Lidar-assisted Extreme Load Reduction by Multi-variable Protective Derating

Florian Haizmann, David Schlipf and Po Wen Cheng
Stuttgart Wind Energy (SWE) at Institute of Aircraft Design, University of Stuttgart, Allmandring 5B, 70569 Stuttgart, Germany
E-mail: haizmann@ifb.uni-stuttgart.de

Abstract. Lidar-assisted control of wind turbines has been an active field of research during the last years and has recently become more attention from industry, as well. The potential of lidar-assisted feed-forward controllers is shown in various simulation studies and proven in first field-testings. This work aims to further push forward the application of lidar-assisted control by introducing a method to bring the wind turbine to a different operating point, when a lidar detects an approaching extreme gust. The method reduces the power output of the wind turbine while keeping the rotor rotation constant. This is achieved by a synchronous multi-variable feed-forwarding of the generator torque and the pitch angle. In combination with a classical lidar-assisted feed-forward controller, this leads to further reduced structural loads under the impact of an extreme gust. The method is tested with a coherent and a corresponding turbulent gust.

1. Introduction

Lidar-assisted control (LAC) has gained an increasing interest during the last years for improving the control of wind turbines. Lidar systems mounted on the nacelle provide wind speed measurements from the inflowing wind field just a couple of seconds before it hits the wind turbine’s rotor. These measurements have been successfully used by feed-forward controllers to reduce rotor speed fluctuations and structural loads caused by fluctuations in the wind field [1–3].

A standard load case for showing the potential of collective lidar-assisted feed-forward control is the so-called “Extreme Operating Gust” (EOG), defined in the standard [4]. Simulation studies with perfect lidar preview show that LAC can almost completely compensate the impact of an EOG to the structural loads of a wind turbine. However, in reality a lidar system cannot provide a perfect and reliable preview signal to the controller because of changing atmospheric conditions, which influence the availability of the measurements. Further, the imperfect reconstruction of the wind field from the limited temporal and spatial sampling of a real lidar system as well as the appearance of extreme gusts as turbulent structures instead of coherent ones, create additional uncertainty and thus less optimal results for LAC in the field.

The idea behind this work is to use the preview information from nacelle-mounted lidar to detect extreme events, such as an EOG, and preemptively bring the wind turbine to a reduced power level in order to assist the feed-forward controller in protecting it from extreme structural loads. Section 2 explains how this is realized and Section 3 shows exemplary results obtained by a reduced non-linear wind turbine model as well as with a full aero-elastic one. Finally, Section 4 closes this paper with some conclusions and an outlook to further work.
Figure 1. Structure of lidar-assisted feed-forward controller with MVPD: The wind turbine (WT) is controlled by a classical feedback (FB) controller, split into the collective pitch controller (CPC) and the indirect speed controller (ISC). The wind field $\nu$ is measured by a lidar and evolves (EVO) as rotor-effective wind speed $v_0$ towards the wind turbine. From the lidar measurements a lidar estimate of the rotor-effective wind speed $v_{0L}$ is reconstructed, which is used by the extreme event detection (EED) to trigger the MVPD. The dashed gray box contains the additional feed-forward controller (FF) and an adaptive filter (AF), cf. Section 3.1.

2. Methodology
The general approach of the presented method uses the reduced non-linear model of a wind turbine called “Simplified Low Order Wind turbine” (SLOW) [5, 6]. It considers the two degrees-of-freedom rotor speed $\Omega$ and tower top displacement $x_T$.

$$J\ddot{\Omega} = M_a - \frac{M_G}{i_{GB}}$$

(1)

models the rotor dynamics, where $J$ is the moment of inertia about the rotation axis, $M_a$ the aerodynamic torque, $M_G$ the generator torque and $i_{GB}$ the gear box ratio. This equation shows that the balance between the aerodynamic and the generator torque needs to be maintained if we want to keep the turbine’s rotational speed constant. Further, the aerodynamic torque needs to be reduced accordingly, if we want to simultaneously reduce the electrical power output of the turbine, which is a function of the generator torque ($P_{el} = \eta_{el} M_G \Omega_G$). This can be achieved by increasing the pitch angle $\theta$, since the aerodynamic torque

$$M_a = \frac{1}{2} \rho \pi R^4 \frac{c_p(\lambda, \theta)}{\lambda} v_{rel}^2$$

(2)

with $R$ the rotor radius, $\lambda$ the tip speed ratio, $c_p$ the power coefficient, and $v_{rel}$ the relative wind speed at the rotor, is a function of $\theta$. In contrast to existing approaches, e.g. in active power control [7] where the derating is either realized by changing the pitch angle or the generator torque, the presented method feed-forwards $M_G$ and $\theta$ simultaneously.

A half cosine function has been chosen as transition sequence for $M_G$ and $\theta$, which is applied in a feed-forward manner, with a small delay subtracted for $\theta$ to account for the pitch actuator dynamics. While the change of the pitch angle is applied as a pitch angle update $\Delta \theta_{FF}$ to
the proportional-integral (PI) pitch controller, the generator torque is changed by altering the aerodynamic power reference $P_a$ to the baseline torque controller (cf. Figure 1). The latter one needs to operate in constant power mode for this purpose. The magnitude of the reduction of $M_G$ is determined by the desired derating of the turbine, here 70%. The magnitude of the complementary increase in $\theta$ can be derived from steady state calculations. The derating of the wind turbine is triggered by the detection of the approaching extreme event in the preview of a lidar system. This method is called “Multi-variable protective derating” (MVPD).

Figure 2 depicts the explained principle of MVPD for the DTU 10 MW reference wind turbine (RWT): As a consequence of the coordinated increase in $\theta$ and the decrease in $M_G$, the power output $P$ and the tower top position $x_T$ are reduced, while the rotor speed $\Omega$ stays nearly constant.

Since the detection of the extreme event is crucial for the MVPD, it is assumed that the detection algorithm works reliably. A detailed evaluation of the detection is out of the scope of this initial study.

3. Results

The previously explained MVPD method is combined with a lidar-assisted feed-forward controller as shown in [5] and depicted in Figure 1. The following sections show the results from simulations with the DTU 10 MW reference wind turbine exposed to an EOG. At first, the reduced order model and then a full aero-elastic model with perfect wind preview is used. Finally, the latter is exposed to a turbulent EOG with realistic lidar measurements.

3.1. Using a reduced order model with perfect preview and a coherent gust

Figure 3 shows the results with the reduced order model SLOW at a wind speed just above rated wind speed and Figure 4 at cut-out wind speed. First, the simplified model is used in order to show the principle, as the nominal case. The MVPD is triggered by a detection of the EOG in the 5 s preview of a perfect lidar measurement. This detection algorithm compares the gradient of the rotor-effective wind speed sensed by the lidar $v_0L$ to a threshold [8]. It triggers the MVPD approximately 1 s before the EOG starts, which is about 6.25 s before the EOG reaches its peak.

The optimal duration time for the half cosine transition of the MVPD, which gives the smallest variations in the rotor speed, is found at 5 s, while the optimal derating is found at a derating down to 65% of the rated output power for both wind speed scenarios. Since the lidar-assisted feed-forward controller acts on the basis of the static pitch curve $\theta_{SS}(v_0)$ of the turbine, the feed-forward controller needs to change over to a different static pitch curve when the MVPD is
triggered. Here, the same half cosine function is used for the transition.

As Figures 3 and 4 and Table 1 show, the additional MVPD reduces the necessary pitch action of the feed-forward controller, represented by the totally traveled distance of the pitch angle $\theta_{TTD}$ and the standard deviation of the pitch angle $\text{std}(\dot{\theta})$, and at the same time keeps the maximum tower base bending moment $M_{yT}$ below its static value from before the impact of the EOG. The variations in $M_{yT}$ induced by the MVPD are negligible compared to the variations induced by the gust. At the same time the rotor speed variation, represented by its standard deviation $\text{std}(\Omega)$, is only slightly increased at 25 m s$^{-1}$ while further decreased at 14 m s$^{-1}$.

3.2. Using a full aero-elastic model with perfect preview and a coherent gust

Similar results are achieved when using a full aero-elastic simulation. In this work DNVGL’s software BLADED is used to simulate the DTU 10 MW reference wind turbine as a full aero-elastic model. Blade modes have been disabled. Furthermore, tower shadow has been switched off for illustrative reasons. The same lidar-assisted feed-forward controller in combination with the proposed MVPD algorithm as described in the Section 3.1 is simulated in BLADED for the transient wind conditions of IEC conform EOGs at 14 m s$^{-1}$ and 25 m s$^{-1}$. Again, the lidar measurement is assumed to be perfect, i.e. the lidar measures exactly the wind speed which the
Figure 4. Reaction to a coherent EOG at cut-out wind speed ($25\,\text{m/s}^{-1}$) with perfect wind preview using the DTU 10 MW RWT. Simulated with reduced non-linear model SLOW: FB controller only (blue), FB with additional MVPD (red), FB with FF (yellow), and FB with FF and with additional MVPD (purple). Steady state tower base bending moment $M_{yT}$ (black).

Table 1. Load statistics at 14 m/s$^{-1}$ and at 25 m/s$^{-1}$ for SLOW.

| $U_{\text{Ref}}$ [m/s] | std($\Omega$) [rpm] | max $M_{yT}$ [MNm] | max ($\Delta M_{yT}$) [MNm] | $\theta_{\text{TTD}}$ [deg] | std($\dot{\theta}$) [deg/s] |
|------------------------|---------------------|---------------------|----------------------------|-----------------|------------------|
|                        | 14 25               | 14 25               | 14 25                      | 14 25           | 14 25            |
| FB                     | 0.37 0.58           | 297.9 255.7         | 428.7 453.9                | 17.59 4.65      | 0.95 0.25        |
| FB+MVPD                | 0.33 0.54           | 240.2 233.6         | 385.6 444.0                | 12.62 4.71      | 0.61 0.24        |
| FB+FF                  | 0.01 0.02           | 167.9 74.2          | 118.7 13.6                 | 27.54 21.67     | 1.83 1.55        |
| FB+FF+MVPD             | 0.03 0.01           | 99.9 53.2           | 58.3 5.1                   | 20.77 20.82     | 1.43 1.49        |

| FB+MVPD FB [%]         | 89.2 93.1           | 80.6 91.4           | 89.9 97.8                  | 71.7 101.3      | 64.2 96.0        |
| FB+FF FB [%]           | 2.7 3.4             | 56.4 29.0           | 27.7 3.0                   | 156.6 466.0     | 192.6 620.0      |
| FB+FF+MVPD FB [%]      | 8.1 1.7             | 33.5 20.8           | 13.6 1.1                   | 118.1 447.7     | 150.5 596.0      |
rotor of the turbine is exposed to. As depicted in Figures 5 and 6 the MVPD in combination with the feed-forward controller leads to very similar results like before when using the simplified model. This shows that the proposed method is robust against model uncertainties, because it has not been re-tuned for the full aero-elastic model. From the numbers in Table 2 it can be seen, that the MVPD reduces the necessary pitch action and at the same time further reduces the rotor speed variation compared to the case where only the FB and the FF controller is applied. Like in the nominal case, the maximum tower base bending moment \( M_{yT} \) can be kept below its static value from before the impact of the EOG by the MVPD.

3.3. Using a full aero-elastic model with realistic lidar measurements and a turbulent gust

Similar results are achieved when using the full aero-elastic simulation, a lidar simulator and a turbulent gust based on [9]. For this study, the lidar simulator of BLADED is used to simulate a pulsed lidar measuring on a circular 8-point trajectory with 5 measurement distances. This measurement configuration has been optimized according to [10] for the DTU 10 MW reference wind turbine. Additionally, the blade modes have been activated. Figures 7 and 8 show that due to the realistic lidar measurement, the MVPD in combination with the FF controller is no longer able to keep the maximum tower base bending moment \( M_{yT} \) below its average value.
Figure 6. Reaction to a coherent EOG at cut-out wind speed (25 m s\(^{-1}\)) with perfect wind preview using the DTU 10 MW RWT. Simulated with full aero-elastic model in BLADED: FB controller only (blue), FB with additional MVPD (red), FB with FF (yellow), and FB with FF and with additional MVPD (purple). Steady state tower base bending moment \(M_{\text{yT}}\) (black).

Table 2. Load statistics at 14 m s\(^{-1}\) and at 25 m s\(^{-1}\) for BLADED.

| \(U_{\text{Ref}}\) [m/s] | \(\text{std}(\Omega)\) [rpm] | \(\text{max} M_{\text{yT}}\) [MNm] | \(\text{max}(\Delta M_{\text{yT}})\) [MNm] | \(\theta_{\text{TTD}}\) [deg] | \(\text{std}(\dot{\theta})\) [deg/s] |
|----------------|-----------------|----------------|----------------|----------------|----------------|
| 14 | 25 | 14 | 25 | 14 | 25 | 14 | 25 | 14 | 25 |
| FB | 0.33 | 0.58 | 214.3 | 196.4 | 273.2 | 312.9 | 14.71 | 4.50 | 0.91 | 0.25 |
| FB+MVPD | 0.31 | 0.54 | 178.7 | 177.9 | 261.4 | 302.7 | 10.33 | 4.48 | 0.63 | 0.23 |
| FB+FF | 0.05 | 0.03 | 139.8 | 71.6 | 111.6 | 23.1 | 30.74 | 21.14 | 1.95 | 1.48 |
| FB+FF+MVPD | 0.03 | 0.02 | 82.1 | 58.8 | 58.5 | 24.0 | 21.72 | 20.18 | 1.49 | 1.42 |
| \(\text{FB+MVPD}/\text{FB}\) [%] | 93.9 | 93.1 | 93.4 | 90.6 | 95.7 | 96.7 | 70.2 | 99.6 | 69.2 | 92.0 |
| \(\text{FB+FF}/\text{FB}\) [%] | 15.2 | 5.2 | 65.2 | 36.5 | 40.8 | 7.4 | 209.0 | 469.8 | 214.3 | 592.0 |
| \(\text{FB+FF+MVPD}/\text{FB}\) [%] | 9.1 | 3.4 | 38.3 | 29.9 | 21.4 | 7.7 | 147.7 | 448.4 | 163.7 | 568.0 |
Figure 7. Reaction to a turbulent EOG close to rated wind speed (14 m s\(^{-1}\)) with simulated lidar measurements using the DTU 10 MW RWT. Simulated with full aero-elastic model in BLADED under a turbulent gust (seed 1): FB controller only (blue), FB with additional MVPD (red), FB with FF (yellow), and FB with FF and with additional MVPD (purple). Steady state tower base bending moment \(M_{yT}\) (black).

from before. However, the MVPD still improves the reduction of the peak \(M_{yT}\) compared to the FB+FF case. MVPD reduces \(M_{yT}\) compared to the FB only case also without the FF controller.

The numbers in Table 3 show averaged results from simulations with 4 seeds and it can be seen, that the MVPD gives better results for the close to rated wind speed of 14 m s\(^{-1}\).

4. Conclusion and Outlook
A method for protecting a wind turbine from extreme structural loads by preemptively derating it to a different operation point is presented. The transition is achieved by feed-forwarding the pitch angle and the generator torque at the same time. Thereby, the rotor speed is kept constant while the power output of the wind turbine is reduced. The so called “Multi-variable protective derating” algorithm is triggered by the detection of an extreme event in the preview measurement of a nacelle-based lidar system and combined with a lidar-based feed-forward controller.

The reduction of extreme structural loads with this method is shown in simulations for the nominal case with a reduced order nonlinear model and for the case with a full aero-elastic simulation model using the software BLADED. For both cases it is shown that the method can keep the maximum tower base bending moment \(M_{yT}\) below its static value from before the impact.
Figure 8. Reaction to a turbulent EOG at cut-out wind speed (25 m s\(^{-1}\)) with with simulated lidar measurements using the DTU 10 MW RWT. Simulated with full aero-elastic model in BLADED under a turbulent gust (seed 1): FB controller only (blue), FB with additional MVPD (red), FB with FF (yellow), and FB with FF and with additional MVPD (purple). Steady state tower base bending moment \(M_y\) (black).

Table 3. Load statistics (mean values over 4 seeds) at 14 m s\(^{-1}\) and at 25 m s\(^{-1}\) for BLADED using a lidar simulator and a turbulent gust.

| \(U_{\text{Ref}}\) [m/s] | \(\text{std}(\Omega)\) [rpm] | \(\max M_y\) [MNm] | \(\max (\Delta M_y)\) [MNm] | \(\theta_{\text{TTD}}\) [deg] | \(\text{std}(\dot{\theta})\) [deg/s] |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
|                 | 14              | 25              | 14              | 25              | 14              | 25              | 14              | 25              |
| FB              | 0.29            | 0.61            | 188.2           | 177.9           | 221.3           | 294.0           | 17.89           | 5.03            | 0.89            | 0.26            |
| FB\+MVPD       | 0.25            | 0.57            | 147.3           | 160.9           | 195.1           | 287.6           | 11.01           | 4.88            | 0.53            | 0.25            |
| FB\+FF         | 0.17            | 0.29            | 152.6           | 117.3           | 152.3           | 147.3           | 12.88           | 11.66           | 0.62            | 0.65            |
| FB\+FF\+MVPD   | 0.14            | 0.27            | 117.7           | 103.7           | 135.8           | 149.4           | 9.52            | 11.18           | 0.43            | 0.64            |
| \(\%\) FB\+MVPD/FB | 87.1            | 93.1            | 78.3            | 90.4            | 88.2            | 97.9            | 61.8            | 97.1            | 60.3            | 94.3            |
| \(\%\) FB\+FF/FB | 59.5            | 46.8            | 81.1            | 65.8            | 68.8            | 49.6            | 72.1            | 232.3           | 70.3            | 251.4           |
| \(\%\) FB\+FF\+MVPD/FB | 49.1            | 44.3            | 62.6            | 58.2            | 61.3            | 50.4            | 53.5            | 222.7           | 48.5            | 247.4           |
of the EOG. Furthermore, it reduces the necessary pitch action of the feed-forward controller as well as the rotor speed variations. Thereby, it can increase the robustness of a lidar-assisted feed-forward controller by bringing the turbine to a reduced thrust level. Finally, the method is also applied to more realistic simulations of lidar-assisted feed-forward control by using turbulent wind gusts and a lidar simulator. This setup shows that the MVPD still reduces the maximum load as well as the necessary pitch action compared to the feed-forward controller alone.

Further work needs to validate these results with even more realistic lidar measurements for example by introducing additionally wind evolution [11]. In a next step the method could also be applied to lidar-assisted individual pitch feed-forward control to reduce extreme loads of shear gusts. Furthermore, it would be interesting to investigate if other approaches like model predictive lidar controllers [12] would end up in derating the wind turbine in a similar way if they would consider the problem of the uncertainty of a lidar measurement.

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