PROSPECTS OF A COLLECTIVE PITCH CONTROL BY MEANS OF PREDICTIVE DISTURBANCE COMPENSATION ASSISTED BY WIND SPEED MEASUREMENTS

David Schlipf, Martin Kühn
Endowed Chair of Wind Energy (SWE), Universität Stuttgart
Allmandring 5B, 70569 Stuttgart, Germany
+49(0)711/685 68254, david.schlipf@ifb.uni-stuttgart.de

Summary

A simple but robust and effective method to improve collective pitch control of variable-speed wind turbines given information on future inflow is proposed. The present paper focuses on the design and prospects of a control concept using predictive disturbance compensation. This feed-forward control structure is based on calculation of a future effective wind speed, on static disturbance compensation from steady turbine data and on estimation of the dynamic behavior. The control strategy is evaluated with regards to stability, robustness and performance in frequency and time domain. The required wind field information is currently not available for common control, but can in general be obtained from measurements with remote sensing technologies and wind modeling. Significant reductions of rotor speed variations, mechanical loads and pitch activity at fatigue and extreme operating conditions are demonstrated.

1. Introduction

Atmospheric turbulence at fatigue and extreme conditions is the main design driver for large wind turbines. In terms of control theory wind gusts experienced by a wind turbine represent an unknown disturbance. However, conventional feedback controller will react to this type of excitation with a delay since the disturbance has to pass the entire wind turbine dynamics before showing its effects in the outputs. This usually results in undesired loads and rotor speed variation of pitch-controlled, variable-speed wind turbines.

Wind field measurements with remote sensing technologies such as Light Detection and Ranging (LIDAR) might pave the way for predictive wind turbine control strategies aiming to reduce excessive loads on turbine components. Remote sensing offers wind speed tracking at various points in space and time well in advance of reaching the swept rotor area and before hitting load sensors at the blades or machinery. This provides the control and safety system with sufficient reaction and processing time.

In Figure 1 the different steps for predictive wind turbine control are shown. The objective of the first step is to obtain wind fields in different distances in front of the turbine, e.g. by use of LIDAR. In the next step, turbulence theory e.g. the “frozen turbulence theorem” and wind models are considered. In the last step, the predicted future wind fields are used to improve wind turbine control.

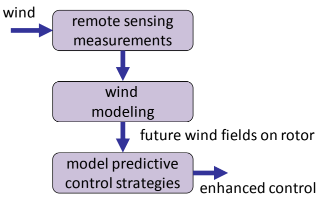

Figure 1: Steps in model predictive wind turbine control assisted by remote sensing

Obviously the quality of the above-mentioned steps in inflow prediction is decisive for the prospects of the new control concept as a whole. The hardware and software requirements of a sufficiently robust and cost-effective LIDAR device are however driven by a proper selection of the control strategy. Therefore this paper concentrates on the model predictive control strategy for full load operation, assuming perfect measurements and wind modeling.

The paper is structured as follows: In Section 2 the new control concept is introduced with application to collective pitch control and a proof of stability based on control theory. Section 3 shows the implementation for a generic 5MW turbine within the simulation program FAST and Simulink. Control performance in time and frequency domain is investigated and evaluated with respect to parametric uncertainty based on stochastic wind field data in Section 4. Conclusions and further research can be found in Section 5.

2. Controller concept

2.1. Predictive Disturbance Compensation (PDC)

In control theory, known disturbance can be compensated, if the influence on the output *y* of the disturbance *d* (system Σ_{yd}) and the system input *u* (system Σ_{yu}) is known and is invertible (Figure 2). Then the update to the feedback output

$$\Sigma_{DC} = -\Sigma_{yu}^{-1}\Sigma_{yd} \qquad (1)$$

compensates the disturbance entirely and the controller Σ_{FB} is only responsible for reference value tracking. Often these conditions are not fulfilled or the disturbance compensation cannot be technically implemented, if Σ_{DC} is not proper [1]. Therefore, a static compensation can be implemented, equivalent to the static value u_{ss} of the system input subject to the static disturbance d_{ss}:

$$\Sigma_{DC} \underset{t\to\infty}{=} u_{ss}\left(d_{ss}\right) \qquad (2)$$

In this case the controller Σ_{FB} has to react during the dynamic transition. If Σ_{yu} has a higher dynamic order than Σ_{yd}, the transition time will increase. Therefore, a Predictive Disturbance Compensation (PDC) is proposed (Figure 2).

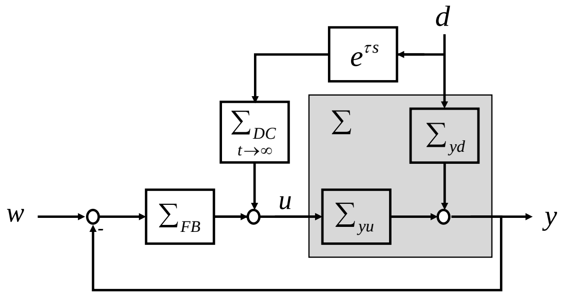

Figure 2: Structure of the Predictive Disturbance Compensation

The static disturbance compensation will be added to the feedback output with a predictive time shift τ. The purpose is to reduce the transition time.
So, this feed-forward control structure consists of two components: the static disturbance compensation law (2) and the predictive time shift τ.

2.2. Stability analysis of PDC

The proposed control structure is stable if and only if the closed loop is stable [2]. With static feed-forward control, poles can neither be manipulated nor generated and so, stability cannot be affected. On the contrary, performance can be influenced through manipulation of the zeros (Section 4.4). The predictive time shift used in the disturbance compensation path can be treated like a time delay in the disturbance path. Here the time delay, usually crucial for stability, has no effect on it, because it is outside the feedback loop.

2.3. PDC for collective pitch control

For collective pitch control of wind turbines, the disturbance with the heaviest impact to the system behavior is the incoming wind field. To reduce rotor speed variation a wind speed estimation within a feed-forward structure has been suggested in [3] to effectively compensate the wind gust influences on the rotor speed. Major drawbacks in dynamic feed-forward pitch control design are parametric and model uncertainties due to complex coupled dynamics and difficulties in nonlinear system inversion. The presented predictive disturbance compensation overcomes these problems. For a given rotor speed there is a unique function determining a steady pitch angle for each steady wind speed. This function can be obtained by modeling the drive train dynamics according to the law of conservation of angular momentum [4] and assuming a constant wind speed over the rotor area. The presented feed-forward with predictive compensation will react before wind changes are detected by rotor speed variation forcing the pitch actuator to its desired value.
For implementation of the proposed PDC the time variant wind field has to be reduced to one effective wind speed v_{eff} (Section 2.4). We consider that wind fields with the same effective wind speed cause equal power. The control variable is the rotor speed Ω, forced to the constant value Ω_{rated} by the manipulated variable, the collective pitch angle β_c. The static disturbance compensation law (2) arises out of the static pitch angle position subject to the static effective wind speed.
To find the adequate predictive time shift τ, a simplified model including the drive-train dynamics and the blade pitch actuator is employed [4]:

$$\begin{aligned} J\dot{\Omega} &= M_a\left(\Omega, \beta_e, v_{eff}\right) - M_{el} \\ \ddot{\beta}_e + 2\xi\omega\dot{\beta}_e + \omega^2\beta_e &= \beta_c \end{aligned} \tag{3}$$

The pitch actuator is usually represented by a linear second order model from the blade pitch control β_c to the effective blade pitch angle β_e, where ω is the un-damped natural frequency and ξ the damping ratio.
The non-linear drive-train shaft dynamics arises from the law of conservation of angular momentum: J is the sum of the moments of inertia resulting from blades, hub and generator, M_{el} the electrical reaction torque and M_{aero} the aerodynamic torque computed as

$$\begin{aligned} M_{aero}\left(\Omega, \beta_e, v_{eff}\right) &= \frac{1}{2}\rho\pi R^2 \frac{c_p\left(\lambda, \beta_e\right)}{\Omega} v_{eff}^3 \\ \lambda &= \frac{\Omega R}{v_{eff}} \end{aligned} \tag{4}$$

where R is the rotor radius, ρ the air density, λ the tip speed ratio, c_p the power coefficient and v_{eff} the effective wind speed. As mentioned before, the transition time of static disturbance compensation depends on the dynamic orders of the different subsystems. Since the control action has to pass through the pitch actuator dynamic, the predictive time shift is chosen to overcome this transition time:

$$\tau = T_{\beta_e \beta_c} \tag{5}$$

where $T_{\beta_e \beta_c}$ denotes the rise time from β_c to β_e.

2.4. Calculation of the effective wind speed

The effective wind speed can be estimated from measured standard signals like electrical power, rotor acceleration and pitch angle, using a simplified model and either a priori calculated tables [3] or a Kalman-Filter [5]. When the wind speed has to be calculated from wind fields, it is important to predict the impact of each measured local wind vector on the overall effective wind speed. Aero-elastic simulation tools use iteration procedures to calculate the overall effect on the turbine. Dynamic states of the turbine are needed and that is why this cannot be done for predictive wind fields. Here a weighting depending on the radial distance is proposed:

$$v_{eff} = \left. \sqrt[3]{\frac{\int_0^{2\pi}\int_0^R v^3(r,\theta)\frac{\partial c_p\left(r,\lambda,\beta_e\right)}{\partial r} r\,dr\,d\theta}{\int_0^{2\pi}\int_0^R \frac{\partial c_p\left(r,\lambda,\beta_e\right)}{\partial r} r\,dr\,d\theta}} \right|_{\substack{\lambda=\lambda_{rated} \\ \beta_e = 0°}} \tag{6}$$

where the span-wise variation of power extraction $\frac{\partial c_p(r,\lambda,\beta)}{\partial r}$ is obtained by modeling tip and root losses [6]:

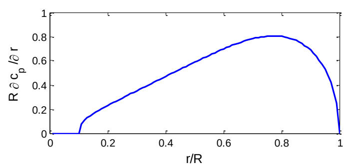

Figure 3: Span-wise variation of power extraction in the presence of tip and root losses

This results in a three-dimensional weighting function (see Figure 4).

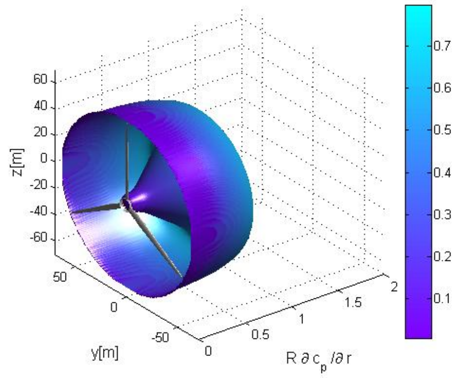

Figure 4: 3D weighting function for the effective wind speed

To mitigate outliers and high-frequency excitation of the control system a single-pole low-pass filter is used for the effective wind speed. Therefore the predictive time shift is prolonged to

$$\tau = T_{\beta_e \beta_c} + \frac{2\pi}{f_c} \qquad (7)$$

where f_c is the corner frequency of the filter.

3. Reference turbine

To test the control strategy proposed above, the following simulation environment has been set up: An aero-elastic model of a 5MW offshore turbine in FAST [7] has been coupled to Simulink. Here the feed-forward control, with pitch actuator model (3), the wind speed filter and the PI feedback controller have been implemented with the same structure and values presented in [7]. Only the PI time constant has been changed due to the added pitch actuator dynamics. The predictive disturbance compensation is designed as discussed in Section 2.1.

The static disturbance compensation law is documented in [7] and is shown in Figure 5.

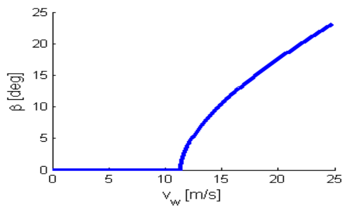

Figure 5: Static pitch over wind speed for the 5MW turbine

Because of the chosen corner frequency and pitch actuator dynamics the prediction time shift results in τ =1s.

4. Evaluation

4.1. Performance in frequency domain

As a first step, the comparison between the different control strategies is performed in the frequency domain. The transfer function represents the dynamics from the effective wind speed v_{eff} to the rotor speed Ω. The time delay in the predictive disturbance compensation has been realized with a Padé approximation [1].

In Figure 6 the solid line represents the common feedback PI controller without any feed-forward, the dotted and dashed lines correspond to the same PI controller enhanced with static and predictive disturbance compensation, respectively. The frequency band shown was chosen according to the magnitudes of the Kaimal spectrum. As operation point v_{eff}=12 m/s is selected. It can be seen that for frequencies up to approximately 0.2 Hz the proposed PDC rejects changes in the wind speed at least with 20 dB more than the conventional controller. Static DC produces a better damping in the considered frequency range than the conventional controller, but cannot overcome the PDC.

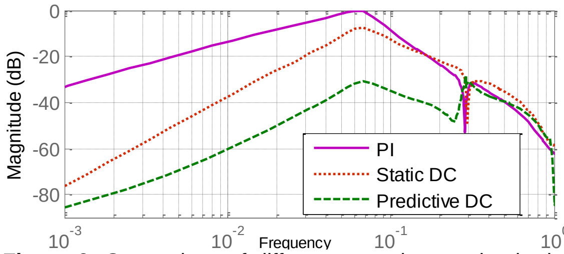

Figure 6: Comparison of different control strategies in the frequency domain

4.2. Effect at extreme operating gusts

In the time domain the different control strategies are compared with their reaction to an extreme operation gust. Therefore a hub-height time series has been created with a gust according to IEC [8] at v_{Hub}=14 m/s. The behavior of the different controller implementations is shown in Figure 7.

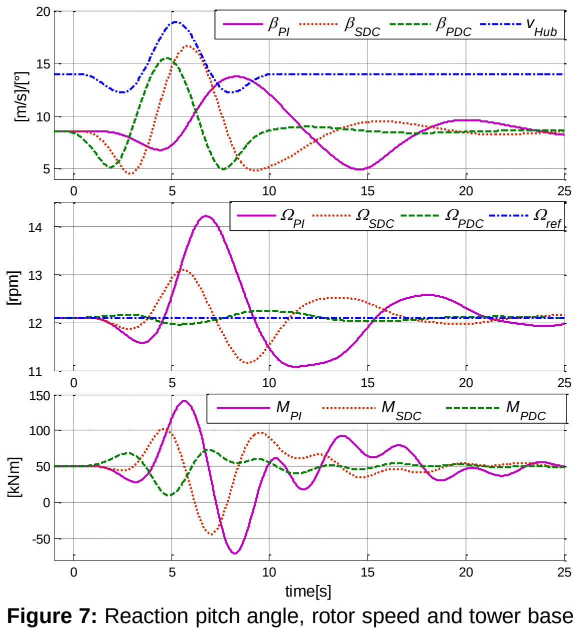

Figure 7: Reaction pitch angle, rotor speed and tower base fore-aft bending moment at extreme operating gust

In simulations with the conventional PI controller the rotor speed reaches 117% of Ω_{rated}. Depending on the safety system this overspeed can be high enough to switch off the power generation. With PDC the rotor speed reaches just 102%. From Figure 7 and Table 1 it can be seen that with PDC the regulation of the rotor speed and therewith the regulation of the aerodynamic torque leads to a much lower increase of the fore-aft bending moment at the tower base.

Table 1: Standard deviation of the signals from Figure 7

	PI	SDC	PDC	PDC/PI
σ(Ω) [rpm]	0.74	0.39	0.07	9%
σ(M_a) [kNm]	4.00	2.42	0.39	10%
σ(M_{yT}) [MNm]	38.2	27.3	11.0	29%

4.3. Effect at turbulence inflow

Furthermore, the different control strategies are compared with their reactions to a stochastic wind field generated with TurbSim [9]. The used grid has a 15x15 spatial resolution every 0.05s and is generated based on a Kaiman spectrum with v_{Hub}=14 m/s and T_I=18%. Figure 8 presents the calculation of the effective wind speed and the simulations for 150 seconds.

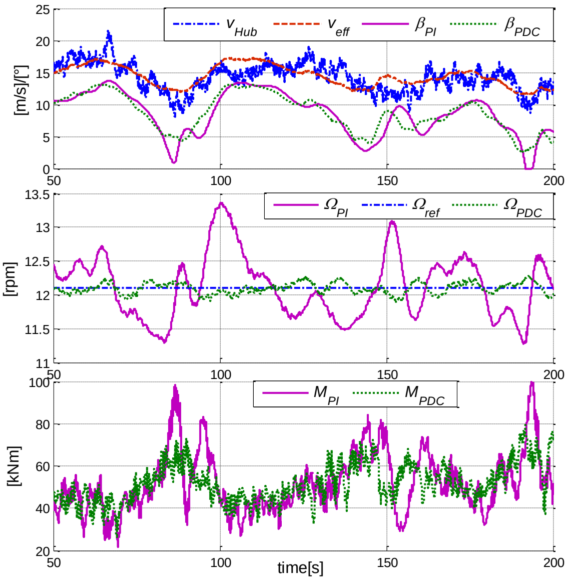

Figure 8: Reaction pitch angle, rotor speed and tower base fore-aft bending moment at turbulence inflow

The beneficial effects seen in the previous sections are confirmed: With PDC there is less rotor speed variation. The extended controller decreases the standard deviation of loads at tower base and blades despite lower pitch dynamics (Table 2).

Table 2: Standard deviation of the signals from Figure 8

	PI	PDC	PDC/PI
σ(Ω) [rpm]	0.42	0.09	21%
σ(M_{yT}) [MNm]	12.8	8.72	68%
σ(M_{yB}) [MNm]	1.85	1.53	83%
σ($d\beta/dt$) [deg/s]	0.60	0.47	78%

4.4. Robustness

As shown in Section 2.2, there is no risk of instability when PDC is applied to a stable feedback controller. But different reasons could degrade the advantages shown in Section 4.1 to 4.3, even to a weaker performance than the conventional PI controller. Measurement errors due to inaccurate measurements of local wind speeds and modulation errors due to inaccurate calculation of the effective wind speed, incorrect static pitch or invalid "frozen turbulence theorem" could be possible weak points, which have not been considered in this paper, yet.

A robustness analysis has been made of the design factor of the PDC. With (5) a rule of thumb has been proposed for the predictive time τ shift, but in reality τ could be over-, or underestimated. Therefore the simulation at turbulence inflow was repeated with different prediction times. Figure 9 illustrates the robustness of the PDC. Even with an overestimation of 500%, i.e. τ =5s, the standard deviation remains below the conventional PI controller.

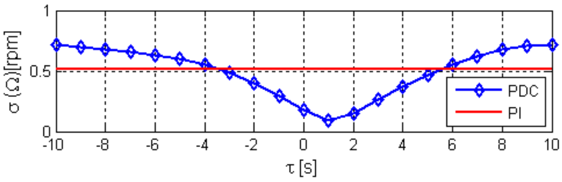

Figure 9: Standard deviation of Ω subject to different prediction times shifts τ for PDC and conventional PI controller

5. Conclusions and outlook

In this paper the proposed Predictive Disturbance Compensation has been presented as a powerful extension to the basic PI controller for rotor speed regulation. If future wind fields are provided, e.g. from remote sensing, a decrease of the standard deviation of the rotor speed by 70%-80% can be achieved. In this way fatigue and also extreme loads on tower, drive-train and blades can be reduced significantly without higher pitch dynamic.

In further research the presented PDC is planned to be applied to torque control at partial load as well as for cyclic or individual pitch.

Acknowledgment

Part of this research is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in the framework of the German joint research project "Development of LiDAR technologies for the German offshore test field" (Contract No. 0327642).

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