Optimization of the Robust Control of the Doubly-Fed Induction Generator used in the Centralized Production of Wind Energy

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***Abstract* – The objective of this article is the study of the Doubly Fed Induction Generator (DFIG) used in the production of wind energy as well as the optimization of the quality of the energy produced by wind turbine by manipulating the heights of the active and reactive power as needed. We use the approach of the control of the converters AC-DC-AC. The optimization of the energy produced by a machine with double feeding will be performed by a group of regulators PI and mathematical equations according to Park's transformation. The control used will be the vectorial control in power of the (DFIG). In our study, the frequency is constant and the vectorial control in power consists in making DFIG undergo a power instruction with the best electric dynamics and taking into consideration the limit of the frequency conversion of switches of power converters. The converter of the machine must ensure the regulation of the exit tension of the rectifier. However, the converter on the side of the electric grid makes it possible to ensure the regulation of tension of continuous bus while absorbing the current which must be as sinusoidal as possible, with the possibility of setting the power factor. The results are made in Matlab-Simulink.**

***Keywords* – Continuous Bus, Control, Converters (AC-DC-AC), DFIG, Park, Power Factor, Wind Turbine.**

I. INTRODUCTION

Today, studies turn on the improvement of the aero generator as well as on the conversion chain of wind energy into electric energy which can be exploited by the grid. The first wind turbines implement asynchronous generator which is linked to the vanes via a gear box, work at a fixed speed and are directly connected to the grid. The most recent systems are inclined towards the variable speed in order to maximize the power picked up from the wind with the insertion of electronics between the generator and the grid [1]. The technique of vectorial control is based on a law of control leading to a characteristic of setting which is similar to that of a machine with a continuous current operating with a separate excitement [3]. In the case of the vectorial control of the DFIG, the task will be to master energy exchanges and notably the active and reactive power transfers sent on the grid [2-5]. In this study, the referential (dq) is adjusted on stator flux [4] and the control concerns, of course, the powers sent on the grid, therefore the side of the stator (generator Convention). Consequently, the rotor will be considered as a tool of control (receptor convention) [7]. However, the coupling existing between the electric variables and parameters makes the control very difficult. To overcome these problems, we adopt vectorial control [9]. It is possible to solve this problem by using methods based on a non linear control, notably the control with orientation of stator flux [6-8]. Also, in order to improve the previous control, an indirect control will be introduced so that the control will be performed in a linear way by controlling the stator powers and the rotor currents separately [6].

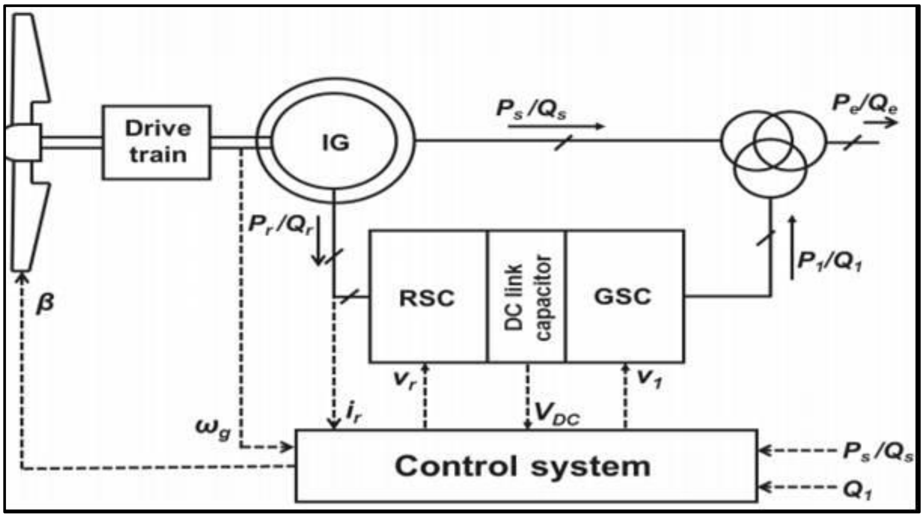

Fig.1. DFIG wind turbine model

Where,
PWM: pulse width modulation;
GSC: Grid side converter;
RSC: Rotor side converter.

The general scheme of electrical energy's generation from the wind power on the basis of using doubly-fed induction generator is shown in figure 1. The stator is considered to be connected to the grid directly whereas the rotor is connected to it via back-to-back converter [4]. Rotor side converter is a current regulate-voltage source inverter [5] and grid side converter is a PWM inverter. The induction-machine model presented in this section may also be used to simulate the operation of a doubly fed induction machine. In addition to the machine model, a model of the power converter and its associated controls must also be included. The controller of a DFIG is typically configured to allow the adjustment of the rotation speed of the wind turbine.

II. Modeling of the Turbine

The modeling of the turbine consists in modeling the power and the couple developed by the turbine and which are given by the following relations:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 \, c_p \qquad (1)$$

$$C = \frac{P_m}{\Omega} = \frac{\rho\pi R^3 \, v^2}{2} c_t \qquad (2)$$

In general, the articles present the coefficient c_p by graphics [2], The latter is different from one turbine to the other [4] and is usually provided by the manufacturer. However, it can be subjected to mathematical approximation [7]. The modeling can be done with a polynomial approximation of the n order [8].

$$c_p\,(\lambda) = a_0 + \sum_{i=1}^{n} a_i \, \lambda_i \qquad (3)$$

The model of the mechanical power developed by the turbine [9]:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 \, c_p(\lambda) \qquad (4)$$

III. Modeling of the DFIG: Control of Active and Reactive Powers

The electric equations of (DFIG) in the bearing dq may be written:

$$V_{ds} = R_s \, i_{ds} - \frac{d}{dt}\phi_{ds} + \omega_s \, \varphi_{qs} \qquad (5)$$

$$V_{qs} = R_s \, i_{qs} + \frac{d}{dt}\phi_{qs} + \omega_s \, \varphi_{ds} \qquad (6)$$

$$V_{dr} = R_r \, i_{dr} + \frac{d}{dt}\phi_{dr} + \omega_r \, \varphi_{qr} \qquad (7)$$

$$V_{qr} = R_r \, i_{qr} + \frac{d}{dt}\phi_{qr} - \omega_r \, \varphi_{dr} \qquad (8)$$

By aligning the stator vector flux with the axis d, we can write:

$$\phi_{ds} = \phi_s \qquad V_{ds} = 0 \qquad (9)$$

$$\phi_{qs} = 0 \qquad V_{qs} = V_s \qquad (10)$$

The electromagnetic couple becomes:

$$C_{em} = -p\frac{M}{L_s}(\phi_s . i_{qr}) \qquad (11)$$

The expression of stator powers, active P_s and reactive Q_s becomes:

$$\begin{cases} P_s = -V_s \frac{M}{L_s} i_{qr} \\ Q_S = V_s \frac{\phi_s}{L_s} - V_s \frac{M}{L_s} i_{dr} \end{cases} \qquad (12), (13)$$

IV. Application of the Indirect Control in Open Loop

The diagram of the whole bloc of the machine's control is illustrated on the figure 2. In this method, the cutting out is performed at the level of output of regulators in rotor currents without any return to the system by imposing the tensions of reference V_{rd}^* and V_{rq}^* which are convenient. Hence, the control by overlapped loop which controls the current i_r is applied to the (DFIG) for security reasons in use. Moreover, the indirect control in open loop allows the separate control of currents i_{rd} and i_{rq} in closed loop and the powers P_s and Q_s, in opened loop [9].

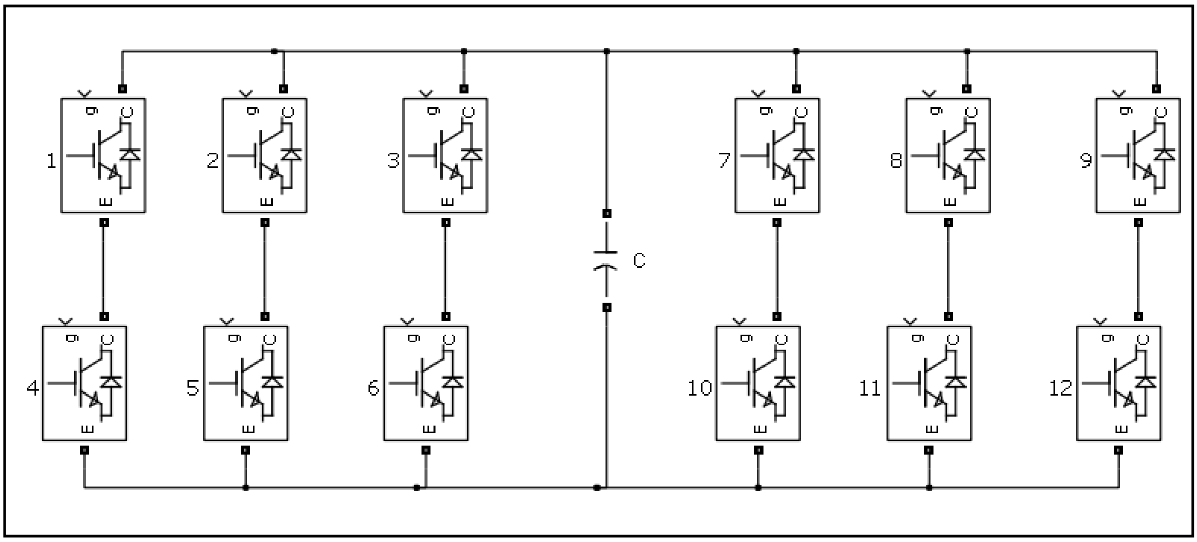

Fig.2. Simulink model of the converters used with DFIG in wind energy and DC-link voltage between them

The indices d and q indicates the direct and quadrature axis components of the reference frame and r and s indicates rotor and stator quantities, respectively. All quantities in (5), (6), (7) and (8) are functions of time [14-15].

β: Blades pitch angle (degree)
Ω_t : Rotation speed of the turbine (rad/s)
R: Radius of the swept area by the blades (m)
λ : Tip speed ratio (dimensionless)
ρ : Air density (kg/m^3)
S : Surface crossed by the wind (m^2)
v : Speed of wind (m/s)
Φ : Flux linkage (Weber)
φ : Flux linkage (Weber)
R : Resistance (Ω)
ω_r and ω_s : Stator and rotor electrical angular velocity (rad/s)

The converter grid side is used to regulate the voltage of the DC bus capacitor. In addition, this model allows using grid side converter to generate or absorb reactive power [10]. The main purpose of the Rotor side converter is to maintain the rotor speed constant irrespective of the wind speed and also the control strategy has been implemented to control the active power and reactive power flow of the machine using the rotor current components [13].

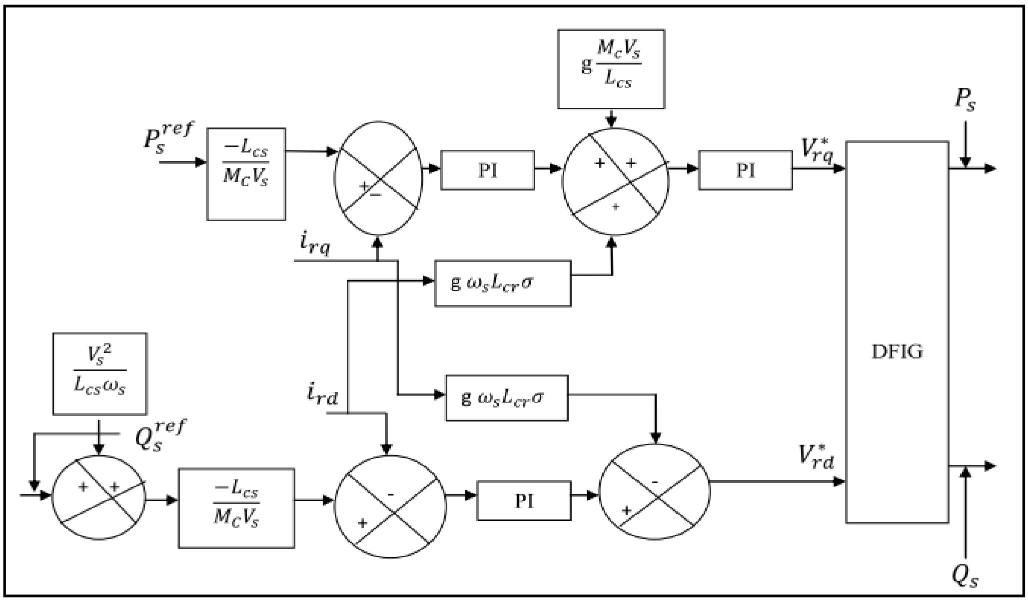

Fig.3. Open loop control

To improve the previous command, we introduce an algorithm of indirect command of active and reactive powers of the DFIG, according to the rotor current, hence the terms of coupling $g\omega_s L_r \sigma\, i_{qr}$ and $g\omega_s L_r \sigma\, i_{dr}$ considered as being not unimportant disturbances, and will be compensated [11]. The command, so decoupled, is realized by means of regulators proportional integral (PI). There are two methods of decoupling in opened loop and in closed loop to control the stator powers. In our study we are interested in indirect control in opened loop [12].

g : Rotor slip (dimensionless)
σ : Leakage flux total coefficient (dimensionless)
L_r: Rotor inductance (Henry)
M : Mutual inductance (Henry)

Table I: The machine parameters

Parameters	Values
Nominal power	1,5 MW
Nominal voltage	240 kV
Nominal frequency	50 Hz
Stator inductance	0.0060 H
Rotor inductance	0.0060 H

V. THE SIMULATION RESULTS WITH MATLAB/SIMULINK AND DISCUSSIONS

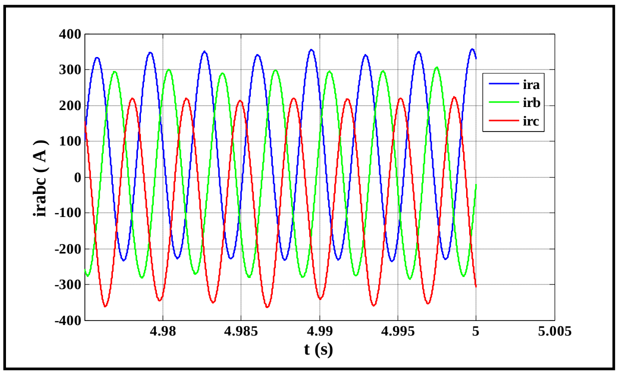

Fig.4. Rotor current irabc (A) according to time (s)

These curves show the evolution of rotor currents; these wave forms depend on the speed of the wind. The frequency of rotor currents depends on the sliding of the machine. For a zero sliding (synchronous mode), the rotor currents are constant. By performing a zoom on the rotor currents, we notice a dephasing between the latters. This can be explained by providing and/or absorbing the rotor reactive power according to the dephasing. These rotor currents vary between $(-400\ \mathrm{A})$ and $(+400\ \mathrm{A})$, in a simulation time of $5\ \mathrm{s}$, which coincides with the high-power wind turbines that uses DFIG.

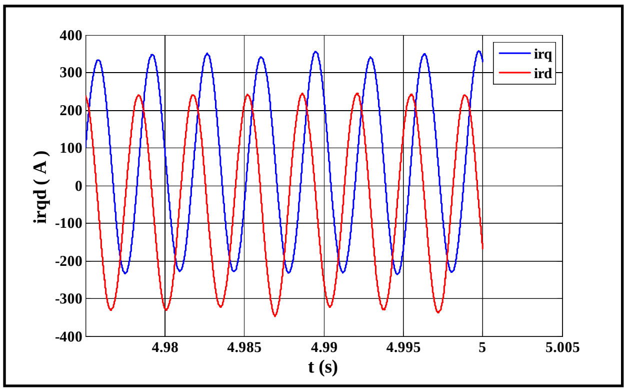

Fig.5. Rotor current irqd (A) according to time (s)

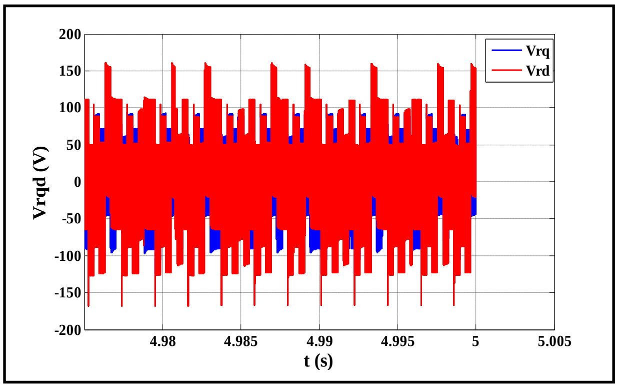

Fig.6. Rotor voltage Vrqd (V) according to time (s)

This curve shows the evolution of rotor voltages; these wave forms depend on the speed of the wind. The frequency of rotor voltages depends on the sliding of the machine. For a zero sliding (synchronous mode), the rotor voltages are constant. By performing a zoom on the rotor voltages, we notice a dephasing between the latters. This can be explained by providing and/or absorbing the rotor reactive power according to the dephasing. These curves reach a maximum of 150 V in a simulation time of 5 s.

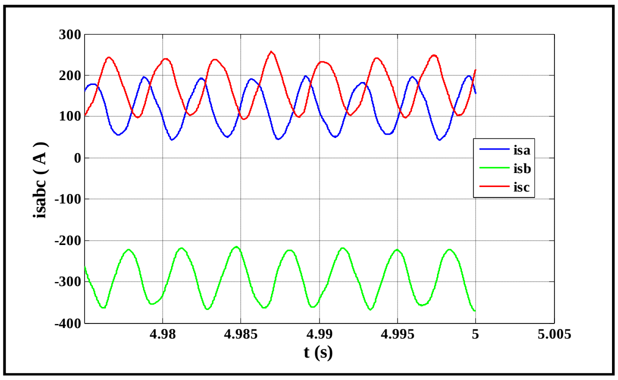

Fig.7. Stator current isabc (A) according to time (s)

The form of the wave of stator currents is linked to that of the stator active power and of the stator reactive power. This means that the stator active power is sent from the generator towards the grid. It is worth noting that the forms of the current are independent of the profile of the wind's speed. These curves vary in a sinusoidal way also there is some phase shift because of the constant of $\frac{2\pi}{3}$ which exists in the park's transformation, the value of these currents reached a maximum of 350 A and a minimum of 65 A.

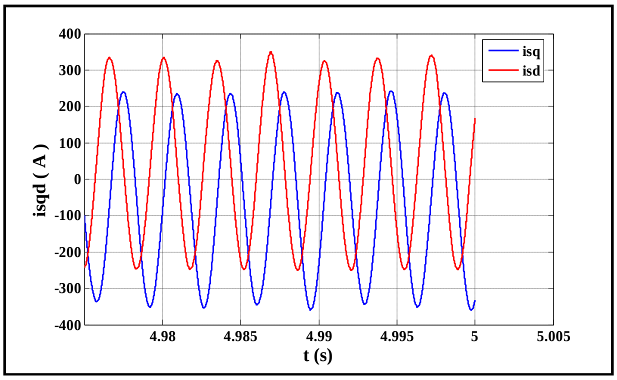

Fig.8. Stator current isqd (A) according to time (s)

The stator currents depend on the variation of the stator active power and the stator reactive power of the machine. These forms of waves depend on the speed of the rotation of the machine as well as on the rotor power according to the absorption or the supply. These curves vary in a sinusoidal way, and the value of this curves reached 320 A.

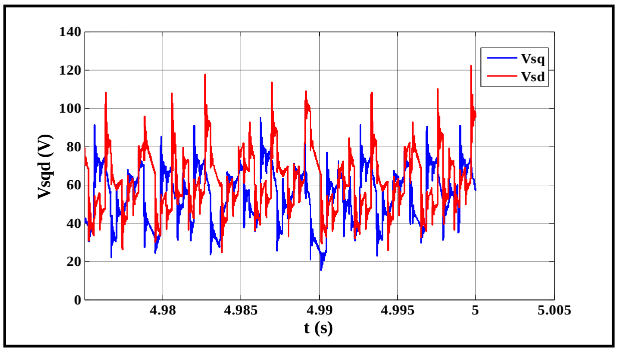

Fig.9. Stator voltage Vsqd (V) according to time (s)

We can remark that the stator voltages is equal to that of the grid. It should be noted that the wave forms of the tension are independent of the profile of the wind's speed. The stator voltages V_{sd} reaches the value of 120 V and a minimum of 30 V, and V_{sq} reaches the value of 90 V and a minimum of 19 V.

The mechanical speed on the slow tree multiplied by the coefficient of multiplying leads to a rapid mechanical couple on the asynchronous machine, and then to the increase in the speed of its rotation. We notice that the generator speed varies between $(-913\ \mathrm{rad/s})$ and $(-922\ \mathrm{rad/s})$ what is adequate with a DFIG used in wind turbines.

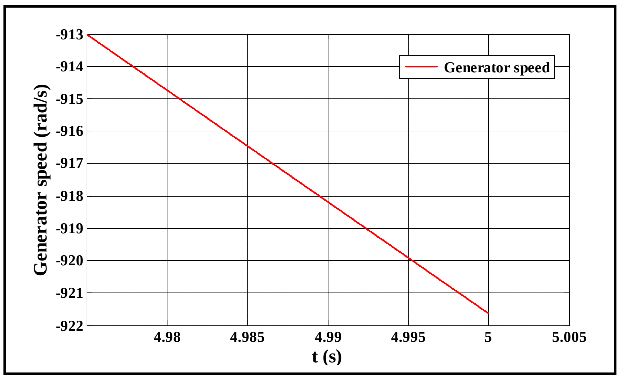

Fig.10. Generator speed (rad/s) according to time (s)

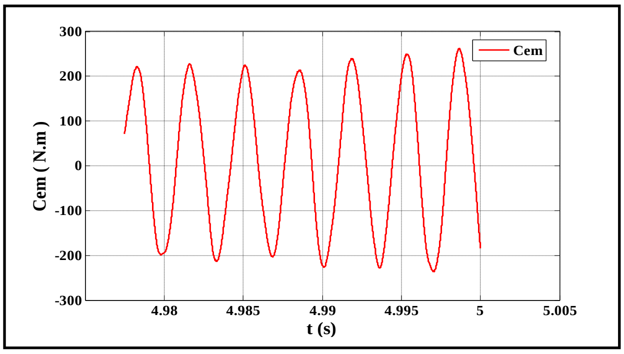

Fig.11. Electromagnetic couple Cem (N.m) according to time (s)

The electromagnetic torque depends on the temporal evolution of the rotation speed of (DFIG). It varies in a sinusoidal way because it follows the evolution of machine with double feeding; we notice that the electromagnetic couples vary between $(-200\ \mathrm{N.m})$ and $(+200\ \mathrm{N.m})$.

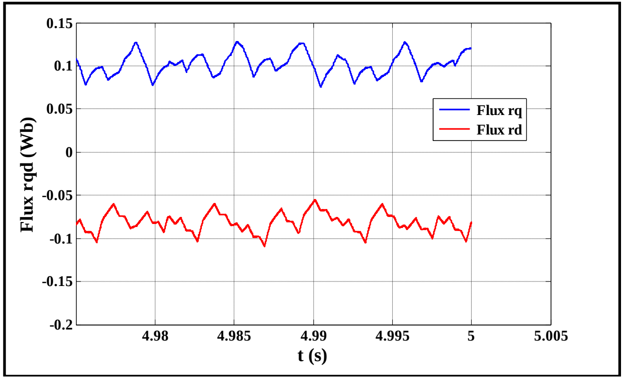

Fig.12. Curve rotor flux (Wb) according to time (s)

The rotor flux depends only on the rotor currents i_{rd} and i_{rq} and it adapts to the variation of these two latters. The rotor flux in the reference frame dq is fixed in 0.1 Wb.

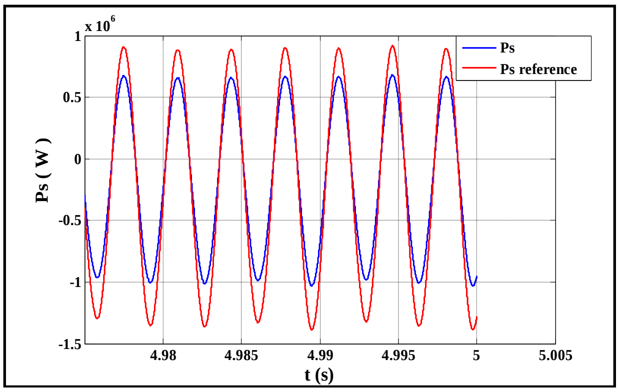

Fig.13. The active stator power Ps (W) according to time (s)

The active stator power varies in a sinusoidal way. It depends on the variation of the stator tension Vs and the rotor current i_{qr}. Also, it is well controlled by the indirect control in opened loop of the asynchronous machine with double feeding; the active stator power is in the order of 1 MW.

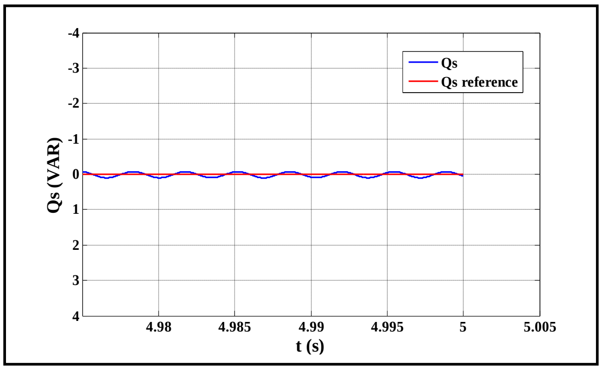

Fig.14. The reactive stator power (VAR) according to time (s)

The reactive stator power shows the robustness of the indirect control of the asynchronous machine with double feeding because it's a zero value allows the diminution of the losses on the grid as well as the increase in the power factor, which is good for the optimization of the energy which is injected in the grid. The reactive stator power is in the order of 0 VAR.

VI. CONCLUSION

From the results obtained, we can conclude that the use of the indirect control in opened loop is well adapted for this kind of system. We were inspired by the modeling of the asynchronous generator with double feeding in order to apply a separate control of active and reactive powers. This approach makes it possible to set the factor of power of the installation and therefore, to obtain better performances. This solution involves numerous advantages on the technical and economic levels, especially with regard to configurations based on cage asynchronous machine and synchronous machine.

REFERENCES

[1] T. Ackermann and Soder, L. « An Overview of Wind Energy-Status 2002 ». Renewable and Sustainable Energy Reviews 6(1-2), 67-127 (2002).
[2] GE Wind Energy. GE Wind brochure: http://www.gepower.com/prod_serv/products/wind_turbines/en/index.html.
[3] T. Burton, D. Sharpe, N. Jenkins and E. Bossanyi, Wind Energy Handbook. John Wiley&Sons, Ltd, 2001.
[4] W. L. Kling and J. G. Slootweg, « Wind Turbines as Power Plants». in Proceeding of the IEEE/Cigré workshop on Wind Power and the impacts on Power Systems, 17-18 June 2002, Oslo, Norway.
[5] L. Xu and C. Wei, « Torque and Reactive Power Control of a Doubly Fed Induction Machine by Position Sensorless Scheme». IEEE Trans, Industry Application, vol. 31, no. 3, pp. 636-642, May/June 1995.
[6] A.Alesina, M.Venturini, « Intrinsic Amplitude Limits and Optimum Design of 9 Switches Direct PWM AC-AC Aonverter ». Proc. of PESC con. pp. 1284-1290, Rec. April 1988.
[7] S. HEIER, Grid Integration of Wind Energy, Conversion Systems. New-York: John Wiley & Sons Ltd (1998).
[8] X. YU, K. STRUNZ, « Combined long-term and short term access storage for sustainable energy system », 2004 IEEE Power Engineering Society General Meeting, vol.2, pp.1946-1951, 10 June 2004.
[9] Matlab-Simulink.
[10] Debiprasad P., Benedict E. L.Venkataramanan G. and Lipo T. A. “A Novel Control Strategy for the Rotor Side Control of a Doubly-Fed Induction Machine”, Proceedings of Thirty-Sixth IAS Annual Meeting Conference IEEE, Vol.3, 30 Sep.-4 Oct. 2001, pp. 1695-1702.
[11] V.Akhmatoy and H.Krudsen, “Modelling of windmill induction generator in dynamic simulation programs,” Proc. IEEE Int. Conference on Power Technology, Budapest,Hungary, paper No. 108.Aug 1999.
[12] Lucian Mihet-Popa, Frede Blaabjerg, “Wind Turbine Generator Modeling and Simulation Where Rotational Speed is the Controlled Variable”, IEEE Transactions on Industry Applications, Vol. 40.No.1,January/February 2004.
[13] Sandy Smith,Rebecca Todd and Mike Barnes “Improved Energy Conversion for Doubly- Fed Wind Generators”, Proceedings of IAS 2005, pp. 7803-9208, June 2005.
[14] R. Pena, J. C. Clare and G. M. Asher, “Doubly fed induction generator using back-to-back PWM converts and its application to variable speed wind-energy generation,” IEE Proceedings Electrical Power Application, Vol.143, pp. 231-241.1996.
[15] D. Zhou and R. Spee, “Field oriented control development for brushless doubly-fed machines,” in Proc. IEEE Industry Applications Conference, vol. 1, Oct., 6–10, 1996, pp. 304–310.

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