Mitigating the Long term Operating Extreme Load through Active Control

Christina Koukoura, Anand Natarajan*

Technical University of Denmark (DTU), Department of wind energy,

Risø Campus, 399 Frederiksborgvej, Roskilde-4000, Denmark

*E-mail: anat@dtu.dk

Abstract. The parameters influencing the long term extreme operating design loads are identified through the implementation of a Design of Experiment (DOE) method. A function between the identified critical factors and the ultimate out-of-plane loads on the blade is determined. Variations in the initial blade azimuth location are shown to affect the extreme blade load magnitude during operation in normal turbulence wind input. The simultaneously controlled operation of generator torque variation and pitch variation at low blade pitch angles is detected to be responsible for very high loads acting on the blades. Through gain scheduling of the controller (modifications of the proportional K_p and the integral K_i gains) the extreme loads are mitigated, ensuring minimum instantaneous variations in the power production for operation above rated wind speed. The response of the blade load is examined for different values of the integral gain as resulting in rotor speed error and the rate of change of rotor speed. Based on the results a new load case for the simulation of extreme loads during normal operation is also presented.

1. Introduction

Reliable design of modern wind turbines requires that the various factors influencing extreme loads are investigated and addressed. Localized gusts above the mean wind speed with extreme rise time have been investigated in [1] as one of the driving factors for excessive loading on the blades. Abrupt blade pitch angle drops or sudden fall in the generator torque can also result in extreme loading on the blades [2]. The relative wind velocity (usually at the 70% to 90% of the rotor span) and the angle of attack (at the same position across the blade) as well as occurrences of dynamic stall can also affect the ultimate loads. In the present work, these factors are examined and their influence on the blade loads is evaluated as a means to mitigate the long term extreme loads.

The extreme loads are investigated under normal operating conditions (load case DLC 1.1 Reference to IEC standard). The interest in this case originates from the fact that the loads acting on a wind turbine under normal operation can be design driving for the rotor nacelle assembly (RNA). The ability to simulate the 50 year operating extreme load usually involves many aeroelastic simulations with different random turbulent seeds and subsequent stochastic extrapolation to a 50 year level. Such extrapolation can often result in large variations in the 50 year load, due to the presence of localized peak loads that skew the parametric fit to the extreme load exceedance probability [2]. Therefore identifying the reasons for such peak loads and mitigating the extreme loads through controller action is required. Conventional choice of controller parameters is a trade-off between conflicting aspects, like faster response of the controller to achieve constant rated power while also reducing the aerodynamic loads due to the pitch action. It is usually the fatigue loads over long time periods that are

intended to be reduced in most control algorithms. However the controller design should consider mitigating the ultimate loads also while maintaining constant rated power above rated wind speed.

Prior investigations regarding the mitigation of extreme and fatigue loads through active control have been done, such as in Ref. [3]. Methods usually suggested for achieving this are the use of filters to mitigate modal response, sensors at the blade root, tower top sensors, accelerations that are fed to the controller for facilitating individual pitch control and generator torque control in the region when the wind speed is just above rated speed [3]. In a recent Sandia report [4], fifteen different devices, like microtabs and active stall strips for active load control are discussed and their potential when implemented on a wind turbine is analyzed. When collective blade pitch control is used and no sensors for load measurement are present, the aim of keeping the power constant at mean wind speeds above rated and mitigating the extreme blade loads simultaneously is achieved through effective control algorithms. This aspect is discussed in the following sections.

2. Problem Formulation

Based on the requirement to identify 50 year extreme loads, an alternative to loads extrapolation is investigated based on the reasons for occurrence of the extreme load. The proposed methodology should demonstrate quick computation of the one year extreme load (considering the NREL database [5]), and also thereby enable mitigation of this extreme load, using improved control parameters. A three bladed 5MW pitch controlled variable speed wind turbine for offshore monopile foundations is considered. Table 1 presents the system properties of the 5MW reference wind turbine used in the simulations. The aeroelastic code HAWC2 [6] is used to simulate the loads on the wind turbine with a Mann wind turbulence input at an IEC reference turbulence intensity $I_{ref} = 0.16$, considering the 90% quantile of the wind speed standard deviation according to the IEC 61400-1standard [7].

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Table 1: Gross properties for the 5MW wind turbine

Rated power	5 MW
Rotor diameter	126 m
Hub height	90 m
Rated wind speed	11.4 m/s
Rated rotor speed	12.1 rpm

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The load simulations are normally performed using 10 minute turbulent wind time series. Though 10 minute simulations is statistically sufficient to represent a stationary turbulent wind field at a given mean wind speed, it is not certain that the time duration is sufficient for loads simulations, since the turbine is a nonlinear time varying system. Variations in the blade peak extreme loads such as the out-of-plane root bending moment over a period of 10 minutes can occur, if the simulations are run for different initial azimuth settings of the blade. These variations can be explained by the fact that depending on the initial position of the blade, a different instantaneous wind speed may be observed by the blade over the rotor. This also implies that wind velocity fluctuations due to spatial coherence of turbulence should be associated with the blade position to increase the probability of occurrence of an extreme load.

The total number of ten minute wind series necessary to compute the one-year extreme load is thereby reduced by enabling many random variations of the initial blade azimuth angle at few different seeds of wind turbulence, instead of randomly choosing many seeds of turbulence. Herein simulations for twelve random Gaussian wind seeds at a mean wind speed of 15m/s are made, where the initial azimuth position of blade 1 was varied with a step of 10 degrees. Figure 1 displays the resulting blade root out-of-plane moment, wherein each load point has a unique blade starting azimuth position which

results in a different absolute maximum of the blade root moment over the 10 minute simulation. The dominant mean wind speed of 15m/s, where the loads were highest, was identified by a number of prior simulations using HAWC2 [6] for different mean wind speeds. The maximum flap wise root bending moment appears for an initial azimuth angle of 80°. It can be shown that this load cannot be simulated with the commonly used initial azimuth settings of 0° with the currently utilized turbulent wind seeds.

The operation of the wind turbine is separated in three regions, depending on the wind speed. Region 1 corresponds to the variable rotational speed operation for optimal power production. In region 2 the rotational speed is kept constant to its rated value and the controller is performing a linear adjustment on the generator torque values. Region 3 corresponds to maintaining the power to rated by pitching the blades [8]. In the 5MW pitch controlled variable speed wind turbine, the proportional integral-controller (PI) designed by NREL is implemented. Additional details on its parameters can be found in Ref. [8]. Further investigations of the variables that influence the blade root load are made, such as between the simulation at 20° initial azimuth angle and the one at 80° initial azimuth angle and thereby improvised controller parameters are implemented to mitigate the extreme loads on the wind turbine.
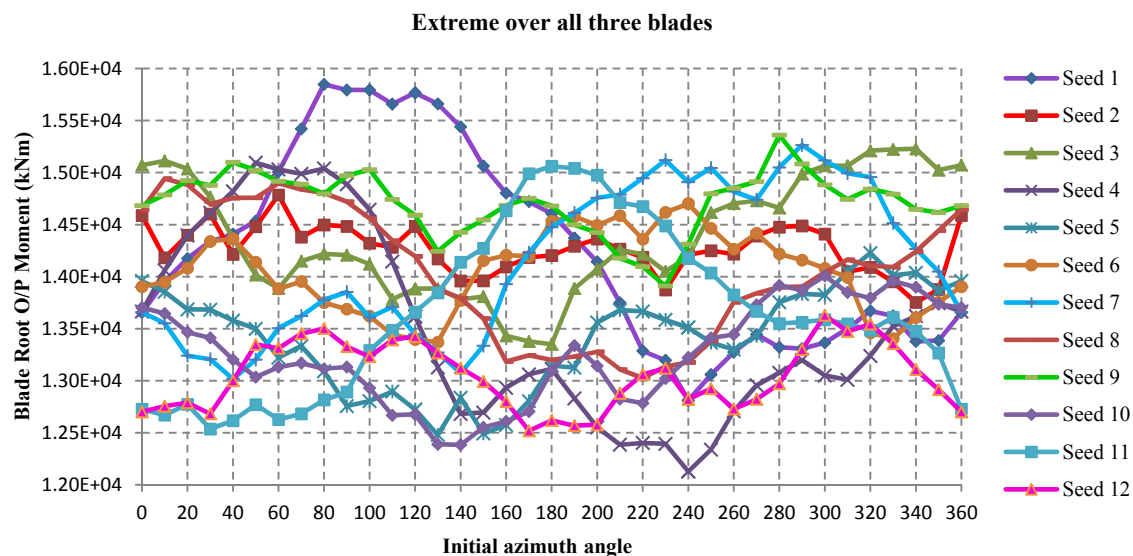

Figure 1: Maximum flapwise root bending moment for all three blades measured over ten minutes simulation as a function of different initial starting azimuth angles, where 0 degrees indicates blade 1 is vertical downwards in front of the tower.

2.1 **Design of Experiment**

For investigating the influence of different parameters on the out-of-plane root bending moment, a Design of Experiment (DOE) method is utilized, implementing a full factorial design, where in each complete trial of the experiment all combinations of the levels of the factors are investigated [9]. In each trial only one of the factors is varied in its allowable range, while keeping all other factors constant. The experiment is complete when the response of the out-of-plane root bending moment is examined for all the factor variations. Considering the simulations in Fig.1, six variables of potential influence on the out-of-plane bending moment are chosen which are the pitch angle, the duration of rotational speed below rated (when the instantaneous wind speed drops below rated so does the rotational speed, but due to the controller delay the rotational speed takes longer time to reach its maximum value again), the generator torque, the difference in the angle of attack at two outboard

blade stations, the instantaneous wind speed at the 70% rotor span nearest the blade tip (due to horizontal wind shear the instantaneous wind speed seen along the blade differs) and the relative wind velocity at the 80% blade station. These factors may directly influence the aerodynamic load or the controller response as seen in prior aeroelastic simulations.

From these initially chosen parameters for the DOE, two of them, the instantaneous free wind speed measured at 70% of the rotor span on the wind grid nearest the blade location and the difference in the angle of attack between the 89% and the 94% of the blade were eliminated, since there was almost no correlation determined between those variables and the out-of-plane root bending moment. Figure 2a depicts the variation of the blade root out-of-plane moment versus the angle of attack difference between the two outboard blade stations. Figure 2b presents the variation in the blade root moment versus the instantaneous horizontal wind speed at the position of the blade that resulted in the extreme load. It can be observed that the relationship between the load value and the independent parameter chosen are poorly correlated. Although it is expected that if the instantaneous wind speed seen by the blade is above the mean wind speed, extreme loads can be observed, this does not seem to be the case here. In most of the cases this can be attributed to the fact that in this area the pitch angle drops below 1° and the generator torque is computed as if it were in region 2. This simultaneous operation of the controllers induces a drop in the generator torque (and the power production) and an excessive loading on the blade as shown in Figure 3. Consequently, four variables that are considered to affect the blade root extreme moment are the pitch angle (x_1) at the time instant of the extreme, the duration of the rotational speed that is below rated (x_2) before the extreme occurs, the generator torque (x_3) and the relative wind velocity corresponding to 80% of the blade span (x_4) at the same time as the ultimate load.
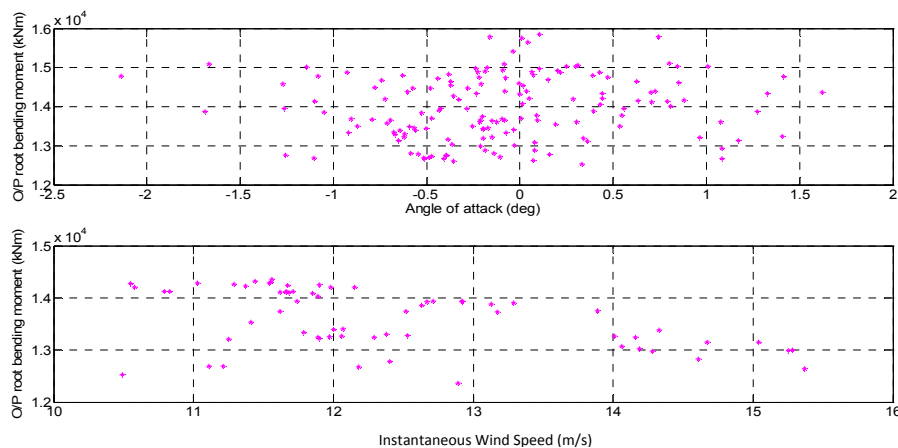

Figure 2*: O/P root bending moment versus a) the difference in the angle of attack between the 89% and the 94% of the rotor span b) the instantaneous wind speed

Coded design variables are utilized, according to which the variables are assigned discrete values -1, 0, and 1 which allow each factor to have equal opportunity to influence the response of the blade load. Therefore, coded design variables with discrete values where implemented. The continuous values of the variables are separated into two or three bins, depending on the number of points on each bin and assuming that the data follows a normal distribution. Table 2 presents the bins for each variable range. The fitted equation that provides the response of the out-of-plane root bending moment considering the linear terms of the variables and the interactions between them in pairs has the following form:

$$f = b_1 + b_2 x_1 + b_3 x_2 + b_4 x_3 + b_5 x_4 + b_6 x_1 x_2 + b_7 x_1 x_3 + b_8 x_1 x_4 + \tag{1}$$
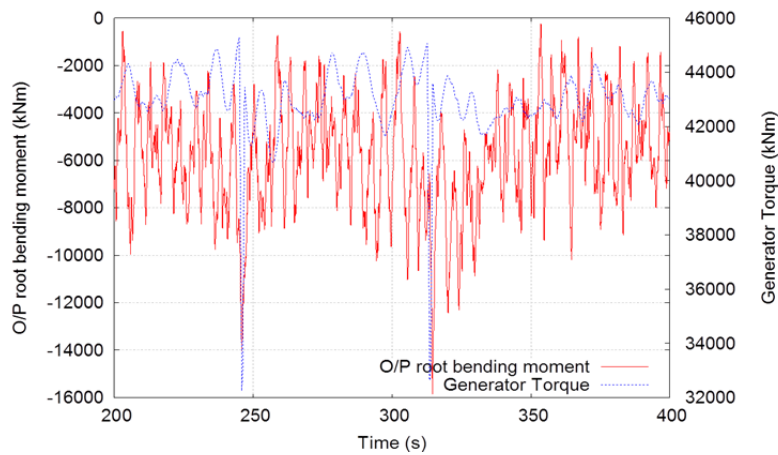$$+ b_9 x_2 x_3 + b_{10} x_2 x_4 + b_{11} x_3 x_4$$

Figure 3: Time series of the out-of-plane blade root bending moment where the extreme load occurs at the time of the generator torque dropping when the pitch angle is below 1°

Figure 4 represents the response of the out-of-plane root bending moment to the four design variables, using the non-dimensional equation, Eq. (1). Each graph in the figure displays the response in the out-of-plane bending moment when one variable is changing and the rest are kept constant (linear relation between the blade load response and the independent variable, green line). The fixed value of each variable is shown in the box below each graph.

Table 2: correspondence between the coded design variables and the bins of the original units for the DOE

Pitch Angle (deg) (x_1)		
-1	0	1
[-1 : 1]	[1 : 2.5]	[2.5 : 8]
Duration of rotational speed below rated (s) (x_2)		
-1	0	1
[0 : 3]	[3 : 9]	[9 : 50]
Generator Torque (kNm) (x_3)		
-1		1
< 42900		> 42900
Relative Wind Velocity (m/s) (x_4)		
-1	0	1
[60 : 68]	[68 : 70]	[70 : 75]

As depicted, the generator torque does not affect the output, but the loads decrease with increasing pitch angle and increase with increasing duration of rotational speed below rated and increasing relative wind velocity.

In the physical coordinate system, an increase or decrease of 5% in the pitch angle (keeping the rest of the variables constant) induces a rate of change in the response of the extreme out-of-plane root bending moment of 30kNm/deg. A similar variation of the values in the duration of the rotational speed below rated causes a rate of change of 29kNm/s in the output.

The root bending moment is less affected by the other two parameters, where a 5% change in the generator torque and the relative wind velocity induces a rate of 2.5kNm/kNm and of 11.4kNm/(m/s) respectively. Consequently, the most influencing parameters to the response of the out-of-plane root bending moment are the pitch angle at the time instant of the extreme and the duration of the rotational speed below rated before the extreme occurs.
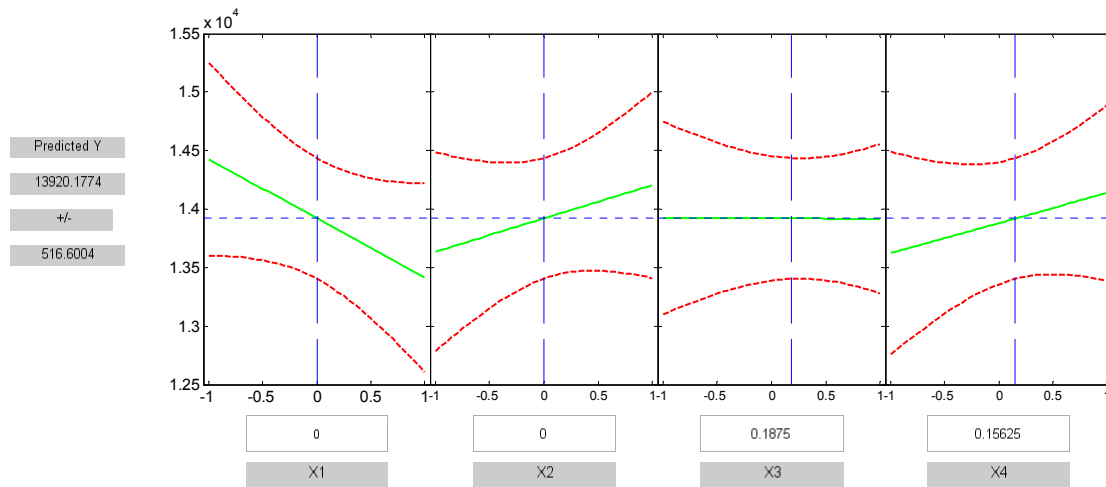
Figure 4: fitted response of the O/P root bending moment against each of the four predictors. Dashed red curves show 95% simultaneous confidence bands for the function (x_1: pitch angle, x_2: duration of rotational speed below rated, x_3: generator torque, x_4: relative wind velocity)

As long as the error in the rotational speed keeps its values below rated, the blade-pitch controller decreases the pitch angle, thereby increasing the probability of excessive loading on the blades due to sudden increase in wind velocity. Since both the pitch angle and the rotational speed are regulated by the controller, modifications in the controller parameters, discussed in the next section, are implemented to mitigate ultimate loads.

3. Controller strategies

For wind speeds above rated, the error between the measured and the rated rotor speed is used as a feedback to the controller to regulate the pitch angle and prevent blade stall, maintaining rated power. According to Ref. [10] the proportional and integral gains of the PI controller are given by Eq. 2 and the gain-correction factor *GK* that corrects the values of proportional gain K_p and integral gain K_i for higher wind speeds, due to non-linear characteristics is given by Eq. 3.

$$K_p(\theta) = \frac{2 I_{Drivetrain} \Omega_0 \zeta_\phi \omega_{\phi n}}{N_{Gear}\left[-\frac{\partial P}{\partial \theta}(\theta=0)\right]} GK(\theta) \qquad K_I(\theta) = \frac{I_{Drivetrain} \Omega_0 \omega^2_{\phi n}}{N_{Gear}\left[-\frac{\partial P}{\partial \theta}(\theta=0)\right]} GK(\theta) \qquad (2)$$

$$GK(\theta) = \frac{1}{1 + \frac{\theta}{\theta_K}} \qquad (3)$$

where $I_{Drivetrain}$ is the inertia of the drivetrain given by $I_{Drivetrain} = I_{Rotor} + N^2_{Gear} I_{Gen}$, Ω_0 is the rated rotor speed (Ω_0 = 12.1 rpm), $\omega_{\phi n}$ is the natural frequency of the system, ζ_ϕ the damping ratio and θ the pitch angle. Equation 3 is derived from the assumption that the sensitivity of aerodynamic power to blade pitch in region 3 follows a linear relation, where θ_K is the blade pitch angle at which the pitch sensitivity has doubled from its value at the rated operating point for $\theta=0$ [8]. By changing the gain correction factor *GK* by applying a different relationship between the sensitivity of aerodynamic power to blade pitch in region 3, an optimal load mitigation schedule for the gain can be setup. In the present work different values for the pitch angle θ_K are proposed so that *GK* is improved for higher wind speeds.

For small θ_K, the value of *GK* drops with a higher rate with the collective pitch angle (as observed in Figure 5), thus decreasing the values of K_i for higher wind speeds. Reduced values of K_i are responsible for greater error in the rotational speed as shown in Fig. 6a. Once this error is perceived,

the pitch angle is drastically reduced, taking values below 1°. This drop in the pitch angle causes drops in the generator torque (pitch controller and torque controller simultaneously in operation) and thus higher fluctuations in the power, as well as higher extreme blade loads (Figure 6b, c). At the same time instant as the second power drop (463s) the extreme out-plane root bending moment is observed. On the other hand for greater values of θ_K the response of the controller is faster (higher frequency) and the error of the rotational speed is reduced (Figure 6a). This along with the smoother changes in the pitch angle causes a reduction in the ultimate load of 5%, while maintaining the power constant. For $\theta_K = 8^o$ before the time instant of the ultimate load (463s) the rotational speed does not drop below its rated value. For lower values of θ_K this is not the case, where the duration of rotational speed below rated is around 8s, causing a higher extreme load.
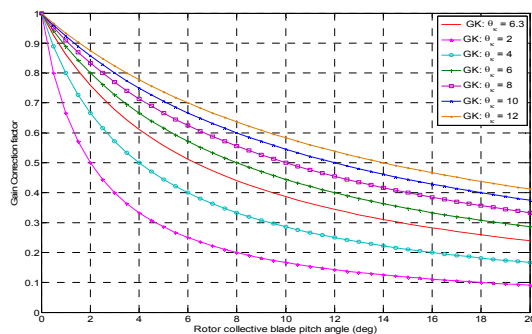

Figure 5: Gain-correction factor versus the rotor collective pitch angle for different values of θ_K The default value, indicated by the red line is $\theta_K = 6.3$ degrees.

It can be inferred that the relationship between the sensitivity of aerodynamic power to blade pitch in region 3 and the rotor-collective blade pitch angle is not linear throughout the whole range of pitch angles as suggested by Ref. [8], but it may be considered piece-wise linear depending on the mean wind speed, as depicted from Figure 7. It is proposed that for mean wind speeds greater than 20% above the rated wind speed, the gain scheduling θ_K in Eq. (3) should be tuned to higher values, thereby adjusting the gain-correction factor *GK* to its optimal level at a given mean wind speed, which yields an optimal rate of the pitch that mitigates the extreme load.
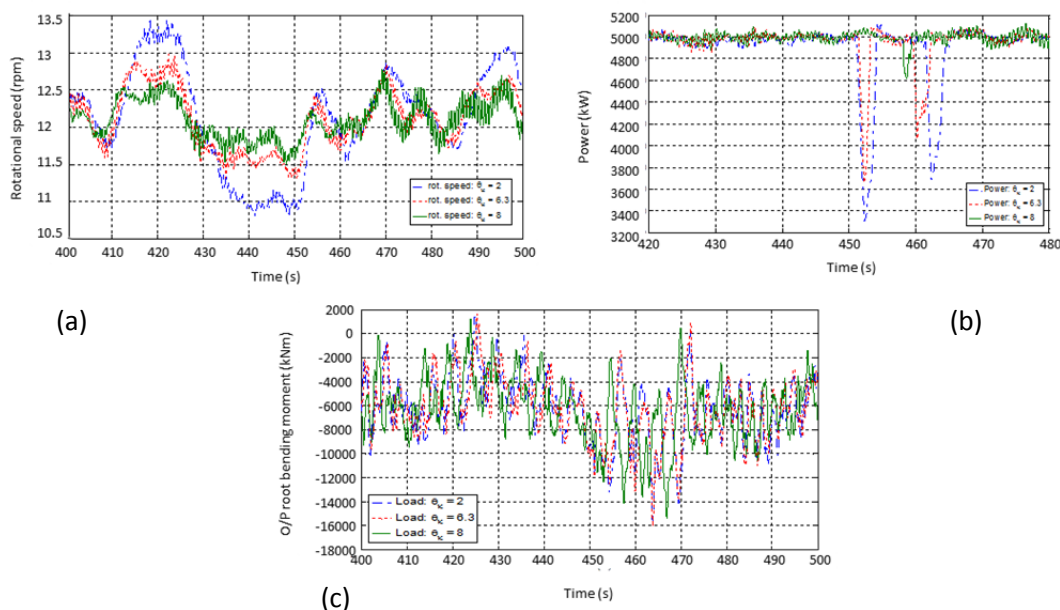

Figure 6: a) rotational speed for 3 different values of θ_K (low = 2°, default = 6.3^o and high=8°) **b)** power production for the same three values of θ_K **c)** out-of-plane root bending moment
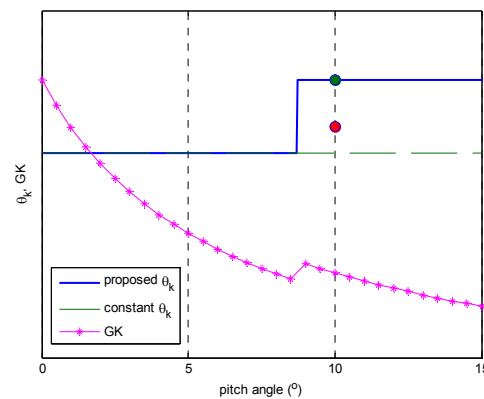
Figure 7: Controller gain GK and θ_K in region 3. Constant value of θ_K (green dashed line) is proposed in Ref. [7] and a piece-wise linear relation (blue solid line) is proposed herein. The two colored dots represent the extreme blade load for the two different profiles of θ_K.

4. Results

More simulations for verifying the influence of the controller were performed based on the results of the extreme loads presented in Table 3. Table 3 describes the result of introducing an optimal gain correction factor that induces load mitigation. At a mean wind speed of 15m/s, an optimal setting of the gain scheduling parameter θ_K of 8° ensures that the rotor speed duration below rated speed is minimized as shown in Fig 6a. The resulting increased values of K_i increase the local frequency of rotor speed oscillation about its mean speed, thus reducing the pitch drop. The localized higher frequency of rotor speed oscillations also induces smoother changes in the blade pitch angle, maintaining constant power and mitigating the extreme load on the blades as per the magnitudes shown in table 3.

If such controller tuning to mitigate the extreme load is not performed, then the uncertainty in the instantaneous value of the integral and the proportional gains of the controller K_i and K_p caused by the gain scheduling, results in greater variability of the extreme load for higher mean wind speeds. Therefore in the absence of mean wind speed specific controls tuning, a load case can be introduced that simulates the peak extreme as in:

1. Simulations are run with twelve random seeds for all mean wind speeds from cut-in to cut-out with the same operating conditions as DLC 1.1
2. A cumulative distribution function (CDF) is fit to the extreme loads at each mean wind speed.
3. The mean wind speed with the maximum extreme load corresponding to the mode of the CDF is identified as in Ref. [11].
4. The simulations at the identified mean wind speed are repeated with a 10° step variation in the initial blade azimuth angle from 0° to 120°.
5. A variation in controller integration parameter, Ki of ±15% is considered and the simulations in step 4 are repeated.
6. The ultimate load is the average of the extremes resulting from the steps 4 and 5.

Table 3: Extreme O/P root bending moment for three seeds with different initial azimuth settings, where the variation in the loads is again observed.

	Load_$\theta_K = 6.302336^o$	Load_$\theta_K = 8^o$
Seed 1_Initial azimuth 50°	14500 (kNm)	13910 (kNm)
Seed 1_Initial azimuth 110°	15520 (kNm)	13340 (kNm)
Seed 1_Initial azimuth 160°	14710 (kNm)	12980 (kNm)
Seed 9_Initial azimuth 120°	14570 (kNm)	13710 (kNm)
Seed 9_Initial azimuth 140°	14420 (kNm)	13890 (kNm)
Seed 9_Initial azimuth 280°	15480 (kNm)	13380 (kNm)

5. Conclusion

The principal factors driving extreme out-of-plane bending moments were determined. At mean wind speeds above rated, the most pronounced effect was the period of the rotor speed oscillations just before the extreme load occurrence. The gain scheduling introduced in the PI pitch control had a significant influence on the pitch behavior at the occurrence of extreme blade loads due to the behavior of the rotor speed. Optimal setting of the gain scheduling depending on the mean wind speed was proven to mitigate the extreme blade out-of-plane load for wind speeds above rated. In the absence of such optimal gain scheduling, a new load case setup was recommended to determine the long term extreme out-of-plane blade moment.

References

[1] Bierbooms, W (2005). Investigation of Spatial Gusts with Extreme Rise Time on the Extreme Loads of Pitch-regulated Wind Turbines. *Wind Energy*, **8**,17-34.

[2] Natarajan, A, & Verelst, D (2011). Outlier robustness for wind turbine extrapolated extreme loads. *Wind Energy*, **15**,679-697.

[3] Bossanyi, E A (2003). Wind Turbine Control for Load Reduction. *Wind Energy*, **6**,229-244.

[4] Johnson, S, van Dam, C, & Berg, D (2008). *Active Load Control Techniques for Wind Turbines.* Albuquerque: Sandia National Laboratories.

[5] Moriatry, P (2008). Database for Validation of Design Load Extrapolation Techniques. *Wind Energy*, **11**,559-576.

[6] Larsen, T; Hansen, A (2007). *How 2 HAWC2, the user's manual*, Risø National Laboratory

[7] IEC 61400-1. (2005). *International Standard for wind turbines Part 1: Design Requirements IEC 61400-1 Edition 3.*

[8] Jonkman, J, Butterfield, S, Musial, W, & Scott, G (2009). *Definition of a 5-MW Reference Wind Turbine for Offshore System Development.* National Renewable Energy Laboratory.

[9] Montgomery, D (2009). *Design and Analysis of Experiments.* John Wiley & Sons, 7th Edition.

[10] Hansen, M, Hansen, A, Larsen, T, Øye, S, Sørensen, P, & Fuglsang, P (2005). *Control Design for a pitch-regulated, variable speed wind turbine. Technical Report Risø - R-1500 (EN),*Risø National Laboratory, Denmark.

[11] Natarajan, A, Holley, W, Penmatsa, R, & Brahmanapalli, B (2008). Identification of Contemporaneous Component Loading for Extrapolated Primary Loads in Wind Turbines. *Wind Energy*, **11**,577-587.