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Conversion Wind Power Using Doubly Fed Induction Machine

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Abstract

In this paper we study different ways of control of the powers active and reactive of a DFIG (Doubly Fed Induction Machine) used in the production of the energy, especially in wind turbine.

The model used for the DFIG is a diphase one obtained by the application of the Park transformation. In order to control stator active and reactive power exchanged between the DFIG and the grid; we present a synthesized control law based on a vector control strategy using classical integral–proportional (PI) controller and polynomial RST controller based on pole-placement theory. Simulation calculations were achieved using MATLAB®-SIMULINK® package. The obtained results are presented for the two controllers.

Index Terms— DFIG, Wind Energy, Power control, RST controllers, PI controllers.

NOMENCLATURE

$v_{ds}, v_{qs}, v_{dr}, v_{qr}$: Two-phase statoric and rotoric voltages.

$i_{ds}, i_{qs}, i_{dr}, i_{qr}$: Two-phase statoric and rotoric currents.

L_s, L_r : Total cyclic statoric and rotoric inductances.

R_s, R_r : Per phase statoric and rotoric resistances.

$\Psi_{ds}, \Psi_{qs}, \Psi_{dr}, \Psi_{qr}$: Two-phase statoric and rotoric fluxes.

V_s : statoric tension.

g : Generator Slip.

M : Magnetizing inductance.

ψ_s : statoric flux.

ω_s, ω : statoric and rotoric angular frequency.

Ω : Mechanical speed.

Γ_{em}, Γ_r : Electromagnetic and resistant Torque.

J , f : Inertia and viscous friction.

p : Number of pole pairs.

P_s, Q_s : Active and reactive statoric power.

C_p : Power ratio.

$\Gamma_{turbine}$: Turbine torque.

$\Omega_{turbine}$: Turbine speed.

G : Gear ratio.

Γ_{dfig} : Torque of the machine

ρ is the air density,

R is the blade length

V the wind speed.

Ω_{mec} : Shaft speed.

λ : Tip-speed ratio.

1. INTRODUCTION

Different ways are used in order to produce the electrical energy (Gas, hydraulic…ect). But, there are several reasons for using variable-speed operation of wind turbine, among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power [6].

In order to produce the energy and to meet the power needs, the DFIG (Doubly Fed Induction Generator) is the alternative given in this paper, because of its wide range of variation in all four quadrants.

The control of electrical power exchanged between the stator of the DFIG and the power network is treated by controlling independently with PI regulators and RST controllers under conditions of unity stator side power factor ($P_{ref} = P_s$ and $Q_{ref} = 0$).

The aim of these regulators is to obtain high dynamic performances

The proposed control system is then simulated using MATLAB®-SIMULINK® package. The obtained results are presented and discussed.

2.MODELING OF THE STUDIED SYSTEM

A. The studied system

The system studied is made up of a wind turbine and a DFIG directly connected through the stator to the grid and supplied through the rotor by static frequency converter (Figure 1).

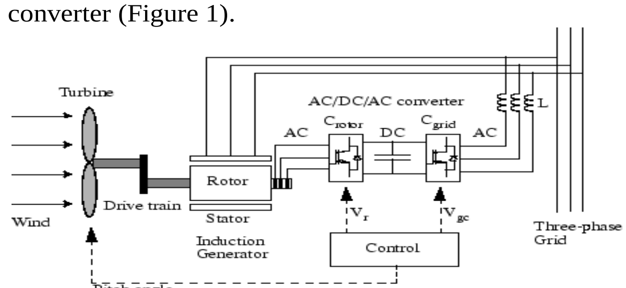

Figure 1. Wind system conversion

B. The double fed induction generator model

The electrical equation is written in d_q reference frame is as follows:

$$\begin{cases} v_{ds} = R_s.i_{ds} + \frac{d}{dt}\Psi_{ds} - \omega_s.\Psi_{qs} \\ v_{qs} = R_s.i_{qs} + \frac{d}{dt}\Psi_{qs} + \omega_s.\Psi_{ds} \\ v_{dr} = R_r.i_{dr} + \frac{d}{dt}\Psi_{dr} - (\omega_s - \omega).\Psi_{qr} \\ v_{qr} = R_r.i_{qr} + \frac{d}{dt}\Psi_{qr} + (\omega_s - \omega).\Psi_{dr} \end{cases} \quad .(1)$$

The stator flux can be expressed as:

$$\begin{cases} \psi_{ds} = L_s.i_{ds} + M.i_{dr} \\ \psi_{qs} = L_s.i_{qs} + M.i_{qr} \end{cases} \quad .(2)$$

The rotor flux can expressed as

$$\begin{cases} \psi_{dr} = L_r.i_{dr} + M.i_{ds} \\ \psi_{qr} = L_s.i_{qr} + M.i_{qs} \end{cases} \quad .(3)$$

The electromagnetic torque is defined as:

$$\Gamma_{em} = p.\left(\psi_{ds}.i_{qs} - \psi_{qs}.i_{ds}\right) \quad .(4)$$

$$\Gamma_{em} = \Gamma_r + J.\frac{d\Omega}{dt} + f.\Omega \quad .(5)$$

C. Wind Turbine Modeling

The power capacity produced by a wind turbine is dependent on the power ratio C_p. It is given by:

$$P_t = \frac{1}{2}.C_p.\rho.S.V_1^3 \quad .(6)$$

The turbine torque is the ratio of the output power to the shaft speed $\Omega_{turbine}$, where

$$\Gamma_{turbine} = \frac{P_t}{\Omega_{turbine}} \quad .(7)$$

The turbine is normally coupled to the generator shaft through a gear box whose gear ratio **G** is chosen so as to maintain the generator shaft speed within a desired speed range. Neglecting the transmission losses, the torque and shaft speed of the wind turbine, referred to the generator side of the gearbox, are given by:

$$\Gamma_{dfig} = \frac{\Gamma_{turbine}}{G} \quad .(8)$$

and $\Omega_{mec} = G.\Omega_{turbine}$.(9)

Where

Γ_{dfig} is the torque of the machine and Ω_{mec} is its shaft speed.

The wind turbine can be characterized by its $C_p(\lambda)$ (curve shown in Figure 2.). where the λ is the tip-speed ratio, that is the ratio between the linear speed of the tip of the blade with respect to the wind speed. It is shown that the power coefficient C_p varies with the tip-speed ratio. It is assumed that the wind turbine is operated at high C_p values most of the time [3].

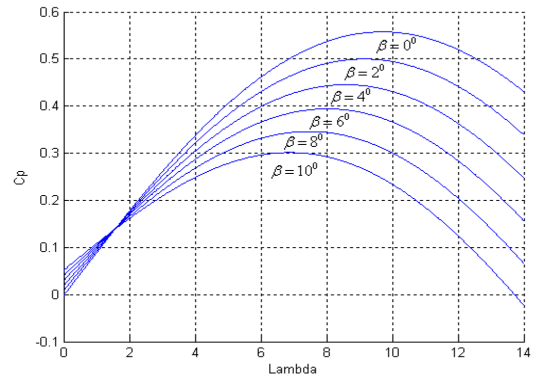

Figure 2. relationship between the power coefficient and the tip-speed ratio

The action of the speed corrector must achieve two tasks:

- It must control mechanical speed Ω_{mec} with its reference Ω_{mec_ref} [4].

It must attenuate the action of the wind torque which constitutes an input disturbance [4]. The simplified representation in the form of diagram blocks is given in Figure 3. We can use different technologies of correctors by in our work we opt for RST regulator to control our model.

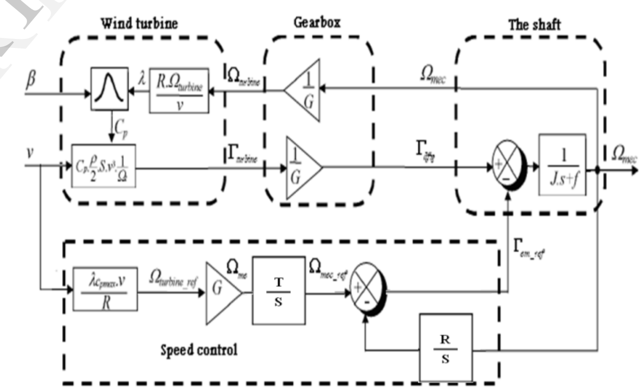

Figure 3. The block diagram of control speed

A. Turbine control with RST regulators

The block-diagram of a system with its RST controller is presented on Figure 10.

The system with the transfer-function $\frac{B(p)}{A(p)}$ has $E(p)$

As reference and is disturbed by the variable $\Omega(p)$. R, S and T are polynomials which constitutes the controller. In our case, we have:

$$\begin{cases} A(p) = f + p.J \\ B(p) = 1 \end{cases} \quad .(10)$$

Where p is the Laplace operator.

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The transfer-function of the regulated system is:

$$Y = \frac{B.T}{A.S + B.R} E + \frac{B.S}{A.S + B.R} P \quad .(11)$$

By applying the Bezout equation, we take:

$$D = A.S + B.R = C.F \quad .(12)$$

Where C is the command polynomial and F is the filtering polynomial. In order to have good adjustment accuracy, we choose a strictly proper regulator. So if A is a polynomial of n degree

$$\deg(A) = n = 1$$

We must have:

$$\deg(D) = 2.n + 1 = 3 \quad .(13)$$

$$\deg(S) = \deg(A) + 1 = 2 \quad .(14)$$

$$\deg(R) = \deg(A) = 1 \quad .(15)$$

In our case:

$$\begin{cases} A = a_1 p + a_0 \\ B = b_0 \\ D = d_3 p^3 + d_2 p^2 + d_1 p + d_0 \\ R = r_1 p + r_0 \\ S = s_2 p^2 + s_1 p + s_0 \end{cases} \quad .(16)$$

To find the coefficients of polynomials R and S, the robust pole placement method is adopted with T_c as control horizon and T_f as filtering horizon [2],[5].

We have:

$$p_c = -\frac{1}{T_c} \text{ and } p_f = -\frac{1}{T_f} \quad .(17)$$

Where p_c is the pole of C and p_f the double pole of F.

The pole p_c must accelerate the system and is generally chosen three to five times greater than the pole of A $p_a \cdot p_f$ is generally chosen three times smaller than p_c. In our case:

$$T_c = \frac{1}{T_f} = -\frac{1}{3.P_a} = \frac{L_s.\left(L_r - \frac{M^2}{L_s}\right)}{5.L_s.R_r} \quad .(18)$$

Perturbations are generally considered as piecewise constant. $P(p)$ can then be modeled by a step input. To obtain good disturbance rejections, the final value theorem indicate that the term $\frac{B.S}{A.S + B.R}$ must tend towards zero:

$$\lim_{p \to 0} p.\frac{S.B}{D}.\frac{P(p)}{p} = 0 \quad .(19)$$

To obtain a good stability in steady-state, we must have D(0)=0 and respect relation (19). The Bezout equation leads to four equations with four unknown terms where the coefficients of **D** are related to the coefficients of polynomials **R** and **S** by the Sylvester Matrix:

$$\begin{pmatrix} s_2 \\ s_1 \\ r_1 \\ r_0 \end{pmatrix} = inv \begin{pmatrix} a_1 & 0 & 0 & 0 \\ 0 & a_1 & 0 & 0 \\ 0 & a_0 & b_0 & 0 \\ 0 & 0 & 0 & b_0 \end{pmatrix} . \begin{pmatrix} d_3 \\ d_2 \\ d_1 \\ d_0 \end{pmatrix} \quad .(20)$$

In order to determine the coefficients of **T**, we consider that in steady state **Y** must be equal to **E**

$$\text{so: } \lim_{p \to 0} \frac{B.T}{A.S + B.R} = 1 \quad .(21)$$

As we know that S(0)=0, we conclude that T=R(0). In order to separate regulation and reference tracking, we try to make the term $\frac{B.T}{A.S + B.R}$ only dependent on **C**.

We then consider T=h.F (where h is real) and we can write:

$$\frac{B.T}{A.S + B.R} = \frac{B.T}{D} = \frac{B.h.F}{C.F} = \frac{B.h}{C} \quad .(22)$$

As $T = R(0)$, we conclude that $h = \frac{R(0)}{F(0)}$

$$S(p) = 0.3601 p^2 + 0.3313 p \quad .(23)$$

$$R(p) = 0.2349 p + 0.0204 \quad .(24)$$

$$T(p) = 0.1312 p^2 + 0.1034 p + 0.0204 \quad .(25)$$

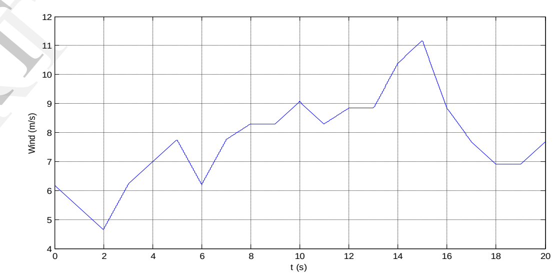

Figure 4. Wind profile

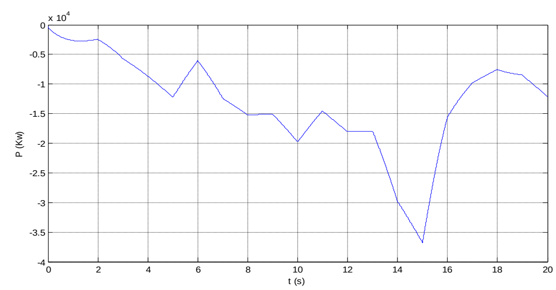

Figure 5. Power profile delivered

3. Power Control

The power control approach presented in this paper is based on a synthesized control law based on a vector control strategy using classical integral–proportional (PI) and polynomial RST controllers. The energy exchanged between DFIG and the grid is obtained by

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controlling independently the active and reactive powers.

The connection of the DFIG to the grid must be done in three steps. In first order we have to do the regulation of of the stator voltages with the grid voltages as reference. Then, the stator connection to the grid can be done. Finally, once the connection is achieved, the transit power and the DFIG can be given.

The stator flux vector is orienting according to the d axis in the Park's reference frame. Where:

$$\psi_{qs} = 0, \psi_{ds} = \psi_s \qquad .(26)$$

and $$v_{ds} = 0 \;,\; v_{qs} = V_s \qquad .(27)$$

If the voltage drops due to the stator resistance R_s, we can write:

$$\begin{cases} v_{dr} = R_r.i_{dr} + (L_r - \frac{M^2}{L_s}).\frac{di_{dr}}{dt} - g.\omega_s.(L_r - \frac{M^2}{L_s}).i_{qr} \\ v_{qr} = R_r.i_{qr} + (L_r - \frac{M^2}{L_s}).\frac{di_{qr}}{dt} + g.\omega_s.(L_r - \frac{M^2}{L_s}).i_{dr} + g.\omega_s.\frac{M.V_s}{\omega_s.L_s} \end{cases} \qquad (28)$$

We can notice that the two equations of rotorique voltage are coupled. The decoupling is obtained by compensation in order to assure the control of Ps and Qs, independently of each other. So we get a first order system, and its control is simplified and realized by a PI controller [1][6].

The stator active Ps and reactive power Qs can be written according to the rotor current:

$$\begin{cases} P_s = -V_s.\frac{M}{L_s}.i_{qr} \\ Q_s = \frac{V_s.\psi_s}{L_s} - \frac{V_s.M}{L_s}.i_{dr} \end{cases} \qquad .(29)$$

The system after compensation becomes:

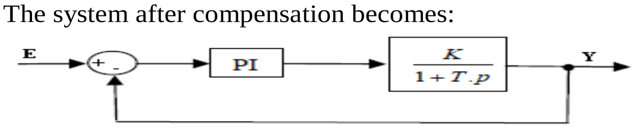

Figure 6. Scheme of the system with feed-back loop

The global scheme of the control through PI controller can be given as follows:

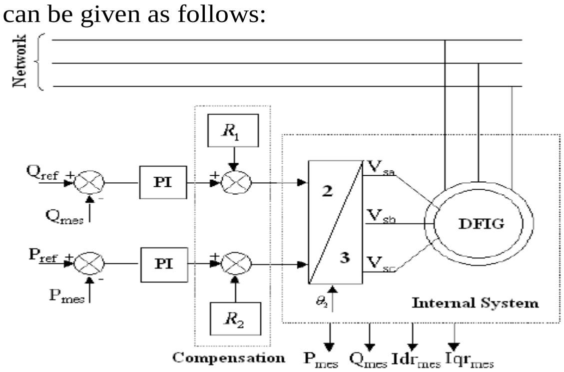

Figure 7. Global scheme of control through PI regulators

Where :

$$R_1 = g.\omega_s.\left(L_r - \frac{M^2}{L_s}\right).i_{qr}$$

$$R_2 = -g.\omega_s.\left(L_r - \frac{M^2}{L_s}\right).i_{dr} - g.\omega_s.\frac{M.V_s}{\omega_s.L_s} \qquad .(30)$$

From the equation (29) we can write:

$$\begin{cases} i_{qr} = -\frac{L_s}{V_s.M}.P_s \\ i_{dr} = \frac{L_s}{V_s.M}.Q_s - \frac{\psi_s}{M} \end{cases} \qquad .(31)$$

The terms, which constitute cross-coupling terms can be neglected because of their small influence [2], and by replacing the equations (31) in (28). We obtain:

$$\begin{cases} v_{dr} = \frac{R_r.L_s}{M.V_s}.Q_s + (L_r - \frac{M^2}{L_s}).(\frac{L_s}{M.V_s}).\frac{dQ_s}{dt} - \frac{R_r.\psi_s}{M} \\ v_{qr} = (\frac{-R_r.L_s}{M.V_s}).P_s + (L_r - \frac{M^2}{L_s}).(\frac{-L_s}{M.V_s}).\frac{dP_s}{dt} + g.\omega_s.\frac{M.\psi_s}{L_s} \end{cases} \qquad .(32)$$

Knowing relation (32), it is possible to synthesize the regulators and establish the global block- diagram of the controlled system (Figure 8.) [7].

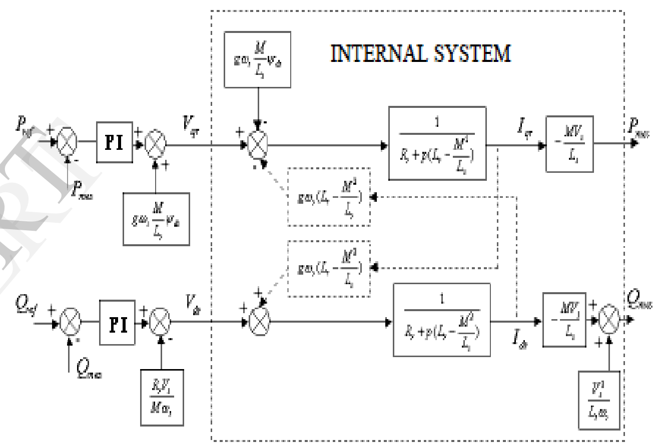

Figure 8. Power control with PI controller

B. Power Control with PI regulators

We can represent the system to control as follow:

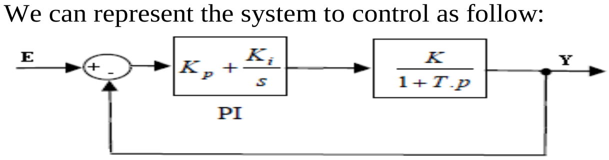

Figure 9. Scheme of the PI and system form with feed-back loop

The gain PI is in the form:

$$C(p) = \frac{K_i}{p}(1 + \frac{K_p}{K_i}.p) \qquad .(33)$$

We suppose: $$T = \frac{A}{B} \qquad .(34)$$

We can compensate the zero introduced by PI with the pole in open loop of the system.

$$\frac{K_p}{K_i} = \frac{A}{B} \Rightarrow K_p = K_i.\frac{A}{B} \qquad .(35)$$

In closed loop we obtain:

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$$H(p)=\frac{\frac{K_i}{p}.K}{1+\frac{K_i}{p}.K}\Rightarrow H(p)=\frac{1}{1+\frac{1}{K_i.K}.p} \quad .(36)$$

Where:

$$\tau=\frac{1}{K_i.K}\Rightarrow K_i=\frac{1}{\tau.K} \quad .(37)$$

τ : is the response time.

C. Power Control with RST regulators

The block-diagram of a system with its RST controller is presented on Figure 10.

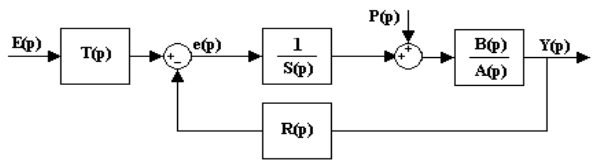

Figure 10. Block diagram of the RST controller

The system with the transfer-function $\frac{B(p)}{A(p)}$ has $E(p)$

As reference and is disturbed by the variable $P(p)$. R, S and T are polynomials which constitutes the controller. In our case, we have:

$$\begin{cases} A(p)=L_S.R_S+p.L_S.\left(L_r-\frac{M^2}{L_S}\right) \\ B(p)=M.V_S \end{cases} \quad .(38)$$

By following the steps above we will have:

$$S(p)=7.9904.10^3\,p^2+1.5513.10^7\,p \quad .(39)$$

$$R(p)=1.5872.10^5\,p+3.9618.10^7 \quad .(40)$$

$$T(p)=R(0)=r_0=3.9618.10^7 \quad .(41)$$

Simulation and results

The simulation of the global studied system is presented using MATLAB/SIMULINK software Parameters identification are obtained from an experimental bench.

A. Parameters identification.

The experimental bench is made up of DFIG (15KW, p=1, N=1500 rpm).mechanically coupled to a DC machine.

We made different tests;

No load test at synchronous, locked rotor test, transformer test and test for define the friction coefficient and moment of inertia.

After calculating the parameters, we obtain the results below:

$R_s = 0.272\ \Omega$, $L_s = 36.4\ mH$, $R_r = 0.269\ \Omega$

$L_r = 36.9\ mH$, $M = 34.9\ mH$, f =0.073 N.m.s/rad

$J = 2.555\ kg.m^2$

B. Simulation calculations.

We make the same conditions in two cases. We take reactive power Qs*=0 and we applied the echelon of active power Ps*=-15 kW at time t=0.5s. Figure 11 and Figure 12 represent active power response obtained respectively when we use PI controller and in the case of RST controller.

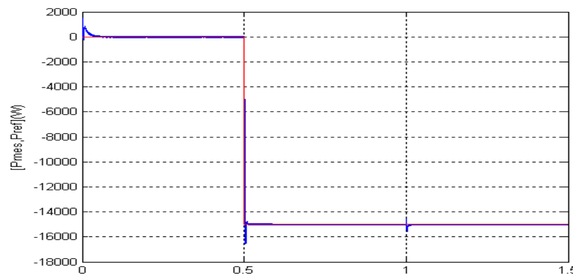

Figure 11. Ps response with its reference (PI controller)

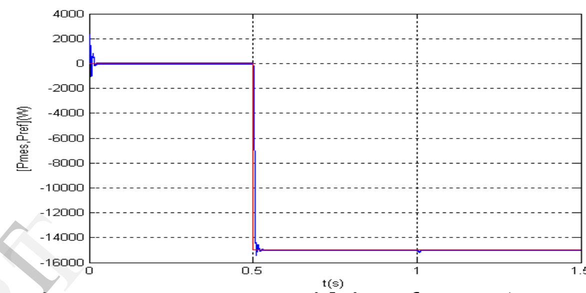

Figure 12. Ps response with its reference (RST controller)

We apply a power providing from the wind turbine. Figure 13. shows random wind turbine speed.

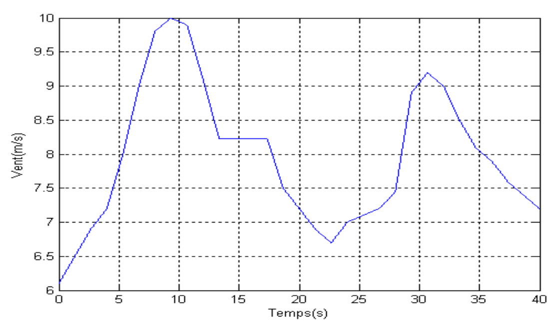

Figure 13. Wind turbine speed

Figure 14. and Figure 15 show respectively the active and reactive stator powers when we use PI controller.

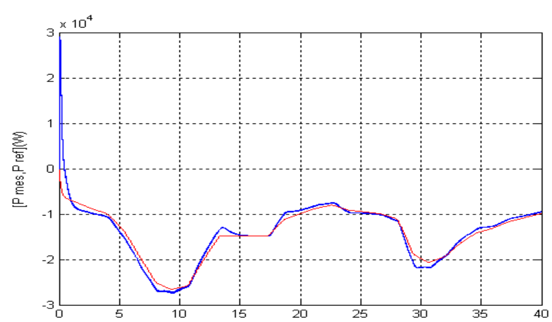

Figure 14. Active power response with its reference (PI controller)

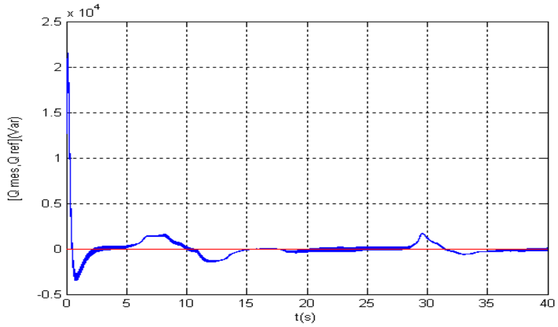

Figure 15. Reactive power response

In Figure 16. and Figure 17. we represent the active and reactive stator powers when we use RST controller.

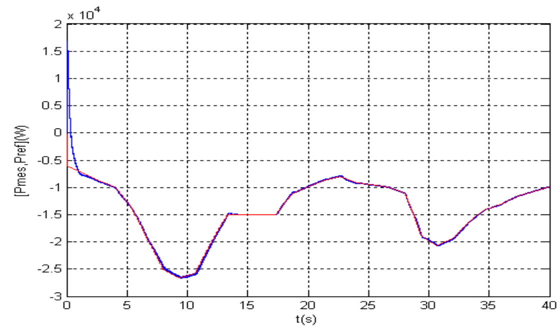

Figure 16. Active power response with its reference (RST controller)

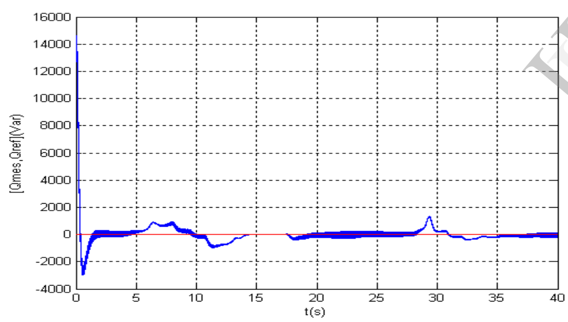

Figure 17. Reactive power response

We can observe in the two cases that the powers follow their reference perfectly and the performances are different.

4.CONCLUSION

This paper is devoted to the study of the performance of a double fed induction generator supplying a conversion wind system, using the turbine win speed control using RST controllers. Vector control strategy has been used to control statoric active and reactive power exchanged between the DFIG and the grid. To evaluate performances of PI controller and RST controller,

Firstly , we have applied the same conditions (active Power step reference -15 KW) and then we have applied parameters variations which showed the efficiency and the robustness of the RST controller.

The simulations presented above show the performance of each control and we have concluded that:

- PI gives the best time responses.
- RST is less sensitive to speed variation.
- RST show a great strength towards the different variations of parameters.

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