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Design Load Basis for Offshore Wind turbines

DTU Vindenergi
E Rapport 2016

Anand Natarajan, Morten Hartvig Hansen, Shaofeng Wang

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By
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Preface

DTU Wind Energy is not designing and manufacturing wind turbines and does therefore not need a Design Load Basis (DLB) that is accepted by a certification body. However, to assess the load consequences of innovative features and devices added to existing offshore turbine concepts or new offshore turbine concept developed in our research, it is useful to have a full DLB that follows the current design standard and is representative of a general DLB used by the industry. It will set a standard for the offshore wind turbine design load evaluations performed at DTU Wind Energy, which is aligned with the challenges faced by the industry and therefore ensures that our research continues to have a strong foundation in this interaction. Furthermore, the use of a full DLB that follows the current standard can improve and increase the feedback from the research at DTU Wind Energy to the international standardization of design load calculations.

Content

Summary

This report describes the full Design Load Basis (DLB) used for load calculations at DTU Wind Energy for offshore wind turbines. It is based on the first edition of the IEC 61400-3 standard, but also takes into account a few of the simplifications in load cases introduced during the revision IEC 61400-3, 2014. It covers the typical cases for assessment of extreme and fatigue loads on the turbine components. Special cases that are intended for specific turbines must be added to this DLB if necessary e.g. faults of specific sensors or actuators. Site Specific environmental conditions are required for predicting the design load basis for the sub structure.

The description is generic and not linked to the development and testing of the HAWC2 aeroelastic software or external models and controllers coupled to HAWC2 through the DLL interface. The description is therefore formulated without direct references to HAWC2 features, commands, or terminology. This generic formulation has the advantage that the DLB can be used independently of the aeroelastic simulation tool.

Each Design Load Case (DLC) of the DLB is described in the following chapter. The DLC description also contains a short description on how the simulation results will be post-processed to obtain the tables of extreme and fatigue loads for the main components. More detailed descriptions of the post-processing methods are given in [2] and [3].

1. Definition of Offshore Wind Turbine

As given in the IEC 61400-3 Ed. 1 [1] standard, a wind turbine is to be considered as an offshore wind turbine, if its support structure is subject to hydrodynamic loading. The following figure taken from the same standard is used to define concepts related to the support structure.

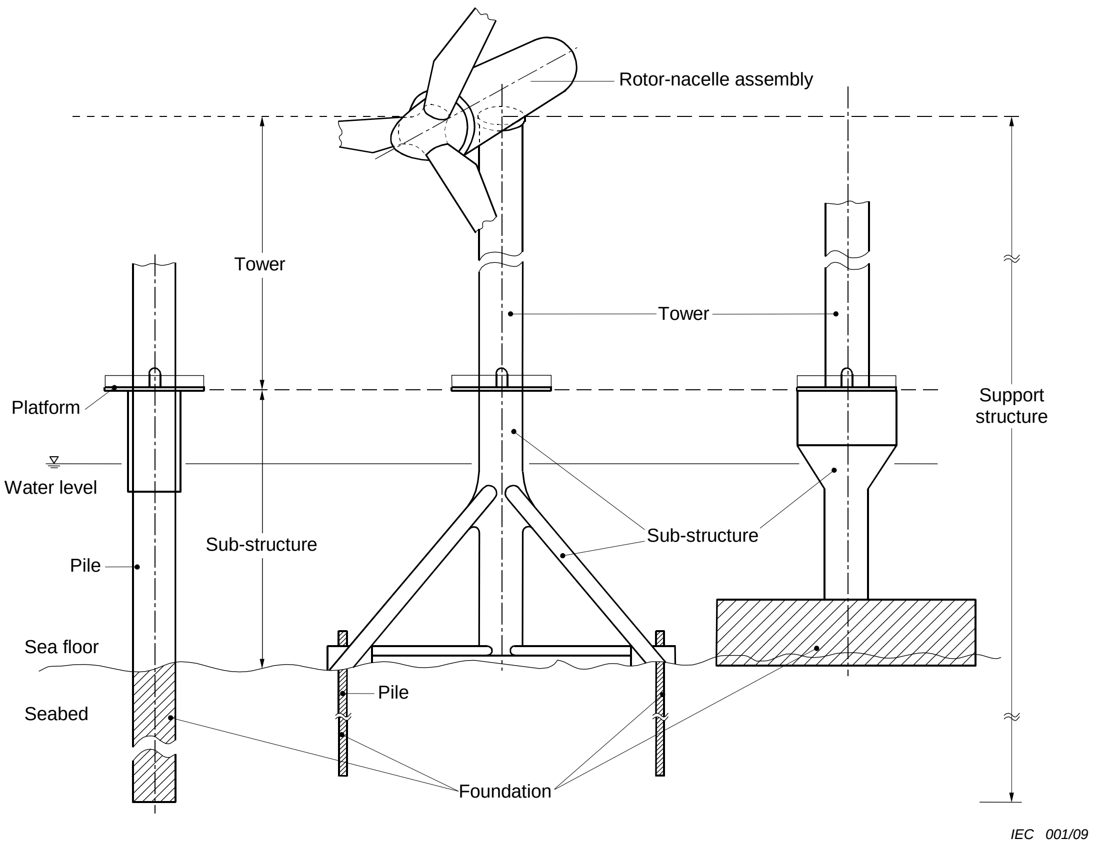

Figure 1 – Components of an offshore wind turbine (Reproduced from [1])

2. Design Load Cases

This chapter contains a description of each Design Load Case (DLC) in the DLB, based on the guidance given in the IEC 61400-3 Ed.1, 2009 [1]. Table 1 shows an overview of the DLCs, where the abbreviations used are defined below:

Name:	Identifier of the DLC
Load:	Type of load analysis (U=extreme/ultimate loads and F=fatigue)
PSF:	Partial safety factor on the loads.
Description:	Short description of the operating conditions.
WSP:	Mean wind speeds at hub height in m/s, e.g. 4:2:26 means the range 4, 6, 8,…, 26 m/s (Vr=rated, Vin=cut-in, Vout=cut-out wind speeds, Vref=reference speed of the IEC class, Vmaint=max. speed during maintenance, V1 and V50 are wind speeds with 1- and 50-year recurrence period).
WCP:	Wave and Current parameters to be used in the load cases
SS:	Sea State Conditions
WWD:	Direction between Wind and Waves – Unidirectional (UNI) or Multi Directional (MUL)
Yaw:	Mean yaw errors in degrees, e.g. -8/+8 deg means that simulations are performed for these two yaw errors for each wind speed and turbulence seed.
Turb.:	Turbulence level or intensity.
NWLR	The normal water level range between highest astronomical tide (HAT) and lowest astronomical tide (LAT).
EWLR	50 year Extreme Water Range under storm conditions, HAT + storm surge – (LAT + storm surge (negative))
MSL	Mean Sea Level
LAT	Lowest Astronomical Tide
HAT	Highest Astronomical Tide
NSS	Normal Sea State
ESS	Extreme Sea State
SSS	Severe Sea State
E[]	Expected Value
Hs	Significant Wave Height
Hs|WSP	Significant Wave Height conditional on the mean wind speed
Hs_1	1-Year Significant Wave Height
Hs_{50}	50-Year Significant Wave Height
NCM	Normal current model

ECM	Extreme current model
RNA	Rotor – nacelle assembly
UNI	Unidirectional
MUL	Multiple directions
Seeds:	Number of wind turbulence seeds or random wave seeds used per mean wind speed and yaw error.
Shear:	Vertical shear exponent or reference to equation in the IEC 61400-1 standard.
Gust:	Gust type according to the IEC 61400-1 standard.
Fault:	Short description of fault type.
T:	Length of simulated load signal used for analysis in seconds.
Files:	Number of result files.

The wind speed range for normal operation is here set to 4 – 26 m/s; however, it must be adjusted to the specific turbine, e.g. in case that the turbine has a storm controller.

All simulations are to be performed with aerodynamic imbalance due to uncertainty in blade pitch calibration of 0.5 deg, whereby one blade has a -0.5 deg pitch offset, another blade has +0.5 deg pitch offset, and the last blade of a three bladed rotor has no offset. Similar, all simulations are performed with a mass imbalance of each blade corresponding to 0.2% of the total blade mass, which is placed on two blades in their centers of gravity.

The load cases using stochastic wind conditions also require stochastic waves. <u>Offshore substructure design (monopiles, jackets etc.) is site specific and this requires that simulations are run with site specific met-ocean conditions</u>. In situations where this is an ultimate load case for the sub structure during turbine operation such as DLC 1.3, DLC 6.1 or DLC 6.2, 10 minutes of simulation time is not sufficient to cover all the phase differences possible between 10 minutes of wind time series and 10 minutes of wave time series and therefore at least 30 minute-60 simulations are required. In all cases of selecting extreme waves, the highest wave height must be chosen from at least 1 hour wave simulation. If this highest height is judged to be a possible breaking wave, then guidance can be taken from Annex C of the IEC 61400-3 or Ref.[4]. The 50 year wave height determination may need prior stochastic extrapolation of measured wave data or the use of the Inverse First Order Reliability Model (IFORM) also explained in the Annex of the IEC 61400-3.

For the listed DLCs with the chosen operational wind speed range, the total number of simulations, and therefore also result files will be more than the corresponding results for land turbines due to increased number of simulations required for DLC1.2, extra load case DLC 1.6, longer time of simulations required for DLC 1.3 and possible repetition of load cases at different water depths for the storm cases. Note that any transients in the simulation start-up must be excluded and are not counted to the time lengths of the simulated load signals that will be used for the load analysis.

Offshore sub structure design is site specific and depending on the type of sub structure, it may be required that some of the operational load cases are repeated with the wind/waves incident over a 360 deg. polar around the turbine. The rotor is in such cases, facing the incident wind. Further for site specific cases, appropriate soil properties need to be considered for the sub structure, whereby both the lateral bending and axial shear interaction between the sub structure and the soil are accounted for [4].

Table 1: Overview of the Design Load Basis of DTU Wind Energy. For turbines with storm operation the wind speed range must be adjusted accordingly.

Name	Load	PSF[1]	Description	WSP [m/s]	Yaw [deg]	Turb.	Seeds	Shear	Gust	WCP	SS	WWD	Other Conditions	No. of Stochastic Wave Seeds	T [s]
DLC11	U	1.25	Normal production	4:2:26	-10/0/+10	NTM	6	0.14	None	E(Hs|WSP), NCM along wave	NSS, MSL, Stochastic, JONSWAP	UNI	Only RNA loads to be extrapolated	3	600
DLC12	F	1.0	Normal production	4:2:26	-10/0/+10	NTM	6	0.14	None	Joint distribution *H*s,Tp, WSP, No currents	NSS, MSL, Stochastic, Pierson Moskovitz	MUL 0 +/- 10 degs	None	3	600
DLC13	U	1.35	Normal production	4:2:26	-10/0/+10	ETM	6	0.14	None	E(Hs|WSP), NCM along wave and against wave	NSS, MSL, Stochastic, JONSWAP	UNI	None	3	1500
DLC14	U	1.35	ECD	Vr – 2, Vr, Vr + 2	Direction change	None	None	0.14	ECD	$H_s = E[H_s \|$ WSP], no currents	NSS, MSL	Initially aligned with wind	None	-	100
DLC15	U	1.35	EWS	Vr – 2, Vr, Vr + 2	0	None	None	Eq. in IEC	None	$H_s = E[H_s \|$ WSP], NCM	NSS, MSL	UNI	None	-	100
DLC16	U	1.35	Normal Production	4:2:26	0	NTM	6	0.14	None	$H_s = H_{s,SSS,}$ NCM	SSS, MSL	UNI	None	3	600

[1] Listed PSFs are for the standard values according to Table 3 of IEC 61400-1 Ed. 3. Note that the PSF can be lowered if gravity is part of the characteristic load for the particular channel.

DLC21	U	1.35	Grid loss	4:2:26	-10/0/+10	NTM	4	0.14	None	$H_s = E[H_s\|$ WSP], NCM	NSS, MSL	UNI	Grid loss at 10s	-	100
DLC22p	U	1.1	Pitch runaway	12:2:26	0	NTM	12	0.14	None	$H_s = E[H_s\|$ WSP], NCM	NSS, MSL	UNI	Max. pitch to fine at 10s	-	100
DLC22y	U	1.1	Extreme yaw error	4:2:26	15:15:345	NTM	1	0.14	None	$H_s = E[H_s\|$ WSP], NCM	NSS, MSL	UNI	Abnormal yaw error	-	600
DLC22b	U	1.1	One blade stuck at fine pitch	4:2:26	0	NTM	12	0.14	None	$H_s = E[H_s\|$ WSP], NCM	NSS, MSL	UNI	1 blade at fine pitch	-	600
DLC23	U	1.1	Grid loss	Vr – 2, Vr, Vr + 2, Vout	0	None	4 differen t azimuth start points	0.14	EOG	$H_s = E[H_s\|$ WSP], NCM	NSS, MSL	UNI	Grid loss at start of gust, max acceleration and max velocity	-	100
DLC31	F	1.0	Start-up	Vin, Vr, Vout	0	None	None	0.14	None	$H_s = E[H_s\|$ WSP], No currents	NSS NWLR	UNI	None	-	100
DLC32	U	1.35	Start-up at four diff. times	Vin, Vr+/-2, Vout	0	None	None	0.14	EOG	$H_s = E[H_s\|$ WSP],	NSS, MSL	UNI	None	-	100
DLC33	U	1.35	Start-up in EDC	Vin, Vr+/-2, Vout	0	None	None	0.14	EDC	$H_s = E[H_s\|$ WSP],	NSS, MSL	Initially aligned with wind	None	-	100
DLC41	F	1.0	Shut-down	Vin, Vr, Vout	0	None	None	0.14	None	$H_s = E[H_s\|$ WSP], No currents	NSS NWLR	UNI	None	-	100
DLC42	U	1.35	Shut-down at six diff. times	Vr+/-2, Vout	0	None	None	0.14	EOG	$H_s = E[H_s\|$ WSP],	NSS MSL	UNI	None	-	100

DLC51	U	1.35	Emergency shut-down	Vr+/-2, Vout	0	NTM	12	0.14	None	*H*s = E[*H*s| WSP],	NSS MSL	UNI	None	-	100
DLC61	U	1.35	Parked in extreme wind	V50	-8/+8	11%	6	0.11	None	$H_s = H_{s50,}$ ECM	ESS, EWLR, Stochastic, JONSWAP	MUL 0 and +/- 30 degs	None	3 seeds	600-1hour
DLC62	U	1.1	Parked grid loss	V50	0:15:345	11%	1	0.11	None	$H_s = H_{s50,}$ ECM	ESS, EWLR, Stochastic, JONSWAP	MUL 0 and +/- 30 degs	None	3 seeds	600-1hour
DLC63	U	1.35	Parked with large yaw error	V1	-20/+20	11%	6	0.11	None	$H_s = H_{s1}$, ECM	ESS, MSL, Stochastic, JONSWAP	MUL 0 and +/- 30 degs	None	3 seeds	600-1hour
DLC64	F	1.0	Parked	4:2:0.7 *Vref	-8/+8	NTM	6	0.14	None	Joint prob. distribution of H_s,T_p, WSP, No Currents	NSS, NWLR, Stochastic, Pierson Moskovitz	MUL 0 and +/- 10 degs	None	3 seeds	600
DLC71	U	1.1	Rotor locked and extreme yaw	V1	0:15:345	11%	1	0.11	None	$H_s = H_{s1}$ NCM	ESS, MSL, Stochastic, JONSWAP	MUL +/- 30 degs	Rotor locked at 0:30:90 deg	1 seed	600
DLC 72	F	1.0	Rotor locked, under normal wind conditions	NTM V_{in} to V_{out}	0	11%	6	0.14	None	Joint prob. distribution of H_s,T_p, WSP	NSS, MSL, MUL, Pierson Moskovitch	MUL 0 and +/- 10 degs	Rotor locked at 0:30:90 deg	3 seeds	600
DLC81	U	1.5	Maintenance	Vmaint	-8/+8	NTM	6	0.14	None	$H_s = E[H_s\|$ WSP], NCM	NSS, MSL, JONSWAP	UNI	Maintenance	1 Seed	600

DLC11	**Power production in normal turbulence**		
Assessment	Extreme extrapolation	**Partial safety factor**	1.25
Description	Simulation of power production without faults performed for wind speeds in the entire operational range with normal turbulence according to the IEC class. Yaw errors during normal operation are set to +/- 10 deg. Six seeds per wind speed and yaw error are used.		
Simulation setup	Length: 600 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: -10/0/+10 deg Turbulence: NTM, Minimum 6 seeds per wind speed and yaw error Shear: Vertical and exponent of 0.14 Waves Stochastic, NSS; 3 seeds Gust: None Fault: None		
Total no. simulations	At least 216		
Post-processing	The extrapolation of extreme loads from cases DLC11 is performed to statistically determine the long term load extremes [3] <u>only for the rotor nacelle assembly and the load case is therefore similar to those used on land</u>. If in case extreme loads only on the support structures are required, this load case may be omitted for fixed sub structures. If it can be shown that the influence of NSS waves on the RNA is negligible, then the simulation of waves for this load case can be omitted.		

DLC12	**Power production in normal turbulence**		
Assessment	Fatigue	**Partial safety factor**	1.0
Description	Simulation of power production without faults performed for wind speeds in the entire operational range with normal turbulence according to the IEC class. At least 3 different wave seeds are used in 3 different directions. Yaw errors during normal operation are set to +/- 10 deg. Six seeds per wind speed and yaw error are used. The wind/wave directions should also have misaligned combinations. If the difference between HAT and MSL is more than 5m, then at least two water depths should be simulated. Note that a Pierson Moskovith wave spectrum is used here.		
Simulation setup	Length: 600 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: -10/0/+10 deg Turbulence: NTM, 6 seeds per wind speed and yaw error Shear: Vertical and exponent of 0.14 Waves Stochastic, 3 seeds, NSS, 3 directions, MSL and HAT depths Gust: None Fault: None		
Total no. simulations	648 (x2 for two water depths), for jacket fatigue analysis repeated simulations for different rotor alignments around 360 degs in steps of 30 degs is recommended.		
Post-processing	A load spectrum is extracted for each load sensor and each wind speed using rainflow counting on the 18 results files for each wind speed representing three hour of normal operation at that particular wind speed. The individual load spectra are then combined to a life-time load spectrum using the wind/wave distribution and then the equivalent fatigue loads are computed from this combined spectrum based on the Palmgren-Miner assumption. Note that the combined load spectrum also contains load cycles from DLC24, DLC31, DLC41, DLC64 and DLC 7.2		

<table>
<tr><td>DLC13</td><td colspan="3">Power production in extreme turbulence</td></tr>
<tr><td>Assessment</td><td>Extreme – normal event</td><td>Partial safety factor</td><td>1.35[2]</td></tr>
<tr><td>Description</td><td colspan="3">Simulation of power production without faults or yaw error performed for wind speeds in the entire operational range with extreme turbulence according to the IEC class. Yaw errors are set to +/- 10 deg. Six seeds per wind speed and yaw error are used. This load case needs larger run time of at least 1500s to include sufficient phase differences between wind and waves to get the right extreme load combination on the sub structure.</td></tr>
<tr><td>Simulation setup</td><td colspan="3">Length: 1500 s
Wind: 4 – 26 m/s with steps of 2 m/s
Yaw: -10/0/+10 deg
Turbulence: ETM, 6 seeds per wind speed
Shear: Vertical and exponent of 0.14
Waves Stochastic, NSS, 3 seeds
Gust: None
Fault: None</td></tr>
<tr><td>Total no. simulations</td><td colspan="3">At least 216: 18 seeds for each joint pair of wind and wave conditions is recommended</td></tr>
<tr><td>Post-processing</td><td colspan="3">The wave seeds can be made in combination with wind seeds to ensure the same number of simulations as in the land case. However note that the length of each simulation should be at least 1500s. The mean of the extremes values for each mean wind speed are extracted for each load sensor as the characteristic extreme load value.</td></tr>
</table>

[2] For load sensors where gravity has a positive effect the partial safety factor can be reduced according IEC61400-1 (3. Ed.)

DLC14	Power production in extreme coherent gust with wind direction change		
Assessment	Extreme – normal event	**Partial safety factor**	1.35[2]
Description	Simulation of power production without faults or turbulence and with extreme coherent gust with wind direction change according to the IEC standard. Wind speeds close to rated are considered to capture the extreme blade tip deflections and flapwise blade moments.		
Simulation setup	Length: 100 s Wind: Vr and Vr +/- 2m/s Yaw: 0 deg Turbulence: None Waves Deterministic NSS Shear: Vertical and exponent of 0.14 Gust: ECD: Equations (23) and (25) of IEC 61400-1 (Ed. 3) Fault: None		
Total no. simulations	3		
Post-processing	The extremes values over all wind speeds are extracted for each load sensor.		

DLC15	Power production in extreme wind shear		
Assessment	Extreme – normal event	**Partial safety factor**	1.35[2]
Description	Simulation of power production without faults performed for wind speeds in the entire operational range without turbulence and with extreme vertical or horizontal wind shear transients in four different combinations, two pairs of opposite sign in the two directions.		
Simulation setup	Length: 100 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: 0 deg Turbulence: None Waves Deterministic, NSS Shear: EWS: Equations (26) and (27) of IEC 61400-1 (Ed. 3) Gust: None Fault: None		
Total no. simulations	48		
Post-processing	The extremes values over all wind speeds are extracted for each load sensor.		

DLC16	**Power production in severe sea states**		
Assessment	Extreme – normal event	**Partial safety factor**	1.35[2]
Description	This load case is only run for offshore wind turbines. Simulation of power production without faults performed for wind speeds in the entire operational range with normal wind turbulence but under severe sea state conditions. It is recommended that nonlinear waves are used either second order nonlinear random waves or a combination of Stokes nonlinear waves and irregular linear waves.		
Simulation setup	Length: Minimum 600 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: -10/0/+10 deg Turbulence: NTM, 6 seeds per wind speed and yaw error Shear: Vertical and exponent of 0.14 Waves Stochastic, 3 seeds, SSS, Nonlinear Waves Gust: None Fault: None		
Total no. simulations	216		
Post-processing	The waves are simulated as part of SSS, implying the joint probability of the normal wind speed and waves should have a 50 year return period. The mean of the extremes values over all wind speeds are extracted for each load sensor. Requires use of nonlinear waves such as described in [5] and the extreme wave height should be based on at least 1-hour wave simulations.		

DLC21	**Power production with grid loss**		
Assessment	Extreme – normal event	**Partial safety factor**	1.35[2]
Description	Simulation of power production with grid loss (generator torque drops to zero) after 10 s and thereafter the overspeed protection of the turbine controller[3] will shut-down the turbine. Normal turbulence and four seeds per wind speed and yaw error are used.		
Simulation setup	Length: 100 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: -10/0/+10 deg Turbulence: NTM, 4 seeds per wind speed and yaw error Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: Grid loss at t=10 s		
Total no. simulations	144		
Post-processing	For each load sensor, the average value of the upper half extreme values of the 12 realizations is computed for each wind speed.		

DLC22b	**Power production with one blade at minimum pitch angle**		
Assessment	Extreme – abnormal event	**Safety factor**	1.1
Description	Simulation of power production with failure in the pitch system or bearing of one blade such that the turbine is operating with this blade at minimum pitch angle. All operational wind speeds and normal turbulence are considered with 12 seeds per wind speed.		
Simulation setup	Length: 100 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: 0 deg Turbulence: NTM, 12 seeds per wind speed Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: Failure of pitch system on one blade leading to this blade remaining at minimum pitch angle.		
Total no. simulations	144		
Post-processing	For each load sensor, the average value of the upper half extreme values of the 12 realizations is computed for each wind speed.		

[3] In case that the controller does not include an overspeed monitoring feature, the simulations are set up by forcing an overspeed shut-down at the time instant where the rotor speed has accelerate to the specific overspeed limit.

DLC22p	**Power production with pitch runaway**[4]		
Assessment	Extreme – abnormal event	**Safety factor**	1.1
Description	Simulation of power production with failure in pitch system after 10 s leads to collective pitching towards minimum pitch angle at the maximum pitch speed. Wind speeds from 12 m/s and above and normal turbulence with 12 seeds per wind speed are considered.		
Simulation setup	Length: 100 s Wind: 12 – 26 m/s with steps of 2 m/s Yaw: 0 Turbulence: NTM, 12 seeds per wind speed Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: Failure in pitch system leading to collective pitch runaway where all blades pitch at t=10 s with maximum speed towards minimum pitch angle.		
Total no. simulations	96		
Post-processing	For each load sensor, the average value of the upper half extreme values of the 12 realizations is computed for each wind speed.		

DLC22y	**Power production with abnormal yaw error**		
Assessment	Extreme – abnormal event	**Safety factor**	1.1
Description	Simulation of power production with abnormally large yaw error due to failure in the turbine safety system. All operational wind speeds and normal turbulence are considered with one seed per wind speed and yaw error.		
Simulation setup	Length: 600 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: 15 to 345 deg with steps of 15 deg Turbulence: NTM, 1 seed per wind speed and yaw error Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: Failure of yaw system leading to abnormal yaw errors.		
Total no. simulations	276		
Post-processing	For each load sensor, the average value of the upper half extreme values of the 12 realizations is computed for each wind speed.		

[4] The DLC may be omitted if it can be argued that there is a redundant safety system that detects a pitch run-away and shuts down the turbine immediately, or that makes a pitch run-away impossible.

DLC23	**Power production with grid loss during extreme operating gust**		
Assessment	Extreme – abnormal event	**Safety factor**	1.1
Description	Simulation of power production with grid loss performed at close to rated and at cut-out wind speeds. To capture the extremes of this abnormal event, the grid loss is initiated at three different time instances after the gust has started.		
Simulation setup	Length: 100 s Wind: Vr+/-2 m/s and Vout Yaw: 0 deg Turbulence: None Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: EOG: Equation (17) of IEC 61400-1 (Ed. 3) Fault: Grid loss initiated at three difference instances in the gust.		
Total no. simulations	9		
Post-processing	The extremes values over all wind speeds and timings are extracted for each load sensor.		

DLC24	**Power production with large yaw errors**		
Assessment	Fatigue	**Safety factor**	1.0
Description	Simulation of power production with large yaw errors of +/-20 deg performed for all operational wind speeds with normal turbulence using three seeds per wind speed and yaw error. The large yaw errors are a result of a failure in the yaw control and the size of the yaw error is defined by the safety system.		
Simulation setup	Length: 600 s Wind: 4 – 26 m/s with steps of 2 m/s Yaw: -20/+20 deg Turbulence: NTM, 3 seeds per wind speed and yaw error Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: Failure in yaw control leading to maximum yaw error ensured by the safety system.		
Total no. simulations	72		
Post-processing	The one hour load spectra obtained from the six realizations of each wind speeds are added to the load spectra from DLC12 assuming that these large yaw errors occur 50h per year.		

DLC31	Start-up in normal wind profile		
Assessment	Fatigue	**Safety factor**	1.0
Description	Simulation of start-up in normal wind profile and at cut-in, rated, and cut-out wind speeds.		
Simulation setup	Length: 100 s Wind: Vin, Vr and Vout Yaw: 0 deg Turbulence: None Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: None		
Total no. simulations	3		
Post-processing	A total of 1000 start-ups at cut-in wind speed, 50 at rated wind speed and 50 at cut-out wind speed per year are assumed, and the load cycles during start-up for each load sensor and each wind speed are added to the combined load spectrum obtained from DLC12 and DLC24.		

DLC32	Start-up during extreme operating gust		
Assessment	Extreme – normal event	**Safety factor**	1.35[2]
Description	Simulation of start-up performed at cut-in, close to rated and cut-out wind speeds. To capture the extremes of this event, the start-up is initiated at four different time instances after the gust has started.		
Simulation setup	Length: 100 s Wind: Vin, Vr+/-2 m/s and Vout Yaw: 0 deg Turbulence None Waves: Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: EOG: Equation (17) of IEC 61400-1 (Ed. 3) Fault: None		
Total no. simulations	16		
Post-processing	The extremes values over all wind speeds and timings are extracted for each load sensor.		

DLC33	**Start-up during extreme wind direction change**		
Assessment	Extreme – normal event	**Safety factor**	1.35[2]
Description	Simulation of start-up during extreme wind direction change performed at cut-in, close to rated and cut-out wind speeds. Two timings for each sign of the direction change is used: start-up is just before the direction change and one half way through the direction change.		
Simulation setup	Length: 100 s Wind: Vin, Vr+/-2 m/s and Vout Yaw: 0 deg Turbulence None Waves: Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: EDC: Equation (21) of IEC 61400-1 (Ed. 3) Fault: None		
Total no. simulations	16		
Post-processing	The extremes values over all wind speeds and timings are extracted for each load sensor.		

DLC41	**Shut-down in normal wind profile**		
Assessment	Fatigue	**Safety factor**	1.0
Description	Simulation of normal shut-down in normal wind profile and at cut-in, rated, and cut-out wind speeds.		
Simulation setup	Length: 100 s Wind: Vin, Vr, and Vout Yaw: 0 deg Turbulence: None Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: None		
Total no. simulations	3		
Post-processing	A total of 1000 shut-downs at cut-in wind speed, 50 at rated wind speed and 50 at cut-out wind speed per year are assumed, and the load cycles during normal shut-down for each load sensor and each wind speed are added to the combined load spectrum obtained from DLC12 and DLC24.		

DLC42	**Shut-down during extreme operating gust**		
Assessment	Extreme – normal event	**Safety factor**	1.35
Description	Simulation of normal shut-down performed at close to rated and cut-out wind speeds. To capture the extremes of this event, the shut-down is initiated at six different time instances after the gust has started.		

Simulation setup	Length: Wind: Yaw: Turbulence Waves: Shear: Gust: Fault:	100 s Vr+/-2 m/s and Vout 0 deg None Deterministic, NSS Vertical and exponent of 0.14 EOG: Equation (17) of IEC 61400-1 (Ed. 3) None
Total no. simulations	18	
Post-processing	The extremes values over all wind speeds and timings are extracted for each load sensor.	

DLC51	**Emergency shut-down**		
Assessment	Extreme – normal event	**Safety factor**	1.35[2]
Description	Simulation of emergency shut-down performed at close to rated and cut-out wind speeds in normal turbulence with 12 seeds per wind speed. The emergency stop may or may not incorporate a mechanical brake dependent on the turbine type.		
Simulation setup	Length: 100 s Wind: Vr+/-2 m/s and Vout Yaw: 0 deg Turbulence: NTM, 12 seeds per wind speed Waves Deterministic, NSS Shear: Vertical and exponent of 0.14 Gust: None Fault: None		
Total no. simulations	36		
Post-processing	The average of the upper half extremes values for each wind speed is computed for each load sensor.		

DLC61	**Parked in 50-year extreme wind**		
Assessment	Extreme – normal event	**Safety factor**	1.35[2]
Description	Simulation of parked turbine with idling rotor and yaw error at a wind speed with 50-year recurrence period and turbulence intensity of 11%. Six seeds per yaw error are used. The combination of extreme wind and wave conditions shall be such that the global extreme environmental action has a combined recurrence period of 50 years. This needs to be repeated at 3 water depths of MSL, HAT +storm surge and LAT-storm surge if the water level that results in the largest loads is not known.		
Simulation setup	Length: At least 600 s (1 hour is recommended) Wind: V50 Yaw: -8/+8 deg Turbulence: 11% intensity, 6 seeds per wind speed and yaw error Waves: Stochastic, ESS, EWLR, 50 year nonlinear waves, 3 seeds Shear: Vertical and exponent of 0.11 Gust: None Fault: None		
Total no. simulations	12 (if fixed water depth) otherwise 36 (for 3 different water depths)		
Post-processing	The average of the extremes values is computed for each load sensor as the characteristic extreme load value. The non-linear waves of height equal to the extreme wave height must be used based on at least 1 hour wave simulation using methods such as given in [5]. If the load simulation length is only 600s, then the extreme wave from a 1-hour wave simulation should be used. For 1-hour load simulations the extreme mean wind speed can be 0.95 of the 10 minute extreme mean wind speed.		

DLC62	**Parked without grid connection in 50-year extreme wind**		
Assessment	Extreme – abnormal event	**Safety factor**	1.1
Description	Simulation of parked turbine with idling rotor and abnormally large yaw error due to grid loss at a wind speed with 50-year recurrence period and turbulence intensity of 11%. One seed per yaw error is used. The combination of extreme wind and wave conditions shall be such that the global extreme environmental action has a combined recurrence period of 50 years. This needs to be repeated at 3 water depths of MSL, HAT +storm surge and LAT-storm surge if the water level that results in the largest loads is not known		
Simulation setup	Length: At least 600 s (1 hour is recommended) Wind: V50 Yaw: 0:15:345 deg Turbulence 11% intensity, 1 seed per wind speed and yaw error Waves: Stochastic, ESS, EWLR, 50 year nonlinear waves, 3 seeds Shear: Vertical and exponent of 0.11 Gust: None Fault: None		
Total no. simulations	72 (2 wave misalignment directions for each wind direction)		
Post-processing	The average of the extremes values is computed for each load sensor as the characteristic extreme load value. Note that the non-linear waves of height equal to the extreme wave height must be used based on at least 1 hour wave simulation. If the load simulation length is only 600s, then the extreme wave from a 1-hour wave simulation should be used. The misalignment within a range of ± 30° that results in the highest loads acting on the support structure shall be considered. For 1-hour load simulations the extreme mean wind speed can be 0.95 of the 10 minute extreme mean wind speed.		

<table>
<tr><td>DLC63</td><td colspan="3">Parked with large yaw error in 1-year wind</td></tr>
<tr><td>Assessment</td><td>Extreme – normal event</td><td>Safety factor</td><td>1.35[2]</td></tr>
<tr><td>Description</td><td colspan="3">Simulation of parked turbine with idling rotor and large yaw error due to failure in yaw control system at a wind speed with 1-year recurrence period and turbulence intensity of 11%. Six seeds per yaw error are used. The combination of extreme wind and wave conditions shall be such that the global extreme environmental action has a combined recurrence period of 1 year. Multiple wave directions of +/- 30 degs are used.</td></tr>
<tr><td>Simulation setup</td><td colspan="3">Length: At least 600 s
Wind: V1
Yaw: -20/+20 deg
Turbulence: 11% intensity
Waves: Stochastic, ESS, MSL, 1 year wave, 3 seeds, misaligned
Shear: Vertical and exponent of 0.11
Gust: None
Fault: None</td></tr>
<tr><td>Total no. simulations</td><td colspan="3">36</td></tr>
<tr><td>Post-processing</td><td colspan="3">The average of the extremes values is computed for each load sensor as the characteristic extreme load value. Note that the non-linear waves of height equal to the extreme wave height must be used based on at least 1 hour wave simulation. If the load simulation length is only 600s, then the extreme wave from a 1-hour wave simulation should be used._For 1-hour load simulations the extreme mean wind speed can be 0.95 of the 10 minute extreme mean wind speed.</td></tr>
</table>

DLC64	**Parked**		
Assessment	Fatigue	**Safety factor**	1.0
Description	Simulation of parked turbine with idling rotor and minor yaw error (according to the standard) at wind speeds from 4 m/s to 70% of the reference wind speed of the IEC class. Six seeds per wind speed and 3 wave seeds and yaw error are used. This needs to be repeated at 3 water depths of MSL, HAT and LAT, if the water level that results in the largest loads is not known		
Simulation setup	Length: 600 s Wind: 4 m/s to 0.7*Vref with steps of 2 m/s Yaw: -8/+8 deg Turbulence: None Waves Stochastic, NSS, NWLR, Misaligned Shear: Vertical and exponent of 0.14 Gust: None Fault: None		
Total no. simulations	192[5] x 3 (To be repeated 3 times at 3 different water depths)		
Post-processing	Assuming that the turbine is idling 2.5% of the time in each wind speed bin, the load cycles during idling for each load sensor and each wind speed are added to the combined load spectrum obtained from DLC12 and DLC24.		

DLC71	**Parked with rotor locked in 1-year extreme wind**		
Assessment	Extreme – abnormal event	**Safety factor**	1.1
Description	Simulation of parked turbine with rotor locked at 0:30:90 deg and abnormally large yaw error due to electrical fault at a wind speed with 1-year recurrence period and turbulence intensity of 11%. One seed per yaw error is used.		
Simulation setup	Length: 600 s Wind: V1 Yaw: 0:15:345 deg Turbulence: 11% intensity Waves: Stochastic, MSL,ESS; 1 year extreme states Shear: Vertical and exponent of 0.11 Gust: None Fault: None		
Total no. simulations	96		
Post-processing	The average of the upper half extremes values is computed for each load sensor.		

[5] The number of simulations will vary with the reference wind speed of the selected IEC wind class.

DLC72	Rotor locked, under normal wind conditions		
Assessment	Fatigue	Safety factor	1.0
Description	Simulation of parked turbine with rotor locked at 0:30:90 deg and normal turbulent wind conditions without yaw error. Normal stochastic wave conditions are used but the waves may be +/- 10 degrees.		
Simulation setup	Length: 600 s Wind: V1 Yaw: 0:15:345 deg Turbulence: 11% intensity Waves: Stochastic, NSS, MSL, Misaligned Shear: Vertical and exponent of 0.14 Gust: None Fault: None		
Total no. simulations	96		
Post-processing	The average of the upper half extremes values is computed for each load sensor.		

DLC81	Maintenance		
Assessment	Extreme – normal event	Safety factor	1.35[2]
Description	Simulation of parked turbine with the rotor locked in the best position[6] and minor yaw error at the maximum wind speed for maintenance and normal turbulence model. Six seeds per yaw error are used. The use of normal stochastic waves is made with normal currents. Vortex induced Vibrations needs to be checked based on the status of the installation or maintenance.		
Simulation setup	Length: 600 s Wind: Vmaint Yaw: -8/+8 deg Turbulence: NTM, 6 seeds per yaw error. Waves: Normal waves and Normal Current model, MSL Shear: Vertical and exponent of 0.14 Gust: None Fault: None		

[6] This best azimuth position of the rotor when it is locked for maintenance may be turbine dependent.

Total no. simulations	12
Post-processing	The average of the upper half extremes values is computed for each load sensor.

References

[1] IEC 61400-3. "International Electro technical Committee IEC 61400-3: Wind Turbines part 3: Design Requirements for Offshore Wind Turbines." Edition1, Geneva, 2009.

[2] Pedersen, M. M. (2014). *Post processing of Design Load Cases using Pdap*. DTU Wind Energy. (DTU Wind Energy I; No. 0371), Online on orbit.dtu.dk.

[3] Natarajan, A. and Holley, W. E., Statistical Extreme Loads Extrapolation with Quadratic Distortions for Wind Turbines, ASME Journal of Solar Energy Engineering, Vol. 130, 031017, Aug 2008.

[4] DNV-OS-J101. Design of Offshore Wind Turbine Structures. Det Norske Veritas, 2014.

[5] Natarajan, A., “Influence of Second-Order Random Wave Kinematics on the Design Loads of Offshore Wind Turbine Support Structures”, Renewable Energy Journal, Vol. 68, 2014, pp. 829-841.

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