Dual pitch revisited: Overspeed avoidance by independent control of two blade sections

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Abstract

Fast, coherent changes of wind speed during normal operation typically challenge the wind turbine's control system and can lead to ultimate loads and overspeed trips. In this work we demonstrate that independently controlling the aerodynamic forces along the blades' span can significantly reduce the risk of overspeeds in such situations. Specifically, we take up the concept of "dual pitch" where the blade is split up in an inner and an outer part with two independent pitch systems. We demonstrate that pitching the outer part towards feather and the inner part in the opposite direction (active stall) enables significant overspeed reduction without thrust force amplification. Simulations with a model of the IWT-7.5-164 reference turbine show that reductions of the maximum rotor speed of more than 10% of rated speed are feasible.

Keywords: Extreme Event, Dual Pitch, Overspeed.

1 Introduction

The literature regarding active load mitigation on wind turbines is traditionally dominated by publications 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 [2] for a survey. 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].

During the early stages of wind turbine commercialization, an active adjustment of a specific rotor blade section was considered in [7]. A so-called "partial pitch" is also part of the new turbine design of the company Envision Energy [8]. This design is characterized by a hub-fixed inner blade section. Only two thirds of the blade span can be pitched.

The improvement of wind turbine control by using additional elements like adjustable flaps or slats is a current objective of many academic research activities. Except for the project ELBA, there are only two works dealing with two independently adjustable blade sections.

In the context of the project UpWind, a dual pitch system was investigated by Energy Research Centre of the Netherlands (ECN) to reduce flap-wise bending moments of the blades [9], [10]. In a pilot study, the flap-wise bending moment in the blade root was reduced to 15%. However, in this case the rotor average aerodynamic thrust and torque remained constant. An independent control of thrust and torque was not achieve because of the selected linear modeling approach. The second work is inspired by aeronautical applications and deals with articulated blade tips in addition to the normal pitch system [11].

In this paper, we consider the reduction in peak values of rotor speed and tower bending moment during a certain extreme operating condition above rated wind speed: a gust with rapidly increasing wind speed after it dropped shortly to near rated, similar to the well-known "Mexican Hat". This situation typically leads to high tower loads and potentially causes overspeed events. The large loads and rotor speeds are the result of the pitch controller acting too slowly. During such an event there is a point in time at which

1. the rotor speed is low,

2. the blade pitch angle is small, and

3. the wind speed increases rapidly.

These conditions occur at around 72 s in Figure *1*. They lead to high rotor thrust force and aerodynamic torque. It seems reasonable to increase the pitching speed in order to mitigate the negative effects.

However, during the development of methods for mitigation strategies, we found that on large scale wind turbines, said operating condition

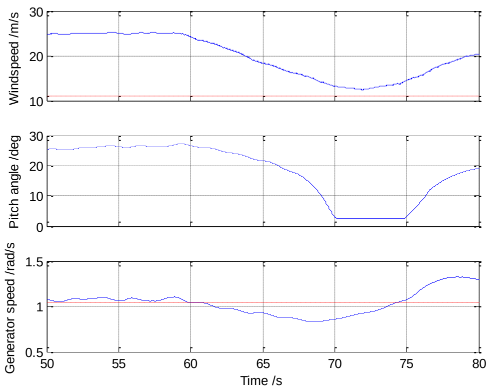

Figure 1: Changes in rotor-effective wind speed, pitch angle and generator speed during considered extreme event including rated values.

can result in qualitatively different aerodynamic conditions along the blade span: While the angles of attack of the outer blade sections stay in a normal range related to attached flow conditions, those at the inner sections are significantly increased. Thus, the inner sections of the blade operate in stall conditions. From an overspeed prevention point of view, this is beneficial since it causes a reduction of aerodynamic torque.

Section 2 outlines the basic idea of the method. Then, Section 3 presents the simulation results, provides an analysis of the results and investigates the possibilities of an independent dual pitch adjustment keeping the aerodynamic thrust constant while decreasing the aerodynamic torques. A discussion of these results follows in Section 4.

2 Main concept

In our investigation, the blade is divided into two sections: the outer section (43% of full blade length) from element 10 at the blade tip to element 6 and the inner section (57% of full blade length) from element 5 to element 1 at the blade root. Thus, the two sections may be pitched independently (see Figure 2).

To separate the influence of the closed-loop controller from the investigations, only feed-forward pitch maneuvers are investigated.

Four kinds of pitch maneuvers are being investigated to demonstrate the potential of the dual pitch approach during the operating condition described above:

a. *full blade active pitch:* pitching the entire blade towards feather with a constant rate of 3 degrees per second

b. *partial blade active pitch*: pitching only the outer blade section towards feather with a constant rate of 3 degrees per second

c. *counter-rotating dual pitch*: pitching the outer blade section towards feather with a constant rate of 3 degrees per second and counter-rotate the inner blade section towards stall with -3 deg/s.

d. *full blade active stall*: pitching the entire blade towards feather with a constant rate of -3 degrees per second

The action (a) would be the standard reaction for state-of-the-art turbines to sudden overspeed situations, as the speed controller would increase full span pitch angle with the maximum pitch rate.

However, some specific turbine types can be found that implement (b) and (d) for power/torque limitation. Maneuver (d) in principle would be possible with standard full-pitch rotor configurations. Clearly, action (c) would require a specific wind turbine rotor configuration with two independent actuators for the two blade sections.

As mentioned before, at the considered extreme situation, it is a desired state that the inner blade sections remain in stalled condition as this effectively reduces the aerodynamic torque with respect to the full blade active pitch action. This explains the advantage of the maneuver (b) with respect to the overspeed prevention. The dual pitch action (c) was implemented as a consequence of this finding. Figure 3 illustrates this condition with the help of the lift coefficients for an outer and inner section profile. The red marker represents the angle of attack as mentioned above. Thus, the counter-rotating movement of the blade sections rapidly decreases the lift coefficients

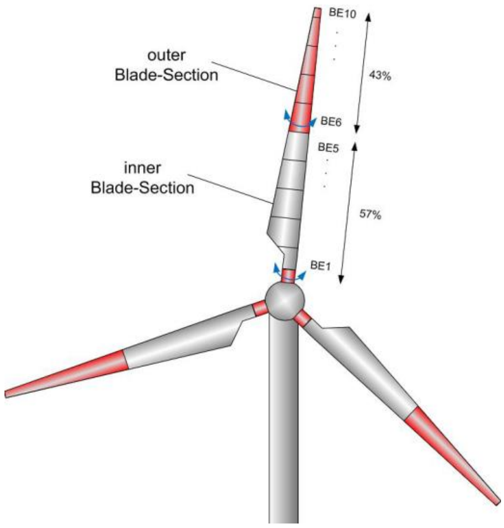

Figure 2: Division of blade sections on large-scale wind turbine for dual pitch.

without passing through the maximum of the curve.

Prior to the investigated pitching maneuvers, the extreme gust is detected and the need for control action is triggered. In this context, we choose a moderate pitch rate and a specific trigger point with a lead time of 6 seconds according to the findings in [12].

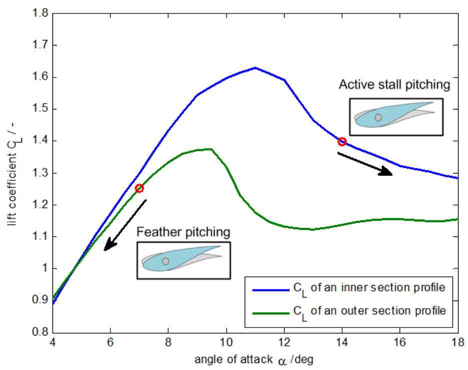

Figure 3: Lift coefficients for an outer and inner section profile during considered extreme event.

3 Simulation results

The simulations have been carried out with the IWES 7.5 MW reference wind turbine [13] using our in-house aero-servo-elastic code “WTsim”, see [14], [15]. The extreme event occurs during an excitation with an extreme turbulence model (ETM) wind field as defined in [16].

Figure 4 shows the development of the generator speed beginning at the trigger point 6 s before the extreme event occurs at 78.58 s. The pitching of the full blade towards feather with a constant rate of 3 degrees per second and its influence on the generator speed is shown by the blue line. One would expect that this maneuver leads to the greatest reduction of the aerodynamic torques as well as generator speed. However, by pitching only the outer five blade elements, further reduction of generator speed is achieved (see orange line in Figure 4). For the dual pitch action with counter-rotating blade sections, the reduction of generator speed is even greater. This is shown by the yellow line. The lowest maximum speed results from the active stall maneuver, i.e. from pitching the entire blade with -3 deg/s.

Figure 5 shows the corresponding aerodynamic torques acting on the entire rotor plane. Clearly, the lower the aerodynamic torque the higher the reduction of the maximum generator speed.

One would expect that the above-mentioned reduction of the aerodynamic torque with a

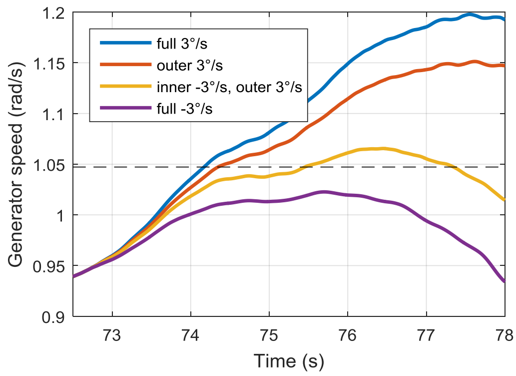

Figure 4: Generator speed during an extreme event using different strategies of blade section movements.

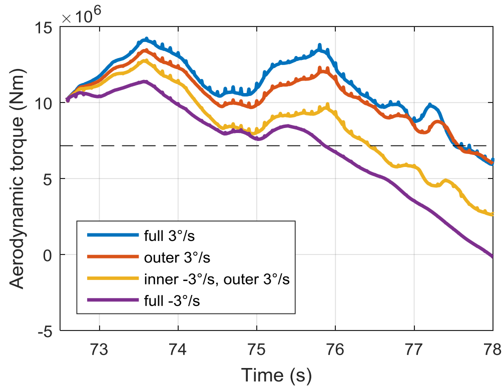

Figure 5: Aerodynamic torque during an extreme event using different strategies of blade section movements.

counter-rotating pitch maneuver leads to a higher structural excitation by increased thrust forces. However, this is not the case. Regarding Figure 6, the following observations can be made:

- For partial blade active pitch and dual pitch, slight reductions in maximum thrust force result as compared to the full pitch maneuver.
- The full blade active stall maneuver, however – driving the outer blade sections into stall – results in a large increase of the maximum thrust force.

Figure 7 shows the effect of the different pitch strategies on the tower base bending moment. As expected, the peak value in tower bottom bending moment has a direct relation with the maximum value in aerodynamic thrust force. Due to the tower oscillation, however, the peak in bending moment occurs with some delay.

For the counter-rotating dual pitch maneuver, a reduction of nearly 10% is achieved as compared to full blade pitching. Note that this is more than the relative reduction in thrust force seen in Figure 6. For full blade active pitch,

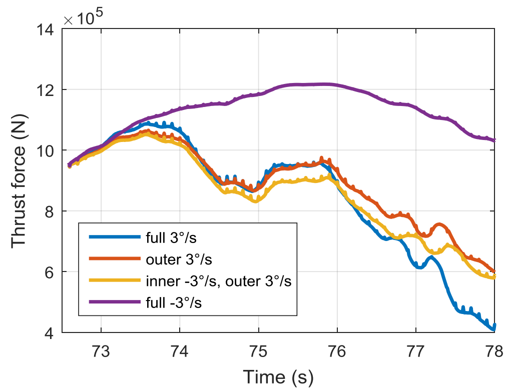

Figure 6: Aerodynamic thrust during an extreme event using different strategies of blade section movements.

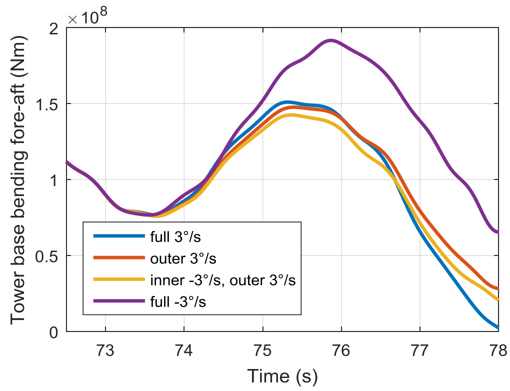

Figure 7: Tower base bending moment in fore-aft direction during an extreme event using different strategies of blade section movements.

however, a large increase in tower bending moment is observed.

To summarize, the counter-rotating dual pitch maneuver seems to be the best option to limit both rotor speed and tower base bending moment for the considered gust situation. To explain this more clearly, in *Figure* 8 the corresponding changes in aerodynamic forces for two representative blade sections are shown in detail.

The first three pitching maneuvers lead to a similar reduction of the aerodynamic torque at the outer blade section (BE8). This is expected, because in all three cases the outer section makes the same rotation relative to the pitch axis. Considering the inner blade element BE3, for full blade pitch, the aerodynamic torque even increases significantly because the aerodynamic operating condition is transitioning from stalled to attached flow. If the pitch angle of BE3 is kept constant, the increase in aerodynamic torque is reduced. For the dual pitch case, by rotating the inner blade element towards active stall, even a reduction in aerodynamic torque can be achieved for the inner blade section. For full blade active stall, the

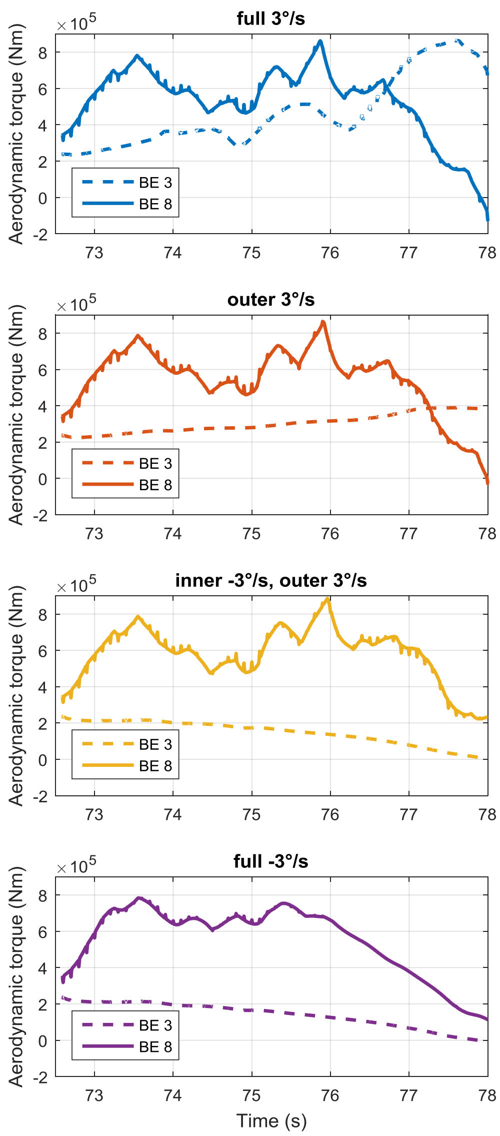

Figure 8: Aerodynamic torque blade element 3 (inner) and 8 (outer) during an extreme event using different strategies of blade section movements.

aerodynamic torque is reduced for both inner and outer blade section, however, at the cost of larger values in thrust force.

4 Conclusion

For a typical gust situation near rated power, different feedforward pitch maneuvers have been analyzed regarding their effect on the maximum values of rotor speed and fore-aft tower base bending moment. Assuming a rotor blade with two independently adjustable sections, a dual pitch action with counter-rotating inner and outer blade sections has been found to be most appropriate.

If such a rotor configuration with two independent actuators would be available, as compared to standard wind turbine control concepts, a more sophisticated response to extreme gust events would be possible, with potential for significant reductions in maximum rotor speed and tower load peaks. As only feedforward maneuvers have been considered so far, the dual pitch still has to be integrated into a suitable controller structure.

Also, only moderate control actions were considered in this paper. High-speed and high-amplitude pitch maneuvers complicate those aspects. Hence, common aerodynamic simulations and design control models begin to lose their validity. There is a need for improved dynamic stall models to describe states in the transient area between steady flow and separated flow (stall) conditions. This will be done by deriving active stall models using CFD simulations and experimental data from wind tunnel tests.

Moreover, beside the principal system dynamic realization of a dual pitch, there are several practical aspects such as

- blade construction details,
- manufacturing aspects,
- logistic aspects and
- economic feasibility,

that have to be taken into account to come to a meaningful assessment.

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