Nonlinear Control of MPPT and Grid Connected for Wind Farm Based on the PMSG

Y. Errami, M. Maaroufi and M. Cherkaoui
Ecole Mohammadia d'Ingénieur, Mohammed V- Agdal University, Department of Electrical Engineering, Rabat, Morocco
errami.emi@gmail.com, maaroufi@emi.ac.ma

M. Ouassaid
Ecole Nationale des Sciences Appliquées- Safi, Cadi Ayyad University, Department of Industrial Engineering, Safi, Morocco
ouassaid@emi.ac.ma

Abstract— **In this paper, nonlinear control for wind farm based on the Permanent Magnet Synchronous Generators (PMSGs) is investigated in order to maximize the generated power from wind turbines. The 6 MW wind farm consists of 3 PMSGs based 2MW generators connected to a common DC-bus. Each PMSG of the system is connected to the DC-bus through a rectifier, but the DC-bus is connected to the grid through only one DC/AC inverter. The efficiency of the variable speed wind energy conversion systems (WECS) can be greatly improved using an appropriate control strategy. So, the control strategy combines the technique of maximum power point tracking (MPPT) method and sliding mode (SM) nonlinear control theory. Considering the variation of wind speed, both converters used the sliding mode control scheme. The PMSGs side converters are used to achieve MPPT, while the grid-side converter regulates DC-link voltage, injects the generated power into the AC network and it's used to achieve unity power factor. Simulation results show the feasibility and robustness of the proposed control schemes for PMSGs based wind farm.**

Keywords- Wind farm; PMSG; MPPT; Lyapunov theory, Sliding mode control, Unity power factor .

I. INTRODUCTION

In recent years, there has been a developing interest in wind energy as it's a potential source for electricity generation with minimal environmental impact [1-3]. The wind generation systems are getting a lot of attention, because they are cost competitive, environmentally clean and safe renewable power sources, if we compare them to fossil fuel and nuclear power generation [3]. At present, the wind turbines generators operate at variable speeds to maximize power capture, reduce noise and reduce stresses [2], [4-6]. In addition, there are mainly three types of generators which are used in wind power system: Induction Generator (IG), Doubly Fed Induction Generator (DFIG) and PMSG [3-6]. PMSG is an attractive choice for variable-speed generation system. It's connected directly to the turbine without gearbox and don't require any external excitation current. So it can operate at low speeds and reduce again weight, losses, costs and maintenance requirements [4], [6]. Because of technology constraints, the size of individual wind energy conversions system is still limited. Therefore, a wind farm is usually composed of a several individual WTGs connected and operating simultaneously.

This paper proposes a control strategy of a wind farm with variable speed PMSGs wind turbines. The wind farm consists of 3 PMSGs connected to a common DC-bus. Each PMSG of the system farm is connected to the DC-bus through a rectifier. Thus, power extracted from wind is transferred from the PMSGs to the DC-bus by the generator-sides rectifiers and then to the utility with the grid-side inverter. A method to control wind power generators at the same time using a common DC/AC inverter is developed. The generator-sides converters control the produced power, that has an arbitrary frequency and magnitude of the voltage and current of the PMSGs driven by wind turbines, to be immediately transferred to the AC system through the grid side converter and the grid-connected transformer [6].

In addition, wind farm has strong nonlinear multivariable with many uncertain factors and disturbances. So the control strategy combines the technique of MPPT method and sliding mode (SM) nonlinear control, that, as it's well known, presents a good performance under system uncertainties [7-13]. Considering the variations of wind speed, both converters used the sliding mode control. So, for power controller, [7-8] propose the nonlinear sliding mode control scheme below the rated wind speed in order to maximize the generated power and, [9-10] introduce high order sliding mode controllers so as to reduce the chattering effect. In this paper, speeds controllers are used so as to maximize the extracted energy from the wind, below the rated power area, while the objectives of grid-side inverter are to deliver the energy from the PMSGs sides to the utility grid, to regulate the DC-link voltage and to achieve unity power factor and low distortion currents [3-4].

The paper is structured as follows. In Sections II, the models of the individual wind turbine generator and PMSG are developed. In Section III, control of the wind farm will be presented. The simulations results are presented and analyzed in Section IV. Finally, some conclusions are given in Section V.

II. MATHEMATICAL MODELING OF INDIVIDUAL WIND TURBINE GENERATOR

A. *Model of wind turbine with PMSG*

The mechanical power available from a variable speed wind turbine is expressed as [1-2]:

$$P_{Turbine} = \frac{1}{2}\rho A C_p(\lambda,\beta)v^3 \tag{1}$$

where, ρ is the air density (typically 1.225 kg/m^3), A is the area swept by the rotor blades (in m^2), C_p is the coefficient of power conversion and v is the wind speed (in m/s). The tip-speed ratio λ is given by [1], [4]:

$$\lambda = \frac{\omega_m R}{v} \tag{2}$$

where ω_m and R are the rotor angular velocity (in rad/sec) and rotor radium (in m), respectively.The wind turbine mechanical torque output T_m given as [5]:

$$T_m = \frac{1}{2}\rho A C_p(\lambda,\beta)v^3\frac{1}{\omega_m} \tag{3}$$

The power coefficient is a nonlinear function of the tip-speed ratio λ and the blade pitch angle β (in degrees). If the swept area of the blade and the air density are constant, the value of C_p is a function of λ, and it's maximum at the particular λ_{opt} [1-2]. Then:

$$P_{Turbine} = \frac{1}{2}\rho A C_{pmax}v^3 \tag{4}$$

A generic equation is used so as to model the power coefficient $C_p(\lambda,\beta)$ based on the modeling turbine characteristics described in [1] as:

$$\begin{aligned} C_p &= \frac{1}{2}\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\left(\frac{21}{\lambda_i}\right)} \\ \frac{1}{\lambda_i} &= \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{aligned} \tag{5}$$

The maximum value of C_p, that is $C_{pmax} = 0.41$, is achieved for $\beta = 0$ and for $\lambda_{opt} = 8.1$. Hence, to fully utilize the wind energy, λ should be maintained at $\lambda_{opt} = 8.1$, which is determined from the blade design. The particular value $\lambda_{opt} = 8.1$ results in the point of optimal efficiency where the maximum power is captured from wind by the wind turbine generator. So, for each wind speed, there exists a specific point in the wind turbine power characteristic, MPPT, where the output power is maximized. Thus, the control of the wind farm load results in a variable-speed operation of the turbine generator. Then, the maximum power is extracted continuously from the wind (MPPT control) [1-2]. That's illustrated in Fig.1.

B. *PMSG modeling*

Dynamic modelling of PMSG can be described in d-q reference system as follows [6]:

$$v_{gq} = \left(R_g + pL_q\right)i_q + \omega_e L_d i_d + \omega_e \psi_f \tag{6}$$

$$v_{gd} = \left(R_g + pL_d\right)i_d - \omega_e L_q i_q \tag{7}$$

where v_{gd} and v_{gq} are the direct stator and quadrature stator voltage,respectively. i_d and i_q are the direct stator and quadrature stator current, respectively. R_g is the stator resistance, L_q and L_d are the inductances of the generator on the d and q axis, ψ_f is the permanent magnetic flux and ω_e is the electrical rotating speed of the generator, defined by

$$\omega_e = p_n \omega_m \tag{8}$$

where ω_m is the mechanical angular speed and p_n is the number of pole pairs of the generator.
The expression for the electromagnetic torque can be described as:

$$T_e = \frac{3}{2}p_n\left[\psi_f i_q - (L_d - L_q)i_d i_q\right] \tag{9}$$

The dynamic equation of the wind turbine is described by:

$$J\frac{d\omega_m}{dt} = T_e - T_m - F\omega_m \tag{10}$$

where J is the moment of inertia , F is the viscous friction coefficient and $T_m$is the mechanical torque developed by the turbine .

III. CONTROL STRATEGY OF THE WIND FARM

A. *Adopted MPPT control algorithm*

For a given wind speed, the optimal rotational speed of the wind turbine rotor, from (2), can be estimated as follows [1-2]:

$$\omega_{m-opt} = \frac{v\lambda_{opt}}{R} \tag{11}$$

Each wind turbine can produce maximum power by (4). Thus, the maximum mechanical output power of the turbine is given as follows:

$$P_{Turbine\_max} = \frac{1}{2}\rho A C_{pmax}\left(\frac{R\omega_{m-opt}}{\lambda_{opt}}\right)^3 \tag{12}$$

Then, we can get the maximum power $P_{Turbine\_max}$ by regulating the turbine speed in different wind speed under rated power of the wind power system. So, an optimum value of tip speed ratio λ_{opt} can be maintained and maximum wind power can be captured. The P_{MPPT} curve is defined as function of ω_{m-opt} , the speed referred to the generator side:

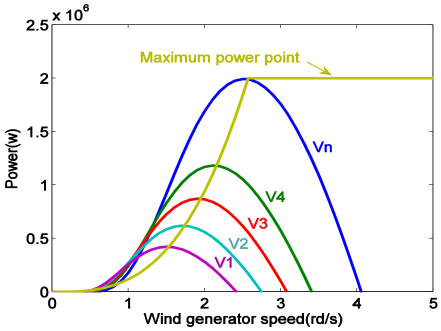

Fig.1. Wind generator power curves at various wind speed

$$P_{MPPT} = K\omega_{m-opt}^3 \tag{13}$$

So as to regulate the aerodynamic power extracted from the wind, the power control is used at high wind speed. Then, when the wind speed reached the nominal value, the pitch angle controller enters in operation in order to decrease the power coefficient. For each wind turbine**, t**he simplified representation of wind turbine control diagram is shown in Fig.2 where P_g is the generated power. Then, when the power output becomes too high the blade pitch is asked to immediately turn the blades slightly out of the wind. So, the rated rotor speed and the power are maintained for above rated wind speeds [5-6].

B. Nonlinear control strategy for generator side converters with MPPT and sliding mode control

For each PMSG, the generator side three-phase converter is used as a rectifier with a Sliding Mode (SM) control strategy. It works as a driver controlling the generator operating at optimum generator speed ω_{m-opt} to obtain maximum energy from wind [1-2]. It's deduced from equations (10) and (11) that the wind turbine speed can be controlled by regulating the q-axis stator current components (i_{qr}). Thus, so as to satisfy the sliding mode condition, define the sliding surface for the speed controller [11-12]:

$$S_\omega = \omega_{m-opt} - \omega_m \tag{14}$$

$\omega_{m-opt}$is generated by a MPPT strategy. In addition, in order to determine the stabilizing function, the following Lyapunov function is defined as [11-12]:

$$\Upsilon_\omega = \frac{1}{2} S_\omega^2 \tag{15}$$

Because of the system stability needs to be proven, so Lyapunovs stability theory is often deployed. The following condition must be fulfilled: $\Upsilon_\omega = S_\omega \dot{S_\omega} < 0$. When the sliding mode occurs on the sliding surface, then: $S_\omega = \dot{S_\omega}$. So, in order to obtain commutation around the surface and good dynamic performances, the control includes two terms [13]:

$$u_c = u_{eq} + u_n \tag{16}$$

u_{eq} is valid only in the sliding surface. During the sliding mode and in permanent regime, u_{eq} is calculated from the expression:

$$\dot{S_\omega} = 0 \tag{17}$$

u_n is used in order to guarantee the attractiveness of the variable to be controlled towards the commutation surface. Then

$$u_n = k_\omega sgn(S_\omega) \tag{18}$$

where $k_\omega > 0$. Nonlinear control SM is a discontinuous control. So as to reduce the chattering, the continuous function as exposed in (19) where $sgn(S_\omega)$ is a sign function defined as:

$$sgn(S_\omega) = \begin{cases} 1 & S_\omega > \varepsilon \\ \dfrac{S_\omega}{\varepsilon} & \varepsilon \geq |S_\omega| \\ -1 & -\varepsilon > S_\omega \end{cases} \tag{19}$$

ε is a small positive number. If the ε is too small or too large, the dynamic quality of the system will be reduced. So, the value of ε should be chosen vigilantly. Therefore, in order to reduce the copper loss by setting the d axis current to be zero and to ensure the PMSG speed convergence to the optimum speed, currents references are derived. The following equation for the system speed is obtained from equations (16-17) and (18):

$$i_{dr} = 0 \tag{20}$$

$$i_{qr} = \frac{2}{3p_n\psi_f}(T_m + J\dot{\omega}_{m_{opt}} + F\omega_m + k_\omega sgn(S_\omega) \tag{21}$$

In addition, a SM control is used in order to regulate the currents to their references. Let us introduce the following sliding surfaces for the current components i_d and i_q [11-12]:

$$S_d = i_{dr} - i_d \tag{22}$$

$$S_q = i_{qr} - i_q \tag{23}$$

where i_{qr}, i_{dr} are the desired values of q- axis current and d-axis current respectively. It follows that:

$$\dot{S}_d = \dot{i}_{dr} - \dot{i}_d \tag{24}$$

$$\dot{S}_q = \dot{i}_{qr} - \dot{i}_q \tag{25}$$

And the function of Lyapunov is written as:

$$\Upsilon_\delta = \frac{1}{2} S_\delta^2 \tag{26}$$

where δ is $d\ or\, q$. So, to guarantee the attraction of the system throughout the surface [7-13] and the following condition must be fulfilled: $\dot{\Upsilon}_\delta = S_\delta \dot{S}_\delta < 0$. Finally, the control includes two terms:

$$u_{c-\delta} = u_{eq-\delta} + u_{n-\delta} \tag{27}$$

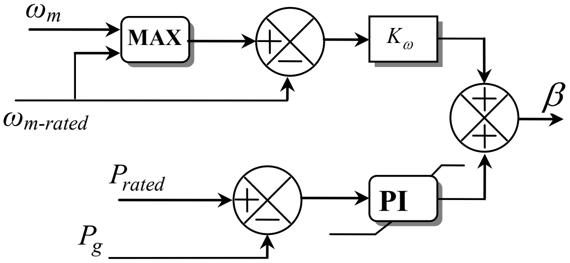

Fig.2. Wind farm Pitch angle controller.

where $u_{eq-\delta}$ is valid only in the sliding surface and $u_{n-\delta} = k_\delta sgn(S_\delta)$ in order to guarantee the attractiveness of the variable to be controlled towards the commutation surface and the controls voltage of q axis and d axis are defined by:

$$v_{dr} = R_g i_d - L_q \omega_e i_q + k_d sgn(S_d) \tag{28}$$

$$v_{qr} = R_g i_q + L_d \omega_e i_d + \omega_e \psi_f + L_q \dot{i}_{qr} + k_q sgn(S_q) \tag{29}$$

where $k_d > 0$ and $k_q > 0$.
Combing (22), (23), (24) and (25), that is

$$\dot{S}_d S_d < 0 \tag{30}$$

$$\dot{S}_q S_q < 0 \tag{31}$$

At last, PWM is used in order to produce the control signal to implement the nonlinear control for the generator side. The double closed-loop control diagram for individual generator-side converter is shown as Fig.3.

C. Grid-side controller methodology with SM

The configuration of the wind farm used for this study is depicted in Fig.4. It consists of 3 PMSGs based 2MW generators connected to a common DC-bus. Each PMSG of the wind farm is connected to the DC-bus through a rectifier, but the DC-bus is connected to the grid through only one DC/AC inverter. The grid side inverter feeds generated power into the grid and it can regulate the grid-side power factor [2-4]. SM control is adopted so as to regulate the output voltage and currents in the inner control loops and the DC voltage controller in the second loop. Then, it can regulate instantaneous values of reactive power and active power of grid connection, respectively. In the rotating dq reference frame, if the grid voltage space vector $\vec{u}$ is oriented on d-axis, then the voltage balance across the inductor L_f is given by [6]:

$$\frac{di_{d-f}}{dt} = \frac{1}{L_f}(e_d - R_f i_{d-f} + \omega L_f i_{q-f} - V \tag{32}$$

$$\frac{di_{q-f}}{dt} = \frac{1}{L_f}(e_q - R_f i_{q-f} - \omega L_f i_{d-f} \tag{33}$$

where L_f and R_f are the filter inductance and resistance respectively; e_d and e_q are the inverter d-axis q-axis voltage components respectively. i_{d-f} ,i_{q-f} are the values of d-axis current and q- axis current respectively. V is the grid voltage component in the d-axis voltage component. Then the reactive power and active power can be given as follows:

$$Q = \frac{3}{2} V i_{q-f} \tag{34}$$

$$P = \frac{3}{2} V i_{d-f} \tag{35}$$

So, active power and reactive power control can be achieved by controlling direct and quadrature current components, respectively. In addition, the DC-side equation can be given by:

$$\frac{1}{2} C \frac{dU_{dc}^2}{dt} = P_{g-t} - P \tag{36}$$

where P_{g-t} is the total output real power of PMSGs stators. The d-axis reference current is determined by DC-link voltage controller in order to control the converter output real power [3]. So, there are two closed-loop controls for the power converter. The fast dynamic is associated with the line current control in the inner loop where the nonlinear SM control is adopted to track the line current control, but in the outer loop slow dynamic is associated with the DC bus control. In addition, the PI regulator is employed so as to generate the reference source current i_{dr-f} and regulate the DC voltage, but the reference signal of the q-axis current i_{qr-f} is produced by the reactive power Q_r according to (34). Let us introduce the following sliding surfaces the currents components [12]:

$$S_{d-f} = i_{dr-f} - i_{d-f} \tag{37}$$

$$S_{q-f} = i_{qr-f} - i_{q-f} \tag{38}$$

where i_{qr-f}, i_{dr-f} are the desired values of q- axis current and d-axis current respectively. The reference i_{qr-f} for the i_{q-f} current is derived from the desired power factor. So:

$$\dot{S}_{d-f} = \dot{i}_{dr-f} - \dot{i}_{d-f} \tag{39}$$

$$\dot{S}_{q-f} = \dot{i}_{qr-f} - \dot{i}_{q-f} \tag{40}$$

And, the function of Lyapunov is written as:

$$\Upsilon_{\delta-f} = \frac{1}{2} S_{\delta-f}^2 \tag{41}$$

where δ is d or q. In addition, the following condition must be fulfilled:

$$\dot{\Upsilon}_{\delta-\mathrm{f}} = S_{\delta-f} \dot{S}_{\delta-f} < 0 \tag{42}$$

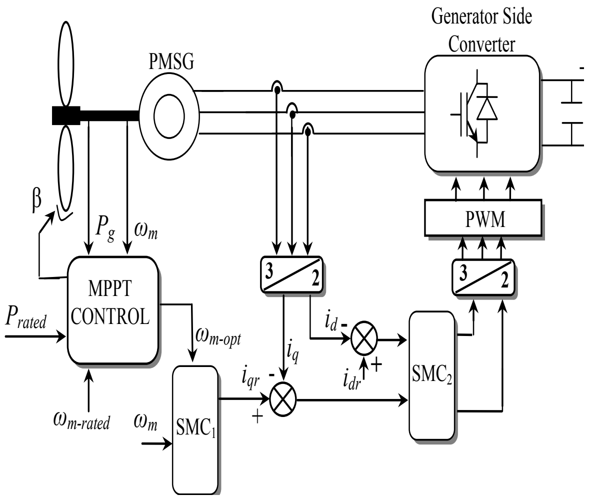

Fig.3. PMSG side converter control diagram

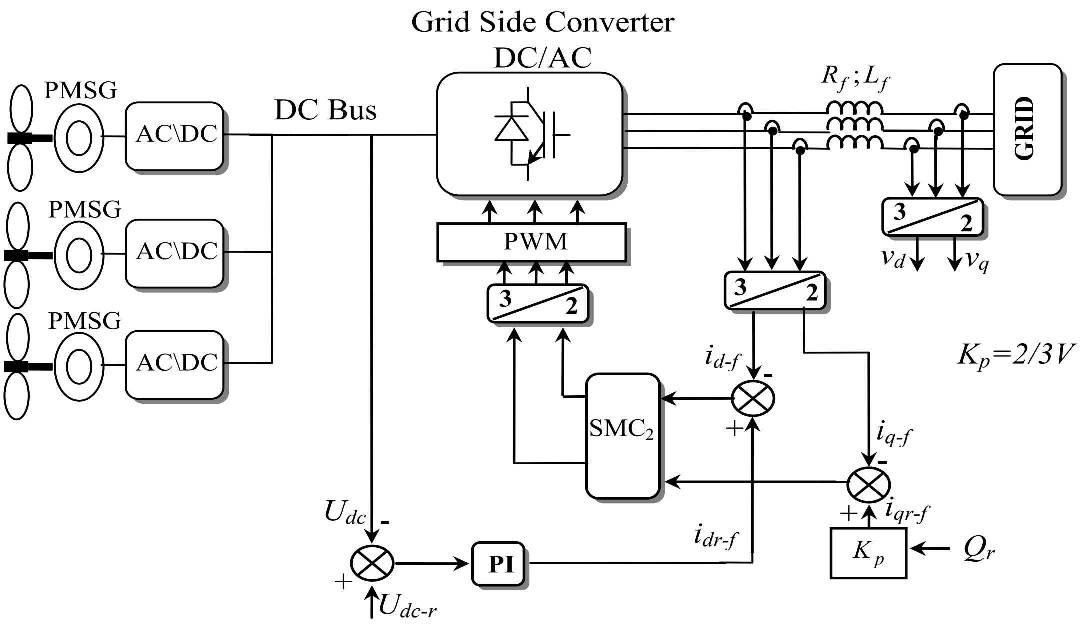

Fig.4. Schematic of nonlinear control strategy for wind farm based on the PMSG.

and the control includes two terms:

$$u_{c-\delta\_f} = u_{eq-\delta\_f} + u_{n-\delta\_f} \tag{43}$$

So, the controls voltage of q axis and d axis are defined:

$$v_{dr-f} = L_f \frac{di_{dr-f}}{dt} + R_f i_{d-f} - L_f \omega i_{q-f} + V + k_{d-f} sgn(S_{d-f}) \tag{44}$$

$$v_{qr-f} = R_f i_{q-f} + L_f \omega i_{d-f} + k_{q-f} sgn(S_{q-f}) \tag{45}$$

Finally, PWM is used in order to produce the control signal. The structure of the DC-link voltage and current controllers for grid-side converter is shown in Fig.4.

IV. SIMULATION RESULTS

The complete wind farm with PMSG was simulated by Matlab/Simulink using the parameters given in Table I. The 6 MW wind farm consists of 3 PMSGs based 2MW generators connected to a common DC-bus. Fig.5 and Fig.6 show the waveforms of wind speeds and power coefficients of the wind farm. It can be seen that the wind speeds increase, for each turbine, the performance coefficient C_p is maintained close their maximum value ($C_{pmax} = 0.41$) until generated power and generator rotor speed exceed rated values. Thus, the power coefficients will drop to maintain the rated output power. In addition, for each turbine, C_p is decreasing because the operation of the pitch angle control is actuated and the pitch angle β increase if the wind speed is up the rated wind speed ($v_n = 12.4$ m/s). The wind farm operates under MPPT control. Fig.7 shows the optimum speed and the speed of PMSG1. It is seen that the speed follows the optimum speed quite well. Fig.8. shows the simulation result of DC link voltage that remains a constant value. Therefore, this proves the effectiveness of the established regulators. Fig.9 shows the variation and a closer observation of three phase current and voltage of GRID. Unity power factor is achieved approximatively. The total power generated is shown in Fig.10. The results show variation in the power extracted when the incoming winds are different for each turbine. In addition, because all the turbines are working at their optimum level, and if the wind speeds are up the rated wind speed, the power generated reaches its maximum level.

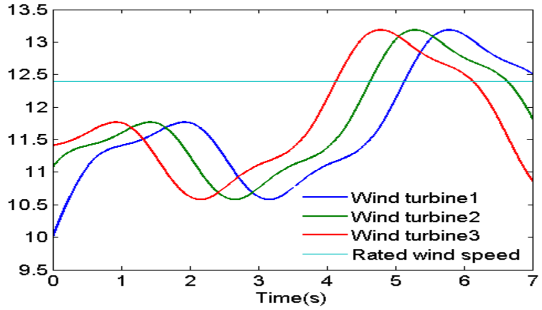

Fig.5. Instantaneous wind speeds (m/s)

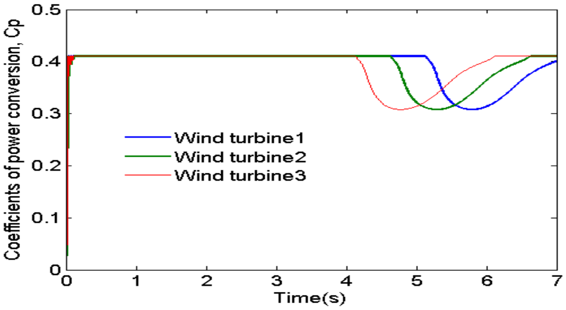

Fig.6. Variations of coefficients of power conversion.

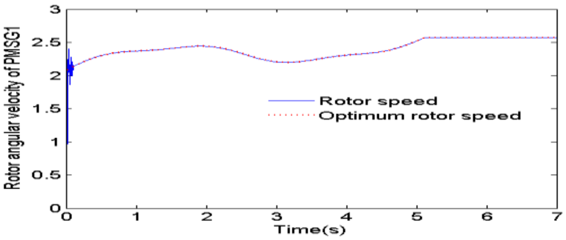

Fig.7. Rotor angular velocity and optimum rotor speed (rd/s) of PMSG1.

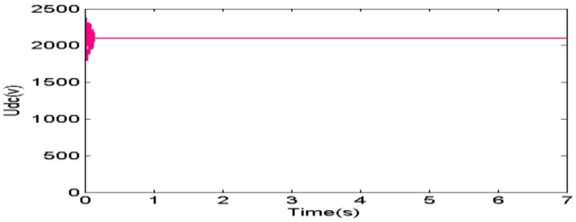

Fig. 8. DC link voltage.

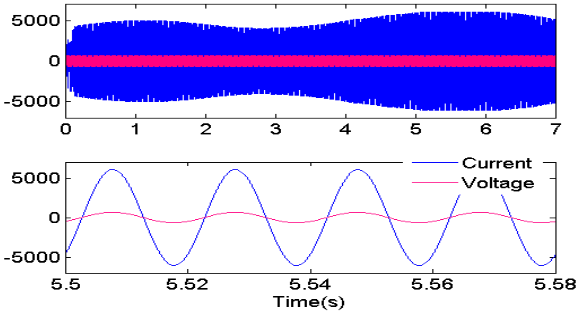

Fig. 9. The waveforms of three phase current and voltage of GRID.

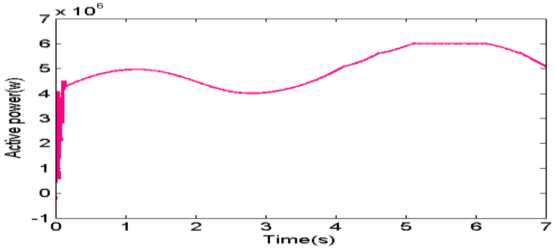

Fig. 10. Total power generated.

V. CONCLUSIONS

This paper has presented the new control of wind farm based on Grid connected PMSGs. Control algorithm based on the sliding mode strategy has been investigated for the system and the conditions for the existence of the SM are found by using the stability conditions of Lyapunov. Each PMSG of the system is connected to the DC-bus through a rectifier, but the DC-bus is connected to the grid through only one DC/AC inverter. In addition, the algorithm of MPPT has been presented in terms of the adjustment of the PMSGs rotor speeds according to instantaneous wind speed and limitation by Pitch angle strategy for high wind speed. As the voltage and frequency of PMSGs outputs vary along the wind speed change, the generator-side converters are used to track the maximum wind power. Nonlinear control strategy of individual PMSG has been discussed. So, each generator can operate at speed independently of the speed of other generator. While, using SM method, the inverter is controlled to maintain the DC-bus voltage and regulate the grid-side power factor. Thus, wind farm with the PMSGs can not only capture the maximum wind power, but also can maintain the frequency and amplitude of the output voltage with unity power factor. Finally, simulation results show clearly that the proposed nonlinear SM controllers are quite efficient for the system and demonstrated the effectiveness and applicability of the proposed control design.

TABLE I
PARAMETERS OF THE POWER SYNCHRONOUS GENERATORS

Parameter	Value
P_r rated power	2 (MW)
ω rated mechanical speed	2.57 (rd/s)
R stator resistance	0.008(Ω)
L_q , L_d stator d-axis and q-axis inductance	0.0003 (H)
p_n pole pairs	60

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