Sliding mode control of a doubly fed induction generator for wind energy conversion systems

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Abstract— **This work presents a sliding mode control for wind energy conversion system based on a Doubly Fed Induction Generator (DFIG). The power transfer between the stator and the network is achieved by acting on the rotor signals via a bidirectional converter. Our objective is to apply this control to command independently the active and the reactive power generated by the DFIG. Simulation results on a 10 kW DFIG system are provided to demonstrate the effectiveness and robustness of the proposed control strategy during variations of active and reactive power and machine parameters, based on software MATLAB / SIMULINK.**

*Keywords— **Doubly Fed Induction Generator, flux orientation control, sliding mode control , wind energy, active and reactive power.***

I. INTRODUCTION

Wind energy is one of the most growing uses of the renewable energy sources since it is clean and available, moreover, because of its reduced cost and improved techniques [6].

Now most wind turbines are equipped with a double-fed induction generator (DFIG) due to noticeable advantages: the variable speed generation (_30% around the synchronous speed), the decoupled control of active and reactive powers, the improvement of the power quality, and the low cost [1]. The stator of the DFIG is usually connected directly to the three-phase grid; the rotor is also connected to the grid but via a transformer and two back-to-back converters [3] "Fig.1". Usually, the rotor-side converter controls the active and reactive power and the grid side converter controls the DC-link voltage and ensures operation of the converter at a unity power factor [14].

The control of DFIG has been well developed, one of the most popular control techniques is the vector control (VC) or flux orientation control (FOC) associated with classical (PI) regulators. The active and reactive power can be regulated by separately controlling the d-axis and q-axis rotor current components. Actually the main drawback of FOC is the unstable system and sensitivity to machine parameters [4], [5].

In the area of the control of the electric machines, the research works are oriented more and more towards the application of the modern control techniques. These techniques are the fuzzy control, the adaptive control, the variable structure control etc. The aim of this paper is to apply a Variable Structure Control (VSC), called also the sliding mode control (SMC) to a DFIG [13].

In recent years, the sliding mode control (SMC) methodology has been widely used for robust control of nonlinear systems. Sliding mode control, based on the theory of variable structure systems (VSS), has attracted a lot of research on control systems for the last two decades [11]. It achieves robust control by adding a discontinuous control signal across the sliding surface, satisfying the sliding condition. [2]

The use of this control mode can be justified by the high performances required by DFIG and the robustness of the controller [15].

In this work, first, a wind turbine system is presented and its characteristics are depicted to estimate its dynamics and performances in different operating conditions. Then, a SMC of the DFIG used to control independently the active and reactive powers between the stator of and the grid is proposed and tested on a wind turbine equipped with a DFIG of 10 kW based on software MATLAB / SIMULINK™.

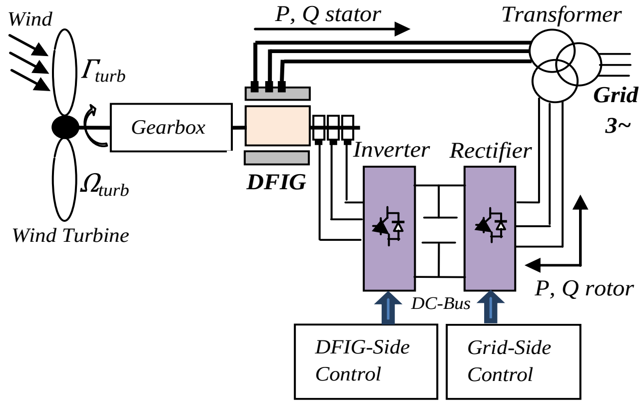

Fig.1. Schematic diagram of the system with a DFIG.

II. Model of Wind Turbine

The relation between the wind speed and mechanic power, delivered by the wind turbine, can be described by the following equation: [14]

$$P_{turb} = C_p(\lambda, \beta)\frac{\pi R^2 v^3}{2} \quad (1)$$

With:

$$\lambda = \Omega_{turb} R / v \quad (2)$$

where: C_p – power coefficient; λ– relative speed; *β*– pitch angle (*deg*); *R*– radius of turbine; *v* – wind speed (*m/s*); Ω_{turb}– turbine speed (*rd/s*); *ρ*– air density *(1.225 kg.m*$^{-3}$*)*.

According to Betz, the power coefficient C_p cannot be greater than 16/27 or 0.59 [7], [8].

The torque produced by the turbine is expressed in the following way:

$$\Gamma_{turb} = P_{turb} / \Omega_{turb} \quad (3)$$

A typical relationship between C_p and λ is shown in "Fig.2". It is clear from this figure that there is a value of *λ* for which C_p is maximized thus maximizing the power for a given wind speed. Because of the relationship between C_p and λ, as the turbine speed that gives a maximum output power.

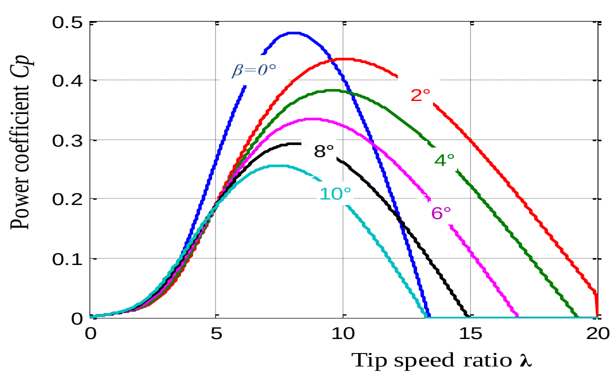

Fig. 2. Power coefficient *Cp* as a function of *β* and λ.

"Fig.3" shows the wind speed effect on the mechanical power for the 10kW turbine used in this work.

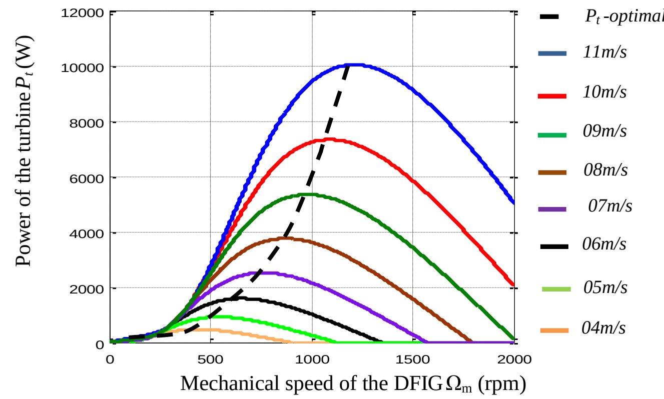

Fig.3. Power-Speed characteristics of the wind turbine.

III. Modeling of the DFIG

The dynamic model of doubly fed induction machine in *d-q* frame can be represented by the following equations: [7], [6]

A. Electrical equations:

$$\begin{cases} V_{ds} = R_s I_s + \dfrac{d\varphi_{ds}}{dt} - \omega_s \varphi_{qs} \\ V_{qs} = R_s I_{qs} + \dfrac{d\varphi_{qs}}{dt} + \omega_s \varphi_{ds} \\ V_{dr} = R_r I_{dr} + \dfrac{d\varphi_{dr}}{dt} - (\omega_s - \omega_r)\varphi_{qr} \\ V_{qr} = R_r I_{qr} + \dfrac{d\varphi_{qr}}{dt} + (\omega_s - \omega_r)\varphi_{dr} \end{cases} \quad (4)$$

B. Magnetic equations:

$$\begin{cases} \varphi_{ds} = L_s I_{ds} + M I_{dr} \\ \varphi_{qs} = L_s I_{qs} + M I_{qr} \\ \varphi_{dr} = L_r I_{dr} + M I_{ds} \\ \varphi_{qr} = L_r I_{qr} + M I_{qs} \end{cases} \quad (5)$$

C. Electromagnetic equation:

Where the electromagnetic torque Γ_{em}: can be written as a function of stator fluxes and rotor currents:

$$\Gamma_{em} = P\frac{M}{L_s}\left(I_{qr}\varphi_{ds} - I_{dr}\varphi_{qs}\right) \quad (6)$$

where: *s* / *r* are stator/rotor subscript; *V* / *I* –voltage/current; φ–flux; *R* – resistance; *M* – mutual inductance; *Lr* / *Ls* – inductance; ω_r / ω_s rotor/stator pulsation; *P* – number of the pairs of poles.

IV. Field Oriented Control of the DFIG

In order to easily control the production of electricity by the wind turbine, we will carry out an independent control of active and reactive powers by orientation of the stator flux [5], [8] and [4].

By choosing a reference frame linked to the stator flux, rotor currents will be related directly to the stator active and reactive power. An adapted control of these currents will thus permit to control the power exchanged between the stator and the grid. If the stator flux is linked to the *d*-axis of the frame "Fig.4" we have: [9], [15]

$$\varphi_{ds} = \varphi_s \;;\; \varphi_{qs} = 0 \qquad (7)$$

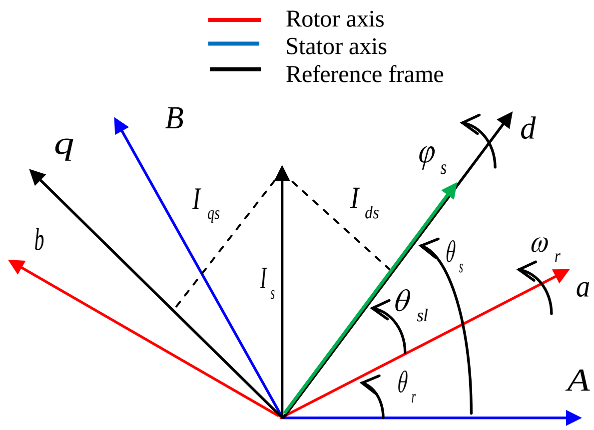

Fig.4. Diagram of the stator flux oriented with *d*-axis.

The electromagnetic torque "(6)" is then written:

$$\Gamma_{em} = p \frac{M}{L_s} I_{qr} \varphi_{ds} \qquad (8)$$

By substituting "(7)" in "(5)" the following rotor flux equations are obtained:

$$\begin{cases} \varphi_{ds} = L_s I_{ds} + M I_{dr} \\ 0 = L_s I_{qs} + M I_{qr} \end{cases} \qquad (9)$$

Using "(9)" a relation between the stator and rotor currents can be established:

$$\begin{cases} I_{ds} = -\dfrac{M}{L_s} I_{dr} + \dfrac{\varphi_s}{L_s} \\ I_{qs} = -\dfrac{M}{L_s} I_{qr} \end{cases} \qquad (11)$$

Or from the rotor currents by:

$$\begin{cases} P_s = -V_s \dfrac{M}{L_s} I_{qr} \\ Q_s = -V_s \dfrac{M}{L_s} I_{dr} + V_s \dfrac{\varphi_s}{L_s} \end{cases} \qquad (12)$$

Equations showing the relationship between the rotor currents and voltages are established and will be applied to control the generator

$$\begin{cases} V_{dr} = R_r I_{dr} + \left(L_r - \dfrac{M^2}{L_s}\right) \dfrac{dI_{dr}}{dt} - g\omega_s \left(L_r - \dfrac{M^2}{L_s}\right) I_{qr} \\ V_{qr} = R_r I_{qr} + \left(L_r - \dfrac{M^2}{L_s}\right) \dfrac{dI_{qr}}{dt} + g\omega_s \left(L_r - \dfrac{M^2}{L_s}\right) I_{dr} + g \dfrac{MV_s}{L_s} \end{cases} \qquad (13)$$

The resulting bloc diagram of the DFIG is presented in "Fig.5".

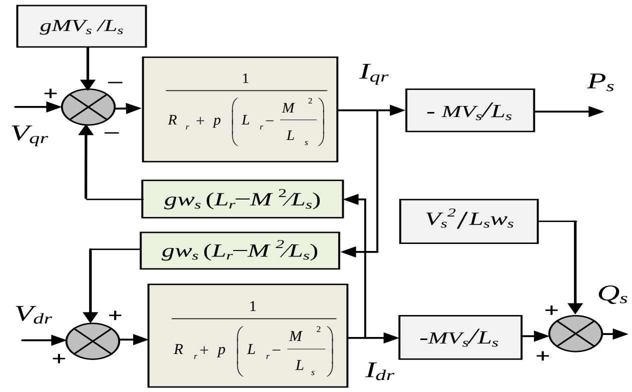

Fig. 5. Block diagram of the DFIG.

V. APPLICATION SLIDING MODE CONTROL

The sliding mode control knows a big success these last years. It is due to the implementation simplicity and the robustness with regard to the system uncertainties and the external disturbances.

The SMC consists to return the state trajectory towards the sliding surface and to develop it above, with a certain dynamics up to the equilibrium .Its design consists mainly to determine three stages. [10], [11], [13]

- *The Switching Surface Choice*

For a non-linear system represented by the following equation:

$$\dot{X} = f(X,t) + g(X,t)\,u(X,t);\; X \in R^n, u \in R \qquad (14)$$

Where: $f(X, t)$, $g(X, t)$ are two continuous and uncertain non-linear functions, supposed limited.

We take the general equation to determine the sliding surface, proposed by J.J. Slotine [12], given by:

$$S(X) = \left(\frac{d}{dt} + a\right)^{n-1} e \;;\; e = X^d - X \qquad (15)$$

where: e – error on the signal to be adjusted; a – positive coefficient; n – system order; X^d – desired signal; X – state variable of the control signal.

- *Convergence Condition*

The convergence condition is defined by the Lyapunov equation; it makes the surface attractive and invariant:

$$S(X)\dot{S}(X) \leq 0 \qquad (16)$$

- *Control Calculation*

The control algorithm is defined by the relation:

$$u = u^{eq} + u^n \qquad (17)$$

with: $$u^{n} = u^{\max} Sat\left(S(X)/\varphi\right) \quad (18)$$

$$Sat\left(S(X)/\varphi\right) = \begin{cases} sign\left(S\right) & if \quad |S| \rangle \varphi \\ S/\varphi & if \quad |S| \langle \varphi \end{cases} \quad (19)$$

where: u – control signal; u^{eq} – equivalent control signal; u^{n} – switching control term; sat ($S(X)/\varphi$) – saturation function; φ – threshold width of the saturation function.

A. Active power control

To control the power, the surface expression of the active power control has the form:

$$S(P) = (P_s^{ref} - P_s) \quad (20)$$

Taking its derivative and replacing it in the active power P_s "(11)" we get:

$$\dot{S}(P) = (\dot{P}_s^{ref} + V_s \frac{M}{L_s} \dot{I}_{qr}) \quad (21)$$

Replacing V_{qr} by $V_{qr} = V_{qr}^{eq} + V_{qr}^{n}$, the control appears clearly in the following equation:

$$\dot{S}(P) = (\dot{P}_s^{ref} + V_s \frac{M}{L_s L_r \sigma}((V_{qr}^{eq} + V_{qr}^{n}) - R_r I_{qr}) \quad (22)$$

With: $\sigma = 1 - M^2 / L_s L_r$, σ – Leakage coefficient.

During the sliding mode and in steady state, we have:

$$S(P) = 0, \quad donc \quad \dot{S}(P) = 0, \quad et \quad V_{qr}^{n} = 0$$

The equivalent control amount V_{qr}^{eq} is found from the previous equations and written as:

$$V_{qr}^{eq} = -\dot{P}_s^{ref} \frac{\sigma L_s L_r}{V_s M} + R_r I_{qr} \quad (23)$$

During the convergence mode, so that the condition $S(P)\dot{S}(P) \leq 0$ is verified, we set:

$$\dot{S}(P) = -V_s \frac{M}{\sigma L_s L_r} V_{qr}^{n} \quad (24)$$

And consequently, the switching term is given:

$$V_{qr}^{n} = KV_{qr} \; sign \; (S(P)) \quad (25)$$

To verify the system stability condition, the parameter KV_{qr} must be positive.

To reduce any possible overshoot of the reference voltage V_{qr}, it is often useful to add a Voltage limiter which is expressed by:

$$V_{qr}^{lim} = V_{qr}^{max} \; sat(P) \quad (26)$$

B. Réactive power control

To control the power, the surface expression of the reactive power control has the form:

$$S(Q) = (Q_s^{ref} - Q_s) \quad (27)$$

Taking its derivative and replacing it in the active power Q_s "(11)" we get:

$$\dot{S}(Q) = (\dot{Q}_s^{ref} - (-V_s \frac{M}{L_s} \dot{I}_{dr}) \quad (28)$$

Replacing V_{dr} by $V_{dr} = V_{dr}^{eq} + V_{dr}^{n}$, the control appears clearly in the following equation:

$$\dot{S}(Q) = (\dot{Q}_s^{ref} + V_s \frac{M}{L_s L_r \sigma}(V_{dr} - R_r I_{dr}) \quad (29)$$

During the sliding mode and in steady state, we have:

$$S(Q) = 0, \quad donc \quad \dot{S}(Q) = 0, \quad et \quad V_{dr}^{n} = 0$$

The equivalent control amount V_{dr}^{eq} is found from the previous equations and written as:

$$V_{dr}^{eq} = -\dot{Q}_s^{ref} \frac{\sigma L_s L_r}{V_s M} + R_r I_{dr} \quad (30)$$

During the convergence mode, so that the condition $S(Q)\dot{S}(Q) \leq 0$ is verified, we set:

To illustrate the control performance of SMC, sliding mode controller applied to DFIG, a block diagram of the system proposed in "Fig.6".

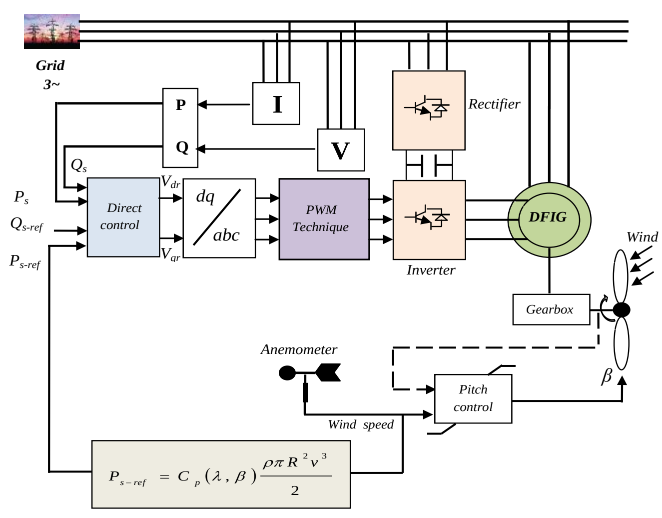

Fig.6. Schematic diagram of SMC strategy for DFIG.

VI. Validation of the Proposed Control

In this part, simulations are investigated with a 10 kW DFIG connected to a 400V/50Hz grid (appendix), by using the Matlab/Simulink. The both control strategies FOC and SMC are simulated, tested and compared in terms of power reference tracking, robustness against machine parameter variations.

According to the “Fig.7- (a) and (b)” and “Fig.8- (a) and (b)” we can see that the power references are followed by the generator both for active and reactive power.

The active power of the stator side is negative, which means that the network in this case is a receiver of the energy supplied by the DFIG, reactive power is adjusted according to the network requirements.

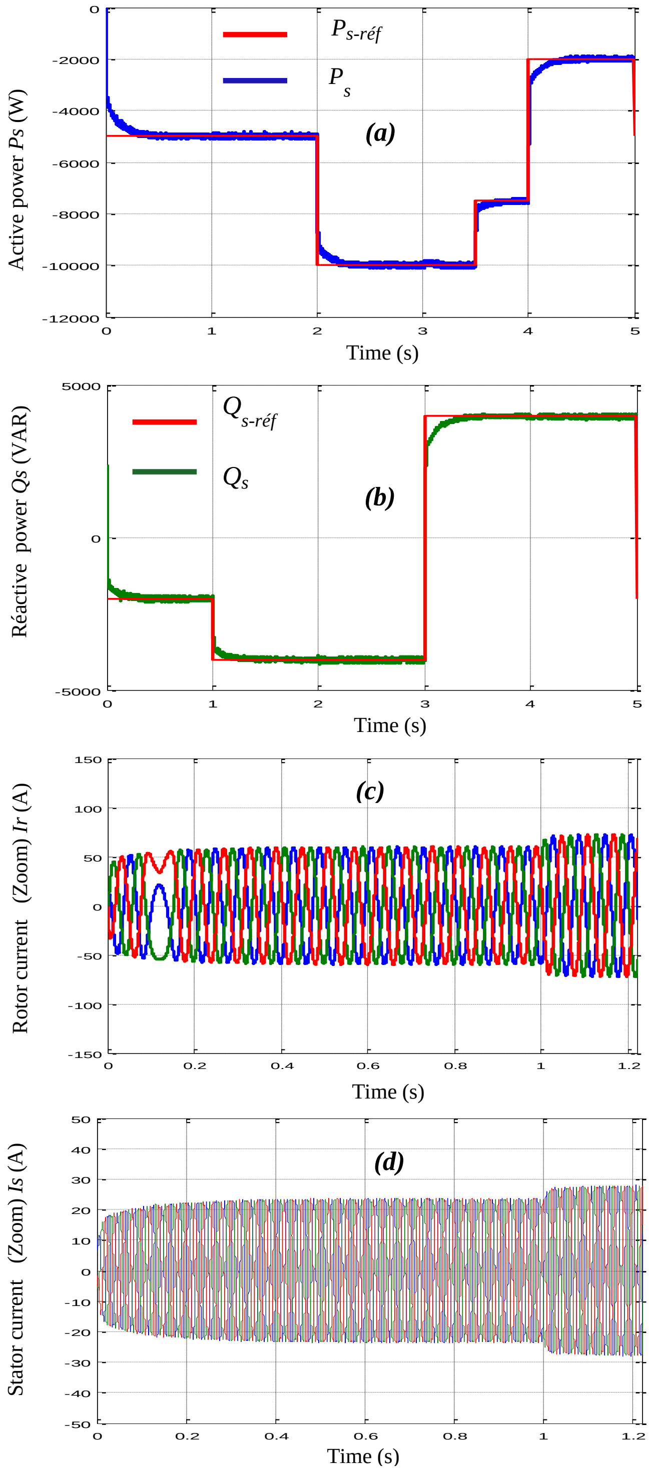

Fig. 7. System responses with conventional controller (PI).

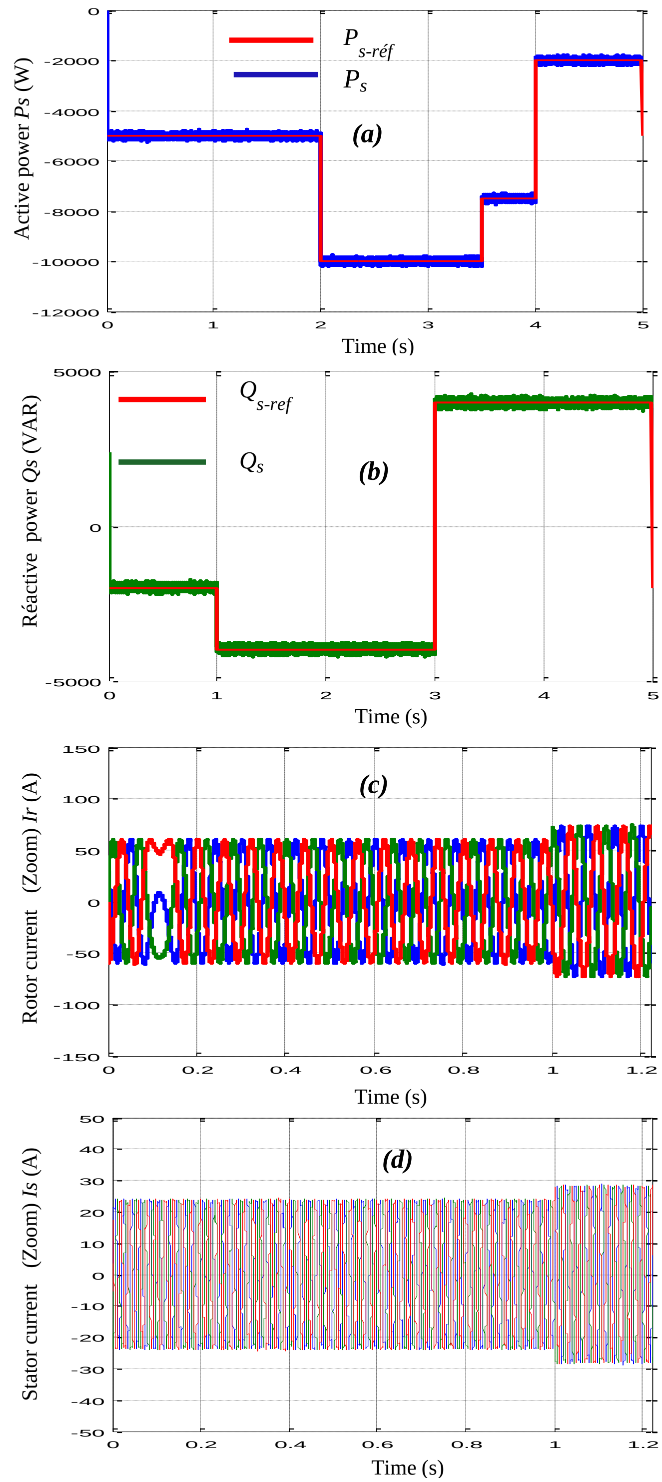

Fig.8. System responses with sliding mode controller (SMC).

The simulation results in “Fig.7-(c) and (d)” and “Fig.8-(c) and (d)” show the response of rotor and stator currents of PI controller and SMC respectively. The changeover from subsynchronous to supersynchronous speed crossing the synchronous speed in 0.12s is observed to be smooth without any transients in the rotor current waveform.

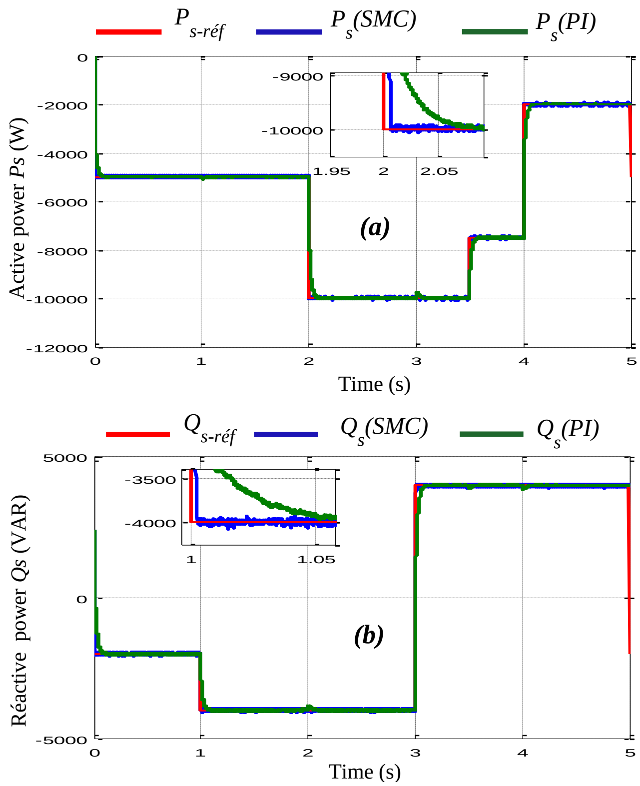

Fig.9. Response of system with 20% (L_s, L_r, M).

From the results obtained by "Fig.9- (a) and (b)" it can be seen that the control of active and reactive power by sliding mode controller provides good performance and robustness compared to PI controller.

VII. CONCLUSION

The modeling, the control and the simulation of a wind energy conversion system based on a doubly fed induction generator (DFIG) connected directly to the grid by the stator and fed by a converter on the rotor side has been presented in this paper. Our objective was the implementation of a sliding mode control method of active and reactive powers generated by the stator side of the DFIG, in order to ensure of the high performance and a better execution of the DFIG, and to make the system insensible with the external disturbances and the parametric variations. In the first step, we started with a study of modeling on the whole system. In second step, we adopted a vector control strategy in order to control statoric active and reactive power exchanged between the DFIG and the grid. In third step, the description of the classical sliding mode controller (SMC) is presented in detail.

The simulation results show the ameliorated quality of the control based on the controller by sliding mode. Through the response characteristics, we observe good performances in terms of response time and reference tracking without overshoots. Furthermore, the strong point of this control technique is the simplicity of implementation and robustness with respect to parameters variation of the DFIG.

APPENDIX

Table1. Doubly fed induction generator parameters

Rated power, P_n	10 kW
Stator rated voltage, V_s	230/400 V
Rated current, I_n	20/30A
Stator rated frequency, f	50 Hz
Stator resistance, R_s	0.455 Ω
Rotor resistance, R_r	0.19 Ω
Rotor inductance, L_s	0.07 H
Inductance rotorique ,L_r	0.0213 H
Mutual inductance, M	0.034 H
Number of pair of poles, p	2
Moment of inertia, J	0.031 kg.m^2
viscous friction, f_r	0.00114 kg.m^2/s

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