Power Control of a Wind Energy Conversion System based on a Doubly Fed Induction Generator using RST

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Abstract*—In order to meet power needs, taking into account economical and environmental factors, wind energy conversion is gradually gaining interest as a suitable source of renewable energy. In this paper, a wind power generation scheme using a doubly fed induction generator is proposed. The aims of this paper are: to model and to simulate the operation of a doubly fed induction generator; the analysis employs a stator flux vector control algorithm; the converter-based rotor current control scheme is highlighted; the system enables optimal Power tracking for high performance active and reactive power regulation used the RST regulator. Lastly, the obtained simulation results, for different operating points, are presented illustrating the good control performances of the system.

***Keywords*— field oriented control (FOC), wind energy conversion system (WECS), Doubly Fed Induction Machine (DFIM), the RST regulator.**

I. Introduction

The wind power is one of renewable energies which news fast growth in the world due to clean and nonpolluting nature [1]. Several machines were used in WECS, but the range of wind speed was limited in classical machines, the advanced technology created DFIM witch solves this problem and makes it more powerful [2].

Several control methods of the DFIM appeared, among them, the vector control [3]. The principle of this control is to make DFIM similar to separate excitation DC machine.

This paper presents a comparison of performance in vector control using PI and controllers RST in WECS. The first regulator is PI which is simple and easy in implementation and gives acceptable performances [4], but it hasn't robustness in case of parameter variations .Then, a control device by Polynomial RST regulator is used. This type of controller proved to be an interesting method for the design of controllers and was applied in many fields. It can present fast dynamic responses if the switching devices support a high frequency. The studied system is presented in (Fig. 1).

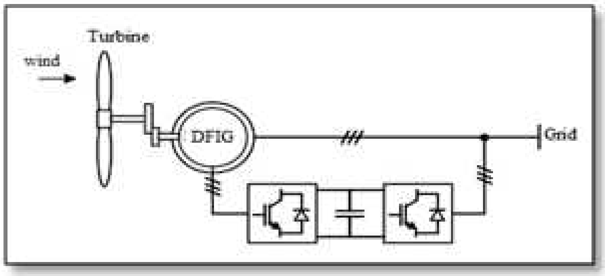

Fig. 1. Scheme of the studied system.

II. Modeling and control of DFIM

A. Modeling of DFIM

The of Park transformation on electrical equations of DFIM in field reference frame gives the following equations [5][6][7]:

$$\begin{cases} V_{sd}=R_s i_{sd}+\dfrac{d\Phi_{sd}}{dt}-\omega_s\Phi_{sq} \\ V_{sq}=R_s i_{sq}+\dfrac{d\Phi_{sq}}{dt}+\omega_s\Phi_{sd} \\ V_{rd}=R_r i_{rd}+\dfrac{d\Phi_{rd}}{dt}-\omega_r\Phi_{rq} \\ V_{rq}=R_r i_{rq}+\dfrac{d\Phi_{rq}}{dt}+\omega_r\Phi_{rd} \end{cases} \quad (1)$$

The fields are given by:

$$\begin{cases} \Phi_{sd}=L_s i_{sd}+M_{sr} i_{rd} \\ \Phi_{sq}=L_s i_{sq}+M_{sr} i_{rq} \\ \Phi_{rd}=L_r i_{rd}+M_{sr} i_{sd} \\ \Phi_{rq}=L_r i_{rq}+M_{sr} i_{sq} \end{cases} \quad (2)$$

The electromagnetic torque is given by:

$$C_{em}=P\frac{M_{sr}}{L_s}\left(\Phi_{sq}i_{rd}-\Phi_{sd}i_{rq}\right) \quad (3)$$

$$J\frac{d\Omega_{mec}}{dt}=C_{em}-C_r-f.\Omega_{mec} \quad (4)$$

B. Power Control

In order to control easily the electrical power produced by the WECS, we applied an independent control of the active and reactive powers by FOC of stator The principle consists in aligning stator field along the d axis of Park reference frame (Fig.2) [3][8]. This choice is to eliminate the coupling between powers.

We have: $\Phi_{sq}=0$ then $\Phi_{sd}=\Phi_s$.

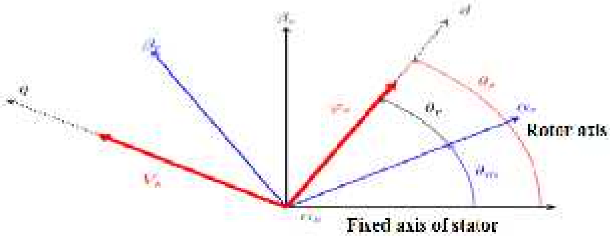

Fig. 2. Position of the stator flux.

The systems of equation (1) and (2) can be simplified as the following form:

$$\begin{cases} V_{sd}=R_s i_{sd} \\ V_{sq}=R_s i_{sq}+\omega_s\Phi_s \\ V_{rd}=R_r i_{rd}+\dfrac{d\Phi_{rd}}{dt}-\omega_r\Phi_{rq} \\ V_{rq}=R_r i_{rq}+\dfrac{d\Phi_{rq}}{dt}+\omega_r\Phi_{rd} \end{cases} \tag{5}$$

For high power machines we can neglect the resistance of the stator windings, so:

$$\begin{cases} V_{sd}=0 \\ V_{sq}=V_s=\omega_s\Phi_s \\ V_{rd}=R_r i_{rd}+\dfrac{d\Phi_{rd}}{dt}-\omega_r\Phi_{rq} \\ V_{rq}=R_r i_{rq}+\dfrac{d\Phi_{rq}}{dt}+\omega_r\Phi_{rd} \end{cases} \tag{6}$$

$$\begin{cases} \Phi_s=L_s i_{sd}+M_{sr} i_{rd} \\ 0=L_s i_{sq}+M_{sr} i_{rq} \\ \Phi_{rd}=L_r i_{rd}+M_{sr} i_{sd} \\ \Phi_{rq}=L_r i_{rq}+M_{sr} i_{sq} \end{cases} \tag{7}$$

$$Cem=-P\frac{Msr}{Ls}\Phi s\ irq \tag{8}$$

The active and reactive stator power in the Park reference, are written:

$$\begin{cases} P=v_{sd}i_{sd}+v_{sq}i_{sq} \\ Q=v_{sq}i_{sd}-v_{sd}i_{sq} \end{cases} \tag{9}$$

According to FOC, this system of equations can be simplified as:

$$\begin{cases} P=v_s i_{sq} \\ Q=v_s i_{sd} \end{cases} \tag{10}$$

$$\begin{cases} i_{sd}=\dfrac{V_s}{\omega_s L_s}-\dfrac{Msr}{L_s}.i_{rd} \\ i_{sq}=-\dfrac{Msr}{L_s}.i_{rq} \end{cases} \tag{11}$$

$$\begin{cases} P=-\dfrac{V_s M_{sr}}{L_s}i_{rq} \\ Q=-\dfrac{V_s M_{sr}}{L_s}i_{rd}+\dfrac{V_s^2}{L_s\omega_s} \end{cases} \tag{12}$$

$$\begin{cases} \Phi_{rd}=\left(L_r-\dfrac{M_{sr}^2}{L_s}\right)i_{rd}+\dfrac{M_{sr}V_s}{\omega_s L_s} \\ \Phi_{rq}=\left(L_r-\dfrac{M_{sr}^2}{L_s}\right)i_{rq} \end{cases} \tag{13}$$

$$\begin{cases} V_{rd}=R_r i_{rd}+\left(L_r-\dfrac{M_{sr}^2}{L_s}\right)\dfrac{di_{rd}}{dt}-g\omega_s\left(L_r-\dfrac{M_{sr}^2}{L_s}\right)i_{rq} \\ V_{rq}=R_r i_{rq}+\left(L_r-\dfrac{M_{sr}^2}{L_s}\right)\dfrac{di_{rq}}{dt}+g\omega_s\left(L_r-\dfrac{M_{sr}^2}{L_s}\right)i_{rd}+g\dfrac{M_{sr}V_s}{L_s} \end{cases} \tag{14}$$

III. CONTROL OF ACTIVE AND REACTIVE POWER OF DFIM

In this FOC in open loop we neither measured nor estimated. The decoupling is due to voltages and currents which are evaluated using transient equations of the machine [4][5]. This method is favored with microprocessors, but it is very sensitive to parameter variations of the machine.

This method in DFIM; the voltages are calculated by using power equations according to the following equations [4].

$$\begin{cases} V_{dr}=g\omega_s\dfrac{\left(L_r-\dfrac{L_m^2}{L_s}\right)}{\dfrac{V_sL_m}{L_s}}*P-\left(\dfrac{R_r\left(L_r-\dfrac{L_m^2}{L_s}\right)}{\dfrac{V_sL_m}{L_s}}p\right)*Q+\left(\dfrac{R_rV_s}{\omega_sL_m}+\left(L_r-\dfrac{L_m^2}{L_s}\right)\dfrac{V_s}{\omega_sL_m}p\right) \\ V_{qr}=-\left(\dfrac{R_r+\left(L_r-\dfrac{L_m^2}{L_s}\right)p}{\dfrac{V_sL_m}{L_s}}\right)*P-g\omega_s\dfrac{\left(L_r-\dfrac{L_m^2}{L_s}\right)}{\dfrac{V_sL_m}{L_s}}*Q+g\omega_s\left(L_r-\dfrac{L_m^2}{L_s}\right)\dfrac{V_s}{\omega_sL_m} \end{cases} \tag{15}$$

In this method, we power is controlled using two cascade controllers, the first is for power control, the second is for current control, the coupling terms appeared after this last, fig.3.

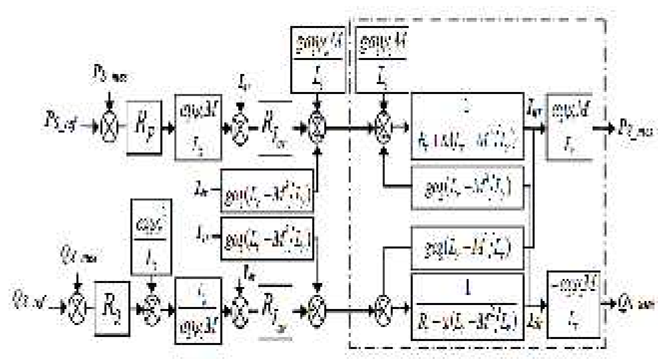

Fig. 3 Control scheme of DFIM

The blocks R_P and R_Q represent active and reactive power regulators a, and $R_{i_{dr}}$ and $R_{i_{qr}}$ are the direct and quadrateu current rotor regulators respectively.

The aim of these regulators is to obtain high dynamic performances in terms of reference tracking, sensitivity to perturbations and robustness. To realize these objectives, two types of regulators are studied and compared: Proportional Integral and RST controller based on pole placement theory [7]. The synthesis of Proportional-integral controller is achieved by the classical method of pole compensation and will not be detailed afterwards. The RST controller synthesis is detailed below.

IV. RST CONTROL

We use the field oriented control with RST regulator. This control technique is conducted to improve the performance of the command (Performing active and reactive power reference tracking; Efficient disturbance rejection; Parametric robustness) [9] [10].

The principle is based on solving the Bezout equation which leads to the identification of the polynomials R, S and T [11].

A. *RST controller synthesis*

The block-diagram of a system with its RST controller is presented on figure 4.

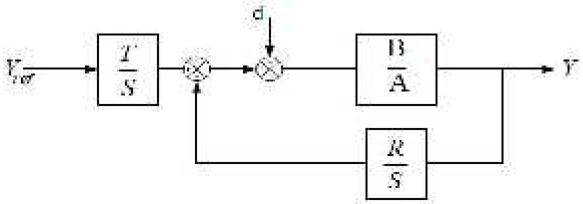

Fig. 4 Block diagram of the RST controller.

With A, B, R, S and T are polynomials of the "s" variable for continuous systems or "z" in the case of discrete systems [10].

The transfer-function of the regulated system is:

$$y = \frac{BT}{AS+BR} \cdot y_{ref} + \frac{RB}{AS+BR} \cdot b \tag{16}$$

By applying the Bezout equation, we put :

$$D = A.S + B.R \tag{17}$$

In our case the control systems are systems of first order (for rotor currents or stator powers). we choose a strictly proper regulator. So if A is a polynomial of n degree (deg(A)=n) we must have :

$$\begin{aligned} &degre\,(S) = degre\,(R) + 1 \\ &degre\,(R) = degre\,(A) \\ &degre\,(D) = 2.degre\,(R) + 1 \end{aligned} \tag{18}$$

In our case:

$$\begin{cases} A = a_1 s + a_0 \\ B = b_0 \\ D = d_3 s^3 + d_2 s^2 + d_1 s + d_0 \\ R = r_1 s + r_0 \\ S = s_2 s^2 + s_1 s + s_0 \end{cases} \tag{19}$$

According to the robust pole placement strategy, the polynomial is written as:

$$\begin{aligned} D &= C \cdot F = (s - P_c) \cdot (s - P_f)^2 \\ &= \left(s + \frac{1}{T_c}\right) \cdot \left(s + \frac{1}{T_f}\right)^2 \end{aligned} \tag{20}$$

Where C is the command polynomial and F is the filtering polynomial.

$P_c = -\frac{1}{T_c}$ is the pole of C with T_c as control horizon;

$P_f = -\frac{1}{T_f}$ double pole of the polynomial filter horizon and T_f as filtering horizon [12].

Perturbations are generally considered as piecewise constant. *d* can then be modeled by a step input. To obtain good disturbance rejections, the final value theorem indicate that the term $\frac{AS}{AS+BR}$ must tend towards zero:

$$\lim_{s \to 0} s \cdot \frac{AS}{AS+BR} \cdot \frac{d}{s} = 0 \tag{21}$$

To obtain a good stability in steady-state, we must have D(0) ≠ 0 and respect relation (21). 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:

$$\begin{bmatrix} d_3 \\ d_2 \\ d_1 \\ d_0 \end{bmatrix} = \begin{bmatrix} a_1 & 0 & 0 & 0 \\ 0 & a_1 & 0 & 0 \\ 0 & a_0 & b_0 & 0 \\ 0 & 0 & 0 & b_0 \end{bmatrix} \begin{bmatrix} s_2 \\ s_1 \\ r_1 \\ r_0 \end{bmatrix} \tag{22}$$

In order to determine the coefficients of T, we consider that in steady state y must be equal to y_{ref} so:

$$\lim_{s \to 0} \frac{BT}{AS+BR} = 1 \tag{23}$$

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

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

$$\frac{BT}{AS+BR} = \frac{BT}{D} = \frac{BhF}{CF} = \frac{BF}{C} \tag{24}$$

As: T=R(0)we conclude that : $h = \frac{R(0)}{F(0)}$ (25)

B. *Application of the RST command to the DFIG*

The terms A and B are expressed by

$$\begin{cases} A = L_s R_r + s L_r L_s \sigma \\ B = L_m V_s \end{cases} \tag{26}$$

In the case of our model of DFIG, one obtains:

$$\begin{cases} A_{PQ}(s) = a_{PQ1} \cdot s + a_{PQ0} \\ B_{PQ}(s) = b_{PQ0} \\ R_{PQ}(s) = r_{PQ1} \cdot s + r_{PQ0} \\ S_{PQ}(s) = s_{PQ2} \cdot s^2 + s_{PQ1} \cdot s^1 + + s_{PQ0} \\ D_{PQ}(s) = d_{PQ3} \cdot s^3 + d_{PQ2} \cdot s^2 + d_{PQ1} \cdot s + d_{PQ0} \end{cases} \quad (27)$$

The choice of these poles is based on the poles of the open loop. The role of the control pole is to accelerate the system, and is generally chosen three to five times greater than the pole of A. In our case:

$$\begin{cases} P_c = 5 \cdot P_a = -5 \frac{L_s R_r}{(L_r L_s - L_m^2)} \\ T_c = -\frac{1}{P_c} = -\frac{(L_r L_s - L_m^2)}{5 L_s R_r} \end{cases} \quad (28)$$

We choose T_c three times higher than T_f, so :

$$T_c = -\frac{1}{3} \frac{(L_r L_s - L_m^2)}{5 L_s R_r} \quad (29)$$

The polynomial D is written as:

$$D_{PQ} = \left(s + \frac{1}{T_c}\right) \cdot \left(s + \frac{1}{T_f}\right)^2 = \left(s + \frac{1}{T_c}\right) \cdot \left(s^2 + \frac{2s}{T_f} + \frac{1}{T_f^2}\right)$$
$$= s^3 + \left(\frac{2}{T_f} + \frac{1}{T_c}\right) s^2 + \left(\frac{1}{T_f^2} + \frac{2}{T_c T_f}\right) s + \frac{1}{T_c T_f^2} \quad (30)$$

By identifying equations (18) and (20), we deduce the coefficients of polynomial D which are linked to the coefficients of R and S by the Sylvester matrix. Thus, we can determine the parameters of the RST controller as follows:

$$\begin{cases} d_3 = a_1 s_2 \to s_2 = \frac{d_3}{a_1} \\ d_2 = a_1 s_1 \to s_1 = \frac{d_2}{a_1} \\ d_1 = a_0 s_1 + b_0 r_1 \to r_1 = \frac{d_1 - a_0 s}{b_0} \\ d_0 = b_0 r_0 \to r_0 = \frac{d_0}{b_0} \\ T = r_0 \end{cases} \quad (31)$$

V. SIMULATION RESULTS

To analyze the system and compare efficiently the two proposed controllers, a set of simulation tests have been performed for 0.8 s, using Matlab/Simulink environment. The PWM inverter on the rotor side of the DFIG is controlled. Both controllers PI and RST are tested and compared by two different criteria, namely, reference tracking, and robustness by varying the parameters of the system. DFIG and the turbine parameters used in the simulation are listed in table I and II, respectively.

The block diagram of indirect command by RST regulator of the active and reactive power and rotor currents represented in the figure (5). The idea is to replace the four PI regulators of FOC by RST regulators.

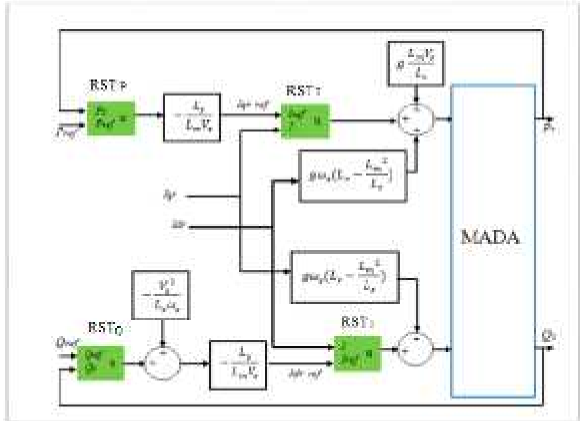

Fig. 5 Global scheme of FOC control with RST regulators

A. *La poursuite de référence*

In this test, the simulation was done while keeping the same parameters of the GADA. It provides echelons of active and reactive power to observe the behavior of this command. The results obtained are illustrated in Figure (6)

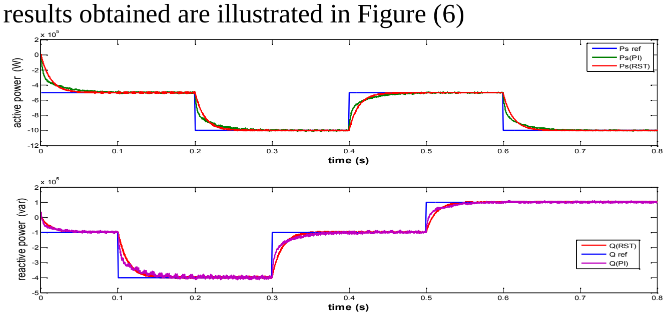

Fig. 6 Simulation results tests of reference tracking using PI and RST regulators.

The simulation results obtained show good performances in following the active and reactive power.

When the reference when changes, it is noticed that the oscillations decrease and the response time is smaller in the case of RST regulator.

A. *Robustness*

In order to test the robustness of PI and RST regulators, the value of the resistor of rotor is 1.5 of its nominal value, the stator and rotor winding values increased by 10% of their nominal values, the value of the mutual is decreased by 10 % of its nominal value.

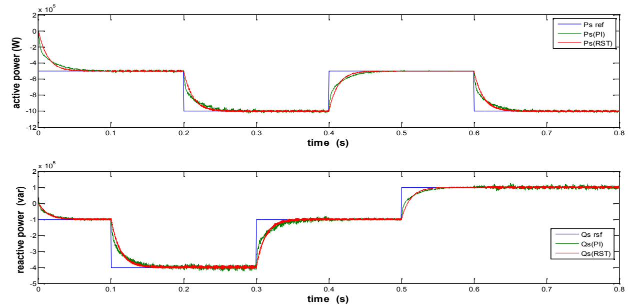

Fig. 7 Influence of rotor resistor variation *Rr* of +50 %.

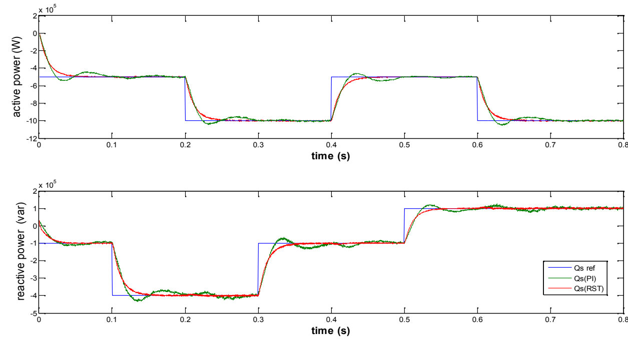

Fig.8 Influence of stator winding variation *Ls* of +10 %.

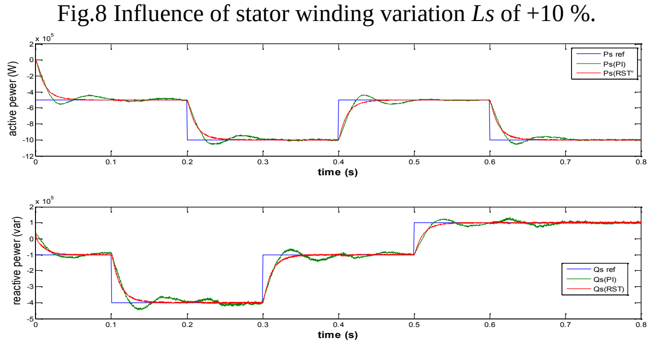

Fig. 9 Influence of rotor winding variation *Lr* of +10 %.

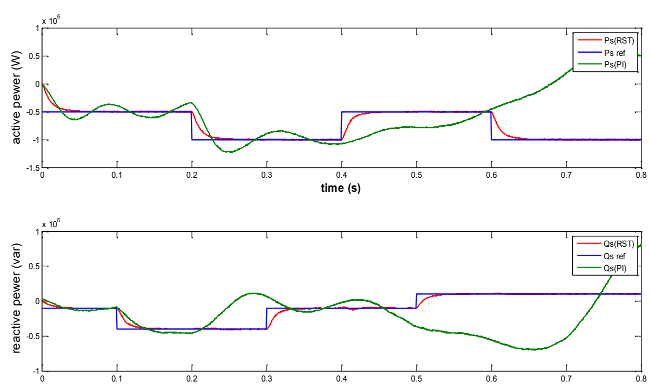

Fig. 10 Influence of mutual winding variation *Lm* of -10 %.

The comparisons between the two controllers' show that the RST presents good performances, but PI controller performances are deteriorate.

VI. Conclusion

This work enabled us to study FOC of DFIG which makes it possible to have a decoupling and an independent control of the active and reactive power. Then we studied the WECS. Firstly, the regulation is made with classical proportional-integral (PI). Secondly, is with polynomial RST.

Results show correct performances of the controller in term of reference tracking and disturbance rejection even under some uncertainties of electrical parameters of the generator. These results are very important in renewable energy application because, generally, the electrical parameter such as the rotor resistance varies with the temperature, the inductance may change with the aging of the motor. These situations involve need of more robust controllers. These studies prove that the RST controller can offer satisfactory performances.

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APPENDIX

Table 1. Parameters of DFIM

Symbol	**Value**
Rated Power PN	1.5 MW
Stator resistance Rs	0.012 Ω
Rotor resistance Rr	0.021 Ω
Stator inductance Ls	0.0137 H
Rotor inductance Lr	0.0136 H
Mutual inductance Lm	0.0135 H
The friction coefficient fr	0.0024 N.m.s1
Slip g	0.03
Pole Pairs p	2

Table 2. Parameters of Turbine

Symbol	**Value**
Radius of the wind turbine R	35.25 m
Gear box G	90
inertia J	1000 kg.m ^{2}
Surface swept by rotor S	$\pi \cdot R^2$ m ^{2}
Air density ρ	1.22 kg/ m ^{3}

Table 3. Parameters of Feed

Symbol	**Value**
Stator rated voltage Vs	*398 / 690 V*
Rated frequency stator f	*50 Hz*
Rotor rated voltage Vr	*225 / 389 V*
Rated frequency stator f2	*14 Hz*