International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 3, March - 2014

RST Control of a Doubly-fed Induction Generator for Wind Energy Conversion

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***Abstract*—The purpose of thispaper is to studya differentcontrol strategyofactive and reactive powera doubly fed induction generator (DFIG)used for energy generation. The DFIG model we used is obtained by the application of the Park transformation. To control the power exchanged between the DFIG and the grid, a vector control strategy using integral-proportional (PI) controller and polynomial RST controller based on pole-placement theory is presented.The simulation calculations were achieved by using MATLAB®-SIMULINK® package. The results obtained from different operating points, illustrate the efficient control performances of the system**

Keywords—DFIG; Wind Turbine; Variable Speed; Power control; PI controller; RST controller.

I. INTRODUCTION

Today, wind energy has become a viable solution for the generation of electrical energy. Although the majority of installed wind turbines have a fixed speed, the number of wind turbines which have a variable speed is increasing [1]. The double-fed asynchronous generator with a vectorial control is a machine that has excellent performance and is commonly used in wind turbine industry. There are many reasons for the use of a double-fed induction generator for a variable speed wind turbine; for instance, the reduction of efforts on the mechanical parts, the reduction of noise and the ability to control the active and reactive power. The wind system which uses DGIF and a "back-to-back" converter that connects the rotor generator to the grid has many advantages. An advantage of this structure is that the used power converters are designed to flow a fraction of the total power of the system [2-3]. The performances of this system depend not only on the DFIG, but also on how the "back-to-back" converter is controlled. While the rotor side converter controls the active and reactive power produced by the generator, the grid side converter allows us to control the DC bus voltage and the power factor of the grid side. In order to control the stator exchanged active and reactive power between the DFIG and the grid, a vector-control strategy is used to control PI and RST controllers independently. The aim of these controllers is to obtain high dynamic performances. The proposed control system is simulated using MATLAB®-SIMULINK® package. The obtained results are presented and discussed.

II. MODELLING OF THE STUDIED SYSTEM

A. The studied system

The scheme of the device studied is given in the Fig.1.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 AC/DC and DC/AC Converter.

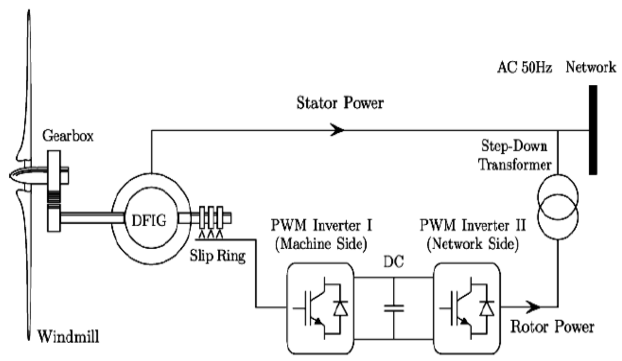

Fig. 1. Wind system conversion

B. The double fed induction generator model

The electrical equations of DFIG in dq reference can be written as follows [4-5]:

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

(1)

With:

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

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

With

$Ls = ls - Ms$: Cyclical inductance of a stator phase.
$Lr = lr - Mr$: Cyclical inductance of a rotor phase.

[ls] , [lr] : Inductances of a stator and rotor phase.
Ms, $, M$: Mutual inductances and Maximum mutual inductance between stator and rotor phases respectively.
The expression of theelectromagnetic torque of theDFIGismore:

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

Wherep: number of pole pairs of the DFIG.
The active and reactive powers of the stator and rotorcan be written as follows [4-5]:

$$\begin{cases} P_s = v_{ds}.i_{ds} + v_{qs}.i_{qs} \\ Q_s = v_{qs}.i_{ds} - v_{ds}.i_{qs} \\ P_r = v_{dr}.i_{dr} + v_{qr}.i_{qr} \\ Q_r = v_{qr}.i_{dr} - v_{dr}.i_{qr} \end{cases} \quad (5)$$

C.Vector control of DFIG

The control strategies of the DFIG are based on two different approaches [2]:
- Flux control in a closed loop, where the frequency and the voltage are considered variable (unstable network).
- Flux control in an open loop where the voltage and the frequency are constant (stable network). In our study, the frequency and the voltage are constant. It can be concluded from equation (11), that there is a strong coupling between fluxes and currents. Indeed, the electromagnetic torque is the cross product between the flux and stator currents, which makes the control of DFIG particularly difficult. To make DFIG control easier, we approximate its model to that of a DC machine which has the advantage of having a natural decoupling between the fluxes and the currents. For this, we apply the vector control. We choose a two-phase dq reference linked to the rotating field. The stator flux Ψ_s is oriented along d axis. Thus, we can write:

$$\begin{cases} \psi_{ds} = \psi_s \\ \psi_{qs} = 0 \end{cases} \quad (6)$$

$$\begin{cases} \psi_{ds} = L_s i_{ds} + M i_{dr} = \psi_s \\ \psi_{qs} = L_s i_{qs} + M i_{qr} = 0 \end{cases} \quad (7)$$

$$\begin{cases} i_{ds} = \frac{\psi_s}{L_s} - M.i_{dr} \\ i_{qs} = -\frac{M}{L_s} i_{qr} \end{cases} \quad (8)$$

The expression of electromagnetic torque becomes:

$$T_{em} = -P\frac{M}{L_s}\psi_s.i_{qr} \quad (9)$$

In the field of wind energy production, medium and high power machines are mainly used. Thus, we neglect the stator resistance. If we consider the stator flux constant, we can write:

$$\begin{cases} v_{ds} = 0 \\ v_{qs} = V_s = \Psi_s.\omega_s \end{cases} \quad (10)$$

Vs is the line voltage.
According to equation (16), we can see that by controlling the magnitude quadrature rotor current (iqr), we can control the electromagnetic torque of the DFIG.
By applying vector control of DFIG we can write the expressions of power as follows:

$$\begin{cases} P_s = v_{qs} i_{qs} = -\frac{M}{L_s} V_s.i_{qr} \\ Q_s = v_{qs} i_{ds} = V_s\left(\frac{\psi_s}{L_s} - \frac{M}{L_s} i_{dr}\right) \\ P_r = v_{dr} i_{dr} + v_{qr} i_{qr} \\ Q_r = v_{qr} i_{dr} - v_{dr} i_{qr} \end{cases} \quad (11)$$

The active and reactive power can be written as:

$$\begin{cases} P_s = -\frac{M}{L_s} V_s.i_{qr} \\ Q_s = \frac{V_s.\psi_s}{L_s} - \frac{V_s.M}{L_s} i_{dr} \\ P_r = g\frac{M}{L_s} V_s.i_{qr} \\ Q_r = g\frac{M}{L_s} V_s.i_{dr} \end{cases} \quad (12)$$

(19)

Total powers involved in the wind turbine are represented by equations (13) and (14):

$$P_t = P_s + P_r = (g-1)V_s \frac{M}{L_s} i_{qr} \quad (13)$$

$$Q_t = Q_s + Q_r = \frac{V_s \psi_s}{L_s} + (g-1)V_s \frac{M}{L_s} i_{dr} \quad (14)$$

The principle of vector control power is used. It is necessary to follow the DFIG an instruction of power, with the best electrical dynamics and taking into account the limitation of the frequency commutation of power switches. In order to obtain a power factor equal to one on the stator side, the reactive power on the stator is maintained zero(Q_s = 0). The reference active power to be imposed on the DFIG is defined by equation (15) [2]:

$$P_{s\_ref} = \eta P_{mec\_opt} \quad (15)$$

With: Performance of the DFIG and two power converters.

C. Turbine modelling

By applying the theory of movement quantity and Bernoulli theorem, we can determine the incidental power (theoretical power) generated by wind [2-3]:

$$P_t = \frac{1}{2}.\rho.S.V^3 \quad (16)$$

S : the area swept by the blades of the turbine [m^2]
ρ : air density ($\rho = 1.225\ kg/m^3$ at atmospheric pressure).
v : wind speed [m/ s]
Due to various losses in wind energy system, the power extracted from the turbine rotor is less than the incidental power. The extracted power is expressed by [3]:

$$P_t = \frac{1}{2}.C_p(\lambda\beta).\rho.\pi.R^2.V^3 \quad (17)$$

Cp (λ, β) : is called the power coefficient, which expresses the aerodynamic efficiency of the turbine. The power coefficient depends on β angle orientation of the blades and the ratio λ, which represents the relationship between the blades speed at their tips and wind speed. The ratio λ can be expressed by the following equation [3-4]:

$$\lambda = \frac{\Omega_t.R}{v} \quad (18)$$

The maximum power coefficient Cp was determined by Albert Betz (1920) as [5]:

$$C_p^{max}(\lambda,\beta) = \frac{16}{27} \approx 0.593 \quad (19)$$

The power factor is intrinsic to the design of the wind turbine and depends on the blades and their profiles. We can model the power coefficient with a single equation that depends on the speed ratio λ and the blade β pitch angle [6]:

$$C_p(\lambda,\beta) = c_1.\left(\frac{c_2}{A} - c_3.\beta - c_4\right).e^{-\frac{c_5}{A}} + c_6.\lambda \quad (20)$$

The six coefficients c1, c2, c3, c4, c5 and c6 are modified for maximumCp equal to 0.498 for β = 0°.
With A which depends onλ and β:

$$\frac{1}{A} = \frac{1}{\lambda + 0.08.\beta} - \frac{0.035}{1+\beta^3} \quad (21)$$

Figure 1 shows the curves of the power coefficient depending on λ with different values of β. A maximum power coefficient of 0.498 is obtained with a speed ratio λ which is 8 (λ_{opt}). By setting β and λ respectively to their optimal values, the wind system provides an optimal electrical power.

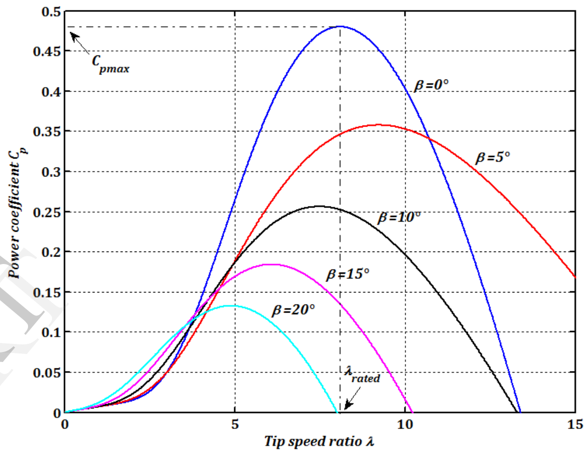

Fig. 2. Power coefficient for the wind turbine model

D. EXTRACTION OF MAXIMUM POWER

To capture the maximum power of the incidental wind energy, it is necessary to adjust the rotation speed of the wind turbine to the wind speed. The optimal mechanical speed of the turbine corresponds to λ_{opt} and $\beta = 0°$. The speed of the DFIG is used as a reference for a proportional-integral controller type (PI….). This type of regulator determines the control instruction which is the electromagnetic torque that should be applied to rotate the generator at its optimum speed.
Thus, the torque determined by the controller is used as a reference torque of the turbine model (Figure 3). The variation of the system of the blades angle orientation (variation of the incidence angle) allows changing the ratio between the lift and the drag. In order to extract the maximum power and keep it constant, we should adjust the angle of the blades to the wind speed.
The "Pitch Control" is a technique that adjusts mechanically the blade pitch angle to shift the curve of the power coefficient of the turbine [7].
However, this technique is quite expensive and is usually used for high and medium wind turbinespower. In our model, the "Stall Control" technique, which is a passive approach that allows a natural aerodynamic stall (decrease of the lift when the wind speed becomes more important). The

Regulation of the rotation speed of the turbine by blade pitch angle occurs when the generator speed exceeds 30% of its ratedspeed. In the opposite case, β will be zero.

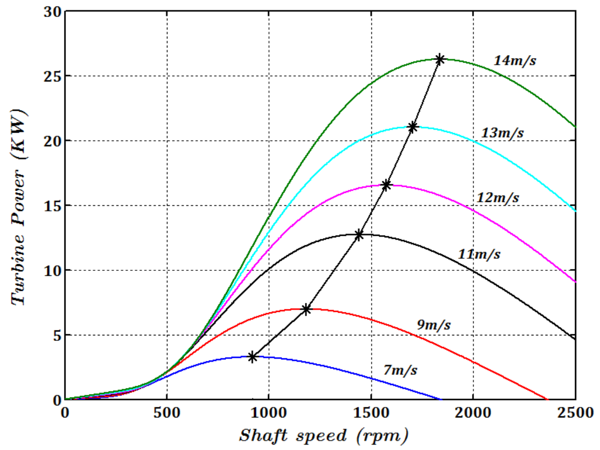

Fig.3. Power-Speed characteristics of the wind turbine

III. POWER CONTROL WITH PI CONTROLLER

We can represent the system to control as follow:

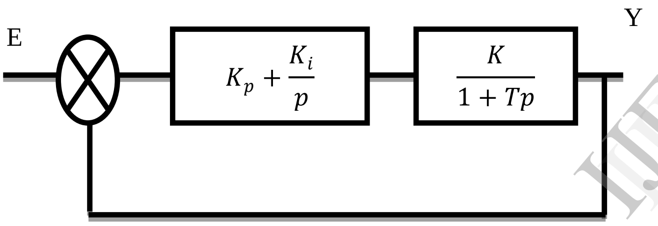

Fig.4. Block diagram of the RST controller.

$$C(p) = \frac{K_i}{p}\left(1 + \frac{K_p}{K_i}p\right) \quad (22)$$

We suppose:

$$T = \frac{A}{B} \quad (23)$$

We can make the compensation of the zero introduced by the Proportional Integral controller with the pole of the open-loop system:

$$\frac{K_p}{K_i} = \frac{A}{B} \quad (24)$$

The transfer function of the closed loop becomes:

$$F(p) = \frac{1}{1 + \tau p} \quad (25)$$

With

$$\tau = \frac{1}{K_i K_p} \quad (26)$$

τis response time.

IV. POWER CONTROL WITH RST CONTROLLER

The block-diagram of a system with its RST controller is presented in fig. 5

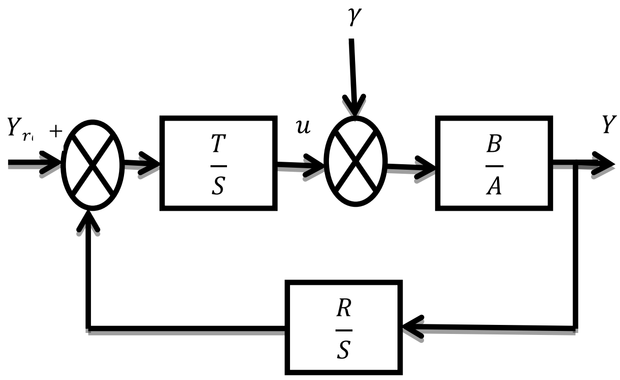

Fig. 5. Block diagram of the RST controller.

The system with the transfer-function $\frac{B}{A}$ has Yref as reference and is disturbed by the variable γ, R, S and T are polynomials which constitutes the controller. In our case, we have:

$$A = L_s R_r + pL_s\left(L_r - \frac{M^2}{L_s}\right) \text{and} B = MV_s \quad (27)$$

Where p is the Laplace operator.
The transfer-function of the regulated system is calculated as:

$$Y = \frac{BT}{AS + BR} Y_{ref} + \frac{BS}{AS + BR} \gamma \quad (28)$$

By applying the Bezout equation, we put:

$$D = AS + BR = CF \quad (29)$$

Where C is the polynomial command and F is the polynomial filtering. In order to have a high accuracy adjustment, we chose a strictly proper regulator. So if A is a polynomial of mdegree ($deg(A) = m$) we must have:

$$\begin{aligned} deg(D) &= 2m + 1 \\ deg(S) &= deg(A) + 1 \\ deg(R) &= deg(A). \end{aligned} \quad (30)$$

In our case:

$$\begin{Bmatrix} A = a_1 p + a_0 \\ B = b_0 \\ R = r_1 p + r_0 \\ S = s_2 p^2 + s_1 p + s_0 \\ D = d_3 p^3 + d_2 p^2 + d_1 p + d_0 \end{Bmatrix} \quad (31)$$

To find the coefficients of polynomials R and S, the robust pole placement method is adopted with Tc as horizon control and T_f as filtering horizon [9][11][12]. We have:

$$p_c = -\frac{1}{T_c} \quad (32)$$

And

$$p_f = -\frac{1}{T_f} \quad (33)$$

Where p_c is the pole of C and p_f is 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 p_a of A.

In our case [12]:

$$T_c = \frac{T_f}{3} = -\frac{1}{3p_a} = \frac{L_s\left(L_r - \frac{M^2}{L_s}\right)}{5L_s R_r} \quad (34)$$

Perturbations are generally considered as piecewise constant. To obtain good disturbance rejections, the final value theorem indicates that the term $\frac{BS}{AS+BR}$ must tend towards zero:

$$\lim_{p \to 0} p \frac{S}{D} \frac{\gamma}{p} = 0 \quad (35)$$

The Bezout equation results 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 [23] [24] [25]:

$$\begin{pmatrix} d_3 \\ d_2 \\ d_1 \\ d_0 \end{pmatrix} = \begin{pmatrix} a_1 & 0 & 0 & 0 \\ 0 & a_1 & 0 & 0 \\ 0 & a_0 & b_0 & 0 \\ 0 & 0 & 0 & b_0 \end{pmatrix} \begin{pmatrix} S_2 \\ S_1 \\ r_1 \\ r_0 \end{pmatrix} \quad (36)$$

To determine the coefficients of T, we consider that in a steady state Y must be equal to Yref so:

$$\lim_{p \to 0} \frac{BT}{AS + BR} = 1 \quad (37)$$

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 $\frac{BT}{AS+BR}$ only dependent on C. We then consider T=hF (where h is real) and we can write:

$$\frac{BT}{AS + BR} = \frac{BT}{D} = \frac{B.h.F}{C.F} = \frac{B.h}{C} \quad (38)$$

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

V. RESULTS AND INTERPRETATION

The simulation presented is that of the DFIG which is directly connected to the network through the stator, and is controlled by its rotor through an AC/DC and DC/AC converter.To control the power exchanged between the stator and the network, one uses the vector control with direct stator flux. We make the variation of the active and reactive references power (Fig.6 to Fig.9).

The results of simulations, are obtained with reactive power Qs_ref = 0 and application of the echelon of active power Ps_ref = -2.5KW at time 1s.

Fig.6 and fig.7 show respectively active power response obtained respectively when use PI controller and in the case of RST controller.

Fig.8 and Fig.9 show respectively reactive stator powerresponse obtained respectively when use PI controller and in the case of RST controller.

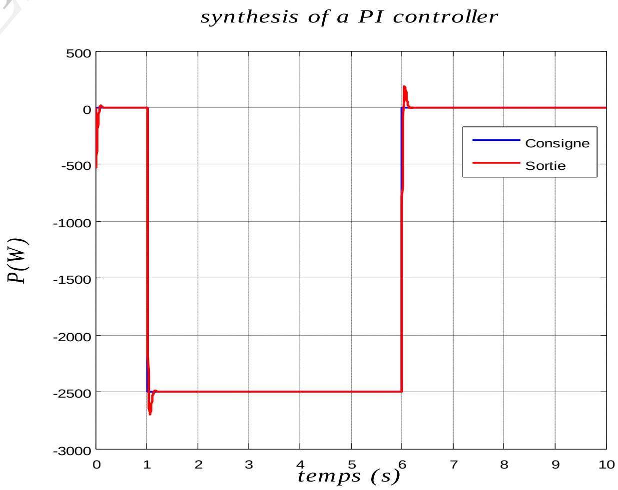

Fig.6. Active stator power response with its reference (PI controller)

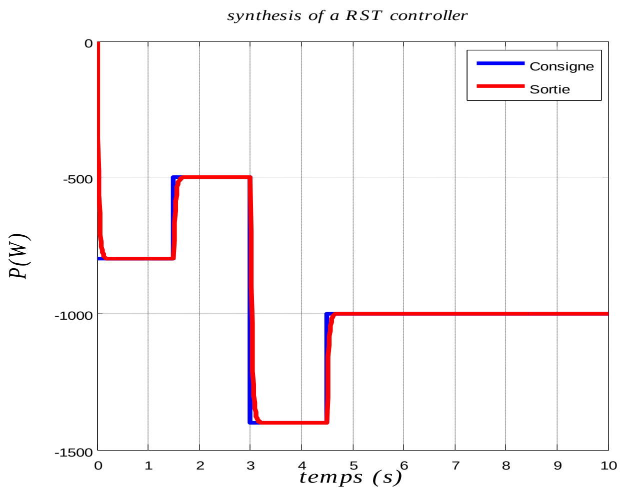

Fig.7. Active stator power response with its reference (RST controller)

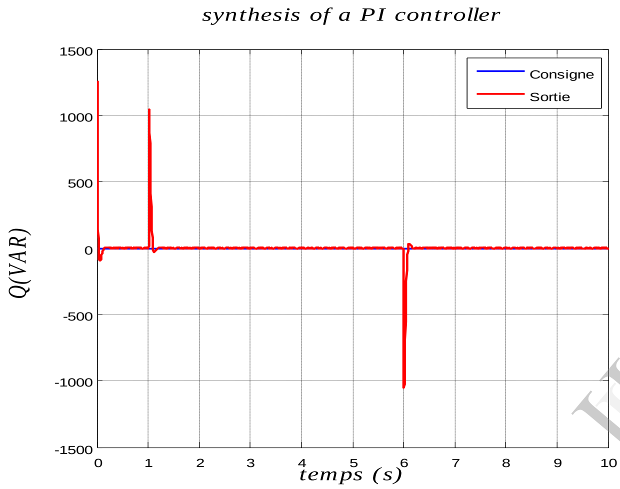

Fig.8. Reactive stator power response with its reference (PI controller)

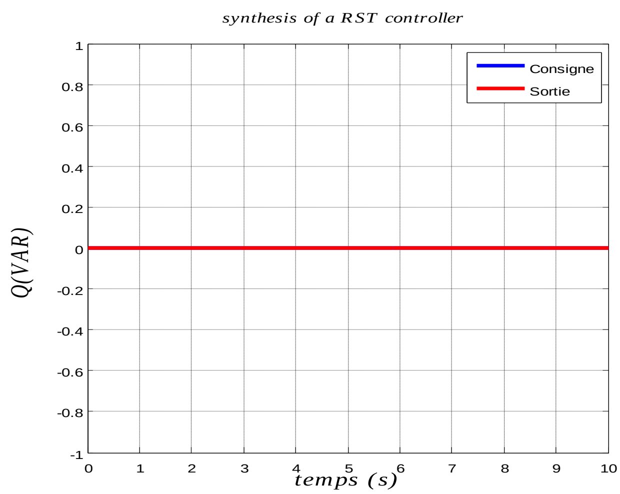

Fig.9. Reactive stator power response with its reference (RST controller)

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

VI. CONCLUSION

The work presented in this research is devoted to the study of the performance of a doubly fed induction generator used in the conversion wind system. The stator-flux oriented control technique has been used to control stator's active and reactive power, using integral-proportional (PI) controller and polynomial RST based on pole-placement theory. To evaluate performances of PI controller and RST controller, we have applied the same conditions. The simulations presented above show the performance of each control and we have concluded that PI controller gives the best time responses and in two cases that the power follow their reference perfectly.

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