Active limitation of extreme loads of large-scale wind turbines: A study on detection and response dynamics

P. Brosche, B. Fischer, P. Loepelmann, M. Shan
{philipp.brosche, boris.fischer, peter.loepelmann, martin.shan}@iwes.fraunhofer.de
Fraunhofer IWES, Dept. Control Engineering, Koenigstor 59, 34119 Kassel, Germany

Summary. Two options are generally available for the active limitation of extreme loads. One is to detect the extreme event in good time and respond anticipatory. Early detection of gusts, for example, necessitates remote sensing. The second option is to use a combination of fast actuators local measurements that allows for an appropriate turbine response, for example by using flaps or other “smart” blade concepts. As both pure remote sensing and very fast actuators have certain technical limitations, combinations might be useful, as well. This study aims to quantitatively analyse the requirements for event detection time and actuator dynamics in the range between those two options.

An extreme operating gust is applied to the IWT-7.5-164 reference turbine. A feed-forward pitch manoeuvre is triggered at different points in time using different pitch rates and aerodynamic efficiencies. The main result of the numerical experiments is not surprising: The later the gust is detected, the faster the actuator needs to respond. However, the simulations also confirmed that pitching the full blade can be substituted efficiently by using faster actuators.

The novelties presented in the study are i) a methodology for investigating the requirements regarding gust detection instant and actuator response dynamics, and ii) the application of this methodology on a reference turbine for exemplary, quantitative results.

Background. The literature regarding active load mitigation on wind turbines is traditionally dominated by papers dealing with fatigue loads. Despite the fact that extreme events can be design-driving load cases, far less has been published with respect to the active limitation of ultimate loads, see [1] and the references therein for an overview of earlier works. In recent years, active mitigation of ultimate loads has gained increasing attention. Control strategies based on remote sensing enable the direct anticipation of gusts, see the survey paper [2] for an overview. Furthermore, advanced control concepts that directly incorporate knowledge of the future wind speed are currently being discussed, see e.g. [3, 4]. So called “smart” blades or rotor concepts inspired studies on active mitigation of ultimate loads, as well, see e.g. [5, 6].

However, there is no public-domain information on how fast the control system actually needs to respond as a function of the point in time when the gust, or – more generally – the extreme event is being detected. To the best of the authors’ knowledge, this is the first proposal for a systematic evaluation of requirements regarding gust detection and actuator response dynamics.

Approach. The proposed method is characterised by triggering feed-forward pitch manoeuvres during an extreme event at pre-defined times; see Figure 1 for the gust and the trigger points used in this study. These trigger points reflect the instant when the extreme event has been detected, irrespective of the detection algorithm. Obviously, detecting the gust long before it reaches the rotor implies remote sensing.

Two kinds of feed-forward pitch manoeuvres are being considered:

A. The first kind of pitch action consists of pitching the entire blade towards feather with different constant speeds. This is a fairly standard action for turbine emergency shut-downs. The blade movement is reflected in the aerodynamics and structural dynamics modules of the simulation. An example is given in Figure 1, where time series with different pitch rates and a baseline case with the normal feedback controller are shown.
B. For the second kind of feed-forward action, we amended the aerodynamics module (based on blade element momentum theory) with a second pitch angle input. It serves to modify the angle of attack of the outer blade elements. Broadly speaking, the outer blade section is "aerodynamically pitched" towards feather with constant speed. That is, while the structural dynamics remain the same, the aerodynamic forces affecting the outer blade sections are modified according to the second pitch angle input. Thus, the changing aerodynamic forces represent a generic aerodynamic actuator that is not specified further at this point. For instance, it is conceivable to integrate flaps into the rotor blades that can be actuated very quickly. The pitch angle of the rest of the blade remains at the value from the trigger instant.

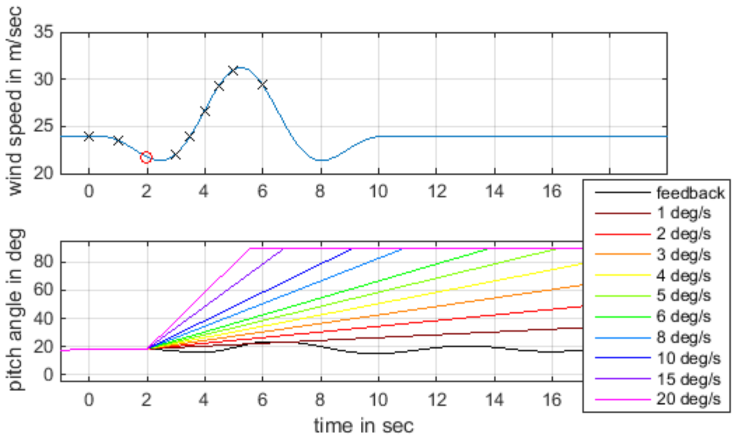

Figure 1. Top: Extreme operating gust with trigger instants. The red circle indicates the trigger instant that corresponds with the time series of the pitch angle in the bottom plot. Bottom: Pitch angle during the manoeuvres with different pitch rates and during the baseline case with a normal feedback controller.

Only the first three seconds following the trigger instant are being evaluated during the post-processing. This is enough to rate the immediate response of the turbine. The signals considered in the numerical study are

- generator speed,
- fore-aft tower base bending moment, and
- flapwise blade root bending moment.

Note that the considered pitch manoeuvres are not being proposed as an appropriate response for load mitigation or overspeed avoidance. In fact, the intention is to analyse the relation between gust detection and actuator dynamics in the first period after the manoeuvre has been triggered.

Also, we are neglecting any effects on the structural dynamics of the blade at this point, such as changes in blade loads caused by sudden change in aerodynamic forces along the blade axis. Moreover, we are not considering non-steady aerodynamics brought on by fast pitch actuation, since the corresponding reduced frequencies are sufficiently low.

Numerical results. The numerical study exemplarily deals with an extreme operating gust (EOG) as defined in [7]. Simulations have been carried out with the IWES 7.5 MW reference wind turbine [8] using our in-house aero-servo-elastic code “WTsim” [9, 10].

Table 1 summarises the variations of the parameters resulting in 2x9x11 = 198 simulation runs for the full blade pitch manoeuvres (case A) and 2x9x14 = 252 simulation runs for each of the three cases B with only the outer section of the blade being “aerodynamically pitched”. The specified maximum pitch rate for the reference turbine is 6°/s. Hence, the full blade pitch rates from 8 °/s upwards are unrealistic and only included for comparison. Three additional pitch rate values are chosen for the cases B to reflect very fast actuation dynamics.

Table 1: Parameter variations of the numerical study.

mean wind speed at operating point[1]	{11; 24}	m/s
trigger points after the start of the EOG	{0; 1; 2; 3; 3.5; 4; 4.5; 5; 6}	s
pitch rates (the last three values are not used for the full blade manoeuvres)	{0; 1; 2; 3; 4; 5; 6; 8; 10; 15; 20; 25; 30; 35}	°/s
outer fraction of blade with respect to full blade length	{13; 23; 33}	%

Case A (full blade pitch) with the EOG at 11 m/s wind speed is shown in Figure 2. Time series of the turbine responses at four different trigger points are given for all pitch rates and a baseline case with the standard controller. Please note again that only the first three seconds after the trigger points are relevant, since the pitch manoeuvre is not intended to be appropriate for integrated load mitigation.

The generator speed is shown in the left column of plots. As expected, detecting the gust before it hits the rotor plane (a1) does not necessitate fast actuator dynamics. However, detecting the gust when the rising slope has already arrived at the turbine (a3) reveals the benefits of fast actuation: Using unrealistically high pitch rates helps to maintain the speed at normal levels and reduces the risk of overspeeds.

The tower loads shown in the center column of plots exhibit a similar behaviour. There is no advantage of unrealistically high pitch rates when the gust is detected early enough (b1). The largest relative benefit from very high actuator dynamics is when the manoeuvre is triggered in the middle of the rising slope (b3).

[1] Only results with 11 m/s are presented in this extended abstract due to space limitation.

Although weaker with respect to relative benefit, the blade loads shown in the right column of the plot reveal that fast actuation helps limiting maximum amplitudes as well when the gust cannot be anticipated (c3). Furthermore, blade load responses are less delayed than the responses of the other two signals.

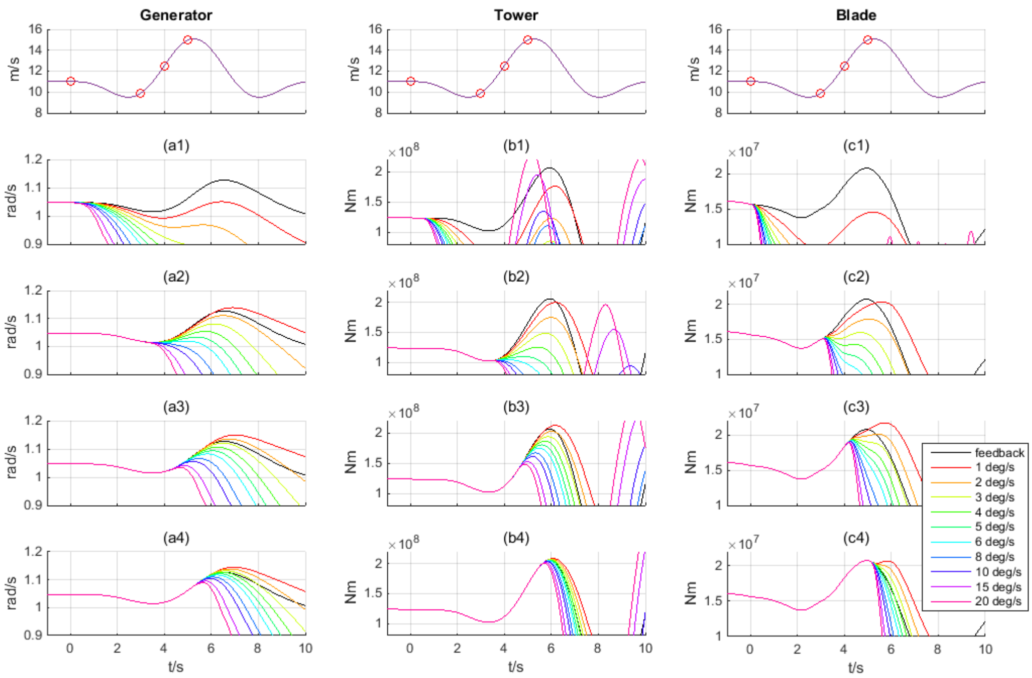

Figure 2. Turbine response to an EOG at 11 m/s for case A (full blade pitch). Upper plots: Hub height wind speed with red circles indicating the four trigger points (0s, 3s, 4s, and 5s). Below: Turbine response for the four trigger points. Left: generator speed. Center: tower base bending moment. Right: blade root bending moment.

The maximum values of the signals occurring during the first three seconds after the trigger point have been determined for a quantitative analysis. Resulting values of generator speed and tower base load for two cases are collectively presented in Figure 3 and Figure 4: Case A and Case B with the 23% blade section at an operating point with 11 m/s wind speed.

The tabulated values are the maxima that occur during the first three seconds after the event detection time. The first row is the reference case with a normal feedback controller. It defines the colour range, where the highest value is set to 100%. The black dotted line in Figure 3 indicates the maximum specified pitch rate. That is, the pitch rates below that line are not feasible on the reference turbine.

The compromise between detection and actuation dynamics is clearly to be seen in all tables: There is a distinct "front" between green and red that ranges from the northwest (early detection and slow actuation) to the southeast (late detection and fast actuation). Please note that three seconds detection time implies remote sensing and four seconds is in the middle of the rising slope, see Figure 1.

Comparing the full blade pitch (A) with the 23% blade pitch (B) reveals that higher pitch rates are necessary in the latter case for obtaining the same limitation. However, if the gust is detected in the middle of the rising slope at four seconds, then the maximum specified pitch rate of the reference turbine limits the generator speed to 1.08 rad/s, see Figure 3. Figure 4 shows that with a 20 °/s pitch rate, the generator speed can be limited so it does not exceed its initial value, which might be achievable with fast aerodynamic actuators.

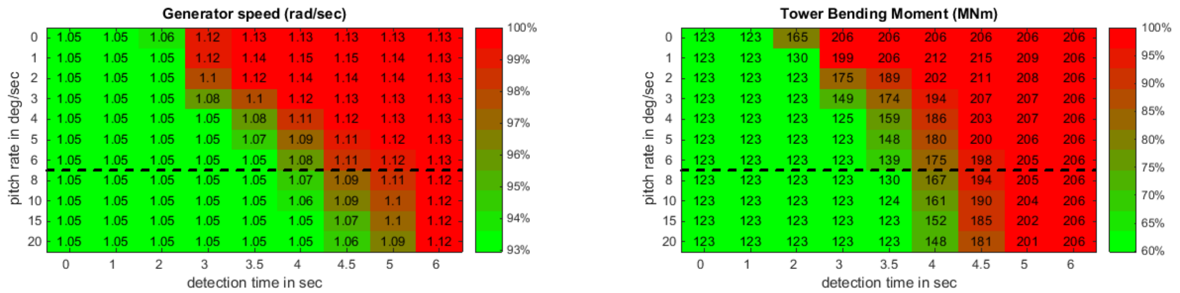

Figure 3. Case A (full blade pitch), maxima occuring during the first three seconds after detecting the event. Pitch rates below the black dotted line are not feasible on the reference turbine.

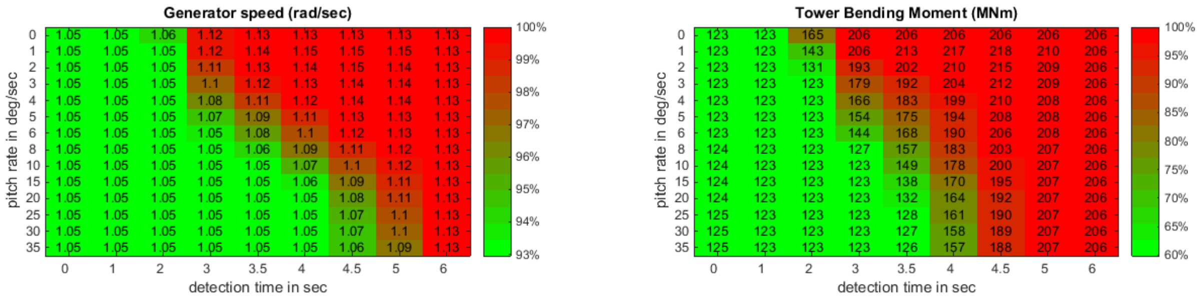

Figure 4. Case B with 23%, maxima occuring during the first three seconds after detecting the event.

Finally, Figure 5 summarises the results for all cases at 11 m/s wind speed. It shows the pitch rates that are necessary to keep generator speed, tower and blade loads below a threshold as a function of the detection time. This threshold is defined as the arithmetic mean between lowest and highest maximum in the reference case with normal feedback controller. Several conclusions can be drawn from this diagram:

- Expectedly, an earlier detection allows for slower actuator response, and less aerodynamic efficiency requires higher pitch rates.
- “Aerodynamically pitching” 33% of the blade has almost the same impact as pitching the full blade.
- Keeping the tower loads below the defined level when the gust is detected after four seconds is not possible with the specified maximum pitch rate of the full blade. However, if the “smaller” aerodynamic actuators corresponding to 33% and 23% of the full blade length allow for the pitch rates 15 °/s and 20 °/s, respectively, an efficient tower load limitation is achievable.

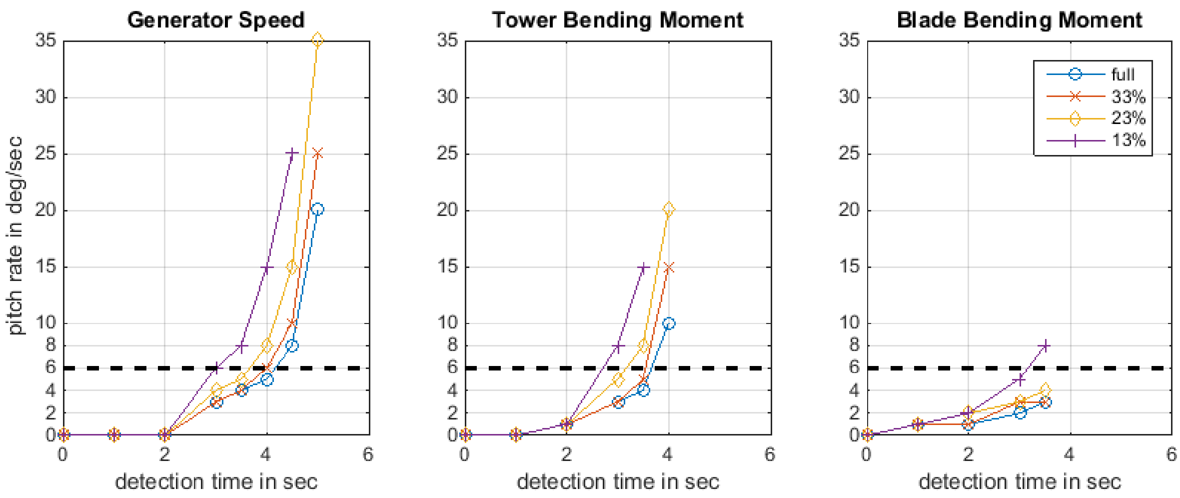

Figure 5: Pitch rates that are necessary to keep speed and loads below a threshold, plotted as a function of the detection time. Pitch rates above the black dotted line are not feasible on the reference turbine.

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