Quasi-Continuous High-Order Sliding-Mode Controller Design for Variable-Speed Wind Turbines

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Abstract— **In this paper, a multivariable control strategy is done which solves the problem of output power regulation of variable speed wind energy conversion systems, while also reduced the mechanical loads by combining a linear control for blade pitch angle with a nonlinear quasi-continuous high-order sliding-mode torque control. The properties of the proposed controller are robustness to parametric uncertainties of the turbine, robustness with respect to external disturbances, robustness to unmodeled dynamics and accuracy, with an accuracy of higher order and finite reaching time. The high-order sliding-mode controller is applied to reduce the effects of chattering in the generated torque that could lead to increased mechanical stress because of strong torque variations. We use a realistic model which takes into account the nonlinear dynamic aspect of the wind turbine and the turbulent nature of the wind. We assume that the rotor speed and electric power are available from measurements on the wind turbine. Simulation results illustrate the effectiveness of the controller in terms of power regulation and load reduction.**

Keywords: Wind turbines, nonlinear control, sliding-mode, multivariable control.

I. INTRODUCTION

As a result of population expansion and increased global integration, has been a great growth in energy consumption. This supposes a risk for the depletion of natural resources, this has caused the increase in demand of renewable energy generation systems (Masters, 2004). Wind energy has proved to be an important source of clean and renewable energy in order to produce electrical energy. Nowadays, wind energy is one the fastest growing renewable energy technologies, the worldwide installed capacity of wind power for 2011 grew by 22.0 %. The WWEA published this year the last updated version for wind turbines installed worldwide, with a total installed capacity of 239000 MW, enough to cover a 3 % of the world's electricity defendant (The World Wind Energy Association, 2012) (see Fig. 1). However, the performance of wind turbine must be improved. There are two primary types of horizontal-axis wind turbines: fixed speed and variable speed (Ofualagba and Ubeku, 2008). In this work we choose the variable speed because although the fixed speed system is easy to build and operate, does not have the ability that the variable speed system has in energy extraction, up to a 20-30 % increase over fixed speed (Ofualagba and Ubeku, 2008). Moreover, the variable speed system is much more complex to control. Advanced control plays an important role in the performance of large wind turbines. This allows better use of resources of the turbine, increasing the lifetime of mechanical and electrical components, earning higher returns. On the other hand, the new technological advancements improve the prospects of wind power allowing the design of cost-effective of wind turbines. Wind turbine controller objectives depend on the operation area (Pao and Johnson, 2011). Variable speed wind turbine operation can be divided into three operating regions (see Fig. 2):

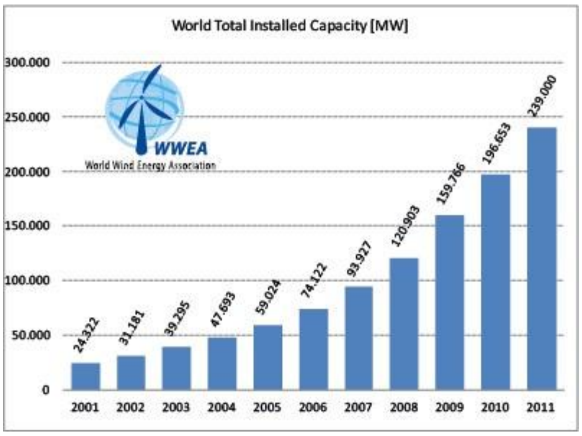

Figure 1. World Total Installed Capacity in MW.

- Region I: Below cut-in wind speed.
- Region II: Between cut-in wind speed and rated wind speed.
- Region III: Between rated wind speed and cut-out wind speed.

In region I wind turbines do not run, because power available in wind is low compared to losses in turbine system. Region II is an operational mode where it is desirable that the turbine capture as much power as possible from the wind, this because wind energy extraction rates are low and the structural loads are relatively small. Generator torque provides the control input to vary the rotor speed, while the blade pitch is held constant.

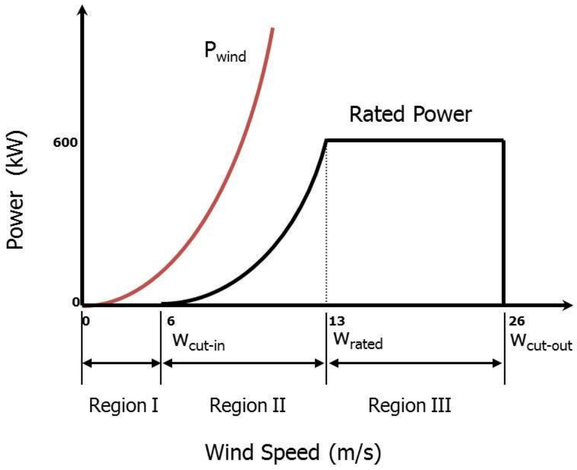

Figure 2. Power curve of steady state for the CART.

Region III is encountered when the wind speeds are high enough, that the turbine must limit the fraction of the wind power captured such that safe electrical, and mechanical loads are not exceeded. If wind speeds exceed contains the region III, the system will make a forced stop the machine, protecting it from aerodynamic loads excessively high. Generally the rated rotor speed and power output are maintained by the blade pitch control with the generator torque constant at its rated value. Region III is considered in the present work.

Several control strategies have been proposed in the literature, mostly based on linear time-invariant models. This, for several reasons. First, linear control theory is a well-developed topic while nonlinear control theory is less developed and difficult to implement. Second, most wind turbine control systems, to date, is based on linear control theory, thus the implemented wind turbine controllers are the based on linearized models (Boukhezzar *et al.*, 2007). Classical controllers have been extensively used, particularly PI control (Hand and Balas, 1999). Another method commonly used is PID controllers. These PID controllers are used in conjunction with gain-scheduled to accommodate to variations in the wind (Hansen *et al.*, 2005). Hammerum (Hammerum, 2006) designed controllers for reduce the load on the turbine structure based on optimal equilibrium points resulting in the definition of modes of operation; it is considered a single hybrid driver, besides the LQI control design which ensure stability to the linearized closed loop system model. Linear methods such as LQ, LQG and H_∞ are studied in (Bossanyi, 2003). Stol and Balas (Stol and Balas, 2001) make a comparison of a constant gain control against periodic gain control to regulate the speed of main shaft of the turbine using a constant generator torque and collective control angle of the blades. Although some of these classical methods have been successfully applied, they are limited and problematic when extended to consider multiple controlled variables, such as controlling tower vibration, rotor speed, and blade vibration simultaneously (see, e.g., (Grimble, 1996; Pao and Johnson, 2011; Thomsen, 2006; Bianchi *et al.*, 2007)).

Most previous work do not consider the nonlinear part directly on their controllers. Recently, nonlinear control of wind turbines has been of interest to the scientific community. Thomsen (Thomsen, 2006) describes the analysis of several nonlinear methods to control wind turbine for a single region of the wind speed. The control methods investigated are: gain scheduling, feedback linearization, sliding-mode, and inverse nonlinear optimal control. In addition, noise measurements have been introduced in the simulation model and lack of measurement of some states. Thomsem and Poulsen (Thomsen and Poulsen, 2007) describe a linearization control law using feedback linearization, the novel aspect of the control law is the ability to decouple the fluctuations of the wind. Johnson (Johnson, 2004) designed an adaptive control to compensate for unknown and time-varying parameters. Boukhezzar and Siguerdidjane (Boukhezzar and Siguerdidjane, 2011) compare two commonly encountered controllers: Aerodynamic Torque Feed Forward controller and Maximum Power Point Tracking, with a nonlinear static and dynamics state feedback control. Four second-order sliding-mode controllers are compared in (Evangelista *et al.*, 2010) working in region II concluding that the Super-Twisting algorithm is the best option for the studied case. A Super-Twisting sliding-mode control with variable gains is design in (Evangelista *et al.*, 2012) which is compared to Super-Twisting algorithm with fixed gains showing a better performance in terms of chattering, mechanical loads, and power tracking. In general, the nonlinear controllers have better performance than the one reached by linear controllers.

Homogeneous quasi-continuous high-order sliding-mode controller suggested in (Levant, 2005*b*) with the homogeneous differentiation (Levant, 2003) is proposed to use, which has not been used in wind turbines, at least in our knowledge. The controller takes into consideration the nonlinear nature of the wind turbine behavior, the flexibility of drive train, as well as the turbulent nature of the wind. This control strategy presents attractive features such as robustness to parametric uncertainties of the turbine, also presents robustness with respect to internal and external disturbances and model uncertainties, finite-time convergence, and reduces the chattering. The controller is design using a single mass model of a wind turbine and its performance has been tested through simulations. The dynamic model of a horizontal axis variable speed wind turbine is simulated in MATLAB-Simulink.

The paper is organized as follows. In Section II the wind turbine model and problem formulation is presented. The robust control design is provided in Section III. Performance of the proposed controller is given in Section IV through simulations. Section V presents some conclusions.

II. WIND TURBINE MODEL AND PROBLEM STATEMENT

The aerodynamic power captured by the rotor is given by the nonlinear expression (Burton *et al.*, 2011)

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

where v is the wind speed, ρ is the air density, and R is the rotor radius. The efficiency of the rotor blades is denoted as C_p, which depends on the blade pitch angle

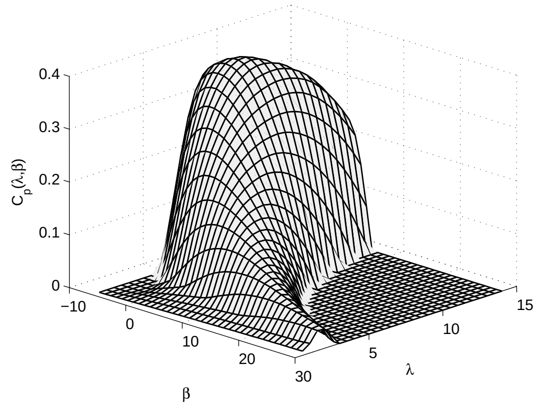

Figure 3. Power coefficient curve.

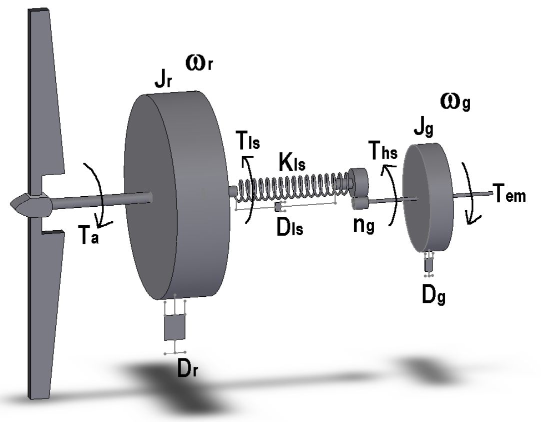

Figure 4. Two-mass wind turbine model.

β, or the angle of attack of the rotor blades, and the tip speed ratio λ, the ratio of the blade tip linear speed to the wind speed. The parameters β and λ affect the efficiency of the system. The coefficient C_p is specific for each wind turbine. The relationship of tip speed ratio is given by

$$\lambda = R\frac{\omega_r}{v}. \tag{2}$$

The turbine estimated $C_p - \lambda - \beta$ surface, derived from simulation is illustrated in Fig. 3. This surface was created with the modeling software WTPerf (Buhl, 2009), which uses blade-element-momentum theory to predict the performance of wind turbines (Burton *et al.*, 2011). The WTPerf simulation was performed to obtain the operating parameters for the CART (Controls Advanced Research Turbine). The wind turbine considered in this study is variable speed one, in which the rotor speed increases and decreases with changing wind speed, producing electricity with a variable frequency. Fig. 3 indicates that there is one specific λ at which the turbine is most efficient. From (1) and (2), one can note that the rotor efficiency is highly nonlinear and makes the entire system a nonlinear system. The efficiency of power capture is a function of the tip speed ratio and the blade pitch. The power captured from the wind follows the relationship

$$P_a = T_a\omega_r \tag{3}$$

where

$$T_a = \frac{1}{2}\rho\pi R^3\frac{C_p(\lambda,\beta)}{\lambda}v^2 \tag{4}$$

is the aerodynamic torque which depends nonlinearly upon the tip speed ratio. A variable speed wind turbine generally consists of an aeroturbine, a gearbox, and a generator, as shown in Fig. 4.

The wind turns the blades generating an aerodynamic torque T_a, which spin a shaft at the speed ω_r. The low speed torque T_{ls} acts as a braking torque on the rotor. The gearbox, which increases the rotor speed by the ratio n_g to obtain the generator speed ω_g and decreases the high speed torque T_{hs}. The generator is driven by the high speed torque T_{hs} and braked by the generator electromagnetic torque T_{em} (Boukhezzar *et al.*, 2007). The mathematical model of the two-mass wind turbine, can be described as follows:

$$\begin{aligned}J_r\dot{\omega}_r &= T_a(\omega_r,\beta,v) - K_{ls}(\theta_r - \theta_{ls}) - D_{ls}(\omega_r - \omega_{ls})\\ &\quad - D_r\omega_r\\ J_g n_g\dot{\omega}_g &= -T_{em}n_g + K_{ls}(\theta_r - \theta_{ls}) + D_{ls}(\omega_r - \omega_{ls})\\ &\quad - D_g n_g\omega_g\end{aligned} \tag{5}$$

where ω_{ls} is the low shaft speed, θ_r is the rotor side angular deviation, θ_{ls} is the gearbox side angular deviation, J_r is the rotor inertia, J_g is the generator inertia, D_r is the rotor external damping, D_g is the generator external damping, D_{ls} is the low speed shaft damping, and K_{ls} is the low speed shaft stiffness. Assuming an ideal gearbox with transmission n_g:

$$n_g = \frac{\omega_g}{\omega_{ls}} = \frac{T_{ls}}{T_{hs}}. \tag{6}$$

If a perfectly rigid low speed shaft is assumed, $\omega_r = \omega_{ls}$, a single mass model of the turbine can then be considered, upon using (6) and (5), one gets:

$$J_t\dot{\omega}_r = T_a(\omega_r,\beta,v) - D_t\omega_r - T_g \tag{7}$$

where $J_t = J_r + n_g^2 J_g$, $D_t = D_r + n_g^2 D_g$, and $T_g = n_g T_{em}$ are the turbine total inertia, turbine total external damping, and generator torque in the rotor side, respectively. The parameters of the model are given in Table I. Those parameters are based on the CART which is a two-bladed, teetered, active-yaw, upwind, variable speed, variable pitch, horizontal axis wind turbine which is located at the National Wind Technology Center in Colorado. The nominal power is 600 kW, the rated wind speed of 13 m/s, a cut out wind speed of 26 m/s, and it has a maximum power coefficient $C_{p\max}$ = 0.3659. The rated rotor speed is 41.7 rpm. The pitch system can pitch the blades up to 18 degrees deg/s with pitch accelerations up to 150 deg/s^2 (Wright and Fingersh, 2008). The required constraints for torque and rotor speed are 162 kNm and 58 rpm respectively (Fingersh and Johnson, 2002). The gearbox is connected to an induction generator via the high speed shaft, and the generator is connected to the grid via power electronics. In this work we will ignore the power electronics control and an ideal performance will be assumed (Thomsen, 2006; Hammerum, 2006).

TABLE I
ONE-MASS MODEL PARAMETERS

Notation	Numerical value	Units
R	21,650	m
ρ	1,308	kg/m^3
J_t	3,920 × 10^5	kg m^2
D_t	400	Nm/rad/s
H	36,600	m
P_{enom}	600	kW
n_g	43,165	

Generator power will be controlled in region III when the wind speeds are high enough that the turbine must limit the fraction of the wind power captured so that safe electrical and mechanical loads are not exceeded. The objective control in this region is to find a control law T_g and $\Delta\beta$ to achieve the best tracking of rated of power while ω_r follows ω_{rnom}, as well as to reject fast wind speed variations and avoiding significant control efforts that induce undesirable torques and forces on the wind turbine structure. We design a controller using blade pitch and generator torque as control inputs.

The aim of this paper is to design a robust controller to work in region III where wind speeds are high and dramatic growth of load structural. In this region the primary objective of the turbine controller is to reduce electrical power and rotor speed fluctuations while also the loads are reduced. To limit loads and maintaining electric power production is necessary to limit the power and the rotational speed at its nominal values. Due to the stochastic operating conditions and the inevitable uncertainties inherent in the system a robust control strategy must be implemented. The proposed control strategy will therefore solve the regulation problem using a quasi-continuous higher-order sliding-mode control.

III. ROBUST CONTROL DESIGN

Using quasi-continuous high-order sliding-mode control is well suited because has desired properties, such as robustness under uncertainties. It also may reduce chattering and provides better transient features than the other high order sliding-mode (Levant, 2005*b*). It is call quasi-continuous because is continuous if the produced control is a continuous function of the state variables everywhere except the r-sliding set:

$$\sigma = \dot{\sigma} = \ddot{\sigma} \cdots = \sigma^{(r-1)} = 0. \tag{8}$$

Control is represented by

$$u = -\alpha\Psi_{r-1,r}(\sigma, \dot{\sigma}, ..., \sigma^{(r-1)}) \tag{9}$$

where

$$\begin{aligned} \varphi_{0,r} &= \sigma \;\; N_{0,r} = |\sigma| \;\; \Psi_{0,r} = \varphi_{0,r}/N_{0,r} = sign(\sigma) \\ \varphi_{0,r} &= \sigma^{(i)} + \beta_i N_{i-1,r}^{(r-i)/(r-i+1)} \Psi_{i-1,r} \\ N_{i-r} &= |\sigma^{(i)}| + \beta_i N_{i-1,r}^{(r-i)/(r-i+1)} \;\; \Psi_{i,r} = \varphi_{i,r}/N_{i,r} \end{aligned} \tag{10}$$

where $\beta_1, \ldots, \beta_r$ are positive numbers, and $\alpha > 0$.

III-A. Quasi-Continuous High-Order Sliding-Mode Controller

A sliding manifold is chosen as follows

$$\varepsilon_p = P_{enom} - P_e \tag{11}$$

where $P_e = \omega_r T_g$ is the electrical power, ε_p is the electrical power error. Because controller (14) requires to know the time derivative $\dot{\varepsilon}_p$, we use the Levant differentiator (Levant, 2003), (Levant, 2005*a*) for the estimations $\dot{\varepsilon}_p$. A first-order real-time differentiator

$$\begin{aligned} \dot{z}_0 &= z_1 - \lambda_2 \left|L\right|^{1/2} \left|z_0 - \varepsilon_p\right|^{1/2} sign(z_0 - \varepsilon_p) \\ \dot{z}_1 &= -\lambda_1 L sign(z_1 - \dot{z}_0) \end{aligned} \tag{12}$$

where z_0, z_1 are real-time estimations of ε_p, $\dot{\varepsilon}_p$ respectively. Here the second order quasi-continuous sliding-mode controller is developed to achieve robust power regulation. For that purpose, let us consider the electric power regulation error ε_p, then using $P_e = \omega_r T_g$ one gets

$$\dot{\varepsilon}_p = -\dot{\omega}_r T_g - \omega_r \dot{T}_g. \tag{13}$$

The following controller (14) is designed for (13)

$$\dot{T}_g = \frac{\alpha(\dot{\varepsilon}_p + \left|\varepsilon_p\right|^{1/2} sign(\varepsilon_p))/(|\dot{\varepsilon}_p| + \left|\varepsilon_p\right|^{1/2})}{\omega_r}. \tag{14}$$

III-B. Pitch Controller

In order to regulate the rotor speed and reduce generator torque oscillation, the torque control is aided by the pitch action. The pitch control allows to maintain the rotor speed around its nominal value. To achieve this, proportional action is used

$$\Delta\beta = K_p e_\omega \tag{15}$$

where $e_\omega = \omega_{r\text{nom}} - \omega_r$ is the rotor speed tracking error and $K_p > 0$. According to (Boukhezzar *et al.*, 2007) more complex action (PI,PID) will make the pitch control more turbulent without a significant improvement of the power regulation performance.

IV. SIMULATION RESULTS WITH TURBULENT WIND

The proposed control approach has been simulated on based on the CART. This turbine was modeled with the mathematical model on Matlab-Simulink. The wind speed is described as a slowly varying average wind speed superimposed by a rapidly varying turbulent wind speed. The model of the wind speed v at the measured point is

$$v = v_m + v_t \tag{16}$$

where v_m is the mean value and v_t is the turbulent component. The wind field was generated following (Hammerum, 2006). The turbulence v_t is being modeled as a 2nd order, linear process

$$\begin{aligned} \dot{w}_1 &= w_2 \\ \dot{w}_2 &= -\frac{p_1 + p_2}{p_1 p_2} w_2 - \frac{1}{p_1 p_2} w_1 + \frac{k}{p_1 p_2} e \end{aligned} \tag{17}$$

where $e \in \mathcal{N}(0, 1)$ is a noise process with intensity $k/(p_1 p_2)$, p_1, p_2, k are parameters depending on the mean wind speed. The wind data consist of 600 s in v_m =20 m/s. Fig. 5 shows the profile of wind speed. In order to improve power regulation, rotor speed, and reduce the mechanical

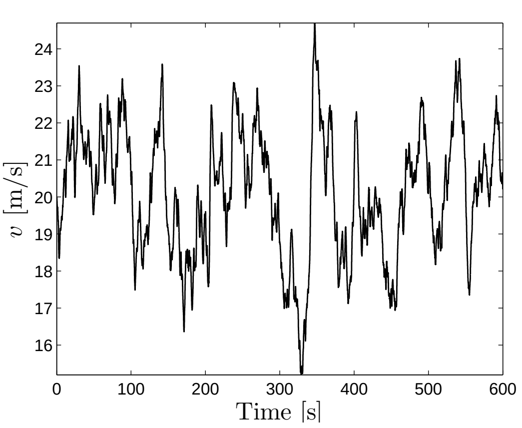

Figure 5. Wind speed profile of 20 m/s mean value.

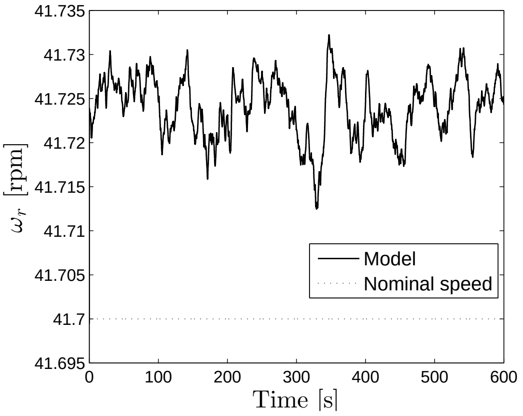

Figure 6. Closed-loop system responses: rotor speed.

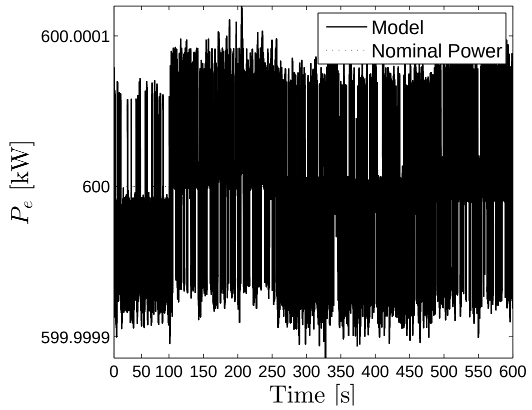

Figure 7. Closed-loop system responses: generator power.

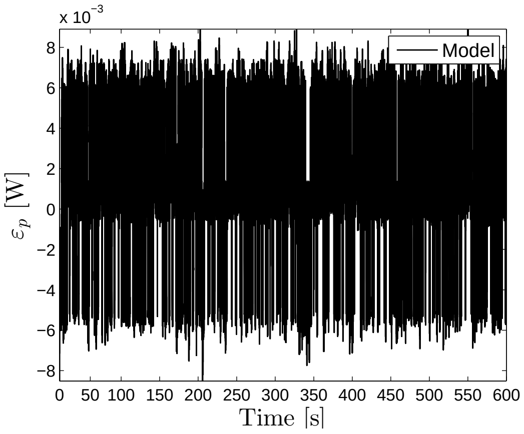

Figure 8. Closed-loop system responses: power error.

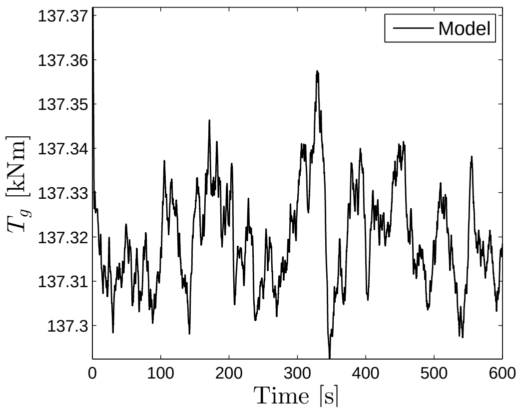

Figure 9. Closed-loop system responses: generator torque.

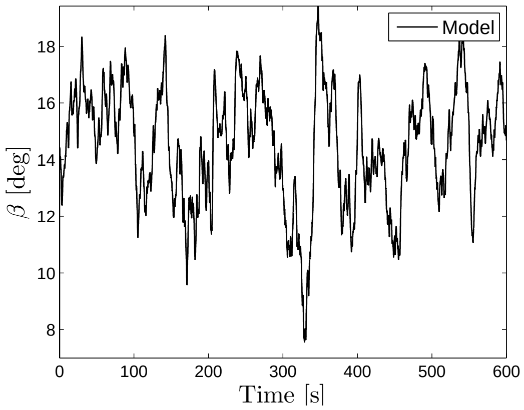

Figure 10. Closed-loop system responses: pitch angle.

loads, we design quasi-continuous second order sliding-mode regulation controller (14). The parameters for the differentiator are $\lambda_1 = 1{,}1$, $\lambda_2 = 1{,}5$, and $L = 1{,}5$ respectively, which were chosen according to (Levant, 2005*b*). Both, $\alpha = 125$ and $K_p = 100$ were found by computer simulation. The nominal values for regulation problem are shown in Figs. 6 and 7; it is observed that the proposed control is able to achieve precise power regulation. In Fig. 6 the rotor speed is well regulated close to its nominal value. Fig. 7 shows that the electrical power P_e follows the nominal power. This value is almost equal to the nominal power $P_{e\text{nom}}$. The power error is shown in Fig. 8. In this region pitch control alters the pitch of the blade, thereby changing the airflow around the blades resulting in the reduced torque capture of wind turbine rotor. Because of the pitch control, the control torque is reduced as shown in Fig. 9; if variation of T_g are large can be result in loads over the wind turbine affecting its behavior, but in this case its value goes up to 137.36 kNm, which is under the maximum one 162 kNm. These result in the reduction of the drive train mechanical stresses and output power fluctuations. In Fig. 10 we see that the collective pitch action did not exceed its limit.

V. CONCLUSIONS

Second order quasi-continuous sliding-mode control was applied to solve the problem of wind turbine regulation electrical power. We have developed the structure for nonlinear finite-time robustly convergent quasi-continuous high-order sliding-mode control in conjunction with a linear control strategy whose design procedure shown to be acceptable to solve the regulation of a power problem and regulation of the rotor speed near of its nominal value. Moreover, this strategy has robustness even in presence of uncertainties and provides very good accuracy of the regulation results, as well as rejection to fast wind speed variations. Simulation results show that the proposed method is able to achieve the power and speed regulation while the load is limited.

VI. ACKNOWLEDGEMENTS

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