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Influence of the control system on wind turbine loads during power production in extreme turbulence: Structural reliability

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ABSTRACT

The wind energy industry is continuously researching better computational models of wind inflow and turbulence to predict extreme loading (the nature of randomness) and their corresponding probability of occurrence. Sophisticated load alleviation control systems are increasingly being designed and deployed to specifically reduce the adverse effects of extreme load events resulting in lighter structures. The main objective herein is to show that despite large uncertainty in the extreme turbulence models, advanced load alleviation control systems yield both a reduction in magnitude and scatter of the extreme loads which in turn translates in a change in the shape of the annual maximum load distribution function resulting in improved structural reliability. Using a probabilistic loads extrapolation approach and the first order reliability method, a large multi-megawatt wind turbine blade and tower structural reliability are assessed when the extreme turbulence model is uncertain. The structural reliability is assessed for the wind turbine when three configurations of an industrial grade load alleviation control system of increasing complexity and performance are used. The load alleviation features include a cyclic pitch, individual pitch, static thrust limiter, condition based thrust limiter and an active tower vibration damper. We show that large uncertainties in the extreme turbulence model can be mitigated and significantly reduced while maintaining an acceptable structural reliability level when advanced load alleviation control systems are used. We end by providing a rational comparison between the long term loads extrapolation method and the environmental contour method for the three control configurations.

1. Introduction

This is the first of a set of papers dealing with the influence of advanced load alleviation control systems on structural reliability and safety factors of wind turbines. Over the past decade, significant advances have been achieved in smart load alleviation control systems and algorithms resulting in impressive reduction in the magnitude and scatter of extreme and fatigue loads. Today, advanced load alleviation control systems are an integral part of the design of large wind turbines. Power production in extreme turbulence (DLC 1.3ETM [1]) ranks as one of the top design driving load cases on various components such as blades and towers. In the IEC61400-1 wind turbine design standard [1] the extreme turbulence model is calibrated to a 50 yr return period. It has recently come under scrutiny with regard to its accuracy in flat terrain versus complex terrain versus offshore versus wake operation in large wind farms. Consequently, an analysis of the effect of smart load alleviation control systems on structural reliability of a wind turbine is warranted especially in the presence of large uncertainty in the extreme turbulence model.

Various aspects related to load control of a wind turbine during power production in extreme turbulence have not been so far studied, specifically: how does the structural reliability of the wind turbine change if the turbulence model is uncertain? How can the uncertainty in the turbulence model be represented? In the presence of such uncertainty how does the structural reliability change with/without smart load alleviation control systems? The aim of this work is thus to assess the structural reliability of a large multi-megawatt wind turbine blade and tower when the turbulence model is uncertain given that various load alleviation control features are used.

[2] have examined the effect of varying turbulence levels and wind speeds on long term extrapolation techniques using a joint probability density function of both mean wind speed and

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Nomenclature

AEP	Annual Energy Production
BEM	Blade Element Momentum theory
CDF	Cumulative Distribution Function
COV	Coefficient of Variation
EC	Environmental Contours
ETM	Extreme Turbulence Model
FORM	First Order Reliability Method
IFORM	Inverse First Order Reliability Method
LSF	Function
PDF	Probability Density Function

turbulence for loads calculations on a constant speed active-stall regulated wind turbine [3]. have demonstrated through a probabilistic based method that a reduction in half of the probability of failure of the control system reduces the structural probability of failure of a wind turbine by approximately 2 times assuming the dominant contribution to the overall reliability is a storm situation in stand-still [4]. have used a cost and reliability based optimization of a wind turbine using various objective function formulations including no reconstruction of the wind turbine in case of structural failure when the control system fails. The authors show that given a target reliability level, the optimal turbine geometry (tower bottom diameter and sheet thickness) is independent of the initial cost of the control system and its failure rate [5]. and [6] have used a classical system reliability approach to assess the overall probability of failure of an actively controlled structure, including the case where the structure is in full reliance on the control system (i.e. series system).

The novelty in this paper is based on the fact that load alleviation control systems not only affect the magnitude of the extreme load level but also the scatter and the shape of the probability distribution function of the extreme loads. The shape and magnitude of the probability distribution is dependent on the sophistication and performance of the load alleviation control systems to limit the excursion of extreme loads. A probabilistic loads extrapolation approach is used to derive the annual maximum load distribution when various configurations of the load alleviation control systems are employed. The extreme load probabilistic model is then used in a First Order Reliability Model (*FORM*) to calculate the structural reliability level of a wind turbine blade and tower under various uncertainty scenarios. Each scenario describes a possible alteration to the reference design turbulence model as defined in the IEC61400-1 ed. 3 design standard. It is generally observed that load alleviation control systems reduce the extreme load and limit their excursion resulting in lower scatter. The rationale behind the implementation of probabilistic methodologies is today's larger variations of climates where wind turbines are installed, as well as smart features in modern controllers which makes it difficult to establish and abide by a relevant deterministic standard for design of wind turbines. In this paper a large commercial multi-megawatt offshore wind turbine is considered with nominal power >5 MW and rotor diameter >130 m. An industrial grade control system is used which includes a cyclic pitch, individual pitch, static thrust limiter, condition based thrust limiter and an active tower vibration damper.

2. The control system

Manufacturers are increasingly deploying sophisticated control systems on wind turbines with the ultimate objective of removing blade, nacelle main frame and tower/foundation load variations due to turbulence and oblique inflow while maintaining maximum power production. In order to reach this goal, a variable speed pitch controlled wind turbine control system is supplemented with load alleviating features capable of: (1) limiting the peak thrust on the rotor, (2) nullifying the effect of asymmetric aerodynamic rotor loading and (3) reducing tower vibrations. The load control features used in this study (Fig. 1) are gain-scheduled PID controllers which have a simple structure and can be easily tuned. The load alleviation control features include a *thrust limiter*, *cyclic pitch*, *individual pitch* and *tower vibration damper*. These features are fairly representative of what can be found on modern wind turbines operating in the field today. The input/output parameters of these load alleviation control features are described in Table 3.

2.1. Description of the load control features

An industrial grade control system[1] equipped with four load alleviation control features is considered:

2.1.1. Thrust limiter

The thrust limiter (thrust clipper) affects thrust driven loads such as blade flap, blade out-of-plane deflection and tower fore-aft. This is a control feature that induces thrust limiting capabilities obtained by prescribing a pitch level to the blades based on an estimated rotor averaged wind speed. Thus the prescribed pitch determines a maximum level that the peak thrust can reach. A static thrust limiter is a feature where the peak thrust allowed is constant regardless of external inflow conditions and loading conditions. Conversely the condition based thrust limiter sets the peak thrust as a function of on the estimated external inflow, estimated wind speed and turbulence and measured turbine load effects such as blade flapwise bending moment.

2.1.2. Cyclic pitch

The cyclic pitch control limits the asymmetric loads such as tilt and yaw caused by aerodynamic wind shear, tower shadow, skew inflow and yaw misalignment. Hence the cyclic pitch effects are limited to around the 1P frequency. The cyclic pitch scheduling and enabling depends mainly on the generator power and rotor speed (which should also be relatively representative for the asymmetric loads affecting the tilt and yaw bending moments on the main shaft and tower top), collective pitch value and rotor azimuth position. The cyclic pitch control handles tilt/yaw loading via a sine offset to the pitch reference. To a large extent this will also reduce the blade bending moments and out-of-place deflection.

2.1.3. Individual pitch

On top of the cyclic pitch controller the individual pitch control (IPC) limits the individual blade loading in addition to asymmetric loads such as tilt and yaw bending moments on the main shaft due to stochastic disturbances caused by turbulence. For increasing rotor size the turbulence driven wind gusts shift from causing thrust variations toward giving rise to asymmetric loading. The IPC algorithm calculates a pitch demand which is augmented to the cyclic tilt/yaw pitch demand. Individual blade load measurements are used to compute a demand pitch for each blade, the algorithm then uses the resulting pitch demand from the preceding blade variably delayed to match rotor azimuth position and pitch actuator dynamics. The IPC effects are limited to around the 3P frequency range.

[1] proprietary control system developed at MiTa-Teknik A/S. The following references give some insight about cyclic pitch, individual pitch and tower damping control features [7–12].