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A Lidar Assisted Feedforward Preview Controller for Load Mitigation in Wind Turbines

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Abstract. A $\mathcal{H}_2$ feedforward blade pitch controller is designed using an algorithm optimized for preview control. The control objectives of the feedforward controller are to regulate the generator speed, reduce tower loads and preserve the pitch system. Its input is a wind preview measurement that is provided by a turbine-mounted LIDAR system. The feedforward enhanced control system is then compared to a baseline feedback controller in aeroservoelastic simulations. The results show that the designed controller is able to reduce generator speed fluctuations, tower loads and pitch activity without reducing the generated power, contributing to the turbine lifetime and hence decreasing the cost of energy.

Keywords. Collective pitch, Feedforward, Light detection and ranging (LIDAR), Preview control, Wind turbine.

1 Introduction

The advancement of renewable energy production is dependent on the reduction of the costs involved. One way to diminish the maintenance costs and increase the lifetime of wind turbines is to mitigate the loads and fatigue experienced by its components.

Present commercial wind turbine control systems rely usually on feedback from a generator speed sensor and occasionally from accelerometers and strain gauges [10]. As the control system can act only on errors that are already present, the regulation quality is restricted due to the large rotor inertia, which causes a delay on the control system response, incrementing actuator activity and the loads experienced by the tower, drivetrain and blades. Advanced control strategies have been developed in the last years to provide better wind input disturbance rejection and load reduction.

A promising way to improve the control systems of wind turbines is to use LIDAR (LIght Detection And Ranging) sensors. LIDARs provide information about the future wind inflow seconds ahead, which can be used by novel control systems to promote better speed regulation and load alleviation. In recent years a number of studies related to LIDAR-enabled control has been reported [7] and feedforward control has already been tested on experimental turbines [13, 14]. The approach used in the field tests [13, 14] was to augment an existing feedback controller with a feedforward term. This technique has

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also been investigated in [2] with various design methods, such as model-inverse, optimized FIR filter and shaped compensators, preview control, non-causal series expansion, zero-phase-error tracking and adaptive methods.

In this paper a feedback controller is also augmented with a feedforward term. The contribution here is the design of a $\mathcal{H}_2$ preview controller with the technique developed by Hazell [6], which offers computational and numerical stability advantages over the ones used in [2,3] and was not explored in the previous studies. The performance of the designed controller against the baseline case is then checked with aeroservoelastic simulations in IEC class A turbulent wind fields.

The paper is structured as follows: in section 2 the modelings of the wind turbine and the LIDAR system are described, as well as the wind fields used for the simulations. In section 3 the controller design steps are explained, from plant linearization to the output weights used. Finally, on section 4 the results of the simulations are presented and discussed.

2 System Modeling

2.1 Wind turbine model

The simulations are performed with the nonlinear simulation program FAST (Fatigue, Aerodynamics, Structures, and Turbulence) provided by the US National Renewable Energy Laboratory (NREL) [9] interfaced with Simulink. A detailed description of the aeroaelastic 16 degrees of freedom model and implementation can be found in [9].

The parameters used in the FAST model come from the NREL 5MW onshore reference turbine described in [10]. The baseline feedback pitch and torque controllers are both described in [4]. The original FAST code does not provide a model for the pitch actuator, so it is also modeled as proposed in [4].

2.2 Wind field simulator

The turbulent wind fields used in the simulations were generated by the NREL code TurbSim [8]. It uses a statistical method to create a grid of wind vectors that marches towards the tower at a constant mean speed assuming Taylor's frozen turbulence hypothesis, which is considered a good approximation by other studies [12]. For this study, 100 realizations of a 18 m/s International Electrotechnical Commission (IEC) class A turbulent wind field [1] were generated, each 630s long. The first 30s of each simulation is not included in the final analysis to allow initial transient effects to settle.

2.3 LIDAR Model

Developing a high-fidelity LIDAR model is out of the scope of this study, so a simpler LIDAR model similar to [7] was adopted. Its laser beam is focused 72m ahead of the turbine in order to provide 4s preview measurements in a 18m/s wind field. This amount of preview time is in line with other studies [2,3,15] and is selected to increase the preview control performance and minimize measurement errors.

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Due to the wind variable nature there is not a single speed that can be measured and fed into the pitch controller. Instead, an estimate of the effective rotor wind speed is made by averaging over 24 measure points each at a radius of 70% the blade span.

The LIDAR measurements are assumed to be point-wise and that the samples are provided at the same 80 Hz rate of the FAST and controller models.

The LIDAR measurements are smoothed using a moving average filter [15]. This helps model the LIDAR ability to measure only the low-frequency part of the wind spectrum and to prevent unnecessary control action, as only the slow fluctuations of the flow can be attenuated by a collective pitch controller [12]. As in [13], additional preview time has to be introduced to account for the filter delay.

3 Feedforward Controller Design

The $\mathcal{H}_2$ optimal preview control problem of figure 1 can be defined as to find find a causal controller K_{FF} which stabilizes the system and minimizes the $\mathcal{H}_2$ norm of the transfer function from η to z, that is, to minimize the power of the output z of figure 1 when the input η is white noise.

3.1 Design procedure

In this study, the input to the feedforward controller is the previewed effective wind speed from the LIDAR and the output is a pitch signal to be added to the existing one from the feedback controller. The pitch system is active in the high wind operating range (11.4 – 25 m/s). In this region, the generator is already at rated speed, so the control objectives are the mitigation of tower movements and loads, and to regulate the generator speed error. In preceding studies preview control was found to increase pitch action [2,15], so in order preserve the life of the actuators a weight on pitch angle was included in the control objectives as in [3].

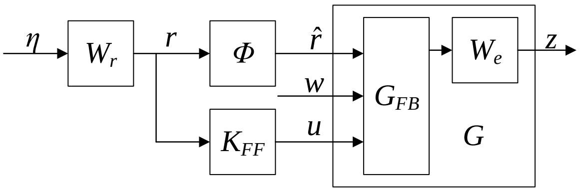

Figure 1: General feedforward controller design problem. G represents a generalized plant, where G_{FB} is the plant with an existing feedback controller and W_e is an output weighting function. K_{FF} is the controller to be designed, Φ is a N-step delay line and W_r is a weighting function describing the spectral content of the previewable signal. η is the future input, r the weighted preview, $\hat{r}$ the delayed input, w the non-previewable disturbance, u the control signal and z the weighted output.

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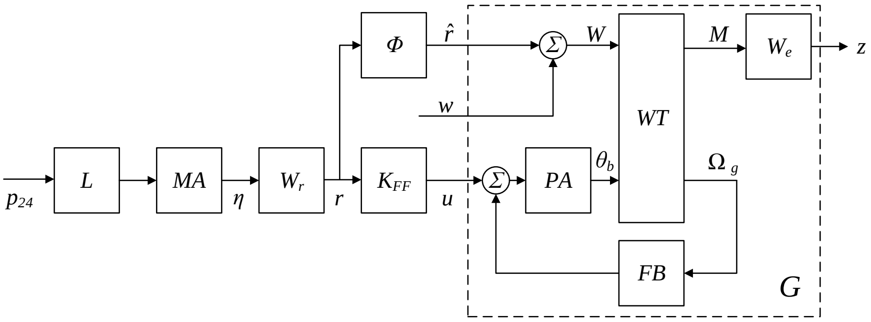

Figure 2: The generalized plant used for $\mathcal{H}_2$ control synthesis. p_{24} represents the vector of the 24 wind speeds read by the laser beams across the measurement circle, L is the LIDAR system, which averages p_{24}, MA is a moving-average filter, PA the pitch actuator, WT the linearized turbine model, FB the baseline feedback controller. The signal W is the effective wind speed. The linearized turbine model has wind speed W and pitch angle θ_b as inputs, and generator speed error Ω_g and the signal M as outputs. M is a vector composed by the generator speed, blade pitch angle and tower fore-aft acceleration. Other notation follows as defined in figure 1.

3.1.1 Linearization

The non-linear model from FAST is linearized with help of FAST linearization routines [9] around the operating point of 18 m/s. A Coleman transformation is applied to filter out the harmonics caused by the blades rotating motion. The result is a state-space model of order 32 that can be further used in the controller design process. The linearization procedure is explained in detail in [11].

3.1.2 Discrete-time $\mathcal{H}_2$ optimal preview control

A generalized plant G in accordance to the $\mathcal{H}_2$ preview control structure from figure 1 is shown in figure 2. With plant G the preview controller is designed using the algorithm given by Hazell [6]. The advantage of this method over traditional preview control is that it greatly reduces the computational complexity and reduces numerical stability problems found in other studies [2, 3].

The number of preview steps is 320, as the preview is of 4s and the control system sample rate is 80Hz. As shown in [6], as the number of preview steps $N \to \infty$, the control becomes independent of Wr. Also, the signal w can be disregarded in the design process, as the feedforward controller has no effect on the transfer function from w to z. Therefore, the only design parameter in the case of a large preview is the output weight W_e. This weight was chosen iteratively with help of Bryson's rule as to equally penalize a 10 rpm generator speed error, 20° pitch movements and a 2 m/s^2 tower fore-aft acceleration. The controller K_{FF} was then calculated with the formulae from section 4.4 of [6], with the

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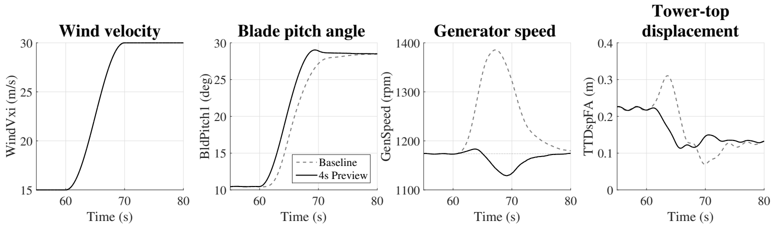
output weight matrix given in the metric system, by

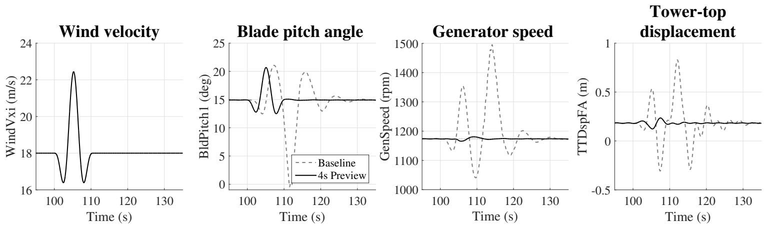
$$W_e = \begin{bmatrix} \frac{1}{\max {z_1}^2} & 0 & 0 \\ 0 & \frac{1}{\max {z_2}^2} & 0 \\ 0 & 0 & \frac{1}{\max {z_3}^2} \end{bmatrix} = \begin{bmatrix} 0.9119 & 0 & 0 \\ 0 & 8.2070 & 0 \\ 0 & 0 & 0.2500 \end{bmatrix} \quad (1)$$

4 Simulation Results

The plant with the feedforward controller was tested in varied conditions and the results were compared to those obtained by the baseline controller with the same wind inputs. Two different classes of test were performed, he first related to extreme wind conditions and the second related to normal operating conditions.



(a) Extreme coherent gust



(b) Extreme operating gust

Figure 3: Extreme wind condition tests

For the first group of simulations two load cases were tested: an extreme coherent gust and an extreme operating gust. The results obtained are presented in figure 3. In these simpler simulations the effects of preview action are clearly visible: the blades start to pitch in advance in relation to the feedback-only system, providing better speed regulation and smaller tower movements.

In the second group of tests, simulations were made with the 100 wind fields from section 2.2. During normal operation in turbulent conditions, the control objective is to reduce loads and prevent component deterioration. The metrics chosen to represent these goals are: mean power output, RMS generator speed error, nacelle displacements and blade pitch rate, time above rated speed and low-speed shaft (LSS), blade root and tower moments Damage Equivalent Loads (DEL). RMS displacements are calculated around the mean value and DELs are computed based on a rainflow counting algorithm from NRELs MLife software [5]. Wohler exponents were chosen as 10 (typical composite materials) for the blades and as 4 (typical steel) for the tower and shaft.

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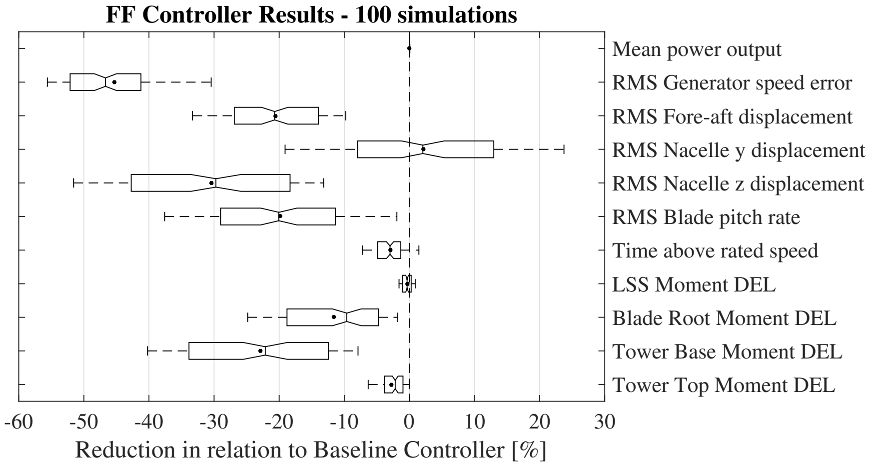

Figure 4: Operating conditions performance improvement from the feedforward controller. The box limits are the 25th and 75th percentiles of the data, the center line shows the median, the dots show the mean and the whiskers extend to the 10th and 90th percentiles. The notches indicate the median 95% confidence interval.

The box plots in figure 4 were made with data from all 200 simulations (100 input wind fields for each controller). The system augmented with preview action has the same mean power output as the baseline controller but has improved speed regulation over 45% and reduced tower fore-aft motion and pitch activity in 20%. The calculated DELs have all decreased with the preview control, especially the tower base DEL, as this variable is closely related to the design parameter (tower fore-aft acceleration). These results confirm that the design objectives were achieved during operational conditions.

5 Conclusions and future work

In this paper a wind turbine feedback control system was augmented with a feedforward controller designed with the $\mathcal{H}_2$ preview control theory developed in [6]. The proposed design was tested in non-linear simulations and the outcomes were measured against a baseline case. In accordance to the design parameters, the feedforward system has better speed regulation, lower structural loads and lower pitch activity. The results here exposed show the feasibility of the proposed design method and its effectiveness.

Topics for future work are the improvement of the LIDAR model, the testing of slower control sampling rates and smaller preview times, the choice of other design parameters and their weights in an algorithmic way and the use of the $\mathcal{H}_\infty$ preview control design methodology also developed in [6].

Acknowledgment

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References

[1] International Electrotechnical Commission, Wind turbine-part 1: Design requirements, IEC 61400-1, (2005).

[2] F. Dunne et. al., Adding feedforward blade pitch control for load mitigation in wind turbines, 49th AIAA Aerospace Sciences Meeting, (2011).

[3] F. Dunne and L. Y. Pao, Benefit of wind turbine preview control as a function of measurement coherence and preview time, American Control Conference, 647–652, (2013).

[4] J. D. Grunnet et. al., Aeolus toolbox for dynamics wind farm model, simulation and control, The European Wind Energy Conference & Exhibition, (2010).

[5] G. Hayman, Mlife theory manual for version 1.00, National Renewable Energy Laboratory, (2012).

[6] A. Hazell, Discrete-time optimal preview control, Doctorate Thesis, Imperial College, (2008).

[7] L. Jespersen and M. Krogen, Model predictive lidar control of wind turbines for load mitigation, Master Dissertation, Aalborg University, (2011).

[8] B. J. Jonkman, TurbSim user's guide: Version 1.50, National Renewable Energy Laboratory, (2009).

[9] J. M. Jonkman and M. L. Buhl, Fast users guide, National Renewable Energy Laboratory, (2005).

[10] J. M. Jonkman et. al., Definition of a 5-MW reference wind turbine for offshore system development, National Renewable Energy Laboratory, (2009).

[11] L. Pereira, A Lidar Assisted Feedforward Preview Controller for Load Mitigation in Wind Turbines, Master Dissertation, Instituto Tecnológico de Aeronáutica, (2015).

[12] D. Schlipf et. al., Testing of frozen turbulence hypothesis for wind turbine applications with a scanning lidar system, 15th International Symposium for the Advancement of Boundary Layer Remote Sensing, (2011).

[13] D. Schlipf et. al., Field testing of feedforward collective pitch control on the cart2 using a nacelle-based lidar scanner, Journal of Physics: Conference Series, v. 555, n. 1, 2090, (2014).

[14] A. Scholbrock et. al., Field testing lidar based feed-forward controls on the nrel controls advanced research turbine, 51th AIAA Aerospace Sciences Meeting, (2013).

[15] N. Wang et. al., Lidar-assisted preview controllers design for a mw-scale commercial wind turbine model, 52nd Annual Conference on Decision and Control, 1678–1683, (2013).