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Aeroelastic load simulation of a 3 MW two bladed wind turbine

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Zusammenfassung / Abstract

Thema der Masterarbeit

Aeroelastischer Lastsimulation einer 3 MW Zweiblatt Windenergieanlage

Stichworte

Wind, Lastsimulation, Pendelnabe, IEC 61400-1, Ermüdung, Extrapolation

Kurzzusammenfassung

Bisher war die Entwicklung moderner Windenergieanlagen fokusiert auf Anlagen mit drei Blättern. Allerdings besitzen Zweiblattanlagen besonders für Offshore Anwendungen einige Vorteile. Durch die Anwendung weiterer Methoden zur Lastreduktion könnten diese erheblich die Kosten für Strom aus Windenergie senken.

Ein vielversprechender Ansatz beinhaltet die Ausstattung einer Zweiblattanlagen mit einer Pendelnabe, welche die Belastungen für den Triebstrang enorm reduzieren kann. Das Potential einer Pendelnabe wird mit den Ergebnissen einer starren Anlage in dieser Arbeit verglichen. Dabei werden sowohl die Extremlasten als auch die Ermüdungslasten nach der IEC 61400-1 Richtlinie bestimmt und verglichen.

Master Thesis Title

Aeroelastic load simulation of a 3 MW two bladed wind turbine

Keywords

Wind, Load simulation, Teeter Hub, IEC 61400-1, Fatigue, Extrapolation

Abstract

Previous development of modern wind turbines has been focused on three bladed turbines. However, two bladed turbines offer some advantages especially for offshore applications. By using additional methods for load reduction, these turbines could significantly reduce the cost of electricity from wind energy.

A promising approach involves equipping the two bladed turbines with a teeter hub, which can reduce the strain on the drive train enormously. The potential of a teeter hub is compared with the loads of a rigid system in this thesis. Both the extreme loads and fatigue loads are determined and compared according to the IEC 61400-1 guideline.

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Contents

Nomenclature

A	Abnormal safety factor
AWT	Adavanced wind turbine
BEM	Blade element and momentum theory
CFD	Computational fluid dynamics
D3	Delta-3 angle
deg	degree
DLC	Design load case
ECD	Extreme coherent gust with direction change
ECG	Extreme coherent gust
EDC	Extreme direction change
Edition 2, ed2	IEC 61400-1 Edition 2
Edition 3, ed3	IEC 61400-1 Edition 3
EOG	Extreme operating gust
Estop	Emergency shut down
ETM	Extreme turbulent model
EWM	Extreme wind model
EWS	Extreme wind shear model
FAST	Fatigue, Aerodynamics, Structures and Turbulence
hor	Horizontal
HSS	High-speed shaft
IEC	International Electrotechnical Comission
LSS	Low-speed shaft
max	Maximum

min	Minimum
N	Normal safety factor
neg	Negative
NREL	National Renewable Energy Laboratory
Nstop	Normal shut down
NTM	Normal turbulence model
NWP	Normal wind profile model
pos	Positive
ra	Rotor azimuth
SCD	Super compact drive
SF	Safety factor
T	Transport safety factor
TI	Turbulence intensity
TSR	tip-speed-ratio
ver	Vertical
WTGS	Wind turbine generator system
yaw, y	Yaw misalignment
ZOFF	Two bladed offshore wind turbines

Symbols

Symbol	Description	Unit
a	Axial flow induction factor	$[-]$
a	Slope parameter	$[-]$
a'	Tangential flow induction factor	$[-]$
k	Skewness parameters	$[-]$
k	Component index (longitudinal, lateral, vertical)	$[-]$
m	Parameter for equivalent loads (4)	$[-]$
n	Number of cycles	$[-]$
n	Rotational speed	$[s^{-1}]$
n_{ref}	Reference number of cycles (10^7)	$[-]$
r	Radius	$[m]$
δr	Radial size of blade element	$[m]$
s	Scale parameters	$[-]$
t	Time	$[s]$
Δt	Time difference	$[s]$
u	Location parameter	$[-]$
v_{add}	Additional wind speed caused by EWS	$[m/s]$
v_{ave}	Annual average wind speed	$[m/s]$
v_{cg}	Size of coherent gust	$[m/s]$
v_{eN}	Extreme steady wind speed (N-year)	$[m/s]$
v_{gust}	Amplitude of wind gust	$[m/s]$
v_{hor}	Horizontal component of wind speed	$[m/s]$
v_{hub}	Wind speed at hub height	$[m/s]$
v_{in}	Cut-in wind speed	$[m/s]$
v_N	Extreme turbulent wind speed (N-year)	$[m/s]$
v_{out}	Cut-out wind speed	$[m/s]$
v_r	Rated wind speed	$[m/s]$
v_{ref}	Reference wind speed	$[m/s]$
v_{tot}	Total wind speed	$[m/s]$
x	Percentage change	$[\%]$
x	Relative change	$[-]$
y	Yaw misalignment	$[deg]$
yaw	Yaw misalignment	$[deg]$
z	Height above ground	$[m]$
z_{hub}	Hub height	$[m]$

Symbol	Description	Unit
D	Drag forces	$[N]$
D	Rotor diameter	$[m]$
F	Force	$[N]$
$F(x)$	Cumulative distribution function	$[-]$
H	Coherency decay constant	$[-]$
I	Moment of inertia	$[kg\,m^2]$
I_{15}	Characteristic turbulence intensity at $15\frac{m}{s}$ (Edition 2)	[%]
I_{ref}	Expected turbulence intensity at $15\frac{m}{s}$ (Edition 3)	[%]
L	Lift forces	$[N]$
L	Load range	$[-]$
L_c	Coherency scale parameter	$[m]$
L_k	Integral scale (component index k)	$[m]$
M	Moment	$[Nm]$
M_R	Restoring moment of the teeter principle	$[Nm]$
P	Power	$[W]$
P_e	Probability of exceedance	$[-]$
P_R	Probability according to Rayleigh distribution	$[-]$
T	Time, duration	$[s]$
T	Torque	$[Nm]$
TI	Turbulence intensity	[%]
U_d	Wind speed in the rotor disc area	$[m/s]$
U_w	Wind speed in the wake area	$[m/s]$
U_∞	Incoming wind speed	$[m/s]$
W	Resultant relative velocity	$[m/s]$
α	Angle of attack	$[deg]$
α	Flow inclination	$[deg]$
α	Wind shear exponent / power law exponent	$[-]$
β	Blade set angle	$[deg]$
$\Delta\beta$	Pitch angle shift	$[deg]$
γ_F	Safety factor for loads	$[-]$
δ_3	Dela-3 angle	$[deg]$
ζ	Teeter angle	$[deg]$
θ_{cg}	Size of ECD direction change	$[deg]$
θ_e	Size of extreme direction change	$[deg]$
σ_k	Standard deviation of the wind velocity (component index k)	$[-]$
ϕ	Angle of relative velocity	$[deg]$
Λ_1	Turbulence scale parameter	$[m]$
Ω	Rotational speed of the rotor	$[rpm]$

Chapter 1

Introduction

1.1 Motivation

The main challenge of renewable energy systems is to achieve a low cost of energy in order to compete with conventional systems. Looking at the wind energy sector, three bladed turbines have been established successfully for the most onshore areas. Two bladed wind turbines could not match this development due to several onshore requirements. [1]

Two bladed turbines rotate faster and appear more disturbing to the eyes, whereas three bladed wind turbines seem calmer and therefore less disturbing in a landscape. But this disadvantage has no effect for offshore conditions. Due to the increasing number of offshore wind farms and increasing rotor sizes, new concepts for cost-efficient wind harvesting are considered. Therefore the two bladed turbines are brought back to discussion. [1, 2]

On the one hand, two bladed wind turbines are cheaper since they have one blade fewer and just a small decrease in aerodynamic efficiency. But on the other hand the dynamic loads caused by the wind shear and turbulence (figure 1.1) are higher. As a solution, different load reduction concepts are available for two bladed turbines, which can eliminate this disadvantage. [2, 1]

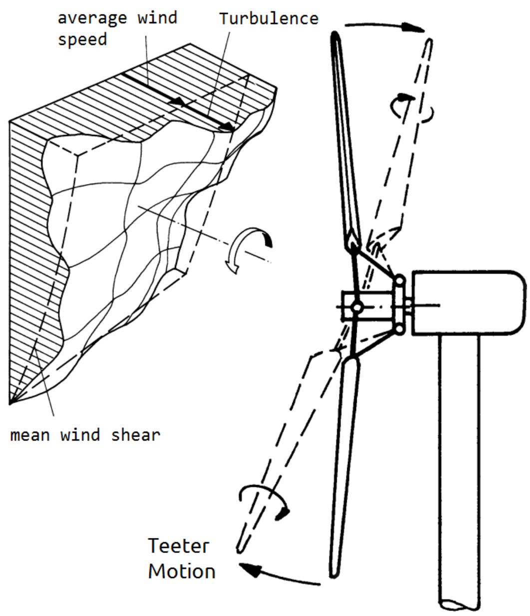


Figure 1.1: Turbulent wind and teeter motion [3, page 215+224 modified]

A well known solution is to attach the rotor or the single rotor blades to a flexible structure with limited pivoting capability (figure 1.1). This can minimize the high bending moments which are the most significant structural loads. This teeter technology is only suitable for two bladed rotors and can have the potential to reduce the loads below any three bladed turbine. [4]

One additional important advantage of offshore applications is the handling of a two bladed rotor during transport and installation. The rotor or even the rotor including the nacelle of a two bladed turbine can be transported fully preassembled and pretested on a ship to a wind farm construction site. The final assemblies can be done on top of a installed tower in a single, time- and cost-saving operation. [4]

So the principal of a two bladed turbine has some encouraging opportunities to reduce the cost of energy. Especially the easy handling is for offshore applications a big advantage. Further development and optimization of efficient turbine concepts should improve these benefits.

1.2 Scope

The scope of this thesis is the load simulation of an existing wind turbine with a rigid hub and a modified teeter hub to reveal the load reduction potential.

The simulation program which is used to calculate the loads and responses of the turbine is Bladed, which is developed by Garrad Hassan. An unvalidated simulation model of the turbine built in Bladed is the starting point of this thesis. As a reference for the model validation the simulation results of the turbine designer are used. These results are validated for the default turbine configuration with a rigid hub.

The goals of this thesis are:

- Explanation of the teeter hub principals by reference to similar concepts of existing turbines.
- Validation of the simulation model and the necessary adaptions to match the simulation results for the turbine with a rigid hub.
- Definition of all design load cases according to IEC61400-1 edition 2 and 3 and a comparison of both editions.
- Evaluation of the resulting extreme and fatigue loads and a comparison between the rigid and teeter hub.

The simulation results are focused on the hub and blade root loads. The loads on the tower, nacelle or single blade sections are not further considered. Other operating conditions are used to verify a correct operating mode.

This thesis will be published in the university library.

1.3 The Research Project

This thesis is part of the research project ZOFF at the University of Applied Sciences Hamburg. ZOFF (Zweiblatt-Offshore-Windenergie) is the abbreviation for two bladed offshore wind energy and works on concepts to reduce the cost of energy for offshore conditions. One main aspect of the ZOFF project is load simulation of two bladed turbines and the consequences on the turbine design, especially with the focus on turbines with a teeter hub. The handling of teeter end impacts appeared to be one of the key points for an efficient teetering concept. [5]

The company aerodyn engineering gmbh is a close partner to this project. It is one of the first companies, which was working on an overall development of wind turbines. The experience of 30 years in the development of complete wind turbines and all of their components is a great benefit for the project. aerodyn provides the information required for the project and data of the existing SCD 3.0 MW wind turbine with a rigid hub. A part of the project is to perform a feasibility study to use the same turbine structure with a teeter hub to minimize the dynamic loads. The turbine belongs to the super compact drive (SCD) series. The rotor bearing, the gear box, the generator and the yaw system are in a single very compact housing. [6]

aerodyn uses aeroFlex for load calculations and turbine development. This program is a result of an in-house customization of the known simulation software FLEX5 which was developed at the Technical University of Denmark by Stig Øye. The simulation data of the default turbine is available for the project and is used for the validation of the Bladed model as a reference.

Chapter 2

Fundamentals

2.1 SCD 3.0 Turbine Info

The SCD 3.0 is the smallest turbine of the SCD series and developed by aerodyn engineering bmbh entirely. It is a two bladed upwind turbine with a rigid hub and a rotor diameter of 100 m. This type is designed for onshore conditions.

Other kinds of the SCD series are two downwind offshore turbines, also with a two bladed rotor and a rated power of 6 and 8 MW. The picture below shows a part of a wind farm in China with four SCD 3.0 turbines.

Figure 2.1: Picture of the SCD 3.0 in a wind farm [6]

The existing hub belongs to the super compact drive series, with a really small hub. The nacelle has nearly the same diameter like the top of the tower and the blade roots. A drawing of the turbine head is shown in figure 2.2.

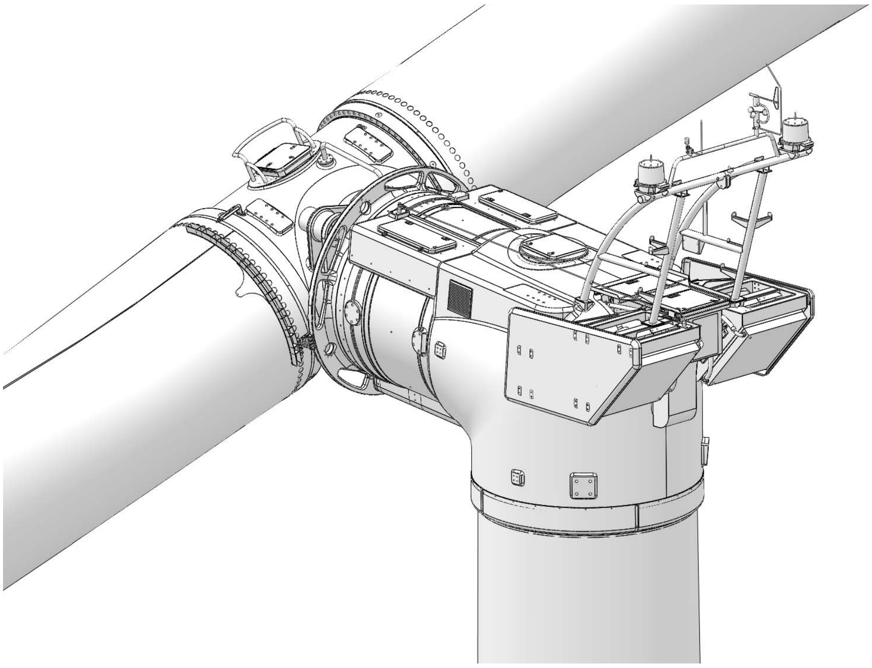


Figure 2.2: Drawing of the turbine head [7]

The wind turbine generator system (WTGS) class and important turbine data is listed in table 2.1. There is already a newer version of the SCD 3.0 with a 110 m rotor diameter released by aerodyn, but this thesis in hand is researching the version with a 100 m rotor diameter.

Table 2.1: SCD 3.0 turbine data [6]

Geometry		**Wind Speeds**	
Type	Horizontal axis	Mean wind speed	8.5 m/s
WTGS class	IIA (TC2A+)	Cut in wind speed*	3 m/s
Rotor	2 blade upwind	Rated wind speed	12.9 m/s
Rotor diameter	100 m	Cut out wind speed	25 m/s
Hub height	85 m	**Diverse Parameter**	
Tilt angle	5 deg	Wind shear gradient	0.2
Drive Train		Mean yaw error	8 deg
Power limitation	Pitch control	Flow inclination	8 deg
Operational mode	Variable speed	Air density	1.225 kg/m^3
Rated power	3 MW	Mean temperature	15 deg C
Rated rotor speed	17.1 rpm	**Generator**	
Converter system	Full converter	Permanent magnet synchronous	

* Cut in wind speed is 4 m/s for the simulations,
because turbulent simulations with 3 m/s don't run stable.

2.2 Teeter Hub Concepts

2.2.1 Teeter Principle

The main purpose of a teeter hub is to mitigate the bending moments in the whole drive train mainly caused by unequal blade loads. The loads are formed by divergent wind conditions on the single blades trough turbulence or wind shear. By allowing the rotor to teeter, the bending moments are not transmitted into the drive train.

While the rotor is rotating a restoring moment M_R, generated by the lateral components of the centrifugal force, is pushing the rotor back into the rotation plane or neutral position (see figure 2.3). This moment is depending on three parameters which are coupled by the following equation. [8, page 271]

$$M_R = I\Omega^2\zeta \tag{2.1}$$

The three parameters have different influences on the restoring moment.

1. **Rotor moment of inertia I:** The moment of inertia also includes the mass of the rotor. A heavy rotor is resulting in a bigger restoring moment.
2. **Rotor speed Ω:** An increasing rotational speed of the rotor is raising the restoring moment with a quadratic ratio.
3. **Teeter angle ζ:** The restoring moment is also linearly dependent on the teeter angle.

A further reduction of the teeter motion can be generated by a rotation of the teeter hinge axis relative to the rotor. So the teeter axis is no longer perpendicular to the blade axes. As a result the blade pitch angles are influenced by the teeter angle. One blade is getting rotated in a positive direction and the other one in a negative direction. The method is called delta-3 coupling. The rotation angle of the hinge is named delta-3 angle (δ_3). The principle is illustrated in figure 2.3. [8, page 271]

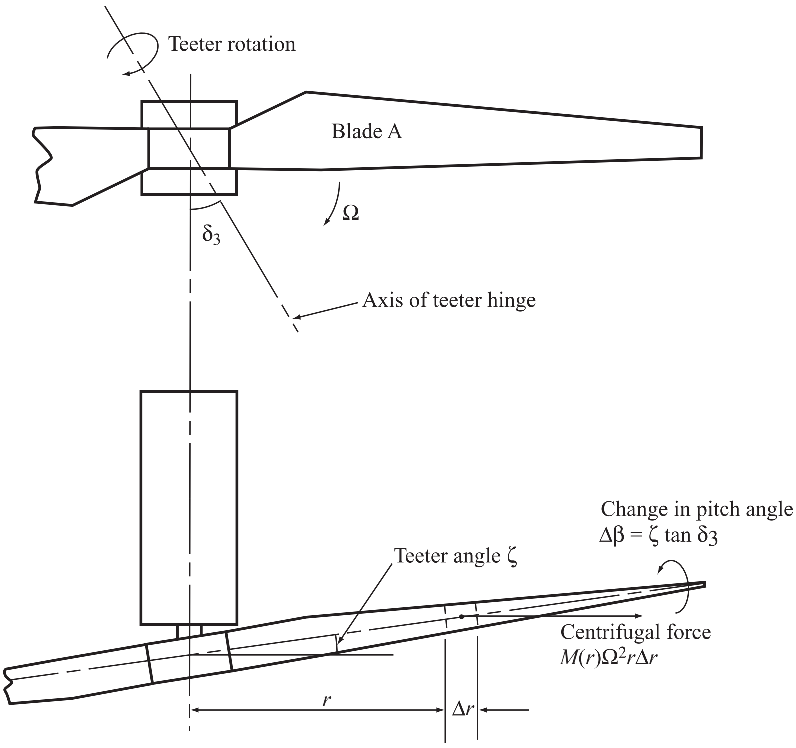


Figure 2.3: Teeter geometry [8, page 272]

The correlation of the produced pitch shift $\Delta\beta$ and the teeter angle ζ is as followed. [8, page 272]

$$\Delta\beta = \zeta \tan \delta_3 \tag{2.2}$$

As an example: if the delta-3 angle is 45 deg the caused pitch shift is matching exactly the teeter angle. A possible teeter angle of 2.5 deg would result in a positive blade shift of 2.5 deg for one blade and a negative blade shift of -2.5 deg for the other blade. The positive pitch angle would reduce the aerodynamic loads on the blade which is charged with a higher load. The total teeter movement would be scaled-down every time the rotor is moving out of it's neutral position. This process would damp the whole teeter movement. [8, page 272]

A coupling of the teeter angle and the pitch angle is a promising method to reduce the teeter movement and also the resulting loads. There are more opportunities to realize this kind of coupling. For instance with a mechanical link built into the hub or an individual pitch control which is managed by the controller.

Describing one possible teeter concept the AWT-26 turbine built by FloWind Corporation is a good and simple example. The development of the advanced wind turbine (AWT) project started in 1990 and was used for extensive testing of power performance, loads, dynamics and noise. The AWT turbines were designed to change there configurations to many different concepts, including a rigid or teeter hub. The AWT-26 is a downwind stall turbine and the concept of teetering can be explained by this research turbine very well. [9]

Considering the cone angle of a downwind turbine (the angle between the blade axis and the rotor plane), the teeter axis has to be located outside the hub center. This is caused by the displacement of the center of gravity of the rotor into the cone direction. If there is a offset between the center of gravity and the teeter axis, the rotor would always drift away from the neutral position. As a result the teeter concept with an external teeter axis can be seen in the following picture.

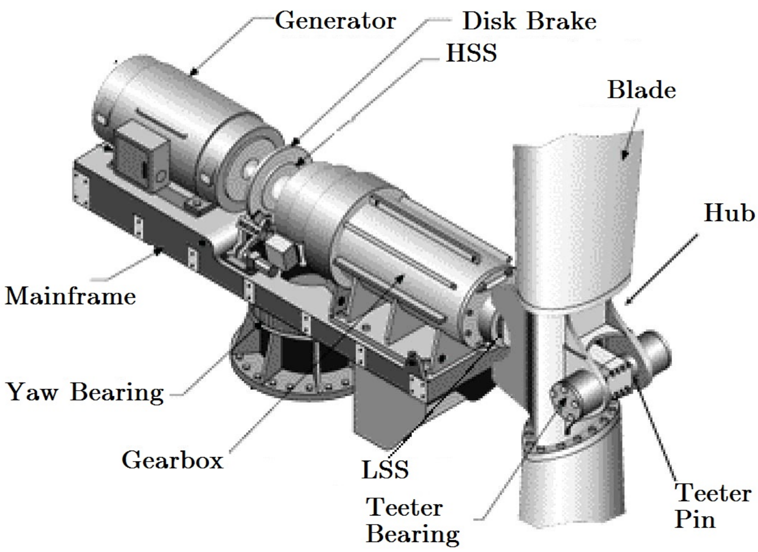


Figure 2.4: Schematic of the AWT-26 hub [10, modified]

To allow the turbine to teeter, the low speed shaft has been extended to reach the center of gravity of the rotor. At the end of the shaft, the teeter bearing is mounted, which allows a free movement around the teeter axis. The whole rotor system is attached by the teeter pin to the shaft.

Limiting the maximal allowable teeter angle, to avoid tower contact with the blades, requires a teeter restraint. The restraint concept of the AWT-26 had been with two teeter damper which were solidly mounted to the hub, with the task to limit extreme teeter angles. During further investigations this concept obtained very intensive end impacts and resultant damper failures. As a further development multiple dampers and other restraint concepts got investigated. [10]

One promising concept was a damper which was supported by a spring and activated trough a sliding motion. The final result construction is shown in the following picture with a cross section of the hub.

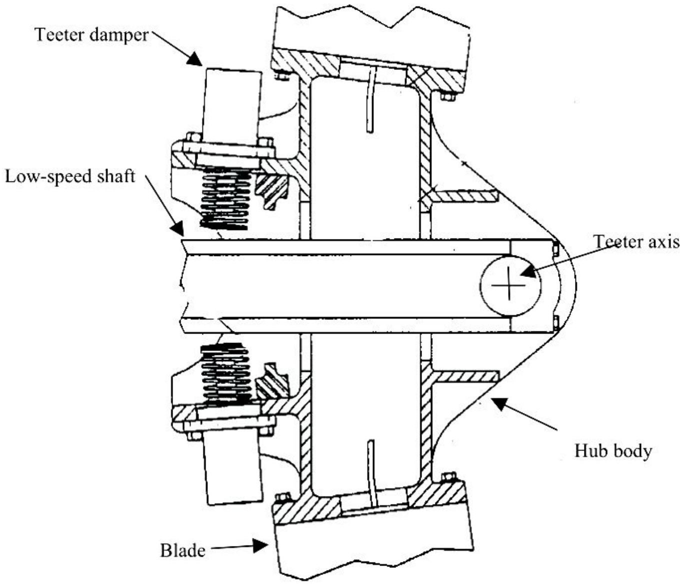


Figure 2.5: Schematic of the AWT-26 teeter restraint [10]

The gap between the low speed shaft and the teeter restraint allows the rotor to teeter absolutely free and without any restraint in a certain range. If the gap gets closed by an exceeding teeter angle, the damper system stops the movement of the rotor. The free teeter range of the AWT turbines could be adjusted up to ±10 deg by changing the position of the damper and thereby the distance between the shaft and the damper.

2.2.2 Current Teeter Concepts

Load reduction is a real important design factor for two bladed turbines and also a driver for the reduction of energy costs. The wide variety of different two bladed turbine concepts shows no best practice in the past and until today. In the 1980s the number of different concepts was based on several research programs to identify possible new options to build wind turbines. A few new two bladed turbines in the 1990s were developed with a rigid hub and had no special load reduction concepts. But newer turbines from 2000 until today showed again a high variety on different concepts. Especially the concept of a teeter hub seems promising. [1]

Looking at actual teeter concepts which are developed after the year 2000 offers a set of three commercial wind turbines built by three different companies. They are in a small power class of 0.5 to 1 MW and are already running in different wind farms. The UK based company Condor Wind Energy Limited is developing a bigger offshore turbine with a teeter hub. A previously announced 5 MW turbine is now replaced by a 6 MW turbine, which is currently under development and will be launched soon [11].

Opposing these turbines to the SCD 3.0 turbine, the main information are listed in table 2.2. A more relevant parameter for teetering would be the rotor mass, but this information is only available for a few turbines, so the total head mass (rotor + nacelle) is included.

Table 2.2: Turbines with a teeter hub after 2000

Turbine	Rated Power	Diameter	Head Mass	Status	Sources
Windflow 500	500 kW	33.2 m	13.7 t	Commercial	[12, 13]
GEV HP 1MW	1 MW	62 m	65 t	Commercial	[14]
Nordic N1000	1 MW	59 m	40 t	Commercial	[15]
Condor 5MW	5 MW	120 m	266 t	Replaced	[4, 11]
Condor 6MW	6 MW	125 m	256 t	Pending	[11]
SCD 3.0	3 MW	100 m	≈108 t	Case Study	[6]

Comparing the data shows that the SCD 3.0 turbine stands between the established small ones and the new developed Condor wind turbine. The head mass of just above 100 t seems relatively small compared to the other turbines, although the increased weight of a possible teeter hub system is not considered yet.

The development of the Condor turbine versions reveals a positive trend. Although the rotor size and the power is increased, the head mass of the 6 MW version could have been reduced about 10 tons.

A comparison of further operating features is listed in the next table. The listed tip-speed-ratios (TSR) which are calculated out of tip-speed and incoming wind speed are determined for rated speed.

Table 2.3: Operating features of the turbines

Turbine	Orientation	Regulation	Rotational Speed	TSR	Tilt Angle
Windflow 500	Upwind	Pitch	≈49 rpm	6.2	n/a
GEV HP 1MW	Upwind	Pitch	23 rpm	5.0	n/a
Nordic N1000	Upwind	Stall	23 rpm	4.4	n/a
Condor 5MW	Upwind	Yawing	20.2 rpm	10.6	7 deg
Condor 6MW	Upwind	Yawing	19.4 rpm	10.2	7 deg
SCD 3.0	Upwind	Pitch	17.1 rpm	6.9	5 deg

As a specific matter of fact, the Condor turbine uses active yawing to control the power. The other turbines use a conventional pitch regulated power control system or in case of the Nordic turbine an active stall principle. Controlling the power by active yawing has the positive effect that there is no need for a complicated pitch system and the hub construction can be focused on the teeter hinge.

Last thing to mention is that the SCD 3.0 turbine hast the lowest rated rotational speed and a medium TSR. The teetering concept benefits a lot of a high rotational speed. A low rotational speed can result in bigger teeter angles during operation and also in intensive end impacts.

The following table provides more information to the teeter concept of the single turbines.

Table 2.4: Teeter information of the turbines

Turbine	Teeter Hinge	Pitch Coupling	Teeter Range	Teeter Lock
Windflow 500	n/a	Mechanical	± 2.2 *deg* (free)	n/a
GEV HP 1MW	Elastic Damper	Delta-3	n/a	n/a
Nordic N1000	Elastomeric Damper	none	± 2 *deg*	n/a
Condor 5MW	Elastomeric	none	$\pm 2 ... 4$ *deg*	yes
Condor 6MW	Elastomeric	none	$\pm 2 ... 4$ *deg*	yes
SCD 3.0	open	open	± 6 *deg* (total)	yes

Two turbines have a pitch-teeter coupling. The small Windflow 500 turbine has a mechanical linked mechanism which shifts the pitch angle corresponding to the teeter angle. The GEV HP 1MW turbine from Vergnet has a built-in delta-3 angle with the same result of a depending shift of the pitch angle.

All known teeter hinges are constructed with a elastomeric bearing. The reason for this is the small permanent movement during operating mode would wear a bearing made of steel tremendous. Teeter ranges of the investigated turbines do not exceed 4 deg. The planned teeter range of the SCD 3.0 turbine with ± 6 deg is the biggest one.

Having a closer look at the GEV HP 1MW turbine reveals another unique feature of a two bladed turbine. The upwind part of the nacelle can be lowered to a service position on the ground without any need of a crane or something similar. As a result, maintenance and blade cleaning can be performed at ground level. This position also grants hurricane protection. A picture of this process can be seen in the following picture.[14]

Figure 2.6: Vergnet lowering system [16]

The delta-3 feature of the Vergnet turbine is shown in the next picture. By rotating the teeter axis in the rotor plane, the teeter movement is linked to a shift of the pitch angle. According to the picture, the delta-3 angle has to be at least 60 deg, because the teeter axis is nearly coaxial with the blade axis. This would create relatively high pitch angle shifts.

Figure 2.7: Vergnet delta-3 hub [16]

Both Condor wind turbines supposed to have the same teeter concept. During normal operation and at a wind speed below rated the teetering movement is limited to about 2 degrees. At higher wind speeds near the cut-out wind speed of 25 $\frac{m}{s}$ the movement increases to its maximum of 4 deg. [11]

The teeter hinge assembly is displayed in the following picture. It consists of a T-shaped low speed shaft with two double elastomeric teeters, which are connected to the hub. In parked conditions the rotor can be locked mechanically, although a teeter lock mechanism cannot be seen on figure 2.8.

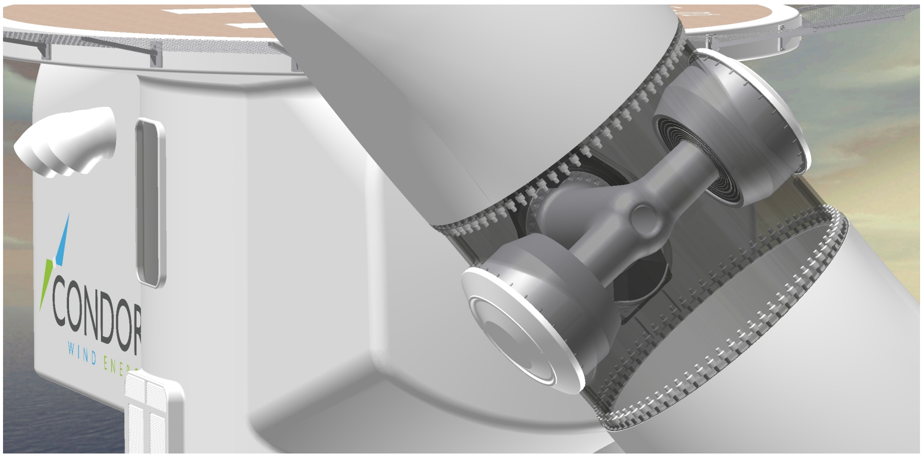


Figure 2.8: Condor teeter hub [11]

A smaller prototype, on which the Condor turbines are based (Gamma 60), had shown a high reduction of the gyroscopic forces with a teeter hub. The Condor 5MW has just 20 % of yaw moments compared to an equivalent three bladed turbine. This reduction makes a power control by active yawing possible. Only two of the three installed yaw drive systems are used to control the turbine and one system provides as system redundancy. [11, 4]

2.3 Simulation Tools

2.3.1 Aeroelastic Simulation Tools

Bladed and aeroFlex belong to the group of aeroelastic simulation tools. There are a lot of other software tools to simulate wind turbines and also some open source projects. But most of them are not validated for a design and certification of wind turbines. One other noteworthy simulation tool is FAST (Fatigue, Aerodynamics, Structures and Turbulence) which is developed and continuously advanced by the U.S. National Renewable Energy Laboratory (NREL). It was evaluated by Germanischer Lloyd and contains many different code packages [17]. However, all the simulation tools are based on similar aeroelastic theories and basic models.

The definition of aeroelasticity is according to Oxford Dictionaries:

> The science of the interaction between aerodynamic forces and non-rigid structures.” [18]

Due to the flexibility of the rotor blades and the tower of a turbine, the interaction of the aerodynamic forces and the resulting deformation of the blades are important. To neglect these interactions would make a realistic load simulation of wind turbines difficult. The combination of structural mechanics and the aerodynamic can be simulated by different methods.

To gain the most exact aerodynamic simulations, the computational fluid dynamics (CFD) would be the best solution. But considering the calculation speed and the efficiency to simulate a lot of different wind conditions for a single turbine, the CFD calculation is far too time-consuming. For a holistic view of a wind turbine and the appearing loads, there are other methods to gain suitable results faster. [2, page 162]

The established model to calculate the rotor aerodynamics is the **combined blade element and momentum theory (BEM)** . This model is based on the simple **actuator disk model**, which treats the rotor as a two-dimensional disk that simply extracts kinetic energy out of the wind. How this works and what happens to the energy is not further considered. The only parameter is the axial flow induction factor a (or inflow factor), which defines the wind speed in the rotor disc area U_d depending on the incoming wind speed U_∞. [8, page 42-43]

$$U_d = (1 - a)\, U_\infty \tag{2.3}$$

The **momentum theory** is dealing with the change of momentum of the air that passes through the disc area. This change is caused by the pressure difference across the actuator disc. As a result of the theory, the wake wind speed U_w can be described by the inflow factor. The wake is the region of the flow, that is downstream of the disc and reduced by speed and static pressure. [8, page 42-44]

$$U_w = (1 - 2a)\, U_\infty \tag{2.4}$$

A further development of the actuator disk model is the **rotor disc theory**, which deals with the extracted energy and how this can be converted into usable energy. One of the main features is the additional wake rotation. The air gets an angular momentum through the reaction torque of the rotor. So in the wake of the rotor disc the air has a velocity component tangential to the rotor plane and in an opposite direction of the rotation. The change of tangential velocity is defined by the tangential flow induction factor a'. Associated to the change of momentum in the wake, this energy is lost for any further energy extraction by the rotor. [8, page 46-47]

As a extension of all these models, the **blade element theory** works with single blade elements. Therefore the rotor disc is divided into span wise elements that are located at the radius r and have the length δr. Each element is assigned to an airfoil with constant two-dimensional aerodynamic characteristics. These resulting ring areas cause an axial and angular momentum to all the air that passes them, based on the rotor disc theory. One element is shown in the following picture. [8, page 59-60]

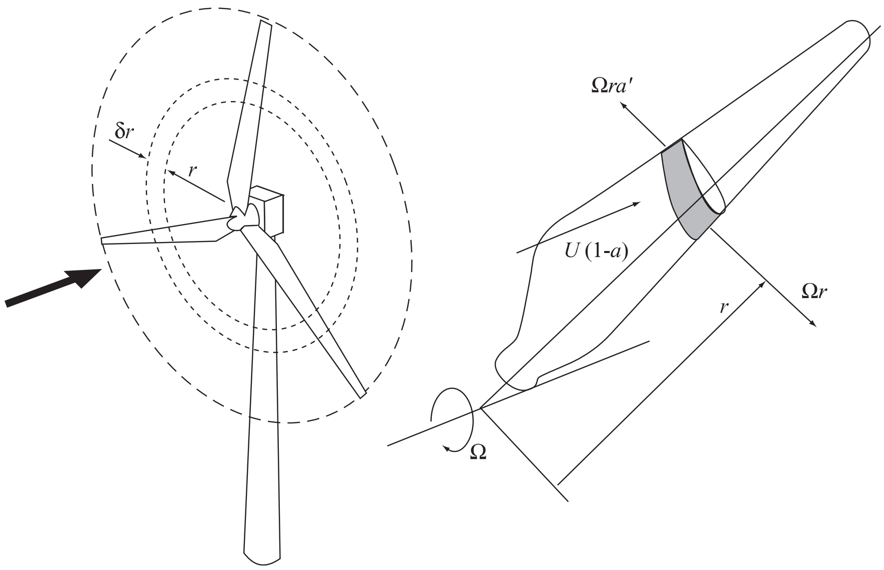


Figure 2.9: Blade element section [8, page 60]

The performance coefficients of an element depend on the airfoil and the angle of attack. The lift and drag coefficients have to be specified for each airfoil and each angle of attack separately.

The velocity components are defined by the wind speed U_∞, the flow factors (a and a') and the rotational speed of the rotor Ω. The resultant relative velocity W at the blade section is the result of the following equation. [8, page 60]

$$W = \sqrt{U_\infty^2 \left(1 - a\right)^2 + \Omega^2 r^2 \left(1 + a'\right)^2} \tag{2.5}$$

The angle of this relative velocity acts at an angle ϕ to the plane of rotation, but the angle of attack α depends also on the blade set angle β. All velocity components and angles are shown in the following figure.

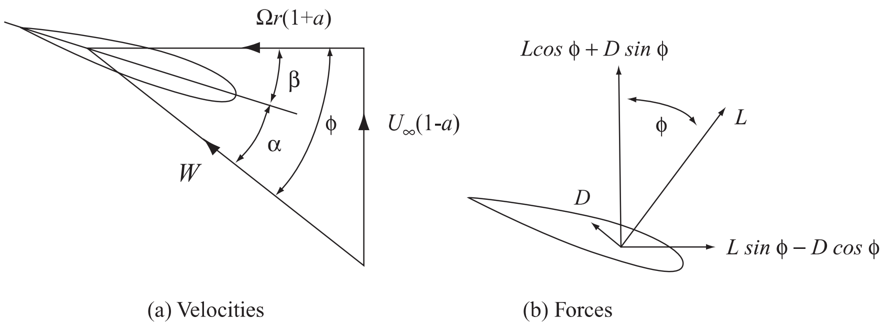


Figure 2.10: Blade element velocities and forces [8, page 61]

With these information (the angle of attack, the velocity speed and the airfoil characteristics) the lift forces L and drag forces D can be determined for each element. The integration of all elements would reveal the total forces of the rotor and the generator torque.

The combination of these simple calculation models is a simple way to determine the resulting forces. As a further improvement the calculation can be extended with empirical parameters. For example simple factors to handle the tip and hub losses. These factors are added to the equations depending on the current wind conditions. [19, page 8]

Structural dynamics, on which the resulting forces have an effect on, can be simulated by two basic approaches. The finite element approach and the modal approach, which are considered as the most reliable methods of dynamic analysis.

The traditional finite element approach is working with rigid bodies that are interconnected. The relative motion between these structural components is coupled to reaction forces with mathematical equations. A basic equation contains a stiffness matrix, a damping matrix and a mass matrix. [2] The simple coupling of two rigid bodies is shown in figure 2.11. Due to the flexibility of several turbine components, this method alone can not produce sufficient results.

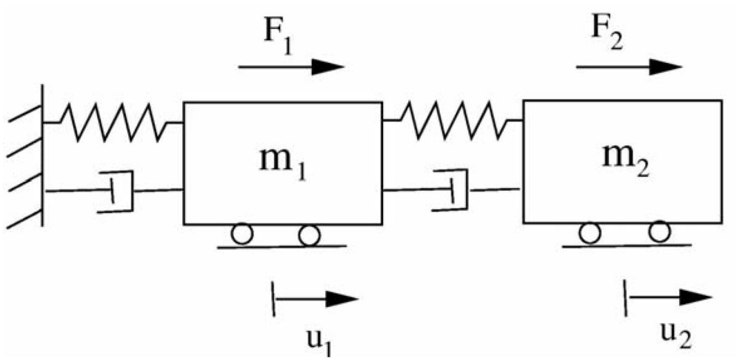


Figure 2.11: Coupled bodies [2]

Wind turbine models involve mostly an additional modal approach to model the flexible components, especially the blades and the tower. The deformation of the flexible bodies is represented by a combination of several pre-calculated mode shape functions, which represent the strains and degrees of freedom of the component. The mode shape functions are calculated by standard linear finite element techniques. Therefore the components are reduced to single linear space beams, with two nodes located at the end and a defined mass and stiffness. [19, page 14-16]

The combination of these models can be called multi-body dynamics approach. The idea of connecting several rigid and dynamic bodies via nodes is displayed in figure 2.12 for a three bladed turbine.

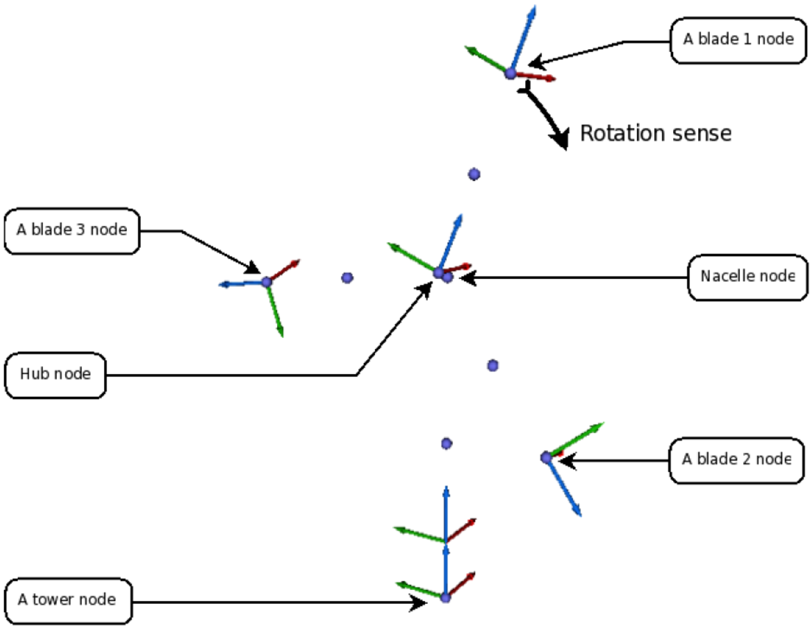


Figure 2.12: Multi-body dynamics nodes [20]

The combination of the BEM to simulate aerodynamic reactions and the two merged structural dynamic models reveals a really efficient way to simulate a full wind turbine. Although there are much more additional models that are involved to achieve sufficient results, the core concept is settled on these methods.

The abstractions which were applied make a fast turbine simulation possible by simultaneously gaining suitable results. More accurate simulations would slow down the whole development process at the present.

2.3.2 Comparing Bladed with aeroFlex

In this section the important differences between Bladed and aeroFlex are described. The focus is on the variations which are important for this thesis.

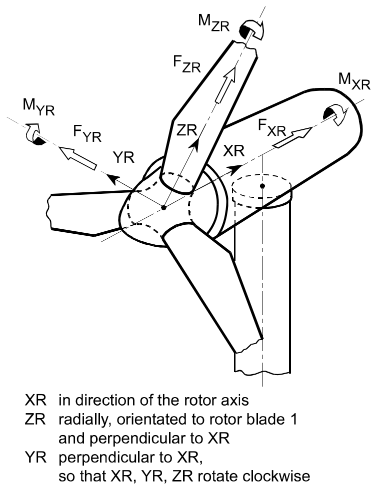
With reference to the applied simulation models, Bladed is working with a combination of the finite element approach and the modal approach, while aeroFlex is using the plain modal approach. The aerodynamic models are both based on the BEM method, with small differences in the further extensions. [19, 7]

Aerodynamic Moment

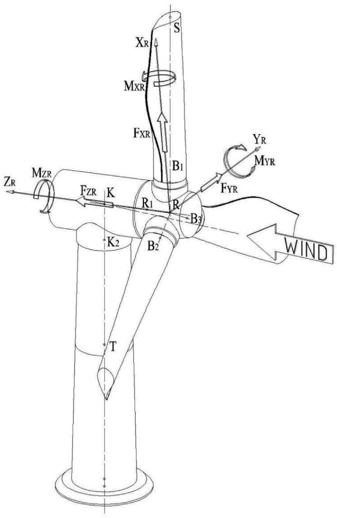
Beside of the lift and drag coefficient Bladed is working with a pitching moment coefficient. These coefficient produces a moment at a fixed point in the airfoil, depending on the wind speed and angle of attack. For the most cases these moment gets opposed by a moment, coming up by the lift forces and the distance to the pitch axis. The resulting moment is nearly zero, to avoid too high pitching forces. These moments are not treated by aeroFlex, which can result in small differences in the pitching forces of the blades.

Coordinate Systems

The two simulation tools work with different coordinate systems. They are shown in the following two pictures.



(a) Bladed [21, page 4.32]



(b) Aeroflex [7]

Figure 2.13: Hub coordinate systems

The shown coordinate systems are related to the hub coordinate systems, but the differences are the same for all used coordinate systems in the turbine. The x- and z-axes are switched and the y-axis is rotated about 180 deg. The differences are listed in the table below.

Table 2.5: Differences in the coordinate systems

Bladed	aeroFlex
x-axis	z-axis
y-axis	- y-axis
z-axis	x-axis

If loads are compared between these two simulation tools, the aeroFlex loads are always converted into the Bladed coordinate system.

In figure 2.14 the blade coordinate system in Bladed is shown. According to the hub coordinate system the aeroFlex coordinate system is rotated again in the same origin. The x- and z-axes are switched and the y-axis is directing in the opposite direction.

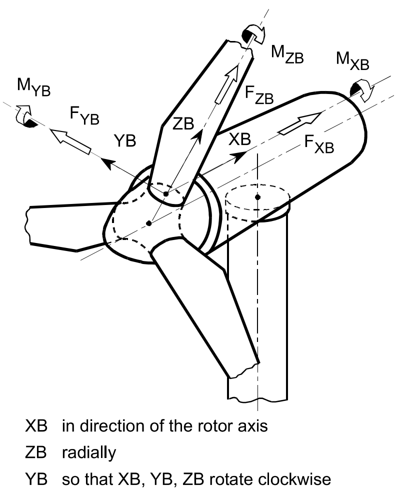


Figure 2.14: Bladed blade coordinate system [21, page 4.31]

Reference Wind Speed

There is a difference in defining the wind speed v_{ref}, which is is the reference wind speed for a simulation. It can be seen in static simulations, where the wind has no variation and just a flow inclination α. In Bladed, this wind speed is the total wind speed v_{tot} and in aeroFlex it is just the horizontal component v_{hor} of the total wind speed.

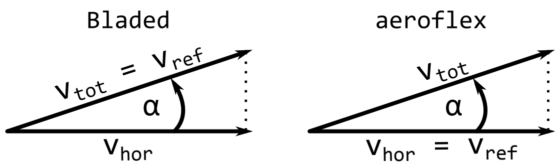


Figure 2.15: Comparison of wind vectors

The relations between these two speed is $\cos\alpha = \frac{v_{hor}}{v_{tot}} = \frac{v_{aeroflex}}{v_{Bladed}}$. Comparing these two simulation tools means, that the regarded wind speeds differ with the factor $\cos\alpha = \cos 8° = 0.99$.

This small difference is attended during the validation between Bladed and aeroFlex. In later simulations and results, this influence is neglected.

Rotor Power

In aeroFlex the rotor power can be displayed for each simulation. In Bladed this value has to be calculated manually.

Using the basic formula for the correlation of power P, torque T and rotational speed n:

$$P = 2\,\pi\,T\,n \tag{2.6}$$

The total torque of the rotor is the sum of the torque on the low-speed shaft (LSS) of the generator T_{LSS} and the mechanical loss torque T_{Loss}.

$$P_{Rotor} = 2\,\pi\,(T_{LSS} + T_{Loss})\,n_{Rotor} \tag{2.7}$$

The resulting power corresponds to the rotor power in aeroFlex.

Speed-Torque Table and Losses

The speed-torque-table is one of the main controller features. It controls the generator torque depending on the actual generator speed. The two simulation tools have a different implementation of this look-up table.

By defining the speed and torque, the current power level is stated. The speed-torque-table controls the power at the section, where the controller is implemented. This point differs in the two simulation tools. The difference is shown in the following figure.

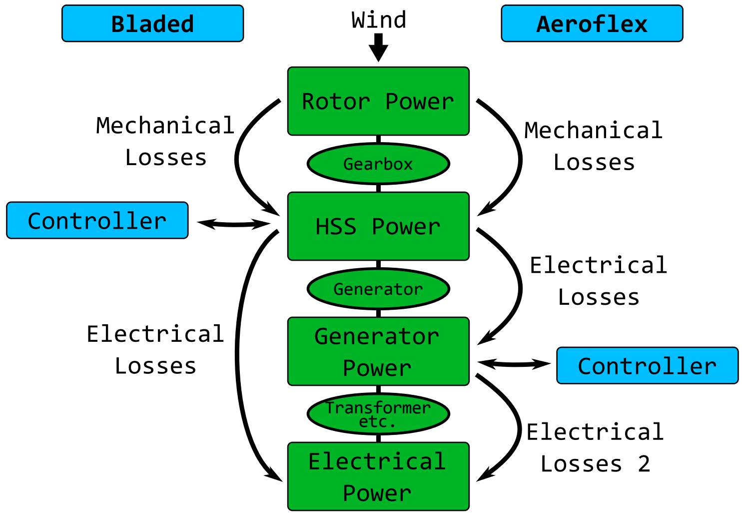


Figure 2.16: Speed-torque table implementation

- The Bladed speed-torque-table is connected to the high-speed shaft (HSS) power. This power is only decreased by the mechanical losses referred to the rotor power.
- The aeroFlex controller is setting the torque of the generator, which is decreased additionally by the electrical losses in the generator. So this power level is lower than on the HSS.

An additional difference is that Aeroflex has two different steps for the electrical losses, while Bladed has one step for electrical losses. To avoid multiple different power levels, the comparison between these two simulation tools is reduced to the rotor power and resulting rotor speed curves. The electrical power and the annual energy yield will not be evaluated as a consequence.

2.4 IEC Guideline 61400-1

The International Electrotechnical Comission (IEC) has published a list of standardization guidelines for wind turbines. They are listed under IEC 61400 with the general title “Wind turbines generator systems”. These standards are the theoretical groundwork for the development of wind turbines all over the world and other guidelines and standards are based on them[3, page 193]. One part of this work in hand is to compare the two newest versions of the the first part, called IEC 61400-1.

1. IEC 61400-1 Edition 2 from 1999 [22]
2. IEC 61400-1 Edition 3 from 2005 [23]

In this thesis they are called IEC Edition 2 and 3 subsequently.

The purpose of the part 1 is to outline a minimum of design requirements for wind turbines. The procedure and the arguments can be modified, if the safety of the wind turbine system is not compromised. So the usage of the guideline is really site and turbine specific.

A big part of the requirements treat the generation of different design situations, to predict all possible loads, that can occur in the turbine life time. Therefore a range of normal and extreme external conditions are defined, where the main focus lies on the definition of wind conditions. Other external conditions like salinity, lightning and earthquakes can be added if they can be expected for the turbine.

These external conditions are combined with design situations to different design load cases (DLC). A DLC can be for example the normal power production or the start up and shut down of the turbine. These design load cases have to be arranged and simulated for each turbine individually. Possible fault situations can be excluded, for example if the turbine manufacturer can prove a redundant safety system.

Changes in Edition 3

The title of the guidelines was changed from "Safety requirements" in the second edition to "Design requirements" in the third edition. This should reflect, that the focus is on a safe design rather than requirements for safety of personal.

A lot of requirements were simplified to reduce the variety of opportunities. For example the gust models are reduced from a 50- and 1-year gust to one remaining gust and the partial safety factors and the requirements for the control and protection system have been adjusted.

But the most important changes are the expansion of the turbulence models and the extreme load extrapolation. These significant renewals are discussed in the following.

While the second edition was working with more steady wind conditions based on the normal wind profile model (NWP), the third edition requires more turbulent wind conditions for the load cases.

As an additional extension a new turbulence model was added, which is called extreme turbulent model (ETM). It is working like the normal turbulence model (NTM) but with a much higher turbulence intensity. A higher turbulence intensity results a more intense variation of wind speed and this will produce high extreme loads. The differences between the both turbulence models depending on the wind speed on hub height is shown in the following diagram.

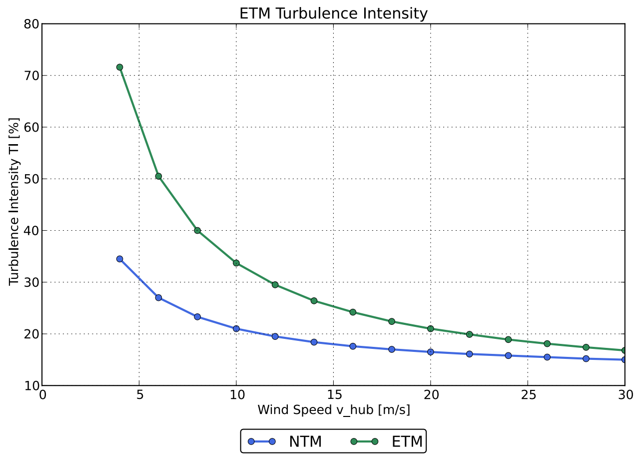


Figure 2.17: Comparison of the NTM and ETM

The rearrangement of the DLC is based on changing some wind models to the NTM and adding the ETM. Changes of the single DLC groups are:

- **DLC1.x Power Production:** Six load cases from the second edition which were simulated with the NWP got reduced to two remaining cases. In addition the ETM is applied to simulate up to cut-out wind speed.
- **DLC2.x Power Production with fault:** Fault situations of the control and protection systems are now simulated with the NTM, which was previously simulated with the NWP in the second edition.
- **DLC3.x and DLC4.x:** The setup of the NWP didn't change for the start up and the normal shut down situations. Just the parameters for the condition changes (e.g. gust) are calculated with different parameters. The sizes of the gust models in edition 3 are also reduced in general. A comparison is made in appendix A.
- **DLC5.x Emergency Shut Down:** Simulations of a emergency shut down are now changed from NWP to the NTM.
- **DLC6.x and DLC7.x:** Parked and idling situations are mainly simulated with high wind speeds, according to the extreme wind model (EWM). The second edition was working with just a steady EWM model, where the third edition has now a steady and a turbulent EWM model.

Most striking is the changing to the NTM for extreme situations (Fault situations, emergency stop and extreme wind for parked situations). Turbulent wind is always a random result of a calculation and can have a big influence on the resulting loads. A advice to handle these problem is not included in the guideline. Best practice would be a simulation of each load case with multiple wind files, but this would multiply the simulation effort.

One other major expansion of the third edition is the statistical extrapolation of extreme loads and events. The attempt is to find long term extreme loads by a set of short time simulations. Due to the turbulence issue, that random wind produces random loads, the extreme loads with a 50-year recurrence period is hard to detect. In the past, the safety factors were used to cover these loads. More information and how this extrapolation should work can be found in section 2.6 on page 28.

In conclusion, the third IEC edition is more lean and modern than the second edition. The increased simulation effort for turbulent wind conditions and statistical extrapolation methods can be absorbed by newer computing power. The turbulent and extreme turbulent simulations will gain more realistic loads, than steady simulations with simple transient changes in wind conditions.

2.5 Fatigue Loads and Rainflow Counting

Determining the lifetime fatigue loads is an important design consideration for a wind turbine. Fatigue loads depend on the occurring load cycles during the lifetime of a turbine mainly. Therefore the expected amount and size of all appearing load cycles has to be determined.

As a first step, the expected distribution of different wind conditions and operating conditions has to be scheduled. A set of load cases is proposed by the IEC guidelines. The following situations belong to this set:

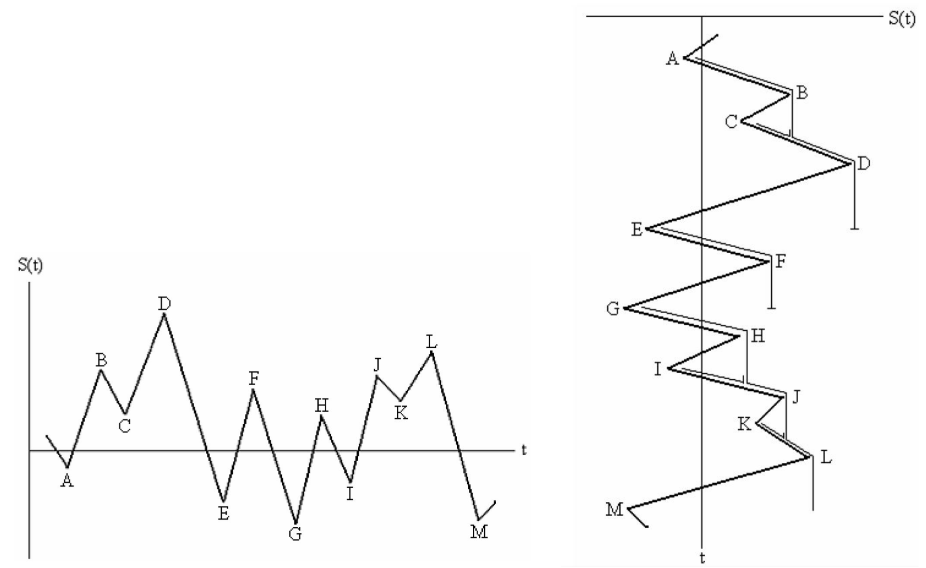
- Normal power production
- Power production with possible faults
- Start up
- Normal shut down
- Parked

All this cases together will cover most of the situations, that will occur in a lifetime of a turbine. According to the WTGS class of the turbine and site specific conditions, these load cases are simulated for different wind speeds. The Rayleigh distribution is used to define the expected time period of each wind speed.

With this information and the simulation results, the appearing load cycles can be counted in each time series and then extrapolated to the total lifetime.

The counting of load cycles can be done by different counting methods, but the rainflow counting is the most established method in wind turbine simulation. [24]

Therefore, the load time series have to be fragmented into single load hystereses. This is done by rotating the time axis in a vertical position and the load curve can be seen as a pagoda roof (the original name of the method was “Pagoda Roof Method”). Water drops are released at each extreme load and running down the roof. The procedure is shown in the figures below.



(a) Simulated time series [24, page 18]

(b) Rainflow counting procedure [24, page 19]

Figure 2.18: Rainflow counting method

After sorting and merging related downfalls, a set of different hystereses can be created. Dividing them into different groups of cycle ranges makes a counting possible. The result is a load histogram, which shows how many cycles of a specific cycle range is contained in the analyzed time series.

With the information of how often a specific time series is contained in the total life time of a turbine, the number of cycles get multiplied by a corresponding factor. The final combining of all load cases and cycles contains the total fatigue load.

For the consideration of the final fatigue loads, these histograms are converted to a load spectrum. These load spectrum will provide the cumulative cycle number of how often a specific load value is exceeded during lifetime. An example for two different load spectra is shown in the following figure.

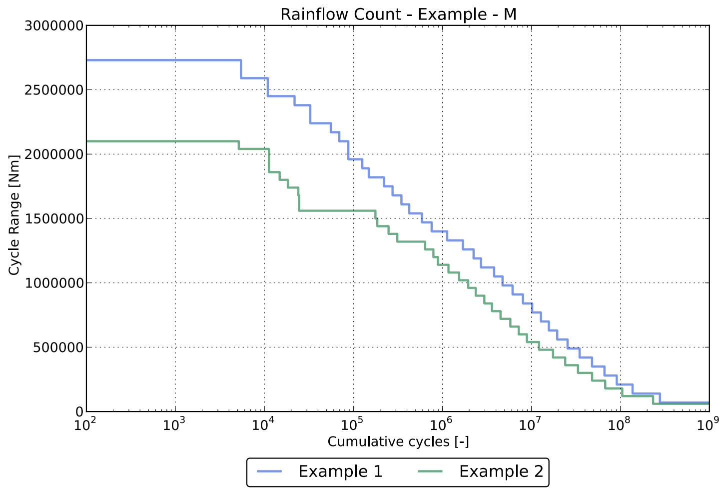


Figure 2.19: Cumulative loads cycles by exceedance

The resulting load spectra have different appearances. To make a comparison more simple, they can be converted into a damage equivalent load. Therefore each step i of the load spectrum is considered with his number of cycles n_i and his load range L_i. As a result of the following formula, the load spectrum has only one equivalent load $L_{Equivalent}$ left for a specific number of cycles n_{ref} [19, p. 105].

$$L_{Eqivalent} = \left[\frac{\sum (n_i \, L_i^m)}{n_{ref}} \right]^{1/m} \tag{2.8}$$

Especially the parameter m is depending on the material and geometry of the considered components. The parameters m and n_{ref} are therefore adopted from the designer of the turbine, to guarantee comparable results.

$m = 4$

$n_{ref} = 10^7$

For the first example in figure 2.19 the damage equivalent loads are shown in the following figure. Each load spectrum is reduced to one load step with a fixed cycle number of n_{ref} and a corresponding cycle range. In all later diagrams, the dashed lines are missed out and just the corner points and the info box will be shown.

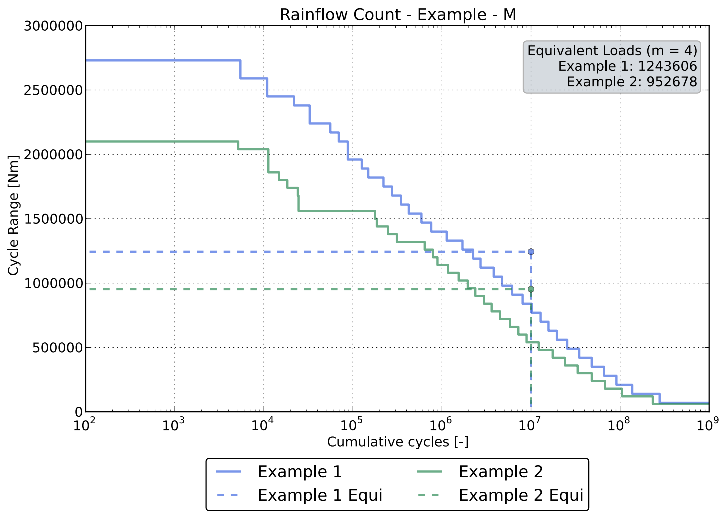


Figure 2.20: Damage equivalent loads

2.6 Statistical Extrapolation

One major renewal in the third edition of the IEC guideline is the statistical extrapolation of loads. It takes the results of the DLC1.1 simulations as a statistical basis, to predict the extreme loads for a specific time period. This new procedure is based on statistical methods mainly. [23, page 78-80]

Considering that the simulated wind files are created by a random process and cover a time period of 10 minutes, the detection of a 50-year extreme load seems impossible. The extrapolation method is assuming that the extreme loads occur at widely separated times and are statistically independent. As a result the simulated load maximums can be fitted to a probability distribution function. The long term exceedance probability will be able to be extrapolated for different time intervals.

To extract extreme values of the simulated loads, the guideline advises to select the largest value between successive upcrossings of the mean plus 1.4 times the standard deviation of the load process. The number and size of these extreme events can be counted, so that a probability for the exceedance of a specific load can be calculated. Based on all included simulations, a statistical distribution can be fit to these extreme events.

It is important to provide a sufficient number of simulation data over the range of significant wind conditions. There are different recommendations of how many simulation data is needed for each bin.

- IEC Guideline (version 2005): “A minimum of 300 min of time series data distributed over the range of significant wind conditions is recommended.” [23, page 79]

- Bladed User Manual: “It is recommended that for a satisfactory distribution fitting, at least 50 simulations are carried out for each external conditions bin. For onshore calculations each simulation is usually 10 minutes long, ...” [25, page 139]
- Bladed Theory Manual: “As a minimum the IEC 61400-1 Edition 3 standard states that 15 simulations are necessary for each wind speed bin from (Vrated – 2m/s) to cut out and six simulations are necessary for each wind speed bin below (Vrated – 2m/s) ...” [19, page 109]

Because there is no specific number of necessary simulation time, the single results have to be checked for plausibility. A built-in verification method is implemented in Bladed, but further checks are recommended.

In Bladed there are two probability functions implemented for the fitting of the extreme data. According to the Bladed theory manual [19, page 108-110] the (2-parameter) Gumbel distribution and the 3-parameter Weibull distribution are the most applicable distributions to wind turbine loading. The following equations are the cumulative distribution function form of them.

Gumbel:

$$F(x) = e^{-e^{-\left(\frac{x-u}{s}\right)}} \tag{2.9}$$

3-parameter Weibull:

$$F(x) = 1 - e^{-\left(\frac{x-u}{s}\right)^k} \tag{2.10}$$

The parameters are:

u = location parameter

s = scale parameter

k = skewness parameter

Because of the additional parameter on the 3-parameterWeibull function, this distribution is more flexible for fitting. But for some distributions, the Gumbel function fits better. This depends on the shape of the simulated distribution curve. This has to be decided case-by-case by comparing the resulting curves.

To find the set of these parameters the method of least squares is used. This method tries to minimize the sum of the squares of the errors between the simulated data and the probability function. These errors can be influenced by different weighting factors. This should ensure, that enough contribution is given to the greatest extreme loads. The default weighting factors used in Bladed are displayed in the following table. The observed maximums a sorted by size and divided into groups. The biggest 5 percent of the maximums are weighted the most.

Table 2.6: Weighting factors for the method of least squares [25]

Range of Maximums	Weighting Factor
0 to 80 %	0.01
80 to 95 %	1
95 to 100 %	10

After finding the best distribution function depending on the weighting factors the resulting tail of the function is used to extrapolate the loads. The following figure shows how the 50-year extreme load F_{50} is determined from the computed long-term exceedance probability for four different fitting methods.

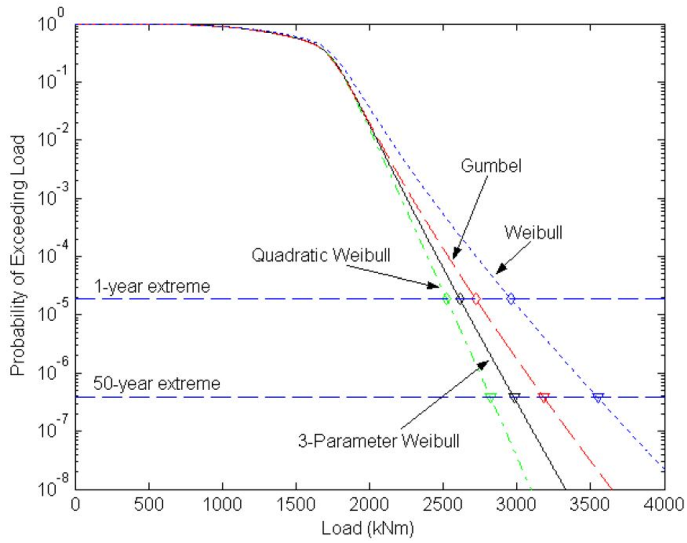


Figure 2.21: Example for an exceedance probability function [26, page 15]

The extrapolated loads are detected by their corresponding exceedance probability. Both of the fitting methods implemented in Bladed reveal medium loads compared to the other fitting methods.

The exceedance probability is $P_e(F_{50}) = 3.8 \cdot 10^{-7}$ for a 50-year recurrence period and a reference period of 10 min. This value is the inverse of the amount of 10 minute intervals in 50 years (or simple $\frac{10min}{50a}$). According to this, the exceedance probability for a 1-year recurrence period is $P_e(F_1) = 1.9 \cdot 10^{-5}$. With this probability value, the loads can be taken out of the diagram graphically. These two exceedance probabilities are demanded by the IEC guideline.

The extrapolation is a challenge and requires significant effort to result in realistic and trustworthy results. In a case study of four state-of-the-art multi-megawatt turbines with different configurations some conclusions were drawn. Some of them are listed below. [27]

- Comparing different fitting methods the log-normal and 3-parameter Weibull functions provide the most reliable results. Other fitting methods like general extreme value and Gumbel may lead to too conservative results.
- Trying to introduce non-linearity to the data distribution with the purpose of tail fitting did not result in improved fits. This can lead to arbitrary loads.
- To achieve realistic and reliable results, a significantly increased amount of simulation time and pre-/post-processing is required. The quality of the results has to be evaluated by visual inspection.
- Even though the extrapolation method is mathematically correct, the variability and interpretability of the results require a wide range of further analysis for any application case.

Based on these conclusions one final recommendation was made. The difficult execution of the load extrapolation should be replaced by other simplified methods. Two possibilities also based on the DLC 1.1 results were tested. A scaling factor on the characteristic loads or a multiplier on the standard deviation can be used to determine the 50-year extreme loads. Although there was no clear tendencies of the factors and multipliers found in this paper, this approaches might be a more practical way to calculate extreme loads. [27]

Chapter 3

Simulation Model

3.1 Control Scheme

External Controller

The external controller has been received from the turbine designer via an external dll file. It should replace all Bladed internal control functions, so the behavior of the turbine is exactly the same as in aeroFlex. During the integration to Bladed some problems occurred, because there are differences in the interpretation of such a dll file between the two simulation tools. Unfortunately, not all functions could get to run.

The normal power production is working fine with this external controller. But other control situations don't perform very well with it (e.g. start up, shut down and fault situations). So these cases had been implemented by the Bladed internal controller with some losses in accuracy. But the missing controller functions would have optimized the different control situations and ignoring these functions would not result in lower loads. So the results of the simulations wont be scaled down by this issue.

Start Up Logic

The start up simulations start from a parked position with no rotor speed and the blades are pitched from 90 degrees down to the final pitch angle. The final pitch angle depends on the applied wind speed and will be defined in the load case description for each wind speed separately.

After reaching this final angle and a certain rotor speed, the external controller takes over control. The moment to put the generator on line, is the first point of the speed-torque table, that produces energy.

The implemented Bladed parameter for the internal controller are listed in table 3.1.

Table 3.1: Parameter for start up simulations

Parameter	Value	Unit
Initial Rotor Speed	0	rpm
Initial Pitch Angle	90	deg
Initial Pitch Rate	-5	deg/s
Generator Speed to put on Line	270	rpm
Final Pitch Angle	0...25	deg

Stop Logic

There are two different types of stops defined in the IEC guideline. The normal and the emergency stop. Both stops do have the same behavior. After triggering the stop, the turbine begins to pitch aiming at 90 degrees. After reaching a lower limit of rotor speed, the shaft brake gets initiated. The two modes just differ in the pitch rate and the cut in moment of the shaft brake (table 3.2).

At the beginning of the stop, the generator gets cut off the grid and stops producing power (like a grid loss). This is correct for an emergency stop, but should be prevented at a normal stop, because of the increasing rotor speed. After talking to the Bladed Support, there are no internal options for this problem. Just a working external controller could solve this problem. An improvised method was applied, by triggering the safety system after a certain time. This will activate a pitch action, where the blades pitch with a defined pitch rate aiming at 90 deg. In this case, the generator moment follows the speed-torque table, until the rotor speed is too low for power production.

Another missing option is the final rotor azimuth angle. The rotor should be parked in a horizontally position, to avoid high loads caused by wind shear. This position can't be guaranteed by the Bladed internal controller and is not further considered.

Table 3.2: Stop logic parameters

		Normal Stop	Emergency Stop
Pitch Rate	[deg/s]	1	5
Final Pitch	[deg]	90	90
Cut in of Shaft Brake	[rpm]	1	6

Idling and Parked Conditions

The idling will not be applied by Aerodyn for this turbine to achieve a hurricane-proof operating mode. So this mode will not be further handled and simulated.

The parked conditions are defined with a pitch angle of 90 degrees. The parked rotor azimuth angle should be, like for all two bladed wind turbines, 90 degrees. This will make sure, that the rotor is horizontally locked and the wind shear over height has no effect on it. The yaw angle will be 270 degrees from north (depending on wind direction) in normal parked conditions. All parameters are listed in table 3.3.

Table 3.3: Parked parameters

		Parked
Pitch angle	[deg]	90
Rotor Azimuth	[deg]	90
Yaw angle	[deg]	270

Shaft Brake Characteristic

The shaft brake is mounted on the high speed shaft. It is working with hydraulic valves, so there is a maximum delay time of 0.5 seconds until the brake acts. It reaches the maximum braking torque of 59 kNm after an additional time of 0.4 seconds. The characteristic curve of the brake torque is described by the following formula.

$$T_{Brake}\left(t\right) = T_{max} - T_{max}\left(1 + \frac{t}{T}\right)e^{-\frac{t}{T}} \tag{3.1}$$

The time constant T was adjusted to 0.03 seconds, in order to reach the maximum after the defined limit. The resulting time-torque curve which was implemented in Bladed is seen in figure 3.1.

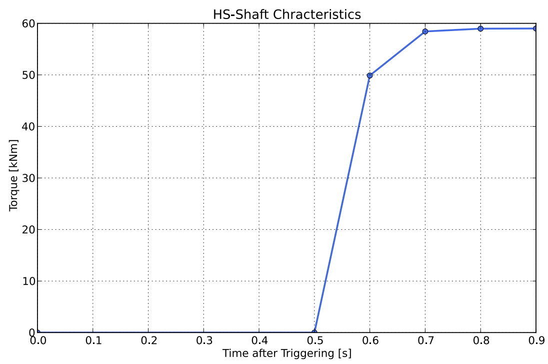


Figure 3.1: Shaft brake characteristics

Safety and Control System

The safety system takes care about different fault situations and monitors the safety relevant turbine parameter. If any value exceeds the allowable ranges, the turbine shuts down automatically.

In the case of a grid loss, a brake chopper is used to consume the energy produced by the generator for a short amount of time, which is fed into the grid usually. So the generator torque stays alive for a short moment which allows the turbine to initiate to shut down progress. This prevents the rotor from overspeed. But this feature isn't realized in the simulation model. During a grid loss, the generator torque is dropping to zero immediately.

While simulations with no defined faults, the safety systems is deactivated. In real conditions it is always activated, but while the simulations an unwanted shut down should be prevented. In the case of a fault, the setting of the safety system is described in the design load cases description in the appendix. In some cases, a stop is triggered manually by setting the stop time, because not all fault situations can be handled by the internal controller system.

3.2 Validation with aeroFlex

3.2.1 General Procedure

To validate the simulation model which was created in Bladed the simulation results in aeroFlex were taken as a basis. Measured data was not available for a further validation.

During the validation progress, the Bladed model was modified to achieve the same loads and operating parameters like the model in aeroFlex. The main focus was put on the hub and blade loads.

In the following sections the validation steps are described by means of the final model, which was the resulting output of the complete validation process.

3.2.2 Modal Analysis

As a first check the modal analysis can be taken to ensure a corresponding structural erection of the model. The blade and tower preferences are the most important parts of the simulation model. If the modal frequencies are different between the model in Bladed and aeroFlex, further simulations are pointless.

Comparing the first two modal frequencies of the tower and the blades is sufficient to obtain certainty. They are listed in the next table.

Table 3.4: First modal frequencies

	Modal frequencies [Hz]	
Tower	aeroFlex	Bladed
1. Tower	0.333	0.333
2. Tower	1.803	1.813
Blade	aeroFlex	Bladed
1. Flap wise	0.86	0.89
2. Flap wise	2.48	2.54
1. Edge wise	1.30	1.31
2. Edge wise	4.34	4.41

The minor differences in the frequencies point out a matching structural simulation model of the tower and the blades. Further validation steps can be concentrated on the aerodynamic responses of the model.

3.2.3 Steady Simulations

Comparing two simulation models should begin with a simple load case. In this case, it is a steady wind, with no yaw misalignment and no change in wind speed.

The selection of the magnitude of the wind speed is related to the wind speeds which are recommended by the IEC guideline. Two wind speeds which cover most of the relevant load situations are specified below.

- $0.8\,v_r$ is below rated and will provide a permanent pitch angle of 0 deg. This would ensure a matching pitch angle in both models.
- $1.2\,v_r$ is above rated. This would reveal the rated rotational speed and a possible pitch angle difference if the simulation models.

According to differences in the reference wind speed, the applied wind speeds in aeroFlex are increased and adjusted in Bladed.

This steady simulation is done with all influences listed below.

- Steady wind (no variation in wind speed)
- Wind shear $\alpha = 0.2$
- Flow inclination $\alpha = 8\,deg$
- Mass and pitch imbalances

The relevant control variables that are important to check are listed in table 3.5. Only the mean values are listed. The deviation of the Bladed values are below 1 percent, except the pitch angle shows a small difference.

Table 3.5: Basic results for validation

Value	Unit	Aeroflex	Bladed	Aeroflex	Bladed
Wind speed	m/s	10.32	10.42	15.48	15.63
Rotor speed	rpm	16.87	16.85	17.1	17.1
Generator speed	rpm	402.7	402.3	408.2	408.2
Rotor Power	kW	2199	2178	3523	3514
Pitch Angle	deg	0	0	8.2	8.0

For the comparison of the resulting loads, a sample of the hub My load is shown below. The other load components have a similar appearance.

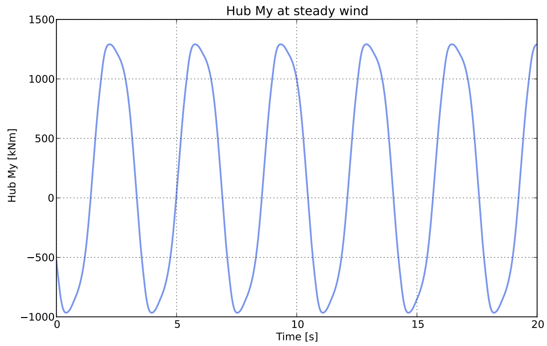


Figure 3.2: Example of steady wind load response

These time series are reduced to the maximum and minimum values to make a comparison easier between the two simulation models. Also the aeroFlex loads were converted into the Bladed coordinate system to obtain uniform terms.

The values in the following tables are calculated by the following formula, which returns the deviation of the Bladed results compared to the Aeroflex results in percent.

$$x = 100 \left(\frac{x_{Bladed}}{x_{aeroflex}} - 1 \right) \tag{3.2}$$

Table 3.6: Comparison of hub loads for steady wind conditions

Wind Speed	0.8 v_r		1.2 v_r	
Load	**Min [%]**	**Max [%]**	**Min [%]**	**Max [%]**
Mx	-5.5	-0.3	-2.7	0.0
My	128.6	36.9	43.0	34.8
Mz	-4.7	-6.0	-4.7	-3.9
Fx	-4.6	-4.5	-4.8	-5.3
Fy	2.2	2.3	2.6	2.2
Fz	4.9	-1.3	4.8	-1.4

There is a huge difference for the hub My moment. All other loads have a deviation of 6 or less percent which would be a really good match.

The different hub My loads in Bladed and aeroFlex were treated by a lot of researches and couldn't get solved. The fact, that all other values match very well is strange. Here is a short list of actions that were done, to solve this problem.

- Deactivated a range of influences (mass and pitch imbalances, flow inclination, tower shadow, stall hysteresis model) and varied the wind exponent, because this is the main source of loads for the hub My.
- For small wind exponents, the loads match better, but the hub My is getting very low. For higher wind exponents, the hub My differs more.

- Assuming a different implementation of the wind shear model, the three wind components over the rotor area were compared. The differences in the definition of the reference wind speed led to this conclusion (**??**). But the components had no big differences, what would explain the high deviations.
- Differences in the origin of the coordinate systems couldn't get eliminated totally, but the R1-system in aeroFlex and the rotating-hub system in Bladed should be located in the intersection of the blade pitch axis.
- Because the hub loads are created out of the blade loads, the loads on the blade roots were compared.

Looking at the blade root loads of the first blade shows similar results than the hub loads (table 3.7). All loads match with a maximal deviation of 10 percent, except the Mz loads. But the absolute values of the Mz loads are very low compared to the Mx and My loads, so a small deviation in this value would result in a high relative deviation to the aeroFlex model. Taking into account that aeroFlex isn't calculating the aerodynamic moments of the airfoils the deviations can be ignored further. Apart from this, a blade Mz load would have no direct effect on the hub My loads. The hub My Loads are mainly created out of the blade My loads, which show a deviation of just 10 %.

Table 3.7: Comparison of root loads of blade 1

Wind Speed	**0.8 v_r**		**1.2 v_r**	
Load	**Min [%]**	**Max [%]**	**Min [%]**	**Max [%]**
Mx	3.1	-0.6	3.0	-0.2
My	-9.9	-2.2	-7.3	-1.7
Mz	-5.6	-19.1	-30.3	26.5
Fx	-9.2	-3.0	-7.4	-2.8
Fy	0.4	0.8	1.5	-0.2
Fz	0.2	0.0	0.7	-0.3

Although there are differences in the hub My loads, the adjustment of the simulation model was finished at this point. The blade loads, which are mainly responsible for the hub loads, are nearly matching in both models. All other loads look good and it was decided to make a model freeze and to continue proceedings.

The comparison of a rigid and teetered hub can be done anyway. A possible mistake in the model would exist in both configurations and would not appear in a direct comparison.

3.2.4 Controller Check

After comparing the aerodynamic loads at steady wind conditions the implementation of the controller dynamics has to be verified. The most important parameter managed by the controller is the rotor speed and the pitch angle.

Step response

For a first check of the controller behavior and it's time constants, a immediate rise in wind speed is applied and the resulting rotor speed and pitch angle are compared. There were three different wind speeds simulated with a rise of 5 m/s in speed. One time series is shown in the following figure and two other step responses are shown in the section C.1 on page 115.

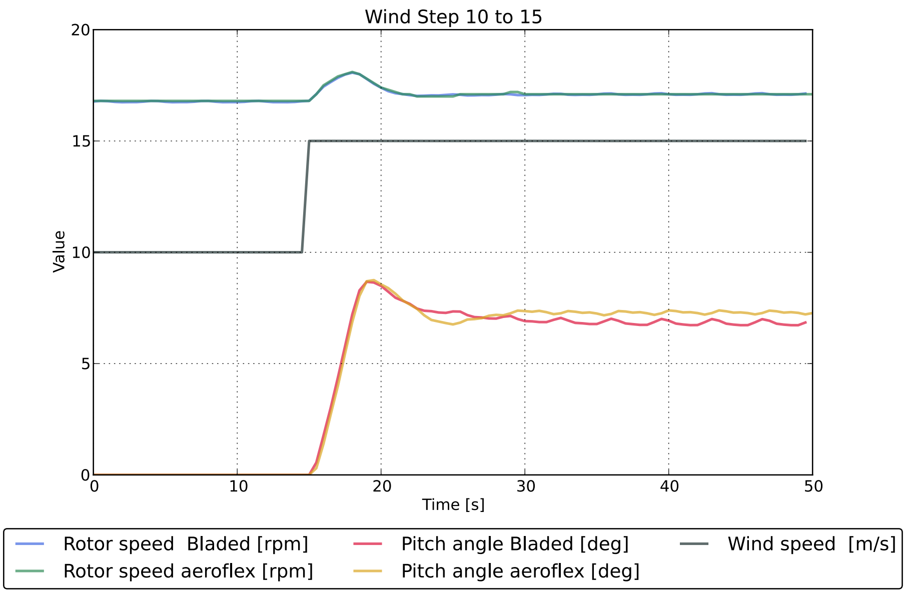


Figure 3.3: Step response for controller validation

The behavior of the rotor speed and the pitch angles look really similar and the implementation of the controller dynamics should be fine. Just a small difference of the pitch angle is seen, similar to the pitch difference at steady wind conditions.

Rotor speed and pitch angles over wind speed

In the next diagram, the pitch angles and the rotor speed is shown for each wind speed. They were simulated by a normal power production with a linear rise of wind speed from 4 to 25 m/s in 900 seconds.

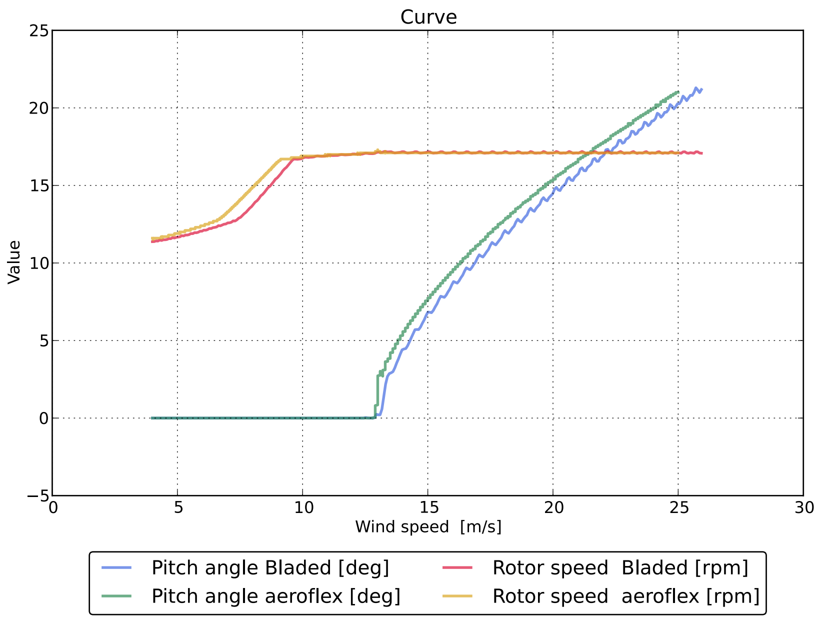


Figure 3.4: Pitch angle and rotor speed over wind speed

There are small differences in the rotor speed for small wind speeds. The rated point, where the blades start to pitch, is nearly the same in both models. Above rated there is a nearly constant pitch offset of about 0.5 deg.

These two parameter are formed by the speed-torque table. Because of the different implementation of the speed-torque table in aeroFlex and Bladed (described in 2.3.2 on page 18), the adjustment of the speed-torque table was challenging. The remaining offset of about 0.5 deg is a sufficient result.

3.3 Teetered Hub Characteristic

The specific construction of the teeter hub is not discussed in this thesis. The simulation in Bladed is working with a look-up table, which defines the teeter restraint for each teeter angle. The teeter restraint is the torque around the teeter axis, which is pushing the rotor back to the neutral position. In addition to this, a damping factor can be entered. These values determine the characteristic curve of the teeter restraint.

A correct definition of this curve is a big part of the ZOFF project and is at the current time in an early stadium. So the taken values are a preliminary draft and will be optimized in further papers. The basis of the definition is the maximal allowable teeter angle, which was stated by the turbine designer to 6 deg. Through this source of information, the teeter restraint was predefined in the ZOFF project by scaling up the teeter restraint parameter from an existing research turbine.

The characteristic curve is divided into 4 different sections, which have a constant spring stiffness over the specific teeter range.

1. Free: For small teeter angles, the teeter restraint is nearly zero. The rotor should move freely in this area, without creating any hub moments through the teetering. The only restraint is caused by the stiffness of the teeter bearing.
2. Soft Stop: After exceeding the free teeter angle section, the rotor should be stopped slowly to prevent too high teeter angles. This stiffness should not be too high, because this would result in really intensive impacts and high hub bending moments.
3. Hard Stop: If the soft stop is also exceeded, the rotor has to be stopped urgently. Otherwise the blade tips could touch the tower, when the teeter angles are getting too big. This stiffness should be really high. The resulting hub loads are in this emergency situation from minor interest.
4. Ultra Stop: This area should not be reached by the rotor, but it is implemented into the simulation model to enable a stable simulation progress, if the maximal allowable angle should be exceeded.

These areas are identical for positive and negative teeter angles. The defined ranges can be seen in the following figure. The challenge is to find the optimal contribution of these areas. High operating loads will be prevented by a big free area, but this reduces the soft stop area and will produce high intensive impacts into the hard stop, if this area is reached in extreme situations.

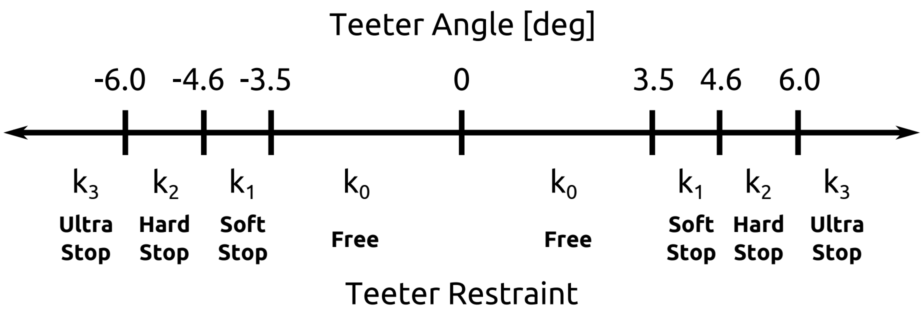


Figure 3.5: Teeter configuration

The spring stiffnesses to the corresponding sections are also a preliminary draft. They are taken as a fixed information and the origin is not further discussed. The stop areas stiffnesses are increasing with the factor 10, to emulate a progressive restraint curve. All values for the teeter restraint are shown in the following table.

Table 3.8: Teeter restraint values

Area	Range [deg]		Teeter Restraint	
	From	To	Spring [kNm/deg]	Damping [kNms/deg]
Free	0	3.5	70	4.7
Soft Stop	3.5	4.6	3’630	
Hard Stop	4.6	6.0	36’300	
Ultra Stop	6.0	...	363’000	

Teeter Lock

The hub should have the possibility to lock the degree of freedom around the teeter axis. This is preferable for situations where a teeter hub would result in higher loads. Possible situations would be if the rotor speed is low and the restoring forces out of the rotation are extremely low. The following situations should be covered by a teeter lock.

- Start Up (DLC 3.x)
- Normal Shut Down (DLC 4.x)
- Parked Situations (DLC 6.x and DLC 7.x)

Any emergency or fault situation will be simulated without a locked teeter hub, because in an accidentally occurring fault or a fast shut down, the lock mechanism can't guarantee a correct behavior.

If a simulation should be locked and the teeter angle has to be evaluated over all runs, the hub has to be teetered with a really high stiffness. Otherwise the teeter angle parameter would be missing and for example a rainflow count could not be done. For these cases, the stiffness of the teeter restraint would be set on the ultra stop level over the whole angle range. The resulting angles would be lower than 0.01 deg for this locked situations.

3.4 IEC Parameter and Design Load Cases

The IEC guidelines contain different wind conditions that should be taken into account. Every condition is described by different parameters, which are turbine specific. They depend on size, class and other characteristics of the turbine. The calculation of these parameters is described in the appendix A on page 68 in detail. In the following tables, the main results are taken together.

Table 3.9: Wind unspecific IEC parameters

Label	Unit	Edition 2	Edition 3
Reference wind speed	m/s	42.5	42.5
1-year extreme wind (steady)	m/s	44.6	47.6
1-year extreme wind (turbulent)	m/s	-	34.0
50-year extreme wind (steady)	m/s	59.5	59.5
50-year extreme wind (turbulent)	m/s	-	42.5
Turbulence scale parameter	m	21	42

IEC parameters that are wind speed specific are listed below for the five most important wind speeds. All other calculated parameter can be found in the design load case descriptions in the appendix.

Table 3.10: Wind specific IEC parameters

Label	Edition	Unit	v_{in}	$0.8\,v_r$	v_r	$1.2\,v_r$	v_{out}
Wind Speed	-	m/s	4	10.3	12.9	15.5	25
Stand. Deviation	2	m/s	1.38	2.14	2.45	2.76	3.90
	3	m/s	1.38	2.13	2.44	2.76	3.90
Turb. Intensity	2	%	34.50	20.74	18.98	17.81	15.60
	3	%	34.40	20.70	18.95	17.78	15.58
EOG 1	2	m/s	4.49	6.95	7.96	8.97	12.68
EOG 50	2	m/s	5.98	9.26	10.61	11.97	16.91
EOG	3	m/s	3.67	5.68	6.51	7.35	10.38
ECD	2	deg	180	69.9	55.8	46.5	28.8
EDC1	2	deg	63.1	38.4	35.2	33.0	29.0
EDC50	2	deg	84.2	51.2	46.9	44.0	38.6
EDC	3	deg	62.11	38.0	34.8	32.7	28.7
EWS	2	m/s	10.22	13.08	14.26	15.44	19.75
	3	m/s	9.38	11.78	12.77	13.76	17.39

Safety Factors

There is a set of different partial safety factors in the IEC guidelines but since the focus is on the resulting forces only the partial safety factor for loads γ_F is treated. Others partial safety factors like the factor for materials are not further considered.

The safety factors are taken directly from the IEC guideline. They will be added to calculate the ultimate loads, depending on the load condition.

Table 3.11: Safety factors

Condition	Abbr.	Safety Factor
Normal	N	1.35
Abnormal	A	1.1
Transport	T	1.5

Loads which are generated by extreme load extrapolation are treated with a safety factor of $\gamma_F = 1.25$.

Design Load Cases

According to the IEC guidelines edition 2 and 3 a range of different design load cases were created. The detailed lists and assumptions which were made are attached in appendix B. An overview of the amount of load cases is shown in the following table.

Table 3.12: Defined design load cases

	Edition 2	Edition 3
DLC 1	3’645	1’749
DLC 2	1’156	2’260
DLC 3	243	243
DLC 4	1’170	1’170
DLC 5	288	288
DLC 6	15	72
DLC 7	81	138
Total	**6’598**	**5’920**

Concerning that each edition gets simulated twice (with teeter hub and rigid hub) the total amount of simulation runs is about 25’000.

Chapter 4

Simulation Results

4.1 Overview of Extreme Events

To get a first impression of the simulation results, a look at the absolute maximal values of important parameters is useful. All values in this section are without any safety factor.

4.1.1 Overview Hub Loads

Studying the hub loads is a first starting point, because all major loads produced by the blades are transferred to the hub. For each hub configuration and IEC edition, all three moments and three forces of the rotating hub coordinate system got treated. The load values are determined for each design load case and each load axis separately.

The following diagrams show the absolute extreme loads for each DLC separately, according to IEC edition 2. All other diagrams and tables, including the IEC edition 3, are attached in the section C.2 on page 117.

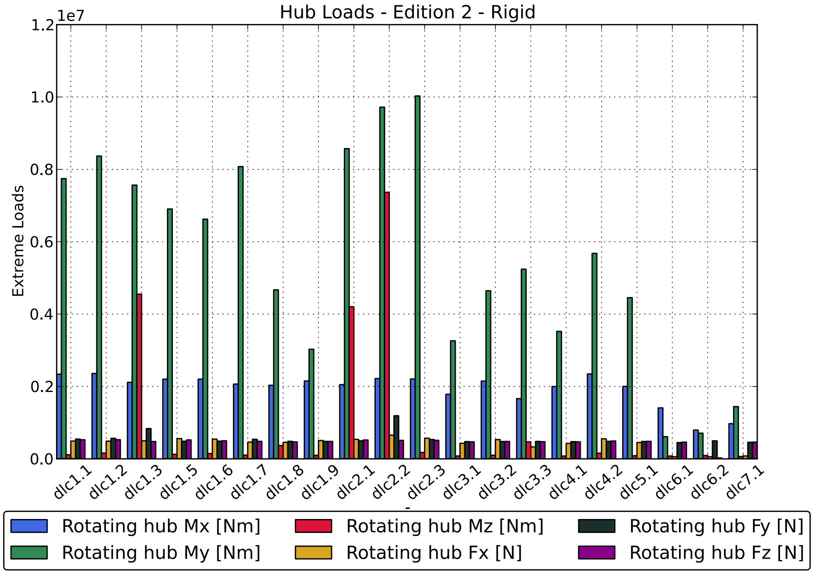


Figure 4.1: Extreme hub loads (Edition 2, rigid hub)

The simulations results of the teeter hub model configuration are simulated without any teeter lock (figure 4.2). Especially the parked situations show big My moments, what would be prevented by a teeter lock.

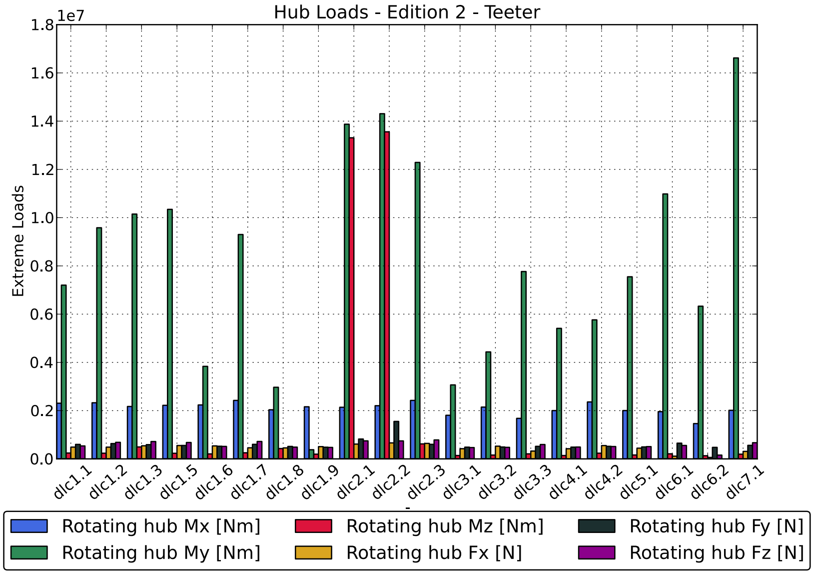


Figure 4.2: Extreme hub loads (Edition 2, teeter hub)

The following table shows the comparison of the previous two diagrams. Each load case and load value is compared between the rigid hub and the teeter hub according to the following formula. A red background color of a cell indicates an increased load maximum produced by the applied teeter hub.

$$x = \frac{x_{teeter}}{x_{rigid}} \tag{4.1}$$

Table 4.1: Compared hub loads (Edition 2)

Edition 2	Hub Load Teeter / Hub Load Rigid					
Casename	Mx	My	Mz	Fx	Fy	Fz
dlc1.1	0.987	0.930	2.171	0.994	1.102	1.018
dlc1.2	0.987	1.145	1.485	0.996	1.121	1.297
dlc1.3	1.028	1.341	0.109	1.091	0.707	1.500
dlc1.5	1.008	1.498	1.856	0.993	1.146	1.297
dlc1.6	1.015	0.579	1.408	0.989	1.073	1.035
dlc1.7	1.173	1.152	2.464	0.994	1.117	1.494
dlc1.8	1.002	0.636	1.162	0.998	1.067	1.044
dlc1.9	1.004	0.125	2.020	1.000	1.005	0.987
dlc2.1	1.043	1.618	3.168	1.143	1.652	1.432
dlc2.2	0.994	1.472	1.841	1.013	1.304	1.460
dlc2.3	1.098	1.225	3.511	1.126	1.128	1.534
dlc3.1	1.013	0.940	1.760	0.985	1.020	0.999
dlc3.2	0.999	0.955	1.589	0.990	1.030	0.996
dlc3.3	1.010	1.482	0.442	0.987	1.081	1.259
dlc4.1	1.002	1.536	1.776	0.986	1.027	1.046
dlc4.2	1.006	1.015	1.507	0.999	1.077	1.038
dlc5.1	1.002	1.695	1.885	0.985	1.033	1.054
dlc6.1	1.390	17.912	2.705	1.865	1.450	1.206
dlc6.2	1.840	8.929	1.445	1.021	0.958	6.487
dlc7.1	2.073	11.506	3.013	3.880	1.225	1.450

Most of the extreme loads are increasing trough a teeter hub. Except the extreme Fx loads, which are the only ones that get reduced by a teeter hub for most of the DLC.

The My moment shows some big deviations, especially the parked situations (DLC6.x and DLC 7.x) create much higher My moments when the hub is teetering. In these cases a teeter lock would prevent the peaks and the loads would be as great as with a rigid hub.

The Mz moment is for the most cases on a low level, but shows some outliers (¿2), which are out standing. These extreme load peaks of the Mz moment look like a simulation error. A closer look on these extreme events and their time series shows, that this is a fault in the dynamic stall hysteresis model. It occurs when there is a big yaw misalignment and the inflow angles for the blade sections exceed the normal range for short moments.

4.1.2 Overview Teeter Angle

The following table contains the maximal occurring teeter angle for each load case and both IEC editions.

Table 4.2: Maximal teeter angles

Edition 2			Edition 3		
Group	**Angle [deg]**	**DLC**	**Group**	**Angle [deg]**	**DLC**
dlc1.1	**4.69**	dlc1.1d-y3	dlc1.1	**4.72**	dlc1.1k-s530-y3
dlc1.2	**4.76**	dlc1.2k-y3	dlc1.2	**4.65**	dlc1.2k-y3
dlc1.3	**4.78**	dlc1.3b-pos-y3-ra13	dlc1.3	**4.72**	dlc1.3k-y3
dlc1.5	**4.79**	dlc1.5d-t2-y3-ra10	dlc1.4	**4.78**	dlc1.4b-pos-y3-ra13
dlc1.6	**4.48**	dlc1.6d-y3-ra10	dlc1.5	**4.72**	dlc1.5d-v-pos-y3-ra21
dlc1.7	**4.76**	dlc1.7d-v-pos-y3-ra21	dlc2.1	**4.97**	dlc2.1.2b-y-neg-ra17
dlc1.8	**4.25**	dlc1.8c-neg-y3-ra11	dlc2.2	**4.81**	dlc2.2.4b-y3-ra1
dlc1.9	**3.54**	dlc1.9b-y1-ra13	dlc2.3	**4.77**	dlc2.3d-t2-y3-ra11
dlc2.1	**4.90**	dlc2.1.2b-y-neg-ra15	dlc2.4	**4.86**	dlc2.4b-y2
dlc2.2	**4.91**	dlc2.2.4b-y-neg-ra4	dlc3.1	*4.10*	dlc3.1f-y3
dlc2.3	**4.85**	dlc2.3b-y2	dlc3.2	*4.43*	dlc3.2e-t1-y3
dlc3.1	*4.27*	dlc3.1f-y3	dlc3.3	*4.71*	dlc3.3e-pos-t3-y3
dlc3.2	*4.61*	dlc3.2e-t1-y3	dlc4.1	*4.64*	dlc4.1f-y3
dlc3.3	*4.71*	dlc3.3e-pos-t5-y3	dlc4.2	*4.65*	dlc4.2d-t1-y3-ra20
dlc4.1	*4.64*	dlc4.1f-y3	dlc5.1	**4.74**	dlc5.1d-y3-ra6
dlc4.2	*4.65*	dlc4.2d-t1-y3-ra19	dlc6.1	*4.59*	dlc6.1b-y2
dlc5.1	**4.70**	dlc5.1d-y3-ra7	dlc6.2	*4.86*	dlc6.2b-y7
dlc6.1	*4.81*	dlc6.1a-y7	dlc6.3	*4.83*	dlc6.3a-y7
dlc6.2	*4.66*	dlc6.2f-y1	dlc6.4	*4.63*	dlc6.4f-y2
dlc7.1	*4.98*	dlc7.1c-f23-y2	dlc7.1	*5.00*	dlc7.1f-f7-y2
Max	4.98	without teeter lock	Max	5.00	without teeter lock
Max	4.91	with teeter lock	Max	4.97	with teeter lock
	Red	Hard Stop reached		**Bold**	No teeter lock
	Yellow	Soft Stop reached		*Italic*	Locked by teeter lock

The color indicates which area of the teeter restraint is reached by the rotor. Most of the load cases are reaching the hard stop (red color).

Comparing the maximal appearing angles in both editions reveals that dlc7.1 load cases produce the worst teeter angles. Both extreme runs are simulated in a parked situation with a fault in the parked rotor azimuth position. But these cases would be prevented by a teeter lock.

More important are the load cases which wont be supported by a teeter lock (bold values). The two following runs generate the worst teeter angles in their specific IEC edition:

- Edition 2:
  - 4.91 deg maximal teeter angle at the run dlc2.2.4b-y-neg-ra4.
  - dlc2.2.4 contains a yaw runaway during power production with a following emergency shut down.
  - b-y-neg stands for the wind speed $v_{out} = 25\frac{m}{s}$ and a shut down at $yaw_{max} = -60deg$.

- Edition 3:
  - 4.97 deg maximal teeter angle at the run dlc2.1.2b-y-neg-ra17.
  - dlc2.1.2 contains a emergency shut down during power production when the maximal allowable yaw angle is exceeded.
  - b-y-neg stands for the wind speed $v_{out} = 25\frac{m}{s}$ and a shut down at $yaw_{max} = -60deg$.

In both editions are nearly the same conditions prevailing when the worst teeter angle appears. During a maximal yaw angle and the cut-out wind speed an emergency shut down is triggered. One difference is that the third edition is simulated with a turbulent wind instead of a steady wind.

The time series of both runs are listed below. They contain the teeter angle, wind direction, rotor speed and the resolved hub torque which is produced by the teeter restraint. Looking at the resolved hub torque makes a identification of the maximal teeter angle easier. The rotor speed indicates when the emergency stop is released and in which situation the teeter angle appears.

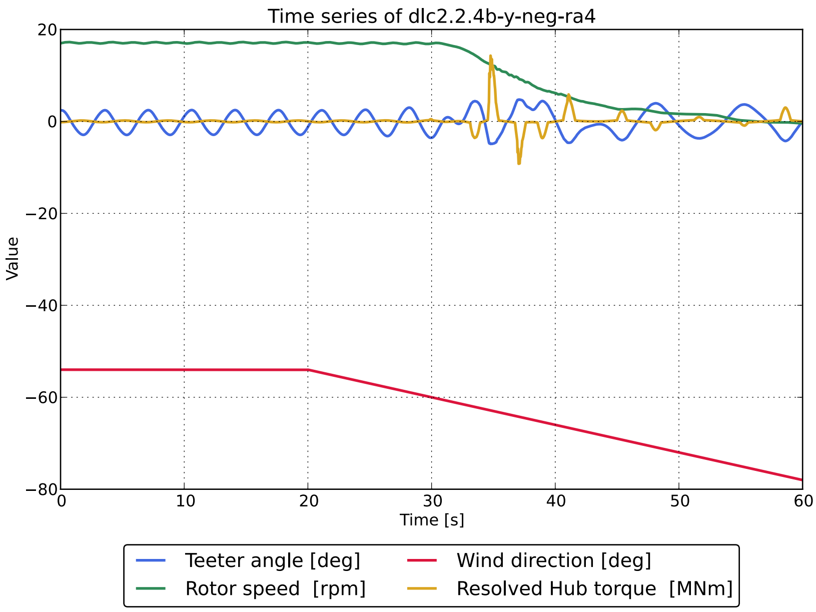


Figure 4.3: Time series with maximal teeter angle (Edition 2)

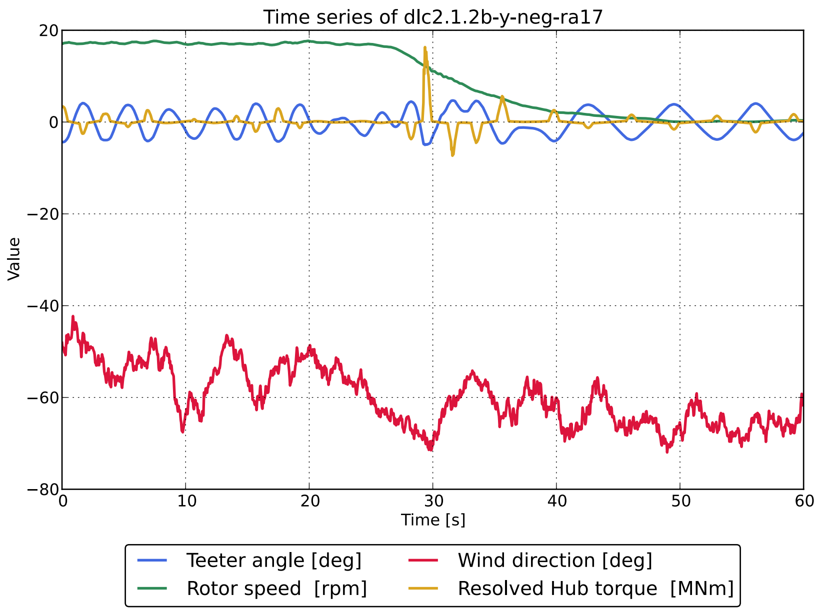


Figure 4.4: Time series with maximal teeter angle (Edition 3)

In both situations the maximal teeter angle appears about 3 seconds after the start of the shut down.

4.1.3 Overview Blade Deflection

A comparison of the maximal blade deflections is shown in the following two diagrams. The values belong to blade number 1 and no teeter lock was applied.

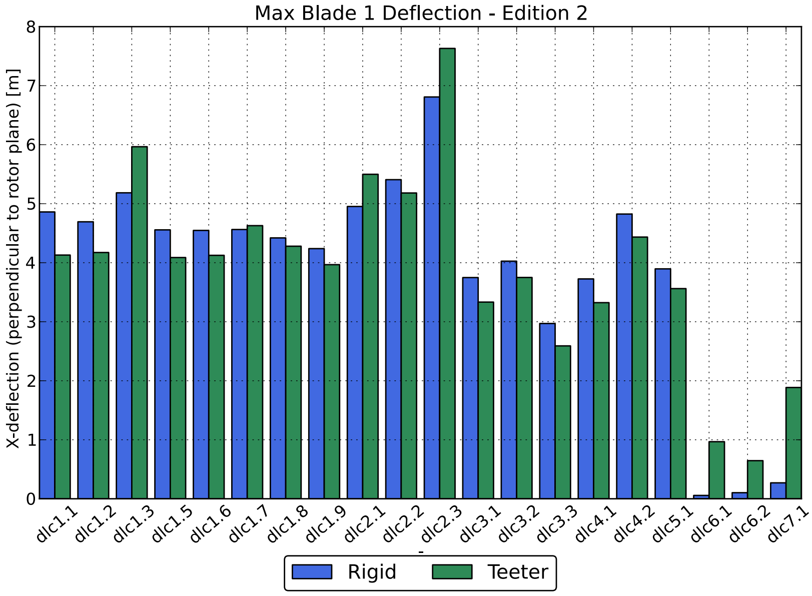


Figure 4.5: Maximal blade deflection (Edition 2)

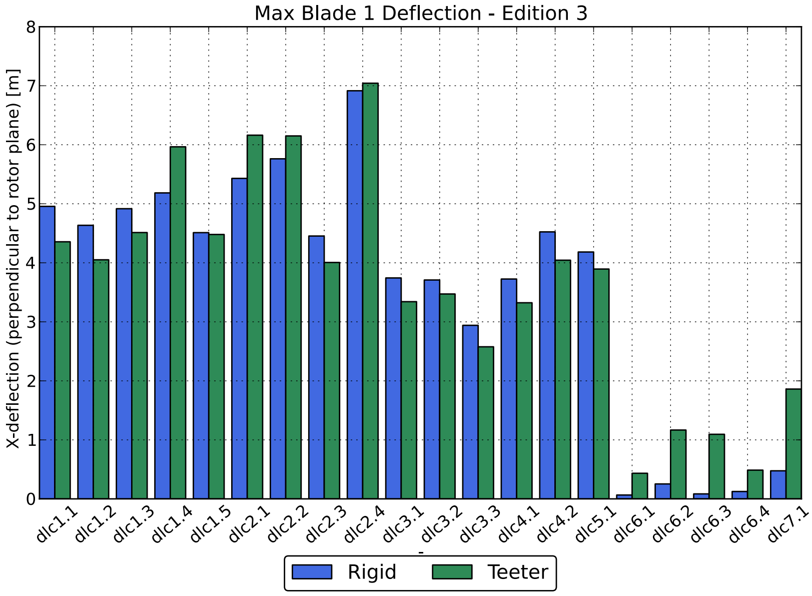


Figure 4.6: Maximal blade deflection (Edition 3)

Comparing the maximal blade deflections of a rigid hub and a teeter hub shows no big varieties. Except the parked situations produce bigger deflections when the hub has a teeter hinge, but these cases would be prevented by a teeter lock. The biggest blade deflections are appearing during fault situations (DLC2.x) in both editions.

4.1.4 Overview Tip-Tower Distance

One of the main design driver for wind turbines is the minimal distance between the blade tips and the tower surface. According to the turbine designer the minimal allowable distance is about 2.3 m.

The closest approaches are arranged in the following two diagrams for the second and third IEC edition. A negative value implies that the blade tip would penetrate the tower surface.

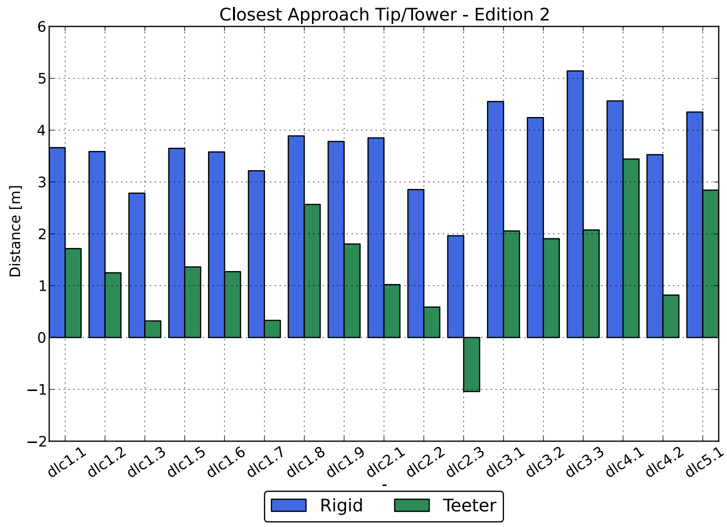


Figure 4.7: Closest tip-tower approach (Edition 2)

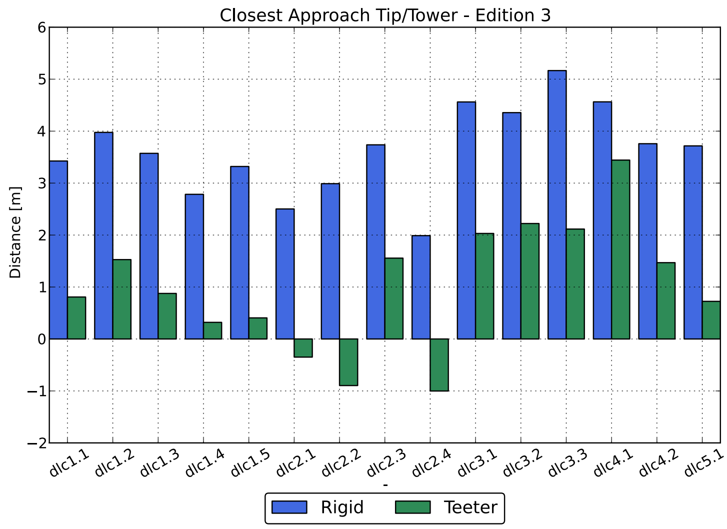


Figure 4.8: Closest tip-tower approach (Edition 3)

Almost every DLC with a teeter hub falls below the minimal allowable tip-tower distance. Also some tower penetrations were simulated.

The absolute closest approaches of the blade tips and the tower surface to the corresponding turbine configurations are collected in the following table.

Table 4.3: Closest approaches

Edition	Hub	Closest approach [m]	DLC
2	Rigid	1.96	dlc2.3b-y2
	Teeter	-1.04	dlc2.3b-y2
3	Rigid	1.98	dlc2.4b-y2
	Teeter	-1.00	dlc2.4b-y2

All load cases with a closest approach contain a permanent power production during a maximal yaw angle without a shut down. The prevailing wind conditions are determined by the wind speed $v_{out} = 25\frac{m}{s}$ and a yaw angle of 60 deg.

4.2 Ultimate Loads

Departing from the extreme loads, the ultimate loads are extreme loads with all other loads which occur simultaneously. The combination of all these loads is used to determine the absolute maximum load which the turbine has to sustain. Also the safety factors according to the IEC guidelines are added.

The ultimate loads are created out of all design load cases, except five load cases, which are taken for the fatigue analysis. An overview of all taken design load cases and the corresponding safety factors (SF) are listed in the next table. In case of a teeter hub, some DLC should be simulated with an activated teeter lock. In these cases, the results of the rigid hub are taken to find the ultimate loads.

Table 4.4: Ultimate load cases

Edition 2			Edition 3		
DLC	Locked	SF	DLC	Locked	SF
1.1	-	N	1.1	-	N
1.3	-	N	1.3	-	N
1.4	-	N	1.4	-	N
1.5	-	N	1.5	-	N
1.6	-	N	2.1	-	N
1.7	-	N	2.2	-	A
1.8	-	N	2.3	-	A
1.9	-	N	3.2	X	N
2.1	-	N	3.3	X	N
2.2	-	A	4.2	X	N
3.2	X	N	5.1	-	N
3.3	X	N	6.1	X	N
4.2	X	N	6.2	X	A
5.1	-	N	6.3	X	N
6.1	X	N	7.1	X*	A
7.1	X*	A			

* Except fault of teeter lock

The following table contains the resulting ultimate load matrix for the IEC edition 3 and a teeter hub. Bold printed values are the biggest occurring loads and the beside them the loads which are occurring at the same time.

Table 4.5: Ultimate hub loads (Edition 3, teeter hub)

Edition 3 - Teeter			Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz	Rotor speed	Wind speed	Yaw angle	Teeter angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[deg]	[-]
Hub Mx	MAX	dlc1.1	**3'258**	-186	178	390	587	190	17.3	31.3	5.4	2.23	1.35
Hub Mx	MIN	dlc2.12	**-3'716**	3'316	-7'718	120	-1'366	-851	5.4	12.4	-85.4	-4.15	1.35
Hub My	MAX	dlc2.12	454	**22'044**	-148	69	33	289	12.2	25.7	68.9	-4.97	1.35
Hub My	MIN	dlc2.12	582	**-21'251**	150	73	39	-317	12.3	25.8	69.6	4.95	1.35
Hub Mz	MAX	dlc2.12	-3'659	-771	**11'911**	-256	1'993	-334	1.2	10.6	-87.5	2.35	1.35
Hub Mz	MIN	dlc2.12	-3'716	3'316	**-7'718**	120	-1'366	-851	5.4	12.4	-85.4	-4.15	1.35
Hub Fx	MAX	dlc2.11	2'811	211	-215	**780**	-657	-47	19.3	15.1	-10.6	-1.99	1.35
Hub Fx	MIN	dlc2.12	151	-11'551	-42	**-348**	-105	929	12.8	23.6	-53.8	4.73	1.35
Hub Fy	MAX	dlc2.12	-3'659	-771	11'911	-256	**1'993**	-334	1.2	10.6	-87.5	2.35	1.35
Hub Fy	MIN	dlc2.12	-3'716	3'316	-7'718	120	**-1'366**	-851	5.4	12.4	-85.4	-4.15	1.35
Hub Fz	MAX	dlc2.12	213	17'558	-116	-205	-28	**1'066**	12.2	25.7	70.3	-4.87	1.35
Hub Fz	MIN	dlc2.12	495	-16'735	119	-182	21	**-1'084**	12.5	24.8	67.7	4.85	1.35

Looking at the matrix shows that nearly every ultimate load happens during a fault situation (DLC2.1 or DLC2.2), below the rated rotational speed and during a big yaw misalignment. The high Mz loads are caused by the fault in the stall model (described in 4.1.1 on page 45).

Comparing the ultimate load matrices (table 4.6) reveals the same result like in the previous chapter. The extreme loads and according to this the ultimate loads increase for a teeter hub. This takes effect for the hub and also the blade root loads. As an example the comparison between a teeter and a rigid hub for IEC edition 3 is seen in the following table. Especially the hub My load is increased by 85 %.

Table 4.6: Compared ultimate hub loads (Edition 3)

Edition 3		Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz
Tet vs Rig		[-]	[-]	[-]	[-]	[-]	[-]
Hub Mx	MAX	**1.023**	-0.053	1.995	0.956	1.224	0.690
Hub Mx	MIN	**1.254**	-5.539	-1.081	-5.618	-0.901	-1.507
Hub My	MAX	0.173	**1.853**	-3.440	0.598	0.387	-0.502
Hub My	MIN	0.267	**1.866**	-1.781	0.688	-0.197	-0.703
Hub Mz	MAX	-2.653	-0.293	**1.231**	1.072	1.369	2.109
Hub Mz	MIN	3.176	1.548	**1.142**	-0.624	1.148	2.307
Hub Fx	MAX	1.022	-0.056	-2.063	**0.982**	-1.022	0.299
Hub Fx	MIN	-0.132	9.450	-0.006	**1.140**	-0.092	1.998
Hub Fy	MAX	1.235	1.288	1.669	11.971	**1.315**	-0.591
Hub Fy	MIN	3.176	1.548	1.142	-0.624	**1.148**	2.307
Hub Fz	MAX	0.084	-10.243	-11.214	-1.074	-1.981	**1.611**
Hub Fz	MIN	0.184	-4.961	2.189	-0.776	-0.182	**1.561**

All ultimate loads matrices can be found in appendix C in the section "Ultimate Hub Loads" and "Ultimate Blade Loads". A clear difference between the IEC edition 2 and 3 is not visible.

The results show also that a teeter lock has no influence on the ultimate loads, because the extreme loads appear in the DLC 2.x cases mostly. And these cases are not supported by a teeter lock.

4.3 Fatigue Loads

4.3.1 Influence Teeter Hub on Hub My

The purpose of a teeter hub is to reduce the loads from wind shear and turbulence. These loads have there main effect on the hub My loads. The following diagram shows the hub My load cycles for the turbine over a period of 20 years. The cycle ranges were counted by a rainflow count for 4 different settings.

- Ed2 Rigid: Turbine simulated with a rigid hub according to IEC edition 2
- Ed2 Teeter: Turbine simulated with a teeter hub according to IEC edition 2
- Ed3 Rigid: Turbine simulated with a rigid hub according to IEC edition 3

- Ed3 Teeter: Turbine simulated with a teeter hub according to IEC edition 3

For the teeter hub turbines, the teeter lock is activated in the corresponding load cases.

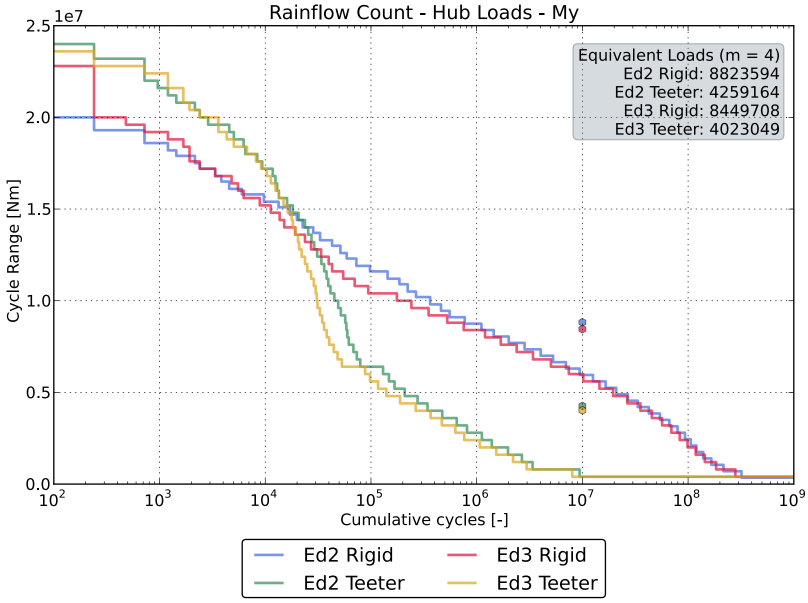


Figure 4.9: Rainflow count for the hub loads

The differences between the IEC edition 2 and 3 fatigue loads are small. There is no difference in the design load cases between these two editions except the method for calculating the turbulent wind and the random seeds.

The graphs show, that a turbine with a teeter hub has more high extreme loads than a turbine with a rigid hub. But the low level operating loads which appear very often over time are reduced very much.

The interpretation of the load reduction potential can be done by comparing the damage equivalent loads, shown in the gray box within the diagram. As a result the relative load reduction of the teeter hub compared to the rigid hub is listed below.

- Reduction for Edition 2: -51.8 %
- Reduction for Edition 3: -52.4 %

All in all, the equivalent hub bending fatigue loads are reduced to the half by a teeter hub.

4.3.2 Influence Teeter Lock

To determine the influence of a teeter lock on the fatigue loads the following diagram shows the load spectra for both IEC editions. It includes the data for a rigid hub, a teeter lock that can not be locked ("Teeter") and a teeter lock that can be locked ("Teeter Lock"). The difference between the teeter hubs is, that the start up, normal shut down and parked situations are simulated with a nearly rigid hub for a lockable hub.

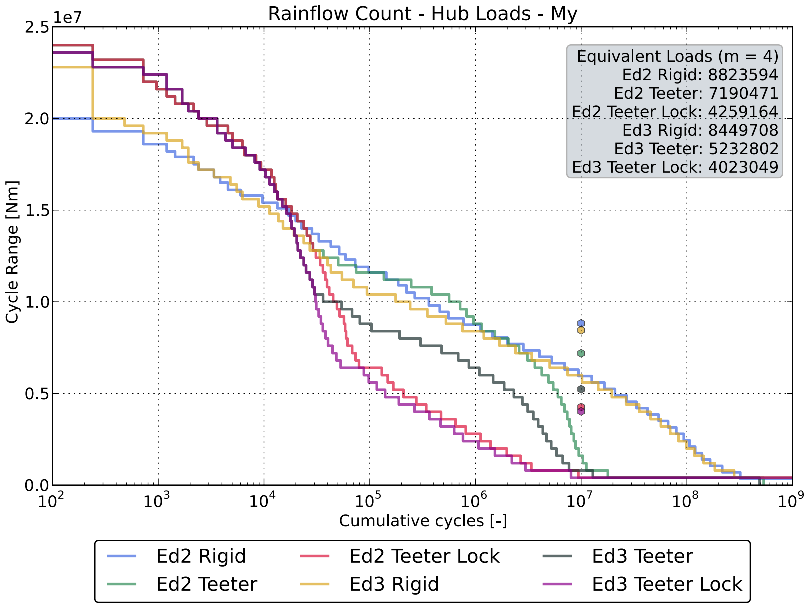


Figure 4.10: Rainflow count with and without teeter lock

Comparing the teeter hub and the teeter hub with a lock function shows two results. The big load cycles are not influenced by the teeter lock. But the smaller load cycles, which occur very often are reduced in quantity a lot by a teeter lock. The big number of small loads will occur during parked situations, where the rotor is teetering freely and a teeter lock would prevent this.

In the next table the reduction potential for a teeter hub with and without a teeter lock is listed.

Table 4.7: Reduction of equivalent loads with and without teeter lock

Turbine	With teeter lock	Without teeter lock
Edition 2	-51.8 %	-18.6 %
Edition 3	-52.4 %	-38,1 %

The reduction potential of a teeter lock is decreased significantly if the rotor contains no teeter lock. All load spectra of the other load components are attached in appendix C in the appendix.

4.3.3 Teeter Angle

To estimate the movement and stress of the teeter bearings during the lifetime of the turbine the rainflow count was applied on the teeter angle. The results can been seen in the following diagram and are separated to a teeter hub that can not be locked ("Free") and one that can be locked ("Lock").

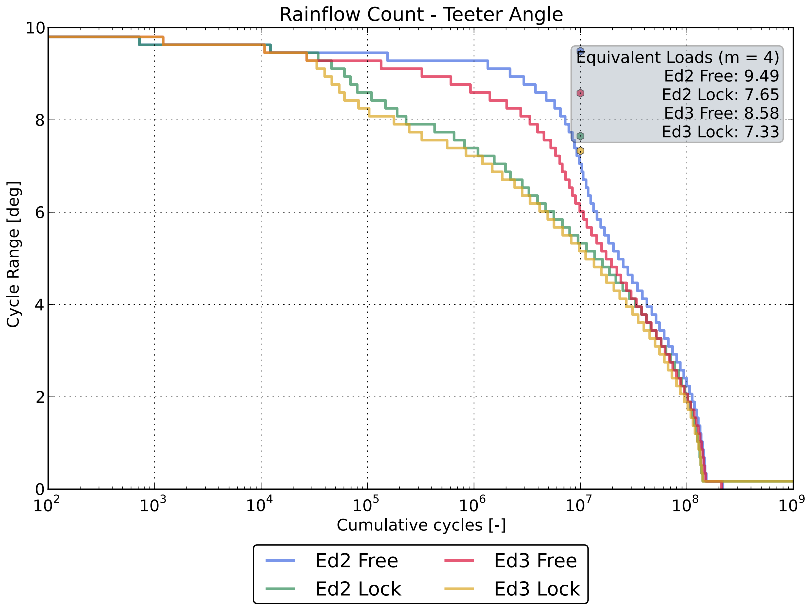


Figure 4.11: Teeter angle cycles over the turbine lifetime

A teeter lock reduces the number of bigger teeter angle cycles slightly and the equivalent load is reduced by about 15 %.

The equivalent load or teeter movement with a teeter lock would be a cycle range of about 7.4 deg for a quantity of 10^7 cycles.

4.3.4 Comparison of Equivalent Loads

In this section the equivalent hub and blade loads are compared. The load reduction is displayed by a scaling factor which indicates the variance of the teeter hub (with teeter lock) based on the rigid hub. The results are listed in the following table. If the absolute deviation is below 5 % it is set to zero to put the focus on the relevant changes.

Table 4.8: Comparison of equivalent loads

Reduction [%]	Hub Loads	Blade Loads
Mx	0	0
My	-52	-32
Mz	+53	0
Fx	0	-26
Fy	0	0
Fz	0	0

Most of the equivalent loads are not influenced by the teeter hub in particular. The reduced loads are hub My, blade My and blade Fx. The only loads which are increased are the hub Mz loads. Considering that there are some issues with the stall model (influence on hub Mz) makes this result inaccurate. Further researches resulted in a correlation between the teeter movement range and the increased hub Mz loads.

All load spectra diagrams are attached in appendix C.

4.4 Extreme Load Extrapolation

The statistical basis for the extreme load extrapolations are 198 simulations with a time period of 10 minutes each. They a distributed to 11 bins over the wind speed range from 3 to 25 $\frac{m}{s}$. There are 6 different turbulent wind fields simulated with 3 different yaw angles for each bin. A number of 18 simulations per bin can be a sufficient amount of simulations for an extrapolation. There can occur problems if there are too few extreme events in the time series, but this has to be considered for each case separately.

The analysis is focused on the hub My moments and the teeter angles. It appeared, that the Gumbel distribution is more suitable to these parameters than the 3-parameter Weibull. For the fitting of the curves, the default weighting factors in Bladed were used. The graphs are attached in the appendix for the 1-year extrapolations. The 50-year extrapolations are based on the same graphs and the fitted functions are just extended to a smaller probability.

The extrapolated values are listed without any safety factors in the following table. The increasing of the extrapolated values compared to the simulated extreme values (called scaling factor) is calculated and included by bold printed values.

Table 4.9: Results of load extrapolation

		Simulated	1 year		50 year	
Hub My (Rigid) [MNm]	max	8.155	9.292	**1.14**	11.409	**1.40**
	min	-8.183	-9.534	**1.17**	-11.954	**1.46**
Hub My (Teeter) [MNm]	max	6.770	8.535	**1.26**	11.971	**1.77**
	min	-8.289	-9.872	**1.19**	-14.860	**1.79**
Teeter Angle [deg]	max	4.724	5.280	**1.12**	6.046	**1.28**
	min	-4.676	-5.129	**1.10**	-5.690	**1.22**

Focusing on the scaling factors some information can be seen:

- Comparing the min and max values shows no big variations.
- The hub load My has a bigger scaling factor for a teeter hub, than for a rigid hub.
- The scaling factor of the teeter angle is relatively small, compared to the other scaling factors.

As a validation of the results the scaling factors for a wind turbine with a rigid hub can be compared to the results of Kai Freudenreich [27]. As a result of this paper the scaling factor, to exceed the 50-year extrapolated loads, has to be at least 1.43. This fits the calculated scaling factors of 1.40 and 1.46 with a rigid hub.

Load extrapolations for the blade root bending moments did not result in reliable fittings. But they are nevertheless attached with the other load extrapolation diagrams in section C.7 on page 133.

A further comparison of the extrapolated hub My loads to the maximal simulated hub My loads is displayed in figure 4.12. The values contain the corresponding safety factors. For results out of fatigue load cases the normal safety factor N was added. All simulated extreme loads are grouped in normal power production (DLC1.x) and power production with fault (DLC2.x) for each IEC edition. These two load case groups hold the load cases with the highest loads.

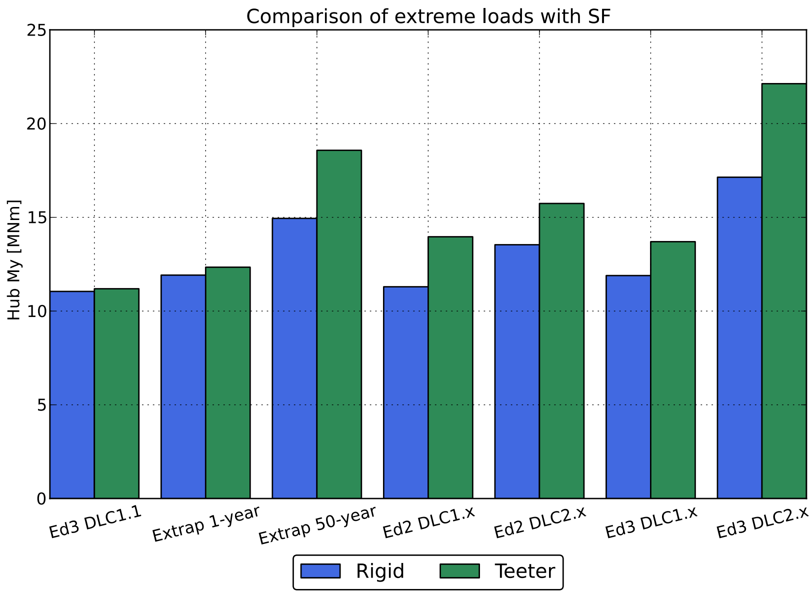


Figure 4.12: Comparison of extreme loads

Taking the extrapolated 50-year extreme moments as a reference, the results of the second IEC edition are exceeded obviously. But the extrapolated values are below the results of the fault situations out of the third IEC edition. These fault situations are simulated with turbulent wind, whereas the second edition is working with steady wind. As a result, the loads of edition 3 exceed the extrapolated 50-year loads.

An extrapolation of the teeter angle was connected with some problems. The data distribution for the extreme events is shown in figure 4.13 and the sections of the teeter restraint are indicated. It is eye-catching, that each restraint section has a different incline and the fitted curve is aligned to the soft stop section. Because the number of events in the hard stop are really low, this section has no big influence on the fitted curve. But this incline would provide the most reliable distribution for extrapolated events if the fitting is checked visually.

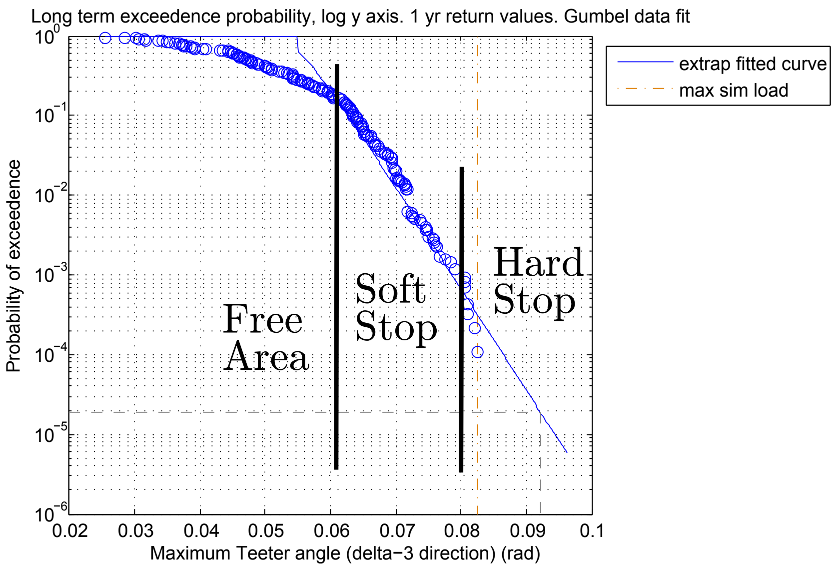


Figure 4.13: Extrapolated maximum teeter angle

4.5 Pitch-Teeter Coupling

An additional option for reducing the hub loads is the pitch-teeter coupling. As an outlook for future researches, a delta-3 angle (D3) of 45 degrees had been simulated for the second IEC edition and only for the fatigue load cases. This implies that the coefficient between the teeter angle and the additional pitch angle shift is $\tan \delta_3 = \tan 45 = 1$ constantly. For example, if the teeter angle is 2 degrees, the additional pitch angle is also 2 degrees.

The following two diagrams should reveal the potential of the pitch-teeter coupling concept. Figure 4.14 displays the resulting teeter angles, which are reduced significantly by the delta-3 angle.

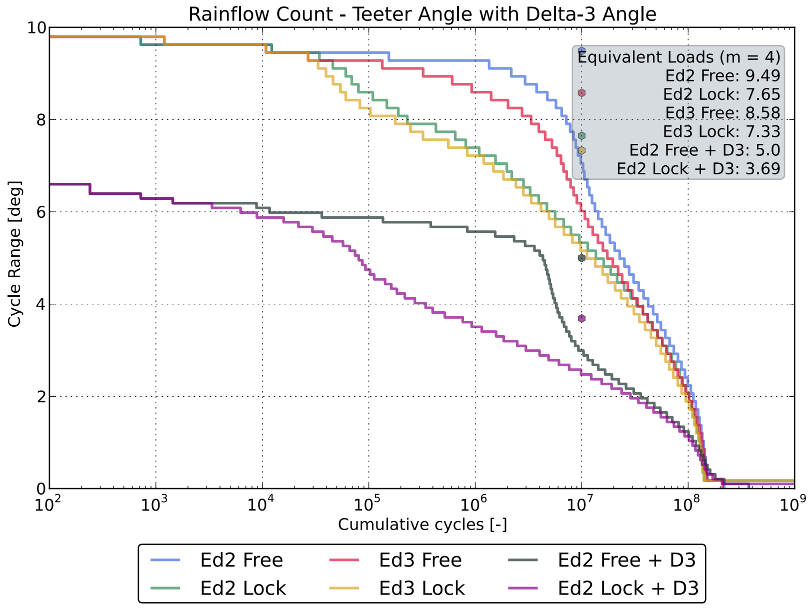


Figure 4.14: Teeter angles containing pitch-teeter coupling

Figure 4.15 contains the corresponding hub My loads. The equivalent loads a reduced to about 25 % based on the rigid hub loads. Compared to the influence of a simple teeter hub, the additional delta-3 angle is also reducing the size of the maximal load cycles.

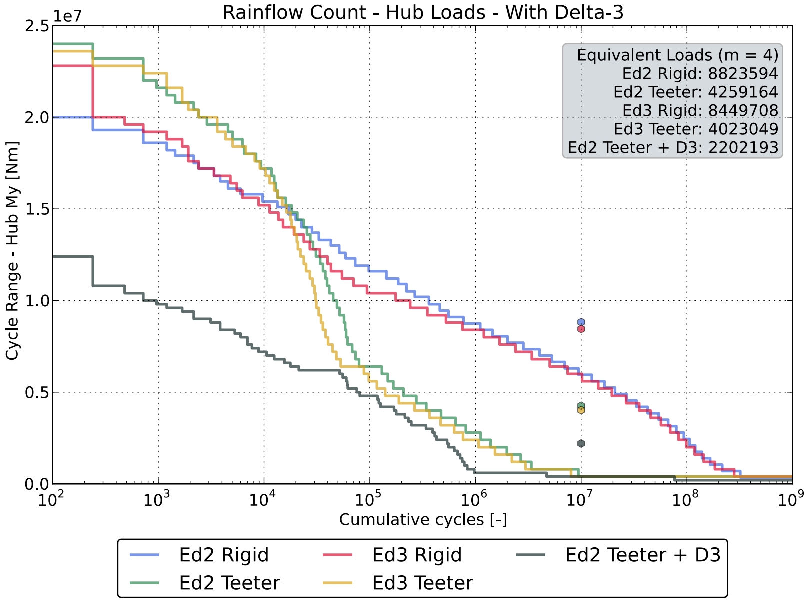


Figure 4.15: Hub My fatigue loads with pitch-teeter coupling

Chapter 5

Conclusion

5.1 Conclusion of Results

Teeter Possibility

The considered idea to equip a rigid turbine with a teeter hub reveals some issues. First among them is that the rotor and nacelle geometry is not adequate enough to compensate the additional movement of the blade tips. During the simulations several impacts of the blade tips into the tower surface were detected.

Trying to modify the teeter restraint or to reduce the maximal allowable teeter angle would not solve this problem. The maximal blade deflections showed no obvious influence by the teeter hub. So any additional teeter movement would reduce the tip-tower distance and the minimal allowable distance is already reached with a rigid hub configuration. The only choice would be to change the turbine geometry (tilt angle, rotor overhang) or to extend the whole teeter concept with additional features.

Nevertheless the simulation results can be used to figure out the potential and characteristics of a teeter concept.

Teeter Restraint

The overall variation of the maximal teeter angles was really small. Comparing the different maximal teeter angles of different DLC reveals that most of the cases reach the hard stop, which starts at 4.6 deg. But the maximal angle is 5.0 deg, which gives an area of 0.4 deg where nearly all maximal angles are located. As a result the maximal allowable teeter angle of 6.0 deg is not even used barely.

Also a closer look at the rainflow count of the teeter angle and single time series shows that the rotor comes to an abrupt end at the hard stop. Although this is the purpose of the end stop, these hard end impacts should be prevented. The soft stop seems to have only a minor influence on the teeter movement.

Intensive impacts produce extreme high loads which are transferred into the drive train. A better option would be a stop over a bigger range to slow down the rotor more gently. But this would reduce the free teeter range, which allows the rotor to move without transferring bending moments to the drive train.

To find an optimal teeter restraint configuration is depending on the maximal allowable teeter angle which is defined by the specific turbine geometry. Further optimization of the teeter restraint will be part of the ZOFF project. However, it can be assumed that the SCD 3.0 hub cannot be modified to a teeter hub without major changes in the turbine geometry.

Ultimate Loads

A look at the extreme and ultimate loads confirms the thoughts about the teeter restraint. The impacts of the rotor into the hard stop produce bigger hub and blade extreme loads. An increasing trend can be seen in every load component of the moments and forces.

As an example, the maximal hub bending moment My is increased about 80 % if the turbine has a teeter hub instead of a rigid hub. Especially a big yaw misalignment leads to critical situations in which a teeter hub reacts inappropriately. In these situations the rotor is smashing directly into the hard stop.

Although the chosen teeter range of ±6 deg is relatively big in relation to other teeter turbines, the rotor seems to react very fast on aerodynamic forces. As already mentioned the restoring forces are mainly influenced by the mass and rotational speed of the rotor. The rotor mass of the SCD turbine is very small and the rated rotational speed is the lowest one of the observed turbines. A larger rotational speed, which has a quadratic influence on the restoring forces, could improve the teeter concept of this specific turbine. But this has to be proven by further investigations.

Considering that the yaw misalignment has a negative effect on the loads of the teeter hub, it is remarkable that the Condor 6MW turbine has an active yawing power control. There is no further information about the used teeter characteristics available, but this could become problematic. It is possible that the teeter restraint has no free restraint section and a constant spring stiffness is pushing the rotor backwards. This could prevent an uncontrolled teeter movement during high yaw misalignment and the resulting end impacts.

Fatigue Loads

Apart from the extreme loads, the fatigue loads are the key performance indicators for the durability of a turbine. A reduction of the fatigue loads extends the lifetime or can be used to scale down the turbine components. Especially the hub bending moment shall be improved by a teeter hub.

The determined load reduction of this moment is about 50 %, which is an enormous result. Cutting the biggest load on the drive train in a half is a huge benefit for the whole turbine. Also the blade root bending moment My and blade root Fx are reduced by 30 %. The only fatigue load component which is increased by a teeter hub is the hub Mz moment. The rise of the equivalent load of the hub Mz moment is 50 %, but this moment is a lot smaller than the Mx and My moments. So this increase is not very critical. All other load components of the hub or the blade roots are not significantly affected by a teeter hub.

Load Extrapolation

Getting reliable data out of the extreme load extrapolation is challenging. To determine correctly the 50-year extreme loads requires a huge number of simulation data and experience. A precise load prediction shall not be given here. But some statements can be made for a teeter hub.

Keeping in mind that the teeter hub will have a low load level most of the time (when the teeter angle is inside the free teeter area) the number of extreme events will be also low under normal conditions. So the total number of simulation runs on which the extrapolation is statistical based on has to be bigger than for a rigid hub. This issue can be also seen in the extrapolation diagrams. The events with a small probability of exceedance are distributed broadly. To make a reliable load prediction would require more simulation data.

Another delicate point is the non linear teeter restraint. The extrapolation method is trying to fit the simulated events into a single probability function, which should match the data. But the loads are not distributed by a continuous function but rather by a step function. After leaving the free area the soft stop is pushing against the rotor with a low spring rate. If the teeter angle gets bigger, the hard stop is applied with a ten times bigger spring rate. These unequal conditions were seen in the extrapolation graph of the maximum teeter angle (figure 4.13).

As a result, the complex load extrapolation is made more complicated by an additional non linear teeter restraint. A greater number of simulation runs are required and the fitting of the curves has to be carefully adjusted. Considering this complexity, a load extrapolation for a teeter hub with a non linear teeter restraint cannot be recommended.

Overall

Overall, the final rating of the tested teeter concept is positive. Although it is not possible to change the hub without further rearrangements, the reduction potential of a teeter hub could be proven. The increased extreme loads should be compensated by the huge reduction of fatigue loads, which mainly determine the lifetime of a turbine. As a key parameter for a successful teeter concept, the teeter restraint characteristics have to be customized for each turbine model. The available space between the blade tips and the tower surface has to be used completely to gain the most profit out of the concept. A wider stop section should be able to slow down the rotor gently without causing any extreme load peaks. Attention should be also paid to the rotational speed of the rotor, which could be one really important factor for an efficient teeter concept.

5.2 Outlook

Further development of the teeter concept should begin with a case study about the teeter characteristics. Balancing the extreme loads against the fatigue loads is thereby the main task. To accelerate the simulation progress the number of load cases has to be reduced. Focusing on the third IEC edition and the load cases which produce the extreme loads (based on the results of this thesis) the number of relevant load cases could be reduced to about 100 for each teeter configuration.

After optimizing the teeter restraint parameters a further advancement of the teeter concept should contain a pitch-teeter coupling. Regardless of whether the coupling is realized by a delta-3 angle or an individual pitch control the additional reduction potential is huge. A case study of a 45 deg delta-3 angle has resulted in an additional 50 % fatigue load reduction of the hub bending moment compared to a simple teeter hub. This method may also have the potential to reduce the extreme loads.

Another more practical case study should treat the teeter lock possibility. In the considered load cases the teeter lock was only applied in normal situations like the normal shut down and start up. But the extreme loads occurred on abnormal situations like fault situations or extreme yaw misalignment. An ideal teeter lock could improve these situations by an emergency lock function. One possibility would be a hydraulic emergency system similar to an airbag. Because of the hydraulic pitch system in the SCD turbine, the emergency system could be operated by this existing hydraulic system. But this has to be adjusted and tested for each load case separately to avoid more unfavorable loads.

Overall the concept of a self-adjusting system has the potential to scale down the loads produced by unsteady wind conditions. Keeping in mind that the turbine and rotor sizes are permanently increasing, the teeter concept is a promising concept to absorb the resulting loads. But the parameter of the turbine geometry, the teeter restraint and the control system have to be adjusted in a coordinated manner to reveal the whole potential. This requires further proceedings and simulation effort.

Appendix A

Calculation of IEC Parameters

A.1 Wind Speed Distribution

The wind speed distribution defines the occurrence time of certain wind speeds. The result is an occurrence time of a wind speed range or bin for one year. Both IEC editions are working with the Rayleigh distribution. The following formula is based on the hub height.

$$P_R\left(v_{hub}\right) = 1 - e^{-\pi\left(\frac{v_{hub}}{2v_{ave}}\right)^2} \tag{A.1}$$

The mean wind speed v_{ave} is given by the wind turbine generator system (WTGS) class in the IEC edition 2. In the third edition, it is defined as $v_{ave} = 0.2\,v_{ref}$. Both values are resulting in a average mean wind speed of $8.5\ \frac{m}{s}$.

The distribution of the probabilities of wind speed are shown in the following figure and table.

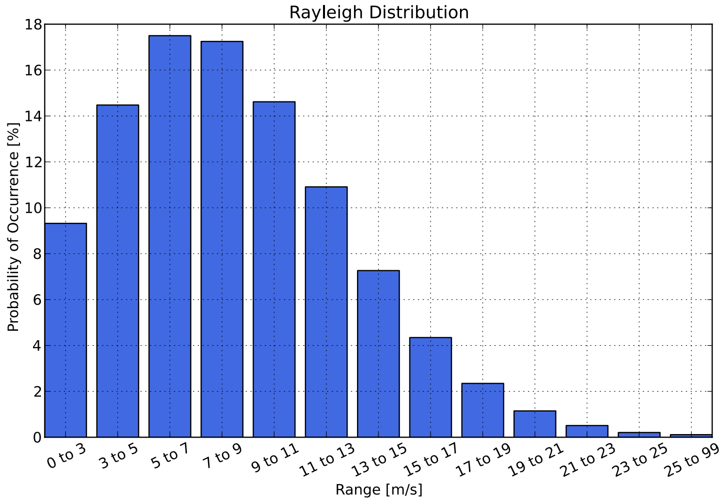


Figure A.1: Rayleigh distribution

Table A.1: Rayleigh distribution

Range [m/s]		Amount	
from	to	%	h/a
0	3	9.32	816.4
3	5	14.48	1268.1
5	7	17.50	1532.9
7	9	17.25	1510.9
9	11	14.62	1280.6
11	13	10.91	955.8
13	15	7.26	636.2
15	17	4.34	380.5
17	19	2.35	205.5
19	21	1.15	100.5
21	23	0.51	44.7
23	25	0.21	18.1
25	∞	0.11	9.8
Overall		100	8760

A.2 Normal Wind Profile Model (NWP)

The NWP defines the average wind speed as a function of height z above ground. For all standard WTGS classes, the wind speed profile should be given by the power law.

$$v(z) = v_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} \tag{A.2}$$

The power law exponent α shall be assumed with $\alpha = 0.2$, independent from the specific WTGS class.

A.3 Normal Turbulence Model (NTM)

The definition of the stochastic variations of the wind velocity is an important procedure for load simulation. The calculation of the characteristic value of the standard deviation are different in the two IEC guidelines. The main parameters are determined by the WTGS classes. In the second edition there are two parameters given.

I_{15} characteristic value of the turbulence intensity at $15\frac{m}{s}$

a slope parameter

The third edition is just working with one Parameter.

I_{ref} expected value of the turbulence intensity at $15\frac{m}{s}$

The WTGS class of the examined wind turbine is IIA. This results the following three parameters.

Table A.2: WTGS class parameters

Edition 2			
Turbulence Intensity	I_{15}	[-]	0.18
Slope Parameter	a	[-]	a
Edition 3			
Turbulence Intensity	I_{ref}	[-]	0.16

The wind turbulence is described by the characteristic value of the standard deviation of the longitudinal wind velocity from the 10 min average. It is calculated by the two following formulas.

For Edition 2:

$$\sigma_1 = I_{15} \frac{15\frac{m}{s} + a\, v_{hub}}{a+1} \tag{A.3}$$

For Edition 3:

$$\sigma_1 = I_{ref}\,(0,75\, v_{hub} + b) \;\; with\; b = 5,6\frac{m}{s} \tag{A.4}$$

The turbulence intensity TI is the quotient of the standard deviation and the wind speed at hub height.

$$TI = \frac{\sigma_1}{v_{hub}} \tag{A.5}$$

The results for both guidelines are shown in the following table.

Table A.3: NTM turbulence intensity

Wind	Edition 2		Edition 3		Wind	Edition 2		Edition 3	
v_{hub}	σ_1	TI	σ_1	TI	v_{hub}	σ_1	TI	σ_1	TI
[m/s]	[-]	[%]	[-]	[%]	[m/s]	[-]	[%]	[-]	[%]
2	1.14	57.00	1.14	56.80	16	2.82	17.63	2.82	17.60
4	1.38	34.50	1.38	34.40	18	3.06	17.00	3.06	16.98
6	1.62	27.00	1.62	26.93	20	3.30	16.50	3.30	16.48
8	1.86	23.25	1.86	23.20	22	3.54	16.09	3.54	16.07
10	2.10	21.00	2.10	20.96	24	3.78	15.75	3.78	15.73
12	2.34	19.50	2.34	19.47	26	4.02	15.46	4.02	15.45
14	2.58	18.43	2.58	18.40	28	4.26	15.21	4.26	15.20

Although the formulas look very different at first glance, the resulting turbulence intensities and standard deviations are in both guidelines nearly the same. The relations to the wind speed can be seen in the following two figures. The differences are hardly to realize, because the graphs lie on top of each other.

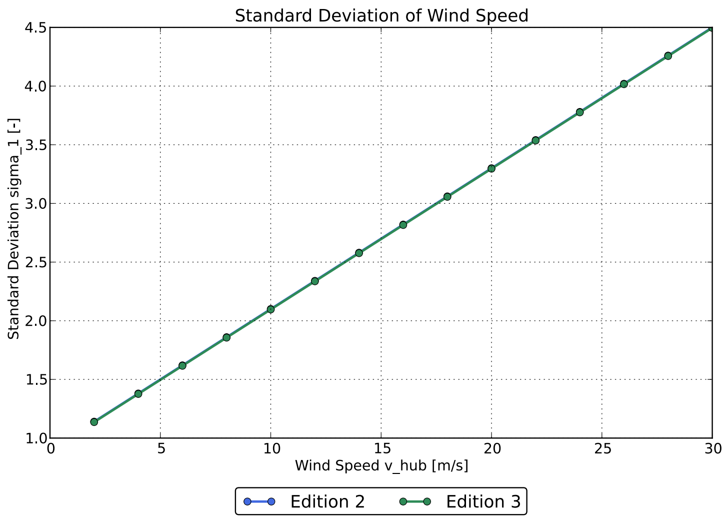


Figure A.2: Standard deviation of wind speed

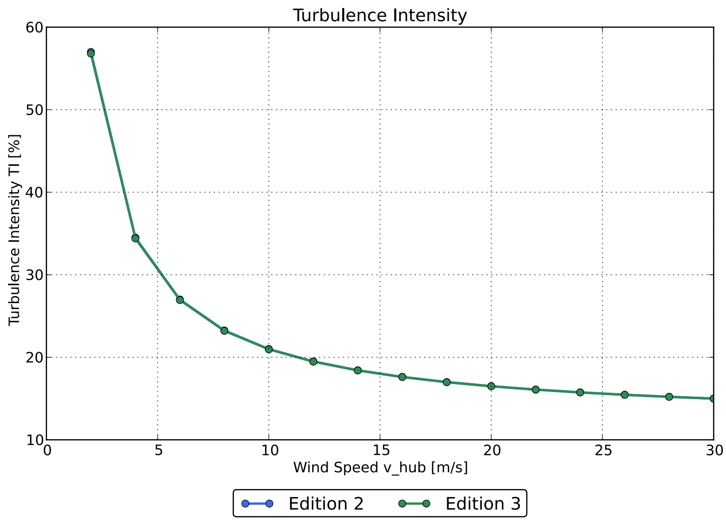


Figure A.3: Turbulence intensity over wind speed

A.4 Turbulence Model (Kaimal)

A turbulence model, which is valid for both IEC guidelines is the "Kaimal spectrum and exponential coherence model". This model is responsible for the generation of the turbulent wind files, which are needed for the NTM. This model is implemented in Bladed and just needs some parameters. There is a specific option for the second IEC edition, but the "General" option is used, because it is validated for both editions. The 5 needed parameters are shown in the following picture.

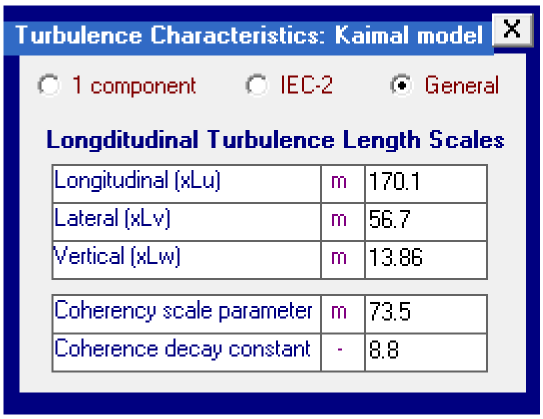


Figure A.4: Bladed settings for the Kaimal turbulence model

The first 3 parameters are the three components of the integral scale length, which are defined in the appendix of the guidelines. There is no difference in the formulas, but the turbulence scale parameter Λ_1 is determined different.

Table A.4: Turbulence spectral parameters for the Kaimal model

	Velocity component index (k)		
	1	2	3
Standard deviation σ_k	σ_k	$0.8\,\sigma_k$	$0.5\,\sigma_k$
Integral scale L_k	$8.1\,\Lambda_1$	$2.7\,\Lambda_1$	$0.66\,\Lambda_1$

The turbulence scale parameter is determined after the following formula for high hub heights.

$$\Delta_1 = \begin{cases} 21m & for\,Edition\,2\,and\,z_{hub} \geq 30m \\ 42m & for\,Edition\,3\,and\,z_{hub} \geq 60m \end{cases} \tag{A.6}$$

The other two parameters are calculated different for each edition. The values are shown in the following table.

Table A.5: Kaimal parameter

		Edition 2	Edition 3
Coherency scale parameter	L_c	$3.5\,\Delta_1$	$8.1\,\Delta_1$
Coherency decay constant	H	8.8	12

The resulting parameters are shown in the table below.

Table A.6: Kaimal model values

		Edition 2	Edition 3
Longitudinal integral scale [m]	$L_1 = L_u$	170.1	340.2
Lateral integral scale [m]	$L_2 = L_v$	56.7	113.4
Vertical integral scale [m]	$L_3 = L_w$	13.86	27.72
Coherency scale parameter [m]	L_c	73.5	340.2
Coherency decay constant [-]	H	8.8	12

For the calculation of the turbulent wind fields in Bladed, there are details for the size and resolution needed. The size of the field should cover the whole rotor plane and the complete tower. Usually the center of the field is aligned at the hub height z_{hub}. Therefore the height of the wind fields have to be at least the double height of the hub. The horizontal size is set on the rotor diameter plus a 20 m margin on each side. The resulting size is consequently 170 x 140 m.

The number of grid points is suggested by the Bladed manual with a maximal distance between the points of 10 m. With an exact distance of 10 m, the number of grid points is 18 x 15. These parameters are used for calculation of all needed wind fields.

A.5 Extreme Wind Speed Model (EWM)

The extreme wind speeds are based on the reference wind speed v_{ref}. There are two different kinds of speeds. The 50 year extreme wind speed v_{e50} and the 1 year extreme wind speed v_{e1}.

The 50 year value is defined in both IEC editions equally. The calculation of the 1 year wind speed differs.

$$v_{e50} = 1.4\, v_{ref} \tag{A.7}$$

$$v_{e1} = \begin{cases} 0.75\, v_{e50} = 1.05\, v_{ref} & for\ Edition\ 2 \\ 0.80\, v_{e50} = 1.12\, v_{ref} & for\ Edition\ 3 \end{cases} \tag{A.8}$$

The EWM is defined as a steady extreme wind model and a yaw misalignment of ±15 deg should be considered.

The third IEC edition has an additional turbulent extreme wind speed model, with the wind speeds v_{50} and v_1, which have a fixed turbulence intensity of 11%.

$$v_{50} = v_{ref} \tag{A.9}$$

$$v_1 = 0.8\, v_{50} = 0.8\, v_{ref} \tag{A.10}$$

The results are summarized in the following table.

Table A.7: EWM values

		Edition 2	Edition 3	σ_1
50 year steady	v_{e50}	59.5	59.5	0
1 year steady	v_{e1}	44.63	47.6	
50 year turbulent	v_{50}	-	42.5	$0,11\, v_{hub}$
1 year turbulent	v_1	-	34	

For all EWM simulations, the wind shear should be defined with a power law exponent $\alpha = 0.11$. This value effects a smaller difference of wind speed over height.

A.6 Extreme Operating Gust (EOG)

The size of the EOG in the second IEC edition is depending on the recurrence period of the defined situation.

$$v_{gust50} = 6.4 \left(\frac{\sigma_1}{1 + 0.1 \left(\frac{D}{\Lambda_1} \right)} \right) \tag{A.11}$$

$$v_{gust1} = 4.8 \left(\frac{\sigma_1}{1 + 0.1 \left(\frac{D}{\Lambda_1} \right)} \right) \tag{A.12}$$

The duration of the gust is $T = 14s$ for a 50-years gust and $T = 10.5s$ for a 1-year gust.

The third edition has just one kind of a EOG, with a duration of $T = 10.5s$.

$$v_{gust} = Min \begin{cases} 1.35 \left(v_{e1} - v_{hub} \right) \\ 3.3 \left(\frac{\sigma_1}{1+0.1\left(\frac{D}{\Lambda_1} \right)} \right) \end{cases} \tag{A.13}$$

The results are shown in the following table and figure. The size of the EOG is in the third edition much lower, than in the second edition.

Table A.8: EOG values

Wind Speed		Edition 2		Edition 3
v_{hub} [m/s]		v_{gust50} [m/s]	v_{gust1} [m/s]	v_{gust} [m/s]
v_{in}	4.0	6.0	4.5	3.7
$0.8\,v_r$	10.3	9.3	7.0	5.7
v_r	12.9	10.6	8.0	6.5
$1.2\,v_r$	15.5	12.0	9.0	7.4
v_{out}	25.0	16.9	12.7	10.4
Duration [s]		14.0	10.5	10.5

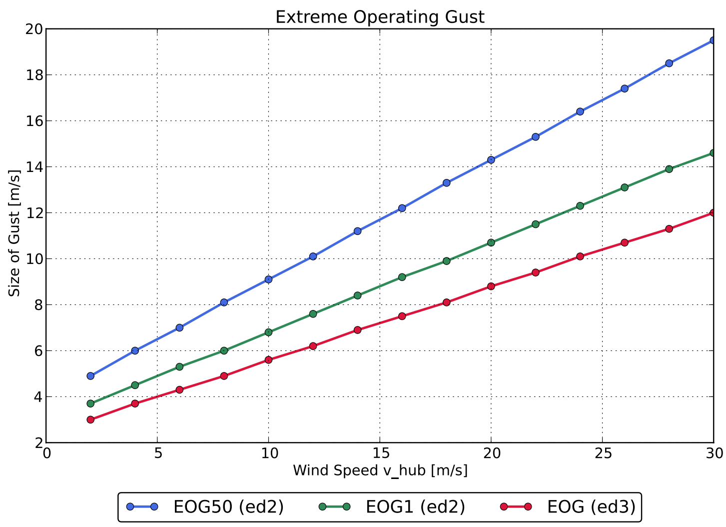


Figure A.5: EOG values

A.7 Extreme Turbulence Model (ETM)

The ETM is a extreme wind condition, which is only used in the third edition of the IEC guideline. It shall be based on the NWP, which defines the average wind speed over the height. On this wind profile the extreme turbulence is applied additionally. The formula for the standard deviation is seen below.

$$\sigma_1 = c\, I_{ref} \left(0.072 \left(\frac{v_{ave}}{c} + 3\right)\left(\frac{v_{hub}}{c} - 4\right) + 10\right) \; with\, c = 2\frac{m}{s} \tag{A.14}$$

The results for a range of wind speeds are shown in the next table.

Table A.9: ETM values

Wind Speed	Stnd. Deviation	Turb. Intensity
v_{hub} [m/s]	σ_1 [-]	TI [%]
5	2.949	59.0
10	3.367	33.7
15	3.785	25.2
20	4.202	21.0
25	4.620	18.5

The difference of the turbulence intensity between the NTM and ETM can be seen in the following figure.

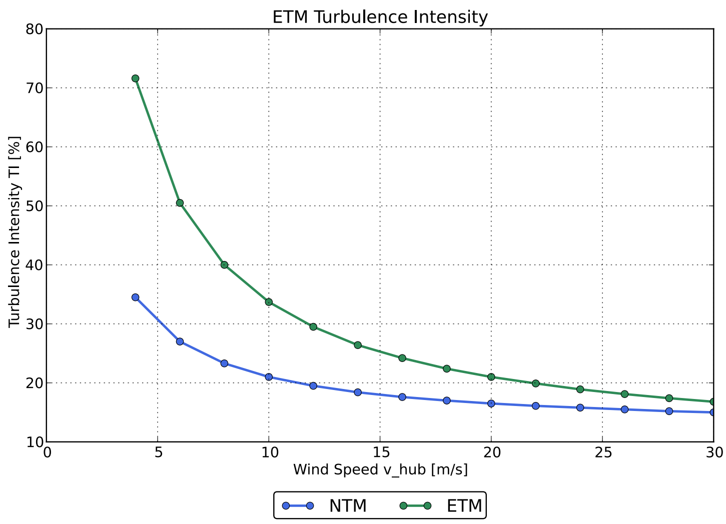


Figure A.6: Difference between NTM and ETM

A.8 Extreme Direction Change (EDC)

The EDC are a fast change of the wind direction in $T = 6s$. These changes are defined in the second edition for a recurrence period of 50 years θ_{e50} and 1 year θ_{e1} and limited to the interval ±180 deg.

$$\theta_{e50} = \pm 6.4\, arctan \left(\frac{\sigma_1}{v_{hub} \left(1 + 0.1 \left(\frac{D}{\Lambda_1}\right)\right)} \right) \tag{A.15}$$

$$\theta_{e1} = \pm 4.8\, arctan \left(\frac{\sigma_1}{v_{hub} \left(1 + 0.1 \left(\frac{D}{\Lambda_1}\right)\right)} \right) \tag{A.16}$$

In the third IEC edition, there is only a single EDC angle defined.

$$\theta_{e} = \pm 4\, arctan \left(\frac{\sigma_1}{v_{hub} \left(1 + 0.1 \left(\frac{D}{\Lambda_1}\right)\right)} \right) \tag{A.17}$$

Some required results are shown in the following table.

Table A.10: EDC values

Wind Speed		EDC50	EDC1	EDC
	v_{hub} [m/s]	θ_{e50} [deg]	θ_{e1} [deg]	θ_e [deg]
v_{in}	4.0	84.2	63.2	62.1
$0,8\, v_r$	10.3	51.2	38.4	38.0
v_r	12.9	46.9	35.2	34.8
$1,2\, v_r$	15.5	44.0	33.0	32.7
v_{out}	25.0	38.6	29.0	28.7

The difference can be seen in the next figure.

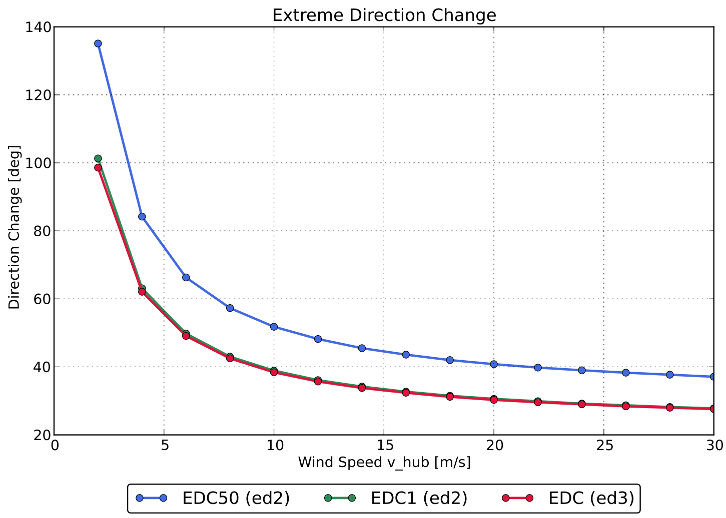


Figure A.7: EDC values

A.9 Extreme Coherent Gust (ECG)

The single ECG case is just implemented in the second edition of the IEC guideline. The gust is reaching after $T = 10s$ it's maximum amplitude of v_{cg} and keeps this wind speed permanently. The other wind conditions conform to the NWP.

$$v_{cg} = 15\,\frac{m}{s} \tag{A.18}$$

A.10 Extreme Coherent Gust with Direction Change (ECD)

In this case, the ECG should be combined with a change of wind direction. These two transient changes shall start and end simultaneously. The duration is in both editions 10s.

Although there is no ECG explicit defined in the third IEC edition, the described parameters are the same. The range of the direction change is defined by the following equation.

$$\theta_{cg}\left(v_{hub}\right) = \frac{720^{\circ}\,\frac{m}{s}}{v_{hub}} \tag{A.19}$$

Some resulting values are shown in the table below.

Table A.11: ECD values

Wind speed v_{hub}	[m/s]	4.0	10.3	12.9	15.5	25.0
Gust v_{cg}	[m/s]	15				
Direction change θ_{cg}	[deg]	180.0	69.9	55.8	46.5	28.8

A.11 Extreme Wind Shear (EWS)

At the extreme wind shear model (EWS), the normal wind shear out of $v_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha}$ gets increased for short period of time. The input parameter in Bladed is the additional wind speed difference between the borders of the rotor plane. The guideline differs between a vertical and a horizontal shear. The additional part of wind speed v_{add} causing of the wind shear is described in the following equations. The vertical part gets the index "ver" and the horizontal ones "hor".

$$v_{add,ver}(z,t) = \left(\frac{z - z_{hub}}{D}\right)\left(2.5 + 0.2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{4}}\right)\left(1 - cos\left(\frac{2\pi t}{T}\right)\right) \tag{A.20}$$

$$v_{add,hor}(y,t) = \left(\frac{y}{D}\right)\left(2.5 + 0.2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{4}}\right)\left(1 - cos\left(\frac{2\pi t}{T}\right)\right) \tag{A.21}$$

To simplify the equation, the three terms of the equations can be reduced by entering the boundary conditions into them.

First of all, the maximum appearing wind speed difference is needed. Because we have a full cycle transient, it occurs at the moment $t = T/2$, where T is the rise time of 12s. With this information, the third term in both equations becomes a constant and the equation is now independent from time.

$$1 - cos\left(\frac{2\pi t}{T}\right) \quad = \quad 1 - cos\left(\pi\right) = 2 \tag{A.22}$$

The vertical shear is defined between the biggest and smallest height of the blade tips. These limits are $z_{top} = z_{hub} + \frac{D}{2}$ and $z_{bottom} = z_{hub} - \frac{D}{2}$. These two limits can be used to get the maximum.

$$v_{add,ver,max} = v_{add,ver}(z_{top}) - v_{add,ver}(z_{bottom}) \tag{A.23}$$

$$v_{add,ver,max} = \left[\left(\frac{z - z_{hub}}{D}\right)\left(2.5 + 0.2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{4}}\right)2\right]_{z_{bottom}}^{z_{top}} \tag{A.24}$$

The term, which are independent from z can be placed outside the brackets.

$$v_{add,ver,max} = 2\left(2.5 + 0.2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{4}}\right)\left[\left(\frac{z - z_{hub}}{D}\right)\right]_{z_{bottom}}^{z_{top}} \tag{A.25}$$

The result of the box brackets is 1. Including the 2 into the brackets, the equation looks way more friendlier.

$$v_{add,ver,max} = 5 + 0.4\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{\frac{1}{4}} \tag{A.26}$$

The limits for the horizontal shear are $y_{neg} = -\frac{D}{2}$ and $y_{pos} = \frac{D}{2}$. By inserting them to the equation, the result is the same than for the vertical shear. So the Bladed parameter are for the horizontal and vertical wind speed difference is the same.

$$v_{add,max} = v_{add,ver,max} = v_{add,hor,max} \tag{A.27}$$

The equations are the same for both IEC guidelines, but two parameters are defined different. The standard deviation σ_1 is nearly the same, but the scale parameter Λ_1 of the third edition is twice the size of the parameter in the second edition. The results are listed below.

Table A.12: EWS values

Wind speed	Edition 2	Edition 3
v_{hub} [m/s]	$v_{add,max}$ [m/s]	$v_{add,max}$ [m/s]
10.3	13.1	11.8
12.9	14.3	12.8
15.5	15.5	13.8
25.0	19.8	17.4

The difference between the editions over wind speed is displayed in additionally in the next figure. The second edition specifies a bigger wind speed difference between the blade tips, than the third edition.

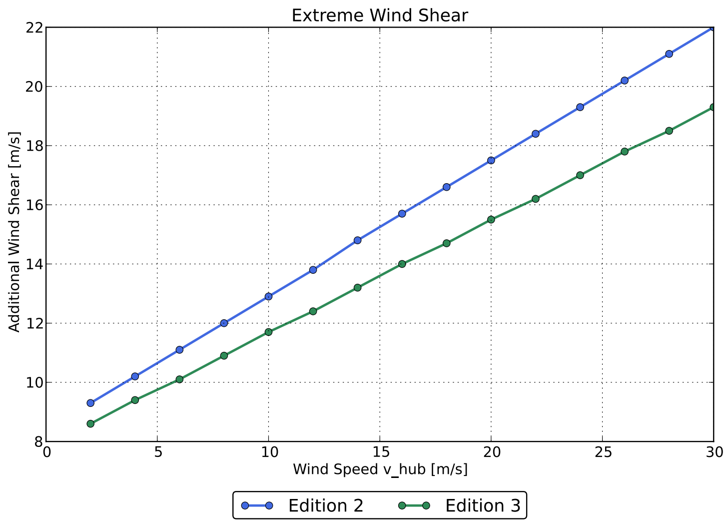


Figure A.8: EWS values

A.12 Fatigue Parameter

In Bladed, the fatigue analysis is based on single runs, with an associated runtime over one year. The following calculated runtimes are given for one defined wind speed. This runtime will be evenly distributed on the associated single wind directions.

For the fatigue calculation there are five design load cases defined in the IEC guidelines. The nominations differ in the IEC editions, but the conditions are the same.

Table A.13: Fatigue load cases

No.	Design situation	Edition 2	Edition 3	Number of Runs
1	Power production	DLC 1.2	DLC 1.2	33
2	Power prod. with fault	DLC 2.3	DLC 2.4	4
3	Start up	DLC 3.1	DLC 3.1	18
4	Normal Shut Down	DLC 4.1	DLC 4.1	18
5	Parked	DLC 6.2	DLC 6.4	18

The first and the last design load case depend on the rayleigh distribution. The other load cases are very turbine and site specific and will be stated by the designer. So these cases get a defined runtime, separated from the rayleigh distribution. And the remaining time of one year will be filled up by the power production and parked situations according to the rayleigh distribution.

The power production with fault should occur 24 hours a year. Where 20 hours should be simulated at v_r and 4 hours at v_{out}. The start up and normal shut downs should be simulated 1100 times each. These conditions got calculated for 6 different wind speeds. Although, they will appear more often at lower wind speeds, this number will be evenly distributed on the 6 wind speeds.

The remaining runtime for a year will be arranged by the rayleigh distribution. The time of the parked situation will be for the wind bins from $0...v_{in}$ and $v_{out}...\infty$. The resulting time interval will also distributed over all 6 wind speeds evenly.

The detailed procedure should be explained by the following list.

1. Power Production with Fault:
   (a) 24 hours in total.
   (b) Distributed as specified above.
2. Start Up:
   (a) 1100 start ups.
   (b) Simulation time of each run is 120 seconds, which would give 36.67 hours a year.
   (c) Distributed evenly on 6 wind speeds, results in 6.11 hours per year for each wind speed.
3. Normal Shut Down:
   (a) 1100 shut downs.
   (b) Average Simulation time of the runs is 95 seconds, which would give 29.03 hours a year.
   (c) Distributed evenly on 6 wind speeds, results in 4.84 hours per year for each wind speed.
4. Remaining time:
   (a) $t = 8760h - 24h - 36.67h - 29.03h = 8670.3h$
   (b) This will be the total time of the rayleigh distribution.
5. Parked:
   (a) Rayleigh distribution with $v_{ave} = 8.5\frac{m}{s}$
   (b) Wind bin from $0\frac{m}{s}$ to $v_{in} = 3\frac{m}{s}$ gives 9.32%
   (c) Wind bin from $v_{out} = 25\frac{m}{s}$ to $\infty\frac{m}{s}$ gives 0.11%
   (d) In total the time is 9.43% of the remaining time, which gives $817.6h$.
   (e) Distributed evenly on 6 wind speeds, results in $136.27h$ per year for each wind speed.
6. Power Production:

(a) Rayleigh distribution with $v_{ave} = 8.5\frac{m}{s}$

(b) Wind bin size is $2\frac{m}{s}$ in a range from $v_{in} = 3\frac{m}{s}$ to $v_{out} = 25\frac{m}{s}$

(c) The resulting times are shown in the next table

Table A.14: Rayleigh distribution for the power production cases

Wind Speed [m/s]		Amount of Remaining Time		Info
from	to	[%]	[h]	
0	3	9.32	808.1	Parked
3	5	14.48	1255.2	dlc1.2a
5	7	17.50	1517.2	dlc1.2b
7	9	17.25	1495.4	dlc1.2c
9	11	14.62	1267.5	dlc1.2d
11	13	10.91	946.0	dlc1.2e
13	15	7.26	629.7	dlc1.2f
15	17	4.34	376.6	dlc1.2g
17	19	2.35	203.4	dlc1.2h
19	21	1.15	99.5	dlc1.2i
21	23	0.51	44.2	dlc1.2j
23	25	0.21	17.9	dlc1.2k
25	∞	0.11	9.7	Parked

Summary of the resulting time distribution.

Table A.15: Fatigue load cases summary

No.	Design situation	Time per Load case [h/a]	Time per run [h/a]
1	Power production	DLC 1.2	Rayleigh
2	Power prod. with fault	24.0	10 / 2
3	Start up	36.7	2.0
4	Normal Shut Down	29.0	1.6
5	Parked	817.6	45.4

Appendix B

Definition of Design Load Cases

B.1 General Assumptions

This chapter summaries the important points, which where made during the definition of the load cases.

Under real conditions, there cannot be an exact yaw angle of 0 deg guaranteed. Therefore these simulations have to be done for different yaw angles, to consider all possible situations. The range of this angles is depending on the turbine controller system and is stated by the designer. The recommended range is ±15 deg according to the IEC guideline. Because of the applied controller system, these angles are ±8 deg for the simulated wind turbine. So the yaw angles -8, 0 and 8 deg are simulated for each of the load cases.

In some specific load cases, the initial rotor azimuth angle is varied, to detect the highest loads and teeter angles. A variation range of 180 deg is insufficient, because the attached pitch error and the mass imbalance between the two blades can make a difference. So the angle should be from 0 to 345 deg, with a stepsize of 15 deg. This results in 24 different initial rotor azimuth angles, which are taken for some chosen design load cases.

The composition of the single runnames has to be consistent, so that the simulation parameters can be identified very fast. The following rules are applied in the given order.

1. **Load case** - Each runname starts with the design load case number (e.g. dlc1.3 for design load case 1.3).
2. **Wind speed** - The following letter indicates the wind speed (e.g. b for for the second wind speed of the specific DLC).
3. **Seed** - If there are multiple wind fields for each wind speed, the seed number is included to the runname by a following "s" (e.g. dlc1.6a-s456 indicates, that for the wind speed a the seed number 456 was taken).

4. **Transient** - For a transient change of wind conditions there are DLC specific terms used, which are described in the corresponding tables (e.g. "neg" for a negative change of direction).

5. **Faults** - Different faults are labeled with a "f". The indexes are specified for each load case individually. For the load cases with a starting 2, the faults are group in new load case number, like dlc2.1.1 and 2.1.3 etc.

6. **Times** - If there are different moments for a start of a fault or a transient change of wind, the time is indicated with a "t" and a following index. The time values are defined in each DLC table separately.

7. **Yaw error** - A predefined error in the yaw system is given with the letter "y" and a following index. The indexes are given in the following table. (e.g. y3 for a +8 deg error in yaw)

8. **Rotor azimuth** - The initial rotor azimuth angle is given with the phrase "ra" and a following index. The indexes are also given in the next table. (e.g. ra5 stands for a initial rotor azimuth angle of 60 deg)

According to the IEC guidelines, in each simulation there is a permanent flow inclination of 8 deg defined. The time after the output starts writing is defined with at least 10s. In the used simulations, this time is set on 30s to ensure a static and stable condition.

Table B.1: Description of the indexes

Index	Yaw Error	Rotor Azimuth	Index	Rotor Azimuth
i	y [deg]	ra [deg]	i	ra [deg]
1	-8	0	13	180
2	0	15	14	195
3	8	30	15	210
4	-	45	16	225
5	-	60	17	240
6	-	75	18	255
7	-	90	19	270
8	-	105	20	285
9	-	120	21	300
10	-	135	22	315
11	-	150	23	330
12	-	165	24	345

The IEC guidelines differ in the definition of the wind speeds, which have to be treated. The validated simulations of the turbine designer have a third definition additionally. The differences are shown in the following table.

Table B.2: Definition of the wind speeds

	1	2	3	4
IEC edition 2	-	v_r	-	v_{out}
IEC edition 3	$v_r - 2\frac{m}{s}$	v_r	$v_r + 2\frac{m}{s}$	v_{out}
Turbine designer	$0.8\,v_r$	v_r	$1.2\,v_r$	v_{out}

To reach a uniform basis of simulations, the definition of the validated simulations are assumed. The advantage is, that the simulations can be compared to existing results. The deviation of the different the values is smaller than $1\,\frac{m}{s}$. And in case of Edition 2, the adopted values are just an extension. The finally taken wind speeds for the simulations are seen in the next table.

Table B.3: Assumed wind speeds

	1	2	3	4
IEC edition 2	-	12.9	-	25
IEC edition 3	10.9	12.9	14.9	25
Turbine designer	10.3	12.9	15.5	25
Taken Values	10.3	12.9	15.5	25

In some load cases, the cut in wind speed v_{in} is required. This should be $3\,\frac{m}{s}$ according to the turbine definition. But the simulation model isn't running very stable at this low wind speed, so the cut in wind speed is set on $4\,\frac{m}{s}$. The results shouldn't differ too much and the loads will be a little bit bigger.

B.2 IEC Edition 2

DLC 1 - Power Production

DLC 1.1 - Normal Turbulence Model (NTM)

Wind conditions:

- NTM

List of events:

30s	Start writing output
630s	End of simulation

Table B.4: Design load case 1.1 - Edition 2

Case	Mean Wind speed	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc1.1a	$0.8\,v_r = 10.3$	20.7	1...3	dlc1.1a-yi
dlc1.1b	$v_r = 12.9$	19.0	1...3	dlc1.1b-yi
dlc1.1c	$1.2\,v_r = 15.5$	17.8	1...3	dlc1.1c-yi
dlc1.1d	$v_{out} = 25$	15.6	1...3	dlc1.1d-yi

DLC 1.2 - Normal Turbulence Model (NTM)

Wind conditions:

- NTM

List of events:

30s Start writing output

630s End of simulation

Table B.5: Design load case 1.2 - Edition 2

Case	Wind Speed	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc1.2a	4	34.5	1...3	dlc1.2a-yi
dlc1.2b	6	27.0	1...3	dlc1.2b-yi
dlc1.2c	8	23.3	1...3	dlc1.2c-yi
dlc1.2d	10	21.0	1...3	dlc1.2d-yi
dlc1.2e	12	19.5	1...3	dlc1.2e-yi
dlc1.2f	14	18.4	1...3	dlc1.2f-yi
dlc1.2g	16	17.6	1...3	dlc1.2g-yi
dlc1.2h	18	17.0	1...3	dlc1.2h-yi
dlc1.2i	20	16.5	1...3	dlc1.2i-yi
dlc1.2j	22	16.1	1...3	dlc1.2j-yi
dlc1.2k	25	15.6	1...3	dlc1.2k-yi

DLC 1.3 - Extreme Coherent Gust with Direction Change (ECD)

Wind conditions:

- NWP + ECD

List of events:

30s Start writing output

50s Start of gust and direction change (half cycle, duration 10s)

90s End of simulation

Table B.6: Design load case 1.3 - Edition 2

Case	Mean Wind	Gust	Dir. Change	Yaw	R.Azimuth	Runname
	[m/s]	[m/s]	[deg]	y	ra	
dlc1.3a	$0.8\,v_r = 10.3$	15	+ 69.9	1...3	1...24	dlc1.3a-pos-yi-ra$i$
			- 69.9	1...3	1...24	dlc1.3a-neg-yi-ra$i$
dlc1.3b	$v_r = 12.9$	15	+ 55.8	1...3	1...24	dlc1.3b-pos-yi-ra$i$
			- 55.8	1...3	1...24	dlc1.3b-neg-yi-ra$i$

DLC 1.4 - Normal Wind Profile with Fault (NWP + Fault)

This load case should contain an external electrical fault. In the case of the current turbine, this is just a grid loss. A grid loss in combination with a gust is defined in the following load case. Because of this, the load case 1.4 can be missed out.

DLC 1.5 - Extreme Operating Gust with Grid Loss (EOG1 + Grid loss)

Wind conditions:

- NWP + EOG1

The gust is starting after 50s of simulation. The begin of the grid loss is triggered at four different points in time. They are defined according to the following criteria.

1. Start of gust
2. Lowest wind speed
3. Highest change of wind speed
4. Highest wind speed

List of events:

30s Start writing output

50s Start of gust (IEC cycle, duration 10.5s)

50s+Δt Grid loss (Emergency Stop with generator moment cut off)

90s End of simulation

Table B.7: Design load case 1.5 - Edition 2

Case	Mean Wind	Gust	Grid Loss		Yaw Error	R.Azimuth	Runname
	[m/s]	[m/s]	t	[s]	y	ra	
dlc1.5a	10.3	7.0	1	+0.00	1...3	1...24	dlc1.5a-t1-yi-ra$i$
			2	+2.45	1...3	1...24	dlc1.5a-t2-yi-ra$i$
			3	+4.00	1...3	1...24	dlc1.5a-t3-yi-ra$i$
			4	+5.25	1...3	1...24	dlc1.5a-t4-yi-ra$i$
dlc1.5b	12.9	8.0	1	+0.00	1...3	1...24	dlc1.5b-t1-yi-ra$i$
			2	+2.45	1...3	1...24	dlc1.5b-t2-yi-ra$i$
			3	+4.00	1...3	1...24	dlc1.5b-t3-yi-ra$i$
			4	+5.25	1...3	1...24	dlc1.5b-t4-yi-ra$i$
dlc1.5c	15.5	9.0	1	+0.00	1...3	1...24	dlc1.5c-t1-yi-ra$i$
			2	+2.45	1...3	1...24	dlc1.5c-t2-yi-ra$i$
			3	+4.00	1...3	1...24	dlc1.5c-t3-yi-ra$i$
			4	+5.25	1...3	1...24	dlc1.5c-t4-yi-ra$i$
dlc1.5d	25	12.7	1	+0.00	1...3	1...24	dlc1.5d-t1-yi-ra$i$
			2	+2.45	1...3	1...24	dlc1.5d-t2-yi-ra$i$
			3	+4.00	1...3	1...24	dlc1.5d-t3-yi-ra$i$
			4	+5.25	1...3	1...24	dlc1.5d-t4-yi-ra$i$

DLC 1.6 - Extreme Operating Gust (EOG50)

Wind conditions:

- NWP + EOG50

List of events:

30s	Start writing output
50s	Start of gust (IEC cycle, duration 14s)
90s	End of simulation

Table B.8: Design load case 1.6 - Edition 2

Case	Mean Wind	Gust	Yaw Error	R.Azimuth	Runname
	[m/s]	[m/s]	y	ra	
dlc1.6a	$0.8\,v_r = 10.3$	9.3	1...3	1...24	dlc1.6a-yi-ra$i$
dlc1.6b	$v_r = 12.9$	10.6	1...3	1...24	dlc1.6b-yi-ra$i$
dlc1.6c	$1.2\,v_r = 15.5$	12.0	1...3	1...24	dlc1.6c-yi-ra$i$
dlc1.6d	$v_{out} = 25$	16.9	1...3	1...24	dlc1.6d-yi-ra$i$

DLC 1.7 - Extreme Wind Shear (EWS)

Wind conditions:

- NWP + EWS

List of events:

30s Start writing output

50s Start of wind shear (full cycle, duration 12s)

90s End of simulation

Table B.9: Design load case 1.7 - Edition 2

Case	Mean Wind	Wind Shear		Yaw Error	R.Azimuth	Runname
	[m/s]	h/v	Δv_{zus}	y	ra	
dlc1.7a	10.3	h	+ 13.1	1...3	1...24	dlc1.7a-h-pos-yi-ra$i$
		h	- 13.1	1...3	1...24	dlc1.7a-h-neg-yi-ra$i$
		v	+ 13.1	1...3	1...24	dlc1.7a-v-pos-yi-ra$i$
		v	- 13.1	1...3	1...24	dlc1.7a-v-neg-yi-ra$i$
dlc1.7b	12.9	h	+ 14.3	1...3	1...24	dlc1.7b-h-pos-yi-ra$i$
		h	- 14.3	1...3	1...24	dlc1.7b-h-neg-yi-ra$i$
		v	+ 14.3	1...3	1...24	dlc1.7b-v-pos-yi-ra$i$
		v	- 14.3	1...3	1...24	dlc1.7b-v-neg-yi-ra$i$
dlc1.7c	15.5	h	+ 15.5	1...3	1...24	dlc1.7c-h-pos-yi-ra$i$
		h	- 15.5	1...3	1...24	dlc1.7c-h-neg-yi-ra$i$
		v	+ 15.5	1...3	1...24	dlc1.7c-v-pos-yi-ra$i$
		v	- 15.5	1...3	1...24	dlc1.7c-v-neg-yi-ra$i$
dlc1.7d	25	h	+ 19.8	1...3	1...24	dlc1.7d-h-pos-yi-ra$i$
		h	- 19.8	1...3	1...24	dlc1.7d-h-neg-yi-ra$i$
		v	+ 19.8	1...3	1...24	dlc1.7d-v-pos-yi-ra$i$
		v	- 19.8	1...3	1...24	dlc1.7d-v-neg-yi-ra$i$

DLC 1.8 - Extreme Direction Change (EDC50)

Wind conditions:

- NWP + EDC50

List of events:

30s Start writing output

50s Start of direction change (half cycle, duration 6s)

90s End of simulation

Table B.10: Design load case 1.8 - Edition 2

Case	Mean Wind	Change	Yaw Error	R.Azimuth	Runname
	[m/s]	[deg]	y	ra	
dlc1.8a	$0.8\,v_r = 10.3$	+ 51.2	1...3	1...24	dlc1.8a-pos-yi-ra$i$
		- 51.2	1...3	1...24	dlc1.8a-neg-yi-ra$i$
dlc1.8b	$v_r = 12.9$	+ 46.9	1...3	1...24	dlc1.8b-pos-yi-ra$i$
		- 46.9	1...3	1...24	dlc1.8b-neg-yi-ra$i$
dlc1.8c	$1.2\,v_r = 15.5$	+ 44.0	1...3	1...24	dlc1.8c-pos-yi-ra$i$
		- 44.0	1...3	1...24	dlc1.8c-neg-yi-ra$i$
dlc1.8d	$v_{out} = 25$	+ 38.6	1...3	1...24	dlc1.8d-pos-yi-ra$i$
		- 38.6	1...3	1...24	dlc1.8d-neg-yi-ra$i$

DLC 1.9 - Extreme Coherent Gust (ECG)

List of events:

30s Start writing output

50s Start of gust (half cycle, duration 10s)

90s End of simulation

Table B.11: Design load case 1.9 - Edition 2

Case	Mean Wind	Gust	Yaw	R.Azimuth	Runname
	[m/s]	[m/s]	y	ra	
dlc1.9a	$0.8v_r = 10.3$	15	1...3	1...24	dlc1.9a-yi-ra$i$
dlc1.9b	$v_r = 12.9$	15	1...3	1...24	dlc1.9b-yi-ra$i$

DLC 2 - Power Production with Fault

This group of design load cases covers the normal power production with an occurrence of fault. The fault situations are defined by the turbine designer, because the behavior of each turbine is highly depending on the control scheme.

Concerning the not fully integrated external controller, the faults are applied and the behavior of the control system imitated by triggering the stops automatically. For example, a pitch runaway starts and the controller should stop the turbine after reaching a defined misalignment to the demanded pitch angle. The needed time is calculated manually and the stop in the simulation is applied at this time, because the controller can not recognize this fault.

DLC 2.1 - Control system fault

Wind conditions:

- NWP

The following 3 faults are considered:

1. Normal Stop at $n > 19.15\,rpm$. The higher rotor speed is caused by a transient rise of wind speed (Amplitude 1 m/s for v_r and 3m/s for v_{out} # Full cycle with a period time of 40 seconds). The pitch angles are stuck in the instantaneous position, till the stop is applied. The stop is applied automatically when the limited rotor speed is reached.
2. Emergency Stop at $yaw > yaw_{max}$. The error is caused by a change of wind direction, which starts at $yaw = yaw_{error} - 5°$ and ends at $yaw = yaw_{error} + 1°$ after 6 seconds (single point history). The stop will be triggered after$\Delta t = 5s$.
3. Normal Stop at $pitch.error > pitch.error_{max} = 2°$. The pitch error angle is the difference between the measured value and the set point of the controller. Both blades run away with -0.5 deg/s and the stop is triggered after$\Delta t = 4s$.

List of events:

30s	Start writing output
50s	Start of fault
50s+Δt	Triggering of stop
120s	End of simulation

Table B.12: Design load case 2.1 - Edition 2

Case	Mean Wind	Yaw Error	R.Azimuth	Runname
	[m/s]	y	ra	
dlc2.1.1a	$v_r = 12.9$	1...3	1...24	dlc2.1.1a-yi-ra$i$
dlc2.1.1b	$v_{out} = 25$	1...3	1...24	dlc2.1.1b-yi-ra$i$
dlc2.1.2a	$v_r = 12.9$	- 80°	1...24	dlc2.1.2a-y-neg-ra$i$
		+ 80°	1...24	dlc2.1.2a-y-pos-ra$i$
dlc2.1.2b	$v_{out} = 25$	- 60°	1...24	dlc2.1.2b-y-neg-ra$i$
		+ 60°	1...24	dlc2.1.2b-y-pos-ra$i$
dlc2.1.3a	$v_r = 12.9$	1...3	1...24	dlc2.1.3a-yi-ra$i$
dlc2.1.3b	$v_{out} = 25$	1...3	1...24	dlc2.1.3b-yi-ra$i$

DLC 2.2 - Protection system fault

Wind conditions:

- NWP

The following 6 faults are considered:

1. Emergency Stop at $n > 20.5\, rpm$. The higher rotor speed is caused by a transient rise of wind speed (Amplitude 5 m/s # Full cycle with a period time of 40 seconds). The pitch angles are stuck in the instantaneous position, till the stop is applied. The stop is applied automatically when the limited rotor speed is reached.
2. Pitch runaway of all blades. All blades are pitching towards 0 deg with the maximum pitch speed of -10 deg/s. An emergency stop is triggered after$\Delta t = 0.5s$.
3. Pitch runaway of one blade. Blade 1 is pitching towards 0 deg with the maximum pitch speed of -10 deg/s. An emergency stop is triggered after$\Delta t = 0.5s$.
4. Yaw runaway. The maximal yaw speed is 0.6 deg/s. Emergency stop at $yaw > yaw_{max}$. The simulation starts at $yaw = yaw_{max} - 6°$ and the stop is triggered after $\Delta t = 10s$. Caused by Change of wind direction with a single point history.
5. Pitch system failure. Blade 1 is stuck in it's current position. An emergency stop is triggered after$\Delta t = 2s$. The failed blade stays in the position, while blade 2 is pitching towards 90 degrees. Blade 1 keeps in it's position.
6. Generator short circuit. In this case, an emergency stop is triggered and the shaft brake is applied immediately. Simulated like a grid loss, with an immediately dropping generator torque.

List of events:

30s	Start writing output
50s	Start of Fault
50s+Δt	Triggering of stop
90s	End of simulation

Table B.13: Design load case 2.2 - Edition 2

Case	Mean Wind [m/s]	Yaw Error y	R.Azimuth ra	Runname
dlc2.2.1a	$v_r = 12.9$	1...3	1...24	dlc2.2.1a-yi-ra$i$
dlc2.2.1b	$v_{out} = 25$	1...3	1...24	dlc2.2.1b-yi-ra$i$
dlc2.2.2a	$v_{out} = 25$	1...3	1...24	dlc2.2.2a-yi-ra$i$
dlc2.2.3a	$v_{out} = 25$	1...3	1...24	dlc2.2.3a-yi-ra$i$
dlc2.2.4a	$v_r = 12.9$	- 80	1...24	dlc2.2.4a-y-neg-ra$i$
		+ 80	1...24	dlc2.2.4a-y-pos-ra$i$
dlc2.2.4b	$v_{out} = 25$	- 60	1...24	dlc2.2.4b-y-neg-ra$i$
		+ 60	1...24	dlc2.2.4b-y-pos-ra$i$
dlc2.2.5a	$v_r = 12.9$	1...3	1...24	dlc2.2.5a-yi-ra$i$
dlc2.2.5b	$v_{out} = 25$	1...3	1...24	dlc2.2.5b-yi-ra$i$
dlc2.2.6a	$v_r = 12.9$	1...3	1...24	dlc2.2.6a-yi-ra$i$
dlc2.2.6b	$v_{out} = 25$	1...3	1...24	dlc2.2.6b-yi-ra$i$

DLC 2.3 - Control or protection system fault

This load case contains a control or protection system fault for the fatigue analysis. According to the turbine designer, this should be a normal power production at maximum yaw error. The turbine is running 24 hours per year in this maximum allowable yaw error. There is no stop applied.

Wind conditions:

- NTM

List of events:

30s Start writing output

630s End of simulation

Table B.14: Design load case 2.3 - Edition 2

Case	Mean Wind	Yaw Error	Runname
	[m/s]	y	
dlc2.3a	$v_r = 12.9$	-80	dlc2.3a-y1
		80	dlc2.3a-y2
dlc2.3b	$v_{out} = 25$	-60	dlc2.3b-y1
		60	dlc2.3b-y2

DLC 3 - Start Up

All start up simulations are starting from the parked situation. The output gets written with no delay, different to the other simulations. The final pitch angle is addicted to the simulated wind speed.

DLC 3.1 - Start Up (Start)

Wind conditions:

- NWP

List of events:

0s Start writing output

0s Start pitching to final pitch angle

120s End of simulation

Table B.15: Design load case 3.1 - Edition 2

Case	Mean Wind	Final Pitch	Yaw Error	Runname
	[m/s]	[deg]	y	
dlc3.1a	4	0	1...3	dlc3.1a-y*i*
dlc3.1b	8	0	1...3	dlc3.1b-y*i*
dlc3.1c	12	0	1...3	dlc3.1c-y*i*
dlc3.1d	16	15	1...3	dlc3.1d-y*i*
dlc3.1e	20	20	1...3	dlc3.1e-y*i*
dlc3.1f	25	25	1...3	dlc3.1f-y*i*

DLC 3.2 - Start Up with Extreme Operating Gust (Start + EOG1)

Wind conditions:

- NWP + EOG1

List of events:

0s Start writing output

0s Start pitching to final pitch angle

t Start of gust # t = [0,10,20,30,40] s # IEC cycle, duration 10.5s

120s End of simulation

Table B.16: Design load case 3.2 - Edition 2

Case	Mean Wind	Final Pitch	Gust	Time	Yaw Error	Runname
	[m/s]	[deg]	[m/s]	t	y	
dlc3.2a	4	0	4.5	1...5	1...3	dlc3.2a-t*i*-y*i*
dlc3.2b	10.3	0	7.0	1...5	1...3	dlc3.2b-t*i*-y*i*
dlc3.2c	12.9	5	8.0	1...5	1...3	dlc3.2c-t*i*-y*i*
dlc3.2d	15.5	15	9.0	1...5	1...3	dlc3.2d-t*i*-y*i*
dlc3.2e	25	25	12.7	1...5	1...3	dlc3.2e-t*i*-y*i*

DLC 3.3 - Start Up with Extreme Direction Change (Start + EDC1)

Wind conditions:

- NWP + EDC1

The final pitch angles are identical with the angles defined in DLC 3.2.
List of events:

0s Start writing output

0s Start pitching to final pitch angle

t Start of extreme direction change # t = [0,10,20,30,40] s # half cycle, duration 6s

120s End of simulation

Table B.17: Design load case 3.3 - Edition 2

Case	Mean Wind [m/s]	EDC [deg]	Time t	Yaw Error y	Runname
dlc3.3a	4	+ 63.2	1...5	1...3	dlc3.3a-pos-ti-yi
		- 63.2	1...5	1...3	dlc3.3a-neg-ti-yi
dlc3.3b	10.3	+ 38.4	1...5	1...3	dlc3.3b-pos-ti-yi
		- 38.4	1...5	1...3	dlc3.3b-neg-ti-yi
dlc3.3c	12.9	+ 35.2	1...5	1...3	dlc3.3c-pos-ti-yi
		- 35.2	1...5	1...3	dlc3.3c-neg-ti-yi
dlc3.3d	15.5	+ 33.0	1...5	1...3	dlc3.3d-pos-ti-yi
		- 33.0	1...5	1...3	dlc3.3d-neg-ti-yi
dlc3.3e	25	+ 29.0	1...5	1...3	dlc3.3e-pos-ti-yi
		- 29.0	1...5	1...3	dlc3.3e-neg-ti-yi

DLC 4 - Normal Shut Down

The normal stops is working with a pitch speed of 1 deg/s. Bladed stops the simulation when the rotor speed is reaching 0 rpm. The maximal simulation time is limited to 180s, but will not be reached.

DLC 4.1 - Normal Shut Down (Nstop)

Wind conditions:

- NWP

List of events:

30s Start writing output

50s Start normal stop

180s End of simulation

Table B.18: Design load case 4.1 - Edition 2

Case	Mean Wind	Yaw Error	Runname
	[m/s]	y	
dlc4.1a	4	1...3	dlc4.1a-yi
dlc4.1b	8	1...3	dlc4.1b-yi
dlc4.1c	12	1...3	dlc4.1c-yi
dlc4.1d	16	1...3	dlc4.1d-yi
dlc4.1e	20	1...3	dlc4.1e-yi
dlc4.1f	25	1...3	dlc4.1f-yi

DLC 4.2 - Normal Shut Down with Extreme Operating Gust (Nstop + EOG1)

Wind conditions:

- NWP + EOG1

List of events:

30s Start writing output

50s+$\triangle t$ Start of gust (IEC cycle, duration 10.5 s)

50s Start normal stop

180s End of simulation

Table B.19: Design load case 4.2 - Edition 2

Case	Wind	Gust	Time of Gust		Yaw Error	R.Azimuth	Runname
	[m/s]	[m/s]	t	[s]	y	ra	
dlc4.2a	10.3	7.0	1	-0.00	1...3	1...24	dlc4.2a-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2a-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2a-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2a-t4-yi-ra$i$
dlc4.2b	12.9	8.0	1	-0.00	1...3	1...24	dlc4.2b-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2b-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2b-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2b-t4-yi-ra$i$
dlc4.2c	15.5	9.0	1	-0.00	1...3	1...24	dlc4.2c-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2c-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2c-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2c-t4-yi-ra$i$
dlc4.2d	25	12.7	1	-0.00	1...3	1...24	dlc4.2d-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2d-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2d-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2d-t4-yi-ra$i$

DLC 5 - Emergency Shut Down

The emergency stops are working with a pitch speed of 5 deg/s. The maximal simulation time is limited to 120s, but will not be reached.

DLC 5.1 - Emergency Shut Down (Estop)

Wind conditions:

- NWP

List of events:

30s Start writing output

50s Start emergency stop

120s End of simulation

Table B.20: Design load case 5.1 - Edition 2

Case	Mean Wind	Yaw	R.Azimuth	Runname
	[m/s]	y	ra	
dlc5.1a	$0.8\, v_r = 10.3$	1...3	1...24	dlc5.1a-yi-ra$i$
dlc5.2b	$v_r = 12.9$	1...3	1...24	dlc5.1b-yi-ra$i$
dlc5.2c	$1.2\, v_r = 15.5$	1...3	1...24	dlc5.1c-yi-ra$i$
dlc5.2d	$v_{out} = 25$	1...3	1...24	dlc5.1d-yi-ra$i$

DLC 6 - Parked

The following design load cases should be simulated for parked or idling conditions. Because of some turbine specific requirements, there is no idling mode designed for this wind turbine. So all simulations of this load case are defined in a parked mode.

Under normal parked conditions, the turbine is parked on a yaw angle of 270 degrees. So the wind direction is 90 degrees from north, oriented to the nacelle. This means, that the simulated yaw angles with the considered yaw misalignment are 82, 90 and 98 deg.

DLC 6.1 - Parked with Extreme Wind Speed (Parked + EWM50)

A Possible loss of the electrical power network should be considered. This results that the turbine can't control the yaw angle, so a maximum yaw error of ±180 deg should be simulated.

Wind conditions:

- EWM v_{e50}

- Wind gradient $\alpha = 0.11$
- No variation in wind speed
- 12 yaw errors # Range: -150 to 180 deg # Stepsize: 30 deg

List of events:

30s	Start writing output
90s	End of simulation

Table B.21: Design load case 6.1 - Edition 2

Case	Mean Wind	Yaw	Runname
	[m/s]	y	
dlc6.1a	$v_{e50} = 59.5$	1...12	dlc6.1a-yi

DLC 6.2 - Parked with Normal Turbulence Model (Parked + NTM)

Wind conditions:

- NTM with $v_{hub} \leq 0.7\, v_{ref} = 29.8 \frac{m}{s}$
- Yaw angles y = [82, 90, 98] deg

List of events:

30s	Start writing output
630s	End of simulation

Table B.22: Design load case 6.2 - Edition 2

Case	Mean Wind	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc6.2a	$v_{in} = 4.0$	34.5	1...3	dlc6.2a-yi
dlc6.2b	$0.8\, v_r = 10.3$	20.7	1...3	dlc6.2b-yi
dlc6.2c	$v_r = 12.9$	19.0	1...3	dlc6.2c-yi
dlc6.2d	$1.2\, v_r = 15.5$	17.8	1...3	dlc6.2d-yi
dlc6.2e	$v_{out} = 25.0$	15.6	1...3	dlc6.2e-yi
dlc6.2f	$0.7\, v_{ref} = 29.8$	15.0	1...3	dlc6.2f-yi

DLC 7 - Parked with Fault

The conditions are similar to DLC 6, but some additional faults are considered.

DLC 7.1 - Parked with Extreme Wind Speed and Fault (Parked + EWM1 + Fault)

Wind conditions:

- EWM v_{e1}
- NWP with $\alpha = 0.11$
- No variation in wind speed
- Yaw angles y = [82, 90, 98] deg

4 Faults are considered:

1. Yaw failure # 12 yaw angles # Range: -150 to 180 deg # Stepsize: 30 deg
2. Pitch failure on one blade (Blade 1) # Other blade is 90 deg # 10 pitch angles # Range: 0 to 90 deg # Stepsize: 10 deg
3. Rotor azimuth failure # 24 azimuth angles # Range: 0 to 345 deg # Stepsize: 15 deg
4. Teeter lock fault # Normal parked conditions

List of events:

0s	Fault is applied
30s	Start writing output
90s	End of simulation

Table B.23: Design load case 7.1 - Edition 2

Case	Mean Wind	Fault		Yaw	Runname
	[m/s]	error	f	y	
dlc7.1a	$v_{e1} = 44.6$	yaw	1...12	-	dlc7.1a-fi
dlc7.1b		pitch	1...10	1...3	dlc7.1b-fi-yi
dlc7.1c		azimuth	1...24	1...3	dlc7.1c-fi-yi
dlc7.1d		teeter lock	1	1...3	dlc7.1d-fi-yi

DLC 8 - Transport, Assembly and Maintenance

DLC 8.1 covers the transport, assembly, maintenance and repair situations. The simulation is very specific and will be not further considered.

B.3 IEC Edition 3

DLC 1 - Power Production

DLC 1.1 - Normal Turbulence Model (NTM) - For Extrapolation

This load case is used for the extrapolation of extreme events. Therefore a set of multiple simulation runs is required. These simulations shall be distributed over a range of significant wind conditions.

Because of the great influence of the turbulence in wind on the loads and the teeter angle, there are also 6 different seeds for each wind speed used. This makes 198 simulations, each over a period of 10 minutes. The total time of 1980 minutes should be a sufficient statistical basis for the extrapolation.

Wind conditions:

- NTM

List of events:

30s Start writing output

630s End of simulation

Table B.24: Design load case 1.1 - Edition 3

Case	Wind Speed	TI	Seed	Yaw	Runname
	[m/s]	[%]	s	y	
dlc1.1a	4	34.4	1...6	1...3	dlc1.1a-s#-y*i*
dlc1.1b	6	26.9	1...6	1...3	dlc1.1b-s#-y*i*
dlc1.1c	8	23.2	1...6	1...3	dlc1.1c-s#-y*i*
dlc1.1d	10	21.0	1...6	1...3	dlc1.1d-s#-y*i*
dlc1.1e	12	19.5	1...6	1...3	dlc1.1e-s#-y*i*
dlc1.1f	14	18.4	1...6	1...3	dlc1.1f-s#-y*i*
dlc1.1g	16	17.6	1...6	1...3	dlc1.1g-s#-y*i*
dlc1.1h	18	17.0	1...6	1...3	dlc1.1h-s#-y*i*
dlc1.1i	20	16.5	1...6	1...3	dlc1.1i-s#-y*i*
dlc1.1j	22	16.1	1...6	1...3	dlc1.1j-s#-y*i*
dlc1.1k	25	15.6	1...6	1...3	dlc1.1k-s#-y*i*

DLC 1.2 - Normal Turbulence Model (NTM) - For Fatigue Analysis

Wind conditions:

- NTM

List of events:

30s Start writing output

630s End of simulation

Table B.25: Design load case 1.2 - Edition 3

Case	Wind Speed	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc1.2a	4	34.4	1...3	dlc1.2a-yi
dlc1.2b	6	26.9	1...3	dlc1.2b-yi
dlc1.2c	8	23.2	1...3	dlc1.2c-yi
dlc1.2d	10	21.0	1...3	dlc1.2d-yi
dlc1.2e	12	19.5	1...3	dlc1.2e-yi
dlc1.2f	14	18.4	1...3	dlc1.2f-yi
dlc1.2g	16	17.6	1...3	dlc1.2g-yi
dlc1.2h	18	17.0	1...3	dlc1.2h-yi
dlc1.2i	20	16.5	1...3	dlc1.2i-yi
dlc1.2j	22	16.1	1...3	dlc1.2j-yi
dlc1.2k	25	15.6	1...3	dlc1.2k-yi

DLC 1.3 - Extreme Turbulence Model (ETM)

Wind conditions:

- ETM

List of events:

30s Start writing output

630s End of simulation

Table B.26: Design load case 1.3 - Edition 3

Case	Wind Speed	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc1.3a	4	71.6	1...3	dlc1.3a-yi
dlc1.3b	6	50.5	1...3	dlc1.3b-yi
dlc1.3c	8	40.0	1...3	dlc1.3c-yi
dlc1.3d	10	33.7	1...3	dlc1.3d-yi
dlc1.3e	12	29.5	1...3	dlc1.3e-yi
dlc1.3f	14	26.4	1...3	dlc1.3f-yi
dlc1.3g	16	24.2	1...3	dlc1.3g-yi
dlc1.3h	18	22.4	1...3	dlc1.3h-yi
dlc1.3i	20	21.0	1...3	dlc1.3i-yi
dlc1.3j	22	19.9	1...3	dlc1.3j-yi
dlc1.3k	25	18.5	1...3	dlc1.3k-yi

DLC 1.4 - Extreme Coherent Gust with Direction Change (ECD)

Wind conditions:

- NWP + ECD

List of events:

30s Start writing output

50s Start of gust and direction change (half cycle, duration 10s)

90s End of simulation

Table B.27: Design load case 1.4 - Edition 3

Case	Mean Wind	Gust	Dir. Change	Yaw	R.Azimuth	Runname
	[m/s]	[m/s]	[deg]	y	ra	
dlc1.4a	$0.8\,v_r = 10.3$	15	+69.9	1...3	1...24	dlc1.4a-pos-yi-ra$i$
			-69.9	1...3	1...24	dlc1.4a-neg-yi-ra$i$
dlc1.4b	$v_r = 12.9$	15	+55.8	1...3	1...24	dlc1.4b-pos-yi-ra$i$
			-55.8	1...3	1...24	dlc1.4b-neg-yi-ra$i$
dlc1.4c	$1.2\,v_r = 15.5$	15	+46.5	1...3	1...24	dlc1.4c-pos-yi-ra$i$
			-46.5	1...3	1...24	dlc1.4c-neg-yi-ra$i$

DLC 1.5 - Extreme Wind Shear (EWS)

Wind conditions:

- NWP + EWS

List of events:

30s Start writing output

50s Start of wind shear (full cycle, duration 12s)

90s End of simulation

Table B.28: Design load case 1.5 - Edition 3

Case	Mean Wind	Wind Shear		Yaw Error	R.Azimuth	Runname
	[m/s]	h/v	Δv_{zus}	y	ra	
dlc1.5a	$0.8\,v_r = 10.3$	h	+ 11.8	1...3	1...24	dlc1.5a-h-pos-yi-ra$i$
		h	- 11.8	1...3	1...24	dlc1.5a-h-neg-yi-ra$i$
		v	+ 11.8	1...3	1...24	dlc1.5a-v-pos-yi-ra$i$
		v	- 11.8	1...3	1...24	dlc1.5a-v-neg-yi-ra$i$
dlc1.5b	$v_r = 12.9$	h	+ 12.8	1...3	1...24	dlc1.5b-h-pos-yi-ra$i$
		h	- 12.8	1...3	1...24	dlc1.5b-h-neg-yi-ra$i$
		v	+ 12.8	1...3	1...24	dlc1.5b-v-pos-yi-ra$i$
		v	- 12.8	1...3	1...24	dlc1.5b-v-neg-yi-ra$i$
dlc1.5c	$1.2\,v_r = 15.5$	h	+ 13.8	1...3	1...24	dlc1.5c-h-pos-yi-ra$i$
		h	- 13.8	1...3	1...24	dlc1.5c-h-neg-yi-ra$i$
		v	+ 13.8	1...3	1...24	dlc1.5c-v-pos-yi-ra$i$
		v	- 13.8	1...3	1...24	dlc1.5c-v-neg-yi-ra$i$
dlc1.5d	$v_{out} = 25$	h	+ 17.4	1...3	1...24	dlc1.5d-h-pos-yi-ra$i$
		h	- 17.4	1...3	1...24	dlc1.5d-h-neg-yi-ra$i$
		v	+ 17.4	1...3	1...24	dlc1.5d-v-pos-yi-ra$i$
		v	- 17.4	1...3	1...24	dlc1.5d-v-neg-yi-ra$i$

DLC 2 - Power Production with Fault

DLC 2.1 - Control System Fault

Wind conditions:

- NTM

There are 3 different faults applied, which are similar to the second IEC Edition:

1. Normal Stop at $n > 19.15\,rpm$. The higher rotor speed is caused by a permanent pitch failure rate of -0.5 deg/s for both blades. The stop is applied when the defined rotor speed is reached.
2. Emergency Stop at $yaw > yaw_{max}$. The error is caused by a change of wind direction, which starts at $yaw = yaw_{error} - 5°$ and ends at $yaw = yaw_{error} + 1°$ after 6 seconds (additional wind direction transient, half cycle). The stop will be triggered after$\Delta t = 5s$.
3. Normal Stop at $pitch.error > pitch.error_{max} = 2°$. The pitch error angle is the difference between the measured value and the set point. Both blades run away with -0.5 deg/s and the stop is triggered after$\Delta t = 4s$.

List of events:

10s	Start time for turbulent wind (more stable)
30s	Start writing output

50s Start of Fault

50s+Δt Triggering of stop

120s End of simulation

Table B.29: Design load case 2.1 - Edition 3

Case	Mean Wind	Yaw Error	R.Azimuth	Runname
	[m/s]	y	ra	
dlc2.1.1a	$v_r = 12.9$	1...3	1...24	dlc2.1.1a-yi-ra$i$
dlc2.1.1b	$v_{out} = 25$	1...3	1...24	dlc2.1.1b-yi-ra$i$
dlc2.1.2a	$v_r = 12.9$	- 80°	1...24	dlc2.1.2a-y-neg-ra$i$
		+ 80°	1...24	dlc2.1.2a-y-pos-ra$i$
dlc2.1.2b	$v_{out} = 25$	- 60°	1...24	dlc2.1.2b-y-neg-ra$i$
		+ 60°	1...24	dlc2.1.2b-y-pos-ra$i$
dlc2.1.3a	$v_r = 12.9$	1...3	1...24	dlc2.1.3a-yi-ra$i$
dlc2.1.3b	$v_{out} = 25$	1...3	1...24	dlc2.1.3b-yi-ra$i$

DLC 2.2 - Protection System Fault

Wind conditions:

- NTM

There are 5 different faults applied, which are similar to the second IEC Edition:

1. Emergency Stop at $n > 20.5\,rpm$. The higher rotor speed is caused by a permanent pitch failure rate of -1.0 deg/s for both blades. The stop is applied when the defined Rotor Speed is reached.
2. Pitch runaway of all blades. All blades are pitching towards 0 deg with the maximum pitch speed of -10 deg/s. An emergency stop is triggered after$\Delta t = 0.5s$.
3. Pitch runaway of one blade. Blade 1 is pitching towards 0 deg with the maximum pitch speed of -10 deg/s. An emergency stop is triggered after$\Delta t = 0.5s$.
4. Pitch system failure. Blade 1 is stuck in it's actual position. An emergency stop is triggered after$\Delta t = 2s$. The failed blade stays in the position, while blade 2 is pitching towards 90 degrees. Blade 1 stays in it's position.
5. Generator short circuit. In this case, an emergency stop is triggered and the shaft brake is applied immediately. Simulated like a grid loss, with an immediately dropping generator torque.

List of events:

10s Start time for turbulent wind (more stable)

30s	Start writing output
50s	Start of fault
50s+Δt	Triggering of stop
90s	End of simulation

Table B.30: Design load case 2.2 - Edition 3

Case	Mean Wind	Yaw Error	R.Azimuth	Runname
	[m/s]	y	ra	
dlc2.2.1a	$v_r = 12.9$	1...3	1...24	dlc2.2.1a-yi-ra$i$
dlc2.2.1b	$v_{out} = 25$	1...3	1...24	dlc2.2.1b-yi-ra$i$
dlc2.2.2a	$v_r = 12.9$	1...3	1...24	dlc2.2.2a-yi-ra$i$
dlc2.2.2b	$v_{out} = 25$	1...3	1...24	dlc2.2.2b-yi-ra$i$
dlc2.2.3a	$v_r = 12.9$	1...3	1...24	dlc2.2.3a-yi-ra$i$
dlc2.2.3b	$v_{out} = 25$	1...3	1...24	dlc2.2.3b-yi-ra$i$
dlc2.2.4a	$v_r = 12.9$	1...3	1...24	dlc2.2.4a-yi-ra$i$
dlc2.2.4b	$v_{out} = 25$	1...3	1...24	dlc2.2.4b-yi-ra$i$
dlc2.2.5a	$v_r = 12.9$	1...3	1...24	dlc2.2.5a-yi-ra$i$
dlc2.2.5b	$v_{out} = 25$	1...3	1...24	dlc2.2.5b-yi-ra$i$

DLC 2.3 - Electrical Fault including Grid Loss

According to the turbine designer, the only electrical fault is a grid loss.
Wind conditions:

- NWP + EOG

The gust is starting after 50s of simulation. The moment of the grid loss is triggered at four different points in time, by an emergency stop (Δt = [0.00,2.45,4.00,5.25]). This load case is similar to the DLC 1.5 in IEC Edition 2.
List of events:

30s	Start writing output
50s	Start of gust (IEC cycle, duration 10.5s)
50s-Δt	Grid loss
90s	End of simulation

Table B.31: Design load case 2.3 - Edition 3

Case	Mean Wind	Gust	Grid Loss	Yaw Error	R.Azimuth	Runname
	[m/s]	[m/s]	t	y	ra	
dlc2.3a	10.3	5.7	1...4	1...3	1...24	dlc2.3a-ti-yi-ra$i$
dlc2.3b	12.9	6.5	1...4	1...3	1...24	dlc2.3b-ti-yi-ra$i$
dlc2.3c	15.5	7.4	1...4	1...3	1...24	dlc2.3c-ti-yi-ra$i$
dlc2.3d	25.0	10.4	1...4	1...3	1...24	dlc2.3d-ti-yi-ra$i$

DLC 2.4 - Fault without Shutdown

This load case contains a control or protection system fault for the fatigue analysis, that causes no shutdown. According to the turbine designer, this should be a normal power production at maximum yaw error. The turbine is running 24 hours per year in this maximum allowable yaw error. There is no stop applied. This load case is similar to DLC 2.3 in IEC Edition 2.

Wind conditions:

- NTM

List of events:

30s	Start writing output
630s	End of simulation

Table B.32: Design load case 2.4 - Edition 3

Case	Mean Wind	Yaw Error	Runname
	[m/s]	y	
dlc2.4a	$v_r = 12.9$	-80	dlc2.4a-y1
		80	dlc2.4a-y2
dlc2.4b	$v_{out} = 25.0$	-60	dlc2.4b-y1
		60	dlc2.4b-y2

DLC 3 - Start Up

The set up is similar to the second edition.

DLC 3.1 - Start Up (Start)

Wind conditions:

- NWP

List of events:

0s	Start writing output
0s	Start pitching to final pitch angle
120s	End of simulation

Table B.33: Design load case 3.1 - Edition 3

Case	Mean Wind	Final Pitch	Yaw Error	Runname
	[m/s]	[deg]	y	
dlc3.1a	4	0	1...3	dlc3.1a-yi
dlc3.1b	8	0	1...3	dlc3.1b-yi
dlc3.1c	12	0	1...3	dlc3.1c-yi
dlc3.1d	16	15	1...3	dlc3.1d-yi
dlc3.1e	20	20	1...3	dlc3.1e-yi
dlc3.1f	25	25	1...3	dlc3.1f-yi

DLC 3.2 - Start Up with Extreme Operating Gust (Start + EOG)

Wind conditions:

- NWP + EOG

List of events:

0s Start writing output

0s Start pitching to final pitch angle

t Start of gust # t = [0, 10, 20, 30, 40] s # IEC cycle - Duration 10.5 s

120s End of simulation

Table B.34: Design load case 3.2 - Edition 3

Case	Mean Wind	Final Pitch	Gust	Time	Yaw Error	Runname
	[m/s]	[deg]	[m/s]	t	y	
dlc3.2a	4	0	3.7	1...5	1...3	dlc3.2a-ti-yi
dlc3.2b	10.3	0	5.7	1...5	1...3	dlc3.2b-ti-yi
dlc3.2c	12.9	5	6.5	1...5	1...3	dlc3.2c-ti-yi
dlc3.2d	15.5	15	7.4	1...5	1...3	dlc3.2d-ti-yi
dlc3.2e	25	25	10.4	1...5	1...3	dlc3.2e-ti-yi

DLC 3.3 - Start Up with Extreme Direction Change (Start + EDC)

Wind conditions:

- NWP + EDC

The final pitch angles are identical with the angles defined in DLC 3.2.

List of events:

0s Start writing output

0s Start pitching to final pitch angle

t Start of extreme direction change # t = [0, 10, 20, 30, 40] s # Half cycle - Duration 6 s

120s End of simulation

Table B.35: Design load case 3.3 - Edition 3

Case	Mean Wind	EDC	Yaw Error	Time	Runname
	[m/s]	[deg]	y	t	
dlc3.3a	4.0	+ 62.1	1...3	1...5	dlc3.3a-pos-ti-yi
		- 62.1	1...3	1...5	dlc3.3a-neg-ti-yi
dlc3.3b	10.3	+ 38.0	1...3	1...5	dlc3.3b-pos-ti-yi
		- 38.0	1...3	1...5	dlc3.3b-neg-ti-yi
dlc3.3c	12.9	+ 34.8	1...3	1...5	dlc3.3c-pos-ti-yi
		- 34.8	1...3	1...5	dlc3.3c-neg-ti-yi
dlc3.3d	15.5	+ 32.7	1...3	1...5	dlc3.3d-pos-ti-yi
		- 32.7	1...3	1...5	dlc3.3d-neg-ti-yi
dlc3.3e	25.0	+ 28.7	1...3	1...5	dlc3.3e-pos-ti-yi
		- 28.7	1...3	1...5	dlc3.3e-neg-ti-yi

DLC 4 - Normal Shut Down

The set up is similar to the second IEC edition.

DLC 4.1 - Normal Shut Down (Nstop)

Wind conditions:

- NWP

List of events:

30s Start writing output

50s Start normal stop

180s End of simulation

Table B.36: Design load case 4.1 - Edition 3

Case	Mean Wind	Yaw Error	Runname
	[m/s]	y	
dlc4.1a	4	1...3	dlc4.1a-yi
dlc4.1b	8	1...3	dlc4.1b-yi
dlc4.1c	12	1...3	dlc4.1c-yi
dlc4.1d	16	1...3	dlc4.1d-yi
dlc4.1e	20	1...3	dlc4.1e-yi
dlc4.1f	25	1...3	dlc4.1f-yi

DLC 4.2 - Normal Shut Down with Extreme Operating Gust (Nstop + EOG)

Wind conditions:

- NWP + EOG

List of events:

30s Start writing output

50s Start of gust (IEC cycle, duration 10,5 s)

50s+$\triangle t$ Start normal stop

180s End of simulation

Table B.37: Design load case 4.2 - Edition 3

Case	Wind	Gust	Time of Stop		Yaw Error	R.Azimuth	Runname
	[m/s]	[m/s]	t	[s]	y	ra	
dlc4.2a	10.3	5.7	1	-0.00	1...3	1...24	dlc4.2a-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2a-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2a-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2a-t4-yi-ra$i$
dlc4.2b	12.9	6.5	1	-0.00	1...3	1...24	dlc4.2b-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2b-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2b-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2b-t4-yi-ra$i$
dlc4.2c	15.5	7.4	1	-0.00	1...3	1...24	dlc4.2c-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2c-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2c-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2c-t4-yi-ra$i$
dlc4.2d	25.0	10.4	1	-0.00	1...3	1...24	dlc4.2d-t1-yi-ra$i$
			2	-2.45	1...3	1...24	dlc4.2d-t2-yi-ra$i$
			3	-4.00	1...3	1...24	dlc4.2d-t3-yi-ra$i$
			4	-5.25	1...3	1...24	dlc4.2d-t4-yi-ra$i$

DLC 5 - Emergency Shut Down

DLC 5.1 - Emergency Shut Down (Estop)

Wind conditions:

- NTM

List of events:

30s Start writing output

50s	Start emergency stop
120s	End of simulation

Table B.38: Design load case 5.1 - Edition 3

Case	Mean Wind	Yaw	R.Azimuth	Runname
	[m/s]	y	ra	
dlc5.1a	$0.8\,v_r = 10.3$	1...3	1...24	dlc5.1a-yi-ra$i$
dlc5.2b	$v_r = 12.9$	1...3	1...24	dlc5.1b-yi-ra$i$
dlc5.2c	$1.2\,v_r = 15.5$	1...3	1...24	dlc5.1c-yi-ra$i$
dlc5.2d	$v_{out} = 25.0$	1...3	1...24	dlc5.1d-yi-ra$i$

DLC 6 - Parked

DLC 6.1 - Parked with Extreme Wind Speed (Parked + EWM50)

Wind conditions:

- Wind gradient $\alpha = 0.11$
- EWM steady - v_{e50} - No variation of wind speed
- EWM turbulent - v_{50} - Turbulence intensity = 11 %
- Yaw angles y = [82, 90, 98] deg

List of events:

30s	Start writing output
90s	End of steady simulations
630s	End of turbulent simulations

Table B.39: Design load case 6.1 - Edition 3

Case	Mean Wind	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc6.1a	$v_{e50} = 59.5$	0	1...3	dlc6.1a-yi
dlc6.1b	$v_{50} = 42.5$	11	1...3	dlc6.1b-yi

DLC 6.2 - Parked + EWM50 + Loss of Electrical Network

A Possible loss of the electrical power network should be considered. This results that the turbine can't control the yaw angle, so a maximum yaw error of ±180 deg should be simulated.

12 yaw errors # Range: -150 to 180 deg # Stepsize: 30 deg

Wind conditions:

- Wind gradient $\alpha = 0.11$
- EWM steady - v_{e50} - No variation of wind speed
- EWM turbulent - v_{50} - Turbulence intensity = 11 %

List of events:

30s Start writing output

90s End of steady simulations

630s End of turbulent simulations

Table B.40: Design load case 6.2 - Edition 3

Case	Mean Wind	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc6.2a	$v_{e50} = 59.5$	0	1...12	dlc6.2a-yi
dlc6.2b	$v_{50} = 42.5$	11	1...12	dlc6.2b-yi

DLC 6.3 - Parked + EWM1 + Extreme yaw misalignment

Wind conditions:

- Wind gradient $\alpha = 0.11$
- EWM steady - v_{e1} - No variation of wind speed
- EWM turbulent - v_1 - Turbulence intensity = 11 %
- 12 yaw errors # Range: -150 to 180 deg # Stepsize: 30 deg

List of events:

30s Start writing output

90s End of steady simulations

630s End of turbulent simulations

Table B.41: Design load case 6.3 - Edition 3

Case	Mean Wind	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc6.3a	$v_{e1} = 47.6$	0	1...12	dlc6.3a-yi
dlc6.3b	$v_1 = 34.0$	11	1...12	dlc6.3b-yi

DLC 6.4 - Parked + NTM

Wind conditions:

- NTM with $v_{hub} \leq 0.7\, v_{ref}$
- Yaw angles y = [82, 90, 98] deg

List of events:

30s	Start writing output
630s	End of simulation

Table B.42: Design load case 6.4 - Edition 3

Case	Mean Wind	TI	Yaw	Runname
	[m/s]	[%]	y	
dlc6.4a	$v_{in} = 4.0$	34.4	1...3	dlc6.4a-yi
dlc6.4b	$0.8\, v_r = 10.3$	20.7	1...3	dlc6.4b-yi
dlc6.4c	$v_r = 12.9$	18.9	1...3	dlc6.4c-yi
dlc6.4d	$1.2\, v_r = 15.5$	17.8	1...3	dlc6.4d-yi
dlc6.4e	$v_{out} = 25.0$	15.6	1...3	dlc6.4e-yi
dlc6.4f	$0.7\, v_{ref} = 29.8$	15.0	1...3	dlc6.4f-yi

DLC 7 - Parked with Fault

DLC 7.1 - Parked with Fault

Wind conditions:

- Wind gradient $\alpha = 0.11$
- EWM steady - v_{e1} - No variation of wind speed
- EWM turbulent - v_1 - Turbulence intensity = 11 %
- Yaw angles y = [82, 90, 98] deg

3 Faults are considered:

1. Pitch failure on blade 1 # Blade 2 is pitched on 90 deg # 10 different pitch angles # Range: 0 to 90 deg # Stepsize: 10 deg
2. Teeter lock fault # Normal parked conditions
3. Rotor azimuth failure # 12 different azimuth angles # Range: 0 to 330 deg # Stepsize: 30 deg

A yaw failure like in the second IEC edition is already considered in the DLC 6.3.

List of events:

0s	Fault is applied
30s	Start writing output
90s	End of steady simulations
630s	End of turbulent simulations

Table B.43: Design load case 7.1 - Edition 3

Case	Mean Wind	Fault		Yaw	Runname
	[m/s]	error	f	y	
dlc7.1a	$v_{e1} = 47.6$	pitch	1...10	1...3	dlc7.1a-fi-yi
dlc7.1b		teeter lock	1	1...3	dlc7.1b-fi-yi
dlc7.1c		azimuth	1...12	1...3	dlc7.1c-fi-yi
dlc7.1d	$v_1 = 34.0$	pitch	1...10	1...3	dlc7.1d-fi-yi
dlc7.1e		teeter lock	1	1...3	dlc7.1e-fi-yi
dlc7.1f		azimuth	1...12	1...3	dlc7.1f-fi-yi

DLC 8 - Transport, Assembly and Maintenance

DLC 8.1 covers the transport, assembly, maintenance and repair situations. The simulation is very specific and will be not further considered.

Appendix C

Diagrams and Tables

C.1 Model Validation

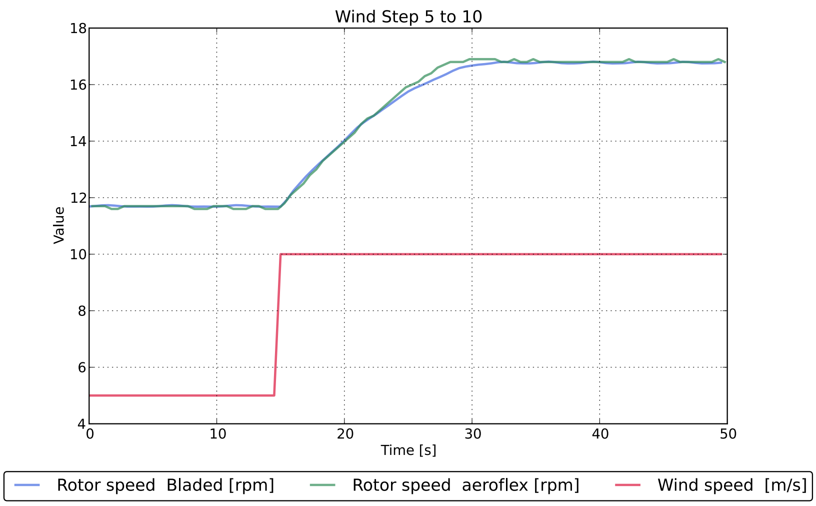


Figure C.1: Step response from 5 to 10 m/s

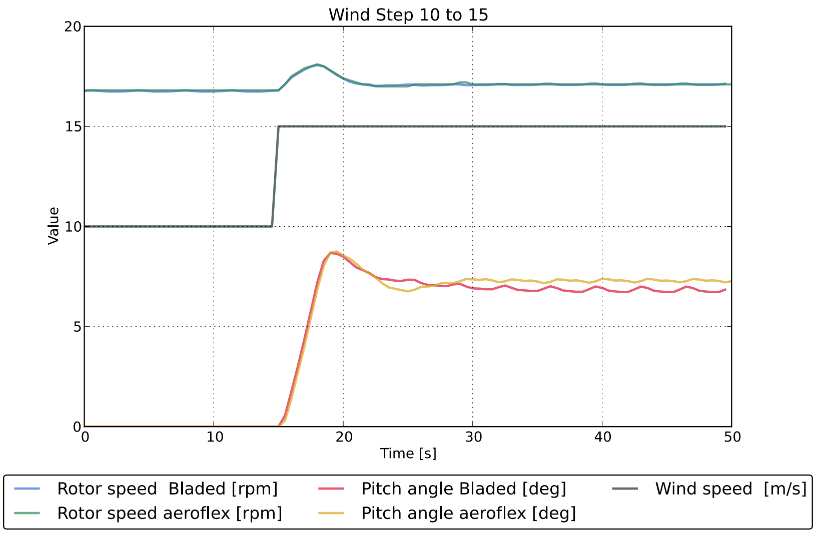


Figure C.2: Step response from 10 to 15 m/s

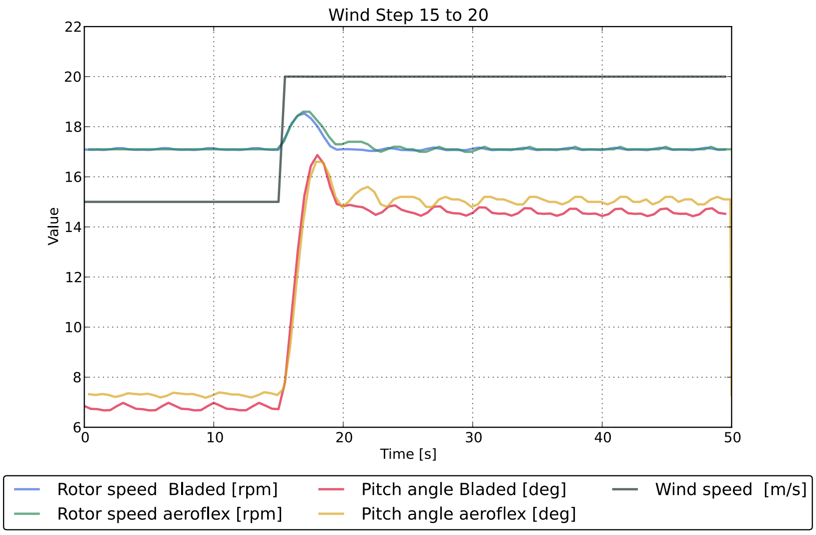


Figure C.3: Step response from 15 to 20 m/s

C.2 Overview Extreme Hub Loads

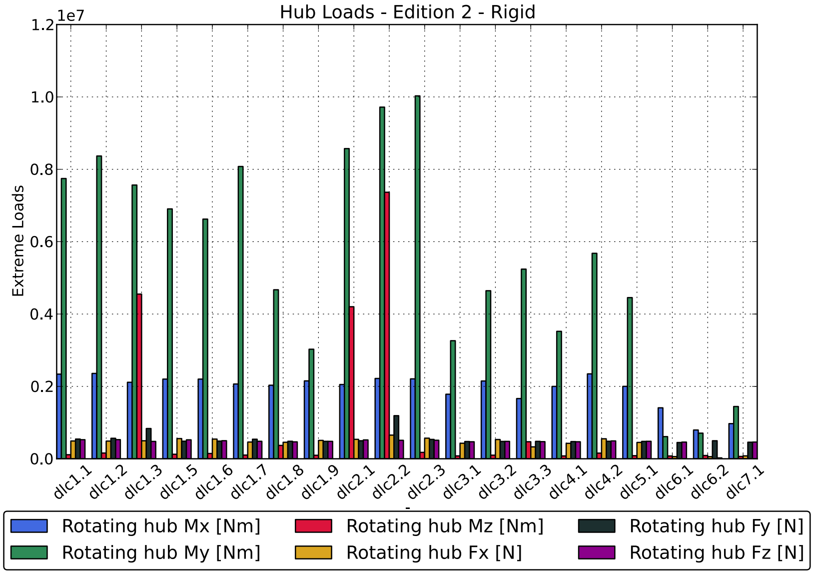


Figure C.4: Extreme hub loads (Edition 2, rigid hub)

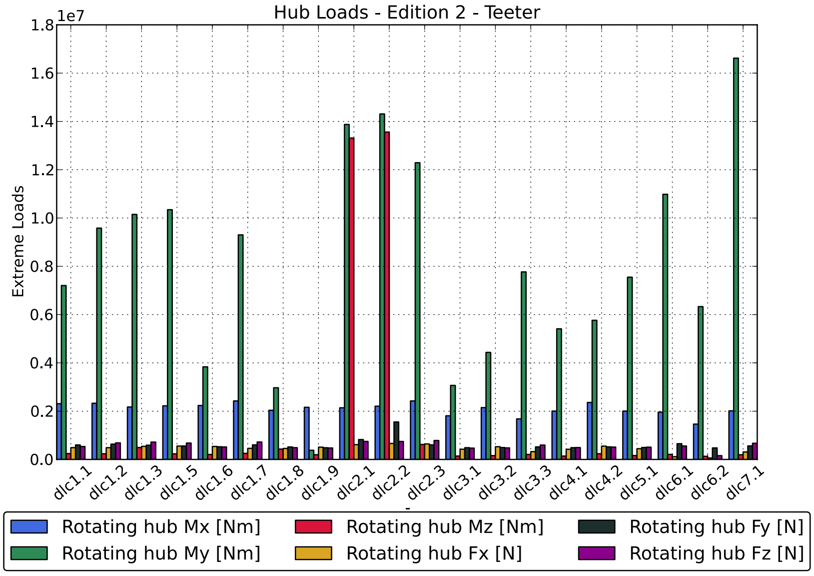


Figure C.5: Extreme hub loads (Edition 2, teeter hub)

Table C.1: Compared hub loads (Edition 2)

Edition 2	Hub Load Teeter / Hub Load Rigid					
Casename	Mx	My	Mz	Fx	Fy	Fz
dlc1.1	0.987	0.930	2.171	0.994	1.102	1.018
dlc1.2	0.987	1.145	1.485	0.996	1.121	1.297
dlc1.3	1.028	1.341	0.109	1.091	0.707	1.500
dlc1.5	1.008	1.498	1.856	0.993	1.146	1.297
dlc1.6	1.015	0.579	1.408	0.989	1.073	1.035
dlc1.7	1.173	1.152	2.464	0.994	1.117	1.494
dlc1.8	1.002	0.636	1.162	0.998	1.067	1.044
dlc1.9	1.004	0.125	2.020	1.000	1.005	0.987
dlc2.1	1.043	1.618	3.168	1.143	1.652	1.432
dlc2.2	0.994	1.472	1.841	1.013	1.304	1.460
dlc2.3	1.098	1.225	3.511	1.126	1.128	1.534
dlc3.1	1.013	0.940	1.760	0.985	1.020	0.999
dlc3.2	0.999	0.955	1.589	0.990	1.030	0.996
dlc3.3	1.010	1.482	0.442	0.987	1.081	1.259
dlc4.1	1.002	1.536	1.776	0.986	1.027	1.046
dlc4.2	1.006	1.015	1.507	0.999	1.077	1.038
dlc5.1	1.002	1.695	1.885	0.985	1.033	1.054
dlc6.1	1.390	17.912	2.705	1.865	1.450	1.206
dlc6.2	1.840	8.929	1.445	1.021	0.958	6.487
dlc7.1	2.073	11.506	3.013	3.880	1.225	1.450

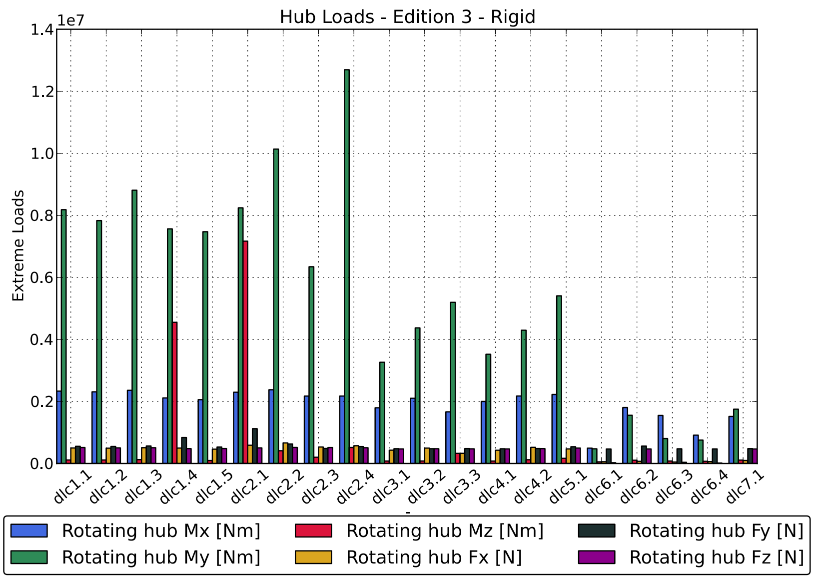


Figure C.6: Extreme hub loads (Edition 3, rigid hub)

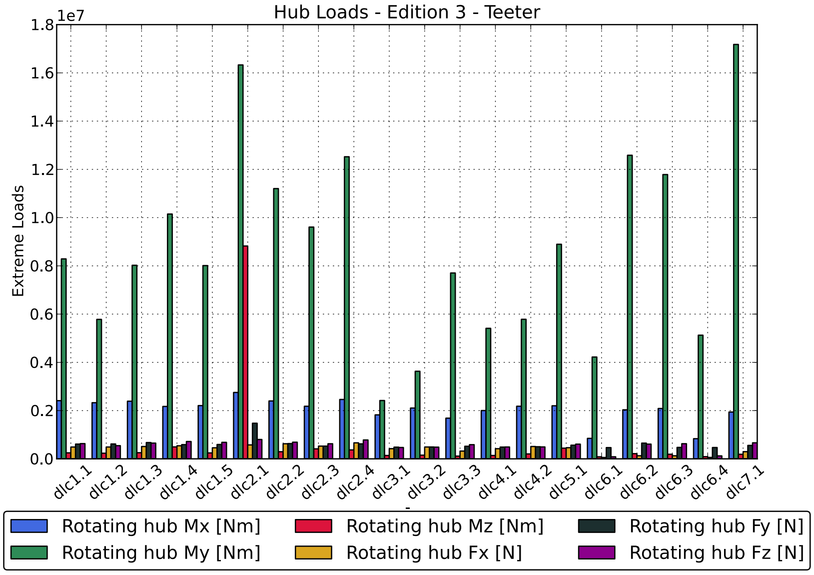


Figure C.7: Extreme hub loads (Edition 3, teeter hub)

Table C.2: Compared hub loads (Edition 3)

Edition 3	Hub Load Teeter / Hub Load Rigid					
Casename	Mx	My	Mz	Fx	Fy	Fz
dlc1.1	1.034	1.013	2.197	0.979	1.107	1.229
dlc1.2	1.007	0.738	2.059	0.995	1.126	1.085
dlc1.3	1.013	0.911	2.048	1.004	1.195	1.282
dlc1.4	1.028	1.341	0.109	1.091	0.707	1.500
dlc1.5	1.073	1.072	2.577	0.993	1.120	1.422
dlc2.1	1.198	1.981	1.231	0.982	1.315	1.593
dlc2.2	1.009	1.105	0.719	0.943	1.006	1.336
dlc2.3	1.003	1.515	2.056	0.993	1.092	1.219
dlc2.4	1.132	0.986	0.719	1.158	1.142	1.538
dlc3.1	1.015	0.741	1.760	0.985	1.017	1.002
dlc3.2	1.002	0.830	1.896	0.990	1.032	1.019
dlc3.3	1.013	1.483	0.350	0.986	1.087	1.243
dlc4.1	1.002	1.536	1.776	0.986	1.027	1.046
dlc4.2	1.002	1.346	1.679	0.984	1.043	1.031
dlc5.1	0.989	1.645	2.661	0.985	1.046	1.223
dlc6.1	1.716	8.894	1.592	1.010	0.997	3.368
dlc6.2	1.127	8.096	2.051	1.838	1.160	1.301
dlc6.3	1.348	14.658	2.382	2.676	1.000	16.464
dlc6.4	0.915	6.786	1.297	0.974	1.000	7.707
dlc7.1	1.280	9.811	1.728	3.083	1.164	1.420

C.3 Ultimate Hub Loads

Table C.3: Ultimate hub loads (Edition 2, rigid hub)

Edition 2 - Rigid			Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz	Rotor speed	Wind speed	Yaw angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[-]
Hub Mx	MAX	dlc4.2d	**3'168**	-2'302	-12	600	217	551	19.7	34.4	0.0	1.35
Hub Mx	MIN	dlc2.24	**-1'504**	278	-3'550	37	-601	-562	3.8	12.9	-87.6	1.10
Hub My	MAX	dlc1.7	2'713	**10'904**	50	166	-26	-598	17.3	25.0	-7.9	1.35
Hub My	MIN	dlc2.12	1'263	**-11'572**	-26	573	-71	571	15.3	25.0	55.2	1.35
Hub Mz	MAX	dlc2.24	-1'014	-65	**3'775**	95	308	513	5.8	12.9	-85.7	1.10
Hub Mz	MIN	dlc2.24	734	1'771	**-8'102**	249	-250	289	5.5	12.9	-86.1	1.10
Hub Fx	MAX	dlc1.5	1'877	2'399	-98	**754**	-588	226	18.8	18.6	7.9	1.35
Hub Fx	MIN	dlc1.5	1'351	1'862	-9	**-356**	333	-535	17.0	13.5	0.1	1.35
Hub Fy	MAX	dlc1.3	922	-1'253	3'385	109	**783**	-493	11.8	25.3	-78.0	1.35
Hub Fy	MIN	dlc2.24	2'441	1'252	-6'152	38	**-1'310**	452	3.4	12.9	86.6	1.10
Hub Fz	MAX	dlc2.12	1'913	1'534	-5'673	167	-673	**704**	2.3	12.9	-81.0	1.35
Hub Fz	MIN	dlc1.1	2'895	2'747	30	245	-168	**-712**	17.4	24.8	-5.5	1.35

Table C.4: Ultimate hub loads (Edition 2, teeter hub)

Edition 2 - Teeter			Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz	Rotor speed	Wind speed	Yaw angle	Teeter angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[deg]	[-]
Hub Mx	MAX	dlc1.7	**3'273**	9'026	-242	216	387	-405	17.4	25.0	0.4	-4.67	1.35
Hub Mx	MIN	dlc2.12	**-2'302**	294	6'261	79	1'113	807	2.1	12.9	81.0	-2.40	1.35
Hub My	MAX	dlc2.12	393	**18'728**	-117	29	53	404	12.4	25.0	61.1	-4.90	1.35
Hub My	MIN	dlc2.12	1'387	**-18'463**	172	382	161	826	15.8	25.0	54.7	4.89	1.35
Hub Mz	MAX	dlc2.12	-1'101	347	**9'063**	255	228	622	6.4	12.9	-81.0	-0.94	1.35
Hub Mz	MIN	dlc2.12	781	-254	**-17'969**	510	-717	117	6.7	12.9	-81.0	2.49	1.35
Hub Fx	MAX	dlc2.12	1'295	137	-155	**829**	-374	252	15.0	25.0	55.0	-2.56	1.35
Hub Fx	MIN	dlc1.5	1'074	7'453	-127	**-381**	-16	-728	15.2	24.2	-8.0	-4.64	1.35
Hub Fy	MAX	dlc2.12	-2'302	294	6'261	79	**1'113**	807	2.1	12.9	81.0	-2.40	1.35
Hub Fy	MIN	dlc2.24	-1'073	-1'464	-14'914	-359	**-1'708**	319	1.7	25.0	-72.7	3.91	1.1
Hub Fz	MAX	dlc2.12	1'651	-13'068	179	327	-26	**1'008**	15.6	25.0	55.0	4.77	1.35
Hub Fz	MIN	dlc2.12	-309	-10'783	67	-77	39	**-1'001**	11.7	25.0	60.7	4.71	1.35

Table C.5: Ultimate hub loads (Edition 3, rigid hub)

Edition 3 - Rigid			Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz	Rotor speed	Wind speed	Yaw angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[-]
Hub Mx	MAX	dlc1.3	**3'185**	3'478	89	408	479	276	17.4	32.9	-3.5	1.35
Hub Mx	MIN	dlc2.12	**-2'963**	-599	7'138	-21	1'516	565	2.0	12.8	74.8	1.35
Hub My	MAX	dlc1.3	2'617	**11'894**	43	115	86	-577	17.1	25.0	-20.2	1.35
Hub My	MIN	dlc1.3	2'176	**-11'387**	-84	107	-199	452	17.5	27.2	-20.7	1.35
Hub Mz	MAX	dlc2.12	1'379	2'635	**9'677**	-239	1'456	-158	1.5	12.0	-81.7	1.35
Hub Mz	MIN	dlc2.12	-1'170	2'143	**-6'760**	-193	-1'190	-369	3.8	12.8	74.5	1.35
Hub Fx	MAX	dlc2.11	2'750	-3'778	104	**794**	643	-157	19.3	15.0	-10.5	1.35
Hub Fx	MIN	dlc2.12	-1'144	-1'222	6'546	**-305**	1'143	465	7.7	11.7	79.9	1.35
Hub Fy	MAX	dlc2.12	-2'963	-599	7'138	-21	**1'516**	565	2.0	12.8	74.8	1.35
Hub Fy	MIN	dlc2.12	-1'170	2'143	-6'760	-193	**-1'190**	-369	3.8	12.8	74.5	1.35
Hub Fz	MAX	dlc1.3	2'551	-1'714	10	191	14	**662**	17.1	23.7	11.8	1.35
Hub Fz	MIN	dlc1.1	2'687	3'373	55	234	-117	**-695**	17.5	26.8	-5.6	1.35

Table C.6: Ultimate hub loads (Edition 3, teeter hub)

Edition 3 - Teeter			Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz	Rotor speed	Wind speed	Yaw angle	Teeter angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[deg]	[-]
Hub Mx	MAX	dlc1.1	**3'258**	-186	178	390	587	190	17.3	31.3	5.4	2.23	1.35
Hub Mx	MIN	dlc2.12	**-3'716**	3'316	-7'718	120	-1'366	-851	5.4	12.4	-85.4	-4.15	1.35
Hub My	MAX	dlc2.12	454	**22'044**	-148	69	33	289	12.2	25.7	68.9	-4.97	1.35
Hub My	MIN	dlc2.12	582	**-21'251**	150	73	39	-317	12.3	25.8	69.6	4.95	1.35
Hub Mz	MAX	dlc2.12	-3'659	-771	**11'911**	-256	1'993	-334	1.2	10.6	-87.5	2.35	1.35
Hub Mz	MIN	dlc2.12	-3'716	3'316	**-7'718**	120	-1'366	-851	5.4	12.4	-85.4	-4.15	1.35
Hub Fx	MAX	dlc2.11	2'811	211	-215	**780**	-657	-47	19.3	15.1	-10.6	-1.99	1.35
Hub Fx	MIN	dlc2.12	151	-11'551	-42	**-348**	-105	929	12.8	23.6	-53.8	4.73	1.35
Hub Fy	MAX	dlc2.12	-3'659	-771	11'911	-256	**1'993**	-334	1.2	10.6	-87.5	2.35	1.35
Hub Fy	MIN	dlc2.12	-3'716	3'316	-7'718	120	**-1'366**	-851	5.4	12.4	-85.4	-4.15	1.35
Hub Fz	MAX	dlc2.12	213	17'558	-116	-205	-28	**1'066**	12.2	25.7	70.3	-4.87	1.35
Hub Fz	MIN	dlc2.12	495	-16'735	119	-182	21	**-1'084**	12.5	24.8	67.7	4.85	1.35

Table C.7: Compared ultimate hub loads (Edition 2, teeter vs rigid)

Edition 2		Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz
Tet vs Rig		[-]	[-]	[-]	[-]	[-]	[-]
Hub Mx	MAX	**1.033**	-3.920	19.906	0.359	1.787	-0.734
Hub Mx	MIN	**1.530**	1.058	-1.764	2.130	-1.851	-1.437
Hub My	MAX	0.145	**1.718**	-2.327	0.175	-2.042	-0.674
Hub My	MIN	1.098	**1.595**	-6.554	0.666	-2.273	1.445
Hub Mz	MAX	1.086	-5.327	**2.401**	2.680	0.739	1.214
Hub Mz	MIN	1.064	-0.143	**2.218**	2.048	2.865	0.406
Hub Fx	MAX	0.690	0.057	1.579	**1.099**	0.637	1.118
Hub Fx	MIN	0.795	4.002	14.015	**1.071**	-0.047	1.360
Hub Fy	MAX	-2.496	-0.235	1.850	0.722	**1.422**	-1.639
Hub Fy	MIN	-0.439	-1.170	2.424	-9.430	**1.304**	0.705
Hub Fz	MAX	0.863	-8.517	-0.032	1.958	0.039	**1.432**
Hub Fz	MIN	-0.107	-3.926	2.258	-0.316	-0.233	**1.405**

Table C.8: Compared ultimate hub loads (Edition 3, teeter vs rigid)

Edition 3	**Tet vs Rig**	Hub Mx [-]	Hub My [-]	Hub Mz [-]	Hub Fx [-]	Hub Fy [-]	Hub Fz [-]
Hub Mx	MAX	**1.023**	-0.053	1.995	0.956	1.224	0.690
Hub Mx	MIN	**1.254**	-5.539	-1.081	-5.618	-0.901	-1.507
Hub My	MAX	0.173	**1.853**	-3.440	0.598	0.387	-0.502
Hub My	MIN	0.267	**1.866**	-1.781	0.688	-0.197	-0.703
Hub Mz	MAX	-2.653	-0.293	**1.231**	1.072	1.369	2.109
Hub Mz	MIN	3.176	1.548	**1.142**	-0.624	1.148	2.307
Hub Fx	MAX	1.022	-0.056	-2.063	**0.982**	-1.022	0.299
Hub Fx	MIN	-0.132	9.450	-0.006	**1.140**	-0.092	1.998
Hub Fy	MAX	1.235	1.288	1.669	11.971	**1.315**	-0.591
Hub Fy	MIN	3.176	1.548	1.142	-0.624	**1.148**	2.307
Hub Fz	MAX	0.084	-10.243	-11.214	-1.074	-1.981	**1.611**
Hub Fz	MIN	0.184	-4.961	2.189	-0.776	-0.182	**1.561**

Table C.9: Compared ultimate hub loads (Rigid, edition 3 vs edition 2)

Rigid	**Ed3 vs Ed2**	Hub Mx [-]	Hub My [-]	Hub Mz [-]	Hub Fx [-]	Hub Fy [-]	Hub Fz [-]
Hub Mx	MAX	**1.005**	-1.511	-7.321	0.679	2.213	0.500
Hub Mx	MIN	**1.970**	-2.154	-2.011	-0.578	-2.522	-1.005
Hub My	MAX	0.965	**1.091**	0.857	0.696	-3.290	0.964
Hub My	MIN	1.722	**0.984**	3.208	0.186	2.815	0.791
Hub Mz	MAX	-1.361	-40.503	**2.564**	-2.509	4.723	-0.309
Hub Mz	MIN	-1.595	1.210	**0.834**	-0.773	4.758	-1.278
Hub Fx	MAX	1.465	-1.575	-1.064	**1.053**	-1.094	-0.698
Hub Fx	MIN	-0.847	-0.656	-723.864	**0.858**	3.432	-0.869
Hub Fy	MAX	-3.214	0.478	2.108	-0.196	**1.937**	-1.147
Hub Fy	MIN	-0.479	1.711	1.099	-5.062	**0.908**	-0.816
Hub Fz	MAX	1.334	-1.117	-0.002	1.144	-0.021	**0.940**
Hub Fz	MIN	0.928	1.228	1.828	0.957	0.694	**0.975**

Table C.10: Compared ultimate hub loads (Teeter, edition 3 vs edition 2)

Teeter		Hub Mx	Hub My	Hub Mz	Hub Fx	Hub Fy	Hub Fz
Ed3 vs Ed2		[-]	[-]	[-]	[-]	[-]	[-]
Hub Mx	MAX	**0.996**	-0.021	-0.734	1.808	1.516	-0.469
Hub Mx	MIN	**1.614**	11.278	-1.233	1.526	-1.228	-1.054
Hub My	MAX	1.155	**1.177**	1.267	2.383	0.623	0.717
Hub My	MIN	0.420	**1.151**	0.872	0.192	0.244	-0.384
Hub Mz	MAX	3.325	-2.225	**1.314**	-1.004	8.749	-0.536
Hub Mz	MIN	-4.759	-13.050	**0.429**	0.236	1.906	-7.265
Hub Fx	MAX	2.171	1.544	1.390	**0.941**	1.755	-0.186
Hub Fx	MIN	0.141	-1.550	0.332	**0.913**	6.696	-1.277
Hub Fy	MAX	1.590	-2.623	1.902	-3.251	**1.792**	-0.413
Hub Fy	MIN	3.463	-2.264	0.517	-0.335	**0.800**	-2.670
Hub Fz	MAX	0.129	-1.344	-0.646	-0.627	1.064	**1.057**
Hub Fz	MIN	-1.600	1.552	1.772	2.351	0.541	**1.083**

C.4 Ultimate Blade Loads

Table C.11: Ultimate blade loads (Edition 2, rigid)

Edition 2 - Rigid			Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz	Rotor speed	Wind speed	Yaw angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[-]
Blade Mx	MAX	dlc1.1	**5'450**	6'323	-1	271	-294	876	17.3	29.1	-10.6	1.35
Blade Mx	MIN	dlc7.1c	**-4'003**	-483	82	-8	190	136	0.0	44.6	-82.1	1.10
Blade My	MAX	dlc1.3	1'407	**12'073**	-23	420	-45	734	17.0	27.9	63.8	1.35
Blade My	MIN	dlc1.5	1'067	**-8'427**	106	-256	-130	996	17.0	28.1	-7.7	1.35
Blade Mz	MAX	dlc1.3	-1'433	1'533	**3'349**	105	138	302	11.8	25.3	-78.0	1.35
Blade Mz	MIN	dlc2.24	-716	722	**-11'266**	147	-62	159	5.5	12.9	-86.1	1.10
Blade Fx	MAX	dlc1.3	1'248	11'728	-12	**433**	-48	1'047	16.9	27.9	-63.8	1.35
Blade Fx	MIN	dlc2.12	-10	-7'948	41	**-260**	-38	732	13.8	25.0	-60.8	1.35
Blade Fy	MAX	dlc1.5	-2'827	7'993	64	288	**193**	1'024	18.5	18.8	7.8	1.35
Blade Fy	MIN	dlc2.24	2'706	702	-6'452	30	**-405**	144	3.4	12.9	86.6	1.10
Blade Fz	MAX	dlc4.2d	354	749	-13	86	-38	**1'584**	21.5	29.3	8.0	1.35
Blade Fz	MIN	dlc1.5	64	-218	-9	-5	5	**-170**	0.1	25.0	8.0	1.35

Table C.12: Ultimate blade loads (Edition 2, teeter)

Edition 2 - Teeter			Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz	Rotor speed	Wind speed	Yaw angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[-]
Blade Mx	MAX	dlc1.7	**6'931**	3'913	-35	189	-324	793	17.1	25.0	-8.3	1.35
Blade Mx	MIN	dlc2.12	**-6'128**	-4'001	-28	-148	205	85	8.8	25.0	61.0	1.35
Blade My	MAX	dlc1.3	4'611	**13'245**	-89	466	-243	826	16.9	27.9	63.4	1.35
Blade My	MIN	dlc2.12	2'010	**-11'151**	160	-415	-98	475	10.6	25.0	-60.4	1.35
Blade Mz	MAX	dlc2.24	-2'251	220	**3'256**	-1	179	-7	1.0	12.9	94.1	1.10
Blade Mz	MIN	dlc2.12	-782	-443	**-17'972**	47	-102	162	6.7	12.9	-81.0	1.35
Blade Fx	MAX	dlc1.3	1'468	12'718	-20	**564**	-40	967	16.7	27.9	-63.7	1.35
Blade Fx	MIN	dlc2.12	408	-8'555	-9	**-488**	-7	796	13.3	25.0	-60.8	1.35
Blade Fy	MAX	dlc2.12	-1'815	55	-369	14	**347**	235	2.1	12.9	81.0	1.35
Blade Fy	MIN	dlc1.7	6'765	4'150	-34	186	**-334**	792	17.1	25.0	-8.3	1.35
Blade Fz	MAX	dlc4.2d	354	749	-13	86	-38	**1'584**	21.5	29.3	8.0	1.35
Blade Fz	MIN	dlc2.12	-382	-141	-2'333	3	-21	**-184**	0.9	12.9	-81.0	1.35

Table C.13: Ultimate blade loads (Edition 3, rigid)

Edition 3 - Rigid			Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz	Rotor speed	Wind speed	Yaw angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[-]
Blade Mx	MAX	dlc1.3	**5'321**	4'411	-12	213	-292	923	17.1	29.4	10.5	1.35
Blade Mx	MIN	dlc7.1	**-4'556**	-571	94	-11	216	136	0.0	47.6	-82.2	1.10
Blade My	MAX	dlc2.12	2'764	**12'769**	-2	480	-151	1'050	17.1	23.8	-54.9	1.35
Blade My	MIN	dlc2.12	-195	**-8'476**	46	-254	-24	439	13.9	25.6	67.8	1.35
Blade Mz	MAX	dlc2.12	-2'652	942	**9'371**	120	269	-25	1.5	12.0	-81.7	1.35
Blade Mz	MIN	dlc2.12	2'258	509	**-6'651**	84	-232	-45	3.8	12.8	74.5	1.35
Blade Fx	MAX	dlc2.12	1'985	12'477	-11	**499**	-93	1'059	17.0	24.2	-56.2	1.35
Blade Fx	MIN	dlc2.12	102	-7'898	50	**-261**	-44	720	13.7	22.9	-52.3	1.35
Blade Fy	MAX	dlc2.12	-3'085	-205	-694	-47	**472**	161	2.0	12.8	74.8	1.35
Blade Fy	MIN	dlc1.3	5'140	5'356	9	246	**-315**	875	17.2	29.8	-6.2	1.35
Blade Fz	MAX	dlc2.11	78	1'614	-23	99	3	**1'414**	20.1	26.7	-1.5	1.35
Blade Fz	MIN	dlc2.12	-365	-74	-3'427	-21	-51	**-178**	1.2	12.9	74.5	1.35

Table C.14: Ultimate blade loads (Edition 3, teeter)

Edition 3 - Teeter			Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz	Rotor speed	Wind speed	Yaw angle	Teeter angle	Safety factor
			[kNm]	[kNm]	[kNm]	[kN]	[kN]	[kN]	[rpm]	[m/s]	[deg]	[deg]	[-]
Blade Mx	MAX	dlc1.3	**7'642**	4'399	-23	213	-390	849	17.0	30.8	-5.9	-4.24	1.35
Blade Mx	MIN	dlc2.12	**-6'328**	-6'915	-59	-234	166	204	11.0	24.7	68.0	4.63	1.35
Blade My	MAX	dlc2.12	4'140	**14'357**	-67	520	-215	678	16.2	24.9	48.5	-4.74	1.35
Blade My	MIN	dlc2.12	2'200	**-13'054**	212	-493	-111	302	12.7	24.8	69.2	4.91	1.35
Blade Mz	MAX	dlc2.12	-5'156	-316	**10'101**	-53	601	-93	1.2	10.6	-87.5	2.35	1.35
Blade Mz	MIN	dlc2.12	-1'445	244	**-6'739**	38	30	-217	1.2	12.4	-83.6	1.06	1.35
Blade Fx	MAX	dlc2.12	548	11'622	5	**634**	-21	948	16.9	24.5	-58.8	-4.74	1.35
Blade Fx	MIN	dlc2.12	1'033	-12'824	146	**-525**	-35	404	12.8	25.3	69.1	4.94	1.35
Blade Fy	MAX	dlc2.12	-5'156	-316	10'101	-53	**601**	-93	1.2	10.6	-87.5	2.35	1.35
Blade Fy	MIN	dlc1.3	7'616	4'483	-20	219	**-392**	847	17.0	31.0	-6.8	-4.30	1.35
Blade Fz	MAX	dlc2.11	1'189	3'972	-13	178	-40	**1'406**	20.0	26.7	-1.4	1.98	1.35
Blade Fz	MIN	dlc2.12	-1'445	244	-6'739	38	30	**-217**	1.2	12.4	-83.6	1.06	1.35

Table C.15: Compared ultimate blade loads (Edition 2, teeter vs rigid)

Edition 2		Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz
Tet vs Rig		[-]	[-]	[-]	[-]	[-]	[-]
Blade Mx	MAX	**1.272**	0.619	41.893	0.695	1.101	0.905
Blade Mx	MIN	**1.531**	8.289	-0.338	17.770	1.080	0.622
Blade My	MAX	3.278	**1.097**	3.908	1.111	5.426	1.126
Blade My	MIN	1.884	**1.323**	1.516	1.623	0.760	0.477
Blade Mz	MAX	1.570	0.143	**0.972**	-0.011	1.301	-0.022
Blade Mz	MIN	1.092	-0.614	**1.595**	0.319	1.642	1.023
Blade Fx	MAX	1.176	1.084	1.623	**1.301**	0.837	0.923
Blade Fx	MIN	-41.630	1.076	-0.229	**1.878**	0.184	1.088
Blade Fy	MAX	0.642	0.007	-5.808	0.050	**1.799**	0.230
Blade Fy	MIN	2.500	5.910	0.005	6.195	**0.824**	5.495
Blade Fz	MAX	1.000	1.000	1.000	1.000	1.000	**1.000**
Blade Fz	MIN	-5.992	0.647	249.152	-0.475	-4.005	**1.083**

Table C.16: Compared ultimate blade loads (Edition 3, teeter vs rigid)

Edition 3		Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz
Tet vs Rig		[-]	[-]	[-]	[-]	[-]	[-]
Blade Mx	MAX	**1.436**	0.997	1.910	0.999	1.335	0.920
Blade Mx	MIN	**1.389**	12.101	-0.629	21.375	0.767	1.499
Blade My	MAX	1.498	**1.124**	32.253	1.083	1.431	0.646
Blade My	MIN	-11.303	**1.540**	4.581	1.939	4.583	0.688
Blade Mz	MAX	1.944	-0.335	**1.078**	-0.445	2.237	3.703
Blade Mz	MIN	-0.640	0.480	**1.013**	0.456	-0.131	4.817
Blade Fx	MAX	0.276	0.931	-0.467	**1.270**	0.228	0.895
Blade Fx	MIN	10.132	1.624	2.932	**2.014**	0.786	0.561
Blade Fy	MAX	1.671	1.539	-14.545	1.135	**1.274**	-0.577
Blade Fy	MIN	1.482	0.837	-2.215	0.890	**1.243**	0.968
Blade Fz	MAX	15.333	2.462	0.556	1.802	-15.585	**0.995**
Blade Fz	MIN	3.964	-3.288	1.967	-1.826	-0.593	**1.221**

Table C.17: Compared ultimate blade loads (Rigid, edition 3 vs edition 2)

Rigid		Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz
Ed3 vs Ed2		[-]	[-]	[-]	[-]	[-]	[-]
Blade Mx	MAX	**0.976**	0.698	14.297	0.787	0.993	1.054
Blade Mx	MIN	**1.138**	1.184	1.150	1.316	1.139	1.000
Blade My	MAX	1.965	**1.058**	0.091	1.144	3.364	1.432
Blade My	MIN	-0.182	**1.006**	0.437	0.995	0.186	0.440
Blade Mz	MAX	1.850	0.615	**2.798**	1.142	1.955	-0.083
Blade Mz	MIN	-3.155	0.705	**0.590**	0.571	3.731	-0.284
Blade Fx	MAX	1.590	1.064	0.849	**1.152**	1.951	1.011
Blade Fx	MIN	-10.389	0.994	1.214	**1.003**	1.178	0.984
Blade Fy	MAX	1.091	-0.026	-10.921	-0.163	**2.447**	0.157
Blade Fy	MIN	1.900	7.628	-0.001	8.200	**0.778**	6.074
Blade Fz	MAX	0.219	2.155	1.782	1.143	-0.068	**0.892**
Blade Fz	MIN	-5.725	0.342	366.005	3.911	-9.623	**1.048**

Table C.18: Compared ultimate blade loads (Teeter, edition 3 vs edition 2)

Teeter		Blade Mx	Blade My	Blade Mz	Blade Fx	Blade Fy	Blade Fz
Ed3 vs Ed2		[-]	[-]	[-]	[-]	[-]	[-]
Blade Mx	MAX	**1.102**	1.124	0.652	1.132	1.205	1.070
Blade Mx	MIN	**1.033**	1.728	2.139	1.583	0.809	2.410
Blade My	MAX	0.898	**1.084**	0.750	1.115	0.887	0.821
Blade My	MIN	1.094	**1.171**	1.320	1.188	1.123	0.635
Blade Mz	MAX	2.291	-1.437	**3.103**	46.298	3.361	13.948
Blade Mz	MIN	1.848	-0.551	**0.375**	0.816	-0.297	-1.339
Blade Fx	MAX	0.373	0.914	-0.244	**1.124**	0.531	0.980
Blade Fx	MIN	2.528	1.499	-15.572	**1.076**	5.030	0.507
Blade Fy	MAX	2.840	-5.746	-27.348	-3.683	**1.734**	-0.394
Blade Fy	MIN	1.126	1.080	0.591	1.178	**1.173**	1.070
Blade Fz	MAX	3.357	5.306	0.990	2.060	1.061	**0.888**
Blade Fz	MIN	3.787	-1.735	2.889	15.019	-1.426	**1.182**

C.5 Rainflow Counts - Hub Loads

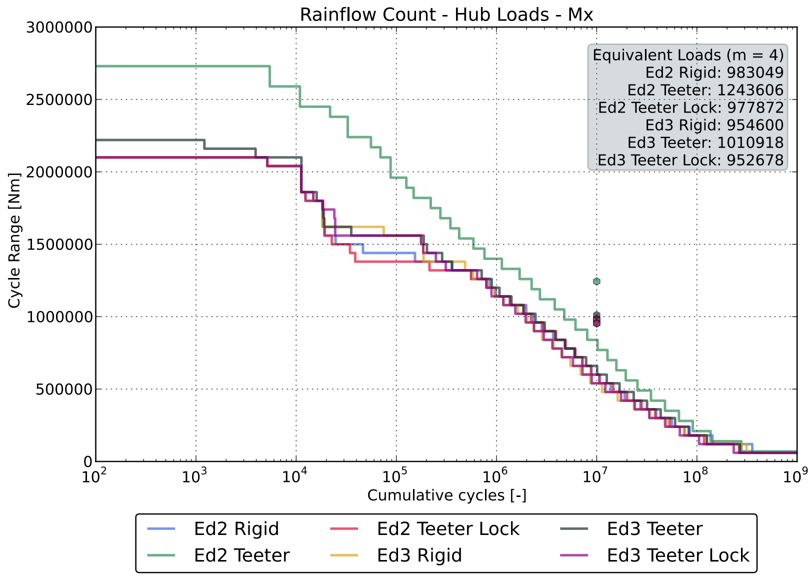


Figure C.8: Rainflow count hub loads - Mx

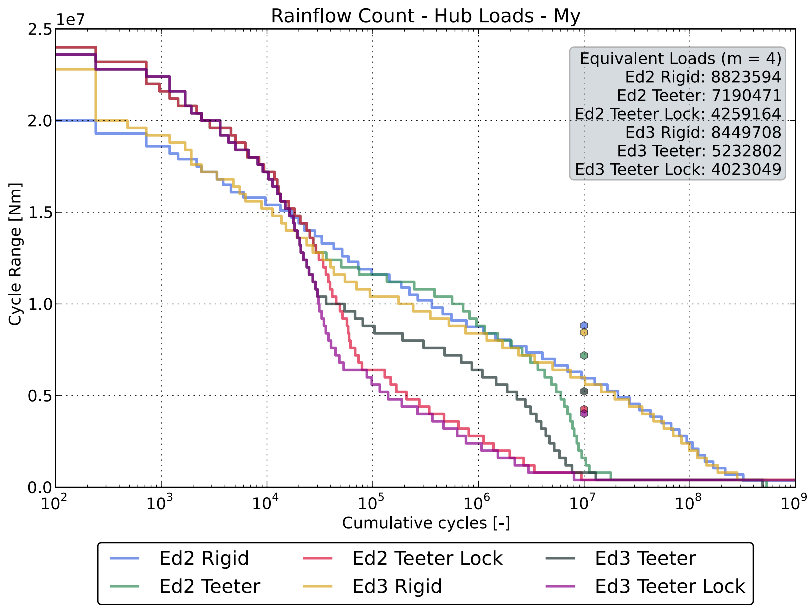


Figure C.9: Rainflow count hub loads - My

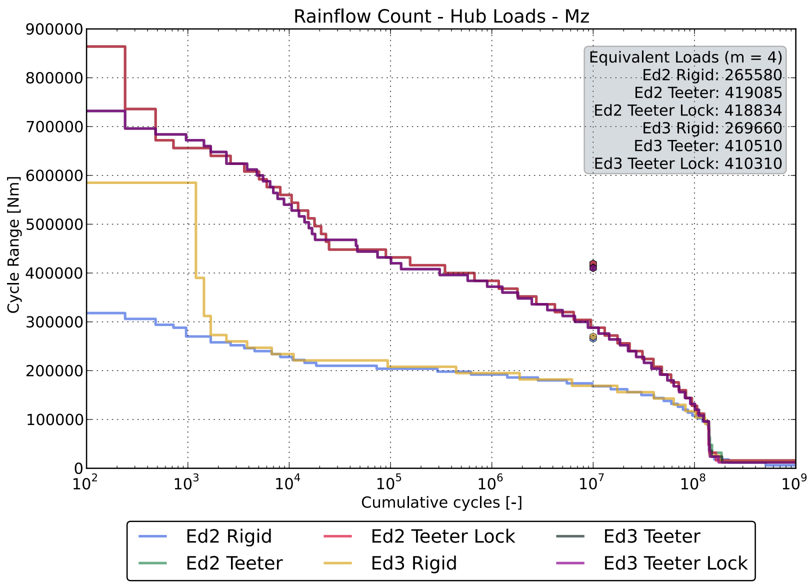


Figure C.10: Rainflow count hub loads - Mz

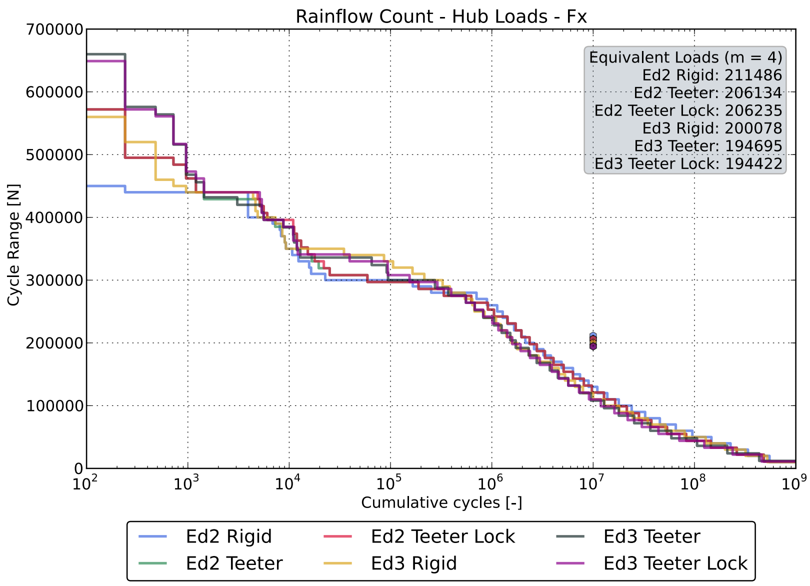


Figure C.11: Rainflow count hub loads - Fx

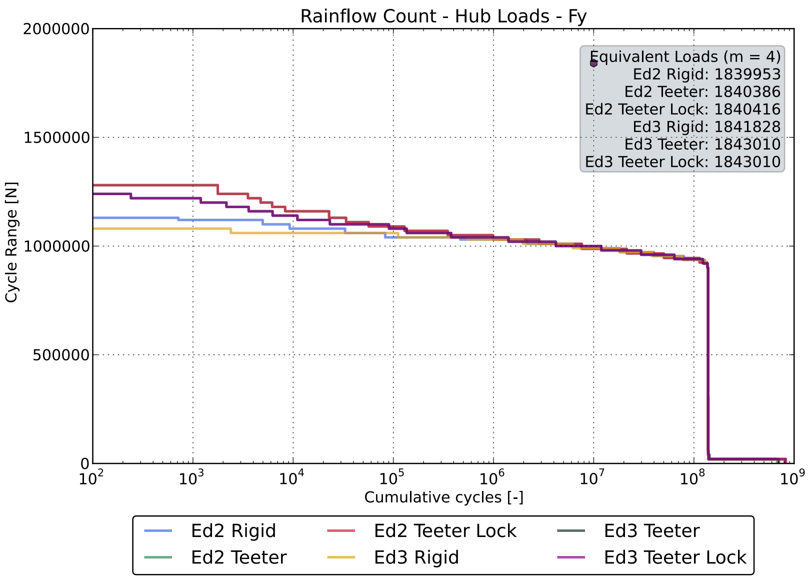


Figure C.12: Rainflow count hub loads - Fy

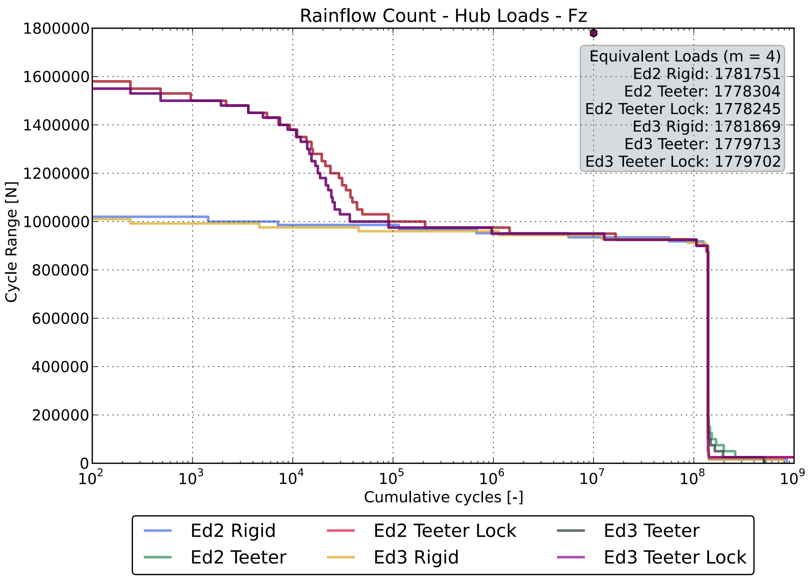


Figure C.13: Rainflow count hub loads - Fz

C.6 Rainflow Counts - Blade Loads

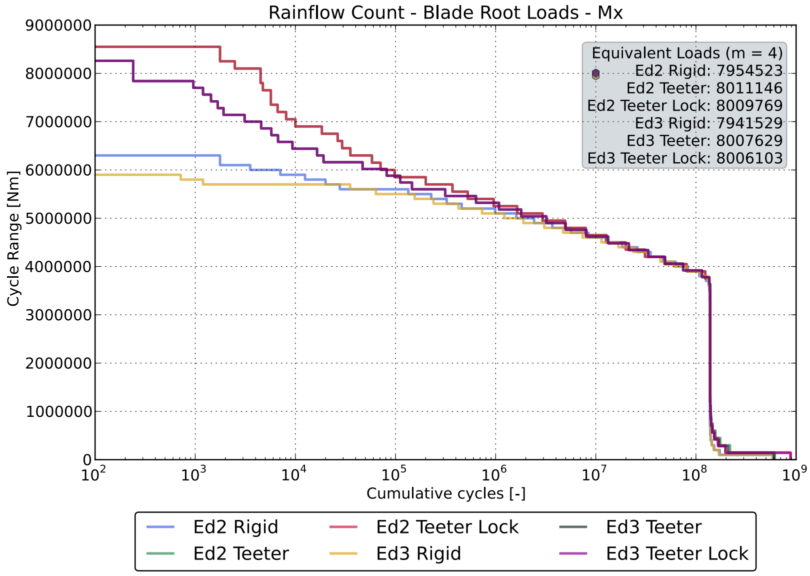


Figure C.14: Rainflow count blade root loads - Mx

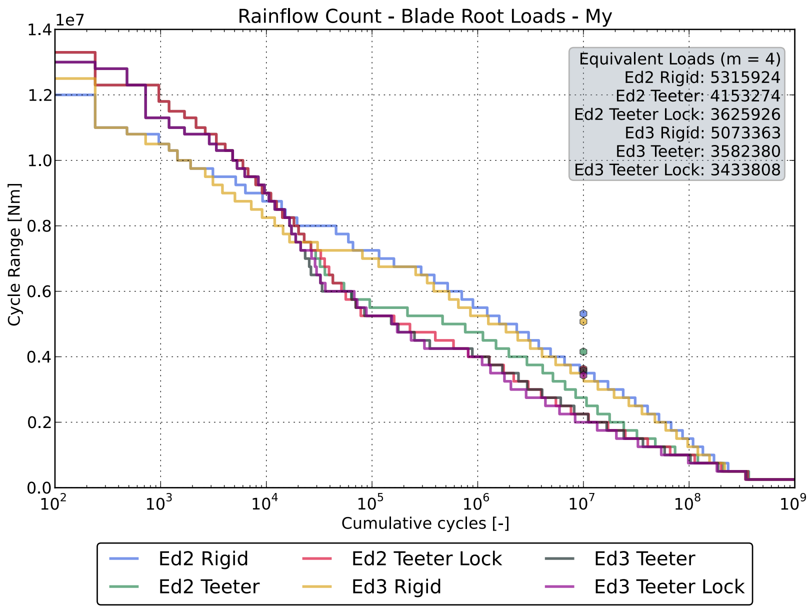


Figure C.15: Rainflow count blade root loads - My

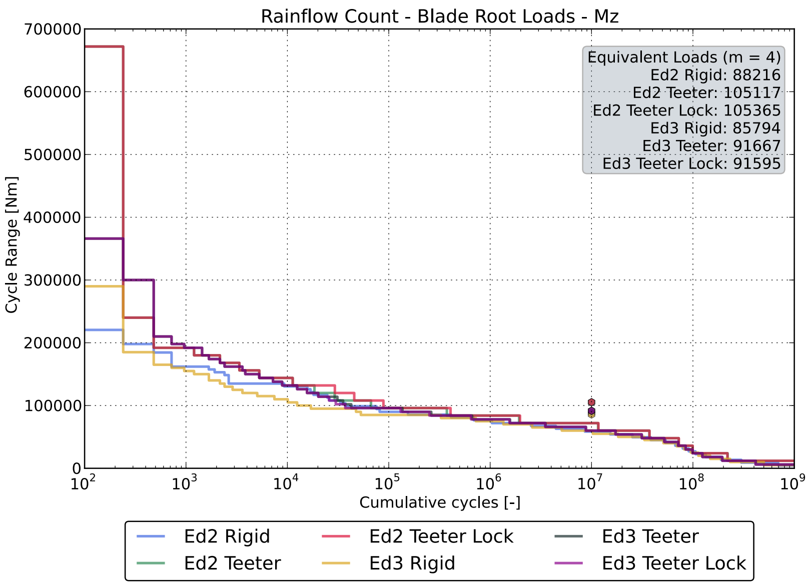


Figure C.16: Rainflow count blade root loads - Mz

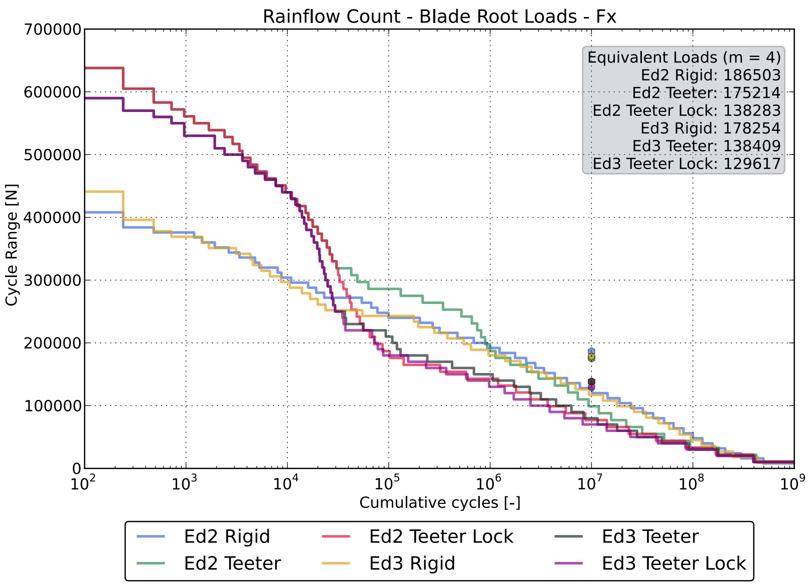


Figure C.17: Rainflow count blade root loads - Fx

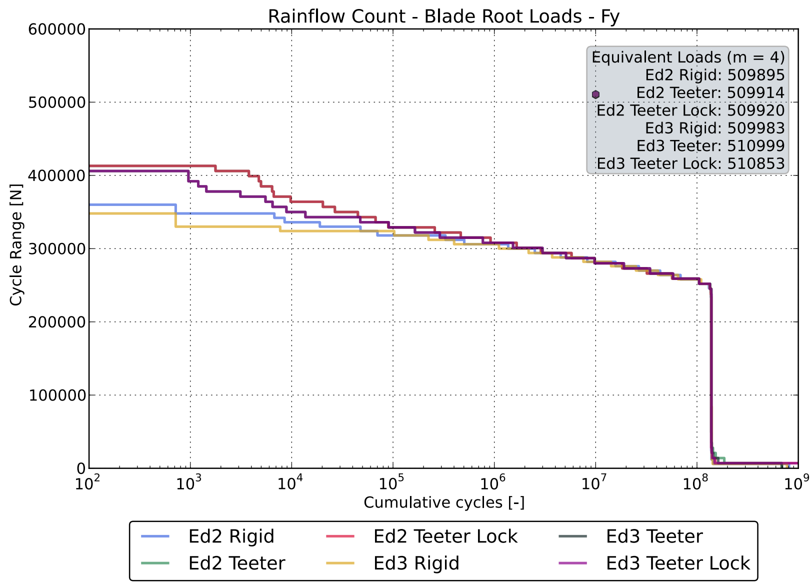


Figure C.18: Rainflow count blade root loads - Fy

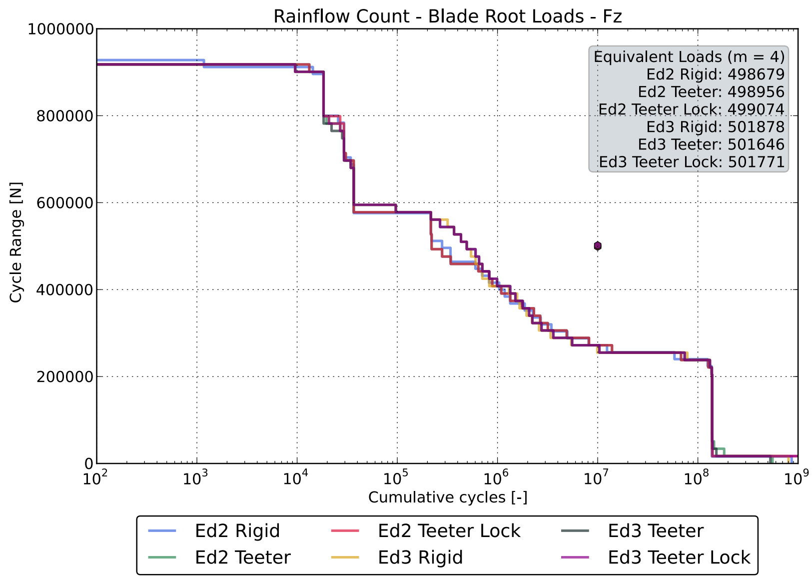


Figure C.19: Rainflow count blade root loads - Fz

C.7 Extreme Load Extrapolation

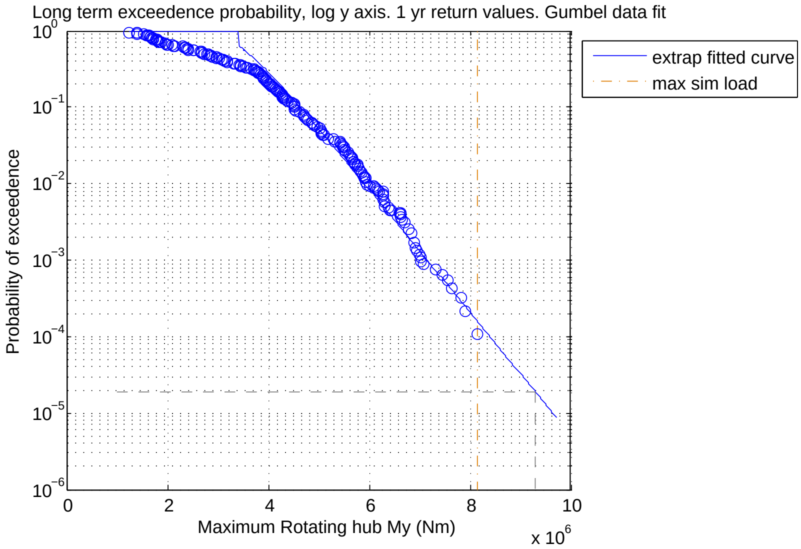


Figure C.20: Extrapolated hub My load (Rigid, maximum)

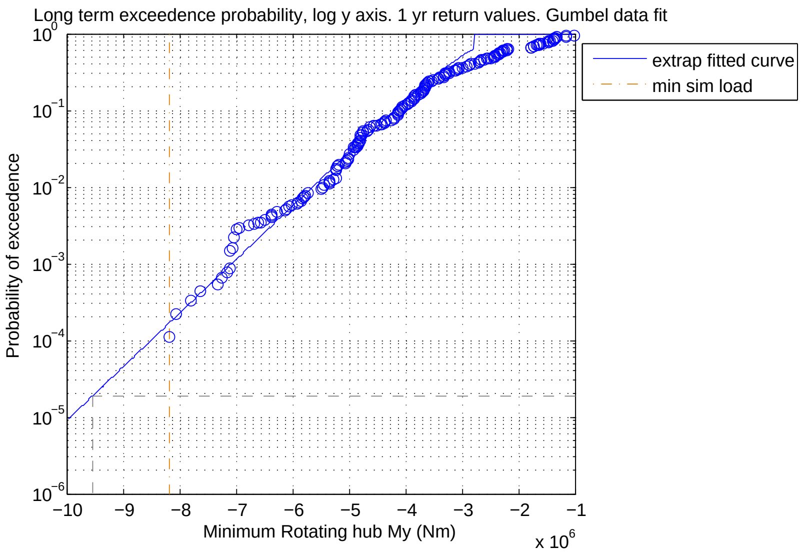


Figure C.21: Extrapolated hub My load (Rigid, minimum)

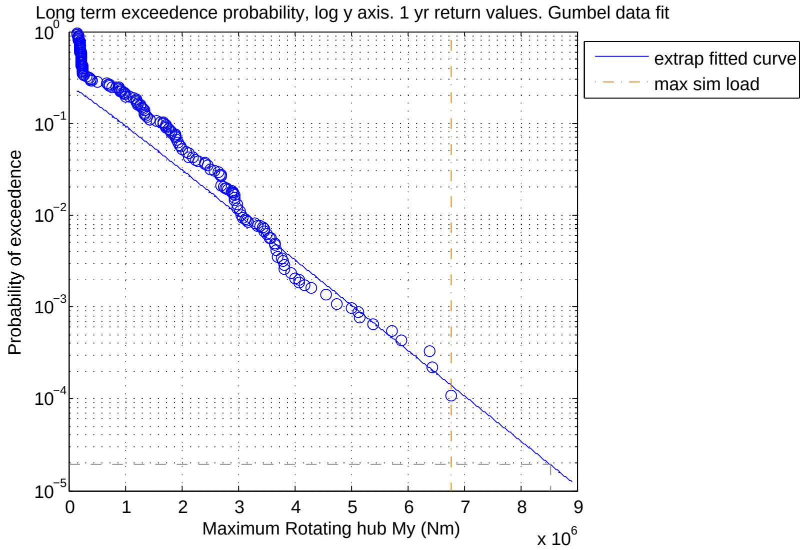


Figure C.22: Extrapolated hub My load (Teeter, maximum)

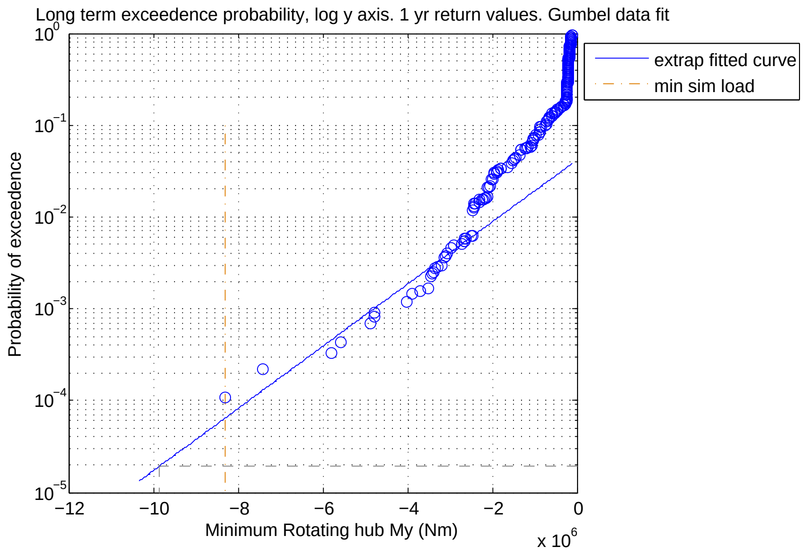


Figure C.23: Extrapolated hub My load (Teeter, minimum)

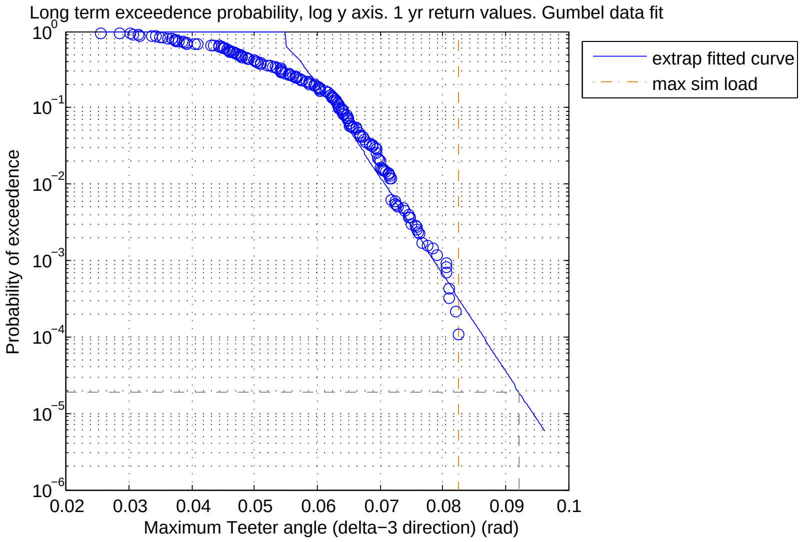


Figure C.24: Extrapolated teeter angle (Maximum)

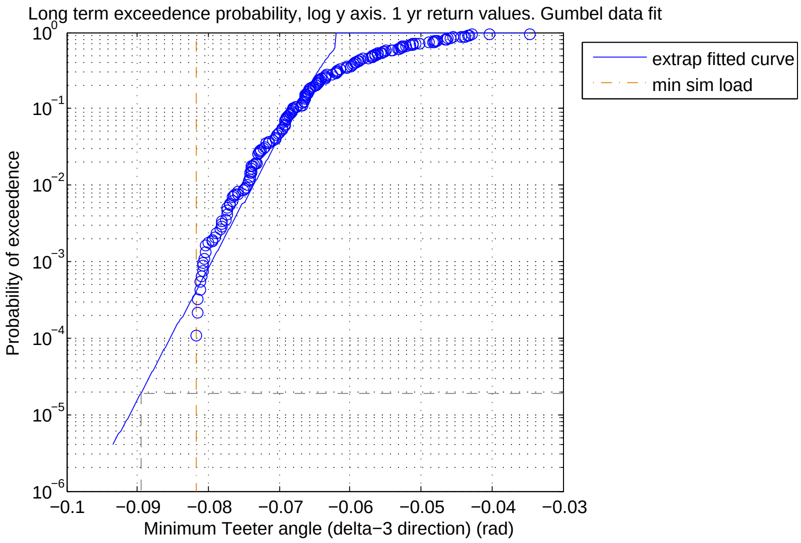


Figure C.25: Extrapolated teeter angle (Minimum)

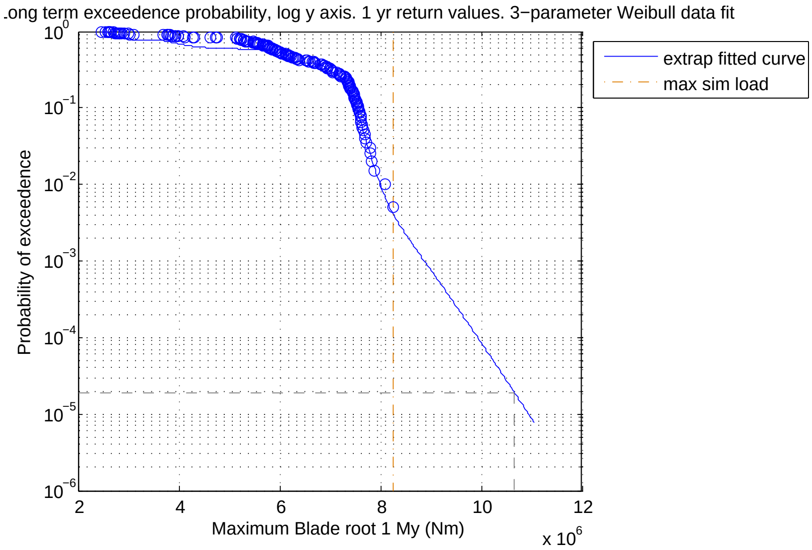


Figure C.26: Extrapolated blade My load (Rigid, maximum)

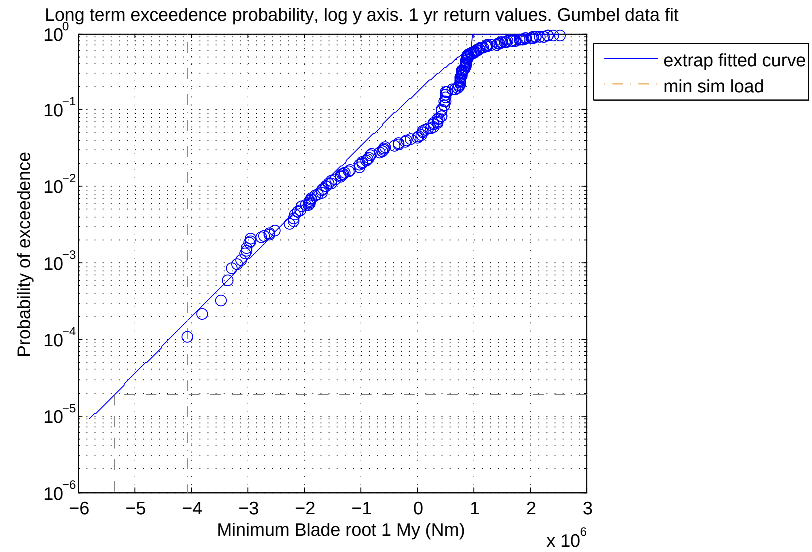


Figure C.27: Extrapolated blade My load (Rigid, minimum)

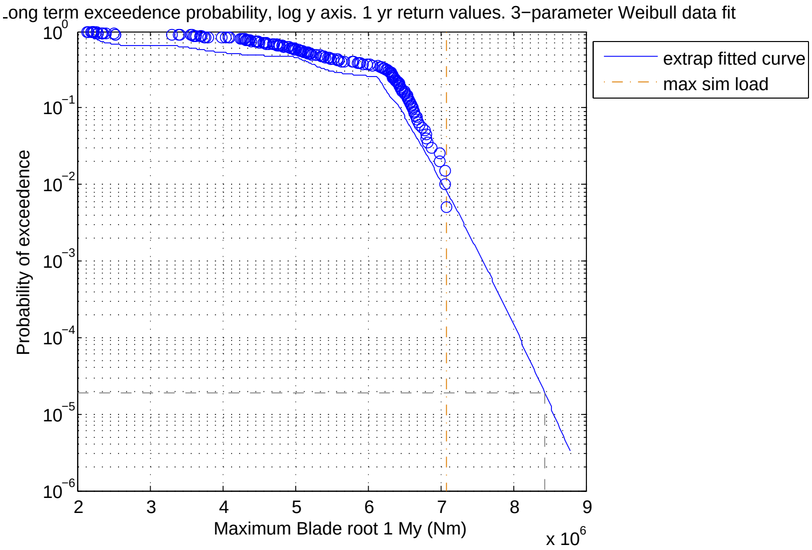


Figure C.28: Extrapolated blade My load (Teeter, maximum)

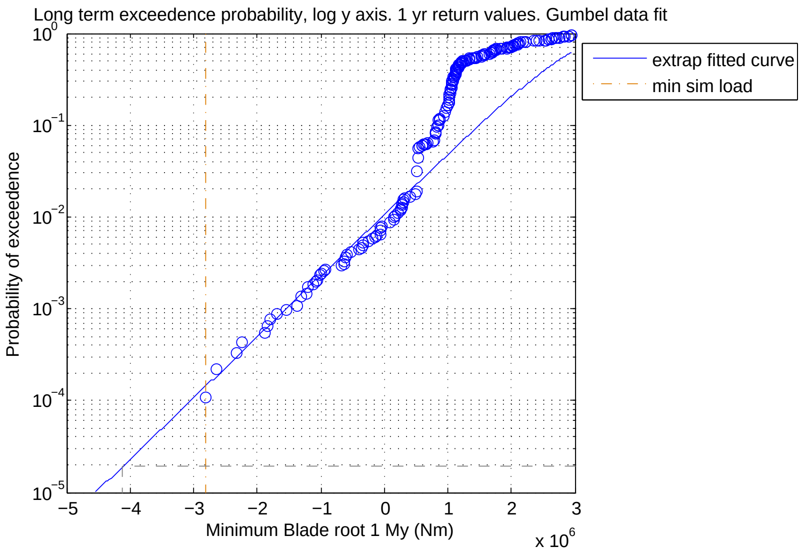


Figure C.29: Extrapolated blade My load (Teeter, minimum)

Bibliography

[1] Schorbach, Vera ; Dalhoff, Peter ; Gust, Peter: Two Bladed Wind Turbines Undetermined For More Than 30 Years. In: *Proceedings of 8th PhD Seminar on Wind Energy in Europe*, 2012

[2] Hansen, Martin: *Aerodynamics of Wind Turbines*. London, UK : Earthscan, 2008

[3] Hau, Erich: *Windkraftanlagen - Grundlagen, Technik, Einsatz, Wirtschaftlichkeit*. 4. vollst. neu bearb. Aufl. 2008. Berlin, Heidelberg : Springer, 2008. – ISBN 978–3–540–72150–5

[4] Vries, Eize D.: Development of two-bladed offshore wind turbine. In: *Wind Stats Report* 24 (2011), Nr. 2. http://www.condorwind.com/other/WS_24_2%20final.pdf. – accessed 2014.05.10

[5] HAW: *ZOFF*. http://www.haw-hamburg.de/?id=29891. Version: 2013. – accessed 2014.04.28

[6] aerodyn engineering gmbh: *SCD Technology Website*. http://www.scd-technology.com. Version: 2014. – accessed 2014.03.04

[7] aerodyn: *Internal Documents*. 2014

[8] Burton, Tony ; Sharpe, David ; Jenkins, Nick ; Bossanyi, Ervin: *Wind Energy - Handbook*. 1. Auflage. New York : J. Wiley, 2001. – ISBN 978–0–471–48997–9

[9] Poore, R.: *NWTC AWT-26 Research and Retrofit Project - Summary of AWT-26/27 Turbine Research and Development*. Seattle, Washington, National Renewable Energy Laboratory, NREL/SR-500-26926, January 2000

[10] Cotrell, J.: *The Mechanical Design, Analysis, and Testing of a Two-Bladed Wind Turbine Hub*, National Renewable Energy Laboratory, NREL/TP-500-26645, June 2002

[11] Condor Wind Energy Ltd: *Company Website*. http://www.condorwind.com. Version: 2014. – accessed 2014.05.10

[12] Windflow Technology Ltd: *Windflow 500 Brochure*. http://www.windflow.co.nz/pdf-folder/misc/Windflow%20Brochure%20Mar%2007.pdf. Version: April 2011. – accessed 2014.05.10

[13] Arimond, John: Teetering toward two-blade turbines. In: *Windpower Engineering and Development* April (2012), 32-35. http://www.windflow.co.nz/news/published-papers/FINAL%20Teetering%20Article%20WPE%20April%202012.pdf

[14] Vergnet Groupe: *GEV HP 1MW Datasheet*. http://www.vergnet.com/pdf/gev-hp-en.pdf. Version: February 2008. – accessed 2014.05.07

[15] Windpower Engineering: *Nordic Windpower's N1000 1-MW turbine*. http://www.windpowerengineering.com/design/nordic-windpower%E2%80%99s-n1000-1-mw-turbine/. Version: June 2010. – accessed 2014.05.10

[16] Vergnet Groupe: *GEV HP 1MW Reveals Innovativa Features*. http://proceedings.ewea.org/ewec2009/allfiles/427_EWEC2009presentation.ppt. Version: March 2009

[17] Jonkman, Jason M. ; Jr., Marshall L. B.: *FAST User's Guide*. Golden, Colorado: National Renewable Energy Laboratory, August 2005. http://wind.nrel.gov/designcodes/simulators/fast/FAST.pdf. – NREL/EL-500-38230

[18] Oxford Dictionaries: *Definition of Aeroelasticity*. http://www.oxforddictionaries.com/definition/english/aeroelasticity. Version: 2014. – accessed 2014.05.25

[19] Garrad Hassan: *Bladed Theory Manual*. Version 4.5. Bristol. England: Garrad Hassan, 2013

[20] Espaze, Andre: *Free software for wind turbine modelling*. Denmark, Technical University of Denmark, Diplomarbeit, September 2007. http://www.fm.mek.dtu.dk/upload/institutter/mek/fm/eksamensprojekter/andreespaze2007.pdf

[21] Germanischer Loyd: *Guideline for the Cartification of Wind Turbines*. Hamburg, 2010

[22] IEC: *61400-1 Wind turbine generator systems - Part 1: Safety requirements*. Geneva, 1999

[23] IEC: *61400-1 Wind turbines - Part 1: Design requirements*. Geneva, 2005

[24] Ariduru, Secil: *Fatigue Life Calculation by Rainflow Cycle Counting Method*. Middle East Technical University, Graduate School of Natural and Applied Sciences, Diplomarbeit, December 2004. http://wind.nrel.gov/designcodes/papers/FatLifeCalcByRFCycleCountingMeth_Ariduru.pdf

[25] Garrad Hassan: *Bladed User Manual*. Version 4.5. Bristol. England: Garrad Hassan, 2013

[26] Moriarty, P.J. ; Holley, W.E. ; Butterfield, S.P.: *Extrapolation of Extreme and Fatigue Loads Using Probabilistic Methods*, National Renewable Energy Laboratory, NREL/TP-500-34421, November 2004. http://www.nrel.gov/docs/fy05osti/34421.pdf

[27] FREUDENREICH, Kai ; ARGYRIADIS, Kimon: Wind turbine load level based on extrapolation and simplified methods. In: *Wind Energy* 11 (2008), Nr. 6, S. 589–600. `http://dx.doi.org/10.1002/we.279`. – DOI 10.1002/we.279. – ISSN 1099–1824

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Erklärung zur selbstständigen Bearbeitung einer Abschlussarbeit

Gemäß der Allgemeinen Prüfungs- und Studienordnung ist zusammen mit der Abschlussarbeit eine schriftliche Erklärung abzugeben, in der der Studierende bestätigt, dass die Abschlussarbeit „– bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit [(§ 18 Abs. 1 APSO-TI-BM bzw. § 21 Abs. 1 APSO-INGI)] – ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt wurden. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich zu machen.“

Quelle: § 16 Abs. 5 APSO-TI-BM bzw. § 15 Abs. 6 APSO-INGI

Dieses Blatt, mit der folgenden Erklärung, ist nach Fertigstellung der Abschlussarbeit durch den Studierenden auszufüllen und jeweils mit Originalunterschrift als letztes Blatt in das Prüfungsexemplar der Abschlussarbeit einzubinden.
Eine unrichtig abgegebene Erklärung kann -auch nachträglich- zur Ungültigkeit des Studienabschlusses führen.

Erklärung zur selbstständigen Bearbeitung der Arbeit

Hiermit versichere ich,

Name: Hansen

Vorname: Carsten

dass ich die vorliegende Masterarbeit bzw. bei einer Gruppenarbeit die entsprechend gekennzeichneten Teile der Arbeit – mit dem Thema:

Aeroelastic load simulation of a 3 MW two bladed wind turbine

ohne fremde Hilfe selbständig verfasst und nur die angegebenen Quellen und Hilfsmittel benutzt habe. Wörtlich oder dem Sinn nach aus anderen Werken entnommene Stellen sind unter Angabe der Quellen kenntlich gemacht.

- die folgende Aussage ist bei Gruppenarbeiten auszufüllen und entfällt bei Einzelarbeiten -

Die Kennzeichnung der von mir erstellten und verantworteten Teile der Masterarbeit ist erfolgt durch:

Hamburg		
Ort	Datum	Unterschrift im Original