POWERS CONTROLS OF A DOUBLY- FED INDUCTION GENERATOR USED IN A CHAIN OF WIND POWER CONVERSION

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ABSTRACT
This paper deals with a study of some controls applied on a Doubly-Fed Induction generator (DFIG) dedicate in a chain of wind power conversion. Two methods are proposed: using a PI controller which synthesis is done by a new method called generalized method (GM) and using a polynomial controller RST one. The object is to apply these techniques to control the active and reactive powers generated by the DFIG. Simulations show that these controllers lead good results on tracking behavior, load disturbance rejection and show robustness following of variation parameters.

Keywords: wind power, Doubly-Fed Induction generator, PI controller, RST controller, vector control

1. INTRODUCTION

The development and the exploitation of renewable energies met a great growth these last years. Among these sources of energies, the windmills represent a significant potential to give solution for the demand, which always increase (Allam, Dehiba, Abid, Djeriri and Adjoudj 2014). The wind power can contribute with a significant part for the new sources of energy not emitting a gas for purpose of greenhouse (Ardjoun, Abid Aissaoui, Ramdani and Bounoua 2010)

In this paper, a DFIG modeling and its vector control are showed. Several methods are been already studied (Adjoudj and Abid 2012, Benbouzid, Beltran and Mangel 2013) for the DFIG which give good performances. Here, the controls of the active and reactive powers generated by the DFIG are given. For this purpose, a generalized method (GM) for PI controller synthesis is proposed. A polynomial RST controller is also applied. It may be noted that these two methods need the function transfer of the system. This paper is organized as follows: first, a presentation of the wind power conversion is given. The DFIG modeling follows this generality. For PI controller synthesis, a generalized method is presented. The application of the polynomial controller RST is then showed. Discussions from various results and a conclusion will finish the paper.

2. WIND POWER CONVERSION SYSTEM

The system, showed by figure 1 is composed of a turbine, multiplier, the DFIG and two converters (Ardjoun, Abid, Aissaoui and Naciri 2012, Meroufel, Massoum and Hammoumi 2010). The turbine transforms the kinetic wind power in mechanical energy. The total kinetic power of the wind is:

$$P = \frac{1}{2}\rho \pi R_T^2 V^3 C_p \qquad (1)$$

For windmills, the coefficient of energy extraction Cp which depends both of the wind velocity and the turbine speed is usually defined in the interval [0,35÷ 0,59] (Adjoudj, Abid, Aissaoui, Ramdani and Bouboua 2010). The DFIG transforms this latest in electrical energy. The converters are used to transfer the maximal energy delivered by the windmill to the grid according the wind velocity.

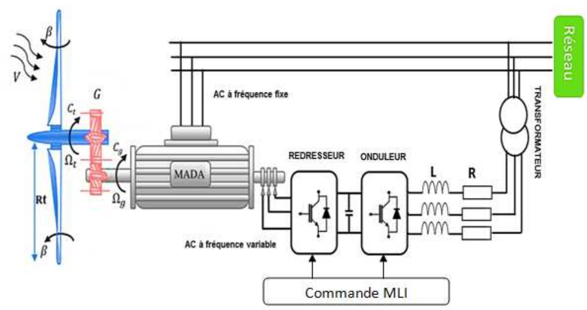


Figure 1: General scheme of a windmill based on DFIG

3. DFIG MODELING AND VECTOR CONTROL

The model of the DFIG is described in Park referential. The different equations give the global modeling of the machine.

3.1. Electrical equations

Te electrical equations give the voltage expressions.

$$\begin{cases} V_{sd} = R_s i_{sd} + \dfrac{d\phi_{sd}}{dt} - \omega_{coor}\phi_{sq} \\ V_{sq} = R_s i_{sq} + \dfrac{d\phi_{sq}}{dt} + \omega_{coor}\phi_{sd} \\ V_{rd} = R_r i_{rd} + \dfrac{d\phi_{rd}}{dt} - (\omega_{coor} - \omega)\phi_{rq} \\ V_{rq} = R_r i_{rq} + \dfrac{d\phi_{rq}}{dt} + (\omega_{coor} - \omega)\phi_{rd} \end{cases} \quad (2)$$

3.2. Magnetic equations

Relation (3) gives the expressions of different flux.

$$\begin{cases} \phi_{sd} = L_s.i_{sd} + M.i_{rd} \\ \phi_{sq} = L_s.i_{sq} + M.i_{rq} \\ \phi_{rd} = L_r.i_{rd} + M.i_{sd} \\ \phi_{rq} = L_r.i_{rq} + Mi_{sq} \end{cases} \quad (3)$$

With Ls, Lr, M design respectively the stator inductance, the rotor inductance and the mutual.

3.3. Torque and powers equations

The electromagnetic torque is expressed as according to current and fluxes by:

$$C_{em} = -p\frac{M}{L_s}(\phi_{sq} i_{rd} - \phi_{sd} i_{rq}) \quad (4)$$

The expressions of the active and reactive powers are:
By stator side,

$$\begin{aligned} P_s &= V_{sd} I_{sd} + V_{sq} I_{sq} \\ Q_s &= V_{sq} I_{sd} - V_{sd} I_{sq} \end{aligned} \quad (5)$$

By rotor side,

$$\begin{aligned} P_r &= V_{rd} I_{rd} + V_{rq} I_{rq} \\ Q_r &= V_{rq} I_{rd} - V_{rd} I_{rq} \end{aligned} \quad (6)$$

3.4. Vector control of the DFIG

In order to control the electricity production, a method, which not depends of the active and reactive powers, is proposed. It consists to establish relations between rotor voltages delivered by the converter with active and reactive stator powers (Ardjoun, Abid, Aissaoui and Naciri 2012, Meroufel, Djeriri, Massoum and Hammoumi 2010).

Referential **d-q** related of spinning field and a stator flux aligned on the axis **d** is adopted. So:

$$\begin{cases} \phi_{sd} = \phi_s \\ \phi_{sq} = 0 \end{cases} \quad (7)$$

Flux equations become:

$$\begin{cases} \phi_{sd} = \phi_s = L_s.i_{sd} + M.i_{rd} \\ 0 = L_s.i_{sq} + M.i_{rq} \\ \phi_{rd} = L_r.i_{rd} + M.i_{sd} \\ \phi_{rq} = L_r.i_{rq} + Mi_{sq} \end{cases} \quad (8)$$

If the grid is supposed stable, the stator flux ϕs is constant. Moreover, the stator resistor may be neglected; it is a realist hypothesis for a generator used in windmill. Taking into account all these considerations:

$$\begin{aligned} V_{sd} &= 0 \\ V_{sq} &= V_s = \omega_s \phi_s \end{aligned} \quad (9)$$

By the equation (8), a relation between stator and rotor currents can be established:

$$i_{sd} = \frac{\phi_s}{L_s} - \frac{M.i_{rd}}{L_s} \quad (10)$$

$$i_{sq} = -\frac{M}{L_s} i_{rq} \quad (11)$$

Using simplifying hypothesis, the equations of powers give:

$$\begin{cases} P_s = -V_s.\dfrac{M}{L_s} i_{rq} \\ Q_s = -V_s.\dfrac{M}{L_s} i_{rd} + \dfrac{V_s^2}{L_s.\omega_s} \end{cases} \quad (12)$$

In order to control the generator, expressions showing the relation between rotor voltages and rotor currents are:

$$\begin{cases} V_{rd} = R_r i_{rd} + L_r\sigma\dfrac{di_{rd}}{dt} - g\omega_s L_r \sigma i_{rq} \\ V_{rq} = R_r i_{rq} + L_r\sigma\dfrac{di_{rq}}{dt} + g\omega_s\left(L_r\sigma i_{rd} + \dfrac{MV_s}{\omega_s L_s}\right) \end{cases} \quad (13)$$

With g, σ denoting respectively the slip and the leakage coefficient.

Using relations (9),(10),(11) and (12), figure 2 shows a diagram where the rotor voltages like input and active and reactive powers like output.

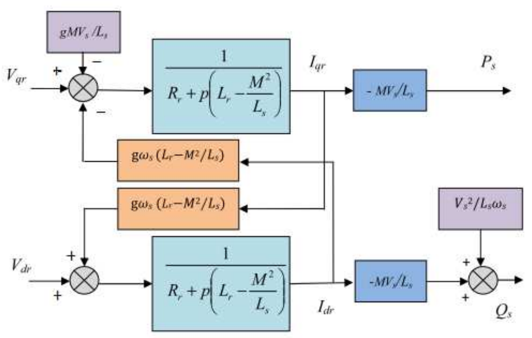


Figure 2: Diagram of the system to be controlled

There are generally two methods to do an independent regulation for the active and reactive powers:

- Direct method, which consists to neglect the coupling terms and to put a controller on each axe to control active and reactive powers. In this case, the controllers command directly the rotor voltages of the machine

- The second method, which takes into account the coupling terms and to compensate them by using two loops permitting to control the powers and the currents of the rotor. It is based on the relations (12) and (13). The diagram is given by figure 3.

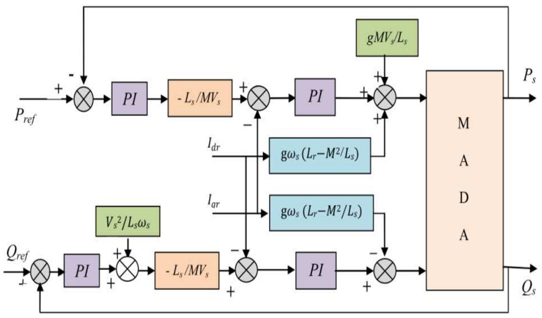


Figure 3 : Indirect vector control diagram

4. PI CONTROLLER

The synthesis is based on the simplified model of the DFIG. A PI controller is a simple one but can offer good performances. Different documentations show several methods (Allam, Dehiba, Abid, Djeriri and Ardjoun 2014, Bühler 1998) for its synthesis. Here, a generalized method (GM) is proposed to determine the parameters of the PI controller. Usually, there are two kinds of function transfer:

$$G_R(p) = \frac{1+pT_n}{pT_i} \qquad G_R(p) = K_p + \frac{K_i}{p} \tag{14}$$

It is easy to find relations between different parameters:

$$\begin{cases} K_p = \dfrac{T_n}{T_i} \\ K_i = \dfrac{1}{T_i} \end{cases} \tag{15}$$

For each loop, the function transfer of first order can be used for the system.

$$G(p) = \frac{K}{1+pT} \tag{16}$$

Usually, the second kind of function transfer is used. The method consists to:

- Impose a response time at ± 5%
- Choose a frequency for closed loop.

Here, the GM method using the first expression of the function transfer is chosen (Razafinjaka N.J. and Andrianantenaina T. 2015). Therefore, the function transfer of opened loop is:

$$G_o(p) = \frac{1+pT_n}{pT_i} \cdot \frac{K}{1+pT} \tag{17}$$

Relation (18) resumes the method:

$$\begin{cases} T_n = a.T & a \geq 0 \\ T_i = b.K.T & b > 0 \end{cases} \tag{18}$$

Example:

1/ **a =1** (the time constant T is cancelled)

$$G_o(p) = \frac{1+pT}{pbKT} \cdot \frac{K}{(1+pT)} = \frac{1}{pbT} \tag{19}$$

The function transfer for the closed loop is then

$$H(p) = \frac{G_o(p)}{1+G_o(p)} = \frac{1}{1+pbT} \tag{20}$$

The function transfer is yet a first order one with the time-constant $T_f = b.T$ *(0<b<1, here)*

2/ **a = 0**

$$G_o(p) = \frac{1}{pbKT} \cdot \frac{K}{1+pT} = \frac{1}{pbT.(1+pT)} \tag{21}$$

The closed loop transfer function is

$$H(p) = \frac{G_o(p)}{1+G_o(p)} = \frac{1}{pbT.(1+pT)} = \frac{1}{p^2bT^2 + pbT + 1} \tag{22}$$

By comparing with the canonical form,

$$\begin{cases} H_o = 1 \\ 2\zeta\omega_n = \dfrac{1}{T} \\ \omega_n^2 = \dfrac{1}{bT^2} \end{cases} \tag{23}$$

Imposing b gives ζ and vice versa. (b = 2 ⇒ ζ = $\frac{\sqrt{2}}{2}$).

Figure 4 shows the powers loop,

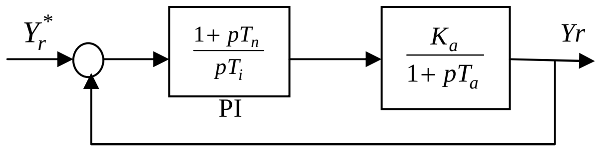


Figure 4: Power loop diagram

Here,

$$\begin{cases} K_a = \dfrac{M.V_s}{L_s.R_r} \\ T_a = \dfrac{L_s.L_r - M^2}{L_s.R_r} \end{cases} \tag{22}$$

For the current loop,

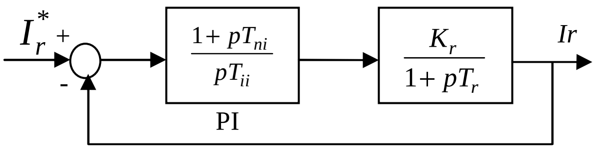


Figure 5: Current loop diagram

With,

$$\begin{cases} K_r = \dfrac{1}{R_r} \\ T_r = \dfrac{\sigma.L_r}{R_r} \end{cases} \qquad (23)$$

4.1. Simulation and results

Tracking test, disturbance rejection and robustness compared to the variation parametric, especially variation of the rotorique resistance *Rr* are used.

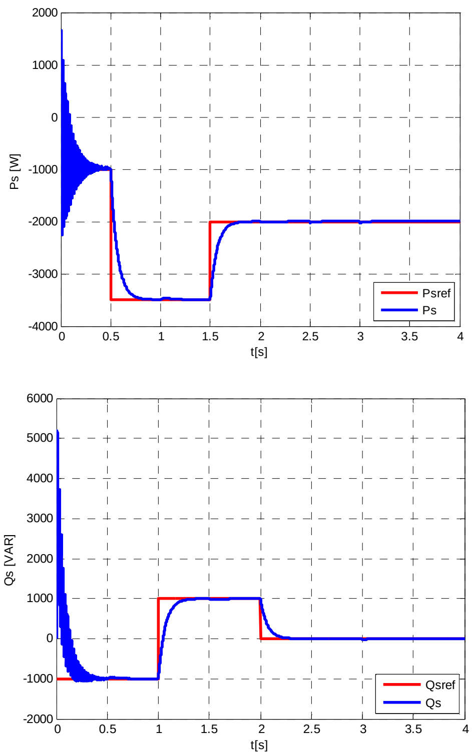
All simulations have the same conditions:

Variation of the power references, P_{sref} and Q_{ref}
t = 2,5[s], Ω :167,5 [rd.s^{-1}] ⟶ 178 [rd.s^{-1}]
t =3[s], *Rr* ⟶ *2*Rr*

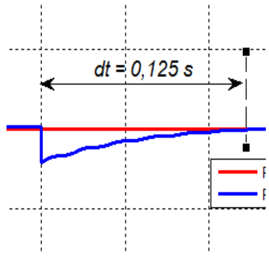
All the parameters of the PI controller are determined by the MG method.

$$\begin{cases} Powers : a = 0 \quad b = 0,058 \\ currents : a = 1 \quad b = 1 \end{cases}$$

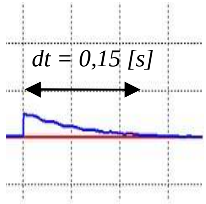
Figures 6 present the simulation results.



(a) : Active and reactive powers curves

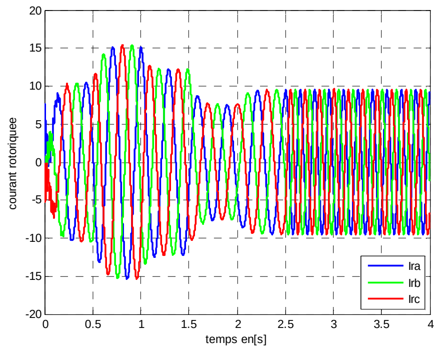


(b)

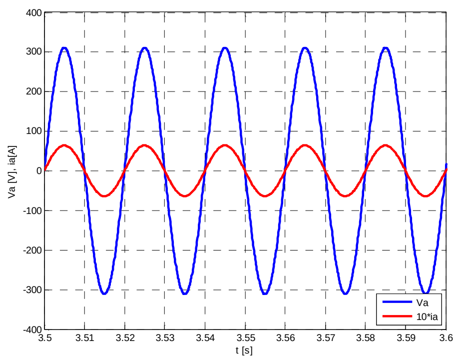


(c)

(b) Active power (Ω:167,5 [rd.s^{-1}] ⟶ 178 [rd.s^{-1}]
(c) Active power (Rr: Rr⟶2*Rr)



(d) Rotorique currents



(e) Statorique Voltage and current when Q_s =0

Figure 6: Simulation results with PI controller

It is clear here to note that PI controller determined by the MG method allows good performances: tracking, disturbance rejection and robustness from parameters. Figures 6 (b)-(c) shows that steady state is reached after Δt= 0,125 ÷ 0,15 [s]. The peak value is: ΔP = 20 [W].

5. RST CONTROLLER

This controller is primarily a digital controller. It generalizes the standard PID controller.. It owes its appellation by the three polynomials R(z), S(z) and T(z) which define it. The command law is :

$$R(z).U(z) = T(z).Y_c(z) - S(z).Y(z) \qquad (24)$$

Where Yc(z), Y(z) are respectively the set point and the output.

The difference between T(z) and S(z) offers more possibility and it is the reason that RST controller is called controller with two degrees of freedom.

5.1. RST synthesis

The RST synthesis is based on poles placement when a desired model $H_m(z)$ in close loop is given. Figure 7 shows the basic idea. Usually, the desired model is with non-high order. Its poles must satisfy absolute and relative conditions of damping.

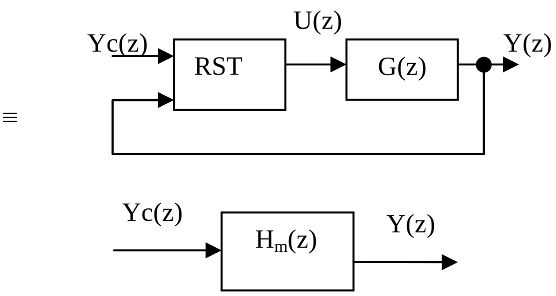


Figure 7: Basic scheme for RST synthesis

The relation (16) shows that power loop and rotorique current loop may be presented by first order transfer function.

$$G(p)=\frac{K}{1+pT}$$

Relation (25) permits to calculate the discrete transfer function G(z) when G(p) is given.

$$G(z)=(1-z^{-1})Z\left\{L^{-1}[\frac{G(p)}{p}]\right\} \qquad (25)$$

So,

$$G(z)=\frac{B(z)}{A(z)}=\frac{b_0}{z-z_0} \qquad (26)$$

With

$$\begin{cases} b_0=K.(1-z_0) \\ z_0=e^{-\frac{h}{T}} \end{cases} \qquad (27)$$

Here ***h*** is the sampling time.

The desired model in close loop is as follows:

$$H_m(z)=\frac{B_m(z)}{A_m(z)} \qquad (28)$$

Using the relations (24), (26) and (28), the followed equality can be established:

$$\frac{T(z).B(z)}{A(z).R(z)+B(z).S(z)}=\frac{B_m(z)}{A_m(z)} \qquad (29)$$

Here, R(z), S(z) and T(z) are to be calculated. Usually R(z) is chosen as a normalized polynomial. Resolving the equation (29) needs zero simplifications. For $H_m(z)$, some considerations must be taken into account.

- To eliminate the position error:
  $e_p=0 \Leftrightarrow H_m(1)=1$
- The denominator is:
  $A_m(z)=z^d.P(z)$

Where d°P = 1 or d°P =2. For the last condition,

$$P(z)=z^2+c_1z+c_2$$

$$\begin{cases} c_1=-2.e^{-\zeta\omega_n h}.\cos(\omega_n h.\sqrt{1-\zeta^2} \\ c_2=e^{-2\zeta\omega_n h} \end{cases} \qquad (29)$$

Because of the expression of G(z), no zero can be cancelled.

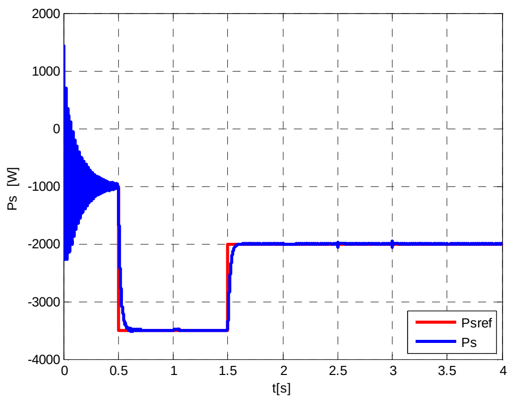
All steps to determine the polynomial RST are resumed in (Longchamp 1991, Razafinjaka 1991). In this paper, a polynomial P(z) with degree 2 and a perturbation compensator (m=1) are used. The results of computation are:

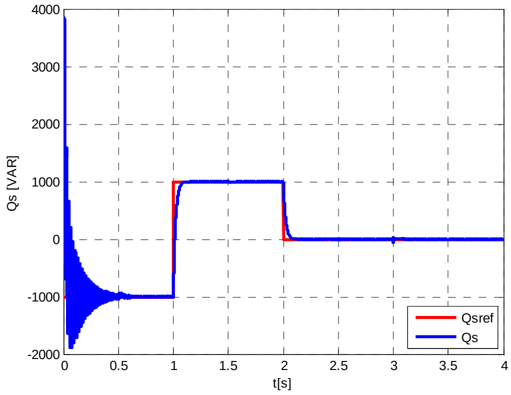
$$\text{Power} \begin{cases} h=10[ms] \quad \zeta=0,707 \quad \omega_n=400\left[\frac{rd}{s}\right] \\ R(z)=z-1 \\ S(z)=0,0089z-0,0039 \\ T(z)=0,005 \end{cases}$$

$$\text{Current} \begin{cases} h=10[ms] \quad \zeta=0,707 \quad \omega_n=400\left[\frac{rd}{s}\right] \\ R(z)=z-1 \\ S(z)=30,6z-13,48 \\ T(z)=17,12 \end{cases}$$

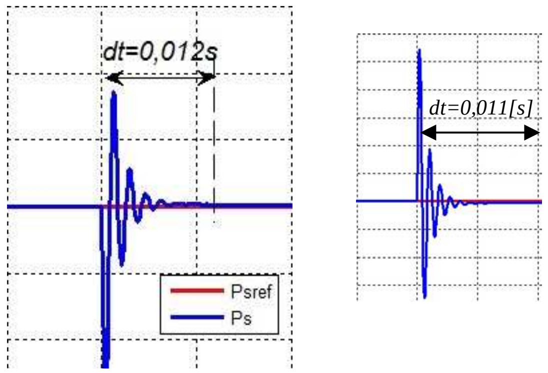
5.2. Simulation results

All conditions for tracking, disturbance rejection and robustness tests are the same like with the PI controller. Figures 8 show different curves.





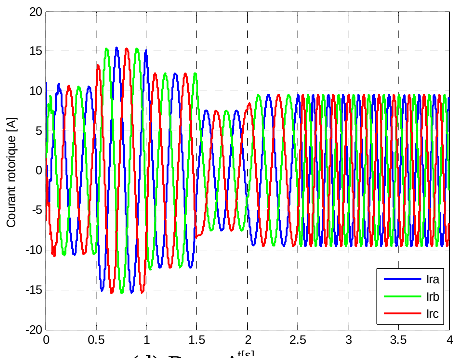
(a) Active and reactive power curves



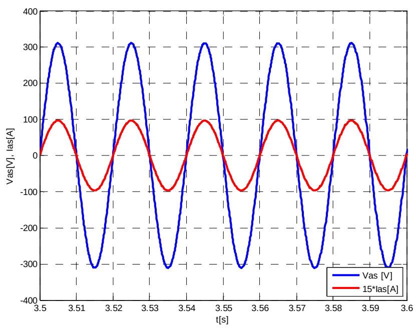
(b) (c)

(b) Active power (Ω:167,5 [rd.s^{-1}] ⟶ 178 [rd.s^{-1}]

(c) Active power (Rr: Rr⟶2*Rr)



(d) Rotorique currents



(e) Statorique voltage and current when Qs =0

Figure 8: Simulation results with RST controller

Figures 8 (b) –(c) shows that the system with RST controller (h = 10 [ms]) is faster but the peak power is higher (ΔP=80 [W]) in comparison with the PI controller one. However, it should be noted that this peak value and the oscillations decrease as the sampling time decreases. In the two cases, the reactive power Qs is null when statorique voltage and current are purely are sinusoidal and in phase ensuring good quality of the energy injected to the grid. The static error is null. At least, good performances are obtained.

CONCLUSION

In this paper, PI and RST controllers are used to control the active and reactive powers generated by a DFIG used in a chain of wind power conversion. A new method called generalized method (GM) is proposed and applied. The results show the effectiveness of this new method. It must be also noted that the RST controller may be inserted in adaptive control.

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