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Sliding mode Control indirect strategy of the active and reactive power for the wind turbine DFIG

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Abstract- ***In this paper, we propose a control indirect of the active and reactive power for the Doubly Fed Induction Generator (DFIG) by sliding mode controller (SMC) and compared the result by de PI controller. A detail dynamic model of a DFIG-based, wind turbine and grid-connected system is presented in the d–q-synchronous reference frame. Simulation results and improvement of the behaviour of the DFIG are presented and discussed to validate the proposed control strategy.***

Keywords - Wind, turbine, DFIG, control, PI, SMC

I. INTRODUCTION

During the last years, there was a strong penetration of the renewable resources of energy in the network of power supply. The wind power production played and will continue to play a very important role in this domain for years to come.

Wind turbines have base of the doubly fed induction generator (DFIG) undoubtedly appeared as one of the high technologies for the manufacturers of wind turbines,

Demonstrating that it is about an actual cost, Effective and a reliable solution.

This paper presents a control method for controlling the active and reactive power exchanged between the generator and the grid. The active power is controlled in order to be adapted to the wind speed in a wind energy conversion system and the reactive power control allows to get a unitary power factor between the stator and the grid.

Such an approach does not manage easily the compromise between dynamic performances and robustness or between dynamic performances and the generator energy cost.

These compromises cannot easily be respected with classical PI controllers proposed inmost DFIG control schemes. Moreover, if the controllers have bad performances in systems with DFIG such as wind energy conversion, the quality and the quantity of the generated power can be affected. It is then proposed to study the Sliding Mode Control (SMC). The two controllers are compared and results are discussed, the objective is to show that complex controllers as (SMC) can improve performances of doubly-fed induction generators in terms of reference tracking, sensibility to perturbations and parameters variations.

II. MODEL OF THE TURBINE

The model is based on the characteristics of steady state power of the turbine [1].

$$P_m = \frac{P_m}{P_{mt}} P_{mt} = C_p . P_{mt} = \frac{1}{2} C_p(\lambda)\rho\pi R^2 V_1^3 \qquad (1)$$

$$\text{With } \lambda = \frac{\Omega_1 R}{V_1} \qquad (2)$$

$\boldsymbol{\Omega_1}$: Rotation speed before multiplier.
R :rotor radius 35.25 m
ρ: air density, 1.225 kg.m^{-3}

$$C_p = f(\lambda,\beta) = C_1\left(\frac{C_1}{\lambda_i} - C_3\beta - C_4\right)\exp\left(\frac{C_5}{\lambda_i}\right) + C_6\lambda \qquad (3)$$

with : $\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3+1}$ et $C_1 = 0.5176$; $C_2 = 116$; $C_3 = 0.4$;$C_4 = 5$;$C_5 = 21$; $C_6 = 0.0068$ [1].

Characteristics of $\mathbf{C_p}$ in terms of λ for different values of the pitch angle are shown in figure 1. The maximum value of $C_p(C_{pmax} = 0.4353$) is reached of β=*2°* and λ=*10.01.* This particular value of λ is defined as the nominal value λ_{nom}[1] ,[2].

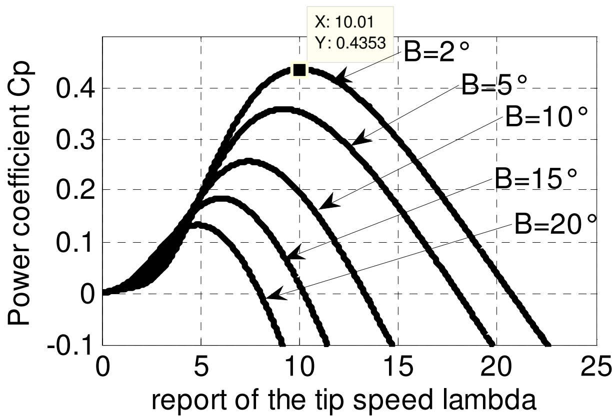

Fig.1 The power factor for different angles of stalls

III. DYNAMIC MODEL OF THE DOUBLY FED INDUCTION GENERATOR

A model always used for the doubly fed induction generator (DFIG) is the model of Park . The electrical equations of the DFIG by reference in the Park are given as follows [2], [3].

$$\begin{cases} v_{sd} = R_s i_{sd} + \frac{d\varphi_{sd}}{dt} - \omega_s\varphi_{sq} \\ v_{sq} = R_s i_{sq} + \frac{d\varphi_{sq}}{dt} + \omega_s\varphi_{sd} \end{cases} \qquad (4)$$

$$\begin{cases} v_{rd} = R_r i_{rd} + \frac{d\varphi_{rd}}{dt} - \omega_r\varphi_{rq} \\ v_{rq} = R_s i_{rq} + \frac{d\varphi_{rq}}{dt} + \omega_r\varphi_{rd} \end{cases} \qquad (5)$$

The stator and rotor flux are given as:

$$\begin{cases}\varphi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \varphi_{sq} = L_s i_{sq} + L_m i_{rq}\end{cases} \quad (6)$$

$$\begin{cases}\varphi_{rd} = L_r i_{rd} + L_m i_{sd} \\ \varphi_{rq} = L_r i_{rq} + L_m i_{sq}\end{cases} \quad (7)$$

In these equations, R_s, R_r, L_s and L_r are respectively the resistances and the inductances of the stator and the rotor windings, $\mathbf{L_m}$ is the mutual inductance.

$v_{sd}, v_{sq}, v_{rd}, v_{rq}, i_{sd}, i_{sq}, i_{rd}, i_{rq}, \varphi_{sd}, \varphi_{sq}, \varphi_{rd}, \varphi_{rq}$ are the d and q components of the stator and rotor voltages, currents and flux, whereas $\boldsymbol{\omega_r}$ is the rotor speed in electrical degree.

The electromagnetic torque is expressed as:

$$C_{em} = p(\varphi_{sd} \cdot i_{sq} - \varphi_{sq} \cdot i_{sd}) \quad (8)$$

Stator and rotor variables are both referred to the stator reference Park frame. With the following orientation, the d component of the stator flux is equal to the total flux whereas the q component of the stator flux is null figure. 2.

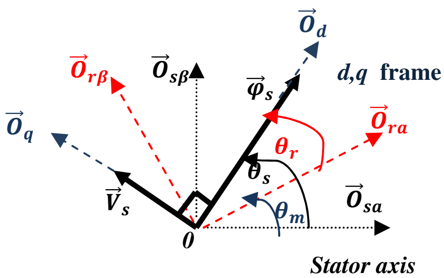

Fig.2 Determination of the electrical angles in Park reference frame

$$\varphi_{sd} = \varphi_s, \varphi_{sq} = 0 \quad (9)$$

By replacing (9) in (6) and (8), the electromagnetic torque can be given as follows:

$$C_{em} = -p\frac{L_m}{L_s} i_{rq}\varphi_{sd} \quad (10)$$

Assuming that the resistance of the stator winding R_s is neglected, and referring to the chosen reference frame, the voltage equations and the flux equations of the stator winding can be simplified in steady state as follows:

$$\begin{cases} v_{sd} = 0 \\ v_{sq} = v_s = \omega_s\varphi_s\end{cases}$$
(11)

$$\begin{cases}\varphi_{sd} = L_s i_{sd} + L_m i_{rd} \\ 0 = L_s i_{sq} + L_m i_{rq}\end{cases} \quad (12)$$

From (12), the equations linking the stator currents to the rotor currents are deduced below:

$$\begin{cases} i_{sd} = \frac{\varphi_s}{L_s} - \frac{L_m}{L_s} i_{rd} \\ i_{sq} = -\frac{L_m}{L_s} i_{rq}\end{cases} \quad (13)$$

The active and reactive powers at the stator side are defined as:

$$\begin{cases} P_s = v_{sd} i_{sd} + v_{sq} i_{sq} \\ Q_s = v_{sq} i_{sd} + v_{sd} i_{rq}\end{cases} \quad (14)$$

Taking into consideration the chosen reference frame, the above power equations can be written as follows:

$$\begin{cases} P_s = v_s i_{sq} \\ Q_s = v_s i_{sd}\end{cases} \quad (15)$$

Replacing the stator currents by their expressions given in (15), the equations below are obtained:

$$\begin{cases} P_s = -v_s \frac{L_m}{L_s} i_{rq} \\ Q_s = \frac{v_s\varphi_s}{L_s} - \frac{v_s L_m}{L_s} i_{rd}\end{cases} \quad (16)$$

The block diagram of the DFIG model in Park reference frame is depicted in figure 3, assuming a constant stator voltage (vs).

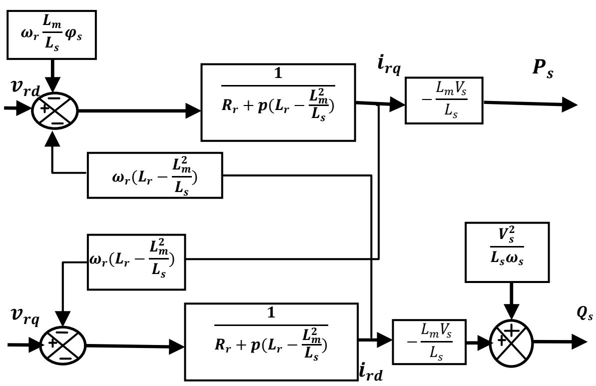

Fig.3 Block diagram of the DFIG model

IV. SLIDING MODE CONTROL (SMC)

A sliding mode controller (SMC) is a Variable Structure Controller (VSC). Basically, a VSC includes several different continuous functions that can map plant state to a control surface, whereas switching among different functions is determined by plant state represented by a switching function. The design of control system will be demonstrated for a following nonlinear system [4]:

$$\dot{x} = f(x,t) + B(x,t).u(x,t) \quad (17)$$

Where $x \in \Re^n$ is the state vector, $(x,t) \in \Re^n$, $B(x,t) \in \Re^{n\times m}$, $\mathbf{u} \in \Re^n$ is the control vector.

From the system (18), it possible to define a set S of the state trajectories x such as:

$$S = \{x(t)|S(x,t) = 0\} \quad (18)$$

Where:

$$S(x,t) = [S_1(x,t), S_2(x,t), S_3(x,t), \dots \dots \dots, S(x,t)]^T \quad (19)$$

And $[]^{\mathbf{T}}$ denotes the transposed vector, S is called the sliding surface.

To bring the state variable to the sliding surfaces, the following two conditions have to be satisfied:

$$S(x,t) = 0 \; \dot{S}(x,t) = 0 \quad (20)$$

The control law satisfies the precedent conditions is presented in the following form:

$$\begin{cases} u_{dq} = u_{eq} + u_n \\ u_n = -K_f.\operatorname{sign}(S(x,t)) \end{cases} \quad (21)$$

Where u_{dq} is the control vector, u_{eq} is the equivalent control vector, u_n is the switching part of the control (the correction factor), K_f is the controller gain. u_{eq} can be obtained by considering the condition for the sliding regime, $S(x,t)$ The equivalent control keeps the state variable on sliding surface, once they reach it. For the defined function:

$$\operatorname{sign}(\varphi) = \begin{cases} 1, \text{if} & \varphi > 0 \\ 0, \text{if} & \varphi = 0 \\ -1, \text{if} & \varphi < 0 \end{cases} \quad (22)$$

The controller described by the equation (21) presents high robustness, insensitive to parameter fluctuations and disturbances, but it will have high-frequency switching (chattering phenomena) near the sliding surface due to sign function involved by introducing a boundary layer with width [5].

In (21) we have:

$$u_{dq} = u_{eq} - K_f.\operatorname{sign}(S(x,t)) \quad (23)$$

Consider a lyapunov function:

$$V = \frac{1}{2}s(x)^2 \quad (24)$$

If the Lyapunov theory of stability is used to ensure that SMC is attractive and invariant, the following condition has to be satisfied:

$$\dot{V} = \frac{1}{2}\frac{d}{dt}s(x)^2 \leq 0 \quad (25)$$

In this paper, we use the sliding surface proposed by J.J. Slotine [6]:

$$S(x) = \left(\frac{\partial}{\partial t} + \lambda_x\right)^{n-1} e(x) \quad (26)$$

Where $e(x)$ is the error vector ($e(x) = x^* - x$), λx is a positive coefficient, n is the system order.

V. APPLICATION OF SMC TO DFIG

The rotor currents (which are linked to active and reactive powers by equation (16), quadrature rotor current i_{qr} linked to stator active power P_s and direct rotor current i_{dr} linked to stator reactive power Q_s) have to track appropriate current references, so, a sliding mode control based on the above Park reference frame is used.

For $n = 1$ and using the equation (26) with satisfying the condition (20), replacing the rotor currents by their expressions, we can obtain the sliding surfaces representing the error between the measured and references rotor currents as follow:

$$\begin{cases} \dot{s_d} = \dot{i}_{dr}^* - \left(\frac{v_{dr}}{\sigma L_r} - \frac{R_r}{\sigma L_r} i_{dr} + \omega_r i_{qr}\right) \\ \dot{s_q} = \dot{i}_{qr}^* - \left(\frac{v_{qr}}{\sigma L_r} - \frac{R_r}{\sigma L_r} i_{qr} - \omega_r i_{qr} + \frac{M}{\sigma L_r L_s} \varphi_s \omega_r\right) \end{cases} \quad (27)$$

v_{dr} and v_{qr} will be the two components of the control vector used to constraint the system to converge to $s_{dq} = 0$ .The control vector u_{eq} is obtain by imposing $\dot{s_{dq}} = 0$ so the equivalent control components are given by the following relation:

$$u_{eq} = \begin{bmatrix} L_r \sigma \dot{i}_{dr}^* + R_r i_{dr} - L_r \sigma \omega_r i_{qr} \\ L_r \sigma \dot{i}_{qr}^* + R_r i_{qr} + L_r \sigma \omega_r i_{dr} - s\frac{M}{L_s} V_{rs} \end{bmatrix} \quad (28)$$

VI. REGULATION WITH BUCKLE OF POWER

To improve the control system the DFIG, we will introduce an additional loop control of active and reactive power in the block diagram of the control loop without power so that each axis controller contains two PI-SMC control, one to control the power and the other rotor current (figure 4) [7].

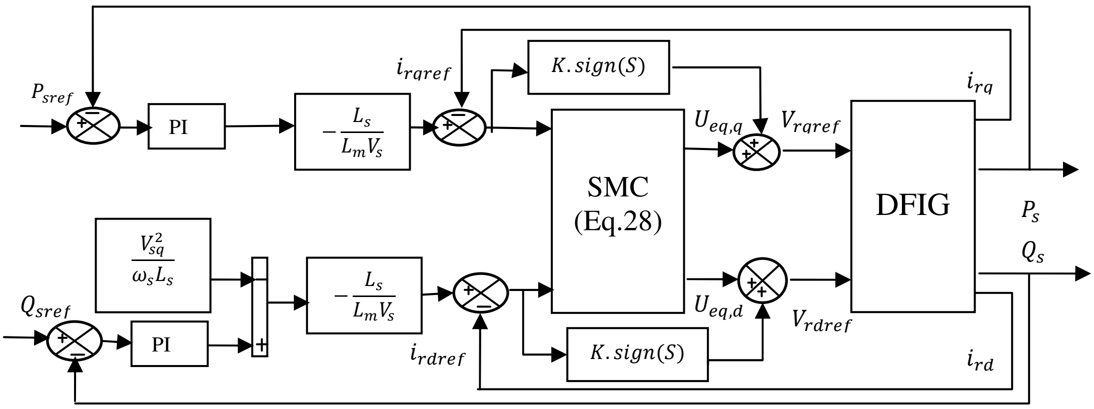

Fig.4 Schema block indirect regulation with SMC

VII. MODEL OF THE MULTIPLIER MECHANICAL PART

The mechanical party of the turbine includes three directional blades pitch and of length R. They are fixed to a drive shaft in a rotation speed Ω_t, a multiplier Connected of gain G. This multiplier causes the electric generator. We can model all the three blades as one and the same mechanical system characterized by the sum of all the mechanical characteristics.

Due to the aerodynamic blade design, we believe that the coefficient of friction with respect to the air is very small and can be neglected. Also, the speed of the turbine being very low, Friction losses will be negligible compared to the friction losses on the side of the generator. On the basis of these hypotheses, is then obtained a mechanical model consisting of two masses as shown in figure 6, the validity, relative to the complete model of the turbine, has already been verified [1], [8].

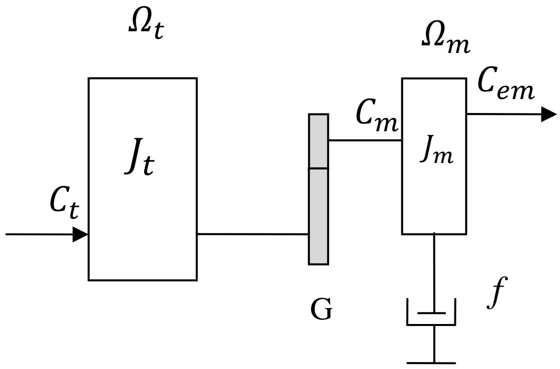

Fig.6 Mechanical model of the wind turbine

With:

· $\mathbf{J_t}$: Moment of inertia of the turbine to the equivalent inertia of the three blades of the turbine.

· $\mathbf{J_m}$: the moment of inertia of the DFIG.

· : The coefficient due to viscous friction of DFIG.

· $\mathbf{C_m}$: mechanical torque on the shaft of the DFIG.

· $\mathbf{\Omega_m}$: the rotational speed of the DFIG.

$\mathbf{C_{em}}$: the electromagnetic torque of the DFIG.

By considering that the multiplier is ideal, That is to say, the mechanical losses are negligible, it is then modelled by the following two equations:

$$C_m = \frac{C_t}{G} \quad (29)$$

$$\Omega_m = \Gamma.\Omega_t \quad (30)$$

From Figure 6, we can write the fundamental equation of dynamics of the mechanical system of the mechanical shaft DFIG by:

$$\left(\frac{J_t}{G^2} + J_m\right)\frac{d\Omega_m}{dt} + f.\Omega_m = C_m - C_{em} \quad (31)$$

The total inertia J :

$$J = \left(\frac{J_t}{G^2} + J_m\right) \quad (32)$$

VIII. CONTROL STRATEGIES OF THE TURBINE

The control strategy is to adjust the torque appearing on the tree turbine speed so as to fix a reference. To achieve this, we will use a speed control [2] ,[3].

According to equation (31) and (32):

$$\frac{d\Omega_m}{dt} = \frac{1}{J}.(C_m - f.\Omega_m - C_{em}) \quad (33)$$

The electromagnetic torque is:

$$C_{em\_ref} = PI.(\Omega_{ref} - \Omega_{mec}) \quad (34)$$
$$\Omega_{ref} = G.\Omega_{turbine\_ref} \quad (35)$$

The reference speed of the turbine corresponds to the optimum value corresponding to the speed ratio $\boldsymbol{\lambda_{pmax}}$ (fixed on the blade angle β to 2°).

$$\Omega_{turbine\_ref} = \frac{\lambda_{Cpmax}.v}{R} \quad (36)$$

The couple thus determined by the controller is used as a reference torque of the turbine model as can be seen in figure 7.

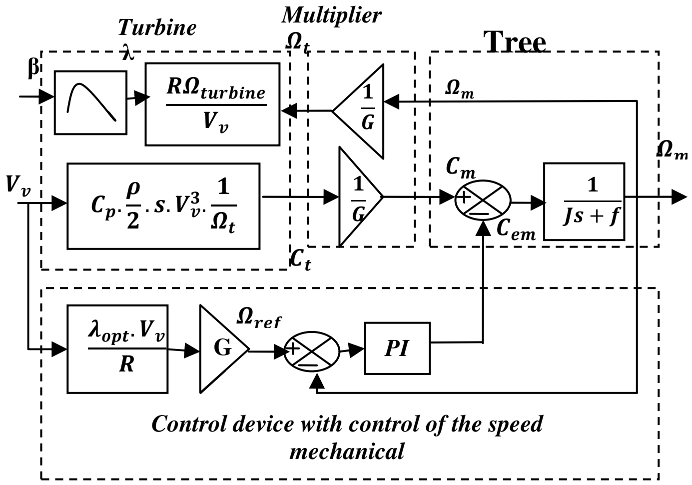

Fig.7 Block diagram of the controller with mechanical speed

IX. CORRECTION OF THE SPEED OF THE TURBINE

Different technologies can be considered markers for control of the speed; in our case we describe the PI Controller with Phase Advance.

We consider a correction proportional integral (PI):

$$C_{em\_ref} = \frac{a_1.s + a_0}{\tau.s + 1}.(\Omega_{ref} - \Omega_{mec}) \quad (37)$$

a_1, a_0 et $\boldsymbol{\tau}$ are the parameters to determine the corrector and s is the Laplace variable. It is necessary to increase the parameter a_0 to reduce the action of C_g wind torque. The natural frequency and damping coefficient are given by:

$$\omega_n = \sqrt{\frac{a_0 + f}{J.\tau}} \text{ and } \xi = \frac{\tau + J + a_1}{a_0 + f}.\frac{\omega_n}{2} \quad (38)$$

X. SIMULATION RESULTS:

The simulation is done by imposing active and reactive power reference (P_{ref}, Q_{ref}), While the machine is entailed in variable speed

$P_{ref} = \eta.P_{m\_opt}$, $Q_{ref} = 0$,

with:

η: Performance DFIG;

$\boldsymbol{P_{m\_opt}}$: The optimal mechanical power

the simulation results are given by the following figures.

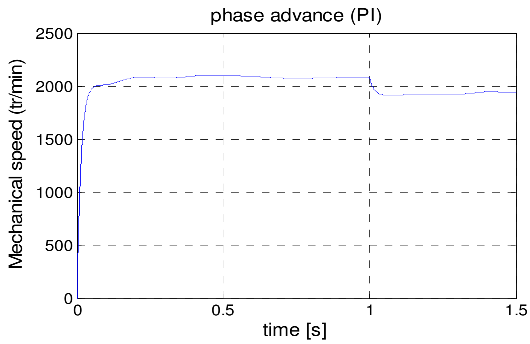

Fig.8 Mechanical speed with PIcontrol

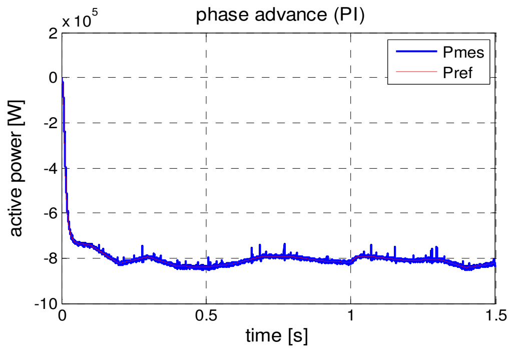

Fig.9 Electrical active power produced with PI control

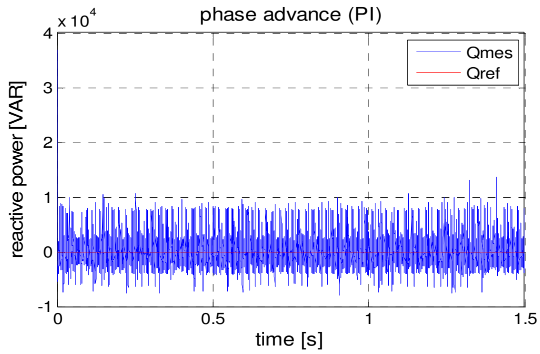

Fig.10 Electrical reactive power produced with PI control

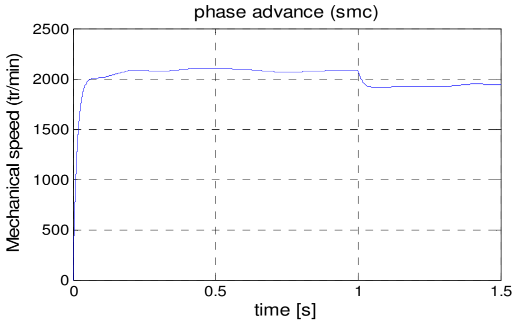

Fig.11 Mechanical speed with SMC control

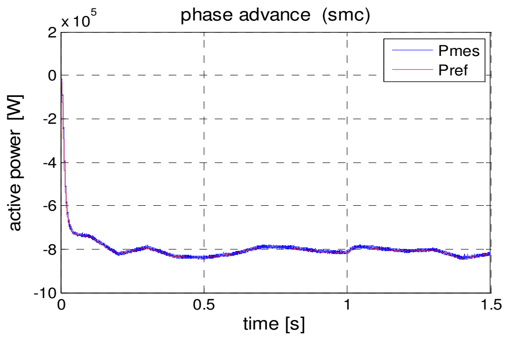

Fig.12 Electrical active power produced with SMC control

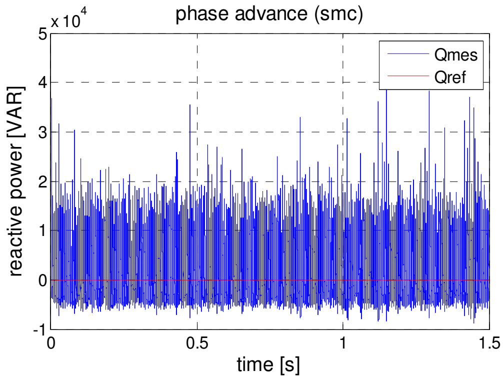

Fig.13 Electrical reactive power produced with SMC control

XI. CONCLUSION

In our work, we have established the model of the machine using its power equations in the dq axis system related to synchronization. We have also developed the method of vector control power of the machine to know the order. The stator of DFIG is directly connected to the grid and the rotor to the grid by the way of two converters. The control of the rotor side converter, which used to regulate the active and reactive powers exchanged between the generator and the grid, is applied by indirect decoupled control without power loop.

Two different controllers are synthesized and compared with simulations. Before, PI-SMC synthesis has been detailed. After, Simulations results have shown that performances are good for the controllers under ideal conditions (no perturbations and no parameters variations). The PI-SMC controller is more efficient and robust under parameters variations then PI controller.

APPENDIX

- Nominal Power =1.5(Mw)
- Stator Per Phase Resistance =0.012 (Ω)
- Rotor Per Phase Resistance=0.021 (Ω)
- Stator Leakage Inductance= $2.0372.10^{-004}$ (H)
- Rotor Leakage Inductance= $1.7507.10^{-004}$ (H)
- Magnetizing Inductance= 0.0135 (H)
- Number Of Poles Pairs=2
- Moment Of Inertia= 1000 ($Kg.M^2$)
- Friction Coefficient =0.0024

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