Power Control of the Wind Turbine for Low Wind Speed

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***Abstract* — In this paper, we present a control strategy in order to optimize the power produced by the wind turbine. This strategy allows the calculation of a control law basing on the study of the stability of nonlinear continuous systems and the second method of Lyapunov. We have two parts to be controlled. In the mechanical part, the control law is used to optimize the rotational speed of wind turbine for low wind speed. In the electrical part, the control law is designed to optimize the electrical produced power.**

Keywords: Wind Energy, Doubly fed induction generator (DFIG), System stability, stator-flux-oriented vector.

I. INTRODUCTION

Wind energy produced from the wind force is an efficient, powerful and sustainable means of production. It has the advantage of being cleaner, safer and quicker to implement. This energy produced current using wind turbine from the kinetic energy of moving air like a nuclear reactor, a hydroelectric dam or a coal fired power station, but the environmental impacts on are not the same.

Captured by a wind turbine, the wind's kinetic energy is converted into electricity using a generator. In this paper we will use the Doubly Fed Induction Generator (DFIG) which is the most used generator in the wind energy sector.

The paper aims to optimize the produced electrical power. The control system is composed of two parts. In the first part the control law allows to the mechanical speed of the turbine to follow the variations of the wind. In the second part the control law must allow the power produced to follow its optimized value calculated from the mechanical speed of the turbine.

Many previous studies had addressed the problem of optimizing the produced power by the wind turbine. In reference [1] was used the fuzzy-PI control to optimize the power. In reference [2], a sliding mode controller has been proposed. Reference [3] proposes an adaptive feedback linearization controller. In reference [4] an LQG controller for a linearised model of the wind turbine has been used. In reference [5] a robust fuzzy controller is developed. Reference [6] proposes a cascaded nonlinear controller for a VSWT to optimize the power. In reference [7] a hierarchical control structure is adopted to optimize the rotor speed and the produced electrical power. Reference [8] presents direct power control using classical PI regulators. Indirect power control using Sliding Mode controller has been used in [9]. In reference [10] a hybrid controller composed of several LPV controllers has been used.

This paper is organized as follows. In section II the description and the modeling of the wind turbine are presented. In section III is shown the control method proposed in [11], this approach will be applied to optimize the power. In section VI simulation results on 300 kW wind turbine are presented.

II. SYSTEM DESCRIPTION AND MODELING

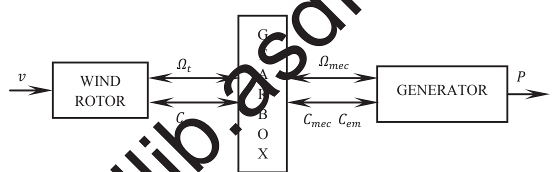

Fig. 1. Structure of the wind turbine system.

Like it is presented in Fig.1, the wind turbine is composed of a wind rotor, a gear system and a generator. The wind rotor includes the blades for converting the wind's kinetic energy into mechanical energy, the gear system adapts to rotor speed to that of the generator and the generator converts mechanical energy to electricity for distribution.

The energy captured by the wind rotor is given by,

$$P_t = C_p\left(\frac{1}{2}\rho\pi R^2 v^3\right). \quad (1)$$

Where, ρ is the air density "Kg/m^3.", R is the blade length "m.", v represents the wind speed "m/s.". C_p, is the power coefficient, it depends on the tip speed ratio (λ) and the pitch angle of the blades (β). It is given by [12],

$$C_p(\lambda,\beta) = 0.5109\left(116\left(\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1}\right)-0.4\beta-5\right)e^{-21\left(\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1}\right)}+0.0068\lambda. \quad (2)$$

Where,

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

Where, Ω_t is the mechanical angular speed of the turbine "rad/sec.".

The mechanical torque on the axis of the generator is given by,

$$C_{mec} = \frac{1}{G}C_t = \frac{1}{G}\frac{P_t}{\Omega_t} = \frac{1}{G}\frac{0.5C_p\rho\pi R^2 v^3}{\Omega_t}. \quad (4)$$

Where, Ω_{mec} is the mechanical angular speed on the axis of the generator, it is given by,

$$\Omega_{mec} = G\Omega_t. \tag{5}$$

Where, C_t is the mechanical torque available on the axis of the turbine "$N.m.$", G is the multiplication ratio.

If we suppose that the low-speed shaft is rigid [13], the mathematical model of the turbine is given by,

$$J\dot{\Omega}_{mec} = C_{mec} - C_{em} - f\Omega_{mec}. \tag{6}$$

Where, J is the total inertia of the rotating parts "$Kg.m^2$.", f is the coefficient of viscous damping, C_{em} is the electromagnetic torque of the generator "$N.m.$"

The gearbox is supposed rigid; it is modeled by a simple gain ***G***.

The generator used is the DFIG; its electrical and magnetic equations in the Park reference frame are given by [14],

$$\begin{cases} V_{sd} = R_s I_{sd} + \frac{d}{dt}\varphi_{sd} - \omega_s \varphi_{sq} \\ V_{sq} = R_s I_{sq} + \frac{d}{dt}\varphi_{sq} + \omega_s \varphi_{sd} \\ V_{rd} = R_r I_{rd} + \frac{d}{dt}\varphi_{rd} - (\omega_s - P\Omega_{mec})\varphi_{rq} \\ V_{rq} = R_r I_{rq} + \frac{d}{dt}\varphi_{rq} + (\omega_s - P\Omega_{mec})\varphi_{rd} \end{cases}. \tag{7}$$

$$\begin{cases} \varphi_{sd} = L_s I_{sd} + L_m I_{rd} \\ \varphi_{sq} = L_s I_{sq} + L_m I_{rq} \\ \varphi_{rd} = L_r I_{rd} + L_m I_{sd} \\ \varphi_{rq} = L_r I_{rq} + L_m I_{sq} \end{cases}. \tag{8}$$

Where,

V_{sd}, V_{sq}, direct and quadrature voltages on the stator axes. V_{rd}, V_{rq}, direct and quadrature voltages on the rotor axes. I_{sd}, I_{sq}, direct and quadrature stator currents. I_{rd}, I_{rq}, direct and quadrature rotor currents. ω_s, the stator currents pulsation. P, the number of machine poles pairs. $\varphi_{sd}, \varphi_{sq}$, direct and quadrature stator flux. $\varphi_{rd}, \varphi_{rq}$, direct and quadrature rotor flux. L_s, the stator inductance. L_r, the rotor inductance. L_m, the mutual inductance between the stator and the rotor.

The stator active and reactive powers of the DFIG are given by [15],

$$\begin{cases} P_s = \frac{3}{2}\left(V_{sd}I_{sd} + V_{sq}I_{sq}\right) \\ Q_s = \frac{3}{2}\left(V_{sq}I_{sd} - V_{sd}I_{sq}\right) \end{cases}. \tag{9}$$

III. CONTROL STRATEGY OF THE WIND TURBINE

The control procedure that we will use in this paper is based on the work of [11]. The control law is calculated from the study of system stability and by using the second method of Lyapunov.

For a nonlinear system given by,

$$\begin{cases} \dot{x}(t) = f(x,t) + G(x,t)u(t) \\ y(t) = h(x,t) \end{cases} \tag{10}$$

The control law that ensures the stability of the reference trajectory y_c is given by,

$$u(t) = \left(H_x G(x,t)\right)^{-1}\left[\dot{y}_c(t) - H_x f(x,t) - \alpha\left(y(t) - y_c(t)\right)\right]. \tag{11}$$

With the condition $H_x G(x,t)$ invertible.

$$H_x = \frac{dy(t)}{dt}. \tag{12}$$

The coupling between stator and rotor makes the control of the DFIG difficult. For that we approximate it model to that of a DC machine by orienting d axis in the direction of the flux φ_s [16].

The expressions of active and reactive powers are given by,

$$\begin{cases} P_s = -\frac{3L_m}{2L_s} V_{sq} I_{rq} \\ Q_s = -\frac{3L_m}{2L_s} V_{sq} I_{rd} + \frac{3{V_{sq}}^2}{2L_s \omega_s} \end{cases}. \tag{13}$$

The expressions of direct and quadrature rotor voltages used as command variables for active and reactive powers are given by,

$$\begin{cases} V_{rd} = R_r I_{rd} + \left(L_r - \frac{L_m^2}{L_s}\right)\dot{I}_{rd} - \omega_{sl}\left(L_r - \frac{L_m^2}{L_s}\right) I_{rq} \\ V_{rq} = R_r I_{rq} + \left(L_r - \frac{L_m^2}{L_s}\right)\dot{I}_{rq} + \omega_{sl}\left(L_r - \frac{L_m^2}{L_s}\right) I_{rd} \\ \quad + \omega_{sl}\frac{L_m V_{sq}}{L_s \omega_s} \end{cases}. \tag{14}$$

A. *Synthesis of the control law*

From (1), (3), (6), (13) and (14), the global mathematical model of the wind turbine is representing by the following nonlinear system,

$$\begin{cases} \dot{x} = f(x) + G(x)u \\ y = h(x) \end{cases}. \tag{15}$$

Where,

$x = \left(\Omega_{mec}, I_{rd}, I_{rq}\right)$ is the state vector.

$$f(x) = \begin{bmatrix} -\frac{f}{J}\Omega_{mec} + \frac{k_1 k_2}{J}\Omega_{mec}^2 \\ -\frac{R_r}{\sigma L_r} I_{rd} + \omega_{sl} I_{rq} \\ k_3 \Omega_{mec} - \omega_{sl} I_{rd} - \frac{R_r}{\sigma L_r} I_{rq} + \frac{L_m V_{sq}}{\sigma L_r L_s} \end{bmatrix},$$

$$k_1 = \frac{0.5\rho\pi R^5}{G^3}, k_2 = \frac{C_p^{max}}{\lambda_{opt}^3}, k_3 = \frac{PL_mV_{sq}}{\omega_s\sigma L_rL_s}, G(x) = \begin{bmatrix} -\frac{1}{J} \\ \frac{1}{\sigma L_r} \\ \frac{1}{\sigma L_r} \end{bmatrix},$$

$$u = \begin{bmatrix} C_{em} \\ V_{rd} \\ V_{rq} \end{bmatrix}, h(x) = \begin{bmatrix} P_t \\ Q_s \\ P_s \end{bmatrix} = \begin{bmatrix} k_1k_2\Omega_{mec}^3 \\ -\frac{3L_m}{2L_s}V_{sq}I_{rd} + \frac{3V_{sq}^2}{2L_s\omega_s} \\ -\frac{3L_m}{2L_s}V_{sq}I_{rq} \end{bmatrix}.$$

The number of variables to be controlled is equal to the number of control variables. So, we can compute for each subsystem of (15) a control law, which enables us to avoid the invertibility problem of H_xG.

$$H_xG = \begin{bmatrix} 3k_1k_2\Omega_{mec}^2 & 0 & 0 \\ 0 & -\frac{3L_m}{2L_s}V_{sq} & 0 \\ 0 & 0 & -\frac{3L_m}{2L_s}V_{sq} \end{bmatrix} \begin{bmatrix} -\frac{1}{J} \\ \frac{1}{\sigma L_r} \\ \frac{1}{\sigma L_r} \end{bmatrix} \Rightarrow$$

$$H_xG = \begin{bmatrix} -\frac{3k_1k_2\Omega_{mec}^2}{J} \\ -\frac{3L_m}{2\sigma L_rL_s}V_{sq} \\ -\frac{3L_m}{2\sigma L_rL_s}V_{sq} \end{bmatrix}. \quad (16)$$

This column matrix cannot be inverted. Therefore, in the following sections we will calculate each command separately

B. Generator speed control law

We have,

$$\dot{\Omega}_{mec} = -\frac{f}{J}\Omega_{mec} + \frac{k_1k_2}{J}\Omega_{mec}^2 - \frac{1}{J}C_{em}$$
$$= f(\Omega_{mec}) + GC_{em}. \quad (17)$$

$$\text{And,} \begin{cases} H_x = 3k_1k_2\Omega_{mec}^2 \\ H_xG = -\frac{3k_1k_2\Omega_{mec}^2}{J} \\ H_xf = 3k_1k_2\Omega_{mec}^2\left(-\frac{f}{J}\Omega_{mec} + \frac{k_1k_2}{J}\Omega_{mec}^2\right) \end{cases}.$$

So, the command of the generator speed is given by,

$$C_{em} = -\frac{J}{3k_1k_2\Omega_{mec}^2}\left[\dot{P}_t^{ref} - 3k_1k_2\Omega_{mec}^2\left(-\frac{f}{J}\Omega_{mec} + \frac{k_1k_2}{J}\Omega_{mec}^2\right) - \alpha\left(P_t - P_t^{ref}\right)\right]. \quad (18)$$

With, $P_t^{ref} = k_1k_2{\Omega_{mec}^{ref}}^3$.

C. Stator reactive power control law

We have,

$$\dot{I}_{rd} = -\frac{R_r}{\sigma L_r}I_{rd} + \omega_{sl}I_{rq} + \frac{1}{\sigma L_r}V_{rd}$$
$$= f\left(\Omega_{mec}, I_{rd}, I_{rq}\right) + GV_{rd}. \quad (19)$$

$$\text{And,} \begin{cases} H_x = -\frac{3L_m}{2L_s}V_{sq} \\ H_xG = -\frac{3L_m}{2\sigma L_rL_s}V_{sq} \\ H_xf = -\frac{3L_m}{2L_s}V_{sq}\left(-\frac{R_r}{\sigma L_r}I_{rd} + \omega_{sl}I_{rq}\right) \end{cases}.$$

So, the command of the stator reactive power is given by,

$$V_{rd} = -\frac{2\sigma L_rL_s}{3L_mV_{sq}}\left[\dot{Q}_s^{ref} + \frac{3L_m}{2L_s}V_{sq}\left(-\frac{R_r}{\sigma L_r}I_{rd} + \omega_{sl}I_{rq}\right) - \alpha\left(Q_s - Q_s^{ref}\right)\right]. \quad (20)$$

With, $Q_s^{ref} = 0$.

The reactive power must be null in order to ensure the unity power factor (if it is less than one, it means that will have transmission losses).

D. Stator active power control law

We have,

$$\dot{I}_{rq} = k_3\Omega_{mec} - \omega_{sl}I_{rd} - \frac{R_r}{\sigma L_r}I_{rq} + \frac{L_mV_{sq}}{\sigma L_rL_s} + \frac{1}{\sigma L_r}V_{rq}. \quad (21)$$

$$\text{And,} \begin{cases} H_x = -\frac{3L_m}{2L_s}V_{sq} \\ H_xG = -\frac{3L_m}{2\sigma L_rL_s}V_{sq} \\ H_xf = -\frac{3L_m}{2L_s}V_{sq}\left(k_3\Omega_{mec} - \omega_{sl}I_{rd} - \frac{R_r}{\sigma L_r}I_{rq} + \frac{L_mV_{sq}}{\sigma L_rL_s}\right) \end{cases}.$$

So, the command of the stator active power is given by,

$$V_{rq} = -\frac{2\sigma L_rL_s}{3L_mV_{sq}}\left[\dot{P}_s^{ref} + \frac{3L_m}{2L_s}V_{sq}\left(k_3\Omega_{mec} - \omega_{sl}I_{rd} - \frac{R_r}{\sigma L_r}I_{rq} + \frac{L_mV_{sq}}{\sigma L_rL_s}\right) - \alpha\left(P_s - P_s^{ref}\right)\right]. \quad (22)$$

With, $P_s^{ref} = -\frac{2L_s}{3L_mV_{sq}} \times \frac{\rho\pi C_p^{max}R^5}{2\lambda_{opt}^3G^3}\Omega_{mec}^3$.

The reference active power is calculated using the generator speed previously controlled.

IV. SIMULATION RESULTS

The control strategy is applied to a 300 kW wind turbine using Matlab/Simulink software. We start by presenting the wind profile [17], it is comprised between $5\ m/s$ and $12\ m/s$.

The parameters of the wind turbine are given by [18],

$R_s = 0.0063\ \Omega, R_r = 0.0048\ \Omega, L_s = 0.0118\ H,$

$L_r = 0.0116\ H, L_m = 0.0116\ H, P = 2$

$J = 50\ Kg.m^2, f = 0, R = 14\ m, G = 23,$

$\rho = 1.225\ Kg/m^3, \lambda_{opt} = 8.1, C_{p_{max}} = 0.475$

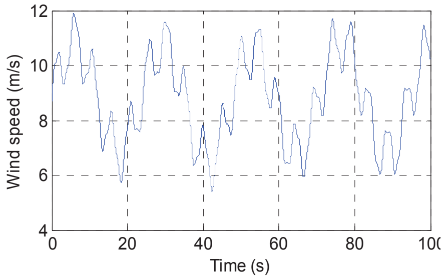

Fig.2 Wind speed

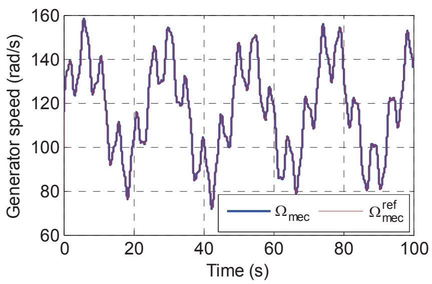

Fig.3 Trajectories of Ω_{mec}^{ref} and Ω_{mec}

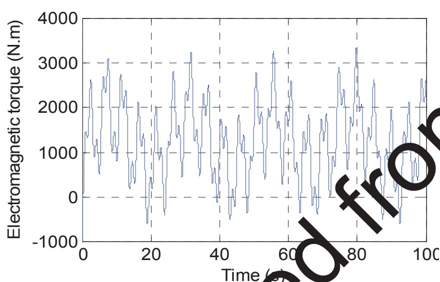

Fig.4 Trajectory of C_{em}

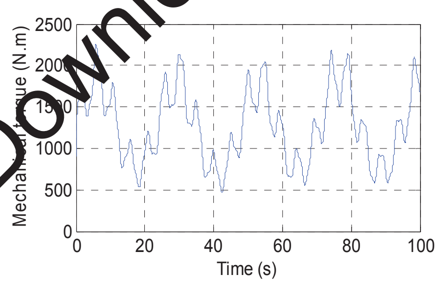

Fig.5 Trajectory of C_{mec}

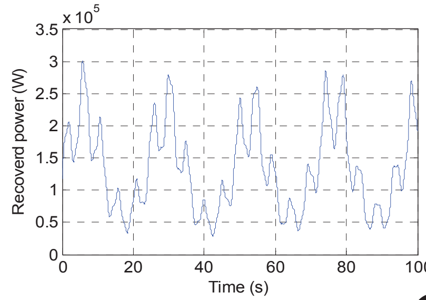

Fig.6 Trajectory of P_t

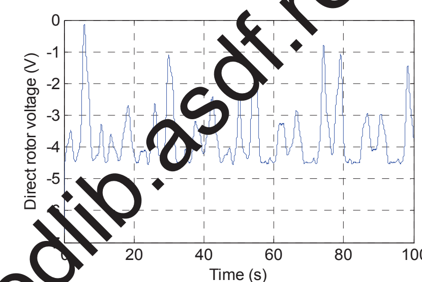

Fig.7 Trajectory of V_{rd}

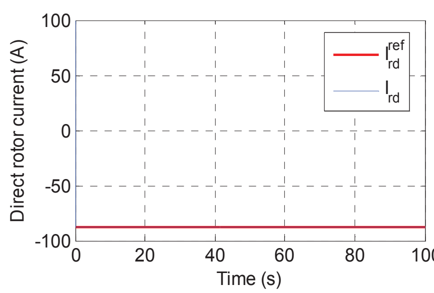

Fig.8 Trajectories of I_{rd}^{ref} and I_{rd}

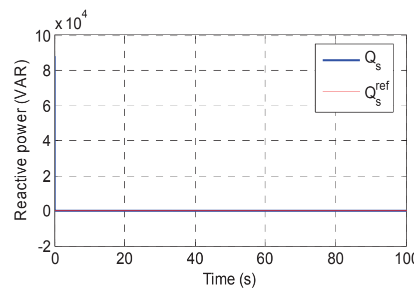

Fig.9 Trajectories of Q_s^{ref} and Q_s

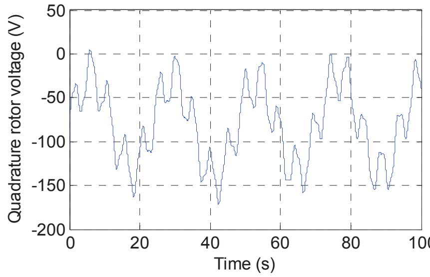

Fig.10 Trajectory of V_{rq}

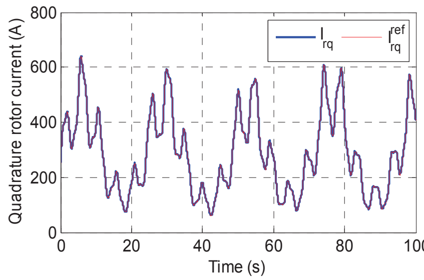

Fig.11 Trajectories of I_{rq}^{ref} and I_{rq}

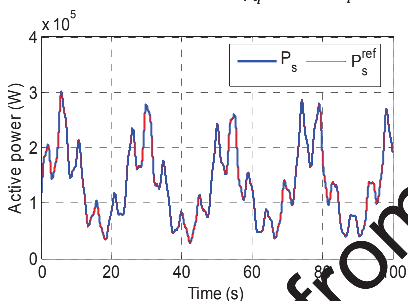

Fig.12 Trajectories of P_s^{ref} and P_s

The obtained results allow the observation of wind turbine operation for low wind speed. In Fig.3 the generator speed follows perfectly its reference trajectory. The applied command is shown in Fig.4 the role of this command is to oppose the mechanical torque shown in Fig.5 in order that the generator speed follows its reference.

In Fig.6 is shown the recovered power by the turbine, this power will be used as a reference for the stator active power.

In Fig.7 is shown the direct rotor voltage, it is the command of stator reactive power shown in Fig.9. The result is perfect; a null reactive power involves unity power factor and full energy transmission to the consumer.

In Fig.10 is shown the quadrature rotor voltage, it represents the command of stator active power shown in Fig.12. The result shows that the active power follows perfectly its reference (the recovered power by the turbine shown in Fig.06).

Stability test

The system is stable if there is a return to equilibrium after the disappearance of the disturbance. In this test we inject a disturbance to the generator shaft between $t = 10\ s$ and $t = 15\ s$; the results are presented in the following figures.

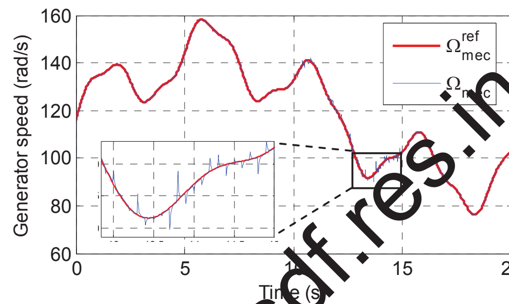

Fig.13 Trajectories of Ω_{mec}^{ref} and Ω_{mec} with disturbance

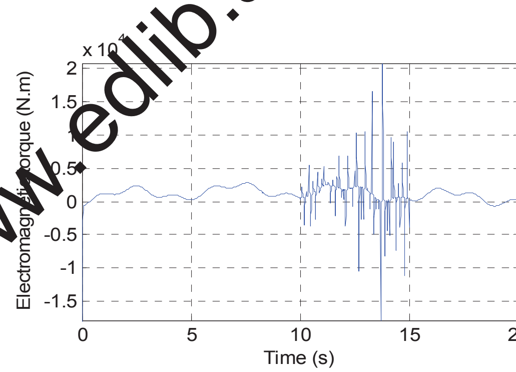

Fig.14 Trajectory of C_{em} with disturbance

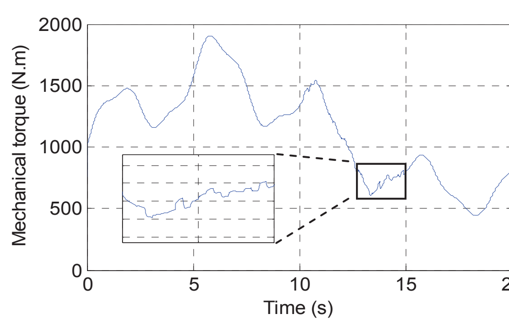

Fig.15 Trajectory of C_{mec} with disturbance

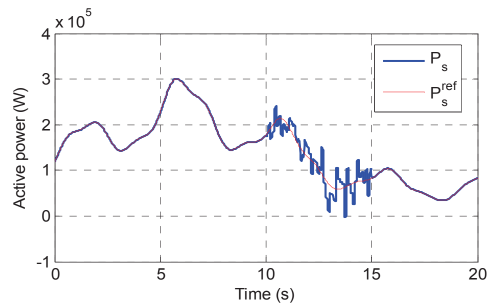

Fig.16 Trajectories of P_s^{ref} and P_s with disturbance

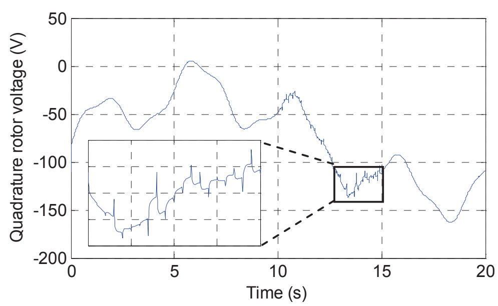

Fig.17 Trajectory of V_{rq} with disturbance

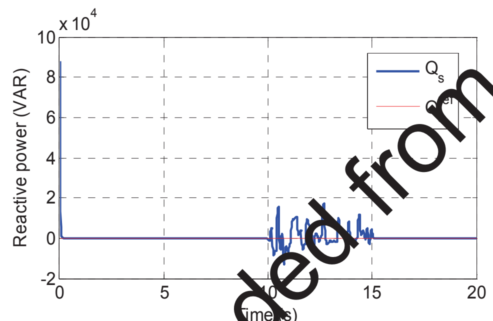

Fig.18 Trajectories of Q_s^{ref} and Q_s with disturbance

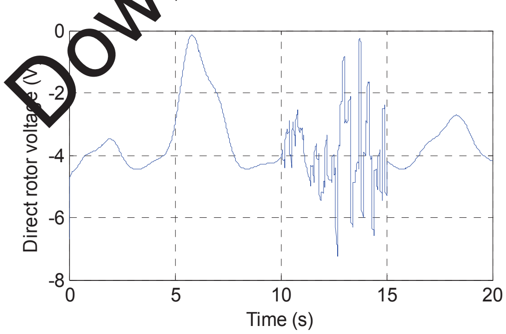

Fig.19 Trajectory of V_{rd} with disturbance

The obtained result shows that the measured output rejoined quickly its equilibrium state after the disappearance of the disturbance. This result shows the effectiveness of the approach and that the system is stable.

V. CONCLUSION

In this paper a strategy was presented to control the electrical produced power whose purpose is to optimize the energy supplied to the consumer. It is based on the study of the stability of nonlinear systems and the second method of Lyapunov. This approach is composed of two parts (mechanical and electrical). In the first part, the control law enables to the generator speed to follow the variation the wind. In the second part, the control law allows the active power to follow its reference which is the recovered power by the wind rotor, it also allows to obtain a null reactive power in order to ensure the unity power factor. To facilitate the control of powers the decoupling between the stator and the rotor is necessary. This strategy was applied for low wind speed and it is simulated on a 300 kW wind turbine.

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