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H_∞ Control of a Wind Turbine

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1 Introduction

Due to recent concerns on global warming and increase in the price of fossil fuel, there has been an increasing interest in green energies of which wind energy is one of the most important ones. Wind turbines are the most common wind energy conversion systems (WECS) and are hoped to be able to compete with fossil fuel power plants on the energy price very soon. However this needs better technology to reduce electricity production price. Control can play an essential part in this context because control methods can decrease the cost of energy by keeping the turbine close to its maximum efficiency and increase the captured power and also reduce structural fatigue and therefore increase lifetime of the wind turbine. There are several methods for wind turbine control ranging from classical control methods [1] which are the most used method in real applications to advanced control methods which have been the focus of research in the past few years [2]. Gain scheduling [3], nonlinear control [4], robust control [5], model predictive control [6], μ-Synthesis [7] just to mention a few. Advanced control methods are thought to be the future of wind turbine control as they can employ new generations of sensors on wind turbines (e.g. LIDAR [8]), new generation of actuators (e.g. trailing edge flaps [9]) and also conveniently treat the turbine as a MIMO system. The last feature seems to become more important than before as wind turbines become bigger and more flexible which make decoupling different modes and designing controller for each mode more difficult. The problem of H_∞ control of a wind turbine is considered in this work. Using H_∞ method a set of controllers are designed based on a 2 degrees of freedom linearized model of a wind turbine. An extended Kalman filter is used to estimate the effective wind speed and the estimated wind speed is used to find the control signals as a convex combination of outputs of the controllers set. The resulting controller is applied on a full complexity simulation model and simulations are performed for stochastic wind speed according to the relevant IEC standard. The wind turbine in this paper is treated as a MIMO system with pitch (θ) and generator reaction torque (Q_g) as inputs and rotor rotational speed (ω_r), generator rotational speed (ω_g) and generated power (P_e) as outputs. This paper is organized as follows: In the section 2 modeling of the wind turbine including modeling for wind speed estimation and simulation model are addressed. In the section 3 controller design is explain. And finally in the section 4 simulation results are presented.

2 Modeling

For modeling purposes, the whole wind turbine can be divided into 4 subsystems: Aerodynamics subsystem, structural subsystem, electrical subsystem and actuator subsystem. The dominant dynamics of the wind turbine come from its flexible structure. Several degrees of freedom could be considered to model the flexible structure, but for control design mostly just a few important degrees of freedom are considered. In this work we only consider two degrees of freedom, namely the rotational degree of freedom (DOF) and drivetrain torsion, the other parts of the dynamics are considered as uncertainties and is handled by a robust approach.

2.1 Modeling for Wind Speed Estimation

Wind can be modeled as a complicated nonlinear stochastic process, however for practical purposes it could be approximated by a linear model [10]. In this model the wind has two elements, mean value term (v_m) and turbulent term (v_t):

$$v_e = v_m + v_t$$

The turbulent term could be modeled by the following transfer function:

$$v_t = \frac{k(v_m)}{(p_1(v_m)s+1)(p_2(v_m)s+1)}e; \quad e \in N(0,1)$$

And in the state space form:

$$\begin{pmatrix} \dot{v}_t \\ \ddot{v}_t \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ -\frac{1}{p_1(v_m)p_2(v_m)} & -\frac{p_1(v_m)+p_2(v_m)}{p_1(v_m)p_2(v_m)} \end{pmatrix} \begin{pmatrix} v_t \\ \dot{v}_t \end{pmatrix} + \begin{pmatrix} 0 \\ \frac{k(v_m)}{p_1(v_m)p_2(v_m)} \end{pmatrix} e \tag{1}$$

This is a second order approximation of the wind power spectrum [11]. For wind speed estimation, a one DOF nonlinear model of the wind turbine is augmented with the wind model given above. An extended Kalman filter uses this model to estimate the effective wind speed.

This wind speed is used to find the operating point of the wind turbine and to calculate appropriate control signals.

2.2 Nonlinear Model

Blade element momentum (BEM) theory [12] is used to calculate aerodynamic torque and thrust on the wind turbine. This theory explains how torque and thrust are related to wind speed, blade pitch angle and rotational speed of the rotor with the following formulas:

$$\begin{aligned} Q_r &= \frac{1}{2}\frac{1}{\omega_r}\rho\pi R^2 v_e^3 C_P(\theta,\omega,v_e) \\ Q_t &= \frac{1}{2}\rho\pi R^2 v_e^2 C_T(\theta,\omega,v_e) \end{aligned} \tag{2}$$

Here Q_r and Q_t are aerodynamic torque and thrust, ρ is air density, ω_r is rotor rotational speed, v_e is effective wind speed, C_P is the power coefficient and C_T is the thrust force coefficient. For the sake of simplicity, they are presented as functions of two variables θ and λ in which $\lambda = \frac{R\omega}{v_e}$ called tip speed ratio. The absolute angular position of the rotor and generator are of no interest to us, therefore we use $\psi = \theta_r - \theta_g$ to describe the drivetrain torsion. Having aerodynamic torque the whole system equation with 2 degrees of freedom becomes:

$$\begin{aligned} J_r\dot{\omega}_r &= Q_r - c(\omega_r - \frac{\omega_g}{N_g}) - k\psi \\ (N_g J_g)\dot{\omega}_g &= c(\omega_r - \frac{\omega_g}{N_g}) + k\psi - N_g Q_g \end{aligned} \tag{3}$$

In which J_r and J_g are rotor and generator moments of inertia, c and k are the drivetrain damping and stiffness factors respectively lumped in the low speed side of the shaft. For numerical values of these parameters and other parameters given in this paper, we refer to [13]. These equations give us a nonlinear model however our control design method is based on linear models.

2.3 Simulation Model

The FAST (Fatigue, Aerodynamics, Structures, and Turbulence) code [14] is used as the simulation model and the 5MW reference wind turbine is used as the plant [13]. In the simulation model 10 degrees of freedom are enabled which are: generator, drivetrain torsion, 1st and 2nd tower fore-aft, 1st and 2nd tower side-side, 1st and 2nd blade flapwise, 1st blade edgewise degrees of freedom.

3 Controller Design

3.1 Control Objectives

The most basic control objective of a wind turbine is to maximize captured power and prolong life time of the wind turbine. The second objective is achieved by minimizing the fatigue loads. Generally maximizing power capture is considered in the partial load and minimizing fatigue loads is mainly considered above rated. As we are operating in the full load region in this work, we have considered the second objective. Control objectives are formulated in the form of weighting functions on input disturbances (d) and exogenous outputs (z) (figure 1). In order to avoid high frequency activity of the actuators, we have put high pass filter on control signals to punish high frequency actions. Also we have setup low pass filters to punish low frequency of some of the system outputs as their high frequency dynamics are outside of our actuator bandwidth and we can not control them. For regulating power and rotational speed, $\int P_e - P_e^*$ and $\int \omega_g - \omega_g^*$ and for minimizing fatigue loads on the drivetrain $\omega_g - N_g\omega_r$ are punished. The resulting controller is a dynamical system with measurements y as its inputs and control signals u as its outputs:

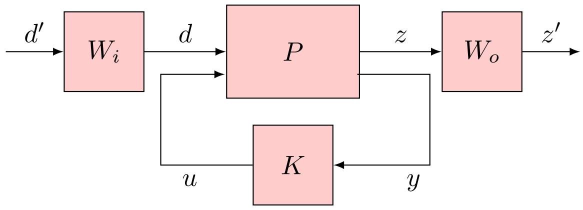

Figure 1: Nominal performance configuration

$$\begin{aligned} \dot{x}_c &= A_c x_c + B_c y \\ u &= C_c x_c \end{aligned} \tag{4}$$

3.2 Theory

H_∞ control theory [15] is used to solve the nominal performance problem which is:

$$K(s) = \arg\min_{K\in\mathcal{K}} \| W_o F_l(P,K) W_i(j\omega) \|_{\mathcal{H}_\infty} \tag{5}$$

In which $F_l(P,K)$ is the lower LFT of plant P and controller K (see figure 1). W_i and W_o are frequency dependent weighting matrices on disturbances and exogenous outputs respectively of the form :

$$\begin{aligned} W_o &= diag(W_{o1},\ldots,W_{o5}) \\ W_i &= diag(W_{i1},W_{i2}) \end{aligned} \tag{6}$$

Bode plots of the weighting functions are given in the figure 2. Input disturbances (d) to the system are:

$$d = \begin{pmatrix} v_e \\ \omega_g^* \end{pmatrix} \begin{matrix} \text{Wind Speed} \\ \text{Rotor rotation reference} \end{matrix}$$

And exogenous outputs (z) are:

$$z = \begin{pmatrix} \theta_{ref} \\ Q_{ref} \\ \omega_r^* - \frac{\omega_g}{N_g} \\ \int \omega_g^* - \omega_g \\ \int P_e^* - P_e \end{pmatrix} \begin{matrix} \text{Pitch reference} \\ \text{Generator reaction torque reference} \\ \text{Deflection of the drivetrain} \\ \text{Integral of rotational speed error} \\ \text{Integral of generated power error} \end{matrix}$$

These weightings are used to specify performance of the system. The optimization problem (5) suggests that we

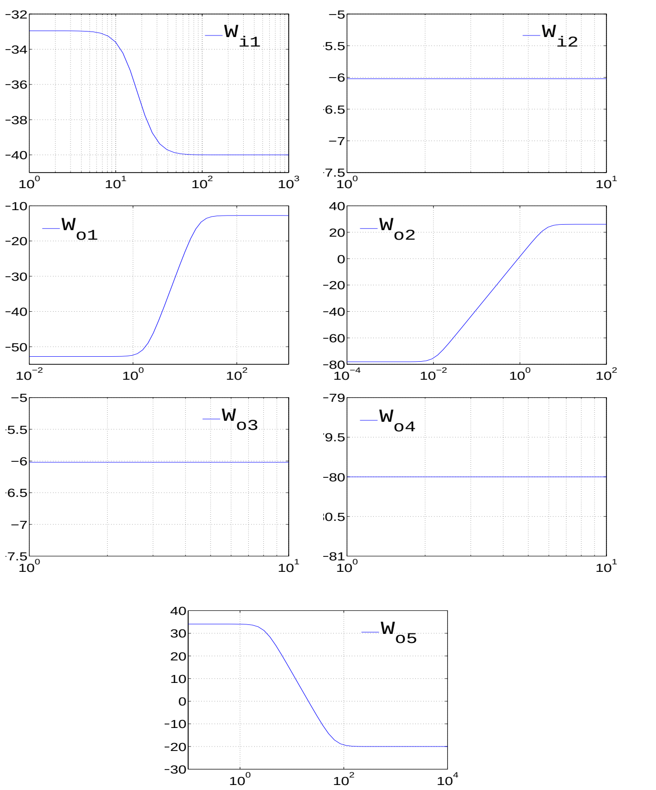

Figure 2: Bode plots for performance specifications(y-axis is in dB and x-axis is in rad/s)

are trying to find a controller in the set of stabilizing controllers that minimizes H_∞-norm of weighted sensitivity function. This means we try to minimize the peak frequency of $W_o S W_i(j\omega)$. The resulting controller guarantees nominal performance if (for more details see [7]):

$$\| W_o F_l(P,K) W_i(j\omega) \|_{\mathcal{H}_\infty} < 1 \qquad (7)$$

3.3 Implementation

The robust control toolbox [16] is used to solve the above problem. Because wind turbines are nonlinear systems one controller can not be used for the whole operational range. Therefore we have designed different controllers based on linearized models for different operational points. Each controller is found trying to minimize transfer function from the disturbances (vector d) to the exogenous outputs (vector z). A convex combination of outputs of the controllers are used to calculate the control signals (see [7]). The controllers that are designed here are used in Simulink on the full complexity FAST model of the 5MW reference wind turbine [13].

4 Simulations

In this section simulation results for the obtained controllers are presented. Kaimal model is used as the turbulence model and in order to stay in the full load region, category C of the IEC turbulence categories with $18m/s$ as the mean wind speed is chosen.

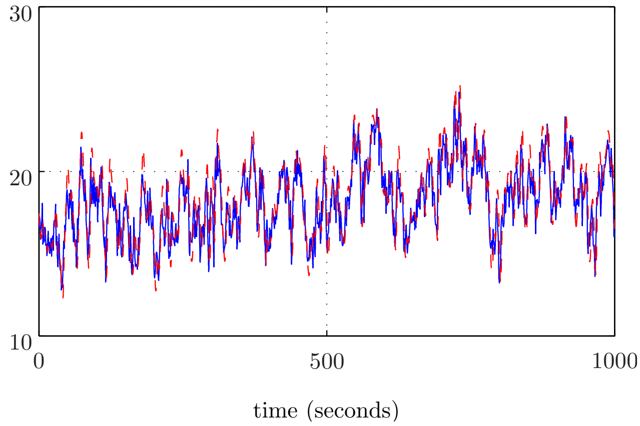

Figure 3: Wind speed (blue-solid), Estimated wind speed (red-dashed), unit is m/s

4.1 Wind Speed Estimation

An extended Kalman filter is used to estimate the wind speed. Figure 3 shows the effective and the estimated wind speeds.

5 Conclusion

In this paper we solved the problem of nominal performance control of a wind turbine using H_∞ theory. As the wind turbine is a nonlinear system we have linearized the system on a grid of operating points and designed controllers for each linear model. Estimated wind speed is used to calculate control signal from outputs of controllers. The final controller is implemented on a FAST simulation model with 10 degrees of freedom and simulation with stochastic wind speed based on IEC standard is done. The results show good regulation of generated power and rotational speed for a big range of wind speed changes.

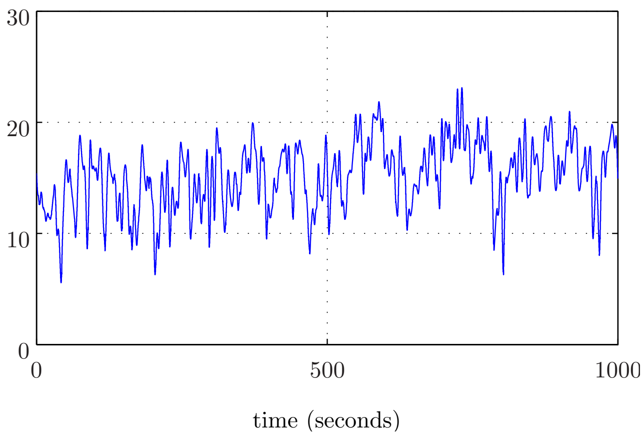

Figure 4: Blade-pitch (degrees)

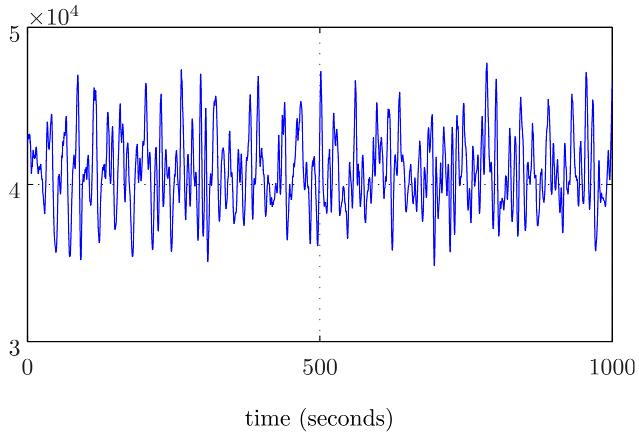

Figure 5: Generator-torque (N.M.)

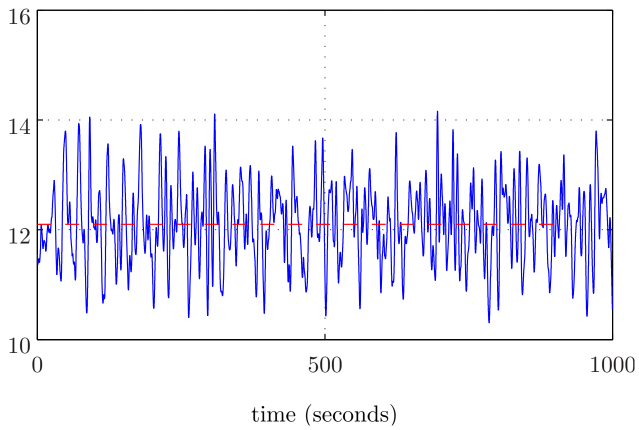

Figure 6: Rotational speed (rpm)

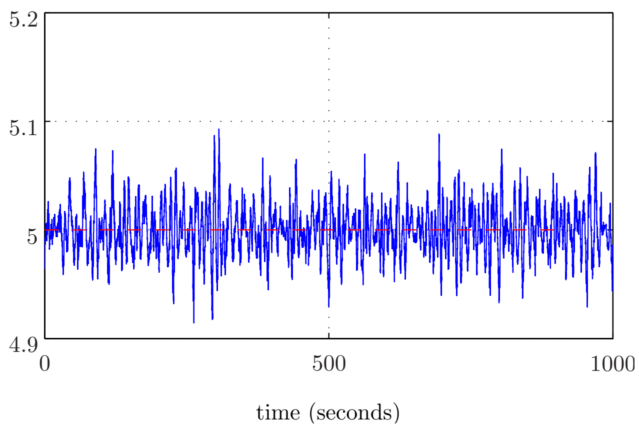

Figure 7: Electrical power (mega watts)

References

[1] W.E. Leithead and Bill Connor. Control of variable speed wind turbines: Design task. *Int J Control*, 73(13):1189–1212, 2000.

[2] J.H. Laks, L.Y. Pao, and A.D. Wright. Control of wind turbines: Past, present, and future. *Proceedings of the American Control Conference*, pages 2096–2103, 2009.

[3] Fernando D. Bianchi, Hernan De Battista, and Ricardo J. Mantz. *Wind Turbine Control Systems: Principles, Modelling and Gain Scheduling Design*. Springer, 2006.

[4] Sven Creutz Thomsen. Nonlinear control of a wind turbine. Master's thesis, Technical University of Denmark, Informatics and Mathematical Modelling, 2006.

[5] Kasper Zinck Østergaard. *Robust, Gain-Scheduled Control of Wind Turbines*. PhD thesis, Automation and Control Department of Electronic Systems, Aalborg University, 2008.

[6] Lars Christian Henriksen. Model predictive control of a wind turbine. Master's thesis, Technical University of Denmark, Informatics and Mathematical Modelling, 2007.

[7] Mahmood Mirzaei, Hans Henrik Niemann, and Niels Kjølstad Poulsen. A μ-synthesis approach to robust control of a wind turbine. In *the 50th IEEE Conference on Decision and Control and European Control Conference*, 2011.

[8] M. Harris, M. Hand, and A. Wright. Lidar for turbine control. Technical report, National Renewable Energy Laboratory, 2006.

[9] Peter Bjørn Andersen. *Advanced Load Alleviation for Wind Turbines using Adaptive Trailing Edge Flaps: Sensoring and Control*. PhD thesis, Technical University of Denmark, 2010.

[10] Allan Juul Larsen, Thomas Stampe Mogensen, Technical University of Denmark Informatics, Mathematical Modelling, IMM, Danmarks Tekniske Universitet Informatik og Matematisk Modellering, and DTU. *Individuel pitchregulering af vindmølle*. Lyngby, 2006. 1–195 s pp.

[11] Thomas Juul Larsen, Allan Stampe Mogensen. Individuel pitchregulering af vindmølle. Master's thesis, Technical University of Denmark, Informatics and Mathematical Modelling, Lyngby, 2006.

[12] Martin O. L. Hansen. *Aerodynamics of Wind Turbines*. Earthscan, 2008.

[13] J. Jonkman, S. Butterfield, W. Musial, and G. Scott. Definition of a 5MW reference wind turbine for offshore system development. Technical report, National Renewable Energy Laboratory, 2009.

[14] Jason M. Jonkman and Marshall L. Buhl Jr. Fast users guide. Technical Report NREL/EL-500-38230, National Renewable Energy Laboratory, August 2005.

[15] Sigurd Skogestad and Ian Postlethwaite. *Multivariable Feedback Control Analysis and design*. JOHN WILEY & SONS, Second Edition, 2001.

[16] Gary J. Balas, John C. Doyle, Keith Glover, Andy Packard, and Roy Smith. *Robust Control Toolbox*. The MathWorks, Inc., June 2001.