VARIABLE STRUCTURE CONTROL FOR MAXIMUM WIND POWER EXTRACTION

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ABSTRACT

The actual wind turbines are provided with adjustable speed generators, like the double feed induction generator, that are capable to work in variable speed operations. One of the main advantage of adjustable speed generators is that they improve the system efficiency compared to fixed speed generators because turbine speed is adjusted as a function of wind speed to maximize output power. However this systems requires a suitable speed controller in order to track the optimal wind turbine speed reference. In this work, it is proposed a sliding mode control for variable speed wind turbines. The robustness analysis of the proposed controller under disturbances and parameter uncertainties is provided using the Lyapunov stability theory and simulated results show that the proposed controller provides a good performance.

KEY WORDS

Wind Power, Variable Structure Control, Nonlinear System, Modeling and Simulation

1 Introduction

Wind energy is an abundant renewable source of electricity 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. Increasingly sophisticated power electronic and computerized control schemes, will lead to excessive improvements and full controllability of available wind power. Large wind energy plants will mean that there are 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. 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) [12]. This can lead to a change in the electric system real power demand resulting in power oscillation.

This paper investigates a new robust speed control method for variable speed wind turbines with Double Fed Induction Generator (DFIG) [6], [9]. The objective is to make the rotor speed track the desired speed in spite of system uncertainties. This is achieved by regulating the rotor current of the DFIG using the sliding mode control theory. In the design it is used a vector oriented control theory in order to decouple the torque and the flux of the induction machine. The proposed control scheme leads to obtain the maximum power extraction from the different wind speeds that appear along time. Finally, 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 modelling

The power extraction of 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 [1], [14]:

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

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:

$$\lambda = \frac{Rw}{v} \qquad (2)$$

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 power output 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 power output 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 aeroturbine, which converts wind energy into mechanical energy, a gearbox, which serves to increase the speed and decrease the torque and a generator to convert mechanical energy into electrical energy.

The mechanical equations of the system can be characterized by [10]:

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

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

$$T_t w_e = -Tw \tag{5}$$

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 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_t is the torque in the transmission shaft after gear box, and T_e is the the the generator torque, w is the angular velocity of the turbine shaft 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:

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

Then, using equations 3, 4, 5 and 6 it is obtained:

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

with

$$J = J_m + \gamma^2 J_e \tag{8}$$

$$B = B_m + \gamma^2 B_e \tag{9}$$

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 it is used a double feed induction generator (DFIG). 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 [8], [9].

3 DFIG control scheme

In order to extract the maximum active power from the wind, the shaft speed of the WTG 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 [4]. In other words, given a particular wind speed, there is a unique wind turbine speed required to achieve the goal of maximum wind 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 12 based on the modeling turbine characteristics [3]:

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} + c_6 \lambda \tag{12}$$

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

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \beta} - \frac{0.035}{\beta^3 + 1} \tag{13}$$

The value of λ_{opt} can be calculated from the roots of the derivative of the equation 12. Then, based on the wind speed, the corresponding optimal generator speed command for maximum wind power tracking is determined by:

$$w^* = \frac{\lambda_{opt} \cdot v}{R} \tag{14}$$

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) [5]. 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. A typical scheme of a DFIG equipped wind turbine is shown in Figure 1.

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 speed
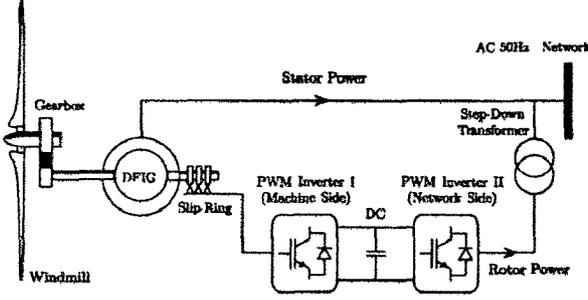
Figure 1. Scheme of a DFIG equipped wind turbine

reference w^* for maximum wind power extraction. This objective are commonly achieved by electrical generator rotor current regulation on the stator-flux oriented reference frame [7].

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. Then, ussing 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:

$$i_{qs} = \frac{L_m i_{qr}}{L_s} \tag{15}$$

$$i_{ds} = \frac{L_m(i_{ms} - i_{dr})}{L_s} \tag{16}$$

$$T_e = \frac{-L_m i_{ms} i_{qr}}{L_s} \tag{17}$$

$$Q_s = \frac{3}{2} \frac{w_s L_m^2 i_{ms}(i_{ms} - i_{dr})}{L_s} \tag{18}$$

$$v_{dr} = r_r i_{dr} + \sigma L_r \frac{di_{qr}}{dt} - sw_s \sigma L_r i_{qr} \tag{19}$$

$$v_{qr} = r_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} \tag{20}$$

$$+sw_s \left(\frac{\sigma L_r i_{dr} + L_m^2 i_{ms}}{L_s} \right) \tag{21}$$

where w_s is the rotational speed of the synchronous reference frame, $sw_s = w_s - w_e$ is the slip frequency and s is the slip, w_e is the generator rotor speed, and

$$i_{ms} = \frac{v_{qs} - r_s i_{qs}}{w_s L_m} \tag{22}$$

$$\sigma = 1 - \frac{L_m^2}{L_s L_r} \tag{23}$$

Since the stator is conectad to the grid, and the influence of the stator resistance is small, the stator magnetizing current (i_{ms}) can be considered constant [8]. Therefore, the electromagnetic torque can be defined as follows:

$$T_e = -K_T i_{qr} \tag{24}$$

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

$$K_T = \frac{L_m i_{ms}}{L_s} \tag{25}$$

Then, from equations 7 and 24 it is deduced that the wind turbine speed can be controlled by regulating the q-axis rotor current components (i_{qr}) while equation 18 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.

From equations 7 and 24 it is obtained the following dynamic equation for the system speed:

$$\dot{w} = \frac{1}{J} (T_m - \gamma K_T i_{qr} - Bw) \tag{26}$$

$$= -aw + f - bi_{qr} \tag{27}$$

where the parameters are defined as:

$$a = \frac{B}{J}, \quad b = \frac{\gamma K_T}{J}, \quad f = \frac{T_m}{J}; \tag{28}$$

Now, we are going to consider the previous dynamic equation (27) with uncertainties as follows:

$$\dot{w} = -(a + \Delta a)w + (f + \Delta f) - (b + \Delta b)i_{qr} \tag{29}$$

where the terms Δa, Δb and Δf represents the uncertainties of the terms a, b and f respectively.

Let us define define the speed tracking error as follows:

$$e(t) = w(t) - w^*(t) \tag{30}$$

where w^* is the rotor speed command.

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

$$\dot{e}(t) = \dot{w} - \dot{w}^* = -a e(t) + u(t) + d(t) \tag{31}$$

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

$$u(t) = f(t) - b i_{qr}(t) - a w^*(t) - \dot{w}^*(t) \tag{32}$$

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

$$d(t) = -\Delta a\, w(t) + \Delta f(t) - \Delta b\, i_{qr}(t) \tag{33}$$

To compensate for the above described uncertainties that are present in the system, it is proposed a sliding control scheme. In the sliding control theory, the switching gain must be constructed so as to attain the sliding condition [13]. In order to meet this condition a suitable choice of the sliding gain should be made to compensate for the uncertainties.

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

$$S(t) = e(t) + \int_0^t (k + a)e(\tau)\, d\tau \qquad (34)$$

where k is a constant gain.

Then the sliding surface is defined as:

$$S(t) = e(t) + \int_0^t (a + k)e(\tau)\, d\tau = 0 \qquad (35)$$

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

$$u(t) = -k\,e(t) - \beta\,\mathrm{sgn}(S) \qquad (36)$$

where the k is the constant gain defined previously, β is the switching gain, S is the sliding variable defined in eqn. (34) 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 $\beta \geq |d(t)|$ for all time.

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

Theorem 1 *Consider the induction motor given by equation (29). Then, if assumptions $(\mathcal{A}1)$ and $(\mathcal{A}2)$ are verified, the control law (36) 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.

<u>Proof</u>: Define the Lyapunov function candidate:

$$V(t) = \frac{1}{2}S(t)S(t) \qquad (37)$$

Its time derivative is calculated as:

$$\begin{aligned}
\dot{V}(t) &= S(t)\dot{S}(t) \\
&= S \cdot [\dot{e} + (k + a)e] \\
&= S \cdot [(-ae + u + d) + (ke + ae)] \\
&= S \cdot [u + d + ke] \\
&= S \cdot [-ke - \beta\,\mathrm{sgn}(S) + d + ke] \\
&= S \cdot [d - \beta\,\mathrm{sgn}(S)] \\
&\leq -(\beta - |d|)|S| \\
&\leq 0 \qquad (38)
\end{aligned}$$

It should be noted that the eqns. (34), (31) and (36) 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, then the equilibrium at the origin $S(t) = 0$ is globally asymptotically stable. 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* [13].

When the sliding mode occurs on the sliding surface (35), then $S(t) = \dot{S}(t) = 0$, and therefore the dynamic behavior of the tracking problem (31) is equivalently governed by the following equation:

$$\dot{S}(t) = 0 \quad \Rightarrow \quad \dot{e}(t) = -(k + a)e(t) \qquad (39)$$

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. 39), where the tracking error tends to zero.

Finally, the torque current command, $i_{qr}^*(t)$, can be obtained from equations (36) and (32):

$$i_{qr}^*(t) = \frac{1}{b}\left[ke + \beta\,\mathrm{sgn}(S) - aw^* - \dot{w}^* + f\right] \qquad (40)$$

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.

4 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 [11].

In this example simulation it is used a variable speed wind farm with a rated power of 9 MW. 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 [11].

In this simulation examples it is assumed that there is an uncertainty around 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, $k = 100$, $\beta = 30$.

In this case study, the rotor is running at subsynchronous speed for wind speeds lower than 10 m/s and it is running at a super-synchronous speed for higher wind speeds. In figure 2, the turbine mechanical power as function of turbine speed is displayed in, for wind speeds ranging from 5 m/s to 16.2 m/s.
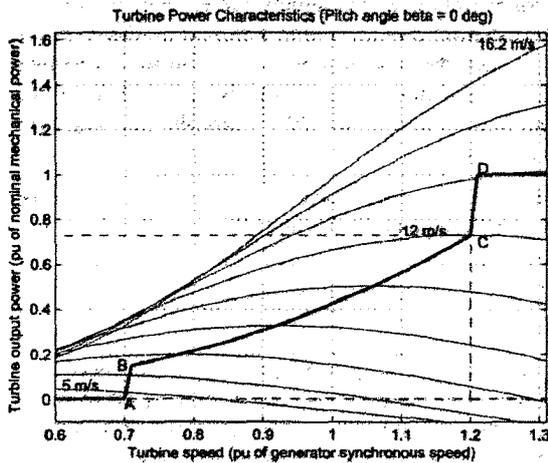

Figure 2. Turbine Power Characteristics

In this simulation it is used a variable wind speed, and figure 3 shows the wind speed used in this simulation. As it can be seen in the figure, the wind speed varies between $0m/s$ and $28m/s$.

Figure 4 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 5 shows the generated active power, whose value is maximized by our proposed sliding mode control
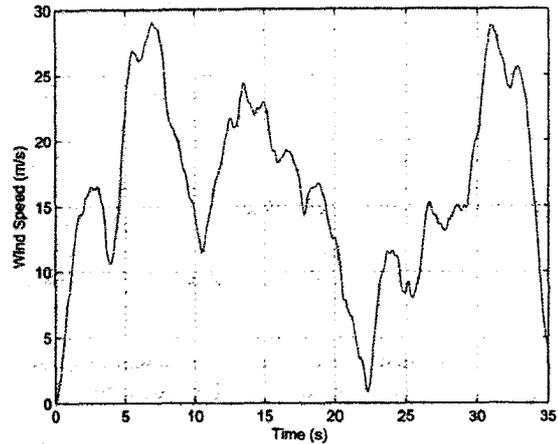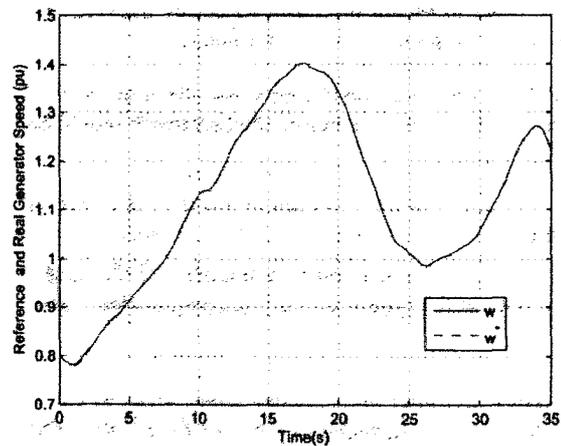

Figure 3. Wind speed

Figure 4. Reference and real rotor speed

scheme. As it can be observed in this figure, at time 13.3s the mechanical power (and therefore the generated active power) should be limited by the pitch angle so as not to exceed the rated power of this system.

5 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. It is proposed a new variable structure control which has an integral sliding surface to relax the requirement of the acceleration signal, that is usual in conventional sliding mode speed control techniques. Due to the nature of the sliding control this control scheme is robust under uncertainties that appear in the real systems. The closed loop stability of the presented design
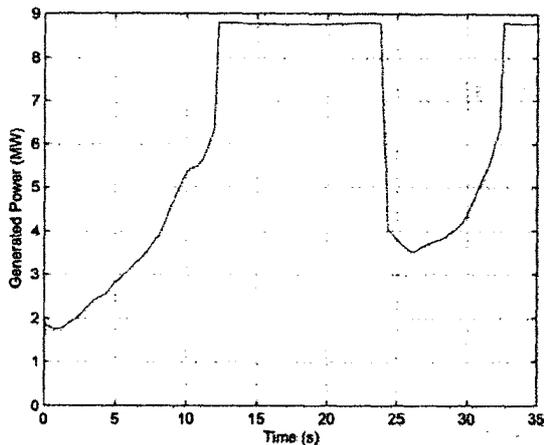
Figure 5. Generated active power

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 simulations show that 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 in the wind speed. At large wind speeds, the power limitation controller sets the blade angle to maintain rated power.

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

Acknowledgments

References

[1] FERNANDO D. BIANCHI, HRNAN DE BATTISTA AND RICARDO J. MANTZ 2007 *Wind Turbine Control Systems* Advances in Industrial Control Series. Springer.

[2] GAGNON, R. SYBILLE, G. ET ALL 2005 Modelling and Real-Time Simulation of a Doubly-Fed Induction Generator Driven by a Wind Turbine *Int. Conf. on Power Systems Transients.* Montreal, Canada. Paper No. IPST05-162.

[3] SIEGFRIED HEIER 1998 *Grid Integration of Wind Energy Conversion Systems* John Wiley & Sons Ltd, 1998, ISBN 0-471-97143-X.

[4] G.M. JOSELIN HERBERT, S. INIYAN, E. SREEVALSAN, S. RAJAPANDIAN 2007, A review of wind energy technologies, *Renewable and Sustainable Energy Reviews.*, 11, pp. 11171145.

[5] YAZHOU LEI, ALAN MULLANE, GORDON LIGHTBODY, AND ROBERT YACAMINI 2006, Modeling of the Wind Turbine With a Doubly Fed Induction Generator for Grid Integration Studies, *IEEE Trans. on Energy Conversion*, vol. 21, no. 1, pp. 257-264.

[6] MULLER, S., DEICKE, M., DE DONCKER, R.W., 2002, Doubly fed induction generator system for wind turbines, *IEEE Industry Application Magazine.*, 8, pp. 26-33.

[7] D. W. NOVOTNY AND T. A. LIPO, 2000 *Vector Control and Dynamics of AC Drives.* Oxford, U.K.: Oxford Univ. Press, 2000.

[8] R. PENA, J. C. CLARE, AND G. M. ASHER 1996 Doubly fed induction generator using back-to-back PWM converters and its application to variablespeed wind-energy generation *Proc. Inst. Elect. Eng.*, vol. 143, no. 3, pp. 231241.

[9] WEI QIAO, WEI ZHOU, JOS M. ALLER, AND RONALD G. HARLEY 2008, Wind Speed Estimation Based Sensorless Output Maximization Control for a Wind Turbine Driving a DFIG *IEEE Trans. on Power Electronics*, vol. 23, no. 3, pp. 1156-1169.

[10] Y.D. SONG, B. DHINAKARAN, X.Y. BAO, 2000, Variable speed control of wind turbines using nonlinear and adaptive algorithms, *Journal of Wind Engineering and Industrial Aerodynamics.*, 85, pp. 293-308.

[11] *SimPowerSystems 5. Users Guide*, The MathWorks

[12] SUN, T., CHEN, Z., BLAABJERG, F., 2005, Transient stability of DFIG wind turbines at an external short-circuit fault, *Wind Energy.*, 8, pp. 345-360.

[13] UTKIN V.I., 1993, Sliding mode control design principles and applications to electric drives, *IEEE Trans. Indus. Electro.*, 40, 26-36.

[14] VLADISLAV AKHMATOV, 2002, Variable-Speed Wind Turbines with Doubly-Fed Induction Generators, *Wind Engineering*, vol. 26, n. 2, pp. 85108.