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ROBUST SPEED CONTROL FOR A VARIABLE SPEED WIND TURBINE

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Abstract. *Modern wind turbines are designed in order to work in variable speed operations. To perform this task, these turbines are provided with adjustable speed generators, like the double feed induction generator (DFIG). One of the main advantages of adjustable speed generators is improving the system efficiency compared with 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. The proposed design also uses the vector oriented control theory in order to simplify the DFIG dynamical equations. The stability analysis of the proposed controller has been carried out under wind variations and parameter uncertainties using the Lyapunov stability theory. Finally, the 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, which usually appear in real systems.*
Keywords: Wind power optimization, Wind turbine control, Sliding mode control, Robust control, Modeling and simulation

1. **Introduction.** Wind energy is an abundant renewable source of electricity which is exploited by converting the kinetic energy of moving air mass into electricity. 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 [1]. The increasingly sophisticated power electronic and computerized control schemes will lead to improvements and full controllability of available wind power.

The wind turbine systems are subjected to disturbances, such as wind fluctuations, wind shear and tower shadows, and electrical generator parameters variations. In this sense, a robust controller seems to be adequate in order to surmount these disturbances. There are various alternatives in order to design a robust controller, like $H\infty$ controllers, fuzzy controllers, and neural network controllers (see, for instance, [2, 3, 4] and the references therein).

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. In [5] the authors present an intelligent system for control of wind turbines. The system integrates data mining, evolutionary computation, predictive control, and time series approaches. The system modifies the control objectives by observing the wind conditions and electricity demand. In the work of [6] a design of a robust RST controller of a variable speed pitch regulated wind turbine for above rated wind speeds is presented. The digital controller is designed following the pole assignment with sensitivity function shaping method. Also, a robust control design for variable speed control of a two-bladed horizontal axis wind turbine similar to the DOE MOD-0 model is proposed recently in literature. The design belongs to the class of chattering controllers, and its robustness quality is attractive for wind control due to the stochastic wind variation and the uncertainties of the model introduced in the controller design. More recently, an optimal control structure for variable speed, fixed pitch wind turbine is presented, in which a linearized model around the operating point (corresponding to the maximal energy conversion efficiency) is used in order to design a linear approach for optimizing the energy captured from the wind.

Due to the robustness properties, during the last decade several papers regarding sliding mode wind turbine control have been published in the technical literature. Some of them use a static Kramer drive that consists of a diode rectifier on the rotor side and a line commutated inverter connected to the supply side [7, 8]. 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 [9, 10]. 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.

In [11], the authors present a sliding mode power control for a wind turbine, but in this work the double feed induction generator (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 produce 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. 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. In the paper, a wind turbine model that incorporates a nonlinear DFIG model is presented. A vector oriented control strategy is used in order to decouple the dynamic for the DFIG. Then, this work presents a robust control scheme that takes into account the mechanical system dynamics and the electrical generator dynamics, which provides a more realistic behavior for the wind turbine system. In the controller design, 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 does not imply the high computational cost that is present in other existing robust control schemes. Therefore, the proposed control scheme could be implemented over a low cost DSP-procesor.

Then, this control scheme leads to obtaining the maximum power extraction from the different wind speeds that appear along time and is robust under the uncertainties that there are in the wind turbine 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 [12]:

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

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

$$\lambda = \frac{Rw}{v} \tag{2}$$

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.

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 aero-turbine, 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.

Driven 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:

$$J_m \dot{w} + B_m w = T_m + T \tag{3}$$

$$J_e \dot{w}_e + B_e w_e = T_t + T_e \tag{4}$$

$$T_t w_e = -T w \tag{5}$$

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)-(6) one obtains:

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

where

$$J = J_m + \gamma^2 J_e \tag{8}$$
$$B = B_m + \gamma^2 B_e \tag{9}$$

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 electrical system equations. In this work a DFIG is used. This induction machine is fed 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, as it is shown in Figure 1.

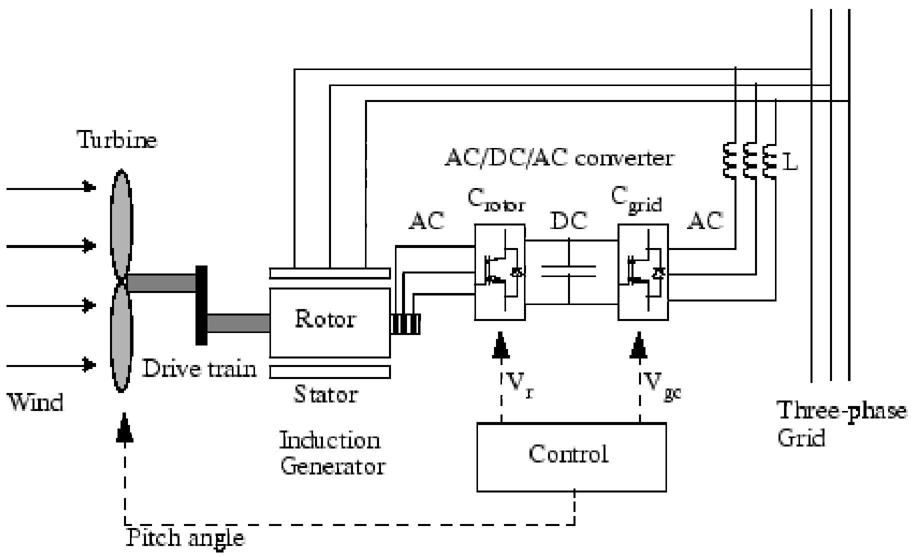

FIGURE 1. Wind turbine system with a DFIG

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 [13].

$$v_{ds} = r_s i_{ds} - w_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \tag{12}$$

$$v_{qs} = r_s i_{qs} + w_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \tag{13}$$

$$v_{dr} = r_r i_{dr} - s\, w_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \tag{14}$$

$$v_{qr} = r_r i_{qr} + s\, w_s \psi_{dr} + \frac{d\psi_{qr}}{dt} \tag{15}$$

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; $sw_s = w_s - w_e$ is the slip frequency, s is the slip and w_e is the generator rotor speed.

The subscripts r and s denote 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 [14]. 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 on the modeling turbine characteristics.

The power coefficient C_p can be approximated by Equation (25) based on the modeling turbine characteristics [15]:

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

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 Equation (25). Then, based on the wind speed, the corresponding optimal generator speed command for maximum wind power extraction 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. See, for example, the wind estimators proposed in [16, 17] and the references therein.

It is noteworthy that the wind signal can present high frequency components coming from the wind fluctuations, and noisy signals coming from the sensors. Therefore, in order to improve the reference speed command the wind speed signal can be filtered using the filtered techniques proposed in [18].

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 is commonly achieved by electrical generator rotor current regulation on the stator-flux oriented reference frame.

In the stator-flux oriented reference frame, the d-axis is aligned with the stator flux linkage vector ψ_s, and then, $\psi_{ds} = \psi_s$ and $\psi_{qs} = 0$. This yields the following relationships [13]:

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

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

$$T_e = \frac{-L_m i_{ms} i_{qr}}{L_s} \tag{30}$$

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

$$v_{dr} = r_r i_{dr} + \sigma L_r \frac{di_{qr}}{dt} - sw_s \sigma L_r i_{qr} \tag{32}$$

$$v_{qr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + sw_s \left(\frac{\sigma L_r i_{dr} + L_m^2 i_{ms}}{L_s} \right) \tag{33}$$

where

$$i_{ms} = \frac{v_{qs} - r_s i_{qs}}{w_s L_m} \tag{34}$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{35}$$

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 [9]. Therefore, the electromagnetic torque can be defined as follows:

$$T_e = -K_T i_{qr} \tag{36}$$

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

$$K_T = \frac{L_m i_{ms}}{L_s} \tag{37}$$

Then, from Equations (7) and (36) 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 (36) it is obtained the following dynamic equation for the system speed:

$$\dot{w} = \frac{1}{J} \left(T_m - \gamma K_T i_{qr} - Bw \right) \tag{38}$$

$$= -aw + f - bi_{qr} \tag{39}$$

where the parameters are defined as:

$$a = \frac{B}{J}, \quad b = \frac{\gamma K_T}{J}, \quad f = \frac{T_m}{J} \tag{40}$$

Now, we are going to consider the previous dynamic Equation (39) with uncertainties as follows:

$$\dot{w} = -(a + \triangle a)w + (f + \triangle f) - (b + \triangle b) i_{qr} \tag{41}$$

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

Let us define the speed tracking error as follows:

$$e(t) = w(t) - w^*(t) \tag{42}$$

where w^* is the wind turbine speed command.

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

$$\dot{e}(t) = \dot{w} - \dot{w}^* = -ae(t) + u(t) + d(t) \tag{43}$$

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

$$u(t) = f(t) - bi_{qr}(t) - aw^*(t) - \dot{w}^*(t) \tag{44}$$

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

$$d(t) = -\triangle aw(t) + \triangle f(t) - \triangle bi_{qr}(t) \tag{45}$$

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 [19]. 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:

$$S(t) = e(t) + \int_0^t (k + a)e(\tau)d\tau \tag{46}$$

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, which is usual in conventional speed control schemes based on sliding mode control theory. The acceleration signal, due to the variability of the wind speed, will introduce a high frequency components in the sliding variable that are undesirable because would increase the chattering phenomenon that usually appear in this kind of controllers.

Then the sliding surface is defined as:

$$S(t) = e(t) + \int_0^t (a + k)e(\tau)d\tau = 0 \tag{47}$$

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

$$u(t) = -ke(t) - \beta \operatorname{sgn}(S) \tag{48}$$

where the k is the constant gain defined previously, β is the switching gain, S is the sliding variable defined in Equation (46) and $\operatorname{sgn}(\cdot)$ 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.

It should be noted that the above assumptions do not limit the applicability of the proposed controller because the the constant k is a parameter of the controller and could be chosen greater than a and an upper limit for the system uncertainties can be always calculated.

Theorem 4.1. *Consider the induction generator given by Equation (41). Then, if assumptions ($\mathcal{A}1$) and ($\mathcal{A}2$) are verified, the control law (48) 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:

$$V(t) = \frac{1}{2}S(t)S(t) \tag{49}$$

Its time derivative is calculated as:

$$\begin{aligned}\dot{V}(t) &= S(t)\dot{S}(t)\\ &= S \cdot [\dot{e} + (k+a)e]\\ &= S \cdot [(-ae + u + d) + (ke + ae)]\\ &= S \cdot [u + d + ke]\\ &= S \cdot [-ke - \beta\,\mathrm{sgn}(S) + d + ke]\\ &= S \cdot [d - \beta\,\mathrm{sgn}(S)]\\ &\leq -(\beta - |d|)|S|\\ &\leq 0\end{aligned} \tag{50}$$

It should be noted that Equations (43), (46) and (48) 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 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* [19].

When the sliding mode occurs on the sliding surface (47), then $S(t) = \dot{S}(t) = 0$, and therefore the dynamic behavior of the tracking problem (43) is equivalently governed by the following equation:

$$\dot{S}(t) = 0 \quad \Rightarrow \quad \dot{e}(t) = -(k+a)e(t) \tag{51}$$

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* followed by *sliding phase*. In the *reaching phase* the trajectories starting off the sliding surface $S = 0$ move toward it and reach it in finite time. During the *sliding phase* the motion will be confined to this surface and the system tracking error will be represented by the reduced-order model (Equation (51)), where the tracking error tends to zero.

Finally, the torque current command, $i_{qr}^*(t)$, can be obtained from Equations (44) and (48):

$$i_{qr}^*(t) = \frac{1}{b}\left[ke + \beta\,\mathrm{sgn}(S) - aw^* - \dot{w}^* + f\right] \tag{52}$$

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 that appear in Equation (52) across the sliding surface, the control law can be smoothed out. In this case a simple and easy solution (proposed in [20]) could be to replace the sign function by a tansigmoid function in order to avoid the discontinuity.

5. **Simulation Results.** In this section we will study the variable speed wind turbine regulation performance using the proposed sliding-mode (SM) 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. In this simulation our proposed SM controller is compared with a traditional PI controller in order to validate the performance of our SM controller. The power regulation performance of the wind turbine system using a PI controller has been studied in several works like [9, 21, 22] and the references therein. Therefore, the PI control will provide a good reference for determining the performance of the proposed SM controller. In particular the proposed SM controller is compared with the PI controller proposed in [21], where the PI controllers have been tuned applying the pole assignment method, in an attempt to reach a critically damped inner loop response with a 40-ms settling time.

The simulation are carried out using the Matlab/Simulink software and the turbine model is the one provided in the SimPowerSystems library [23].

In this 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 (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 $J = 5.04$ s expressed in seconds, the combined viscous friction factor $B = 0.01$ pu 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 [23].

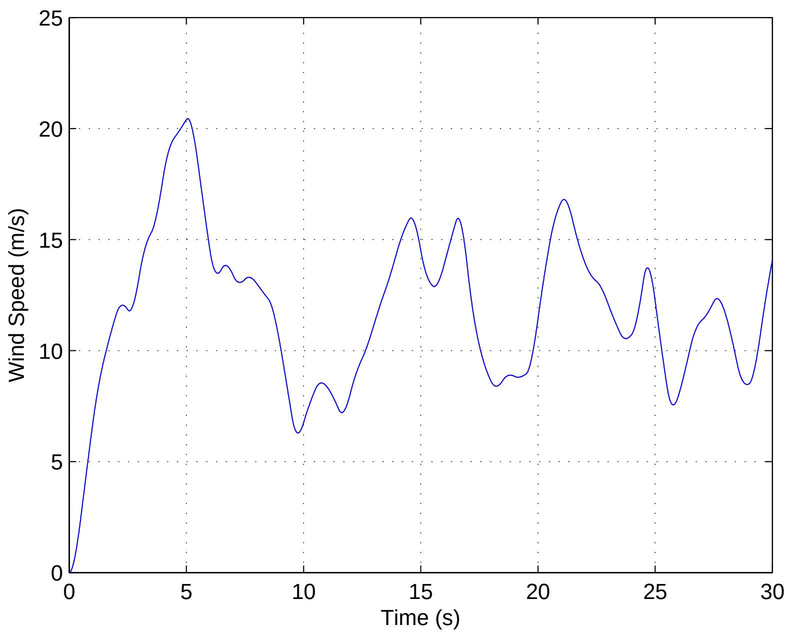

FIGURE 2. Wind speed

In this simulation example it is assumed that there is an uncertainty of 20% in the system parameters, which 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 Figure 2, the wind speed varies between 0 m/s and 20 m/s.

Figure 3 shows the reference (solid line), the real rotor speed obtained with the proposes SM controller (dashed line) and the real rotor speed obtained using a traditional PI controller (dashed doted line). It is clear that the speed tracking performance is improved using the proposed SM controller because as it may be observed in the figure, 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).

Figure 4 shows the generated active power using our proposed SM control scheme (solid line) and the generated active power using a traditional PI control scheme (dashed line). As expected, the SM controller presents a better optimization of the power generated,

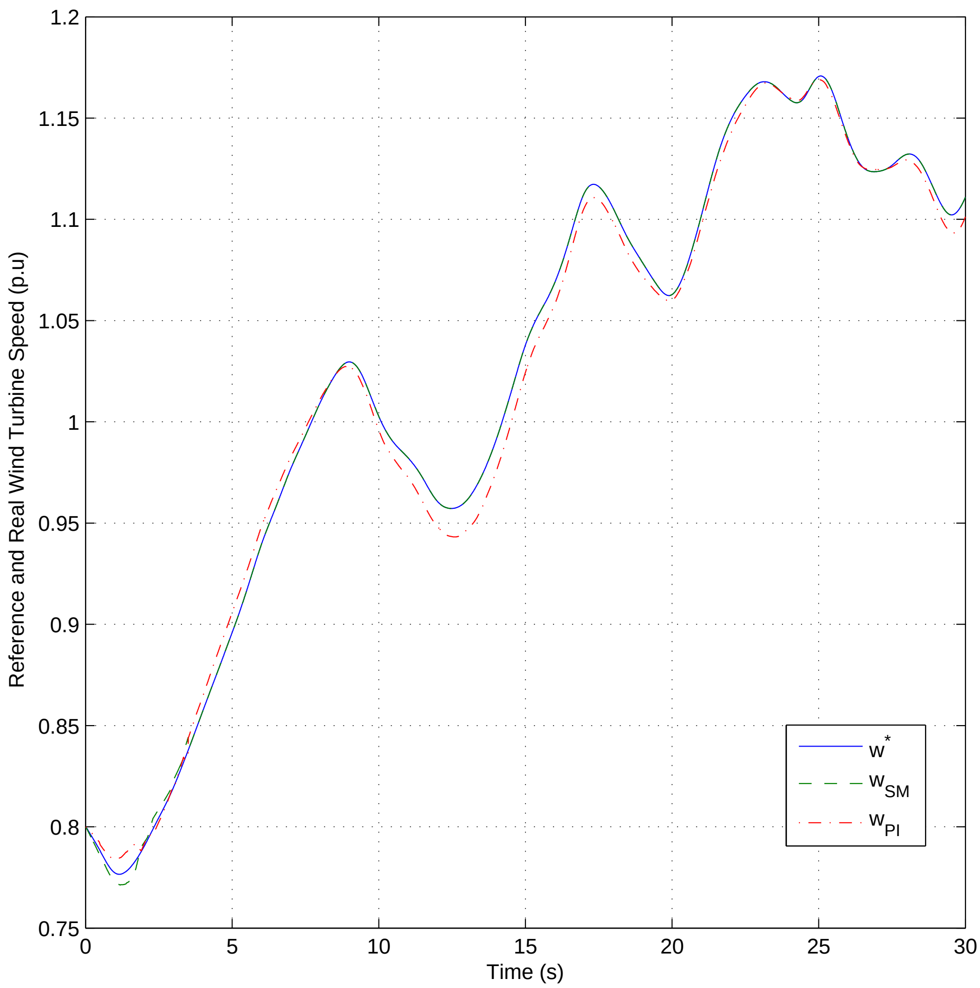

FIGURE 3. Reference and real wind turbine speed

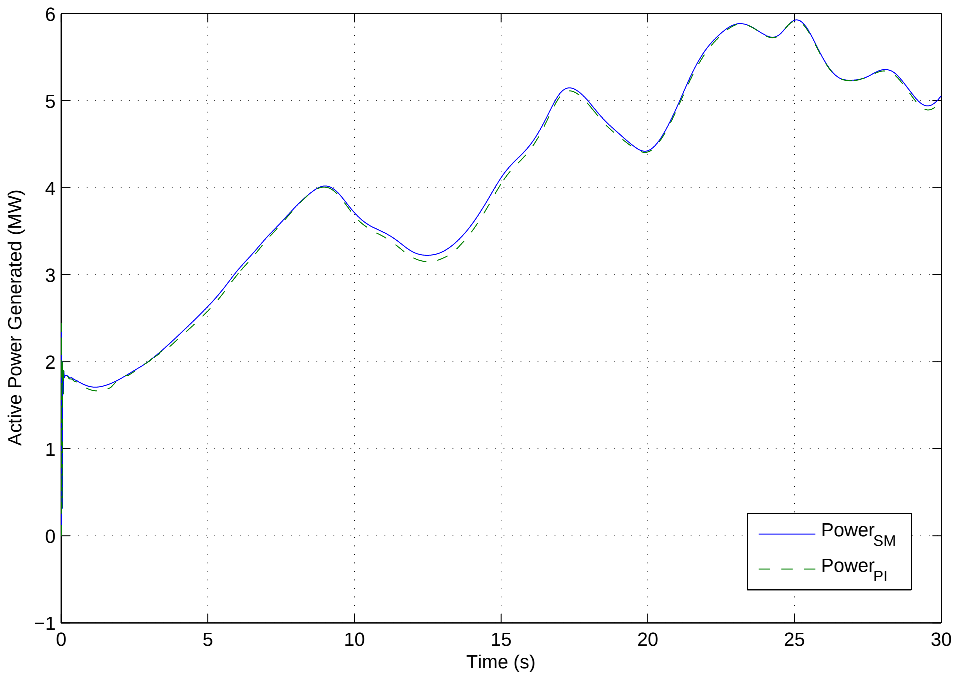

FIGURE 4. Generated active power

because as it can be seen in the previous figure the SM controller achieves a better speed tracking for maximum power generation. Moreover, the computational cost of the proposed SM algorithm is similar to the PI controller, but the SM controller is more robust under wind speed variations and system uncertainties. Therefore, the SM controller provides better tracking for the optimal generator speed command, and then a better power extraction from the wind is achieved.

Finally, some computational issues have been carried out. In particular it is observed that the computational cost of the proposed SM controller is similar to the PI controller. Both controllers present a low computational cost and therefore could be implemented in a low cost DSP processor. However, the SM controller is more robust an present a better performance under system uncertainties and wind speed variations. Therefore, the SM controller provides better tracking of the optimal generator speed command and then a greater power extraction from the wind is obtained.

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 presents more simplicity of computation and less time execution consuming than other robust control schemes.

The variable structure control has an integral sliding surface in order to relax the requirement of the acceleration signal in the sliding variable. 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, which would increase the chattering. 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 proposed control method allows the wind turbine to operate with the optimum power efficiency over a wide range of wind speed. This control method successfully controls the wind turbine speed within a range of normal operational conditions in order to obtain the maximum electrical power. At wind speeds below the rated wind speed, the proposed speed controller seeks to maximize the power according to the maximum coefficient curve.

Finally, simulation examples have 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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