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The Wind energy Conversion System Using PMSG Controlled by Vector Control and SMC Strategies

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Abstract- This paper deals with dynamic simulation of a directly driven wind generator with a full scale converter as interface to the grid. Using the Permanent Magnet Synchronous Generator (PMSG), the system is controlled by two control strategies. I the first step, we have consider the vector (VC) strategy and in the second one, we have applied the sliding mode control (SMC) strategy. Simulation results investigate good performances of both proposed non linear approaches.

Keywords- Permanent Magnet Synchronous Generator, wind turbine, vector control, Sliding

1. Introduction

The research for wind power industry started to be improved in the last century, mainly due to the oil crisis and natural resources ripening. By increasing the wind turbine size the electrical power production is also increased [1]. The growing interest in wind turbine applications and the fast development of power electronics is making the manufacturers to find the most suitable and low cost technologies to put in practice.

The variable speed wind turbine with full scale frequency converter is an attractive solution for research on distributed power generation systems.

The generator used in this case can be double fed induction generator or a PMSG. The advantages of PMSG over induction generators are the high efficiency and reliability, since there is no need of external excitation, smaller in size and easy to control [1, 2]. Actually, the PMSG has become a more attractive solution to use it in variable speed wind turbine applications.

In this sector, our study will be focused on the direct driven PMSG wind turbine control. As shown in the figure 1, the generator is connected through a full scale voltage source converter; the two converters are connected by a DC link capacitor in order to have a separate control for each one. The stator- side converter (SSC) is used to control the torque and the speed. The grid-side converter (GSC) is used to control the transit power in order to keep the DC-link voltage constant. The first control strategy used in this work is field oriented control (FOC), that’s why it is necessary to know the speed and rotor position. To improve the efficiency and the reliability of the control, the nonlinear SMC strategy is applied.

This paper is organized as follows: In second section, we present a modeling of a wind power generation system based on PMSG. Third section deals with the development of the VC strategy for the back-to-back converters. Fourth section is devoted to a nonlinear SMC strategy. The two control approaches are tested with dynamic simulation using Matlab/Simulink; the results are represented in section five.

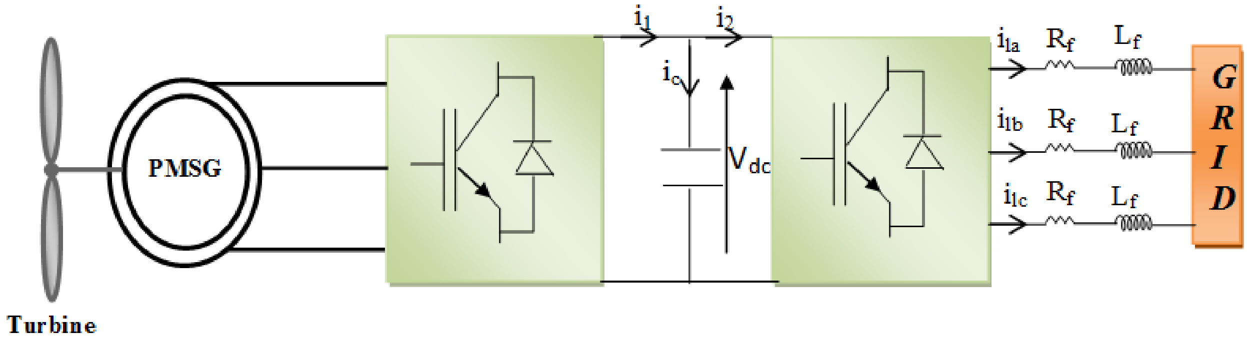


Fig. 1. The structure of the power generating system built around a PMSG

2. Modeling of the Wind Generation System

2.1. A Modeling of the Wind Turbine:

The expression of the mechanical torque developed by a wind turbine T_m is given by the following [3]:

$$T_m = \frac{1}{2}\,\rho\pi R_t^2\, C_p(\lambda,\beta)\,\frac{V^3}{\Omega_r} \quad \ldots. \quad (1)$$

such that:

$$\lambda = \frac{R_t\Omega_r}{V} \quad (2)$$

In order to simulate the wind generation system, an empirical expression of C_p (λ,β) has been considered in [4], such that:

$$C_p = [0.5 - 0.00167(\beta - 2)]\sin\left(\frac{\pi(\lambda + 0.1)}{12 - 0.3(\beta - 2)}\right) - 0.00184(\beta - 2)(\lambda - 3) \quad (3)$$

In our study, the pitch angle β is set to zero.

2.2. Modeling of the PMSG

Accounting for the hypothesis commonly considered in AC machine modeling, the electrical equations of the PMSG in a (d, q) reference frame, linked to the rotor flux vector, are [5, 6]:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} r_s & 0 \\ 0 & r_s \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} \varphi_d \\ \varphi_q \end{bmatrix} + \omega_r\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} \varphi_d \\ \varphi_q \end{bmatrix} \quad (4)$$

For a sinusoidal distribution of the back e.m.f, the flux and current phasors are linked by the following expressions:

$$\begin{cases} \varphi_d = L_d\, i_d + \varphi_r \\ \varphi_q = L_q\, i_q \end{cases} \quad (5)$$

where φ_r is the rotor flux.

Substituting equation (5) on equation (4), we obtain the following system via *Laplace* transformation:

$$\begin{cases} v_d = (r_s + L_d.p)\, i_d - e_d \\ v_q = (r_s + L_q.p)\, i_q + e_q \end{cases} \quad (6)$$

such that the direct and the quadrature back e.m.f components are expressed us:

$$\begin{cases} e_d = \omega_r L_q i_q \\ e_q = \omega_r L_d i_d + \omega_r\varphi_r \end{cases} \quad (7)$$

The stator active and reactive powers are given by the equations (8):

$$\begin{cases} P_s = \frac{3}{2}(v_d i_d + v_q i_q) \\ Q_s = \frac{3}{2}(v_q i_d - v_d i_q) \end{cases} \quad (8)$$

Under generator operation, the mechanical equation is expressed as follows:

$$T_m - T_{em} = J\frac{d\Omega_r}{dt} + K_f\Omega_r \quad (9)$$

The electromagnetic torque can be expressed, in the reference frame (d, q), as follows:

$$T_{em} = \frac{3}{2}n_p(\varphi_r - (L_q - L_d)i_d)i_q \quad (10)$$

3. PMSG Control

3.1. Stator-side Converter Control

The control of the SSC consists of two strategies:

- The Maximum Power Point Tracking, MPPT, block generates the reference speed which maximizes the power extracted from the turbine. The MPPT algorithm gives the reference torque applied to the turbine, so that, at any wind velocity below the maximum value, the extracted power is maximum [7]. The expression of the reference torque is given by:

$$T_m = \frac{1}{2}\,\rho\pi R_t^3\, C_{pmax}\,\frac{V^2}{\lambda_{opt}} \quad (11)$$

- The second strategy, in this paper, can be the vector control or the sliding mode control. This scheme will generate the stator current references and, thus, the voltage references which are compared to a reference voltage. The obtained errors are applied to bang-bang voltage regulators in order to generate the control signals for the inverter IGBTs.

3.1.1. Vector Control

The most commonly used method of control for PMSG is the field oriented control (FOC) [8]. The FOC represents the attempt to reproduce, for a PMSM, a dynamical behavior similar to that of the dc machine, characterized by the fact that developed torque is proportional to the stator current: to reach this objective, it is necessary to keep the rotor flux value constantly equal to the nominal value and to impose the direct component current ids to zero [9]. This method minimizes the losses of the generator and destroys the power factor [10]. In this case, the expression (10) of the electromagnetic torque is reduced to:

$$T_{em} = \frac{3}{2} n_p \varphi_r i_q \tag{12}$$

In that way, the torque depends only on quadrature component of the current.

Flux Control Loop

The flux loop is designed to keep the stator flux constant by acting on the current component id which his reference is imposed to zero. The open-loop transfer function is:

$$\frac{i_d}{v_{d1}} = \frac{1/r_s}{1+(L_d/r_s).p} \tag{13}$$

where

$$v_{d1} = (r_s + L_d.p)\, i_d \tag{14}$$

The chosen controller is a PI whose transfer function is:

$$C_d(p) = K_d\left(\frac{1+\tau_d.p}{p}\right) \tag{15}$$

Opting for the pole compensation technique, $\tau_s = L_d/R_s$ is determined in such a way that the stator time constant under open loop operation is compensated, which leads to the following closed-loop transfer function:

$$F_d(p) = \frac{1}{1+\frac{r_s}{K_d}.p} \tag{16}$$

K_d is chosen in such a way that the cut-off frequency in closed-loop is, at least, one decade higher than the cut-off frequency in open loop, which gives $K_d = r_s^2/L_d$

Torque Control Loop

According to equation (12), the electromagnetic torque is controlled through the control of the quadrature component current . The reference of this current will be generated from the speed control loop. The open-loop transfer function is:

$$\frac{i_q}{v_{q1}} = \frac{1/r_s}{1+(L_q/r_s).p} \tag{17}$$

where

$$v_{q1} = (r_s + L_q.p)\, i_q \tag{18}$$

The same method treated in flux control loop is considered to identify the PI controller parameters. Thus

$$\begin{cases} \tau_q = L_q/r_s \\ K_q = r_s^2/L_q \end{cases} \tag{19}$$

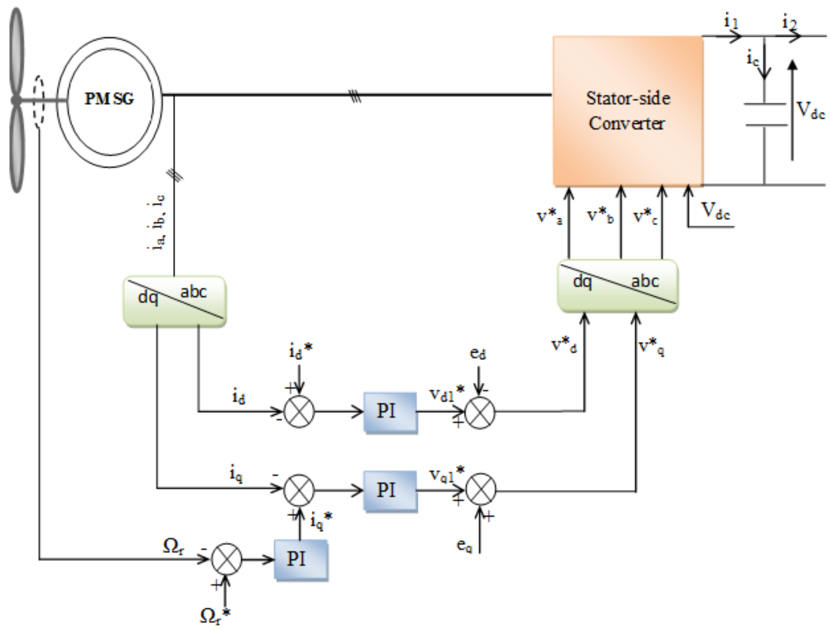


Fig. 2. Scheme of the vector control strategy implemented in the stator-side converter

Speed control loop

Let us remind the mechanical equation of the generator:

$$T_{em} = J\frac{d\Omega_r}{dt} + K_f\Omega_r \tag{20}$$

The reference speed Ω_r^* is a first-rate function as:

$$\Omega_r^* = \frac{K}{1+\tau.p} \tag{21}$$

The transfer function between i_q and Ω_r is given by:

$$\frac{i_q}{\Omega_r} = \frac{\frac{3}{2}n_p\varphi_r}{K_f+J.p} = \frac{\frac{K_t}{K_f}}{1+\frac{J}{K_f}.p} \tag{22}$$

where $K_t = \frac{3}{2}n_p\varphi_r$

and the transfer function of the PI controller is:

$$C_s(p) = K_s(\frac{1+\tau_s.p}{p}) \tag{23}$$

which leads to the following closed-loop transfer function:

$$F_s(p) = \frac{(1+\tau_s.p)}{\frac{J}{K_tK_s}.p^2+\left(\tau_s+\frac{K_f}{K_tK_s}\right).p+1} \tag{24}$$

The complete scheme of the vector control strategy applied to the stator-side converter is represented in figure 2.

3.1.2. Sliding Mode Control:

Variable structure control with SMC is one of the effective nonlinear robust control approaches since it provides system dynamics with an invariance property to uncertainties once the system dynamics are controlled in the sliding mode. The first step of SMC design is to select a sliding surface that models the desired closed-loop performance in state variable space.

Then the control should be designed such that system state trajectories are forced toward the sliding surface and stay on it.

The system state trajectory in the period of time before reaching the sliding surface is called the reaching phase. Once the system trajectory reaches the sliding surface, it stays on it and slides along it to the origin. The system trajectory sliding along the sliding surface to the origin is the sliding mode.

Let's remember the electrical and mechanical equations describing the system:

$$\begin{cases} \frac{di_d}{dt} = -\frac{r_s}{L_d}i_d + \frac{\omega_r L_q}{L_d}i_q + \frac{v_d}{L_d} \\ \frac{di_q}{dt} = -\frac{r_s}{L_q}i_q - \frac{\omega_r L_d}{L_q}i_d - \frac{\omega_r\varphi_r}{L_q} + \frac{v_q}{L_q} \\ \frac{d\Omega_r}{dt} = \frac{T_m}{J} - \frac{T_{em}}{J} - \frac{K_f}{J}\Omega_r \end{cases} \tag{25}$$

This non-linear system can be presented by the following equation [10]:

$$\dot{x}(t) = f(t,x) + g(t,x)u(t) \tag{26}$$

where

$$x(t) = (i_d \;\; i_q \;\; \Omega_r)^T \tag{27}$$

and

$$u(t) = (v_d \;\; v_q)^T \tag{28}$$

The speed control requires the current control, therefore we have defined three sliding surfaces: $S(\Omega_r)$, (i_q) , $S(i_d)$ to speed, quadrature current component and direct one respectively.

The components of the discontinuous feedback are given by:

$$u_i = \begin{cases} u_i^+(t,x), if\ S_i(x) > 0 \\ u_i^-(t,x), if\ S_i(x) < 0 \end{cases} \tag{29}$$

where $S_i(x)$ is the i-th sliding surface.

Different approaches have been proposed in the literature [10, 11, 14, 16]. A possible structure for the control of (29) is:

$$u_i = u_{ieq} + u_{iN} \tag{30}$$

where u_{ieq} is the i-th component of the equivalent control (which is continuous) who guarantees $\dot{S} = 0$ and where u_{iN} is the discontinuous term of (29), it depends in sign of S .

Using the equations (26) and (30) provides the component of the equivalent control u_{eq} , the structure of the $\dot{S}(x)$ is given by:

$$\dot{S}(x) = \frac{\partial S}{\partial x}\frac{\partial x}{\partial t} = \frac{\partial S}{\partial x}\left[f(x,t) + g(x,t).u_{eq}\right] + \frac{\partial S}{\partial x}\left[g(x,t).u_N\right] \tag{31}$$

In the steady-state, $\dot{S}(x) = 0$ hence:

$$u_{eq} = -\left[\frac{\partial S}{\partial x}.g(x,t)\right]^{-1}\left[\frac{\partial S}{\partial x}.f(x,t)\right] \tag{32}$$

u_N is chosen as a relay with constant gain so that:

$$u_N = K.sign(S(x)) \tag{33}$$

During this mode of control, the *Lyapunov* condition must be verified: the product of the surface with its derivative must be less than zero [12, 13]:

$$S(x).\dot{S}(x) < 0 \tag{34}$$

Let's start with the speed control, we have:

$$S(\Omega_r) = \Omega_r^* - \Omega_r$$

Taking into account the demonstration mentioned above, the expressions of the continuous and the discontinuous components of i_q are given by:

$$\begin{cases} i_{qeq} = \frac{k_f\Omega_r - T_m}{-n_p[\varphi_r + (L_d - L_q)i_d]} \\ i_{qN} = K_\Omega.sign\big(S(\Omega_r)\big),\;\; K_\Omega \geq 0 \end{cases} \tag{35}$$

as a result the reference of the quadrature current component is given by:

$$i_q^* = i_{qeq} + i_{qN} \tag{36}$$

$$S(i_q) = i_q^* - i_q$$

The expressions of the continuous and the discontinuous components of the voltage $v_q{}^*$ are given by:

$$\begin{cases} v_{qeq} = r_s i_q + n_p \Omega_r L_d i_d + n_p \Omega_r \varphi_r \\ v_{qN} = K_q . sign\left(S(i_q)\right),\ K_q \geq 0 \end{cases} \quad (37)$$

then, the quadrature voltage component reference is expressed as:

$$v_q{}^* = v_{qeq} + v_{qN} \quad (38)$$

$$S(i_d) = i_d{}^* - i_d$$

The expressions of the continuous and the discontinuous components of the voltage $v_q{}^*$ are given by:

$$\begin{cases} v_{deq} = r_s i_d - n_p \Omega_r L_q i_q \\ v_{dN} = K_d . sign(S(i_d)), K_d \geq 0 \end{cases} \quad (39)$$

then the expression of the reference of the direct voltage current is given by:

$$v_d{}^* = v_{deq} + v_{dN} \quad (40)$$

The Simulink scheme of sliding mode control strategy is represented in figure (3).

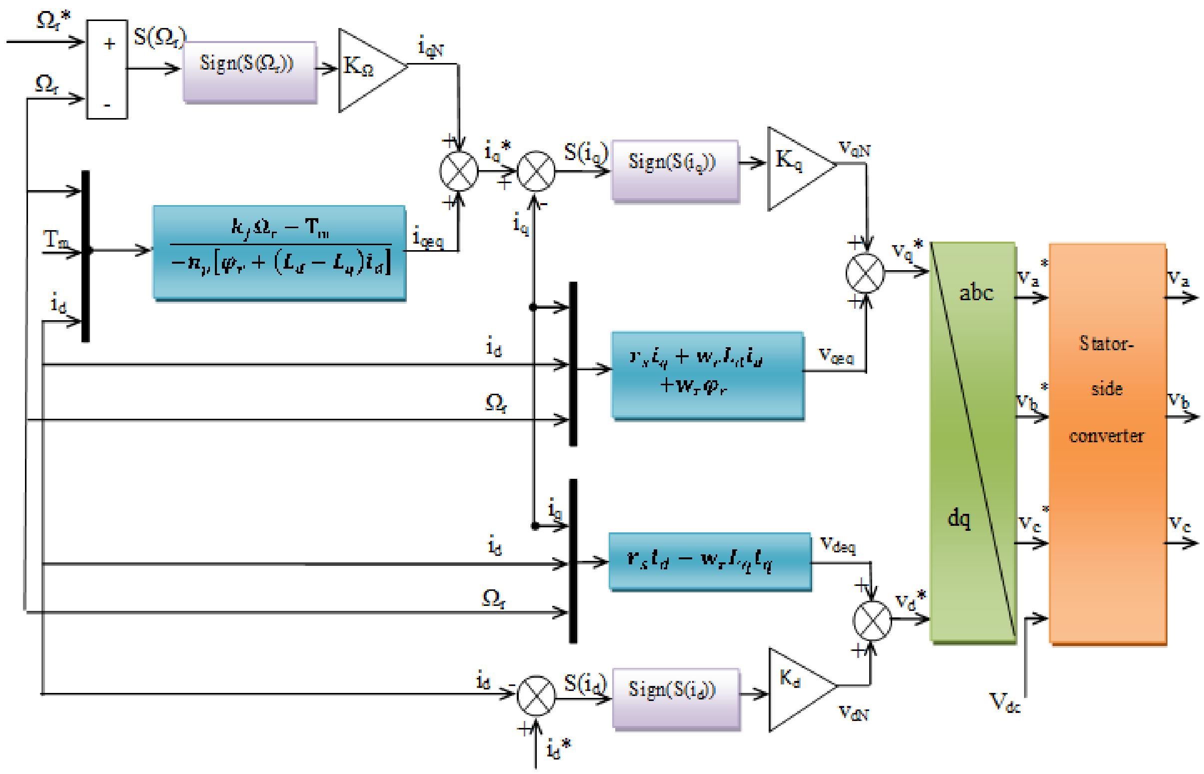


Fig. 3. Simulink scheme of Sliding Mode Control of the PMSG.

3.2. Grid-side Converter Control

The GSC is used to control the power flow in order to keep the DC-link voltage constant. The control strategy is based on the control of the DC bus voltage which kept constant and the control of line currents in order to regulate the power delivered by the stator circuits to the grid. For this, a filter was designed and implemented between the inverter and the grid.

3.2.1. Line Current Control

The grid-side electrical equations expressed in the (d, q) reference frame are the following [15]:

$$\begin{cases} v_{dm} - v_{dg} = (R_f + L_f . p)\, i_{ld} - L_f \omega i_{lq} \\ v_{qm} - v_{qg} = (R_f + L_f . p)\, i_{lq} + L_f \omega i_{ld} \end{cases} \quad (41)$$

So that, the current control is made up of three terms: compensation term, decoupling term and correction term.

The references of current components are generated from the power control loop and are expressed as follows:

$$\begin{cases} i_{ld}{}^* = \frac{P^* v_{dg} + Q^* v_{qg}}{v_{dg}^2 + v_{qg}^2} \\ i_{lq}{}^* = \frac{P^* v_{qg} - Q^* v_{dg}}{v_{dg}^2 + v_{qg}^2} \end{cases} \quad (42)$$

3.2.2. DC-voltage Control

The DC voltage can be expressed as follows:

$$V_{DC} = \frac{1}{C} \int i_c dt \quad (43)$$

where i_c is the DC bus current, it's given by:

$$i_c = i_1 - i_2 \quad (44)$$

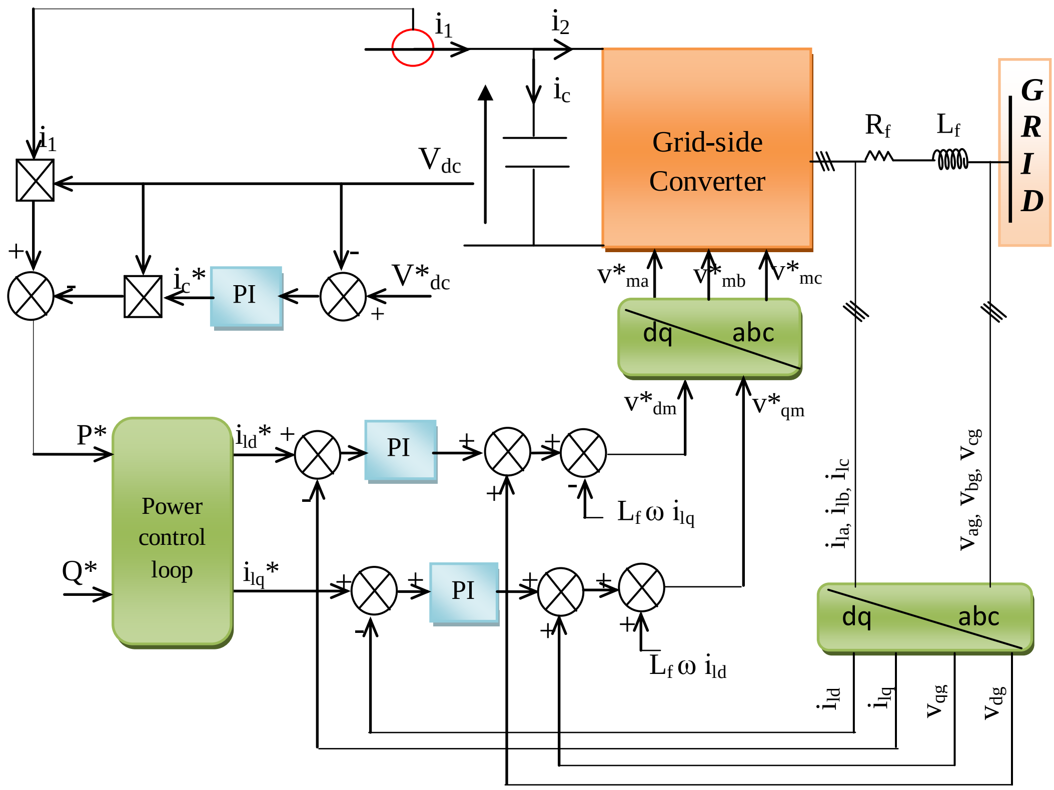


Fig. 4. Scheme of grid-side converter control strategy

where i_1 is the modulate current from the stator side and i_2 is the current delivered to the grid side as illustrated in figure (4).

Beyond losses in wind system generation, the power transported to the grid is given by:

$$P = V_{DC}.i_1 - V_{DC}.i_c \tag{45}$$

such as $V_{DC}.i_c$ is the stored power in the DC bus and $V_{DC}.i_1$ is the power delivered to the DC bus. During the simulation, the reference value of the reactive power is set to zero.

4. Simulation Results

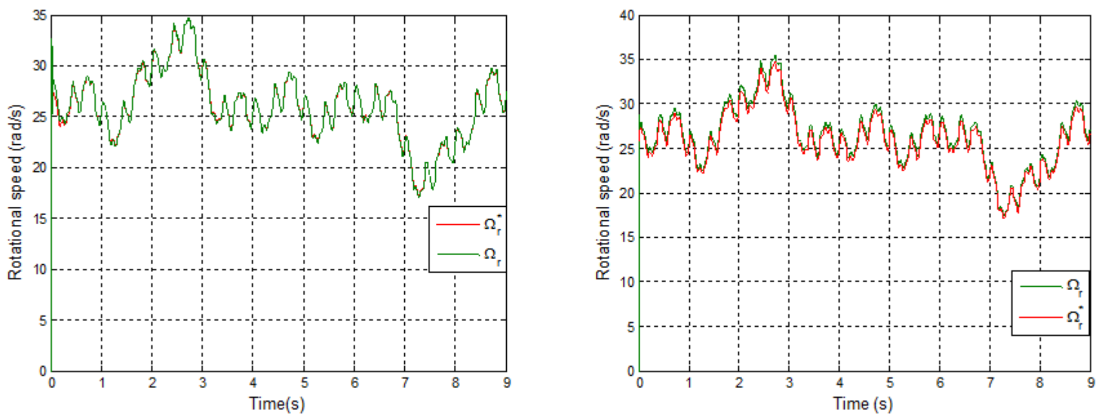
Simulation has been carried out considering a low generator with 10 pole pairs, whose stator terminals are connected to a three-phase power grid of 550V, 50Hz. The rotor of the wind turbine is directly coupled to the generator shaft.

The wind velocity is modeled by the following relation [15]:

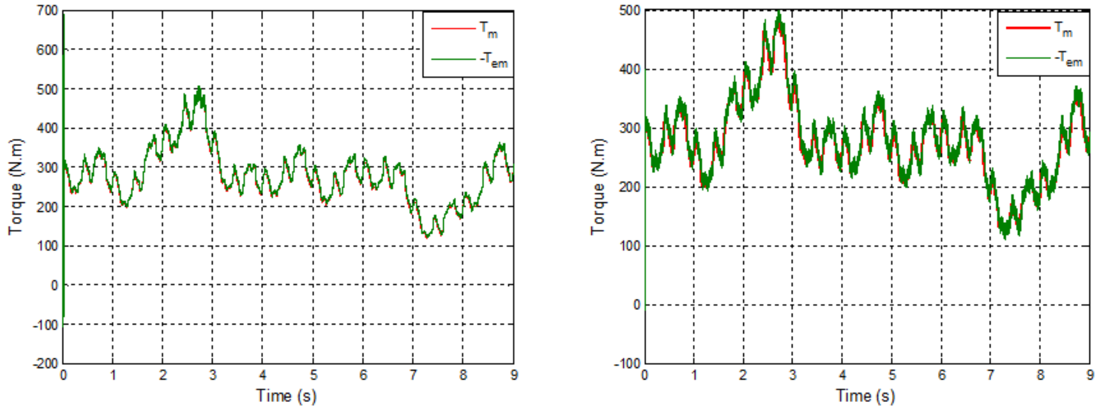
$$V = 10 + \sin(x) - 0.87\sin(3x) + 0.75\sin(5x) - 0.625\sin(10x)$$
$$+0.5\sin(30x) + 0.25\sin(50x) + 0.125\sin(100x) \tag{46}$$

where $x = \frac{2\pi}{10}$

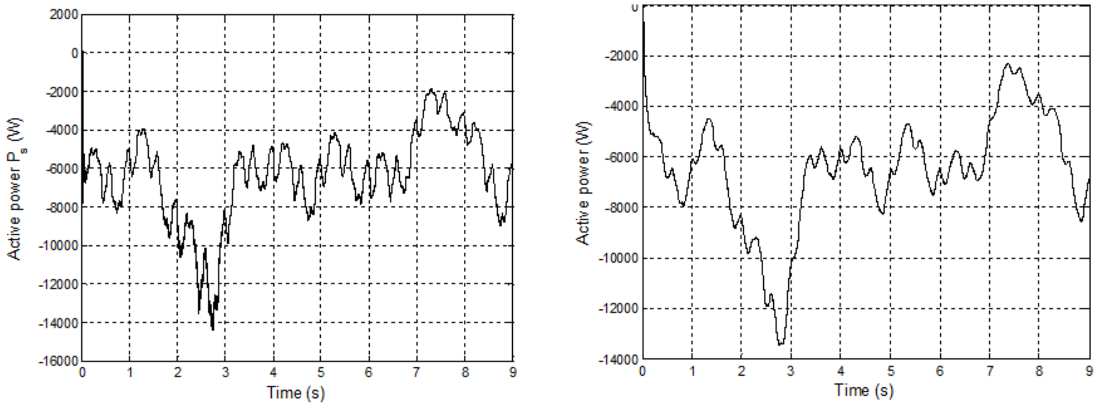
We present in the rest of this paragraph the simulation results relating to the two control strategies applied to the PMSG whose parameters are given in the appendix.



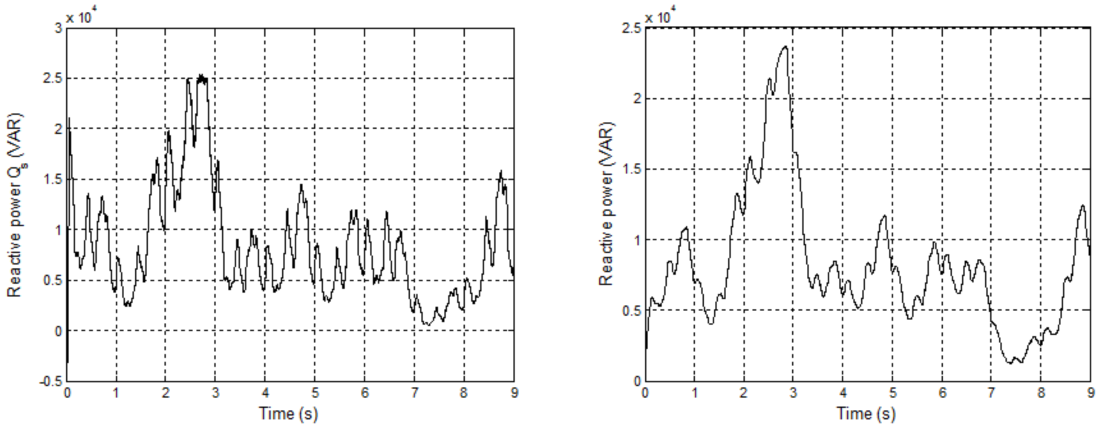
(a)


Torque (N.m)
Time (s)
Tm
-Tem
Torque (N.m)
Time (s)
Tm
-Tem

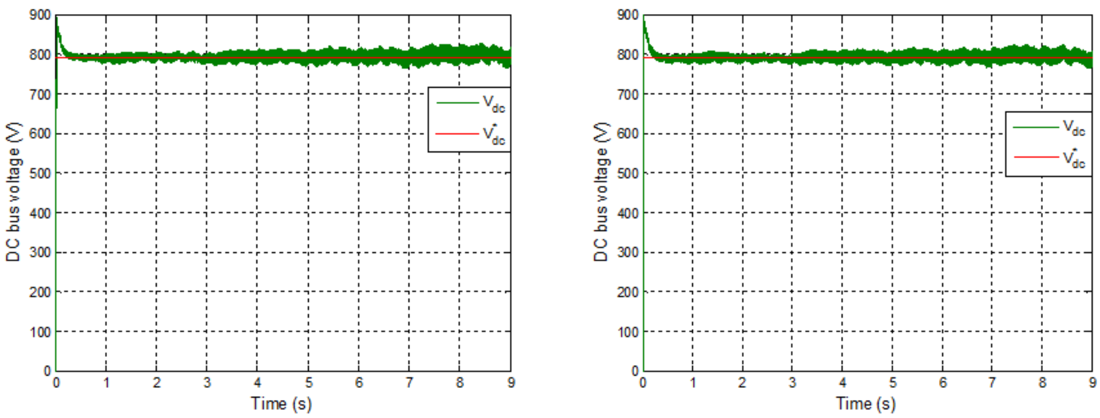
(b)


Active power Ps (W)
Time (s)
Active power (W)
Time (s)

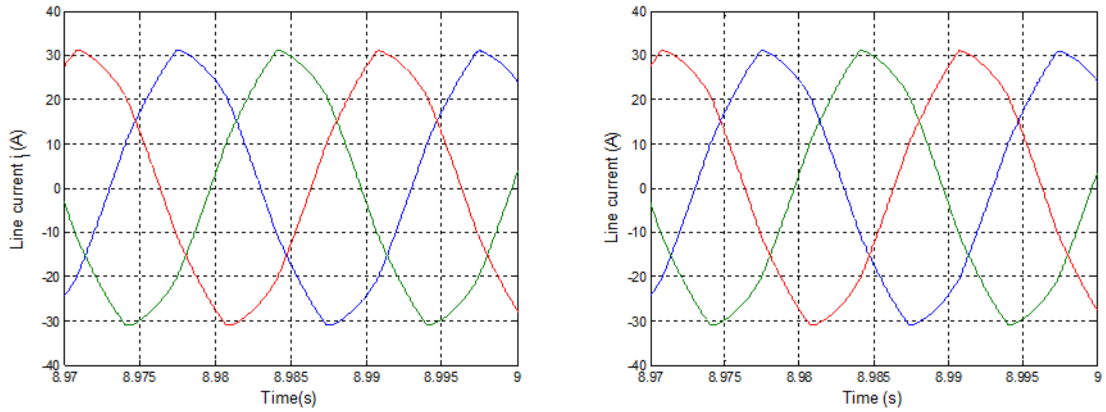
(c)


x 10^4
Reactive power Qs (VAR)
Time (s)
x 10^4
Reactive power (VAR)
Time (s)

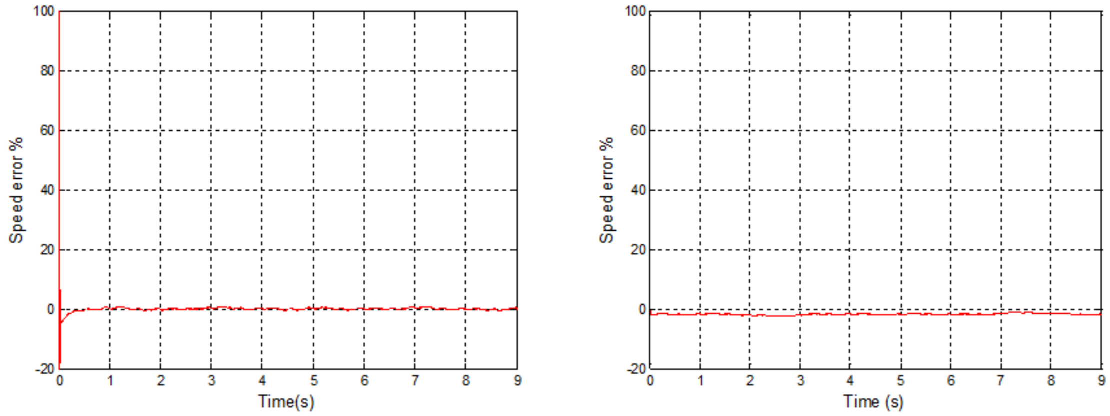
(d)


DC bus voltage (V)
Time (s)
Vdc
V*dc
DC bus voltage (V)
Time (s)
Vdc
V*dc

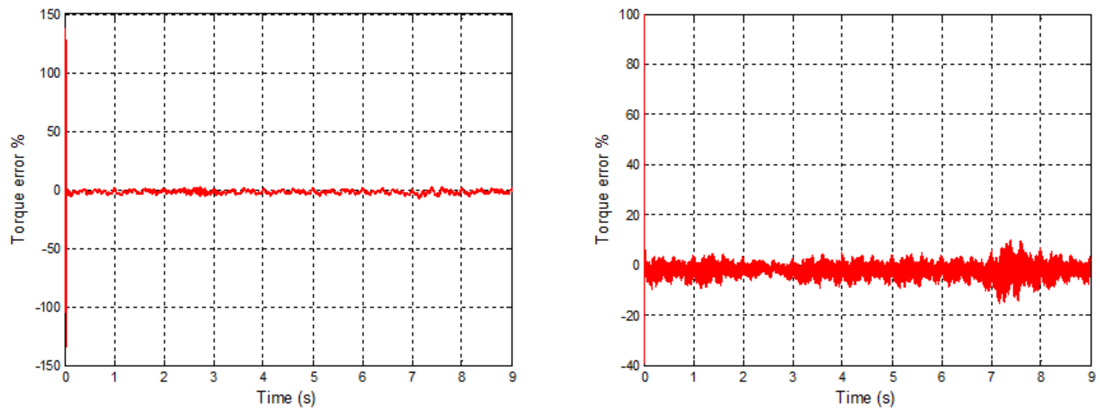
(e)



(f)



(g)



(h)

Fig. 5. Simulation results of the vector control (in the left) and the SMC (in the right) of the PMSG. Legend: (a): rotational speed Ω_r, (b): torques T_m and T_{em}, (c): stator active power P_s, (d): stator reactive power Qs, (e): DC-bus voltage V_{dc}, (f): line current i_l, (g): error speed %, (h): error torque %.

Referring to figure (5) and comparing the vector control to the SMC, one can notice the following remarks:

- The speed and torque curves illustrate the high performance of the control loops. At the starting, an exceeding of the measured speed to the reference one is observed with the vector control, the same remark for the torque,
- The turbine torque and the PMSG electromagnetic one have the same amplitude but with opposite signs which confirms the generator operation,
- The electromagnetic torque has fewer oscillations with the vector control than with the SMC, and these are showed in the torque error (SMC). Referring to the errors of speed and torque, We can notice that the vector control is more suitable for the PMSG,
- The active power is negative and the reactive one is positive, thus, one can notice that the PMSG sends active power to the grid and pulls reactive power from the grid. The power curves has fewer oscillations with SMC than with the vector control,
- There is no much difference between the two control schemes, but the most notable is: the response time and the calculation one are less with

SMC than with vector control strategy. This confirms the high performance and the reliability of the proposed non linear control.

5. Conclusion

In this study, two control strategies are applied to a PMSG directly connected to the wind turbine: the vector control and the sliding mode control. The system uses two stator power converters linked by a DC voltage which allows the power energy transient between the local grid and the wind energy conversion system. In the first phase, we used the rotor flux oriented control principle to control the stator side inverter; we imposed the direct stator current to zero in order to maximize the electromagnetic torque. The control of the DC-bus voltage is assured by the regulation of the active and the reactive powers. In the second phase, the nonlinear sliding mode control is presented, thus, we have three sliding surfaces: one for the speed, others for the stator currents. During the SMC, the *Lyapunov* condition is applied.

To show the validity of the mathematical analysis and, hence, to investigate the performance of the proposed nonlinear control scheme, simulations works are carried out for the drive system using MATLAB SIMULINK.

Perfect tracking responses and robust characteristics are obtained. Moreover, simulation results show that the PMSG is suitably adapted for wind power generation systems with high performance of the speed, flux and torque with the vector control.

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Appendix

PMSG data

Rated power	5kW
Rated stator voltage	550V
Nominal frequency	50 Hz

Pole pairs number	np=10
Stator resistance	rs=1.78Ω
Direct inductance	Ld=34.2mH
quadrature inductance	Lq=48.5mH
Rated torque	156N.m
Rated rotational speed	314rad/s
Moment of inertia	J = 0.1kg/m2
Blade radius	Rt = 2.7m
Power coefficient	Cpmax = 0.5
Optimal relative wind speed	λopt=7
Damping coefficient	Kf = 0.2

Nomenclature

P_s: Stator active Power (W),
Q_s: Stator reactive Power (VAR),
P: Output active Power (W),
Q: Output reactive Power (VAR).
n_p: pole pairs number,
p: Laplace operator,
T_m: Turbine torque (N.m),
R_t: Blade radius (m),
C_p: Power coefficient,
λ: Tip speed ratio,
β: Pitch angle (rad),
ρ: Air density (kg/m^3),
V : Wind velocity (m/s),
Ω_r: Rotational speed (rad/s),
$\omega_r = n_p \Omega_r$: Electrical pulsation (rad/s),
T_{em}: Electromagnetic torque (N.m),
K_f : Friction coefficient,
J: Moment of inertia,
φ_r : Rotor flux (Wb),
v_d, v_q: Direct and quadrature stator voltages (V),
i_d, i_q: Direct and quadrature stator currents (A),
φ_d, φ_q: Direct and quadrature stator fluxes (Wb),
r_s: Stator resistance (Ω),
L_d and L_q: Direct and quadrature stator inductances (H),
ν_m: Grid-side converter output voltage (V),
ν_g: Grid voltage (V),
i_l: Line current (A),
ω:Grid pulsation,
R_f : Filter resistance (Ω),
L_f : Filter inductance (H),