Sliding Mode Control Law for a Variable Speed Wind Turbine

OSCAR BARAMBONES, JOSE MARIA GONZALEZ DE DURANA, PATXI ALKORTA
JOSE ANTONIO RAMOS AND MANUEL DE LA SEN
University of the Basque Country
EUI de Vitoria. Nieves cano 12. SPAIN
oscar.barambones@ehu.es, josemaria.gonzalezdedurana@ehu.es, patxi.alkorta@ehu.es
josean.ramos@ehu.es, manuel.delasen@ehu.es

Abstract: Modern wind turbines are designed in order to work in variable speed operations. To perform this task, wind turbines are provided with adjustable speed generators, like the double feed induction generator. One of the main advantage of adjustable speed generators is improving the system efficiency compared to fixed speed generators, because turbine speed can be adjusted as a function of wind speed in order to maximize the output power. However this system requires a suitable speed controller in order to track the optimal reference speed of the wind turbine. In this work, a sliding mode control for variable speed wind turbines is proposed. An integral sliding surface is used, because the integral term avoids the use of the acceleration signal, which reduces the high frequency components in the sliding variable. The proposed design also uses the vector oriented control theory in order to simplify the generator dynamical equations. The stability analysis of the proposed controller has been carried out under wind variations and parameter uncertainties by using the Lyapunov stability theory. Finally simulated results show, on the one hand that the proposed controller provides a high-performance dynamic behavior, and on the other hand that this scheme is robust with respect to parameter uncertainties and wind speed variations, that usually appear in real systems.

Key–Words: Wind Turbine Control, Variable Structure Control, Modeling and Simulation.

Nomenclature

v	Wind speed (m/s).
ρ	Air density (kg/m^3.
R	Rotor radius (m).
P_m	Wind power (W).
T_m	Wind torque ($N.m$).
λ	Tip speed ratio.
C_p	Power coefficient.
w	Wind turbine rotor speed (rad/s).
w_e	Generator rotor speed (rad/s).
T_e	Generator electromagnetic torque ($N.m$).
J	Equivalent moment of inertia ($kg.m^2$).
B	Equivalent viscous friction ($N.m/s$).
i	Current (A).
ψ	Flux (Wb).
L	Inductance (H).
K_T	Torque constant ($N.m/A$).

1 Introduction

The wind energy is an abundant renewable source of electricity by converting the kinetic energy of moving air mass into electricity [1], [2]. Wind power is characterized as distributed/dispersed local generation with the exception of large offshore wind farms, which are considered as local power plants with range sizes over 100 MW in ratings.

The expected development of wind power technology will affect the extent of the impact that wind power will have on the power system. Very large wind farms (hundreds of MW) are a new trend that can pose serious technical challenges. However, large wind farms will also pave the way for other new technologies that will help with the full electric grid integration [3].

The increasingly sophisticated power electronic and computerized control sche-mes, will lead to excessive improvements and full controllability of available wind power. Large wind energy plants will lead to new interface requirements regarding the full integration of emerging wind power into the power grid system. Increasingly, wind farms will be required to be fully connected to the electric grid [4]-[6]. Reactive power compensation is an important issue in the control of distribution and transmission systems. Reactive current increases feeder system losses, reduces system power factor, and can cause large-amplitude variations in load-side voltage. Moreover, rapid changes in the reactive power consumption of large load centers can cause voltage amplitude oscillations (e.g., voltage flicker in the case of arc furnaces) [7], [8]. This can lead to a change in the electric system real power demand resulting in power oscillation.

Several key areas of research in control of wind turbines have been identified during the recent 8th World Wind Energy Conference 2010, held in Istanbul. Of particular interest to wind power industry is the development of innovative control algorithms for smoother and more efficient operation of wind power generation systems [9]-[11]. Traditionally, most wind turbines operate at fixed speeds except when starting and stopping [12]. Fixed-speed operation means that the maximum coefficient of performance is available only at a particular wind speed, but a low coefficient of performance is observed for all other.

During the last decade several papers regarding sliding mode wind turbine control have been published in the technical literature. Some of them uses a static Kramer drive that consists of a diode rectifier on the rotor side and a line commutated inverter connected to the supply side [13], [14]. However this converter is only able to provide power from both stator and rotor circuits, under super-synchronous operation. In order to overcome this problem a more technologically advanced method using back-to-back converters has been proposed [15], [16]. In these works a vector oriented control strategy is used in order to simplify the induction generator dynamical equations. In this sense the machine is controlled in a synchronously rotating reference frame with the d-axis orientated along the stator-flux vector. Then the rotor current was decomposed into d-q components, where the d-axis current is used to control the electromagnetic torque in order to provide the maximum energy transfer. However these approaches use the classical PI controllers in order to maximize the wind power generation.

On the other hand, some papers [17], [18] present a sliding mode power control for a wind turbine, but in these works the DFIG dynamic is not considered; only the mechanical system dynamics is regarded. In these control schemes the generator torque is considered as a system input and then this input is controlled in order to produces the maximum power extraction. However in a real system the generator torque should be controlled in an indirect way controlling the stator and rotor voltages and currents.

This paper investigates a new robust speed control method for variable speed wind turbines with a DFIG [19]-[22]. The objective is to make the rotor speed track the desired speed (the speed that maximizes the power generation) in spite of system uncertainties. This is achieved by regulating the rotor current of the DFIG using the sliding mode control theory. In the proposed design a vector oriented control theory is used to decouple the torque and the flux of the induction machine, in order to simplify the generator dynamical equations. Thus, the proposed controller is more simple than other existing sliding mode control schemes.

The main contribution of our paper is that a simple sliding mode control for a wind turbine system is proposed. A vector oriented control strategy is used in order to simplify the dynamic for the DFIG. Then, this work presents a robust control that takes into account the mechanical system dynamics and the electrical generator dynamics, which provides a more realistic behavior for the wind turbine system. Moreover, an integral sliding surface is proposed, because the integral term avoids the use of the acceleration signal in the sliding variable. It should be noted that due to the variability of the wind speed, the acceleration signal will introduce high frequency components in the sliding variable that are undesirable. In addition, the proposed robust control law is also very simple and do not implies the high computational cost that are present in other existing robust control schemes.

Then, this control scheme leads to obtain the maximum power extraction from the different wind speeds that appear along time and is robust under the uncertainties that appear in the real systems. The stability analysis of the proposed controller is carried out under wind variations and parameter uncertainties by using the Lyapunov stability theory. Finally, a test of the proposed method based on a two-bladed horizontal axis wind turbine is conducted using the Matlab/Simulink software. In this test, several operating conditions are simulated and satisfactory results are obtained.

2 System modeling

The power extraction of the wind turbine is a function of three main factors: the wind power available, the power curve of the machine and the ability of the machine to respond to wind fluctuation. The expression for power produced by the wind is given by [23], [24]:

$$P_m(v) = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 v^3 \tag{1}$$

where ρ is air density, R is radius of rotor, v is wind speed, C_p denotes power coefficient of wind turbine, λ is the tip-speed ratio and β represents pitch angle. The tip-speed ratio is defined as:

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

where w is the turbine rotor speed.

Therefore, if the rotor speed is kept constant, then any change in the wind speed will change the tip-speed ratio, leading to the change of power coefficient C_p, as well as the generated output power of the wind turbine. However, if the rotor speed is adjusted according to the wind speed variation, then the tip-speed ratio can be maintained at an optimal point, which could yield maximum output power from the system.

Moreover, this wind speed tracking will reduce the system mechanical fatigue because when the wind speed increases/decreases, then the controller increases/decreases the generator speed which will reduces the mechanical stress in the shaft and in the gearbox.

For a typical wind power generation system, the following simplified elements are used to illustrate the fundamental work principle. The system primarily consists of an aeroturbine, which converts wind energy into mechanical energy, a gearbox, which serves to increase the speed and decrease the torque and a electric generator to convert mechanical energy into electrical energy.

Driving by the input wind torque T_m, the rotor of the wind turbine runs at the speed w. The transmission output torque T_t is then fed to the generator, which produces a shaft torque of T_e at generator angular velocity of w_e. Note that the rotor speed and generator speed are not the same in general, due to the use of the gearbox.

The mechanical equations of the system can be characterized by [25]:

$$\begin{aligned} J_m \dot{w} + B_m w &= T_m + T && (3) \\ J_e \dot{w}_e + B_e w_e &= T_t + T_e && (4) \\ T_t w_e &= -T w && (5) \end{aligned}$$

where J_m and J_e are the moment of inertia of the turbine and the generator respectively, B_m and B_e are the viscous friction coefficient of the turbine and the generator, T_m is the wind generated torque in the turbine, T is the torque in the transmission shaft before gear box, T_f is the torque in the transmission shaft after gear box, and T_e is the the generator torque, w is the angular velocity of the wind turbine rotor and w_e is the angular velocity of the generator rotor.

The relation between the angular velocity of the turbine w and the angular velocity of the generator w_e is given by the gear ratio γ:

$$\gamma = \frac{w_e}{w} \tag{6}$$

Using equations (3), (4), (5) and (6) one obtains:

$$J \dot{w} + B w = T_m + \gamma T_e \tag{7}$$

where

$$\begin{aligned} J &= J_m + \gamma^2 J_e && (8) \\ B &= B_m + \gamma^2 B_e && (9) \end{aligned}$$

are the equivalent moment of inertia and viscous friction coefficient of the system

From equations (1) and (2) it is deduced that the input wind torque is:

$$T_m(v) = \frac{P_m(v)}{w} = \frac{P_m(v)}{\frac{\lambda v}{R}} = k_v \cdot v^2 \tag{10}$$

where

$$k_v = \frac{1}{2} C_p \, \rho \, \pi \frac{R^3}{\lambda} \tag{11}$$

Now we are going to consider the system electrical equations. In this work a DFIG is used. This induction machine is feed from both stator and rotor sides. The stator is directly connected to the grid while the rotor is fed through a variable frequency converter (VFC).

In order to produce electrical active power at constant voltage and frequency to the utility grid, over a wide operation range (from subsynchronous to supersynchronous speed), the active power flow between the rotor circuit and the grid must be controlled both in magnitude and in direction. Therefore, the VFC consists of two four-quadrant IGBT PWM converters (rotor-side converter (RSC) and grid-side converter (GSC)) connected back-to-back by a dc-link capacitor [15], [20].

The DFIG can be regarded as a traditional induction generator with a nonzero rotor voltage. The dynamic equation of a thee-phase DFIG can be written in a synchronously rotating d-q reference frame as [26].

$$\begin{aligned} v_{ds} &= r_s i_{ds} - w_s \psi_{qs} + \frac{d\psi_{ds}}{dt} && (12) \\ v_{qs} &= r_s i_{qs} + w_s \psi_{ds} + \frac{d\psi_{qs}}{dt} && (13) \\ v_{dr} &= r_r i_{dr} - s\, w_s \psi_{qr} + \frac{d\psi_{dr}}{dt} && (14) \\ v_{qr} &= r_r i_{qr} + s\, w_s \psi_{dr} + \frac{d\psi_{qr}}{dt} && (15) \end{aligned}$$

where v is the voltage; r is the resistance; i is the current; ψ is the flux linkage; w_s is the rotational speed of the synchronous reference frame; $s\, w_s = w_s - w_e$ is the slip frequency, s is the slip and w_e is the generator rotor speed.

The subscripts r and s denotes the rotor and stator values respectively, and the subscripts d and q denote the dq-axis components in the synchronously rotating reference frame.

The flux linkages are given by:

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr} \tag{16}$$
$$\psi_{qs} = L_s i_{qs} + L_m i_{qr} \tag{17}$$
$$\psi_{dr} = L_r i_{dr} + L_m i_{ds} \tag{18}$$
$$\psi_{qr} = L_r i_{qr} + L_m i_{qs} \tag{19}$$

where L_s, L_r, and L_m are the stator inductance, rotor inductance and mutual inductances, respectively. The electrical torque equation of the DFIG is given by:

$$T_e = \frac{3p}{4} L_m (i_{qs} i_{dr} - i_{ds} i_{qr}) \tag{20}$$

where p is the pole numbers.

The active and reactive stator powers are:

$$P_s = \frac{3}{2}(v_{ds} i_{ds} + v_{qs} i_{qs}) \tag{21}$$
$$Q_s = \frac{3}{2}(v_{qs} i_{ds} - v_{ds} i_{qs}) \tag{22}$$

Similarly, the rotor power (also called slip power) can be calculated as:

$$P_r = \frac{3}{2}(v_{dr} i_{dr} + v_{qr} i_{qr}) \tag{23}$$
$$Q_r = \frac{3}{2}(v_{qr} i_{dr} - v_{dr} i_{qr}) \tag{24}$$

Then, when the power losses in the converters are neglected, the total real power P_e injected into the main network equals to the sum of the stator power P_s and the rotor power P_r. In the same way, the reactive power Q_e exchanged with the grid equals to the sum of stator reactive power Q_s and the rotor reactive power Q_r.

3 DFIG control scheme

In order to extract the maximum active power from the wind, the rotor speed of the wind turbine must be adjusted to achieve an optimal tip-speed ratio λ_{opt}, which yields the maximum power coefficient $C_{p_{max}}$, and therefore the maximum power [27]. In other words, given a particular wind speed, there is a unique value for the generator speed in order to achieve the goal of maximum power extraction. The value of the λ_{opt} can be calculated from the maximum of the power coefficient curves versus tip-speed ratio, which depends of the modeling turbine characteristics.

The power coefficient C_p can be approximated by equation (25) based on the modeling turbine characteristics [28]:

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} + c_6 \lambda \tag{25}$$

where the coefficients c_1 to c_6 depends on the wind turbine design characteristics, and λ_i is defined as

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{26}$$

The value of λ_{opt} can be calculated from the roots of the derivative of the equation (25). Then, based on the wind speed, the corresponding optimal generator speed command for maximum wind power tracking is determined by:

$$w^* = \frac{\lambda_{opt} \cdot v}{R} \tag{27}$$

In this work the wind speed is measured using an anemometer but the proposed control scheme could be applied using the wind speed calculated from a wind speed estimator [20], [29].

The DFIG wind turbine control system generally consists of two parts: the electrical control on the DFIG and the mechanical control on the wind turbine blade pitch angle. Control of the DFIG is achieved controlling the variable frequency converter (VFC), which includes control of the rotor-side converter (RSC) and control of the grid-side converter (GSC). The objective of the RSC is to govern both the stator-side active and reactive powers independently; while the objective of the GSC is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The GSC control scheme can also be designed to regulate the reactive power or the stator terminal voltage of the DFIG.

The RSC control scheme should be designed in order to regulate the wind turbine speed for maximum wind power capture. Therefore, a suitably designed speed controller is essential to track the optimal wind turbine reference speed w^* for maximum wind power extraction. This objective are commonly achieved by electrical generator rotor current regulation on the stator-flux oriented reference frame [26].

In the stator-flux oriented reference frame, the d-axis is aligned with the stator flux linkage vector ψ_s, and then, ψ_{ds}=ψ_s and ψ_{qs}=0 . This yields the following relationships:

$$i_{qs} = \frac{L_m i_{qr}}{L_s} \tag{28}$$

$$i_{ds} = \frac{L_m(i_{ms} - i_{dr})}{L_s} \quad (29)$$

$$T_e = \frac{-L_m i_{ms} i_{qr}}{L_s} \quad (30)$$

$$Q_s = \frac{3}{2}\frac{w_s L_m^2 i_{ms}(i_{ms} - i_{dr})}{L_s} \quad (31)$$

$$v_{dr} = r_r i_{dr} + \sigma L_r \frac{di_{qr}}{dt} - s w_s \sigma L_r i_{qr} \quad (32)$$

$$v_{qr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} \quad (33)$$

$$+ s w_s \left(\frac{\sigma L_r i_{dr} + L_m^2 i_{ms}}{L_s} \right) \quad (34)$$

where

$$i_{ms} = \frac{v_{qs} - r_s i_{qs}}{w_s L_m} \quad (35)$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \quad (36)$$

Since the stator is connected to the grid, and the influence of the stator resistance is small, the stator magnetizing current (i_{ms}) can be considered constant [15]. Therefore, the electromagnetic torque can be defined as follows:

$$T_e = -K_T i_{qr} \quad (37)$$

where K_T is a torque constant, and is defined as follows:

$$K_T = \frac{L_m i_{ms}}{L_s} \quad (38)$$

Then, from equations (7) and (37) it is deduced that the wind turbine speed can be controlled by regulating the q-axis rotor current components (i_{qr}) while equation (31) indicates that the stator reactive power (Q_s) can be controlled by regulating the d-axis rotor current components, (i_{ds}). Consequently, the reference values of i_{qr} and i_{dr} can be determined directly from w_r and Q_s references.

4 Sliding mode controller design

Now we are going to design a robust speed control scheme in order to regulate the wind turbine speed for maximum wind power capture. This wind turbine speed controller is designed in order to track the optimal wind turbine speed reference w^* for maximum wind power extraction.

From equations (7) and (37) it is obtained the following dynamic equation for the system speed:

$$\dot{w} = \frac{1}{J}\left(T_m - \gamma K_T i_{qr} - B w\right) \quad (39)$$

$$= -aw + f - b i_{qr} \quad (40)$$

where the parameters are defined as:

$$a = \frac{B}{J}, \quad b = \frac{\gamma K_T}{J}, \quad f = \frac{T_m}{J}; \quad (41)$$

Now, we are going to consider the previous dynamic equation (40) with uncertainties as follows:

$$\dot{w} = -(a + \triangle a)w + (f + \triangle f) - (b + \triangle b) i_{qs}^e \quad (42)$$

where the terms $\triangle a$, $\triangle b$ and $\triangle f$ represents the uncertainties of the terms a, b and f respectively.

Let us define define the speed tracking error as follows:

$$e(t) = w(t) - w^*(t) \quad (43)$$

where w^* is the rotor speed command.

Taking the derivative of the previous equation with respect to time yields:

$$\dot{e}(t) = \dot{w} - \dot{w}^* = -a\, e(t) + u(t) + d(t) \quad (44)$$

where the following terms have been collected in the signal $u(t)$,

$$u(t) = f(t) - b\, i_{qr}(t) - a\, w^*(t) - \dot{w}^*(t) \quad (45)$$

and the uncertainty terms have been collected in the signal $d(t)$,

$$d(t) = -\triangle a\, w(t) + \triangle f(t) - \triangle b\, i_{qr}(t) \quad (46)$$

To compensate for the above described uncertainties that are present in the system, a sliding control scheme is proposed. In the sliding control theory, the switching gain must be constructed so as to attain the sliding condition [30]. In order to meet this condition a suitable choice for the sliding gain should be made in order to compensate the uncertainties.

Now, we are going to define the sliding variable $S(t)$ with an integral component as:

$$S(t) = e(t) + \int_0^t (k + a) e(\tau)\, d\tau \quad (47)$$

where k is a constant gain.

The proposed sliding variable is defined with an integral component in order to relax the requirement of the acceleration signal, that is usual in conventional sliding mode speed control schemes. The acceleration signal, due to the variability of the wind speed, will introduce a high frequency components in the sliding variable that are undesirable.

Then the sliding surface is defined as:

$$S(t) = e(t) + \int_0^t (a + k) e(\tau)\, d\tau = 0 \quad (48)$$

Now, we are going to design a variable structure speed controller in order to control the wind turbine speed.

$$u(t) = -k\, e(t) - \beta\, \mathrm{sgn}(S) \tag{49}$$

where the k is the constant gain defined previously, β is the switching gain, S is the sliding variable defined in eqn. (47) and $\mathrm{sgn}(\cdot)$ is the signum function.

In order to obtain the speed trajectory tracking, the following assumptions should be formulated:

($\mathcal{A}\,1$) The gain k must be chosen so that the term $(k + a)$ is strictly positive, therefore the constant k should be $k > -a$.

($\mathcal{A}\,2$) The gain β must be chosen so that $\beta \geq \bar{d}$ where $\bar{d} \geq \sup_{t \in R^{0+}} |d(t)|$.

Note that this condition only implies that the uncertainties of the system are bounded magnitudes.

Theorem 1 *Consider the induction motor given by equation (42). Then, if assumptions* $(\mathcal{A}\,1)$ *and* $(\mathcal{A}\,2)$ *are verified, the control law (49) leads the wind turbine speed* $w(t)$*, so that the speed tracking error* $e(t) = w(t) - w^*(t)$ *tends to zero as the time tends to infinity.*

The proof of this theorem will be carried out using the Lyapunov stability theory.

Proof : Define the Lyapunov function candidate:

$$V(t) = \frac{1}{2} S(t) S(t) \tag{50}$$

Its time derivative is calculated as:

$$\begin{aligned}
\dot{V}(t) =&\ S(t)\dot{S}(t) \\
&= S \cdot [\dot{e} + (k + a)e] \\
&= S \cdot [(-a\, e + u + d) + (k\, e + a\, e)] \\
&= S \cdot [u + d + k\, e] \\
&= S \cdot [-k\, e - \beta\, \mathrm{sgn}(S) + d + k\, e] \\
&= S \cdot [d - \beta\, \mathrm{sgn}(S)] \\
&\leq -(\beta - |d|)|S| \\
&\leq 0
\end{aligned} \tag{51}$$

It should be noted that the eqns. (47), (44) and (49) and the assumption $(\mathcal{A}\,2)$ have been used in the proof.

Using the Lyapunov's direct method, since $V(t)$ is clearly positive-definite, $\dot{V}(t)$ is negative definite and $V(t)$ tends to infinity as $|S(t)|$ tends to infinity (i.e. $V(t)$ is radially unbounded). Then the equilibrium at the origin $S(t) = 0$ is globally asymptotically stable, and therefore $S(t)$ tends to zero as the time tends to infinity. Moreover, all trajectories starting off the sliding surface $S = 0$ must reach it in finite time and then will remain on this surface. This system's behavior once on the sliding surface is usually called *sliding mode* [30].

When the sliding mode occurs on the sliding surface (48), then $S(t) = \dot{S}(t) = 0$, and therefore the dynamic behavior of the tracking problem (44) is equivalently governed by the following equation:

$$\dot{S}(t) = 0 \quad \Rightarrow \quad \dot{e}(t) = -(k + a)e(t) \tag{52}$$

Then, under assumption $(\mathcal{A}\,1)$, the tracking error $e(t)$ converges to zero exponentially.

It should be noted that, a typical motion under sliding mode control consists of a *reaching phase* during which trajectories starting off the sliding surface $S = 0$ move toward it and reach it in finite time, followed by *sliding phase* during which the motion will be confined to this surface and the system tracking error will be represented by the reduced-order model (eqn. 52), where the tracking error tends to zero.

Finally, the torque current command, $i^*_{qr}(t)$, can be obtained from equations (49) and (45):

$$i^*_{qr}(t) = \frac{1}{b}\left[k\, e + \beta\, \mathrm{sgn}(S) - a\, w^* - \dot{w}^* + f\right] \tag{53}$$

Therefore, the proposed variable structure speed control resolves the wind turbine speed tracking problem for variable speed wind turbines in the presence of uncertainties. This wind turbine speed tracking let us obtain the maximum wind power extraction for all values of wind speeds.

To avoid the chattering effect in the control signal caused by the discontinuity in eqn. 53 across the sliding surfaces, the control law can be smoothed out. In this case a simple and easy solution could be replace the sign function by a tansigmoid function in order to avoid the discontinuity [31].

5 Simulation Results

In this section we will study the variable speed wind turbine regulation performance using the proposed sliding-mode field oriented control scheme. The objective of this regulation is to maximize the wind power extraction in order to obtain the maximum electrical power. In this sense, the wind turbine speed must be adjusted continuously against wind speed.

The simulation are carried out using the Matlab/Simulink software and the turbine model is the one provided in the SimPowerSystems library [32].

In this example simulation a variable speed wind farm with a rated power of 9 MW is used. The farm consists of six 1.5 MW wind turbines connected to a 575 V bus line. The wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter.

The system has the following mechanical parameters. The combined generator and turbine inertia constant is $J = 5.04s$ expressed in seconds, the combined viscous friction factor $B = 0.01pu$ in pu based on the generator rating and there are three pole pairs. It should be noted that in the simulation the per unit system is used. The per unit system is widely used in the power system industry to express values of voltages, currents, powers, and impedances of various power equipment [32].

In this simulation examples it is assumed that there is an uncertainty of 20 % in the system parameters, that will be overcome by the proposed sliding control.

Finally, the following values have been chosen for the controller parameters, $k = 1.15$, $\beta = 1.35$.

In the simulation a variable wind speed is used, and as it can be seen in the figure 1, the wind speed varies between $0m/s$ and $28m/s$.

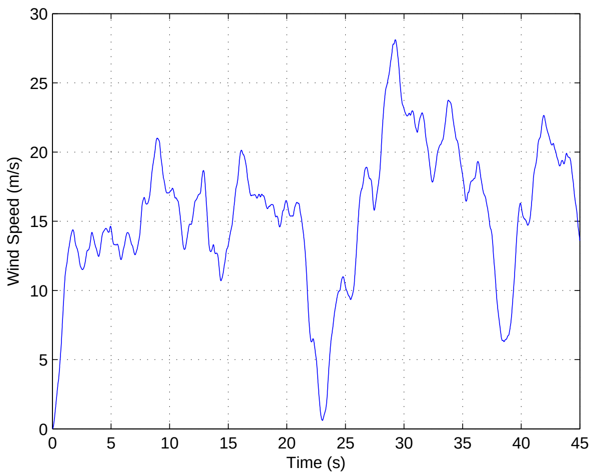

Figure 1: Wind speed

Figure 2 show the reference (dashed line) and the real rotor speed (solid line). As it may be observed, after a transitory time in which the sliding mode is reached, the rotor speed tracks the desired speed in spite of system uncertainties. In this figure, the speed is expressed in the per unit system (pu), that is based in the generator synchronous speed $w_s = 125.60 rad/s$.

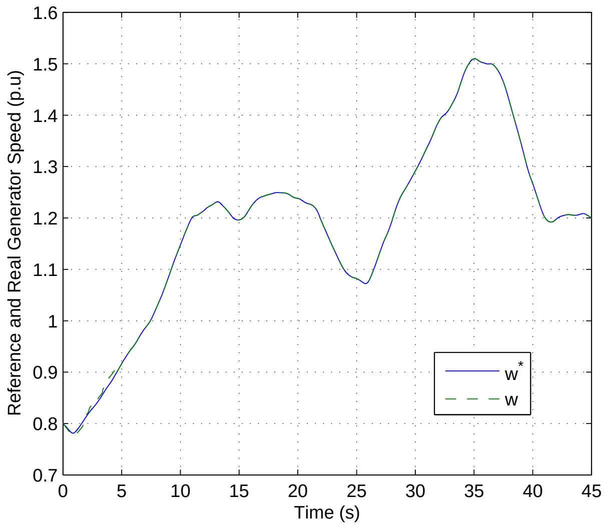

Figure 2: Reference and real rotor speed

Figure 3 shows the generated active power, whose value is maximized by our proposed sliding mode control scheme. As it can be observed in this figure, at time $11.76s$ the mechanical power (and therefore the generated active power) should be limited by the pitch angle (as it is shown in figure 4) so as not to exceed the rated power of this system.

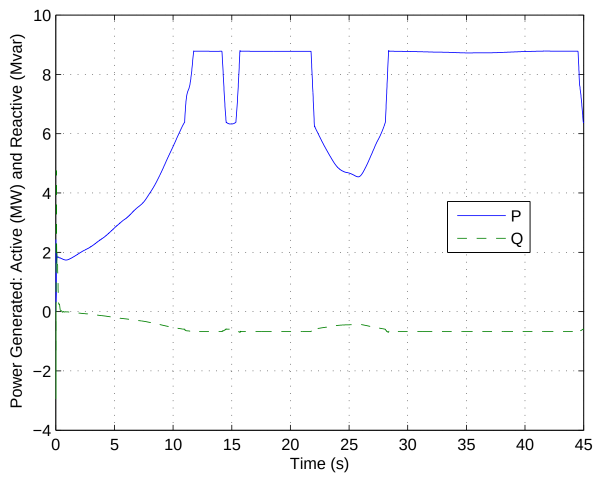

Figure 3: Generated active and reactive power

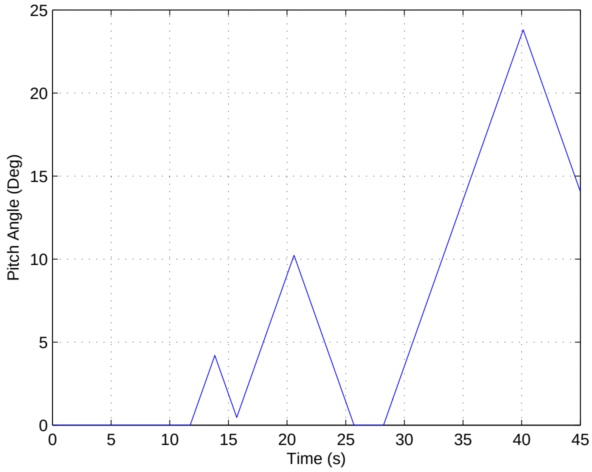

Figure 4: Pitch Angle

6 Conclusion

In this paper a sliding mode vector control for a doubly feed induction generator drive, used in variable speed wind power generation is described. The presented design uses the vector oriented control theory in order to simplify the DFIG dynamical equations. Thus the proposed controller is more simple than other existing sliding mode control schemes.

The variable structure control has an integral sliding surface in order to relax the requirement of the acceleration signal. The acceleration signal is usual in the conventional sliding mode based control speeds; however in the proposed controller the acceleration signal is eliminated in order to reduce the high frequency components in the sliding variable. Due to the nature of the sliding mode theory, this control scheme is robust under uncertainties that appear in the real systems. The robustness and the closed loop stability of the presented design has been proved through Lyapunov stability theory.

The implemented control method allows the wind turbine to operate with the optimum power efficiency over a wide range of wind speed. The control method successfully controls the variable speed wind turbine efficiently, within a range of normal operational conditions. At wind speeds less than the rated wind speed, the speed controller seeks to maximize the power according to the maximum coefficient curve. As result, the variation of the generator speed follows the slow variation of the wind speed. At large wind speeds, the power limitation controller sets the blade angle to maintain rated power.

Finally, simulation examples has been shown that the proposed control scheme performs reasonably well in practice, and that the speed tracking objective is achieved in order to maintain the maximum power extraction under system uncertainties and wind speed variations.

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