Robust sliding mode control for large scale wind turbine for power optimization

Jován O. Mérida[1], Luis T. Aguilar[1], and Jorge A. Dávila[2]

[1]Instituto Politécnico Nacional. Avenida del Parque 1310 Mesa de Otay, Tijuana, 22510 Baja California, México
[2]Instituto Politécnico Nacional. Av. Ticomán 600, Col. San José Ticomán, Delegación Gustavo A. Madero, 07340 Méx. D.F., México.
jmeridao0900@ipn.mx, laguilarb@ipn.mx
jadavila@ipn.mx
Paper received on 22/09/12, Accepted on 15/10/12.

Abstract. Wind turbine control must covered different objectives such as: power, speed, and load control to achieve a low cost of energy. In this paper, the problem of designing an output feedback control scheme of variable speed wind energy conversion system without wind speed measurement is addressed. The control objective is to track a wind speed profile to operate the wind turbine in maximum power extraction while reducing mechanical loads. In order to bring some improvement a combination of sliding-mode state feedback torque controller with wind speed estimator are derived. In order to validate the mathematical model and evaluate the performance of proposed controller in presence of disturbances and measurement noise, we used Matlab-Simulink. Simulation results show that the proposed control strategy is effective in terms of tracking speed, power extraction and load reductions in comparison with existing controllers.

Keywords: Renewable energy, nonlinear control, robust control, sliding mode, wind turbines, observer.

1 Introducción

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 [13]. Wind energy is currently one the fastest growing renewable energy technologies in the world implemented in over 80 countries [17]. The worldwide installed capacity of wind power for 2011 grew by 20.3%. The WWEA published this year the last updated version for wind turbines installed worldwide, with a total installed capacity of 237016 MW, enough to cover a 3% of the world's electricity defendant [17].

Wind turbines present great challenges at scientific level because they are complex systems, nonlinear and are subjected to parameters uncertainties, unmodeled dynamics and unknown disturbances. Ongoing research is focused on increasing energy efficiency and reducing mechanical stress. One solution is the use of advanced control strategies that enhance the performance of the turbine, this allows better use of resources of the

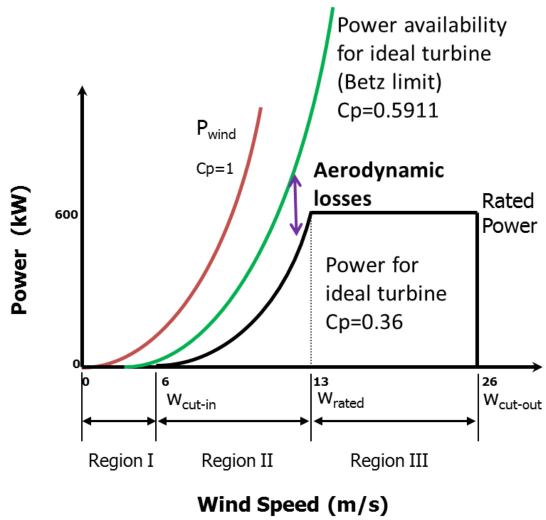


Fig. 1. Power curve for the CART.

turbine, increasing the lifetime of mechanical and electrical components, earning higher returns.

There are two primary types of horizontal-axis wind turbines: fixed speed and variable speed [15]. 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 [15]. Wind turbine controller objectives depend on the operation area [16]. Variable speed wind turbine operation can be divided into three operating regions (Fig. 1):

– 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. 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 II 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 [6]. Classical controllers have been extensively used, particularly PI control [11]. Another method commonly used is PID controllers. These PID controllers are used in conjunction with gain-scheduled to accommodate to variations in the wind [12]. Linear methods such as LQ, LQG and H_∞ are studied in [5]. 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., [16, 9, 18, 4]). Recently, nonlinear control of wind turbines has been of interest to the scientific community. A first-order sliding-mode controller for power regulation in Region III is developed in [2], demonstrating the viability and effectiveness of the control strategy. Beltran et al. [3] extended the control to Region II and III in conjunction with a Maximum Power Point Tracking algorithm, results show that the proposed control strategy is effective in terms of power capture and regulation reduction of the drive train mechanical stresses and output power fluctuations.

In this paper a strategy of sliding mode control for the problem of tracking the optimal rotor speed is developed. This control strategy presents attractive features, such as, robustness to parametric uncertainties of the turbine, robustness with respect to unknown disturbances and model uncertainties.

The paper is organized as follows. In Section 2 the wind turbine model and problem formulation is presented. The wind speed estimator is given in Section 3. The robust control design is provided in Section 4. Performance of the proposed controller is given in Section 5 through simulations. Section 6 presents some conclusions.

2 Wind Turbine Model and Problem Statement

2.1 Mathematical Model

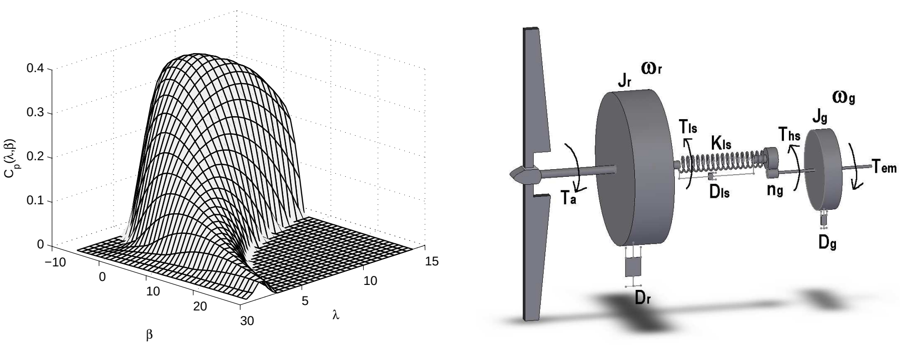
The aerodynamic power captured by the rotor is given by the nonlinear expression [8]

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

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 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. 2(a). This surface was created with the modeling software WTPerf [7], which uses blade-element-momentum theory to predict the performance of wind turbines [8]. The



a) b)

Fig. 2. (a) Power coefficient curve; (b) Two-mass model.

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. 2(b)). Fig. 2(a) 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. 2(b). 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} [1]. The mathematical model of the two-mass wind turbine, can be described as follows

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

where ω_{ls} is the low shaft speed, θ_r is the rotor side angular deviation, θ_{ls} is the gearbox side angular deviation, $J_r > 0$ is the rotor inertia, $J_g > 0$ is the generator inertia, $D_r > 0$ is the rotor external damping, $D_g > 0$ is the generator external damping, D_{ls}

Table 1. 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
n_g	43.165	

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 1. 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 $C_{pmax} = 0.3659$. The rated rotor speed is 41.7 rpm. The pitch system can pitch the blades up to 18 deg/s with pitch accelerations up to 150 deg/s^2 [19]. The required constraints for torque and rotor speed are 162 kNm and 58 rpm respectively. 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 [18].

2.2 Problem Statement

The main objective in the region II is to maximize the power extracted from the wind. While energy is captured from the wind, the aerodynamic power should be maximized below rated wind speed. In (2) the tip speed ratio can be altered to include the optimized points shown in (8), this leads to a unique maximum point (see (9)) that corresponds to a maximum power production, that is

$$\lambda_{opt} = R \frac{\omega_{ropt}}{v}, \tag{8}$$

$$C_p(\lambda_{opt}, \beta_{opt}) = C_{p\max}. \tag{9}$$

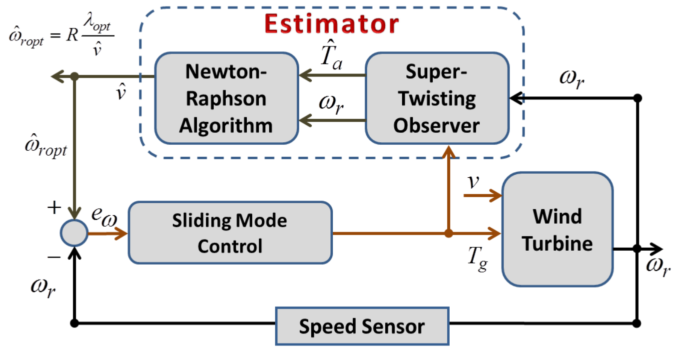


Fig. 3. Proposed control scheme.

To maximize the extracted energy the maximum rotor efficiency must be maintained during operation. For this β is fixed to β_{opt} and ω_{ropt} must change depending on the wind speed variations

$$\omega_{ropt} = R\frac{\lambda_{opt}}{v}. \tag{10}$$

Then, the objective control is to find a control law T_g to track the optimal rotor speed ω_{ropt} while the loads on the turbine are reduced. The controller should take into consideration the nonlinear nature of the wind turbine behavior, the flexibility of drive train, as well as the turbulent nature of the wind. There are numerous generator torque controllers. In the aim of making a comparison between the proposed and a existing control law, a brief description of this last one is given below. In [1] the next nonlinear static state feedback control (NSSFC) is done.

$$T_g = T_a - D_t\omega_r - J_t\dot{\omega}_{ropt} - J_t a_0 e_\omega. \tag{11}$$

The control technique presented above shows a main drawback: it is not so robust with respect to perturbation. The proposed control strategy, therefore, shall overcome this problem in order to have a better performance.

3 Wind Speed Estimation

An estimator of the wind speed is developed using the wind turbine itself as a measuring device as it is crucial for deriving the optimal rotor speed ω_{ropt}. As is shown in Fig. 3, the estimator is composed of two blocks [1].

1) A first block, that allows to estimate, from the rotor speed measurement ω_r and the generator control torque T_g, the value of the aerodynamic torque T_a.

2) A second block with, as input, the estimate of the aerodynamic torque $\hat{T}_a$. The block output is the effective wind speed estimate $\hat{v}$.

3.1 Aerodynamic Torque Estimation

In order to construct a robust output feedback controller that recovers the performance of the state feedback, Super-Twisting Observer (STO) is designed [14], which is able to reconstruct the state and uncertain functions. These estimated values are used in the controller instead of the true ones. The controller requires aerodynamic torque which cannot be easily measured. According to wind turbine dynamics the rotor speed ω_r and aerodynamic torque T_a are related by (7), the unknown term is T_a and ω_r is the measured variable. It is clear that the relative degree between them is one so the structural requirement to implement sliding-mode observer, in this case to the relative degree is one, which allows to reconstruct T_a. To estimate T_a by means of the measurement of the rotor speed ω_r, the following observer is proposed

$$\begin{aligned} \dot{\hat{\omega}}_r &= \hat{x} - \frac{1}{J_t}\left(D_t\omega_r + T_g\right) - k_1\left|e_{\omega_r}\right|^{\frac{1}{2}} sign\left(e_{\omega_r}\right) - k_2 e_{\omega_r} \\ \dot{\hat{x}} &= -k_3 sign\left(e_{\omega_r}\right) - k_4 e_{\omega_r} \end{aligned} \tag{12}$$

where $e_{\omega_r} = \hat{\omega}_r - \omega_r$ is the measurement error, $k_1 - k_4$ are adjustable gains, and $\hat{T}_a = J_t\hat{x}$ is the estimation of the aerodynamic torque. Choosing the parameter of the observer (12) according to [14] then its state and unknown term converge in finite time to ω_r and T_a respectively.

3.2 Wind Speed Computation

The estimate of the wind speed $\hat{v}$ is related to the one of $\hat{T}_a$ by the following equation:

$$\hat{T}_a - \frac{1}{2}\rho\pi R^3 C_q\left(\frac{\hat{\omega}_r R}{\hat{v}}\right)\hat{v}^2 = 0 \tag{13}$$

where $C_q(\hat{\lambda}) = C_q(\hat{\lambda}, \beta_{opt})$ is a tabulated function of $\hat{\lambda}$. In order to use a numerical method for (13) solved with respect to $\hat{v}$, this function is interpolated with a polynomial in λ

$$C_q(\lambda) = \sum_{i=0}^{n} \alpha_i \lambda^i. \tag{14}$$

The Newton-Raphson algorithm is then used to calculate $\hat{v}$. This value is exploited to deduce the optimal rotor speed $\hat{\omega}_{ropt} = \lambda_{opt}\hat{v}/R$.

4 Robust Control with Estimator

In this section a combination of sliding mode controller (SMC) with a estimator is presented (Fig. 3). The proposed controller will track the wind speed in order to achieve $\hat{\omega}_{ropt}$. A sliding manifold is chosen as follows

$$e_\omega = \hat{\omega}_{ropt} - \omega_r \tag{15}$$

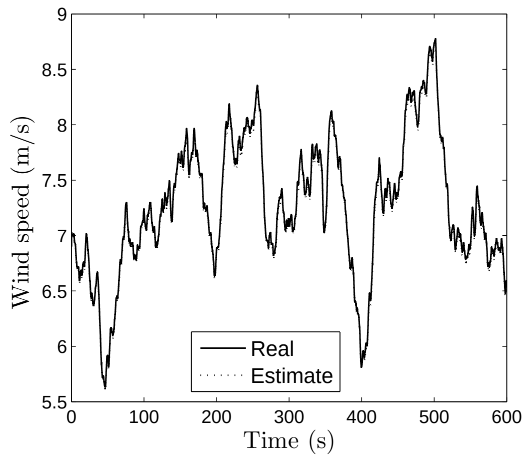


Fig. 4. Wind speed profile of $v_m = 7$ m/s mean value.

where e_ω is the rotor speed error. Here the controller is developed to achieve robust speed tracking. For that purpose we impose a first-order dynamics to e_ω

$$\dot{e}_\omega + c_0 \omega_r = 0 \tag{16}$$

where $c_0 > 0$ then developing (16) one gets

$$J_t \dot{\hat{\omega}}_{ropt} + J_t c_0 e_\omega + D_t \omega_r + T_g - \hat{T}_a = 0. \tag{17}$$

The following controller (18) is designed for (17)

$$T_g = \hat{T}_a - D_t \omega_r - J_t \dot{\hat{\omega}}_{ropt} - J_t c_0 e_\omega - J_t k_s sign(e_\omega) \tag{18}$$

where $k_s > 0$.

5 Simulation Results

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

$$v = v_m + v_t \tag{19}$$

where v_m is the mean value and v_t is the turbulent component. The wind field was generated following [10]. The turbulence v_t is being modeled as a 2nd order, linear process

$$\begin{aligned} \dot{w}_1 &= w_2 \\ \dot{w}_2 &= -\frac{p_1 + p_2}{p_1 p_2} w_2 - \frac{1}{p_1 p_2} w_1 + \frac{k}{p_1 p_2} e \end{aligned} \tag{20}$$

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.

This turbine was modeled in Matlab-Simulink. Simulations were performed under the next operating conditions: in presence of a constant additive control input disturbance of 500 Nm, an additive measurement noise on ω_r with a SNR around 7 dB, and wind speed profile of v_m =7 m/s with turbulence intensity of 15%. As seen in Fig. 4, the strategy gives a good wind speed estimation, this allows to get a better rotor speed reference.

The results show that with the proposed approach, power increases slightly and decreases the loads when is compared with the control (11). The rotor speed (Fig. 5) with the proposed controller tracks a little more closely the optimal rotor speed ω_{ropt} leading to more power capture, also the dynamic characteristics improve with slightly lower mechanical stresses as illustrated in Fig. 6. Figs. 7 and 8 show that the power extraction obtained with our strategy is better.

6 Conclusions

This paper addresses the problem of power generation control in variable speed wind turbines. The objectives are: synthesizing a robust controller to maximize the energy extracted from the wind, while ensuring reduction of mechanical loads. To this end, a strategy of sliding mode control with an estimate of the wind speed was proposed. The developed estimator allows the estimation of the aerodynamic torque as well as the effective wind speed from noisy measurements. The proposed controller provides a suitable compromise between conversion efficiency and mechanical stresses, also has a better perturbation rejections in comparison with existing controllers. The control strategy has been validated with an aeroelastic wind turbine simulator and the results shown the feasibility of the proposed strategy.

References

1. Nonlinear Control of Variable Speed Wind Turbines without wind speed measurement (Dec 2005)
2. Beltran, B., Ahmed-Ali, T., Benbouzid, M.: Sliding mode power control of variable speed wind energy conversion systems. In: Electric Machines Drives Conference, 2007. IEMDC '07. IEEE International. vol. 2, pp. 943 –948 (May 2007)
3. Beltran, B., Ahmed-Ali, T., El Hachemi Benbouzid, M.: Sliding mode power control of variable-speed wind energy conversion systems. Energy Conversion, IEEE Transactions on 23(2), 551 –558 (June 2008)
4. Bianchi, F.D., de Battista, H., Mantz, R.J.: Wind turbine control systems: principles, modelling and gain scheduling design. Advances in Industrial Control, Springer-Verlag, London Limited, 1st edn. (2007)
5. Bossanyi, E.A.: Individual blade pitch control for load reduction. Wind Energy 6(2), 119–128 (2003), `http://dx.doi.org/10.1002/we.76`
6. Boukhezzar, B., Lupu, L., Siguerdidjane, H., Hand, M.: Multivariable control strategy for variable speed, variable pitch wind turbines. Renewable Energy 32(8), 1273–1287 (2007)

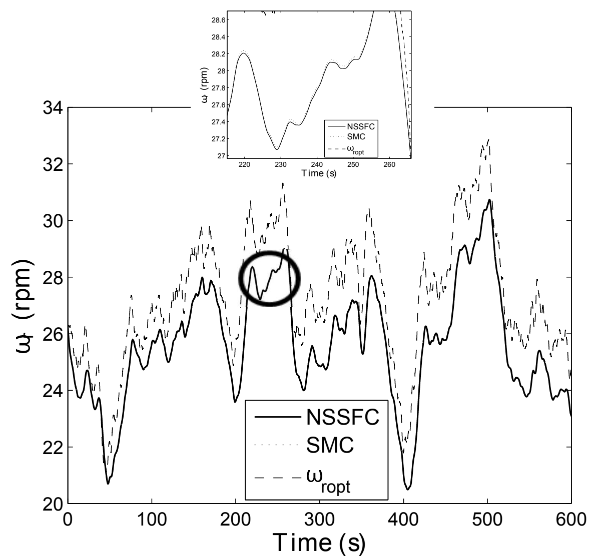


Fig. 5. Closed-loop system responses: rotor speed.

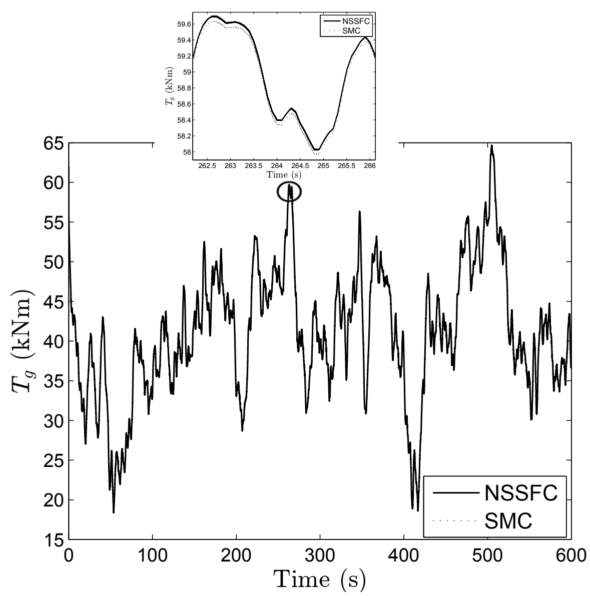


Fig. 6. Closed-loop system responses: generator torque.

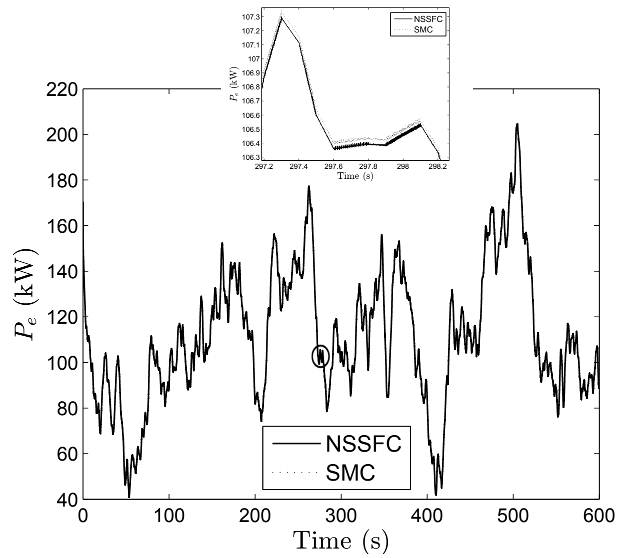


Fig. 7. Closed-loop system responses: electrical power.

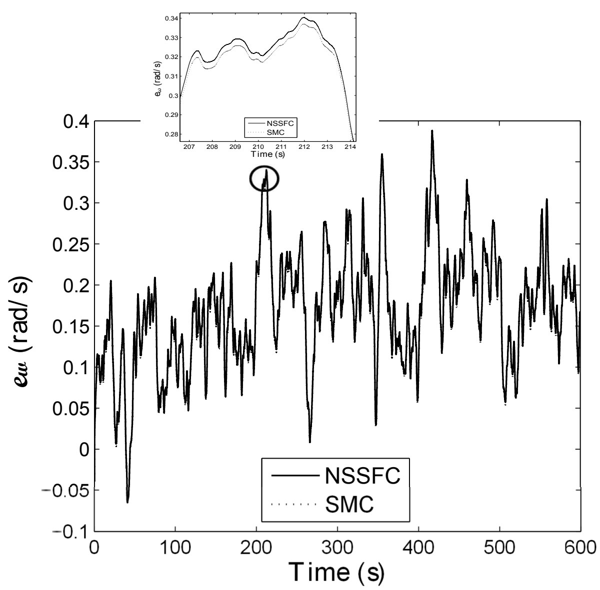


Fig. 8. Closed-loop system responses: rotor speed error.

7. Buhl, M.: NWTC design codes WTPerf. [Online]. Available: http://wind.nrel.gov/designcodes/simulators/wtperf/ (2009)
8. Burton, T., Jenkins, N., Sharpe, D., Bossanyi, E.: Wind Energy Handbook. John Wiley & Sons, 2da edn. (2011)
9. Grimble, M.: Horizontal axis wind turbine control: comparison of classical, LQG and H_∞ designs. Dynamics and Control 6(2), 143–161 (April 1996)
10. Hammerum, K.: A fatigue approach to wind turbine control. Me thesis, Informatics and Mathematical Modelling, Technical University of Denmark, DTU, Richard Petersens Plads, Building 321, DK-2800 Kgs. Lyngby (2006), `http://www2.imm.dtu.dk/pubdb/p.php?4980`
11. Hand, M.M., Balas, M.J.: Non-linear and linear model based controller design for variable-speed wind turbines. In: 3rd ASME/JSME Joint Fluids Engineering Conference. San Francisco, California (1999)
12. Hansen, M., Hansen, A., Larsen, T., Øye, S., Sørensen, P., Fuglsang, P.: Control design for a pitch regulated, variable speed wind turbine. Tech. Rep. Risø-R-1500(EN), Risø National Laboratory, Denmark (2005)
13. Masters, G.M.: Renewable and efficient electric power systems. John Wiley & Sons (2004), `http://books.google.com.mx/books?id=NFb\_mM580nAC`
14. Moreno, J.A.: A linear framework for the robust stability analysis of a generalized super-twisting algorithm. In: Proc. 6th. Int. Conf. Elect. Eng., Comp. Sci. and Aut. Cont. (CCE 2009). pp. 12–17. Mexico (Nov 2009)
15. Ofualagba, G., Ubeku, E.U.: Wind energy conversion system- wind turbine modeling. In: IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century. pp. 1–8 (July 2008)
16. Pao, L.Y., Johnson, K.E.: Control of wind turbines. IEEE Control Systems Magazine 31(2), 44–62 (April 2011)
17. The World Wind Energy Association: World wind energy report 2011. Tech. rep. (2012)
18. Thomsen, S.: Nonlinear Control of a Wind Turbine. Me thesis, Lyngby: Informatik og Matematisk Modellering, Danmarks Tekniske Universitet (2006)
19. Wright, A.D., Fingersh, L.J.: Advanced control design for wind turbines. part I: Control design, implementation, and initial tests. Tech. Rep. NREL/TP-500-42437, NREL (March 2008)