 + e_d[k_d e_d - \frac{V_{sd}}{L_{sd}} + \frac{r_s}{L_{sd}} - \frac{L_{sq}}{L_{sd}}\Omega i_{sq} + \frac{3p}{2J}(L_{sd} - L_{sq})e_\Omega i_{sq}]$$

$$+ e_q[k_q e_q + \frac{2(k_\Omega J - f)}{3p\Phi_f}.(\frac{3p\Phi_f}{2J}e_q + \frac{3p}{2J}(L_{sd} - L_{sq})e_d i_{sq} - k_\Omega e_\Omega) \quad (24)$$

$$+ \frac{3p\Phi_f}{2J}e_\Omega - \frac{V_{sq}}{L_{sq}} + \frac{r_s}{L_{sq}}i_{sq} + \frac{L_{sd}}{L_{sq}}\Omega i_{sd} + \Omega\frac{\Phi_f}{L_{sq}}]$$

The expression (24) found above requires the following control laws:

$$V_{sd} = k_d L_{sd} e_d + r_s i_{sd} - L_{sq}\Omega i_{sq} + \frac{3pL_{sd}}{2J}(L_{sd} - L_{sq})e_\Omega i_{sq}$$

$$V_{sq} = \frac{2L_{sq}(k_\Omega J - f)}{3p\Phi_f}\left(\frac{3p\Phi_f}{2J}e_q + \frac{3p}{2J}(L_{sd} - L_{sq})e_d i_{sq} - k_\Omega e_\Omega\right) + \frac{3p\Phi_f L_{sq}}{2J}e_\Omega + r_s i_{sq} + L_{sd}\Omega i_{sd} + \Omega\Phi_f + k_q L_{sq} e_q \quad (25)$$

With this choice the derivatives of (25) become:

$$\dot{V}_2 = -k_\Omega e_\Omega - k_d e_d - k_q e_q \le 0 \quad (26)$$

6. SIMULATION RESULTS

The overall model of the wind system was simulated in Matlab/ Simulink/SimPowerSystems environment. The model includes: wind turbine, Doubly-Fed Asynchronous Generator (DFIG), two power converters that connect the rotor to the network (Figure 7).

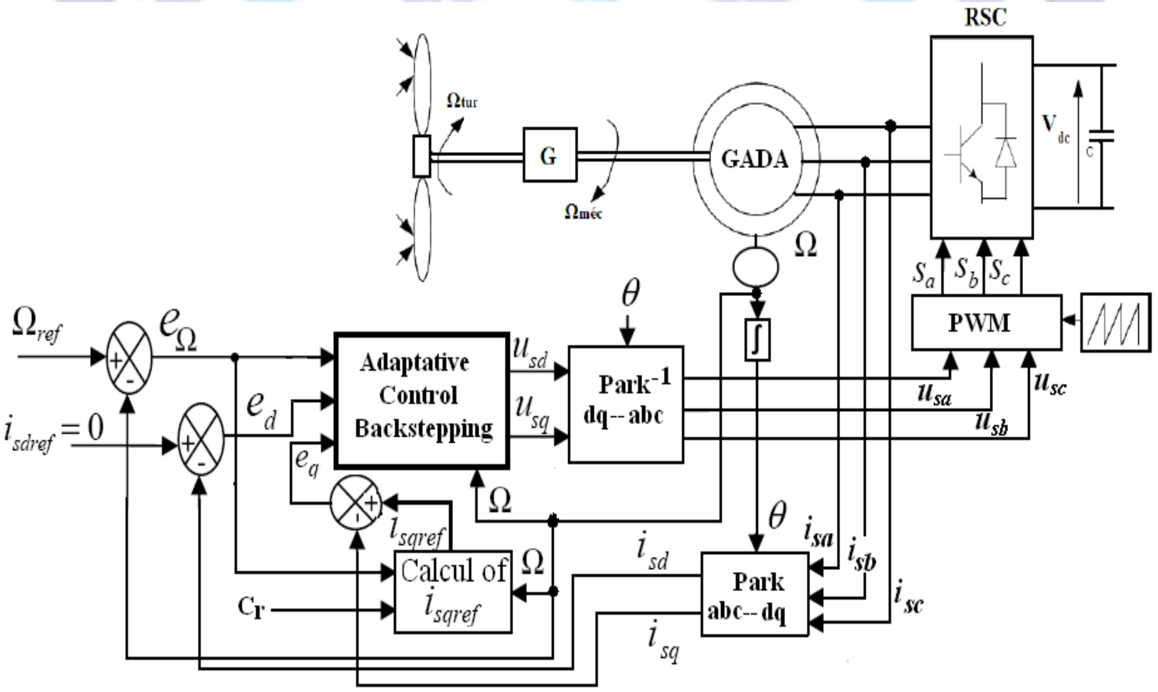

Fig.7: Simulation scheme of adaptive Backstepping Control applied for DFIG-wind-turbine

6.1. DFIG 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: $\gamma_1 = 0.15$, $\gamma_2 = 0.01$, $\gamma_3 = 0.015$.

➢ **Follow of the trajectory**

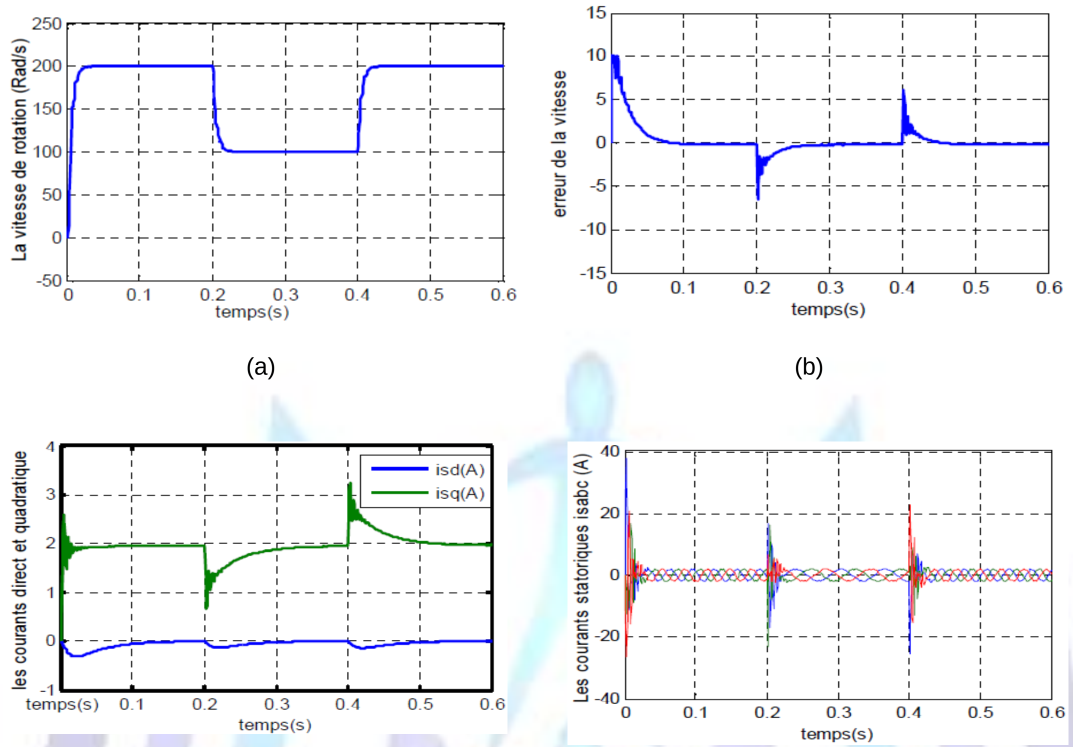

Fig.8: Test performance of the adaptive controller for trajectory tracking, (a) Speed response trajectory (b) Error Speed response (c) d-q axis current without uncertainties (d) abc axis current

➢ **Disturbance rejection**

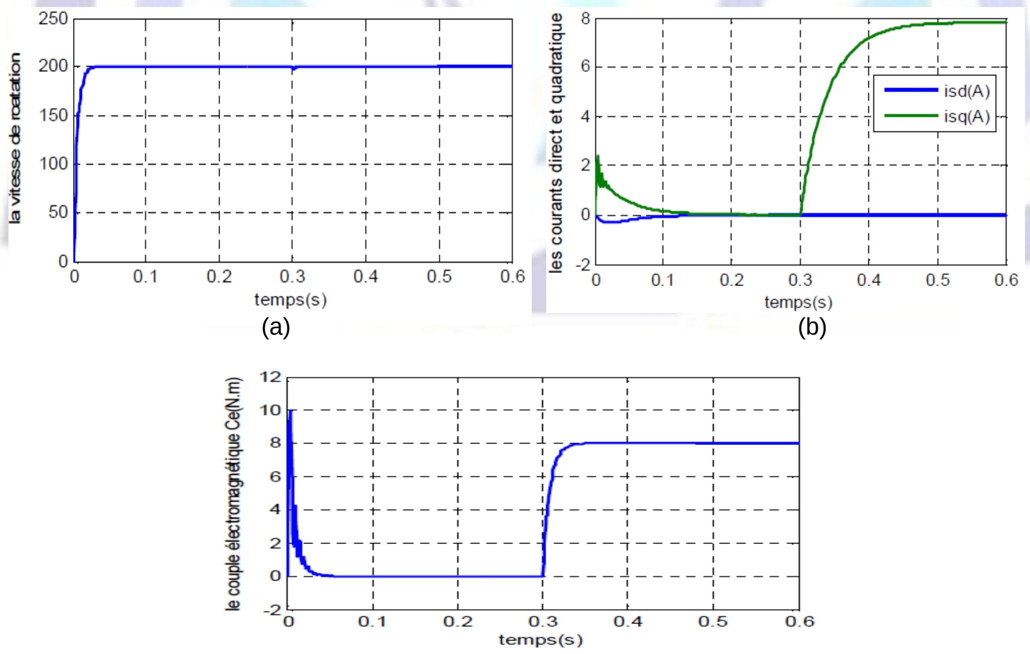

Fig.9: Test performance of the adaptive controller for rejecting disturbance torque load applied at t = 0.3s. (a)Speed response trajectory (b) d-q axis current without uncertainties (c) Electromagnetic Torque

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➢ **Parametric uncertainties**

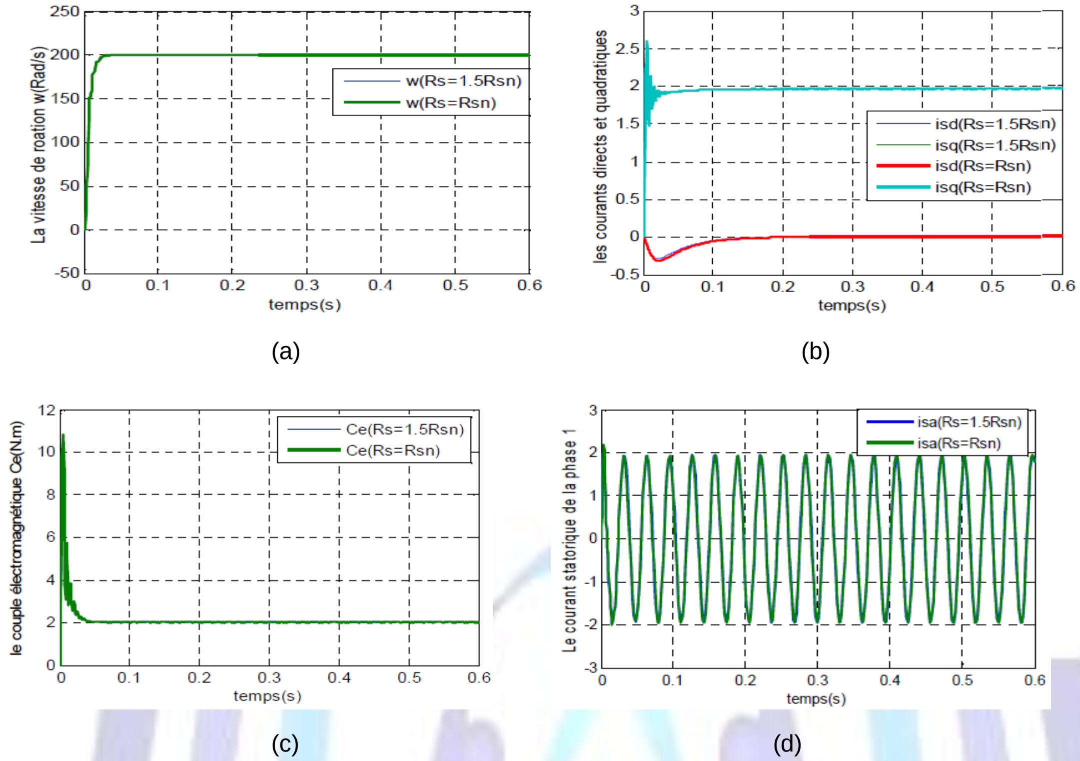

Fig.10: Test performance of the adaptive controller following a change in Rs. (a) Speed response trajectory (b) d-q axis current without uncertainties (c) Electromagnetic Torque (d) current isa

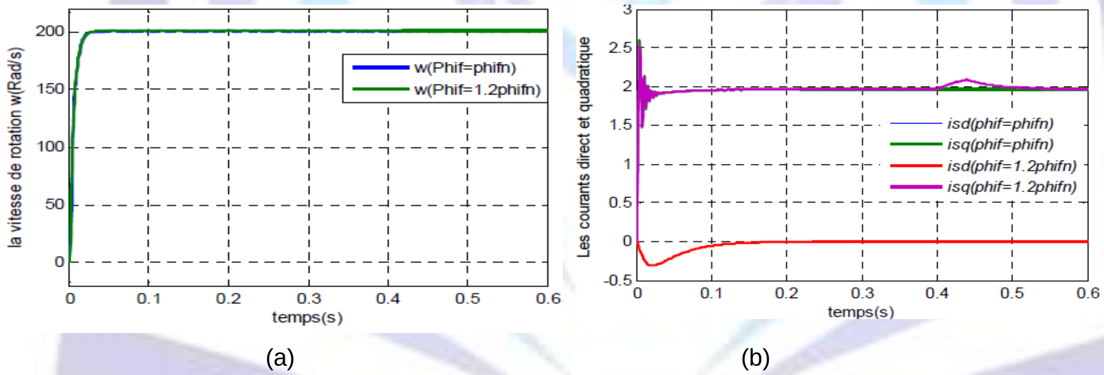

Fig.11: Test performance of the adaptive controller following a change in Φ_f. (a) Speed response trajectory (b) d-q axis current without uncertainties

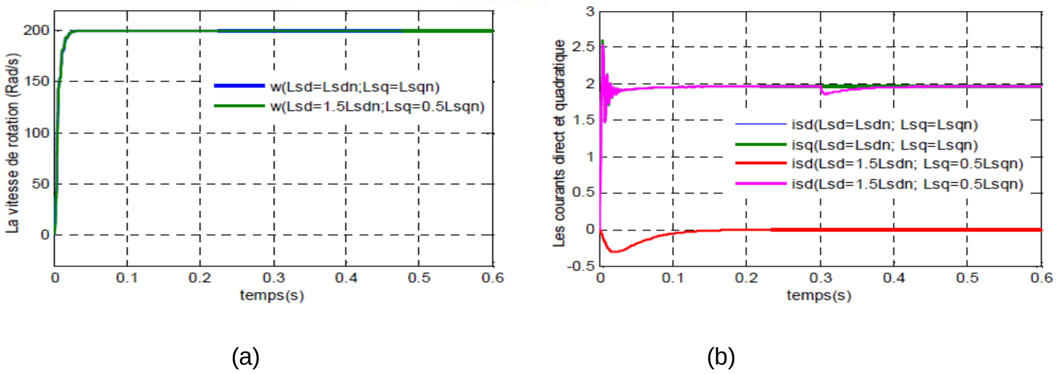

Fig.12: Test performance of the adaptive controller following a change in L_{sd} and L_{sq}, (a) Speed response trajectory (b) d-q axis current without uncertainties

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6.2. Wind-turbine performances

Using the reduced model, we applied a profile closer to the evolution of the real wind was filtered to suit the slow dynamics of the system studied random wind. The objective is to see the degree of continuing point of maximum power and efficiency of the speed control provided by the backstepping controller. The *Fig.13* shows the wind profile filtered and applied to the system in this case.

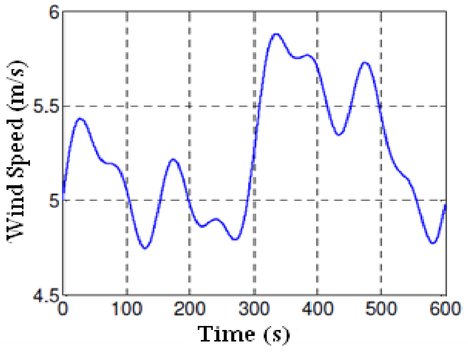
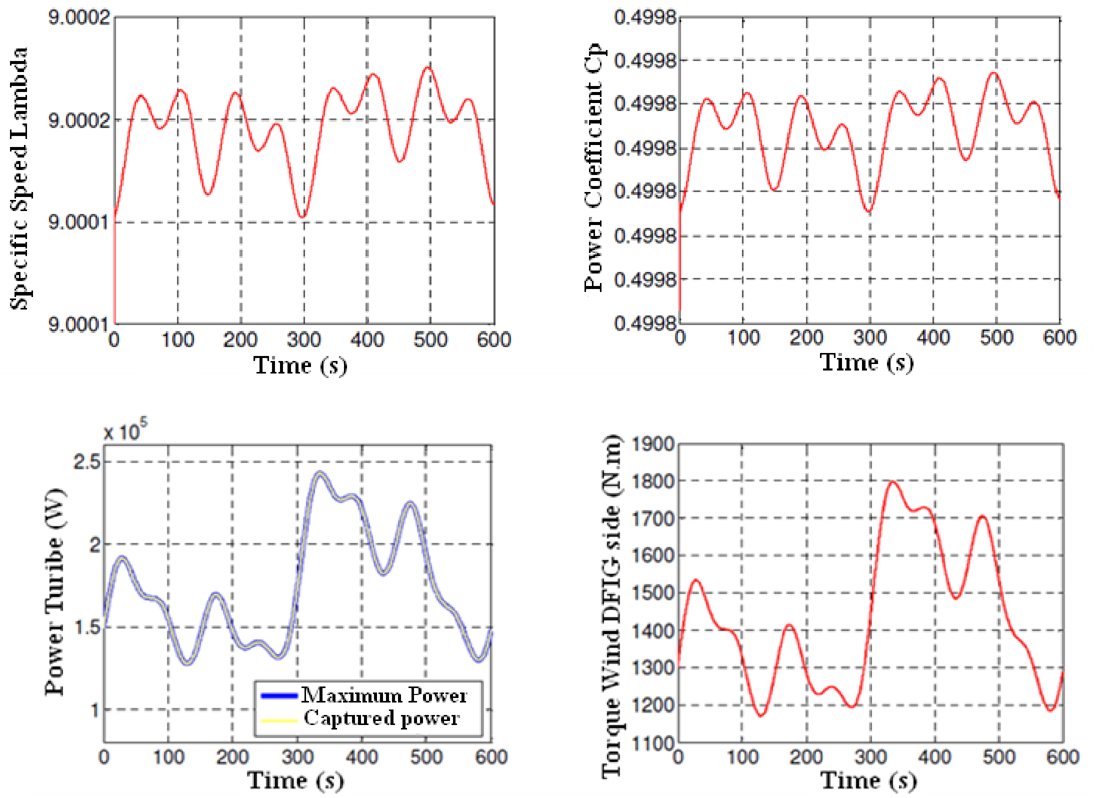


Fig. 13: Profile applied to random wind wind turbine.

The figure 14 shows the results obtained for this application, where the following observations can be distinguished:

- The specific speed *λ* and the power coefficient C_p does not change a lot of values, they are almost equal to their optimal values references 9 and 0.4999 successively;
- The wind power captured follows its optimal reference and has the same shape as the wind profile applied, this rate is also consistent with the wind torque side of the MADA;
- The speed of the DFIG is the image of wind causing the wind, it properly follows its reference;
- The shapes of the electromagnetic torque of the DFIG and its reference, are virtually identical, but different from the shape of the profile of the wind speed due to the dynamic torque due to inertia;
- The phase shift between the voltage 180˚ and the stator current phase reflects a production of active power only to the stator as illustrated in figure powers;
- The shape of the components of the stator flux orientation shows a good flow to ensure vector control well decoupled from the DFIG.



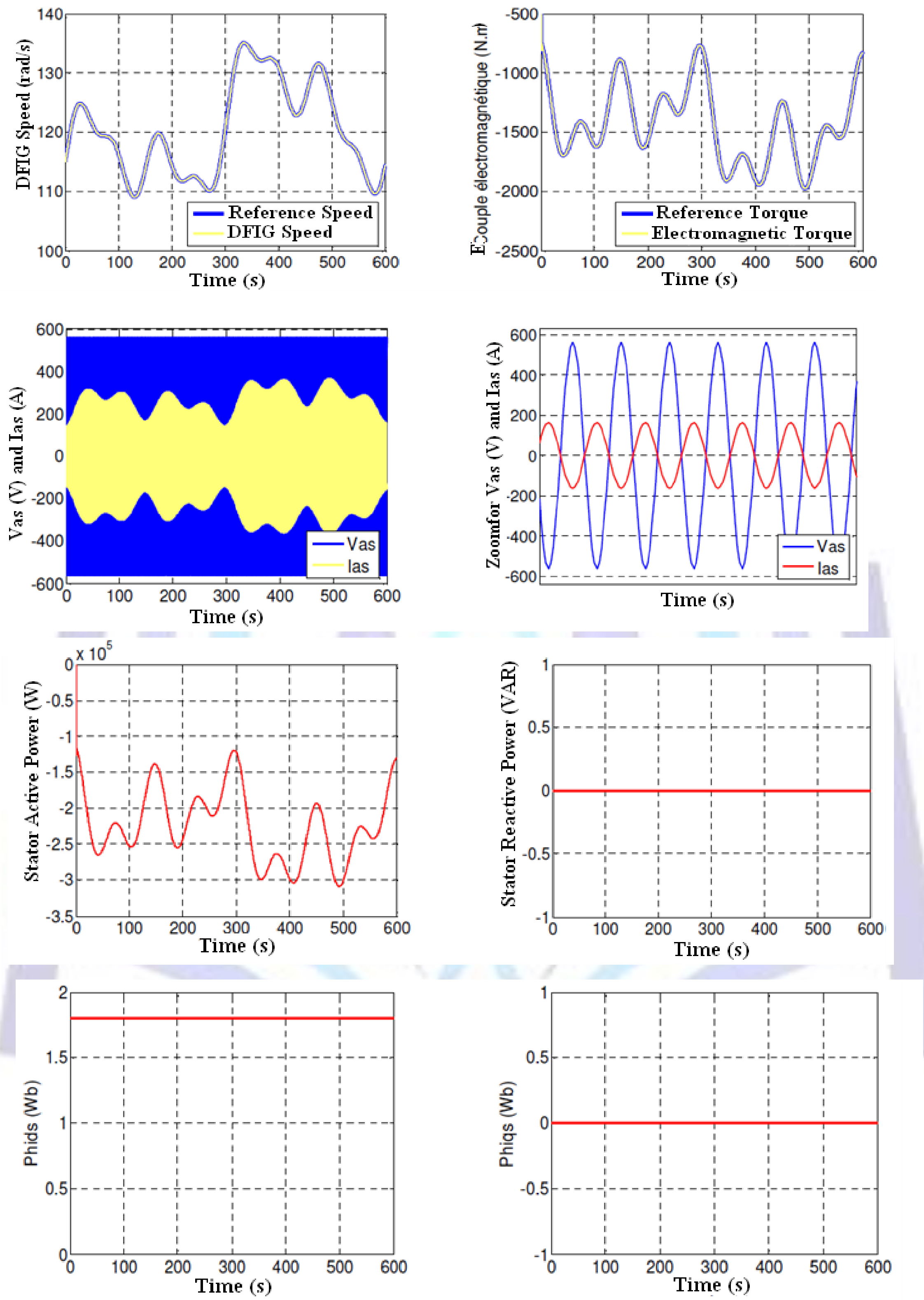


Fig.14: The Simulation results of the asynchronous wind generator dual power and stator flux oriented, with a Backstepping controller (Case scale model of the DFIG and profile of random wind).

7. CONCLUSION

This work has been devoted to modeling, simulation and analysis of a wind turbine operating at variable speed. A stable operation of the wind energy system is obtained with the application of nonlinear Backstepping Adaptive control. The overall operation of the wind turbine and its control system were illustrated by responses to transient and permanent control systems.

Generator supplied power to the network with an active power whatever the mode of operation. The wind generator has been tested and modeled with a variable speed operation for a power of 200 kW. Simulation results show that the proposed wind system and is feasible and has many advantages.

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