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## Influence of the control system on wind turbine reliability in extreme turbulence

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**Abstract.** One of the critical design driving load cases for modern large onshore/offshore wind turbines is power production in extreme turbulence. According to the IEC 61400-1 edition 3 design standard, the normal production extreme loads are extrapolated and compared to the extreme loads obtained under extreme turbulence input. This study shows that using a probabilistic approach and the first order reliability method, wind turbine structural reliability can be assessed when the extreme turbulence model is uncertain. The structural reliability is assessed for a wind turbine with/without structural load alleviation control features. It is shown that large uncertainties in inflow conditions and turbulence can be significantly reduced while maintaining an acceptable structural reliability through the use of advanced structural load alleviation control features. However, that comes at a cost of increased controller complexity and loss in annual energy production.

### 1. Introduction

The extreme turbulence load case (DLC1.3ETM in the IEC61400-1 [1]) generally ranks as a top design driving case for extreme loading on wind turbine components. Special load alleviation control features are designed by manufacturers to specifically reduce the adverse effects of this load case. The motivating questions in this paper are: how does the structural reliability of the wind turbine change if the extreme turbulence model is uncertain? In the presence of such uncertainty how does the structural reliability change with/without advanced load alleviation features? The objective of this paper is to investigate the structural reliability of a wind turbine in the presence of uncertainties in the extreme turbulence model when increasing levels of complexity of the load alleviation features in the control system are employed. First the turbulence model and the control features are described, then the load probabilistic model is derived and finally the structural reliability is performed using the First Order Reliability Method (FORM).

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## 2. The IEC61400-1 extreme turbulence model

The background for the extreme turbulence model in [1] is described below based on environmental contours derived through the Inverse FORM methodology (IFORM). The annual distribution of the 10 minute mean wind speed, denoted by random variable  $V$ , is given by a Rayleigh distribution defined as:

$$f_V(v) = \frac{2v}{(2\mu_V/\sqrt{\pi})^2} \exp\left[-\left(\frac{v}{2\mu_V/\sqrt{\pi}}\right)^2\right] \quad (1)$$

Where  $v$  is the hub wind speed and  $\mu_V$  is the mean wind speed. The standard deviation of the 10-minute wind speed is taken as the measure of turbulence, whose longitudinal component is denoted by  $\sigma_1$ . The long term conditional distribution of turbulence  $\sigma_1$  given the wind speed  $V$  is assumed to follow the lognormal distribution:

$$f_{\sigma_1|V}(\sigma_1|v) = \frac{1}{\sqrt{2\pi}\zeta\sigma_1} \exp\left[-\frac{1}{2}\left(\frac{\ln(\sigma_1)-\lambda}{\zeta}\right)^2\right] \quad (2)$$

where the parameters of the lognormal distribution,  $\lambda$  and  $\zeta$ , are defined as:

$$\zeta = \sqrt{\ln(\delta_{\sigma_1|V}^2 + 1)} \quad (3)$$

$$\lambda = \ln(\mu_{\sigma_1|V}) - \frac{1}{2}\zeta^2 \quad (4)$$

With the coefficient of variation  $\delta_{\sigma_1|V} = \frac{\sigma_{\sigma_1|V}}{\mu_{\sigma_1|V}}$ .

The conditional mean and standard deviation of turbulence are given by the equations [1]:

$$\mu_{\sigma_1|V} = I_{ref}(0.75v + c) \quad (5)$$

$$\sigma_{\sigma_1|V} = 1.44I_{ref} \quad (6)$$

The parameters  $I_{ref}$  and  $c$  are found in table 1 for turbulence class A through C.

**Table 1.**  $I_{ref}$  and  $c$  for turbulence classes A-C.

Turbulence Class	$I_{ref}$	$c$ [m/s]
A	0.16	3.8
B	0.14	3.8
C	0.12	3.8

The joint PDF of wind speed and turbulence is obtained by multiplying Equations 1 and 2:

$$f_{\sigma_1,V}(\sigma_1, v) = f_{\sigma_1|V}(\sigma_1|v)f_V(v) \quad (7)$$

The resulting joint PDF for class IEC-IB is shown in figure 1a. Now assuming a probability of failure,  $P_f$ , defined in terms of the return period  $r$ , an “environmental contour” can be constructed in the standard Normal  $u$ -space which represents all points on a circle such that

$$\sqrt{u_1^2 + u_2^2} = \beta_r \quad (8)$$

where the reliability index  $\beta_r$  and the probability of failure  $P_f$  are defined as follows  $\Phi(-\beta_r) = P_f$  with  $\Phi(\cdot)$  being the distribution function for the standardized Normal distribution. The independent standard Normal random variables  $U_1$  and  $U_2$  can be transformed into contours in the physical space utilizing the above equations and the following Rosenblatt transformations:

$$\Phi(u_1) = F_V(v); \rightarrow v = F_V^{-1}(\Phi(u_1)) \quad (9)$$

$$\Phi(u_2) = F_{\sigma_1|V}(\sigma_1|v); \rightarrow t = F_{\sigma_1|V}^{-1}(\Phi(u_2)) \quad (10)$$



large data set of wind simulations was compiled. Wind simulations were run over a range of mean wind speeds between 4–25 m/s in 1-m/s increments and turbulence levels between 1–8 m/s in 1m/s increments. Each wind speed and turbulence level combination is repeated using 48 stochastic seeds, resulting in a total of 8448 10-minute simulations. The output used from the simulations are the blade root flapwise bending moment, and the tower bottom fore-aft bending moment. The maxima of the bending moment data are extracted using the method of the Global Maxima for each 10 minute time series. These maxima are further used as the basis for determining probability models of the extreme loads:

- $f_L(l|\sigma_1, v)$ : PDF of the load effect  $l$  given turbulence and wind speed, determined using the load simulations.
- $f_{\sigma_1, v}(\sigma_1, v) = f_{\sigma_1|v}(\sigma_1|v)f_V(v)$ : Joint PDF of wind speed and turbulence determined as described in section 2 (figure 1a).

#### 4.2. Loads extrapolations

In order to analyse the structural reliability in the presence of uncertainties in the turbulence model, it is necessary to derive the probability distribution of the load with a yearly reference period. This distribution is derived through the long term extrapolated probability distribution. The long term probability distribution for the maximum 10-minute load effect  $l$  conditional on wind speed  $v$  and turbulence  $\sigma_1$  is modelled as follows:

$$F_{short.term}(l|T_{10min}, v, \sigma_1) = F_{local}(l|T_{10min}, v, \sigma_1)^{n(\sigma_1, v)}$$

$$F_{long.term}(l|T_{10min}) = \int_{V_{in}}^{V_{out}} \int_0^{\infty} F_{short.term}(l|T_{10min}, v, \sigma_1) f_{\sigma_1|v}(\sigma_1|v) f_V(v) d\sigma_1 dv \quad (12)$$

where  $n(\sigma_1, v)$  is the expected number of uncorrelated maxima in 10 minutes.  $F_{local}$  is the local probability distribution for the load process which is chosen to be a 3-parameter Weibull distribution function [3]. The long-term probability of exceedance is then computed by integrating all of the short-term loads distributions with the joint PDF of wind speed and turbulence. The annual maximum probability distribution is finally derived as follows<sup>2</sup>:

$$F_{long.term}(l|T_{1year}) = F_{long.term}(l|T_{10min})^N \quad (13)$$

where  $N$  is the number of 10min periods in one year ( $=365 \cdot 24 \cdot 60 \text{min} / 10 \text{min}$ ). The annual maximum distributions for the load effect are plotted in figures 2-3 for the blade root flapwise bending moment and tower bottom fore-aft bending moment respectively<sup>3</sup>. The plots indicate that the resulting long term distributions with/without load alleviation control features differ significantly. At the fifty year return period, the observed reduction in the blade flapwise extreme bending moment is approximately 14% while the observed reduction in the tower bottom fore-aft extreme bending moment is approximately 25%. A conclusion can be drawn at this point:

A turbine designer should assess the impact of the controller on structural reliability of the wind turbine. Should a total control failure take place, an increase in exceedance probability occurs. The sophistication and performance of the structural load control system could vary drastically amongst manufacturers. We will investigate this issue further in section 5.

<sup>2</sup> Say  $L = \max(X_1, X_2, \dots, X_N)$  where  $X$  is a random variable with distribution  $F_X$ . Using the accumulation of probability in independent repeated trials, the distribution of  $L$  can be written as:  $F_L(x) = P(\max X_i \leq x \{i = 1, \dots, N\}) = P(X_1 \leq x \cap X_2 \leq x \cap \dots \cap X_N \leq x) \Rightarrow F_L(x) = \prod_{i=1}^N P(X_i \leq x) = F_X(x)^N$ . If  $F_L$  is the distribution (non-exceedance probability) of maximum load in a reference period  $t_r$ , and  $F_X$  is the distribution of maximum load occurring in much shorter period  $\tau$ , the exponent  $n$  is then equal to  $t_r / \tau$ . Example: the 50-year non-exceedance probability with a reference period of 10min corresponds to 0.98 non-exceedance probability with a reference period of 1 year.

<sup>3</sup> The extrapolated loads are normalized with the 50-year extrapolated load level derived from the simulations with control configuration 2.

### 4.3. The probabilistic model

Structural failure occurs in the tail of the extreme load distribution, hence the loads probabilistic model is derived by fitting a 3-parameter Weibull distribution to the tail of the empirical annual maximum distribution. The parameters of the fitted distributions are estimated through the Maximum Likelihood Estimation method using the data points between the 80<sup>th</sup> and the 90<sup>th</sup> percentiles of the empirical annual maximum distribution. The fits and the corresponding PDF's are shown in figures 4-5.

## 5. Structural reliability in extreme turbulence

Structural reliability is expected to differ significantly depending on the performance of the structural load alleviation control system. Former reliability analyses were performed in normal turbulence or in stand-still in extreme wind conditions (see [2], [5]), in this study the reliability analysis is done in extreme turbulence under the influence of industrial control systems equipped with load alleviation features<sup>4</sup>.

### 5.1. Limit state function

The design equation for loads and resistance for a given failure mode can be expressed as:

$$z \cdot SRF \cdot \frac{R_c}{\gamma_m} - L_c \gamma_l = 0 \quad (14)$$

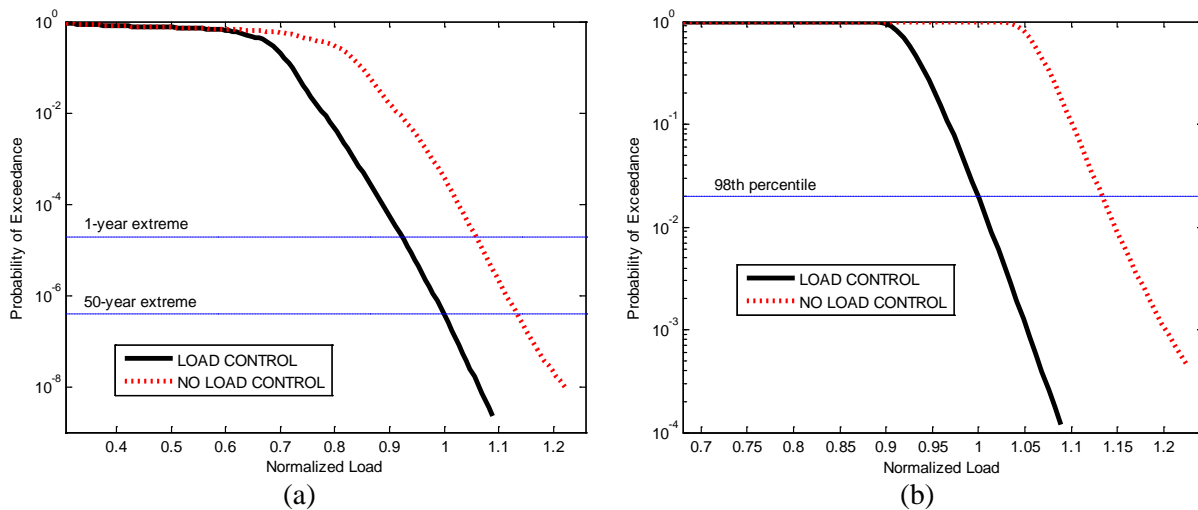
where  $R_c$  is the characteristic material strength,  $L_c$  is the characteristic load (i.e. bending moment),  $\gamma_m = 1.2$  is the material safety factor,  $\gamma_l = 1.35$  is the load safety factor,  $z$  is the design variable which depends on the geometry and stiffness of the component and  $SRF$  is the Stress Reserve Factor. If the component has not been designed to the limit, the  $SRF$  will be larger than 1, reflecting the extra safety margin [7]. For the structural reliability analysis an ultimate Limit State Function (LSF) is defined in order to include the load and resistance uncertainties:

$$g = zM_{cr}X_R - L_{ULT}(t, v)X_{dyn}X_{st}X_{ext}X_{sim}X_{exp}X_{aero}X_{str} \quad (15)$$

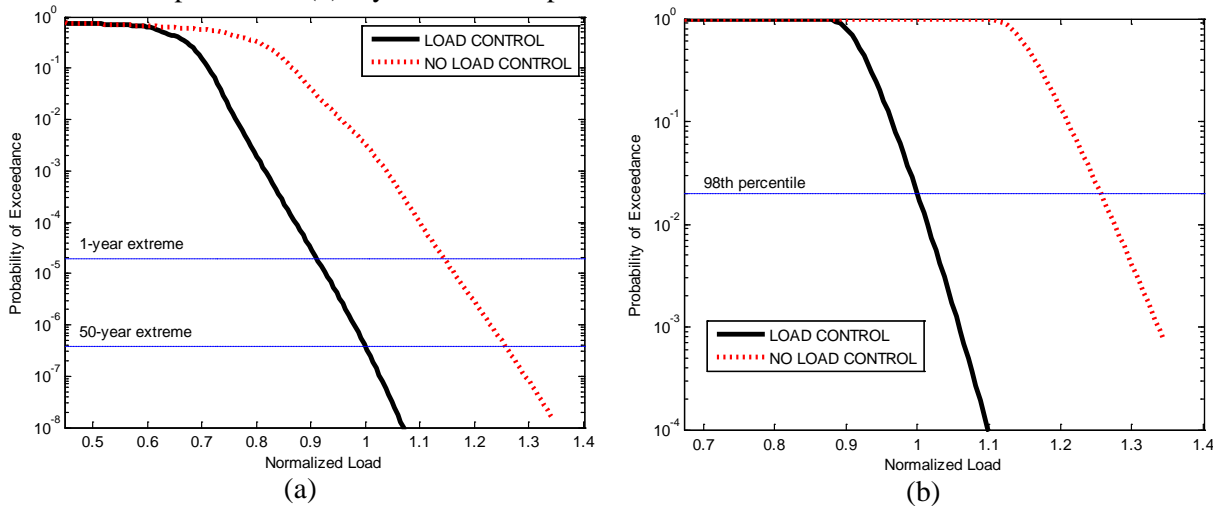
$M_{cr}$  is the ultimate bending strength of the structure and  $L_{ULT}(t, v)$  is the extreme load model as defined in terms of the turbulence and wind speed. Additional stochastic variables are defined as multiplicative factors to the resistance and load to take into account the model and statistical sources of uncertainties.  $X_R$  represents the model and statistical uncertainty of the resistance.  $X_{dyn}$  accounts for model uncertainty due to the modelling of the wind turbine dynamic response.  $X_{st}$  accounts for the statistical uncertainty of wind climate assessment.  $X_{ext}$  is associated with the extrapolated load model.  $X_{sim}$  accounts for statistical uncertainties caused by the limited number of loads simulations.  $X_{exp}$  accounts for the model uncertainties related to modelling the terrain and roughness.  $X_{aero}$  accounts for the model uncertainties related to the assessment of aerodynamic lift and drag coefficients. Finally the uncertainties related to the computation of the stresses on components from the loads is considered through  $X_{str}$ . Uncertainties related the control parameters are not directly included here. The stochastic variables of the LSF are described in Appendix A. The structural reliability is assessed by solving the LSF using FORM<sup>5</sup>. The outcome is defined by the reliability index  $\beta$ . This approach yields an upper bound of the probability of failure since (1) it assumes no correlation amongst stochastic variables and events and (2) the components stress reserves factors are assumed to equal one [7].

<sup>4</sup> Control system parameters uncertainty and failure rate are not considered here.

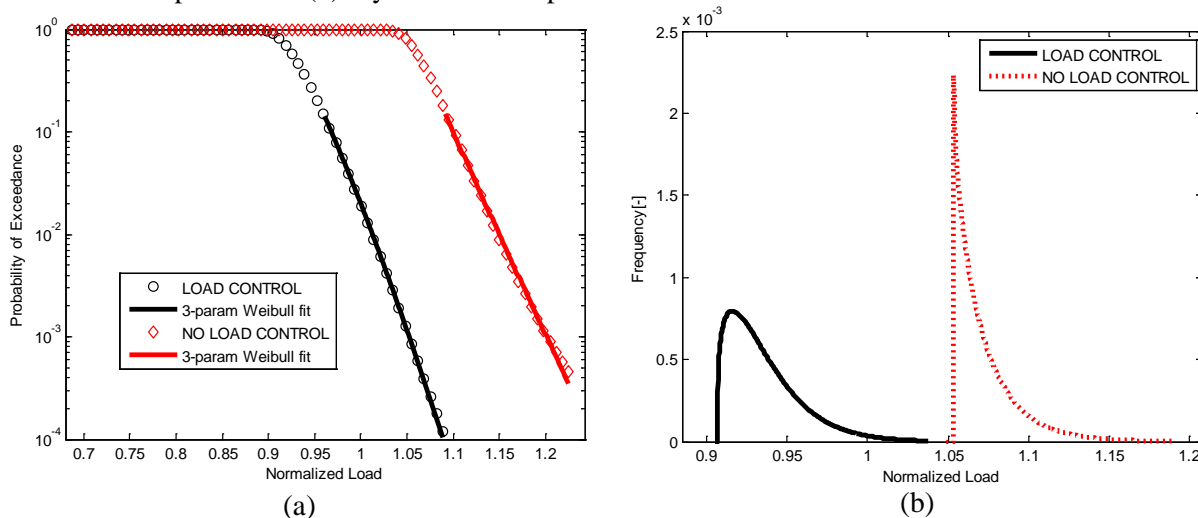
<sup>5</sup> A custom First Order Reliability Method is written in Matlab<sup>®</sup> to solve the limit state functions and derive the reliability index.



**Figure 2.** Long term exceedance probability for the blade root flapwise bending moment for (a) 10-min reference period and (b) 1-year reference period.

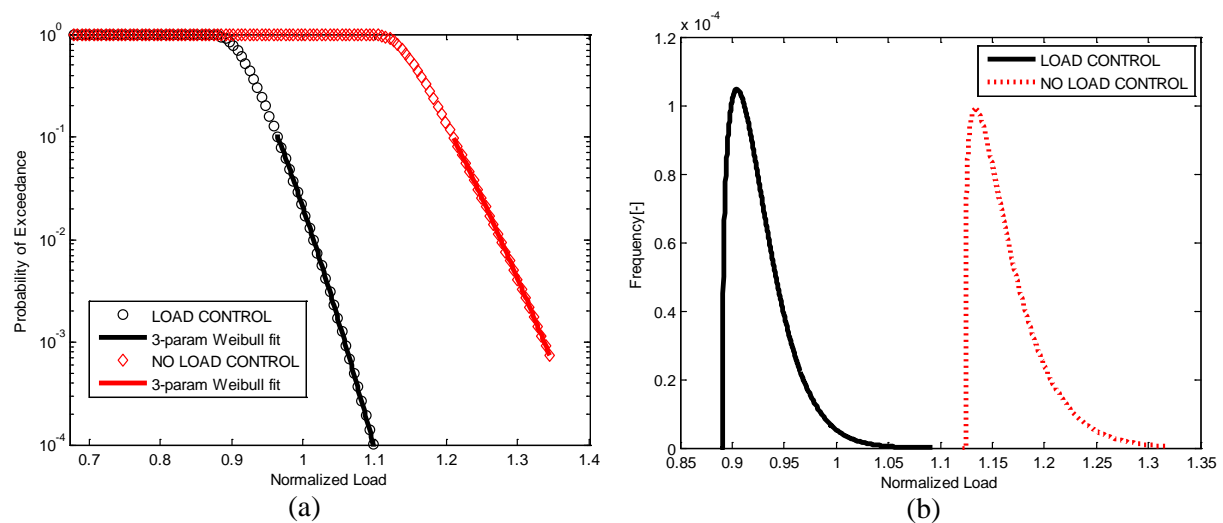


**Figure 3.** Long term exceedance probability for the tower bottom fore-aft bending moment for (a) 10-min reference period and (b) 1-year reference period.



**Figure 4.** (a) 3-parameter Weibull distribution fit to the annual maximum probability distribution and (b) the corresponding density function for the blade root flapwise bending moment.





**Figure 5.** (a) 3-parameter Weibull distribution fit to the annual maximum probability distribution and (b) the corresponding density function for the tower bottom fore-aft bending moment.

### 5.2. Reliability results

The reliability results are presented for four uncertainty scenarios:

**Scenario 1:** this is the reference scenario where the turbulence model is as defined in [1] with an  $I_{ref}=0.14$  and mean wind speed of 10m/s.

**Scenario 2:** this scenario is similar to scenario 1 except the turbulence is assumed to follow an extreme value distribution instead of the lognormal distribution. The objective here is to study the effect on structural reliability if the turbulence were not log-normally distributed.

**Scenario 3:** this scenario is similar to scenario 1 except the mean wind speed is set to 11m/s instead of 10m/s and follows a Rayleigh distribution. The objective here is to study the effect on structural reliability if the mean wind speed is higher than the reference design.

**Scenario 4:** In this scenario the turbulence is assumed to follow a lognormal distribution with  $I_{ref}=0.16$  instead of 0.14 and the mean wind speed is set to 10m/s and follows a Rayleigh distribution. The objective here is to study the effect on structural reliability if  $I_{ref}$  is higher than the reference design.

The structural reliability of the blade (blade root extreme flapwise bending moment) and tower (tower bottom extreme fore-aft bending moment) are assessed for each of the four scenarios for the three control system configurations described in section 4. An acceptable reliability index is  $\beta \geq 3.3$  corresponding to an annual probability of failure  $P_f \leq 5 \cdot 10^{-4}$ . The results are shown in tables 2 and 3 for the blade and tower respectively. The absolute value of the reliability index is not necessarily of interest here but the relative change in reliability index amongst control configurations and uncertainty scenarios. Note that the results discussed below are generally applicable beyond the turbine studied here.

### 5.3. Discussion

#### *How to interpret the structural reliability results?*

The reference control design performance in extreme turbulence operation delivers acceptable structural reliability with  $\beta \geq 3.3$  (configuration 2 in tables 2-3). Uncertainty in  $I_{ref}$  seems to have the largest impact on structural reliability (scenario 4 in tables 2-3). The structural reliability in all scenarios drops significantly when no load alleviation features are included in the control system (configuration 1). This is not unexpected as the load alleviation features are an integral part of the reference turbine structural load calculations in configuration 2. This indicates that when a turbine design relies heavily on control features to achieve structural load reductions (lighter turbine design),

control architecture and failure modes analysis should be studied very closely beyond the load cases recommended in the IEC61400-1 due to the severe drop in reliability.

*How does the control system complexity and performance affect the structural reliability when the extreme turbulence model is uncertain?*

Advanced load control features which are able to adapt their parameters settings to external inflow conditions (configuration 3 in tables 2-3) show a satisfactory performance in improving the structural reliability as showcased, for instance, in scenario 4 corresponding to a large increase in the turbulence compared to the design turbulence; for the blade the reliability index increases from 3.33 to 3.60 and from to 4.53 for the tower. This indicates that large uncertainty in the extreme turbulence model can be significantly lowered through the use of advanced load control features. However, the complexity of the control system increases which warrants additional failure modes analysis of the controller and its architecture and probably additional maintenance provisions. Inadvertently this leads to the logical next step of an integrated design and optimization approach of the wind turbine control system and structural reliability from a cost-benefit point of view.

*Effect of structural load control on AEP?*

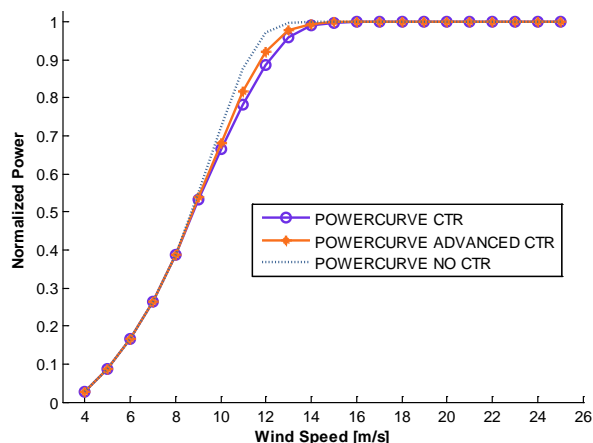
Increased structural reliability is achieved with increased complexity of the load alleviation features of the control system. The next logical step is to verify the impact of the load control on the Annual Energy Production (AEP) of the wind turbine. Generally, load reduction is achieved by reducing the aerodynamic thrust on the rotor. Power  $C_p$  and  $C_T$  thrust coefficient are related through the axial induction factor  $a$  (2D actuator disk:  $C_p = 4a(1 - a)^2$  and  $C_T = 4a(1 - a)$ ). Hence any reduction in thrust is accompanied with a reduction in power and vice-versa. Figure 6 shows a comparison of the power curves when no load control features are included, when load control features are included and when advanced load control features are included (configurations 1-3). In the case where the load control features are included (configuration 2) a 3.1% loss in AEP is incurred relative to configuration 1. However this value drops to 1.8% AEP loss when advanced load reduction features are included (configuration 3). Generally the AEP loss is accepted in light of the overall cost of energy achieved. The AEP are calculated for an average wind speed of 10m/s and turbulence intensity of 10%. The AEP results will differ slightly if the mean wind speed and turbulence intensity are varied, but the trend amongst the various control configurations remains the same.

**Table 2.** Structural reliability of the blade (blade root extreme flapwise bending moment).

Uncertainty Scenario	Annual Reliability Index $\beta$ for the blade		
	Control Configuration 1: No structural load alleviation features, simple controller	Control Configuration 2: with structural load alleviation features (Reference)	Control Configuration 3: with advanced structural load alleviation features
1	<b>2.77</b>	<b>3.66</b>	<b>3.96</b>
2	<b>3.14</b>	<b>3.92</b>	<b>4.07</b>
3	<b>2.76</b>	<b>3.58</b>	<b>3.83</b>
4	<b>2.54</b>	<b>3.33</b>	<b>3.60</b>

**Table 3.** Structural reliability of the tower (tower bottom extreme fore-aft bending moment).

Uncertainty Scenario	Annual Reliability Index $\beta$ for the tower		
	Control Configuration 1: No structural load alleviation features, simple controller	Control Configuration 2: with structural load alleviation features (Reference)	Control Configuration 3: with advanced structural load alleviation features
1	<b>2.24</b>	<b>3.66</b>	<b>4.80</b>
2	<b>2.26</b>	<b>3.83</b>	<b>4.76</b>
3	<b>2.21</b>	<b>3.52</b>	<b>4.73</b>
4	<b>2.06</b>	<b>3.33</b>	<b>4.53</b>



**Figure 6.** Power curves (normalized by rated power) when (1) no structural load control features are included, when (2) structural load control features are included and when (3) advanced structural load control features are included.

## 6. Conclusion

Using a probabilistic approach, a wind turbine structural reliability is assessed when the extreme turbulence model is uncertain and when various levels of complexity of the structural load alleviation features in the control system are used. The structural reliability index drops significantly below an acceptable level of  $\beta=3.3$  when the load alleviation features are not included in the control system. Additionally, it was found that when the turbulence level increases due to uncertainty in the extreme turbulence model, the structural reliability index of the blade and tower drop to 3.33 from 3.66. However, advanced load control features which are able to adapt their parameters settings to external inflow conditions show a satisfactory performance in improving the structural reliability: The reliability index increases from 3.33 to 3.60 for the blade and to 4.53 for the tower. This indicates that large uncertainty in the extreme turbulence model can be significantly lowered through the use of advanced load control features. However, the complexity of the control features increases which warrants additional failure modes analysis of the controller and its architecture. In addition, the improvement in the structural reliability comes at a cost of 1.8% loss in annual energy production. Future work could include similar reliability analyses when the extreme turbulence is modelled directly and not based on the normal turbulence model and deriving the distribution of the annual maximum load effects based on adaptive sampling techniques instead of extrapolation.

## Acknowledgments

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### Appendix A. The stochastic variables of the Limit State Function

Variable	Description	Dist	Scenario 1	Scenario 2	Scenario 3	Scenario 4	COV <sup>6</sup>
			Expected Value (Ref.)	Expected value	Expected Value	Expected value	
X <sub>dyn</sub>	Structural dynamics	LN	1	1	1	1	0.05
X <sub>aero</sub>	Airfoil data uncertainty	G	1	1	1	1	0.065
X <sub>sim</sub>	Simulation statistics	N	1	1	1	1	0.03
X <sub>exp</sub>	Exposure (terrain)	LN	1	1	1	1	0.05
X <sub>ext</sub>	Extrapolation	LN	1	1	1	1	0.03
X <sub>st</sub>	Climate statistics	LN	1	1	1	1	0.03
X <sub>str</sub>	Stress evaluation	LN	1	1	1	1	0.03
X <sub>R</sub>	Resistance model uncertainty	LN	1	1	1	1	0.05
M <sub>cr,B</sub>	Blade Resistance strength	LN	1	1	1	1	0.10
M <sub>cr,T</sub>	Tower Resistance strength	LN	1	1	1	1	0.05
$\sigma_1$	Turbulence [m/s]	LN	I <sub>ref</sub> =0.14 <sup>a</sup>	EV 0.14 <sup>b</sup>	I <sub>ref</sub> =0.14	I <sub>ref</sub> =0.16	--
V	Mean wind speed [m/s]	WBL	10	10	11	10	k=2

<sup>a</sup>I<sub>ref</sub> affects both the mean ( $\mu_{T|V} = I_{ref}(0.75v + c)$ ) and std ( $\sigma_{\sigma_1|V} = 1.44I_{ref}$ ) of turbulence

<sup>b</sup>This scenario is the same as the reference except that turbulence follows an extreme value distribution

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- Climate statistics are considered in the  $t$  and  $v$  and hence a smaller COV for  $X_{st}$  is used.
- A smaller COV for terrain exposure is considered in  $X_{exp}$  because it is an offshore turbine
- A smaller COV for extrapolation uncertainty is considered in  $X_{ext}$  because the loads response is calculated for a large range of turbulence and mean wind speeds, in addition to a large number of seeds.
- A smaller COV for simulations statistics uncertainty is considered in  $X_{sim}$  because the loads response is calculated with 48 seeds for each mean wind speed and turbulence level.