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DK-Iteration Robust Control Design of a Wind Turbine

Mahmood Mirzaei, Hans Henrik Niemann and Niels Kjølstad Poulsen

Abstract—The problem of robust control of a wind turbine is considered in this paper. A controller is designed based on a 2 degrees of freedom linearized model. An extended Kalman filter is used to estimate effective wind speed and the estimated wind speed is used to find the operating point of the wind turbine. Due to imprecise wind speed estimation, uncertainty in the obtained linear model is considered. Uncertainties in the drivetrain stiffness and damping parameters are also considered as these values are lumped parameters of a distributed system and therefore they include inherent uncertainties. We include these uncertainties as parametric uncertainties in the model and design a robust controller using *DK*-iteration method. The controller is applied on a full complexity simulation model and simulations are performed for wind speed step changes.

I. INTRODUCTION

There is an increasing interest in wind energy and wind turbines are the most common wind energy conversion systems (WECS). Control is an essential part of the wind turbine system because control methods can decrease the cost of energy by increasing the power capture by keeping the turbine close to its maximum efficiency and also by reducing structural loadings and therefore increasing lifetime of the wind turbine. Wind turbines essentially have two regions of operation, partial load and full load. In the partial load wind speed is not fast enough to produce rated power. In this region the main control objective is to track the maximum power coefficient (C_{Pmax}) and extract as much power as possible. Pitch is mostly fixed in this region and generator reaction torque is adjusted to control rotational speed and keep the operating point close to C_{Pmax} . In the full load region wind speed is above rated and wind power exceeds rated power of the generator, therefore by decreasing aerodynamics efficiency of the rotor we try to control the captured power and this is done by pitching the blades. 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 and model based control methods which have been the focus of research in the past few years [2]. Gain scheduling [3], adaptive control [4], time invariant MIMO methods [5], nonlinear control [6], robust control [7], model predictive

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Fig. 1: Wind turbine subsystems

control [8] are 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 [9]), new generation of actuators (e.g. trailing edge flaps [10]) 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 wind turbine in this paper is treated as a MIMO system with pitch reference (θ_{ref}) and generator reaction torque (Q_{ref}) 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 II modeling of the wind turbine including modeling for wind speed estimation, linearization and uncertainty modeling is addressed. In the section III-A controller design is explained and in the section IV robust performance problems are addressed. And finally in the section V simulation results are presented.

II. MODELING OF THE WIND TURBINE

For modeling purposes, the whole wind turbine can be divided into 4 subsystems: Aerodynamics subsystem, structural subsystem, electrical subsystem and actuator subsystem. Figure 1 shows the basic subsystems and their interactions. 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. Mostly the degrees of freedom whose eigen frequencies lie inside actuator bandwidth are considered otherwise including them into the design model is useless and makes the design model unnecessarily complicated. In this work we only consider two degrees of freedom,

namely the rotational degree of freedom(DOF) and drivetrain torsion. The aerodynamics subsystem in the model gets effective wind speed(v_e), pitch angle(θ) and rotational speed of the rotor(ω_r) and returns aerodynamic torque (T_r) and thrust(F_T). This subsystem is responsible for the nonlinearity in the wind turbine model. More details are presented in the section II-B.

A. Wind Model

Wind model can be modeled as a complicated nonlinear stochastic process, however for practical purposes it could be approximated based on a linear model. 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 state space model:

$$\begin{bmatrix} \dot{v}_t \\ \ddot{v}_t \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -\frac{1}{p_1(v_m)p_2(v_m)} & -\frac{p_1(v_m)+p_2(v_m)}{p_1(v_m)p_2(v_m)} \end{bmatrix} \begin{bmatrix} v_t \\ \dot{v}_t \end{bmatrix} + \begin{bmatrix} 0 \\ \frac{k(v_m)}{p_1(v_m)p_2(v_m)} \end{bmatrix} e, \quad e \in N(0, 1) \quad (1)$$

The parameters $k(v_m)$, $p_1(v_m)$ and $p_2(v_m)$ are estimated by approximating wind power distribution and as it is indicated, they are dependent on the mean wind speed (v_m).

B. Nonlinear Model

Blade element momentum(BEM) theory [11] 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:

$$Q_r = \frac{1}{2} \frac{1}{\omega_r} \rho \pi R^2 v_e^3 C_P(\theta, \omega, v_e)$$

$$Q_t = \frac{1}{2} \rho \pi R^2 v_e^2 C_T(\theta, \omega, v_e)$$

In which 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, instead of presenting these two coefficients as functions of three variables ω , v_e and θ , they are presented as a function of two variables λ and θ in which $\lambda = \frac{R\omega}{v_e}$ and it is called tip speed ratio. As we have not used individual pitch in this work absolute angular position of the rotor and generator are of no interest to us, therefore we use $\psi = \theta_r - \theta_g$ instead which is the drivetrain torsion. Having aerodynamic torque the whole system equation with 2 degrees of freedom becomes:

$$J_r \dot{\omega}_r = Q_r - c(\omega_r - \frac{\omega_g}{N_g}) - k\psi$$

$$(N_g J_g) \dot{\omega}_g = c(\omega_r - \frac{\omega_g}{N_g}) + k\psi - N_g Q_g \quad (2)$$

In which J_r and J_g are rotor and generator moments of inertia, ψ is the drivetrain torsion, 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 the reader to [12]. These equations give us a nonlinear model however our control design method is based on linear models, therefore we need to linearize the nonlinear model of the system which could be easily achieve using Taylor expansions around the operating points.

C. Uncertain Model

As it was mentioned, for control design we need to have a linear model of the system and the following model of the wind turbine is used:

$$\begin{bmatrix} \dot{x} \\ y_\Delta \\ y \end{bmatrix} = \begin{bmatrix} A & B_1 & B_2 \\ C_1 & D_{11} & D_{12} \\ C_2 & D_{21} & D_{22} \end{bmatrix} \begin{bmatrix} x \\ u_\Delta \\ u \end{bmatrix}$$

In which states, inputs and outputs are:

$$x = [\omega_r \quad \omega_g \quad \psi \quad \theta \quad Q_g \quad v_e \quad \dot{v}_e]^T$$

$$u = [\theta_{ref} \quad Q_{ref}]^T$$

$$y = [\omega_r \quad \omega_g \quad P_e]^T$$

ω_r is rotational speed of the rotor, ω_g is rotational speed of the generator, ψ is drivetrain deflection, θ pitch of the blade, Q_g is the generator reaction torque, v_e and $\dot{v}_e$ are wind model states, θ_{ref} is the reference value for pitch angle and Q_{ref} is the reference value for the generator reaction torque and P_e is the electrical power. System equations are:

$$\dot{\omega}_r = \frac{a-c}{J_r} \omega_r + \frac{c}{J_r} \omega_g - \frac{k}{J_r} \psi + b_1 \theta + b_2 v_e$$

$$\dot{\omega}_g = \frac{c}{N_g J_g} \omega_r - \frac{c}{N_g^2 J_g} \omega_g + \frac{k}{N_g J_g} \psi - \frac{Q_g}{J_g}$$

$$\dot{\psi} = \omega_r - \frac{\omega_g}{N_g} \quad \dot{\theta} = -\frac{1}{\tau_\theta} \theta + \frac{1}{\tau_\theta} \theta_{ref}$$

$$\dot{Q}_g = -\frac{1}{\tau_g} Q_g + \frac{1}{\tau_g} Q_{ref} \quad P_e = Q_{g0} \omega_g + \omega_{g0} Q_g$$

$$\ddot{v}_e = -\frac{1}{p_1 p_2} v_e - \frac{p_1 + p_2}{p_1 p_2} \dot{v}_e + \frac{k}{p_1 p_2} e$$

There are always discrepancies between real system and mathematical models, which lead to uncertain models. In this work, sources of uncertainties are taken to be:

- Uncertainty in the drivetrain stiffness and damping parameters.
- Uncertainty in the linearized model.

Uncertainty in the linearized model could be a result of approximate C_P curve calculations, wrong wind speed estimation which results in picking the wrong operating point or aerodynamic changes due to blade flexibility or ice coatings on the blades. Multiplicative uncertainty is used to represent the uncertain parameters. The uncertainty matrix becomes:

$$\begin{bmatrix} u_a \\ u_{b_1} \\ u_k \\ u_c \end{bmatrix} = \begin{bmatrix} \delta_a & 0 & 0 & 0 \\ 0 & \delta_{b_1} & 0 & 0 \\ 0 & 0 & \delta_k & 0 \\ 0 & 0 & 0 & \delta_c \end{bmatrix} \begin{bmatrix} y_a \\ y_{b_1} \\ y_k \\ y_c \end{bmatrix}$$

Fig. 4: Bode plots for performance specifications(y-axis is in dB and x-axis is in rad/s)

the linearization parameters therefore the weighting matrix becomes:

$$W_{\Delta} = \text{diag}(0.2, 0.2, 0.1, 0.1)$$

Δ_P (scaled by W_i and W_o matrices) defines performance of the system in the form of a complex perturbation matrix. W_i and W_o are frequency dependent weight matrices on disturbances and exogenous outputs respectively of the form:

$$W_o = \text{diag}(W_{o1}, \dots, W_{o5})$$

$$W_i = \text{diag}(W_{i1}, W_{i2})$$

Bode plots of the weighting functions are given in the figure 4. Figure 4 shows bode plots of weighting functions. Input disturbances (d) to the system are:

$$d = \begin{bmatrix} v_e \\ \omega_g^* \end{bmatrix} \begin{array}{l} \text{Wind Speed} \\ \text{Rotor rotation reference} \end{array}$$

And exogenous outputs (z) are:

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

These weightings are used to specify performance of the system. As we have parametric uncertainties in the plant and

Fig. 5: Closed loop mixed μ

Iteration number	1	2	3
Controller Order	19	19	19
γ Acheived	9682006.84	45.289	7.347
Peak μ -Value	2482.23	0.865	0.808

TABLE I: DK-iteration summery

complex perturbation for performances, mixed μ is used to design the controller. The resulting mixed- μ is given in figure 5 and the iteration summery is given in the table I. The obtained controller is of the order 19, and has maximum gain of 15.86dB. As high order controllers are problematic in the real implementations, we have used balanced order reduction [16] to reduce its order to 10. Hankel singular values of the controller are shown in figure 6 and the jump from order 10 to 11 is found a reasonable place for controller order reduction.

V. SIMULATION RESULTS

In this section simulation results for the obtained controller are presented. The controller is implemented in MATLAB and tested on full complexity FAST model of the reference wind turbine [12]. As it is mentioned in section II-E we have augmented model of wind turbine with a stochastic wind model, however in order to make evaluation of the controller on nominal and worst case, we have used simulations with step changes in the wind speed.

Fig. 6: Hankel singular values of the controller

Fig. 7: Wind speed

Fig. 8: Blade-pitch reference

Fig. 9: Generator-torque reference

Fig. 10: Rotor rotational speed(ω_r)

A. Robust performance simulations

In this section simulation results of a step change in wind speed is presented. Control inputs which are pitch reference θ_{ref} and generator reaction torque reference T_{ref} along with system outputs which are rotor rotational speed ω_r and electrical power P_e are plotted in figures 7-11.

B. Simulation for the worst case

In this section worst case scenarios, in which all the uncertainties are taken to be the maximum values, are presented. To do so, wind speed is taken to be $2m/s$ away from the linearization point and nominal values of the drivetrain stiffness and damping are replaced by the following values:

$$\begin{aligned} k &= \bar{k}(1 + P_k \delta_k) & \text{for } \delta_k = \pm 1 \text{ \& } P_k = 0.1 \\ c &= \bar{c}(1 + P_c \delta_c) & \text{for } \delta_c = \pm 1 \text{ \& } P_c = 0.1 \end{aligned}$$

As it is seen in figures 12 and 13, in the worst cases the system becomes oscillatory but it maintains a reasonable performance.

VI. CONCLUSION

In this paper we solved the problem of robust control of a wind turbine using DK -iteration technique. The controller is designed for the full load region, and an extension of this work would be to solve the problem for partial load too. Parametric uncertainty is considered in the uncertain model and then we have used μ -synthesis method to design the

Fig. 11: Electrical power

controller. The full model with augmented wind model is of the order 8 and the resulting controller is of the order 19, however balanced truncation model order reduction is used to reduce order of the controller to 10. The final controller is implemented on a FAST simulation model with 10 degrees of freedom and simulations with wind speed step changes are done for nominal plant and worst case plant. The results suggest that the controller can handle nominal case pretty well and the worst case with a little loss of performance.

Fig. 12: Worst case scenario with $+2\text{m/s}$ wind speed estimation error

Fig. 13: Worst case scenario with -2m/s wind speed estimation error

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] Johnson and Fingersh. Adaptive pitch control of variable-speed wind turbines. *J. Sol. Energy Eng. (USA)*, 130(3):031012–1–7, 2008.
- [5] M. Geyler and P. Caselitz. Robust multivariable pitch control design for load reduction on large wind turbines. *J. Sol. Energy Eng. Trans.-ASME J SOL ENERG J SOL ENERG-T ASME J SOL ENERGY ENG Journal of solar energy engineering*, 130(3):–, 2008.
- [6] Sven Creutz Thomsen. Nonlinear control of a wind turbine. Master's thesis, Technical University of Denmark, Informatics and Mathematical Modelling, 2006.
- [7] Kasper Zinck Østergaard. *Robust, Gain-Scheduled Control of Wind Turbines*. PhD thesis, Automation and Control Department of Electronic Systems, Aalborg University, 2008.
- [8] Lars Christian Henriksen. Model predictive control of a wind turbine. Master's thesis, Technical University of Denmark, Informatics and Mathematical Modelling, 2007.
- [9] M. Harris, M. Hand, and A. Wright. Lidar for turbine control. Technical report, National Renewable Energy Laboratory, 2006.
- [10] Peter Bjørn Andersen. *Advanced Load Alleviation for Wind Turbines using Adaptive Trailing Edge Flaps: Sensing and Control*. PhD thesis, Technical University of Denmark, 2010.
- [11] Martin O. L. Hansen. *Aerodynamics of Wind Turbines*. Earthscan, 2008.
- [12] 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.
- [13] Jason M. Jonkman and Marshall L. Buhl Jr. Fast users guide. Technical Report NREL/EL-500-38230, National Renewable Energy Laboratory, August 2005.
- [14] Sigurd Skogestad and Ian Postlethwaite. *Multivariable Feedback Control Analysis and design*. JOHN WILEY & SONS, Second Edition, 2001.
- [15] The MathWorks, Inc. *μ -Analysis and Synthesis Toolbox*, June 1998.
- [16] A. Varga. Balancing free square-root algorithm for computing singular perturbation approximations. *Proc IEEE Conf Decis Control*, 2:1062–1065, 1991.