Increased Aerodynamic Performance of Wind Turbines Through Improved Wind Gust Detection and Extreme Event Control

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Abstract
The performance of a wind turbine design is analyzed through several standardized design load cases (DLCs). Some of these load cases are constructed in such way that the inflicted ultimate loads are design driving: they determine the required strength of mechanical components. Such a load peak is often realized by extreme wind gusts. The extreme loads are usually amplified when the turbine exceeds a critical limit (such as generator over speed), and initiates a shutdown procedure. This paper introduces a technique which detects these gusts at an early stage. This detection, in combination with a transition to a reduced generators speed and power setpoints before the peak of the wind gust, reduces the ultimate loads significantly. The proposed wind gust detection and response to this detection was implemented in the controller of a commercial 6 MW offshore wind turbine design (developed by 2-B energy), and evaluated through a full load set calculation. Reductions in ultimate tower nodding moments and blade flap moments of around 7% were obtained.

Keywords: control, wind turbine design, wind gust detection, extreme even control, ultimate load reduction, tower blade clearance.

1. Introduction
The possibilities to improve the aerodynamic performance of a wind turbine in its design phase are growing rapidly. In order to maximally profit from these opportunities, the wind turbine controller must limit load increases that accompany these innovations. Such design loads are obtained from simulations of aero-elastic models of various standardized design load cases (DLCs). Some of these cases involve extreme wind gusts, such as the Extreme Coherent Gust (ECG, DLC 1.3 and 1.9, referring to IEC 61400-1 edition 3) and Extreme Operating Gust (EOG, DLC 1.5 and 1.6). These simulations are often design driving, i.e. their ultimate loads determine the required strength of mechanical components. By early detection of these wind gusts, followed by suitable control actions, the ultimate loads can be reduced, which clears the path for aerodynamic performance enhancing innovations. Moreover, these actions can avoid the turbine to reach absolute limits, such as the maximum allowable rotor speed, and thereby allowing the turbine to ride through the gust (i.e. avoid a shutdown procedure). Such a ride-through causes an additional reduction of the ultimate loads and ensures a minimum loss of power production.

There have been several publications on wind gust detection. The patented method in [1], bases gust detection on rotor acceleration. Such detection is difficult, because the observed acceleration may, besides wind gusts, be due to pitch or generator torque actions. Kanev et al. have introduced the CUSUM test to detect wind gusts [2]. This method was shown to be able to detect rising gusts and even extreme direction changes in an early stage. However, the method did not consider early detection of an EOG, which is one of the toughest gusts to detect. The same authors have presented a novel detection technique based on the Generalised Likelihood Test [3]. This method looks promising, but full load set evaluations were not reported in that publication. In [4], the detection of the EOG wind gust is performed by an artificial neural network that is trained on simulation data. It was shown that in full load set calculations the detector is able to detect the EOG in time to allow an early stop.

In this paper we propose a novel method for wind gust detection which is based on (least squares) fitting of wind profiles to estimated wind data. After a gust has been detected, simple control actions are taken which allow the turbine to be prepared for the upcoming gust. The detection and control method is verified in full load set calculations for the 2B6, a two bladed, downwind 6MW offshore wind turbine with full jacket structure (developed by 2-B Energy), illustrated in Figure 1.
The paper is constructed as follows. Section 2 presents ..., Section ... presents ....

2. Wind gust detection

The 2B6, as every wind turbine, is equipped with a hub wind sensor. This measurement is merely a single point observation in the entire rotor plane and shows high amounts of turbulence. Using this signal will yield many false gust detections. What is required for gust detection is the wind speed averaged over the rotor plane. This rotor effective wind speed cannot be measured directly and must be estimated from other measurements.

2.1 Wind speed estimation

Such estimation can be done using direct search methods, as proposed in [5], [6]. However, these algorithms solve a nonlinear optimization problem which might contain local minima. Such behaviour makes such methods less robust and less reliable. In this work we have applied a Luenberger-like Nonlinear Observer (LNO, [7]), which estimates the rotor effective wind speed online. This high gain observer is based on a nonlinear model of the wind turbine (derived from the model presented in [6]). In this model the rotor speed is defined by $\Omega(t)$, the generator torque by $T_G(t)$ and the pitch angles by $\theta_1, \theta_2$. Note that this work restricts itself to a two bladed turbine, but can easily be extended to three bladed systems. For a given rotor diameter $R$, the tip speed ratio is defined by

$$\lambda(t) \equiv \Omega(t)R/v(t),$$  \hfill (1)

where $v(t)$ is the rotor effective wind speed, and $R$ is the rotor radius. The aerodynamic torque $T_A(t)$ is a function of the pitch angles and tip speed ratio. This torque is modelled through (static) nonlinear rotor thrust ($C_T$) and torque ($C_Q$) coefficients. The relation between rotor speed and aerodynamic and generator torque is modelled by a simple linear differential equation:

$$\frac{d}{dt} \Omega = i_{GB}(T_A(\theta_1, \theta_2, \lambda) - T_G),$$  \hfill (2)

where $i_{GB}$ is the gearbox ratio. The nonlinear observer seeks the rotor effective wind speed $v(t)$ which drives the rotor speed $\Omega(t)$ of the nonlinear model to its corresponding measurement $\Omega_{MEAS}(t)$.

The advantages of this method are guaranteed convergence of the estimate under well-defined conditions and there is no need for iterations (as in [5]) or special additional precautions (as in [6]). Since this estimator only depends on its internal model, it requires minimal tuning. When evaluating different aerodynamic designs (such as new blades) in the design

Figure 1: Computer generated image of the 2B6, a two bladed, downwind 6MW offshore wind turbine with full jacket structure (developed by 2-B Energy).
process, only the $C_T$ and $C_Q$ coefficients need to be updated. Such flexibility makes this technique well suited to practical use when optimizing aerodynamic performance.

### 2.2 Wind profile fitting

The estimated rotor-effective wind speed signal $v(t)$ is computed online using the NLO estimator and its historical data $V_f(t)$ over a fixed interval of length $T$ (in seconds) is stored. This data can be compared to some predetermined profile $P(t)$ (for instance the EOG or ECG). By setting $\eta = (\eta_1, \eta_2)$ the following residual function can be defined:

$$r(\eta) \equiv || \eta_2 V_f(t) + \eta_1 - P(t) ||_F,$$

where $|| \cdot ||_F$ is the 2-norm defined over interval $T$. By sampling over the interval and applying a straightforward linear regression method, the following least squares problem can be solved

$$\eta^* = \arg \min r(\eta).$$

The computed parameter $\eta^*$ contains important information on the correlation between the fixed pattern $P(t)$ and the estimated wind data $V_f(t)$. First of all, note that $\eta_1^*$ is a measure for the mean wind speed over the fitting window $T$. Gusts are in general not causing ultimate loads at wind speeds well below rated speed, which makes this parameter a useful tool to threshold the detection (only flag a wind gust if $\eta_1^* > B_1$ for some predetermined value of $B_1$). The second parameter $\eta_2^*$ estimates the amplitude of the potential gust. Note that only positive amplitudes ($\eta_2^* > 0$) are relevant. The amplitude is a very effective indicator for the presence of the wind pattern in the stored data. By placing a threshold $B_2$ on this value, it can be decided whether the pattern $P(t)$ is present in the data. I.e. if

$$\eta_1^* > B_1 \text{ and } \eta_2^* > B_2 > 0,$$

a wind gust is likely to be present.

The three tuneable parameters of this scheme are $B_1$, $B_2$, and $T$. In order to detect the gust at an early stage, the length of the detection window $T$ should always be a lot smaller than the duration of the gust. Figure 2. illustrates a choice of $T$ for the ECG and EOG.

![Figure 2: Profiles of the ECG and EOG wind gusts. Only the first section (up to $T$, in blue) is used for wind gust detection.](image)

Note that even though the wind profiles of the EOG and ECG have specific patterns, the profile selections $P(t)$ are quite general. The ECG detection deals with all suddenly steep increasing gusts and the EOG detection focuses on all gusts where a dip is followed by a sudden increase in wind speed. Hence, this wind gust detection method does not predict whether an ECG or EOG is present, it estimates the likelihood that an ECG or EOG might follow. In practice, the partial profile without the rest of the gust will occur occasionally. In order to avoid these frequent detections, the data computed in DLC 1.2 (normal power production) can be used to select parameters $B_1$ and $B_2$ such that $\eta^*$ never exceeds them in these load cases. Nonetheless, the actions taken after a partial profile detection should be appropriate, regardless whether the rest of the profile will follow.

### 3. Extreme Event Control

The control system of the 2B6 turbine (Figure 1), developed by 2-B Energy and DotX Control Solutions, is based on a conventional rotor speed and power controller and includes modules for tower top motion damping, drive-train oscillations damping, individual pitch control (IPC) and yaw control. The controller has been developed and tuned for optimal power with minimal fatigue loads.
On a higher level, a supervisory controller determines the state in which the turbine operates. Wind gust detection as described in the previous section can easily be implemented in this supervisory module. The key issue now becomes what to do when a wind gust is detected. Note that the controller should reduce ultimate loads and avoid the turbine to reach and exceed absolute limits. In practice, this is typically done by open loop control actions (for instance by a shutdown procedure where the blades are pitched to feather at maximum speed). Such control strategies do not only ignore all aforementioned fatigue load reducing modules, they also prevent the turbine to resume power production quickly. Moreover, when not chosen carefully, it can even cause an increase of ultimate loads. Such behaviour is extremely undesirable in this application, where occasionally a partial gust is detected and the expected profile does not occur (i.e. the blue lines in Figure 2 are observed, but the dotted lines do not happen). In these cases extreme loads are inflicted without the presence of a gust and there will be a considerable loss of power production. Therefore, in this work, the Extreme Event Controller (EEC) is not implemented as an open loop controller, but rather functions as a master and deploys the power production controller, including all its modules, as a slave. This is done by treating the setpoints of the rotor speed and power controller as dynamic variables. When an early wind gust detection occurs (i.e. before any limits have been reached), the EEC reduces the setpoints of generator speed and power instantly, which results in immediate control actions (as in a open loop shutdown procedure), though keeping all control modules active. Striving for such a reduced operational state of the turbine before the

Figure 3: Data computed by GH Bladed for DLC 1.3 at 14 m/s (left) and load case 1.6 at 25 m/s (right). Note that without EEC, the turbine reaches its maximum rotor speed in both cases, and initiates a shut down procedure. By the actions caused by the EEC, the turbine can ride through the gust and quickly resume power production.
peak of the gust arrives, allows the turbine to ride through the gust (i.e. not reach its absolute limits such as the maximum allowable rotor speed). After the gust has passed, the controller can easily restore its initial set points, and resume power production. Such a ride-through reduces ultimate loads and the loss in power production significantly.

Unfortunately, a ride-through is not possible in all situations. DLC 1.5 contains an EOG combined with a critically timed grid-loss. This will force the supervisory controller to overrule the EEC and initiate a shutdown procedure as soon as grid-loss is observed. As it turns out, when the gust is detected before the moment of grid-loss, the outlined strategy reduces the rotor speed significantly, causing the grid-loss to have less of an impact. This reduces the ultimate loads considerably, albeit not with the same degree as a ride-through.

Note that such a procedure treats the presence of a partial profile always the same, regardless of what wind will come after the moment of detection. The ECG and EOG are designed as worst case scenarios. It can be expected that the ultimate loads computed with these profiles are representative for all extreme gusts. This boils the matter of generality of this method down to whether the partial profiles in Figure 2 are appropriate for extreme wind gusts of all kinds. More on this in the discussion section.

4. Load set calculations

The outlined scheme (wind gust detection and extreme event control) for ECG and EOG has been implemented in the 2B6 controller. This controller is designed in such way that it can be linked to aero-elastic codes such as GH Bladed and the PLC of a prototype.

Figure 3, shows data (computed by GH Bladed) of DLC 1.3 and 1.6 using the controller with and without EEC. DLC 1.3 contains an ECG, which causes the turbine to reach the upper speed limit and forcing it to initiate a shutdown procedure. When EEC is activated, the sudden drop in setpoint after detection causes the controller to instantly start pitching to feather. The maximum allowable rotor speed is not reached and the turbine can ride through the gust. When the gust has passed the controller resumes power production by resetting the setpoints. Note how all fatigue load reducing modules (like IPC) remain active during this entire procedure.

Similar results are obtained for load case 1.6, which contains an EOG (Figure 4, right graphs). Again, the gust would cause the turbine to reach over-speed and initiate a shutdown. When EEC is activated, the turbine is able to ride through the gust, and quickly resume normal power production after the gust has passed.

![Figure 4: Profile view of the 2B6, including the blade flap wise bending moment $M_{FLAP}$ and the tower nodding moment $M_{NOD}$.](image)

<table>
<thead>
<tr>
<th>DLC</th>
<th>1.3</th>
<th>1.5</th>
<th>1.6</th>
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<td>-7%</td>
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<tr>
<td>Blade Flap-wise Moment</td>
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<td>-5%</td>
<td>-16%</td>
<td>-8%</td>
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Table 1: Improvements on ultimate loads for individual load cases and complete load set calculations.

Some of the loads of interest during these simulations are the ultimate tower nodding moment and the blade flap-wise bending moment. Figure 4, illustrates these quantities on a schematic view of the 2B6. These maximum loads have been computed with and without EEC. Table 1, shows how these situations relate in individual DLCs as well as in the entire load set. The loads are computed over the entire load case (i.e. over all different initial wind speeds and azimuth angles). The results clearly show that the method outlined in this work reduces the ultimate loads significantly in load case 1.3 and 1.6. Recall that DLC 1.5 contains a grid-loss, which forces the turbine to initiate a shutdown. As predicted in section 3, this still yields some load reductions.
The overall impact of EEC is around 7-8% over the entire load set. For many loads, the DLCs 1.3, 1.5 and 1.6 are no longer design driving.

4. Conclusion & Discussion

The ultimate loads, computed by aero-elastic codes, play a crucial role in the design and certification of a wind turbine. Reducing these loads is especially important for large off shore turbine designs, where blades tend to be bigger, and the corresponding loads more design driving.

In many load cases, these ultimate loads are reached when the DLC contains an extreme wind gust like the ECG or EOG. As shown in this paper, model based wind speed estimation combined with least-squares wind gust detection is able to detect these gusts in an early stage. By using the standard power production controller as a slave, the EEC is able to reduce the ultimate loads and, if possible, allow a quick return to normal power production after the gust has passed. Complete load set calculations verify and quantify these statements (Table 1).

One might argue that there is a potential drawback of this method: it is designed for specific wind profiles. The ECG and EOG profiles might not occur in the exact form as shown in Figure 2 in real life. However, the shapes used in the gust detection algorithm only contain a small section of the entire profile. In the ECG case, it merely is a steeply ramping gust and in the EOG case it contains a dip followed by a short increase in speed. These patterns are a lot more generic than the rest of the profile suggests. The EEC will strive for a reduced operational state, no matter which gust (if any) follows the moment of detection. By the worst-case design of the EOG and ECG, the loads will be similar to the ones computed in this work. Though this work focuses on the design phase on DLC level, further studies are needed to see whether this method misses essential gusts, and if so, how it needs to be adapted.

As mentioned, another issue is that even though the detection levels in equation (5) are chosen such that there is no detection during DLC 1.2, in actual operation the partial profiles might be present without being followed by a gust at all. Again, the EEC is designed in such way that the loss in power production is minimal. Without the presence of a gust, the turbine can reach its reduced operational state quickly (there is no gust which would prohibit it from doing so), and as a consequence the EEC would reset its operational setpoints. The dip in power production would not last longer than 10-20 seconds.

In this work a conventional rotor speed and power controller have been deployed as a slave to the EEC. In future work, it will be investigated if using an advanced Nonlinear Model Predictive Controller (NMPC), as e.g. presented in [8], can be advantageous in handling wind gusts. Such methods can incorporate wind predictions in their computation of control actions. After a positive gust detection, the expected profile (Figure 2) can be used as such a prediction. Since NMPC methods are designed to optimally control any disturbance, it can be expected that this strategy can yield even better results than the results presented in this paper.

References