STANDARD

DNVGL-ST-0437

Edition November 2016

Loads and site conditions for wind turbines

DNV GL AS

FOREWORD

DNV GL standards contain requirements, principles and acceptance criteria for objects, personnel, organisations and/or operations.

Any comments may be sent by e-mail to *rules@dnvgl.com*

CHANGES – CURRENT

General

This is a new document.

Contents

Contents

SECTION 1 INTRODUCTION

1.1 General

This DNV GL standard provides principles, technical requirements and guidance for loads and site conditions of wind turbines. For the first time, the requirements for onshore and bottom mounted offshore wind turbines are defined consistently and concisely in a single document. The definition of offshore turbulence classes has been revised significantly to include turbulence distributions adapted to the offshore environment. In addition marine parameters have been included to define offshore type classes which may be used for the type certification of an offshore rotor-nacelle assembly (RNA) and sub-structure.

Based on more than three decades of experience as standard setter and certification body in the wind industry, this standard fills gaps and provides clarity and additional guidance, where existing standards lack such guidance. The requirements of this standard focus on reaching the intended safety level in an economic way. Where the intended safety level could have been reached in several ways, the requirements of this standard have in general been aligned with requirements of other international standards, in particular with the IEC 61400 series of standards.

This standard has been developed and updated by DNV GL and undergoes external hearing by the committee of experts and other external stakeholders prior to publication as part of the quality assurance process. This standard is checked regularly to ensure its content is in accordance with the state of the art. It will be updated to keep it current and to ensure appropriate coverage in areas of ongoing technological development.

The standard has been written for world-wide application. National and governmental regulations may include requirements in excess of the provisions given in this standard. The DNV GL wind turbine standards as listed in Table 1-1 have been aligned technically, regarding the provided safety level and their requirements. Along with the DNV GL service documents as listed in Table 1-1 they form the most comprehensive basis for the design and certification of wind turbines and wind farms.

The standard contains five sections:

Sec.1 gives an introduction and provides context towards other DNV GL standards and service specifications and towards other existing loads standards.

Sec.2 covers external conditions relevant for the loads of wind turbines. External conditions for onshore wind turbines are identical to those in IEC 61400-1, whereas marine conditions are covered in depth in this standard and refer partly to IEC 61400-3.

Sec.3 covers site conditions and requirements for determining site specific design conditions as part of the design basis.

Sec.4 covers the calculation of loads, including different sources of loading, safety factors, load case definitions and evaluation of loads.

Sec.5 covers requirements for type testing, in particular regarding verification of design loads through comparison of simulations and measurements.

Guidance note:

The present DNV GL standard will cover the technical requirements to be applied for the DNV GL certification schemes according to DNVGL-SE-0190 and DNVGL-SE-0441, and it is also intended to cover the requirements implied when using IEC 61400-22 related certification schemes.

The latest revision of all DNV GL documents may be found on the DNV GL website https://rules.dnvgl.com.

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1.2 Objectives

The objectives of this standard are to:

— provide an internationally acceptable level of safety by defining minimum requirements for the determination of loads of wind turbines (in combination with referenced standards, recommended practices, etc.)
— serve as a design basis for designers, suppliers, purchasers and authorities
— specify requirements for wind turbines and wind farms subject to DNV GL certification.

1.3 Scope and application

This standard is applicable for the determination of design loads for onshore and bottom mounted offshore wind turbines, the relevant site conditions are also within the scope of this standard. For floating offshore wind turbines see DNV-OS-J103. Unless stated otherwise, within this standard the term wind turbine refers to the rotor-nacelle assembly including the support structure of both onshore and offshore wind turbines. Any reference to offshore requirements is meant for offshore wind turbines only.

The standard should be applied in combination with other DNV GL standards. DNV GL recommended practices may be utilised to cover specific requirements as outlined in this standard. Where no DNV GL standards and recommended practices exist, relevant international standards should be utilised.

All applicable requirements specified in this standard shall be fulfilled. Deviations from these requirements, or the application of alternative means to comply with these requirements, may be acceptable, provided that an equivalent level of safety and reliability can be demonstrated. For onshore wind turbines the level of safety resulting from applying IEC 61400-1 in its latest edition will result in an equivalent level of safety. As a consequence, for onshore wind turbines either this standard or IEC 61400-1 may be applied. The mixing of requirements of this standard with requirements of other standards is generally not permitted unless it can be demonstrated that an equivalent or higher level of safety and reliability is reached by doing so.

This standard may be applied as part of the technical basis for carrying out type or component certification of wind turbines according to DNVGL-SE-0441 as well as for carrying out a project certification of wind power plants according to DNVGL-SE-0190. It is also intended for application in connection with IEC 61400-22 related certification schemes as described in DNVGL-SE-0073 and DNVGL-SE-0074.

The standard is applicable to all types of wind turbines, however, it is most comprehensive for two or three bladed and grid connected horizontal axis wind turbines with active pitch and yaw systems. When this standard is applied for other turbine types, the standard shall be applied logically rather than literally with the target of reaching the same level of safety.

This standard contains the:

— definition and theory regarding external conditions
— determination of site specific design conditions
— calculation and evaluation of loads
— model validation by measurement of loads and power curve.

1.4 Normative references

This document makes reference to relevant international documents and DNV GL documents. Unless otherwise specified in the certification agreement or in this service specification, the latest valid revision of each document referenced applies. In so far as amendments exist for any of the given documents, they shall be taken into account.

Table 1-1 DNV GL documents

Reference	*Title*
DNV-RP-C205	Environmental Conditions and Environmental Loads
DNV-OS-J103	Design of Floating Wind Turbine Structures
GL-TN-TC	Certification of Wind Turbines for Tropical Cyclone Conditions
DNVGL-RP-0363	Extreme temperature conditions for wind turbines
DNVGL-RP-0416	Corrosion protection for wind turbines
DNVGL-SE-0073	Project certification of wind farms according to IEC 61400-22
DNVGL-SE-0074	Type and component certification of wind turbines according to IEC 61400-22
DNVGL-SE-0190	Project certification of wind power plants
DNVGL-SE-0441	Type and component certification of wind turbines
DNVGL-ST-0076	Design of electrical installations for wind turbines
DNVGL-ST-0125	Grid code compliance
DNVGL-ST-0126	Support structures for wind turbines

Table 1-1 DNV GL documents (Continued)

Reference	*Title*
DNVGL-ST-0262	Lifetime extension of wind turbines
DNVGL-ST-0361	Machinery for wind turbines
DNVGL-ST-0376	Rotor blades for wind turbines
DNVGL-ST-0438	Control and protection systems for wind turbines

Table 1-2 IEC documents

Reference	*Title*
IEC 61400-1	Wind Turbines – Part 1: Design requirements
IEC 61400-3	Wind Turbines – Part 3: Design requirements for offshore wind turbines
IEC 61400-12-1	Wind Turbines – Part 12-1: Power performance measurements of electricity producing wind turbines
IEC 61400-13	(not yet published) – Wind turbines – Part 13: Measurement of mechanical loads
IEC 61400-22	Wind turbines – Part 22: Conformity testing and certification
WT CS CBC-004C	Wind turbine type designation
WT CS CBC-005C	Extent of load measurements in case of design changes e.g. tower

Table 1-3 ISO documents

Reference	*Title*
ISO 19906	Petroleum and natural gas industries. Arctic offshore structures

Table 1-4 Other documents

Reference	*Title*
EN 1991-1-4	Eurocode 1: Actions on structures – Part 1-4: General actions – Wind actions
EN 1998-1	Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings;

1.5 Informative references

The documents in Table 1-5 include other documents, which may be used in connection with this standard with due care.

Table 1-5 Informative references

Reference	*Title*
CEM	Coastal Engineering Manual, Manual No. 1110-2-1100, Department of the army, U.S. Army Corps of Engineers
DLWF II	Dynamic Loads in Wind Farms II (DLWF II), Final Report, EU Joule Project JOU2-CT92-0094
ESDU 87034	World-wide extreme wind speeds, Part 1: origins and methods analysis, ESDU International
Frandsen, S.	Turbulence and turbulence-generated structural loading in wind turbine clusters", Risø-R–1188(EN), 2007
Gumbel, E.J.	Statistics of Extremes, Columbia University Press 1958, p73
Massel, S.	On the largest wave height in water of constant depth, Ocean Engineering, Vol 23, No. 7, pp 553-573, 1996
Nelson, R.C.	Depth limited design wave height in very flat regions, Coastal Engineering, Vol 23, pp 43-59, 1994
Palutikof, J.P.	Palutikof, J.P.; Brabson, B.B.; Kister, D.H.; Adcock, S.T.: A Review of Methods to Calculate Extreme Wind Speeds, Meteorological Applications (1999), 6:119-132, Cambridge University Press

1.6 Terminology

Table 1-6 Definitions of verbal forms

Verbal forms	*Definition*
shall	verbal form used to indicate requirements strictly to be followed in order to conform to the document
should	verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required
may	verbal form used to indicate a course of action permissible within the limits of the document

Table 1-7 Definitions of terms

Term	*Definition*
abnormal operating conditions	abnormal operating conditions denote situations with serious failures and/or combinations of more than one unlikely external condition
design lifetime	the time period that was considered for strength verification when the device was designed
extreme external conditions	extreme external conditions are events with a probability of being exceeded once in 50 years
foundation	part of the support structure for a wind turbine or substation that transfers the loads acting on the structure into the soil
metocean data	term describing collectively the meteorological and oceanographic data relevant for offshore wind turbines
normal external conditions	normal external conditions are in general those events which have a probability of being exceeded once a year or more often
normal operating conditions	normal operating conditions denote situations, which can may reasonably be expected to occur during the operating life of a wind turbine
p-y-curve	pressure-deflection-curves (p-y-curves) are used to model the elastic embedment of piles in soil and their ability to resist loads applied in lateral direction Pp-y curves relate the force applied to soil to the lateral deflection of the soil by describing non-linear springs attached to the pile in place of the soil.
rotor-nacelle assembly (RNA)	the rotor-nacelle assembly of a horizontal axis wind turbine comprises the rotor with rotor blades and related systems as well as the nacelle with all components and systems, which follow the yaw motion The rotor-nacelle assembly includes the yaw-system and is attached to the support structure.
sub-structure	term referring to the part of the support structure for a wind turbine which extends upwards from the soil and connects the foundation and the tower The term is also used to designate the part of the support structure for a substation which extends upwards from the soil and connects the foundation and the topside or platform.
support structure	the support structure of a wind turbine is defined as the structure below the yaw system of the rotor-nacelle assembly and includes tower structure, sub-structure and foundation The term is also used to designate the structure below of the topside structure and includes sub-structure and foundation of a substation.
wind turbine	system which converts kinetic wind energy into electrical energy Whenever, in this standard the term is used to describe the wind turbine in general, it describes the rotor-nacelle assembly including the support structure, as this is the power generating unit.

1.7 Acronyms, abbreviations and symbols

1.7.1 Acronyms and abbreviations

The acronyms and abbreviations used in this standard are listed below.

Table 1-8 Acronyms and abbreviations

Short form	*In full*
A	abnormal
ALS	accidental limit state
API	American Petroleum Institute
COD	co-directional
CQC	complete quadratic combination
DAF	dynamic amplification factor
DLC	design load case
ECD	extreme coherent gust with direction change
ECM	extreme current model
EDC	extreme direction change
EOG	extreme operating gust
ESS	extreme sea state
ETM	extreme turbulence model
EWH	extreme wave height
EWLR	extreme water level range
EWM	extreme wind speed model
EWS	extreme wind shear
F	fatigue
FLS	fatigue limit state
FMEA	failure mode and effect analysis
GRP	glass fibre reinforced plastics
HAT	highest astronomical tide
HSWL	highest sea water level consisting of highest astronomical tide plus storm surge with 50-year return period
JONSWAP	Joint North Sea Wave Project
LAT	lowest astronomical tide
LDD	load duration distribution
LSWL	lowest sea water level consisting of lowest astronomical tide plus negative storm surge with 50-year return period.
MIS	misaligned
MLC	measurement load case
MSL	mean sea level
MTBF	mean time between failures
MUL	multi-directional
MWL	mean water level
N	normal
NCM	normal current model
NSS	normal sea state
NTM	normal turbulence model
NWLR	normal water level range
NWP	normal wind profile model
OWT	offshore wind turbine

Table 1-8 Acronyms and abbreviations (Continued)

Short form	*In full*
RMS	root mean square
RNA	rotor-nacelle assembly
SLS	serviceability limit state
SSDA	site specific design assessment
SSS	severe sea state
SWL	still water level
T	transport and installation
U	ultimate strength
ULS	ultimate limit state
UNI	uni-directional

1.7.2 Symbols

The symbols used in this standard are listed below.

a	slope parameter for turbulence intensity characteristics
a	generalised Phillips' constant
a	added mass coefficient
A	category for high turbulence intensity values
A	amplitude
A_c	Charnock's constant
B	category for medium turbulence values
B	size reduction factor
c	spring stiffness
c_f	aerodynamic force coefficient
c_d	aerodynamic drag coefficient of an aerofoil section
c_D	hydrodynamic drag coefficient
c_{DS}	hydrodynamic drag coefficient for steady-state flow
c_l	aerodynamic lift coefficient of an aerofoil section
c_m	aerodynamic moment coefficient of an aerofoil section
c_M	hydrodynamic inertia coefficient
c_p	aerodynamic power coefficient of a wind turbine
c_t	aerodynamic thrust coefficient of a wind turbine
c_{max}	maximum chord length
c_{min}	chord length at the blade tip, linearly extrapolated from the blade contour
C	category for low turbulence values
C	scale parameter of the Weibull function
C	wave celerity
C_S	slamming factor
d	water depth measured from still water level (taken as positive)
D	rotor diameter
D	diameter of a cylinder
D	projected width of a structure
d_r	separation in rotor diameters within rows
d_f	separation in rotor diameters between rows
E_{kin}	kinetic energy

E_{spring}	elastic deformation energy
f	frequency
$f_{HsTp}(h_s,t)$	joint probability density of the significant wave height H_s and the peak period T_p
f_p	spectral peak frequency
F	force
$F_{boat\ impact}$	boat impact force
F_D	drag force component
F_D	design sea current load
$F_{H\|HsTp}(h)$	short-term cumulative distribution function for the wave height H conditioned on H_s and T_p
F_k	characteristic value for loads
F_M	inertia force component
F_{res}	resulting force
F_S	slamming force component
F_{total}	total wave force from spilling breaking wave
$F_{total,max}$	total force/moment
$F_{wave,max}$	maximal force/moment due to wave action
$F_{wind,max}$	maximal force/moment due to wind action
$F_{wind,mean}$	mean force/moment due to wind action
$F_{x,max}$	maximum horizontal force on a vertical cylinder
g	acceleration due to gravity
$G(\mu_e)$	directional distribution function
h	significant wave height
h	single wave height
h	hub height
h_f	arm of force on a vertical cylinder measured from the seabed
h_T	transition wave height
d_0	reference depth for wind-generated current
H	wave height
H_b	breaking wave height
H_c	Wave crest height
H_{max}	highest wave height
$H_{max,mean}$	mean of the highest wave height
$H_{max,mode}$	mode of the highest wave height
H_{ref}	significant reference wave height
H_{RMS}	root mean square value of the wave height
H_s	significant wave height
$H_{s,N}$	*N*-year significant wave height
$H_{s,NSS}$	significant wave height of the normal sea state
$H_{s,SSS}$	significant wave height of the severe sea state
I	turbulence intensity
I_{ref}	reference value of the wind speed turbulence intensity corresponding to the 90% quantile at 15 m/s
I_c	characteristic turbulence intensity at hub height
I_{eff}	effective turbulence intensity
k	shape parameter of the Weibull function
k	parameter to determine the wind generated current at still water level
k	surface roughness

K	frost index
KC	Keulegan-Carpenter number
M	electromagnetic torque
M_{res}	resulting moment
m	vessel displacement
m	Wöhler exponent
M_{Bmin}	minimum required braking torque
M_{Bmaxn}	maximum braking torque
N	number of neighbouring turbines
n_{A}	activation speed
$n_{\max}$	maximum overspeed
n_{r}	rated speed
n_{ref}	reference load cycle number
n_1	minimum operating rotational speed
n_2	set value of the speed controller
n_3	maximum operating rotational speed
n_4	cut-out rotor speed
p	probability density function of the wind direction
P_{W}	Weibull probability distribution: cumulative probability function
$P(95)_{,\mathrm{site}}$	95% quantile of the wind speed distribution at hub height at the site
P_{A}	activation power
P_{r}	rated electrical power output
P_{R}	Rayleigh probability distribution: cumulative probability function
P_{T}	over-power
q_{D}	design sea current pressure
R	rotor radius
R	radius of a cylinder
Re	Reynolds number
$S(f)$	power spectral density
t	ice thickness
t_{a}	turbulence offset factor
t_{b}	turbulence shape factor
t_{limit}	limiting thickness of moving ice in sheltered waters
T	time interval
T_{b}	period of breaking wave
T_{i}	intrinsic period of the wave
T_{p}	spectral peak period
T_{R}	return period
T_{ref}	wave peak period corresponding to H_{ref}
T_{z}	zero-crossing period
$U(z)$	total current velocity at level z
U_{D}	design sea current speed
$U_{\max}$	maximum horizontal particle velocity at still water level
$U_{\mathrm{tide}}(z)$	tidal current velocity at level z
U_{tide0}	tidal current velocity at still water level
$U_{\mathrm{wind}}(z)$	wind-generated current velocity at level z
U_{wind0}	wind-generated current velocity at still water level

v	spectral width parameter
$V(z)$	wind speed at the height z above ground level/still water line
V_{amb}	ambient 10-minute average wind speed at hub height
V_{ave}	annual average wind speed
V_A	short-term cut-out wind speed
V_{cg}	magnitude of the extreme coherent gust during ECD
V_{eN}	maximum 3-second extreme wind speed with N-year recurrence period
V_{gust}	maximum value of the wind speed for the extreme operating gust
V_{hub}	10-minute average wind speed at hub height
V_{ice}	sea ice speed
V_{impact}	impact speed
V_{in}	cut-in wind speed
$V_m(z)$	10-minute average wind speed at height z
V_{maint}	maximum wind speed for performing maintenance work
V_N	maximum 10-minute average wind speed with N-year recurrence period
V_{out}	cut-out wind speed
V_r	rated wind speed
V_{ref}	reference wind speed with 50-year recurrence period
V_T	maximum 10min-mean wind speed for maintenance
$v_0(h_s,t)$	zero-upcrossing rate of the sea elevation process for given H_s and T_p
V_1	reference wind speed with 1-year recurrence period
x	horizontal distance
$\dot{x}$	horizontal wave-induced velocity of water
$\ddot{x}$	horizontal wave-induced acceleration of water
z	height above ground/ vertical coordinate from still water level, positive upwards
z_{hub}	hub height of HAWT
z_0	roughness parameter
Δz	vertical deviation of the terrain from the plane
Δt	time distance
Δh	deviation of the terrain from the plane

1.7.3 Greek symbols

The Greek symbols used in this standard are listed below.

α	power law exponent
α	slope angle of the sea floor
α	coefficient to determine maximum horizontal force from linear waves
β	parameter for the models of extreme operating gust, extreme direction change and extreme wind shear
γ	peak-enhancement factor
γ_F	partial safety factor for loads
γ_N	partial safety factor for consequence of failure
Γ	gamma function
θ_{cg}	magnitude of the wind direction change during ECD
θ_{eN}	extreme direction change with a recurrence period of N-years
κ	von Karman's constant
λ	wave length
λ	curling factor

Λ_1	turbulence scale parameter
μ_{E}	mass distribution of ice on the rotor blade
μ_{e}	deviation from mean wave direction
ν	kinematic viscosity
ξ	coefficient to determine maximum horizontal force from linear waves
ξ_{b}	wave steepness of shallow water waves
ξ_0	wave steepness of deep water waves
ρ	air density
ρ_E	density of ice accumulating on wind turbine parts (not sea ice)
ρ_W	density of water
σ	standard deviation
$\bar{\sigma}$	mean value of standard deviation
σ_{ETM}	extreme turbulence model standard deviation of the longitudinal wind speed at hub height
σ_{T}	maximum extreme centre wake standard deviation
σ_σ	standard deviation of the standard deviation of the longitudinal wind speed
σ_1	standard deviation of the longitudinal wind speed at hub height
σ_{V}	standard deviation of the longitudinal mean wind speed based on a 10-min time series
σ_{c}	characteristic ambient turbulence standard deviation
φ_A	maximum yaw error for shut down
Φ	inclination of a plane fit for the terrain
ψ	wake amplification factor

SECTION 2 EXTERNAL CONDITIONS

2.1 Fundamentals

2.1.1 Relevant types of external conditions

Wind turbines are exposed structures, which are subject to various external effects. Medium to high wind speeds are a functional requirement for operating wind turbines but along with other meteorological conditions, such as turbulence and wind shear also form a major source for the loading of wind turbines. For offshore wind turbines, oceanographic and other marine climate conditions are the second main category of external conditions, which substantially impact the loading of wind turbines.

While meteorological, oceanographic and other marine conditions generally form the main source of loading for wind turbines and are covered extensively in [2.3] and [2.4], other external conditions may become design driving for wind turbines, too. Other external conditions, which may be relevant for the turbine design include ambient temperature, seismic activity, geotechnical conditions, scour, icing, electrical grid conditions, corrosion and erosion, altitude, lightning, solar radiation, abrasive particles in air or water and others. Guidance on how to consider some of these conditions is given in [2.5]. However, special design features or site conditions may require consideration of other or additional external conditions.

Guidance note:

Within this standard the entity of meteorological, oceanographic and other marine conditions is also referred to as metocean data. Environmental conditions form a subset of the external conditions and summarize those external conditions, which are not related to infrastructure or other human actions (e.g. grid conditions and road ways are external conditions but not environmental conditions).

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2.1.2 External conditions for turbine types and wind farm sites

Within the scope of a wind turbine type and component certification according to DNVGL-SE-0441, it is common practice to make assumptions about the external conditions. In [2.2] this standard defines type classes and related design parameters both for onshore and for offshore wind turbine types. Besides pre-defined type classes, where the most relevant parameters are fixed, also the special class “S” is available, which allows the user freedom in defining a custom type class.

Within the scope of project certification of wind power plants according to DNVGL-SE-0190, the conditions prevailing at the installation site shall be determined and shall serve as design basis. The site specific design conditions are given in more detail in Sec.3.

2.1.3 Consideration of external conditions in the design

To ensure the appropriate level of safety and reliability, the relevant external conditions and parameters describing them shall be taken into account in the design, and shall be explicitly stated in the design documentation. External conditions shall be specified in a way that they cause the most adverse effect on the structure under consideration of the relevant probability level. The superposition of environmental design parameters shall be based on physical relations or on statistical correlations among those parameters or to the environmental phenomena to which they belong. Special attention shall be paid to extreme locations, such as polar regions and areas in which tropical cyclones or earth quakes may occur. For further guidance on regions subject to extreme climatic conditions, see DNVGL-RP-0363; for further guidance on regions subject to tropical cyclones, see GL-TN-TC.

For the purpose of combination with the operating conditions, the external conditions are subdivided into normal and extreme ones. Normal external conditions are in general those events which have a probability of being exceeded more than once a year. Extreme external conditions are events with a recurrence period of 50-years. The normal and extreme conditions which are typically to be considered in the design are prescribed in the following sub-sections.

Limiting environmental design conditions may be specified on the basis of statistical observations, if available. Estimation of design parameters on the basis of environmental design conditions (e. g. estimation of wave particle velocity or acceleration on the basis of wave height and period) or probabilistic estimations, which are not specified in the standard, may be applied in agreement with DNV GL.

For sites in regions of particular risks or if the environmental conditions are not determined according to the requirements of the standard, the safety factors shall be adjusted to uphold the safety level of the present standard. Similarly if estimates of environmental design parameters are based on assumptions that are more appropriate for the design case than those specified in the standard, a change of the partial safety factor shall be agreed with DNV GL.

For further information on how corrosion influence and protection shall be taken into account, see DNVGL-ST-0076, DNVGL-ST-0126 and DNVGL-ST-0361. Analogous considerations are to be applied with regard to the possibility of erosion, in particular for the rotor blades, see DNVGL-ST-0376.

2.2 Wind turbine classes

This standard defines wind turbine classes for both onshore and offshore types. According to the different external conditions which are typically experienced onshore and offshore, the definitions of parameters for onshore type classes and for offshore type classes are different. Table 2-1 specifies the basic parameters which define wind turbine classes for onshore and offshore wind turbines.

Wave classes have been introduced in terms of generic wave heights and periods in cases where support structures are subject to component or type certification. Wave classes may also be used for the type certification of a rotor-nacelle assembly (RNA) in combination with a hypothetical support structure.

Guidance note:
The new concept of offshore wind turbine classes is developed to allow designers to demonstrate feasibility of their design or design concept for generic offshore conditions. As the generic offshore conditions are limited to turbulence and extreme waves they will not replace the site specific calculations for the final design. Based on the experience applying the new offshore wind turbine classes, further conditions may be added to the offshore wind turbine classes in future editions of this standard.

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2.2.1 Wind data for turbine classes

For an on- and offshore wind turbine the definition of wind turbine classes in terms of wind speed and turbulence parameters remains appropriate as the basis for the design of the RNA within the scope of component/type certification. The values of the wind speed parameters and turbulence intensity are intended to represent the characteristic values of many different sites and do not give a precise representation of any specific site. The goal is to achieve a wind turbine classification with clearly varying degrees of robustness governed by the wind speed and turbulence intensity parameters.

Wind turbines shall be designed to safely withstand the wind conditions valid at the site or the selected wind turbine class. The design lifetime of the wind turbine for the standard type classes shall be at least 20 years. A shorter or longer design lifetime may be specified for type class S.

In the design and for the specific site the following basic parameters for the wind shall be determined as a minimum (see also App.E and App.F):

— reference wind speed V_{ref}
— annual average wind speed V_{ave}
— wind speed probability distribution
— wind direction distribution
— turbulence intensity I
— wind shear.

A turbine designed according to the wind turbine class with a reference wind speed V_{ref} is designed such that it can withstand the environmental conditions in which the 10-min mean of the extreme wind speed with a recurrence period of 50-years at hub height is equal to or less than V_{ref}.

The mean wind speed V_{ave} is a statistical mean of the instantaneous value of the wind speed, averaged over a certain period ranging from a few seconds to many years. In the present standard V_{ave} means the annual average of the wind speed over many years. This value is used in the Weibull or Rayleigh functions which represent the wind speed distribution at a certain site or for the standard wind turbine classes, respectively.

The turbulence of the wind is represented by energy carried along by the turbulence eddies. Its distribution over frequencies and space – represented by power spectra and coherence functions – may generally be regarded as an adequate representation of the turbulence over a period of approx. 10 minutes. This is in line with other assumptions taken in this standard. The values of the turbulence intensity shall be taken at hub height. The following general requirements shall be observed for load calculations with turbulent wind:

— The simulation period of each simulation run using a turbulence model shall be at least 10 minutes per simulation run.
— In the load calculation, each simulation run shall be performed with a different initial value ("seed") for producing the turbulent wind field.
— Three-dimensional turbulence fields shall be applied.
— The resolution of the turbulent wind fields shall be adequate. The grid spacing should be in line with the recommendations of IEC 61400-1.
— For the evaluation of loads (rotor and/or support structure), the wind field shall cover the entire plant (rotor and support structure) above water level for offshore resp. ground level for onshore wind turbines.

Specifications for stochastic turbulence models are given in IEC 61400-1. Other stochastic turbulence models are acceptable after agreement with DNV GL. For the standard wind turbine classes, the use of other turbulence models is only permissible, if they have been validated beforehand. Such other turbulence models shall result in a fatigue load level that is higher or equal than those given in IEC 61400-1 or it shall be demonstrated, that across various sites they lead to more realistic and sufficiently conservative loads.

The wind conditions for a specific site shall be determined as described in Sec.3.

2.2.2 Wave data for offshore wind turbine classes

A support structure designed for a to wave class with a reference significant wave height H_{ref} and period T_{ref} is designed to withstand the environmental conditions in which the 3-hour average of the extreme sea state, in combination with a JONSWAP spectrum, with a recurrence period of 50-years is equal to or less than H_{ref} and T_{ref}, respectively.

The design of support structures for offshore wind turbines shall be based on environmental conditions, including the marine conditions, which are characteristic at the specific site at which the offshore wind turbine shall be installed. In some cases a generic design of the support structure or parts of it is acceptable. The corresponding metocean conditions to be used for a generic design may be derived using wave classes OA-OC.

2.2.3 Wind turbine classes

This standard defines both onshore and offshore wind turbine classes. The offshore wind turbine classes include not only wind conditions but also wave conditions to be considered for the turbine design. The basic parameters, which define the wind turbine classes, are specified in Table 2-1.

Guidance note:
The design of an offshore wind turbine and its support structure depends on more parameters than turbulence and extreme wave height and period. Wave spectra, long-term wave distribution, water depths, soil conditions, current profile etc. have all major influence on the design and must therefore be carefully determined by the designer.

The provided offshore wind turbine classes allow designers to demonstrate feasibility of their design or design concept for generic offshore conditions without needing extensive knowledge of the extreme waves and turbulence. For the actual offshore project, the final design will need to be adapted to the full set of specific offshore site conditions.

The provided offshore wind turbine classes correspond to typical conditions in the German Bight of the North Sea, the Baltic Proper and land-protected nearshore conditions.

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Table 2-1 Basic parameters for wind turbine classes

Wind turbine class			*I*	*II*	*III*	*S*
V_{ref} [m/s]			50	42,5	37,5	Values to be specified by the manufacturer
V_{ave} [m/s]			10	8,5	7,5	
Onshore	A + I_{ref} [-]		0,18			
	A I_{ref} [-]		0,16			
	B I_{ref} [-]		0,14			
	C I_{ref} [-]		0,12			
Offshore	OA	H_{ref} [m]	10			
		T_{ref} [s]	12,5			
		I_{ref} [-]	0,14			
		t_a [$\frac{m}{s}$]	10			
		t_b [-]	0,566			
		A_C [m]	0,018			
	OB	H_{ref} [m]	6			
		T_{ref} [s]	10,0			
		I_{ref} [-]	0,12			
		t_a [$\frac{m}{s}$]	10,5			
		t_b [-]	0,561			
		A_C [m]	0,014			
	OC	H_{ref} [m]	2			
		T_{ref} [s]	5,5			
		I_{ref} [-]	0,10			
		t_a [$\frac{m}{s}$]	11			
		t_b [-]	0,556			
		A_C [m]	0,011			

The values given in Table 2-1 apply at hub height, where:

V_{ref} = reference wind speed
V_{ave} = annual average wind speed
H_{ref} = significant reference wave height with a recurrence period of 50-years
T_{ref} = wave period corresponding to H_{ref}
I_{ref} = reference value of the wind speed turbulence intensity at 15 m/s
t_a = turbulence offset factor
t_b = turbulence shape factor
A_C = Charnock's constant
$A+$ = category for very high turbulence intensity values (onshore)
A = category for higher turbulence intensity values (onshore)
B = category for medium turbulence intensity values (onshore)
C = category for lower turbulence intensity values (onshore)
OA = category for high turbulence intensity and significant wave height (offshore)
OB = category for medium turbulence intensity and significant wave height (offshore)
OC = category for low turbulence intensity and significant wave height (offshore)

In addition to these basic parameters, several other parameters are required to completely specify the external wind and marine conditions to be used in the design of a wind turbine. The values of these additional parameters are specified in [2.3] to [2.5].

The definition of other specific combinations of reference wind speed and turbulence intensity than given in Table 2-1, such as for typhoon, hurricane, tornado conditions etc., are possible, for further information see

GL-TN-TC. In this case the wind turbine class ‘S’ shall be chosen and a design basis with all relevant parameters shall be subject to verification.

The design of support structures of offshore wind turbines shall be based on environmental conditions that are representative for the specific site at which the offshore wind turbine shall be installed.

2.3 Wind conditions

2.3.1 General

Wind turbines are subject to large aerodynamic loads. A description of normal wind conditions as well as of extreme wind conditions is therefore an important part of the design basis.

Normal wind conditions are used to determine fatigue and extreme wind loads acting on operating wind turbines. In combination with load extrapolation methods, they serve as a main basis for defining the turbine loads.

The extreme wind conditions are used to determine the extreme wind loads acting on wind turbines. These conditions include peak wind speeds due to storms and rapid changes in wind speed and direction.

Unless explicitly stated, both normal and extreme wind conditions as used within this standard are defined according to IEC 61400-1, 6.3.

2.3.2 Offshore normal turbulence model

Deviating from IEC 61400-1, the normal turbulence model (NTM) for offshore wind turbines is defined in this section. For the standard offshore wind turbine classes, the random wind velocity field for the turbulence models shall satisfy the following requirements:

The roughness of the sea surface increases with wind speed and the turbulence intensity increases as a function of wind speed. The representative value for the standard deviation of the longitudinal wind velocity component at hub height for offshore wind turbines is given by:

$$\sigma_1 = \frac{8 \cdot V_{\mathrm{hub}}}{\ln(z_{\mathrm{hub}}/z_0)} + t_a \cdot I_{\mathrm{ref}} - 0{,}0025\,\tfrac{\mathrm{s}}{\mathrm{m}} \cdot V_{\mathrm{hub}}^2 - t_b \cdot V_{\mathrm{hub}} \tag{2.1}$$

where

v_{hub} = 10-minute average wind speed at hub height

z_{hub} = hub height

I_{ref} = reference value of the wind speed turbulence intensity

t_a = turbulence offset factor

t_b = turbulence shape factor

σ_1 = representative standard deviation of the longitudinal wind speed at hub height. The standard deviation shall be assumed to be invariant with height. The averaging time for the mean wind speed V_{hub}, used in the present Standard, is 10 minutes.

z_0 = the surface roughness parameter z_0 may be solved implicitly from the following equation for neutral atmospheric conditions:

$$z_0 = \frac{A_{\mathrm{c}}}{g}\left(\frac{\kappa\, V_{\mathrm{hub}}}{\ln(z_{\mathrm{hub}}/z_{\mathrm{o}})}\right)^2 \tag{2.2}$$

where

z_0 = roughness parameter

g ≈ *9,81* m/s² is the acceleration due to gravity;

κ = *0,4* is von Karman’s constant;

A_c = Charnock’s constant. Values for Charnock’s constant A_{c} are given in Table 2-1 for the different offshore wind turbine classes.

Guidance note:

A_C is usually higher for young developing and rapidly growing waves than for old fully developed waves. For open sea with fully developed waves, A_c=*0.011-0.014* is recommended. For near-coastal locations, A_c is usually higher with values of A_c=*0.018* or more. Expressions for A_C, which include the dependency on the wave velocity and the available water fetch, are available in the literature.

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The turbulence intensity for the different offshore wind turbine classes as a function of wind speed are depicted in Figure 2-1.

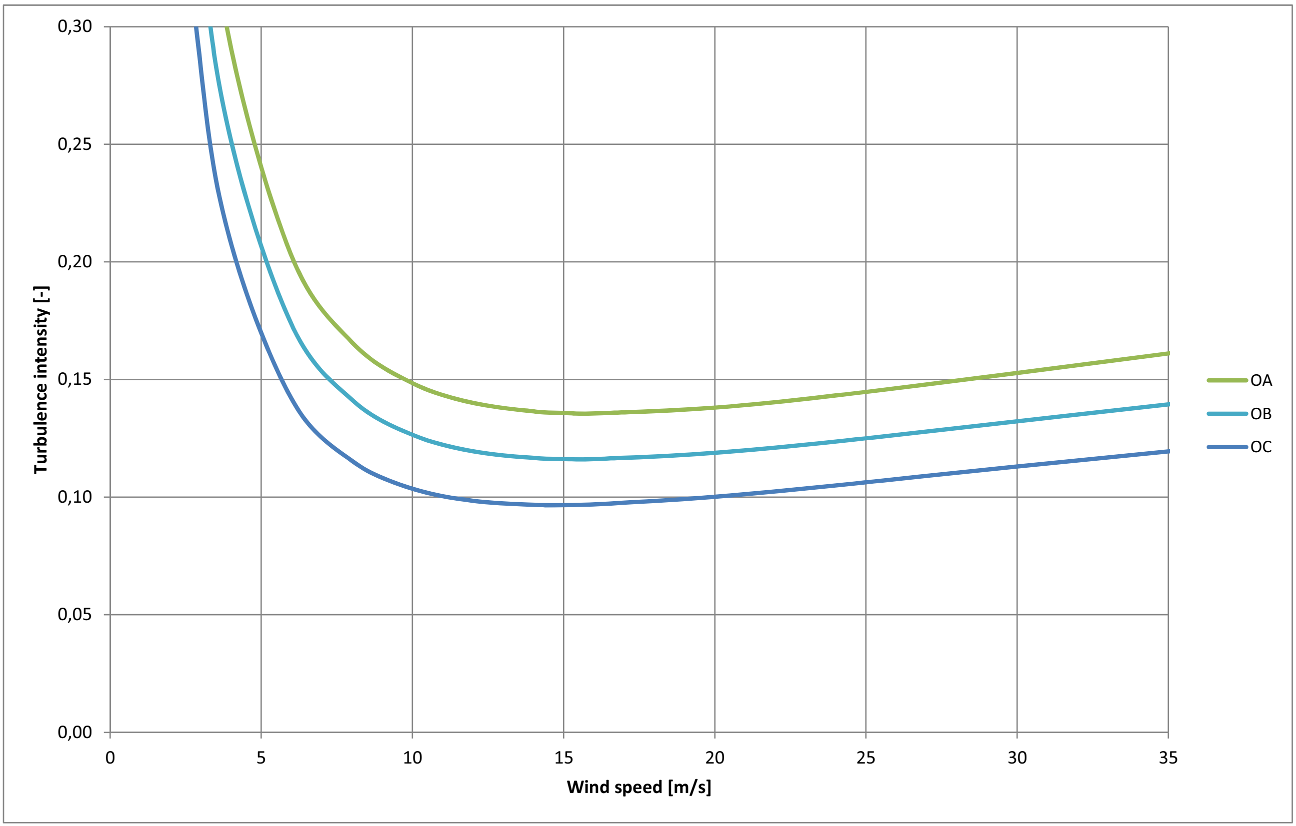

Figure 2-1 Turbulence intensity for offshore type classes at 100 m hub height

Towards the high frequency end of the inertial sub-range, the power spectral density of the longitudinal component of the turbulence $S_1(f)$ shall asymptotically approach the form:

$$S_1(f) = 0.05\sigma_1^2(\Lambda_1/V_{\text{hub}})^{-2/3}f^{-5/3} \tag{2.3}$$

where:

$S_1(f)$ = power spectral density [m^2/s^2]

Λ_1 = turbulence scale parameter, defined as the wave length at which the dimensionless longitudinal power spectral density term $fS_1(f)/\sigma_1^2$ equals 0.05 [m]

f = frequency [s^{-1}]

For standard classes the turbulence scale parameter Λ_1 shall be given by:

$$\Lambda_1 = \begin{cases} 0{,}7 z_{\text{hub}} & \text{for } z_{\text{hub}} < 60\text{m} \\ 42\text{m} & \text{for } z_{\text{hub}} \geq 60\text{m} \end{cases} \tag{2.4}$$

Specifications for stochastic turbulence models are given IEC 61400-1. Other stochastic turbulence models are acceptable provided that this does not lead to a reduction of the safety level after agreement with DNV GL. For the standard wind turbine classes, the use of other turbulence models is only permissible, if they have been validated beforehand. Such other turbulence models shall result in a fatigue load level that is higher or equal than those given in IEC 61400-1 or it shall be demonstrated, that across various sites they lead to more realistic and sufficiently accurate loads.

For site specific analysis the characteristic value of the standard deviation may be derived by adding 1,28 standard deviations to the mean value of the standard deviation of the wind speed:

$$\sigma_1(V) = \bar{\sigma}(V) + 1{,}28\sigma_\sigma(V) \tag{2.5}$$

where:

$\bar{\sigma}$ = mean value of standard deviation of the longitudinal wind speed at the specific site
σ_σ = standard deviation of the standard deviation of the longitudinal wind speed.

2.3.3 Offshore extreme turbulence model

Deviating from IEC 61400-1, the extreme turbulence model (ETM) for offshore wind turbines is defined according to this section. The extreme turbulence model shall use the normal wind profile model according to IEC 61400-1. The characteristic value for the standard deviation of the longitudinal wind velocity component of the extreme turbulence model at hub height is given by:

$$\sigma_{\mathrm{ETM}} = b \cdot 1{,}4 \cdot I_{\mathrm{ref}} \left[\frac{3V_{\mathrm{hub}} + 38\ \mathrm{m/s}}{4} - \frac{V_{\mathrm{hub}} - V_{\mathrm{ave}}}{18} \right] \tag{2.6}$$

where:

σ_{ETM} = extreme turbulence model standard deviation of the longitudinal wind speed at hub height. This standard deviation shall be assumed to be invariant with height;
I_{ref} = reference value of the turbulence intensity at 15 m/s;
V_{ave} = annual average wind speed over many years at hub height;
b = 1 m/s.

For site-specific classes or project certification, the characteristic value of the standard deviation of the longitudinal wind velocity of the extreme turbulence model may be given by:

$$\sigma_{ETM}(V) = \bar{\sigma}(V) + \alpha \cdot \sigma_\sigma(V) \tag{2.7}$$

where:

$\bar{\sigma}$ = mean value of standard deviation of the longitudinal wind speed at the specific site;
σ_σ = standard deviation of the standard deviation of the longitudinal wind speed;
α = 4,5 for open waters. Higher values will be required for areas close to the shore.

Guidance note:

Within site specific analysis the influence of neighbouring wind farms or big wind farms on mean ambient turbulence intensity should be taken into account. A method to derive this influence on mean standard deviation is given in IEC 61400-1.

Within load analysis of wind turbines in wind farms the maximum of the standard deviation according to equation (2.6) or (2.7) and the centre wake standard deviation shall be used as extreme turbulence model standard deviation.

Alternatively, the value for the ambient turbulence intensity may also be determined by IFORM or similar.

The maximum extreme centre wake standard deviation may be derived as described in IEC 61400-1.

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2.4 Marine conditions for offshore wind turbines

2.4.1 General

For offshore wind turbines, marine conditions are the second main source of external loading besides wind conditions. The requirements for marine conditions to be applied are described within this [2.4]. IEC 61400-3 may be used to supplement the definition of marine conditions given in this standard, where this standard contains no requirements.

2.4.2 Wave climate

The wave climate is represented by the significant wave height H_S and the spectral peak period T_P. In the short term, i.e. over a 3-hour or 6-hour period, stationary wave conditions with constant H_S and constant T_P are assumed to prevail.

Guidance note:
The significant wave height H_S is defined as four times the standard deviation of the sea surface elevation. The significant wave height is a measure of the intensity of the wave climate as well as of the variability in the arbitrary wave heights. The peak period T_P is related to the mean zero-crossing period T_Z of the sea elevation process.

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The wave height H of a wave cycle is the difference between the highest crest and the deepest trough between two successive zero-up-crossings of the sea surface elevation. The arbitrary wave height H under stationary 3- or 6-hour conditions in the short term follows a probability distribution which is a function of the significant wave height H_S.

The wave period is defined as the time between two successive zero-up-crossings of the sea surface elevation. The arbitrary wave period T under stationary 3- or 6-hour conditions in the short term follows a probability distribution, which is a function of H_S, T_P and H.

The wave crest height H_C is the height of the highest crest between two successive zero-up-crossings of the sea surface elevation. The arbitrary wave crest height H_C under stationary 3- or 6-hour conditions in the short term follows a probability distribution which is a function of the significant wave height H_S.

The short term 3- or 6-hour sea state may be represented by a wave spectrum, i.e. the power spectral density function of the sea surface elevation, *S(f)*. *S(f)* is a function of H_S and T_P and expresses how the energy of the sea elevation is distributed between various frequencies.

2.4.3 Wind-wave misalignment

Wind-wave misalignment, i.e. differences of the mean wind and wave directions can have an important influence on loads of offshore wind turbines and shall thus be considered. Besides the correlation of the wind and wave directional distributions, the dynamic behaviour and in particular the damping and mode shapes of the wind turbine and its support structure determine the influence of wind-wave misalignment on the loading. Aligned (co-directional) wind and waves shall only be assumed, if this can be shown to be a conservative assumption. The assumptions regarding wind and wave directions are considered for the design load cases in Table 4-3.

2.4.4 Reference sea states and wave heights

For use in load combinations for design, a number of reference sea states and reference wave heights are defined.

2.4.4.1 Normal sea state

The *normal sea state (NSS)* is characterised by a significant wave height, a peak period and a wave direction. It is associated with a concurrent mean wind speed. The significant wave height $H_{S,NSS}$ of the normal sea state is defined as the expected value of the significant wave height conditioned on the concurrent 10-minute mean wind speed. The normal sea state is used for calculation of ultimate loads and fatigue loads. For fatigue load calculations a series of normal sea states shall be considered, associated with different mean wind speeds. It shall be ensured that the number and resolution of these normal sea states are sufficient to predict the fatigue damage associated with the full long-term distribution of metocean parameters. The range of peak periods T_P appropriate to each significant wave height shall be considered. Design calculations shall consider a sufficient number and resolution of normal sea states to account for the fatigue damage associated with the full long term distribution of metocean parameters. Alternatively they may be based on values of the peak period which result in the highest loads or load effects in the structure.

Guidance note:
In deep waters, the wave periods T to be used with normal wave height may be assumed to be within the range given by

$$11{,}1\sqrt{H_{S,NSS}(V_{\mathrm{hub}})/g} \le T \le 14{,}3\sqrt{H_{S,NSS}(V_{\mathrm{hub}})/g} \qquad (2.8)$$

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2.4.4.2 Severe sea state

The *severe sea state (SSS)* is characterised by a significant wave height, a peak period and a wave direction. It is associated with a concurrent mean wind speed. The significant wave height of the severe sea state $H_{S,SSS}$ is defined by extrapolation of appropriate site-specific metocean data such that the load effect from the combination of the significant wave height $H_{S,SSS}$ and the 10-minute mean wind speed V_{hub} has a return period of 50-years. The *SSS* model is used in combination with normal wind conditions for calculation of the ultimate loading of an offshore wind turbine during power production. The *SSS* model is used to associate a severe sea state with each mean wind speed in the range corresponding to power production. For all 10-minute mean wind speeds V_{hub} during power production, the unconditional extreme significant wave height, $H_{S,50\text{-}yr}$, with a return period of 50-years may be used as a conservative estimate for $H_{S,SSS}(V_{\text{hub}})$. The range of peak periods T_P appropriate to each significant wave height shall be considered. Design calculations shall be based on values of the peak period which result in the highest loads or load effects in the structure.

Guidance note:

In deep waters, the wave periods *T* to be used with severe wave height may be assumed to be within the range given by

$$11{,}1\sqrt{H_{S,SSS}(V_{\text{hub}})/g} \le T \le 14{,}3\sqrt{H_{S,SSS}(V_{\text{hub}})/g} \quad (2.9)$$

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2.4.4.3 Extreme sea state

The e*xtreme sea state (ESS)* is characterised by a significant wave height, a peak period and a wave direction. The significant wave height $H_{S,ESS}$ is the unconditional significant wave height with a specified return period, determined from the distribution of the annual maximum significant wave height as outlined in [2.4.5.2]. The extreme sea state is used for return periods of 50-years and 1-year, and the corresponding significant wave heights are denoted $H_{S,50\text{-}yr}$ and $H_{S,1\text{-}yr}$, respectively. The range of peak periods T_P appropriate to each of these significant wave heights shall be considered. Design calculations shall be based on values of the peak period which result in the highest loads or load effects in the structure.

2.4.4.4 Extreme wave height

The e*xtreme wave height (EWH)* H_{EWH} is a wave height with a specified return period. It may be determined from the distribution of the annual maximum wave heights as outlined in [2.4.5.5]. In deep waters, it may be estimated based on the significant wave height $H_{S,ESS}$ with the relevant return period as outlined in [2.4.4.3]. The extreme wave height is used for return periods of 50-years and 1-year, and the corresponding wave heights are denoted $H_{50\text{-}yr}$ and H_{1yr}, respectively. The range of wave periods *T* appropriate to the severe wave height shall be considered. Design calculations shall be based on values of the wave period within this range that result in the highest loads or load effects in the structure.

Guidance note:

In deep waters, the wave periods *T* to be used with H_{EWH} may be assumed to be within the range given by

$$11{,}1\sqrt{H_{S,ESS}(U_{10})/g} \le T \le 14{,}3\sqrt{H_{S,ESS}(U_{10})/g} \quad (2.10)$$

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2.4.5 Wave modelling

Site-specific spectral densities of the sea surface elevation may be determined from available wave data. When selecting a model for representation of the spectral density of the sea surface elevation, it is important to consider both wind sea and swell.

2.4.5.1 Wave spectra

Unless data indicate otherwise, the spectral density of the sea elevation process may be represented by the JONSWAP spectrum,

$$S(f) = \frac{ag^2}{(2\pi)^4} f^{-5} e^{\left(-\frac{5}{4}\left(\frac{f}{f_p}\right)^{-4}\right)} \gamma^{e^{\left(-0.5(f-f_p/\sigma f_p)^2\right)}} \quad (2.11)$$

where

f = wave frequency, $f = 1/T$
T = wave period
f_p = spectral peak frequency, $f_p = 1/T_p$
T_p = peak period
g = acceleration of gravity
α = generalised Phillips' constant
= $5 \cdot (H_S{}^2 f_p{}^4/g^2) \cdot (1- 0{,}287 \ln\gamma) \cdot \Pi^4$
σ = spectral width parameter
= $0{,}07$ for $f \leq f_p$ and $\sigma = 0{,}09$ for $f > f_p$
γ peak-enhancement factor.
The zero-upcrossing period T_Z depends on the peak period T_p through the following relationship,

$$T_z = T_p \sqrt{\frac{5+\gamma}{11+\gamma}} \tag{2.12}$$

The peak-enhancement factor is

$$\gamma = \begin{cases} 5 & \text{for } \dfrac{T_p}{\sqrt{H_s}} \leq 3{,}6 \\ e^{\left(5{,}75-1{,}15\frac{T_p}{\sqrt{H_s}}\right)} & \text{for } 3{,}6 < \dfrac{T_p}{\sqrt{H_s}} \leq 5 \\ 1 & \text{for } 5 < \dfrac{T_p}{\sqrt{H_s}} \end{cases} \tag{2.13}$$

where T_p is in seconds and H_S is in metres.

The JONSWAP spectrum may not necessarily suffice for representation of a sea elevation process with a significant swell component. When the sea elevation process has a significant swell component, a two-peaked spectrum such as the Torsethaugen spectrum may form a better representation of the spectral density of this process than the JONSWAP spectrum. Details of the Torsethaugen spectrum are given in DNV-RP-C205.

Guidance note:
When $\gamma = 1$ the JONSWAP spectrum reduces to the Pierson-Moskowitz spectrum.

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2.4.5.2 Long-term wave conditions

The long-term probability distributions for the wave climate parameters H_S and T_P that are interpreted from available data may be represented in terms of generic distributions or in terms of scatter diagrams. A typical generic distribution representation consists of a Weibull distribution for the significant wave height H_S in conjunction with a lognormal distribution of T_P conditional on H_S. A scatter diagram gives the frequency of occurrence of given pairs (H_S, T_P) in a given discretisation of the (H_S, T_P) space.

Unless data indicate otherwise, a 3-parameter Weibull distribution (α, β and γ) may be assumed for the significant wave height,

$$F_{H_s}(h) = 1 - e^{-\left(\frac{h-\gamma}{\alpha}\right)^{\beta}} \tag{2.14}$$

where h is the significant wave height.

When $F_{Hs}(h)$ denotes the distribution of the significant wave height in an arbitrary t-hour sea state, the distribution of the annual maximum significant wave height H_{Smax} may be taken as

$$F_{H_{s,max},1year}(h) = \left(F_{H_s}(h)\right)^N \tag{2.15}$$

where N is the number of t-hour sea states in one year. For t = 3 hours, N = 2920.

Guidance note 1:
The quoted power-law approximation to the distribution of the annual maximum significant wave height is a good approximation to the upper tail of this distribution. Usually, only quantiles in the upper tail of the distribution are of interest (particularly the 98% quantile which defines the 50-year significant wave height). The upper tail of the distribution may be well approximated by a Gumbel distribution, whose expression is more operational than the quoted power-law expression.

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The significant wave height with return period T_R in units of years is defined as the ($1- 1/T_R$) quantile in the distribution of the annual maximum significant wave height, i.e. it is the significant wave height which probability of exceedance in one year is $1/T_R$. It is denoted $H_{S,TR}$ and is expressed as

$$H_{S,T_R} = F_{H_{s,max}\ ,1year}{}^{-1}\left(1-\frac{1}{T_R}\right) \tag{2.16}$$

in which T_R > one year.

The significant wave height with a return period of one year is defined as the mode of the distribution function of the annual maximum of the significant wave height.

Guidance note 2:
The 50-year significant wave height becomes

$$H_{S,50} = F_{Hs,max,1\ year}{}^{-1}(0,98)$$

and the 100-year significant wave height becomes

$$H_{S,100} = F_{Hs,max,1\ year}{}^{-1}(0,99).$$

Note that these values, calculated as specified, may be considered as central estimates of the respective significant wave heights when the underlying distribution function $F_{Hs,max}$ is determined from limited data and is encumbered with statistical uncertainty.

In the southern and central parts of the North Sea, experience shows that the ratio between the 100- and 50-year significant wave heights $H_{S,100}/H_{S,50}$ attains a value approximately equal to $1,04$ to $1,05$. Unless data indicate otherwise, this value of the ratio $H_{S,100}/H_{S,50}$ may be applied to achieve the 50-year significant wave height $H_{S,50}$ in cases where only the 100-year value $H_{S,100}$ is available, provided the location in question is located in the southern or central parts of the North Sea.

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2.4.5.3 Deep water (short- and long-term conditions)

In deep waters, the short-term probability distribution of the arbitrary wave height H may be assumed to follow a *Rayleigh* distribution when the significant wave height H_S is given,

$$F_{H|H_s}(h) = 1 - e^{-\frac{2h^2}{(1-\nu^2)H_s^2}} \tag{2.17}$$

where $F_{H|Hs}$ denotes the cumulative distribution function, h is the single wave height and ν is a spectral width parameter which value is $\nu = 0$ for a narrow-banded sea surface elevation.

The maximum wave height H_{max} in a 3-hour sea state characterised by a significant wave height H_S may be calculated as a constant factor times H_S.

Guidance note:
The maximum wave height in a sea state may be estimated by the mean of the highest wave height in the record of waves that occur during the sea state, or by the most probable highest wave height in the record. The most probable highest wave height is also known as the mode of the highest wave height. Both of these estimates for the maximum wave height in a sea state depend on the number of waves, N, in the record. N may be defined as the ratio between the duration T_S of the sea state and the mean zero up-crossing period T_Z of the waves. For a narrow-banded wave train, the appropriate expression for the mean of the highest wave height H_{max} reads

$$H_{\text{max,mean}} = \left(\sqrt{\frac{1}{2}\ln N} + \frac{0{,}2886}{\sqrt{2\ln N}}\right)H_s \tag{2.18}$$

while the expression for the mode of the highest wave height reads

$$H_{\text{max,mode}} = \left(\sqrt{\frac{1}{2}\ln N}\right)H_s \tag{2.19}$$

For a sea state of duration $T_S = 3$ hours and a mean zero up-crossing period T_Z of about $10,8$ sec, $N = 1000$ results. For this example, the mean of the highest wave height becomes $H_{max} = 1,936H_S \approx 1,94\ H_S$, while the mode of the highest wave height becomes

H_{max} = *1,858* H_S ≈ *1,86* H_S. For shorter mean zero up-crossing periods than the assumed *10,8 sec, N* becomes larger, and so does the factor on H_S. Table 2-2 gives the ratio H_{max}/H_S for various values of *N*.

Table 2-2 Ratio for deep water waves in narrow-banded wave trains

No. of waves $N=T_S/T_Z$	Ratio H_{max}/H_S	
	mode $\sqrt{\frac{1}{2}\ln N}$	mean $\sqrt{\frac{1}{2}\ln N}+\frac{0.2886}{\sqrt{2\ln N}}$
500	1.763	1.845
1000	1.858	1.936
1500	1.912	1.988
2000	1.949	2.023
2500	1.978	2.051
5000	2.064	2.134

Other ratios than those quoted in Table 2-2 apply to waves in shallow waters and in cases where the sea surface elevation is not narrow-banded.

It is common to base the estimation of H_{max} on the results for the mode rather than on the results for the mean.

Table 2-2 is valid for H_S/d < *0,2*, where *d* denotes the water depth.

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2.4.5.4 Shallow water (short- and long-term conditions)

In shallow waters, the wave heights will be limited by the water depth. Unless data indicate otherwise, the maximum wave height may be taken as 78% of the water depth. The Rayleigh distribution of the wave heights become distorted in the upper tail to approach this limit asymptotically. The use of the unmodified Rayleigh distribution for representation of the distribution of wave heights in shallow waters may therefore be on the conservative side.

In shallow waters with constant seabed slope, the *Battjes and Groenendijk* distribution may be used to represent the probability distribution of the arbitrary wave height *H* conditional on the significant wave height H_S. It is a requirement for the use of the Battjes and Groenendijk distribution that it is validated by measured site-specific wave data. The Battjes and Groenendijk distribution is a composite Weibull distribution which cumulative distribution function reads

$$F_{H|H_s}(h) = \begin{cases} 1 - e^{-\left(\frac{h}{h_1}\right)^2} & \text{for } h \le h_T \\ 1 - e^{-\left(\frac{h}{h_2}\right)^{3.6}} & \text{for } h > h_T \end{cases} \tag{2.20}$$

where *h* is the single wave height and in which the transition wave height h_T is defined as

$$h_T = (0{,}35 + 5{,}8\tan\alpha)d \tag{2.21}$$

where α is the slope angle of the sea floor and *d* is the water depth. The parameters h_1 and h_2 are functions of the transition wave height h_T and of the root mean square H_{RMS} of the wave heights. The root mean square H_{RMS} is calculated from the significant wave height H_S and the water depth *d* as

$$H_{RMS} = 0{,}6725H_s + 0{,}2025\frac{H_s^2}{d} \tag{2.22}$$

and the parameters h_1 and h_2 may be derived from the following approximate expressions, valid for $0{,}05H_{RMS} < h_T < 3H_{RMS}$,

$$\frac{h_1}{H_{RMS}} = \frac{1}{0{,}0835\left(\frac{h_T}{H_{RMS}}\right)^3 - 0{,}583\left(\frac{h_T}{H_{RMS}}\right)^2 + 1{,}3339\left(\frac{h_T}{H_{RMS}}\right)} \tag{2.23}$$

$$\frac{h_2}{H_{RMS}} = 1{,}06 - 0{,}01532\left(\frac{h_T}{H_{RMS}}\right)^2 + 0{,}083259\left(\frac{h_T}{H_{RMS}}\right)^3 - 0{,}01925\left(\frac{h_T}{H_{RMS}}\right)^4 \quad (2.24)$$

The Battjes and Groenendijk distribution is not defined for $h_T > 3H_{RMS}$.

Guidance note:

The Battjes and Groenendijk distribution has the drawback that it has an unphysical "knee" at the transition height h_T. Its upper-tail behaviour may also be of concern. The Battjes and Groenendijk distribution should therefore be used with caution and only when supported by data.

Other distribution models for wave heights in shallow waters exist and may be used as alternatives to the Battjes and Groenendijk distribution as long as they provide an adequate representation of the true distribution of the wave heights. Examples of such distribution models include the Glukowski, Bitner and Næss distribution models.

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2.4.5.5 Single wave conditions

The long-term probability distribution of the arbitrary wave height H may be found by integration over all significant wave heights

$$F_H(h) = \frac{1}{\overline{\nu_0}} \int_{h_s} \int_t \nu_0(h_s,t) F_{H|H_sT_p}(h_s,t)\, dt\, dh_s \quad (2.25)$$

where

$$\overline{\nu_0} = \int_{h_s} \int_t \nu_0(h_s,t) f_{H_sT_p}(h_s,t)\, dt\, dh_s \quad (2.26)$$

in which $f_{HsTp}(h_s,t)$ is the joint probability density of the significant wave height H_S and the peak period T_P and $\nu_0(h_s,t)$ is the zero-upcrossing rate of the sea surface elevation for given combinations of H_S and T_P. $F_{H|HsTp}(h)$ denotes the short-term cumulative distribution function for the wave height H conditioned on H_S and T_P.

When $F_H(h)$ denotes the distribution of the arbitrary wave height H, the distribution of the annual maximum wave height H_{max} may be taken as

$$F_{H_{\max,1\text{year}}}(h) = \left(F_H(h)\right)^{N_W} \quad (2.27)$$

where h is the single wave height and N_W is the number of wave heights in one year.

The wave height with return period T_R in units of years is defined as the $(1\text{-}1/T_R)$ quantile in the distribution of the annual maximum wave height, i.e. it is the wave height which probability of exceedance in one year is $1/T_R$. It is denoted H_{TR} and is expressed as

$$H_{T_R} = F^{-1}_{H_{\max,1\text{year}}}\left(1 - \frac{1}{T_R}\right) \quad (2.28)$$

in which $T_R >$ *one* year.

The wave height with a return period of one year is defined as the mode of the distribution function of the annual maximum wave height.

Guidance note:

The 50-year wave height becomes

$$H_{50} = F_{Hmax,1\ year}{}^{-1}(0{,}98)$$

and the 100-year wave height becomes

$$H_{100} = F_{Hs,max,1\ year}{}^{-1}(0{,}99).$$

Note that these values, calculated as specified, should be considered as central estimates of the respective wave heights when the underlying distribution function F_{Hmax} is determined from limited data and is encumbered with statistical uncertainty.

Note also that the 50-year wave height H_{50} is always greater than the maximum wave height H_{max} in the 3-hour sea state which return period is 50-years and which significant wave height is denoted $H_{S,50}$. This implies that in deep waters H_{50} will take on a value greater than H_{max} = 1,86 $H_{S,50}$. Values of H_{50} equal to about 2,0 times $H_{S,50}$ are not uncommon in deep waters.

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2.4.5.6 Other conditions

Directionality of waves shall be considered for determination of wave height distributions and wave heights with specified return periods when such directionality has an impact on the design of a wind turbine structure.

2.4.6 Wave theories and wave kinematics

The kinematics of regular waves may be represented by analytical or numerical wave theories, which are listed below:

— linear wave theory (airy theory) for small-amplitude deep water waves; by this theory the wave profile is represented by a sine function
— stokes wave theories for high waves
— stream function theory, based on numerical methods and accurately representing the wave kinematics over a broad range of water depths
— Boussinesq higher-order theory for shallow water waves
— solitary wave theory for waves in particularly shallow water.

For details about wave kinematics see DNV-RP-C205.

2.4.7 Breaking waves

The wave height is limited by breaking. The maximum wave height H_b is given by

$$\frac{H_b}{\lambda} = 0{,}142\ tanh\left(\frac{2\pi d}{\lambda}\right) \tag{2.29}$$

where λ is the wave length corresponding to water depth d. In deep water the breaking wave limit corresponds with a maximum steepness $S_{max} = H_b/\lambda = 1/7$.

The breaking wave height as a function of the wave period for different water depths is given in Figure 2-2. In shallow water the limit of the wave height may be taken as 0,78 times the local water depth. Note that waves propagating over a horizontal and flat seabed may break at a lower wave height. Laboratory data [R. C. Nelson] and theoretical analysis [S. Massel] indicate that under idealized conditions the breaking limit may be as low as 0,55.

Design of coastal or offshore structures in shallow water requires a reliable estimation of maximum wave height. More details on modelling of shallow water waves and their loads may be found in [CEM].

Breaking waves are generally classified as spilling, plunging, collapsing or surging. Formation of a particular breaker type depends on the non-dimensional parameter β

$$\beta = \frac{H_b}{gT^2 m} \tag{2.30}$$

where H_b is the wave height at breaking, m is the beach slope, assumed to be constant over several wave lengths.

Spilling breakers are characterized by foam spilling from the crest down on the forward face of the wave. They occur in deep water or on gentle beach slopes. Spilling breakers usually form when $\beta > 5$.

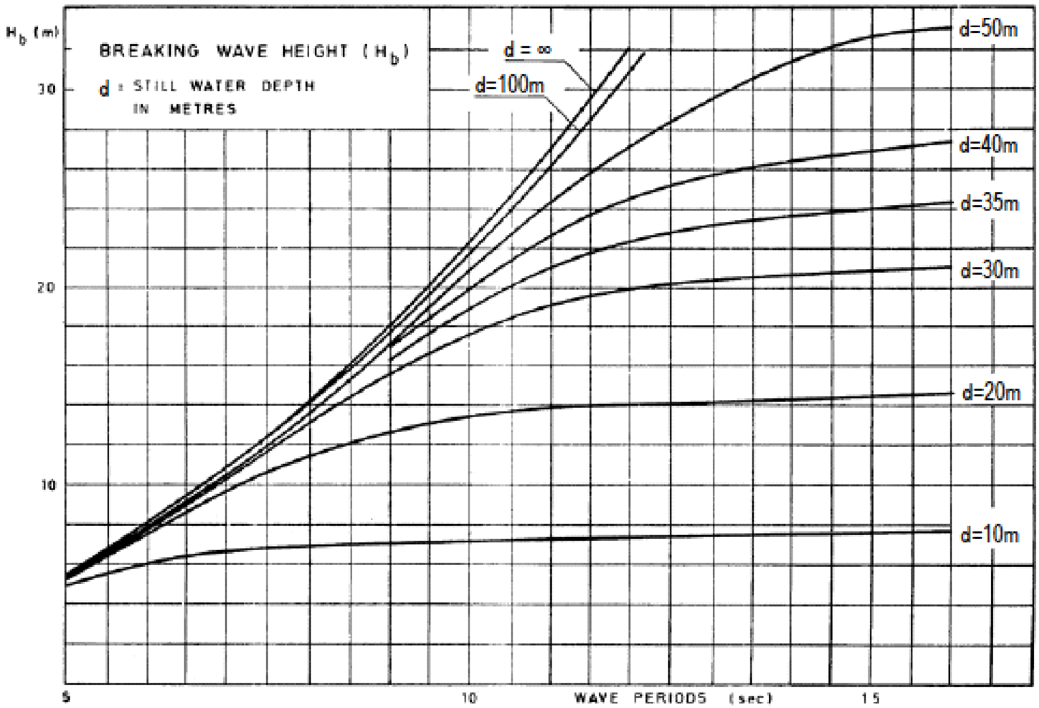

Figure 2-2 Breaking wave height dependent on still water depth

Plunging breakers occur on moderately steep beach slopes. They are characterized by a well-defined jet of water forming from the crest and falling onto the water surface ahead of the crest. Plunging breakers form when $0,1 < \beta < 5$.

Surging breakers occur on relatively steep beaches in which there is considerable reflection with foam forming near the beach surface. Surging breakers form when $\beta < 0,1$.

The collapsing wave foams lower down the forward face of the wave and is a transition type between plunging and surging breakers, $\beta \sim 0,1$.

2.4.8 Sea currents

Sea currents consist of wind-generated currents and tidal currents.

The current is represented by the wind-generated current velocity U_{wind0} at the still water level and the tidal current velocity U_{tide0} at the still water level.

Other current components than wind-generated and tidal currents may exist.

Examples of such current components are

— density currents
— currents generated by storm surge and atmospheric pressure variations
— near-shore, wave-induced surf currents running parallel to the coast.

2.4.8.1 Normal current model

The normal current model (NCM) is the combination of wind generated currents and tidal currents, where tidal currents may be taken as the mean of tidal current speeds. The normal current model does not include storm-generated sub surface currents.

2.4.8.2 Extreme current model

The extreme current model (ECM) includes storm-generated currents associated with the ESS. The one-year ECM current and the fifty-year ECM current are denoted as U_1 and U_{50}, respectively. The current U_1 and U_{50} shall be based on the long term joint probability distribution of currents associated with the extreme sea state. The values from the joint probability distribution resulting in the highest loading acting on the offshore wind turbine shall be used.

If the long term joint probability distribution of extremes can't be determined with sufficient accuracy and reliability, extreme currents with recurrence period of 1 and 50 years, may be applied co-directional with the waves.

2.4.8.3 Current modelling

When detailed field measurements are not available, the variation in current velocity with depth may be taken as

$$U(z) = U_{\text{tide}}(z) + U_{\text{wind}}(z) \tag{2.31}$$

where

$$U_{\text{tide}}(z) = U_{\text{tide0}}\left(\frac{d+z}{d}\right)^{\frac{1}{7}} \tag{2.32}$$

for $z \leq 0$

and

$$U_{\text{wind}}(z) = U_{\text{wind0}}\left(\frac{d_0+z}{d_0}\right) \tag{2.33}$$

for $-d_0 \leq z \leq 0$

in which

$v(z)$	=	total current velocity at level z
z	=	vertical coordinate from still water level, positive upwards
U_{tide0}	=	tidal current at still water level
U_{wind0}	=	wind-generated current at still water level
d	=	water depth from still water level (taken as positive)
d_0	=	reference depth for wind-generated current; d_0 = 50 m.

The variation in the current profile with variation in water depth due to wave action shall be accounted for. In such cases, the current profile may be stretched or compressed vertically, such that the current velocity at any proportion of the instantaneous depth is kept constant. By this approach, the surface current component remains constant, regardless of the sea elevation during the wave action.

Unless data indicate otherwise, the wind-generated current at still water level may be estimated as

$$U_{\text{wind0}} = kV_m(10\text{ m}) \tag{2.34}$$

where

k	=	0,016 to 0,033.
V_m(10 m)	=	10-minute mean wind speed at 10 m height.

2.4.9 Sea level, bathymetry

2.4.9.1 Water level parameters

The water level consists of a mean water level in conjunction with tidal water and a wind- and pressure-induced storm surge. The tidal range is defined as the range between the highest astronomical tide (*HAT*) and the lowest astronomical tide (*LAT*), see Figure 2-3. The mean sea level (*MSL*) is defined as the average of *HAT* and *LAT*. In Figure 2-3 the chart datum (CD) is given for reference only, it is often equal to LAT.

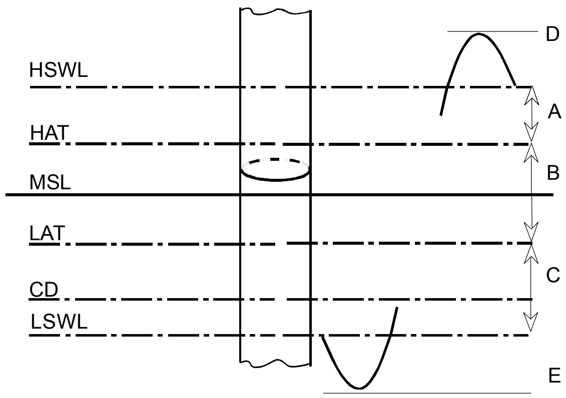

Figure 2-3 Water levels

Guidance note 1:
HAT is the highest water level that can be predicted to occur under any combination of astronomical conditions, i.e. the level of high tide when all harmonic components causing the tide are in phase. *LAT* is the lowest water level that can be predicted to occur under any combination of astronomical conditions, i.e. the level of low tide when all harmonic components causing the tide are in phase.

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For design purposes either a high water level or a low water level will be governing and both need to be considered. The highest water level consists of an astronomical tide above *MSL* plus a positive storm surge component (*HSWL*). The lowest water level consists of an astronomical tide below MSL plus a negative storm surge component (*LSWL*).

Guidance note 2:
When a high water level is governing, usually a high water level with a specified return period will be needed for the design. Likewise, when a low water level is governing, usually a low water level with a specified return period will be needed for the design.

When the storm surge component at a location in question is insignificant and can be ignored, the water level will be governed by tide alone, and the maximum and minimum water levels to be used in design become equal to *HAT* and *LAT*, respectively.

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2.4.9.2 Water level modelling

For determination of the water level for the calculation of loads and load effects, both tidal water and pressure- and wind-induced storm surge shall be taken into account.

Guidance note:
Water level conditions are of particular importance for the prediction of depth-limited wave heights.

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2.4.10 Sea ice

As a basis for the design against ice loads, the frost index *K* may be used. The frost index for a location is defined as the absolute value of the sum of the daily mean temperatures over all days which mean temperatures are less than 0°C in one year. The frost index *K* exhibits variability from year to year and may be represented by its probability distribution.

Guidance note 1:
Unless data indicate otherwise, the frost index may be represented by a three-parameter Weibull distribution,

$$F_{\mathrm{K}}(k) = 1 - e^{-\left(\frac{k-b}{a}\right)^{\beta}} \tag{2.35}$$

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The frost index with return period T_R in units of years is defined as the $(1\text{-}1/T_R)$ quantile in the distribution of the frost index, i.e. it is the frost index which probability of exceedance in one year is $1/T_R$. It is denoted K_{TR} and is expressed as

$$K_{T_R} = F_K^{-1}\left(1 - \frac{1}{T_R}\right) \tag{2.36}$$

The ice thickness t at the end of a frost period may be estimated by

$$t = 0{,}032\sqrt{0.9K - 50} \tag{2.37}$$

where t is in units of metres and K is the frost index in units of degree-days.

In near-coastal waters and in sheltered waters, such as in lakes and archipelagos, the ice sheet is normally not moving after having grown to some limiting thickness, t_{limit}. The limiting thickness may therefore be used to define extreme thickness events for moving ice in such waters. Unless data indicate otherwise, the limiting thickness t_{limit} may be taken as the long-term mean value of the annual maximum ice thickness. No such limiting thickness is associated with moving ice in open sea, for which larger thicknesses may therefore be expected in the extreme thickness events.

Guidance note 2:
The long-term mean value of the annual maximum ice thickness may be interpreted as a measure of the ice thickness associated with a "normal winter".

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Further sea ice parameters to be considered are:

2.4.10.1 Ice bulk salinity

The salinity varies from 0.6% in the north of the Baltic Sea to about 2% in the south of the Baltic Sea.

2.4.10.2 Ice brine volume

The volume of enclosed saline brine influences porosity and density of sea ice. Typical brine volumes are in the range of 20ppt to 100ppt, depending on salinity, temperature, type and age of the ice.

2.4.10.3 Ice porosity

Naturally grown sea ice contains various inclusions and irregularities which lead to a porosity of typically 3ppt to 20ppt.

2.4.10.4 Ice temperature

The surface temperature of the sea ice cover is dominated by the air temperature and the gradient between the surface and bottom depends mainly on the history of air temperatures during recent days, the ice density and structure.

2.4.10.5 Ice density

The sea ice density depends on salinity, temperature and the age of the ice. Typical values are in range of 912 kg/m³ to 925 kg/m³.

2.4.10.6 Ice strength

Tensile strength, compressive (=crushing) strength and flexural (=bending) strength are basic properties of sea ice used in any analytical or empirical model. Approximation methods to calculate these values are given in ISO 19906.

2.4.10.7 Ice flow velocity

Sea ice in the Baltic Sea is mainly driven by wind. Currents are rather irrelevant. As an estimation of the sea ice speed the following relation may be used:

$$v_{\text{ice}} \approx 0.025 V_{\text{m}}(10\ \text{m}) \tag{2.38}$$

Guidance note:
Three different ice phenomena may occur, depending on the ice speed. Low ice speeds below 0,04 m/s may lead to *intermittent crushing*. Moderate ice speeds in the range of 0.04 m/s to 0,1 m/s may lead to *frequency lock-in*. High ice speeds of more than 0.1 m/s may lead to *continuous brittle crushing*. For more details refer to ISO 19906 and [4.2.8].

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2.4.11 Marine growth

The plant, animal and bacteria life at the site causes marine growth on structural components in the water and in the splash zone. The potential for marine growth shall be addressed. Marine growth adds weight to a structural component and influences the geometry and the surface texture of the component. The marine growth may hence influence the hydrodynamic loads, the dynamic response, the accessibility and the corrosion rate of the component.

Marine growth may broadly be divided into hard growth and soft growth. Hard growth generally consists of animal growth such as mussels, barnacles and tubeworms, whereas soft growth consists of organisms such as hydroids, sea anemones and corals. Marine growth may also appear in terms of seaweeds and kelps. Marine organisms generally colonise a structure soon after installation, but the growth tapers off after a few years.

The thickness of marine growth depend on the position of the structural component relative to the sea level, the orientation of the component relative to the sea level and relative to the dominant current, the age of the component, and the maintenance strategy for the component.

Marine growth also depends on other site conditions such as salinity, oxygen content, pH value, current and temperature.

Guidance note:
Unless data indicate otherwise, the following marine growth profile may be used for design in Norwegian and UK waters:

Depth below MWL (m)	Marine growth thickness (mm)	
	Central and Northern North Sea (56° to 59° N)	Norwegian Sea (59° to 72° N)
–2 to 40	100	60
>40	50	30

Somewhat higher values, up to 150 mm between sea level and LAT –10 m, may be seen in the Southern North Sea.

For the Baltic Sea, 100 mm should be considered below -2 m MSL unless data indicate otherwise.

Offshore central and southern California, marine growth thicknesses of 200 mm are common.

In the Gulf of Mexico, the marine growth thickness may be taken as 38 mm between LAT+3 m and 50 m depth, unless site-specific data and studies indicate otherwise.

Offshore West Africa, the marine growth thickness may be taken as 100 mm between LAT and 50 m depth and as 300 mm in the splash zone above LAT, unless data indicate otherwise.

The values given should be understood as hard growth equivalent value, i.e. it may be hard growth or a thicker layer of soft growth, which has approximately the same effect as the given thickness of hard growth.

The outer diameter of a structural member subject to marine growth should be increased by twice the recommended thickness of the marine growth at the location in question.

The type of marine growth may have an impact on the values of the hydrodynamic coefficients that are used in the calculations of hydrodynamic loads from waves and current.

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Unless more accurate data are available, the density of the marine growth may be set equal to 1325 kg/m³.

The corrosive environment is normally modified by marine growth in the upper submerged zone and in the lower part of the splash zone of the structural component. Depending on the type of marine growth and on other local conditions, the net effect may be either an enhancement or a retardation of the corrosion rate. Marine growth may also interfere with systems for corrosion protection, such as coating and cathodic protection. For guidance on corrosion protection, see DNVGL-RP-0416.

2.5 Other environmental conditions

2.5.1 General

Environmental (climatic) conditions other than wind and oceanographic phenomena may affect the integrity and safety of the wind turbine, by thermal, photochemical, corrosive, mechanical, electrical or other physical actions. Moreover, combinations of these climatic parameters may increase their effect.

The climatic conditions for the design shall be defined in terms of representative values or by the limits of the variable conditions. The probability of simultaneous occurrence of the climatic conditions shall be taken into account when the design values are selected.

Variations in the climatic conditions within normal limits, what correspond to a one-year recurrence period or higher, shall be considered as normal external conditions.

At least the environmental conditions given in IEC 61400-1 shall be taken into account and the action taken stated in the design documentation, supplemented by the requirements given in [2.5.2] to [2.5.10].

2.5.2 Other environmental conditions

Other normal and extreme environmental condition values should be carried out in accordance with latest version of IEC 61400-1, 6.4 and IEC 61400-3, 6.5. Furthermore, the following values should be taken into account for offshore conditions, if no other data are available:

— water density of 1025 kg/m^3
— water salinity of 3,5%.

When additional external condition parameters are specified by the designer, these parameters and their values shall be stated in the design documentation.

The lowest water temperature at sea level may be assumed to be 0°C.

Wind turbines shall be designed for an ambient air temperature range of −20°C to +50°C with a mean value +15°C. Operation shall be possible at ambient temperatures from −10°C to +40°C.

The atmospheric and water temperatures stated in this standard shall be one-hour average values.

2.5.3 Extreme temperatures

Estimates of the design temperatures for air and water shall be based on relevant data provided by competent institutions.

If the air temperature at the installation site is lower than –20°C or greater than +50°C on more than 9 days a year as a mean over many years, the temperature range shall be altered accordingly. It shall be verified that the wind turbine is operative and structurally sound within the chosen temperature limits.

If the mean value of the temperature over many years at the site deviates more than 15 K from the assumed mean temperature according to [2.5.2], this shall be taken into account.

The air density shall be corrected in relation to the prevailing temperature of the site. The corrected air density shall be considered in the load calculation and in the determination of the power curve. In addition, it shall be observed that ice formation may influence the aerodynamic coefficients.

For more details on extreme climatic conditions, see DNVGL-RP-0363.

Guidance note:
If the extreme temperature is lower than -20°C a relative increase in air density should be included in the load calculation for the extreme load cases

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2.5.4 Atmospheric ice formation

Ice on onshore and offshore turbines may accumulate through a number of occurrences:

— freezing sea spray
— freezing fog and supercooled cloud droplets (in-cloud icing)
— freezing rain and old wet snow (precipitation).

Ice aggregation on structures may influence the total mass of the wind turbine and imbalance of the rotor.

The accumulation of ice caused by sea spray or precipitation and in-cloud icing may be regarded as independent events.

The ice thickness may be obtained from site measurements, and/or from national and international standards such as ISO 19906. The procedure and applied standard shall be documented in a design basis and shall be subject to verification.

Ice accumulation caused by sea water spray may be taken to decrease linearly to zero from the level corresponding to the highest wave elevation to a level sea spray may reach. The ice thickness shall cover the whole circumference of the element.

In absence of any spray ice data, a thickness of 100 mm at sea level may be assumed. The ice thickness may be taken to decrease linearly to 0 mm from a level corresponding to the highest wave elevation to 60 m above that level. The density of the ice shall be taken as

$$\rho_E = 850 \text{ kg/m}^3.$$

Until a DNV GL standard on icing is published, the following assumptions shall be made: For the assumption of precipitation icing and in-cloud icing on all non-rotating parts of the wind turbine, ice formation with a thickness of 30 mm on all sides shall be assumed. The density of the ice should be taken as ρ_E = 700 kg/m^3. In the case of operating conditions in which the rotor is at standstill or idling, the rotor blades shall also be verified for this degree of ice formation on all sides.

With the rotor rotating under in-cloud icing conditions, the cases "ice formation on all rotor blades" and "ice formation on all rotor blades except one" shall be investigated. The mass distribution (mass/unit length) shall be assumed at the leading edge. It increases linearly from zero in the rotor axis to the value μ_E at half the radius, and then remains constant up to the outermost radius. The value μ_E is calculated as follows:

$$\mu_E = \rho_E \cdot k \cdot c_{\min}(c_{\max} + c_{\min}) \tag{2.39}$$

where:

μ_E	=	mass distribution on the leading edge of the rotor blade at half the rotor radius [kg/m]
ρ_E	=	density of the ice (900 kg/m^3)
k	=	0,00675 + 0,3 exp(−0,32 R/R_1)
R	=	rotor radius
R_1	=	1 m
$c_{\max}$	=	maximum chord length
$c_{\min}$	=	chord length at the blade tip, linearly extrapolated from the blade contour

2.5.5 Earthquakes

The consideration of earthquake requirements shall be carried out in accordance with the latest version of IEC 61400-1. See also [3.5.2] and [4.2.9] of this standard.

2.5.6 Wind farm influence

Within wind farms the ambient environmental conditions are influenced by wake effects. The consideration of wake effects should be carried out in accordance with the latest version of IEC 61400-1.

Other validated calculation models may be used for the analysis of the wind farm induced loads provided that these will not lead to a reduction of the safety level.

2.5.7 Soil properties

The soil properties at the intended site shall be analysed in accordance with the local situation (subsoil, building codes) by a geotechnical report as a rule. For this, DNVGL-ST-0126 shall be taken into account.

The geotechnical investigation for pile-supported structures shall provide, as a minimum, the soil engineering property data as defined in DNVGL-ST-0126.

The characteristic value of a soil property is defined as the 5% quantile in the distribution of the soil property, when a low value of the soil property is unfavorable for the design. When a high value of the soil property is unfavourable for the design, the 95% quantile shall be used as characteristic value instead of the 5% quantile. When the average of the soil property governs the design, the characteristic value shall be taken as the mean value of the soil property.

The characteristic value of a soil property shall account for the variability in that property based on an assessment of the soil volume that governs the limit state in consideration.

Guidance note:
Variability in a soil property is usually a variability of that property from point to point within a soil volume. When small soil volumes are involved, it is necessary to base calculations on the local soil property with its full variability.

When large soil volumes are involved, the effect of spatial averaging of the fluctuations in the soil property from point to point over the soil volume comes into play. Calculations may then be based on the spatially averaged soil property, which eventually becomes equal to the mean of the soil property when the soil volume is large enough.

Two examples are given in the following:

— For axial pile capacity of a long pile in clay it is usually the average undrained shear strength along the pile which is of interest for design since local fluctuations of the strength from point to point along the pile may be assumed to average out over the length of the pile; hence the mean value of the strength may be used as characteristic value.

— Small anchors, such as fluke or plate anchors of a few meters width, have such a small extent and involve such a small soil volume that the soil strength used to calculate their capacity is a local strength; hence an unfavourable low value is used as characteristic value.

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2.5.8 Risk analysis

Owing the location of certain sites, a risk analysis may be necessary. This analysis includes the risk estimation of particular damage events occurring at the wind turbine, e.g. collision with ships at offshore wind turbines, taking into account the environment (e.g. transport routes, oil pipelines). The scope and type of investigation shall be chosen appropriately.

2.5.9 Sea bed and scour

Offshore wind turbine structures founded on the sea bed may be affected by sea bed variations characterized as

a) Local scour: scour pits around structural elements.
b) Global scour: due to multiple structure interaction (for example global erosion within the footprint of a jacket).
c) Bathymetrical changes (e.g. moving sand bar) that are not induced by the presence of support structure.

Those changes influence the structural integrity and shall be accounted for, alternatively the seabed may be protected by installing scour protection. For more information see DNVGL-ST-0126.

2.5.10 Electrical power network conditions

The consideration of electrical power network conditions should be carried out in accordance with the latest version of IEC 61400-1 for onshore turbines and IEC 61400-3 for offshore turbines.

SECTION 3 DETERMINATION OF SITE SPECIFIC DESIGN CONDITIONS

3.1 General

3.1.1 External conditions

The site design conditions shall denote all external influences that act on the wind turbine from outside. These are influences resulting from orographic, topographic, meteorological, oceanographic, bathymetric, and soil conditions as well as from other external sources.

The conditions prevailing at the installation site shall be analysed and the rules and premises to be applied for the design shall be documented. This includes the aspects listed in the following sections. Other conditions that are not listed and may influence the design of the wind turbine shall also be stated with clear references to background and the reasoning for using the data. Special considerations have to be made for locations at which special events, e.g. cyclones and floods, can happen. It is recommended to agree with DNV GL in advance.

In general, documentation of the site specific design conditions is part of the design basis documentation, which shall besides the site specific design conditions at least contain a general description of the wind turbine/farm and its characteristics. Furthermore the standards to be applied shall be defined in hierarchical order for the various fields of applicability, e.g. design or loads.

The following data is relevant for loads and site conditions of wind turbines and shall be documented:

a) general wind farm location data, turbine positions, see [3.1]
b) meteorological data, see [3.3]
c) oceanographic data, see [3.4] (offshore only)
d) bathymetry, see [2.4.9] (offshore only)
e) soil data, see [3.5.1]
f) sea bed and scour data, see [3.4.7] (offshore only)
g) other environmental data, see [3.5]
h) assumptions for aerodynamic and hydrodynamic analysis (offshore only), see [2.3] and [2.4]
i) operational requirements
j) transport and installation requirements
k) maintenance requirements.

Guidance note:
The external conditions may in principle be determined from various sources:

— existing data bases, if it is possible to calibrate the existing data to adequately fit the local site conditions
— numerical methods (e.g. hindcast)
— measurements
— a combination of the above.

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The following shall be considered:

— data period used and usable data thereof
— corrections and assumptions applied and the inherent sensitivity for the resulting design values
— statistical procedures applied
— error estimate
— interpretation of results and concluding values for the design.

The site specific design conditions shall be taken as basis for analysing the structural integrity of a wind turbine design (e.g. calculation of site-specific loads).

3.1.2 Wind farm location data

A general description of the wind farm location shall be given. For onshore sites, at least the type of surrounding terrain (flat terrain, rolling hills, mountainous, etc.), the type of vegetation or buildings surrounding the site (agricultural areas, forests, suburban buildings, industrial buildings, etc.) and existing or planned other wind turbines in the surrounding shall be included. For offshore sites the range of water depths within the wind farm and the existence of other wind turbines in the surrounding shall be included. Furthermore local peculiarities of the site that are important, considering the external conditions with respect to the design or the load analysis, e.g. sandbanks, river inlets with high current speeds, chalkstone soil etc., shall be considered.

The corner coordinates of the wind farm shall be given.

3.2 Methods for determining site specific meteorological design conditions

3.2.1 General

The determination of site specific design conditions relies on a combination of different methods, commonly including long-term data from data bases, measurements performed on the actual wind farm site but covering a shorter time and numerical analysis in order to determine the design conditions for each wind turbine position.

3.2.2 Meteorological data bases

The use of data from meteorological data bases is permissible for offshore sites and for onshore sites on non-complex terrain. If existing data bases are intended to be used, correction of the existing data shall account for the following variations, if present:

— coastal effects
— surface roughness (onshore only)
— temperature gradients
— measurement height
— measurement location
— corrections for mast effects or others
— seasonal and diurnal effects.

Prior to usage of existing data bases, special attention shall be given to the source of the data by addressing the reliability of the data source. With respect to existing data bases, such as regional wind climate maps, it shall be described how it is ensured that the existing data adequately fit the local site conditions. In this context, corrections of the existing data are common practice.

For onshore turbines, the location of the data base with long-term measurements should be less than 50 km from the wind turbine site and show similar topographic conditions (roughness, fetch). For distances above 50 km, numerical analysis shall be used to transfer the data to the intended site.

Guidance note:
The use of data bases alone is usually not exact enough to derive design values. Data bases with long-term wind data are used to verify numerical models and/or to provide long-term correction to short-term measurements.

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3.2.3 Meteorological measurements

The meteorological conditions may be determined at the intended site by measurements. The site conditions shall be correlated with long-term records of nearest local meteorological stations. In general, measurements shall be performed by an accredited measurement institute. Measurements of meteorological data should be performed in accordance with IEC 61400-12-1 and should follow MEASNET procedures. In situations, where non-accredited measurements are to be used and are acceptable (e.g. in case of historical measurements by national meteorological offices) non-accredited measurements may be used. If this is the case, the quality of data shall be state-of-the-art. And safety margins shall be considered, if the data accuracy is reduced compared with measurements fulfilling the requirements of ISO 17025.

To obtain a reliable estimation of extreme wind conditions, measurements between 0,2 V_{ref} and 0,4 V_{ref} as a minimum shall be used for later extrapolation.

The properties of the anemometer, the sampling rate and the averaging period for the logging of the measurement values can influence the determination of wind data. These influences shall be taken into account in the measurement post-processing. The anemometer data and their calibration shall be documented.

The measurement period of at least one of the measurement positions at the site should be sufficient to obtain reliable data for at least 12 months. The measurement period is acceptable if it can be shown that all load-relevant aspects are taken into account by the measurement period chosen. These are, in particular:

— seasonal and diurnal effects
— thermal effects
— site-specific stability classes.

Significantly longer measurement periods should be considered for extrapolation of extreme events, in order to reach an acceptable statistical confidence level, see also [3.3.3].

The measurement data shall, if present, be corrected from:

— mast effects
— changes of the anemometry, the surrounding or other aspects with falsifying impact on the raw data.

In complex terrain (see [3.5.3]), the influence of the topography on the wind speed, the wind profile, the turbulence intensity and any inclination of flow shall be considered at each turbine site.

3.2.4 Numerical methods

The relevant characteristic values of the meteorological parameters may be determined by numerical methods. It shall be documented, which numerical methods have been used. Standard linkages of external parameters, such as effective fetch of the wind, roughness length, mean wind speed etc., to power spectra and coherence functions of the wind speed are regarded as fundamentally permissible as the starting point for a description of the wind speed.

If wind data are intended to be used from mesoscale models, these data shall at least be corrected, including local mesoscale and microscale corrections.

3.3 Determination of meteorological data

3.3.1 General

In the design and at the specific site, the basic parameters for the wind listed below shall be determined as a minimum:

— air density ρ
— reference wind speed V_{ref} (10-min mean value) and extreme 50-year gust wind speed v_{e50} (3-sec gust)
— annual average wind speed V_{ave}
— wind speed distribution
— wind direction distribution (wind rose) –per wind speed bin and accumulated
— characteristic ambient turbulence intensity and standard deviation of the turbulence intensity at hub height as a function of wind speed and wind direction
— wind shear
— inflow angle. If a significant part of the energy comes from a sector with negative inflow angle or with more than 8° inflow angle, the directional dependency of the inflow angle shall be considered.

The averaging time for the mean wind speed V_{hub} shall be 10 minutes. The interval of each wind speed bin may be at most 2 m/s, and that of the wind direction sector at most 30°.

Guidance note:
For the determination of V_{ave} from the extrapolation of long-term data, data of at least 10 years have to be evaluated.

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3.3.2 Turbulence intensity

3.3.2.1 Ambient turbulence intensity

The undisturbed ambient turbulence intensity and its standard deviation at the site shall be analysed by measurements and/or numerical analysis.

For site-specific analysis, the ambient turbulence intensity as a function of the wind speed and wind direction shall be determined.

For a given wind speed at hub height, the characteristic value of the turbulence I_c is estimated by adding (a) 1.28 times the standard deviation of the standard deviation of the wind speed ($\bar{\sigma}_{\sigma}$) to (b) the standard deviation of the wind speed ($\bar{\sigma}_{meas}$). This sum is to be divided by the actual mean wind speed.

$$I_C = \frac{\bar{\sigma}_{meas}}{\bar{V}_{meas}} + 1{,}28 \cdot \frac{\bar{\sigma}_{\sigma}}{\bar{V}_{meas}} \tag{3.1}$$

where:

I_c	=	characteristic turbulence intensity at hub height
$\bar{\sigma}_{\sigma}$	=	estimated standard deviation of the measured turbulence standard deviation at hub height
$\bar{\sigma}_{meas}$	=	mean value of the measured ambient turbulence standard deviation
$\bar{v}_{meas}$	=	mean value of measured wind speed at hub height.

Guidance note:
Caution should be exercised when the distribution of the standard deviation σ_U conditioned on the longitudinal 10-min mean wind speed V_{hub} is derived from data to describe stationary conditions. Here, it is important to identify and remove data, which belong to 10-minute series for which the stationarity assumption for V_{hub} is not fulfilled. If this is not done, such data may confuse the determination of an appropriate distribution model for σ_U conditioned on V_{hub}. Techniques for detrending of data are available for application in the case that the mean wind speed follows a trend rather than stays stationary during a considered 10-minute period.

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3.3.2.2 Turbulence intensity within wind farms

Wake effects from neighbouring wind turbines during power production shall be considered. The assessment of the suitability of the wind turbine at a site in a wind farm shall take into account the flow characteristics associated with single or multiple wakes, including such effects as wind speed deficit and added turbulence in near and far wake conditions. Wake effects shall be considered for all ambient wind speeds and wind directions relevant for power production. The mutual influence of wind turbines through the wake interaction behind the rotor shall be considered in a wind farm configuration at least up to a distance of 20*D*.

The increase in fatigue loading resulting from wake effects may be accounted for by considering a fatigue equivalent turbulence intensity, which shall include adequate representation of the influence on loading of ambient turbulence and wake effects. Calculation models (e.g. [S. Frandsen], see Table 1-5), as given in App.H of this standard may be used. The wake meandering model according to IEC 61400-1 4th Edition Annex E.2 may be used if sufficiently validated. The applicability of these models depends among others on the spacing between machines within the wind farm. The models shall be validated. For large wind farms, an increase in the environmental turbulence or terrain roughness shall be taken into account.

3.3.3 Extreme wind extrapolation

The measurement period as an input for the extrapolation of the extreme wind speeds shall be sufficiently long to obtain reliable data, and depends on the extrapolation method used. It shall be ensured that the extrapolation ratio used leads to reliable extreme wind design data.

The choice of the base values, such as mean value (e.g. 10-min or hourly mean), or maxima (e.g. monthly or annual maxima), for the extreme value analysis may have a significant impact on the extreme wind extrapolation outcome.

The site-specific wind climate may be dominated by one or several particular storm mechanism(s). The extreme wind analysis shall consider all types of storms that are characteristic for the site in question. If a type of storm is considered non-characteristic, the reasoning for this shall be given. If two or more types of storms dominate the site-specific wind climate, the extreme values shall be separated and classified into sets according to the specific type of storm. The separated sets shall be analysed independently.

For the analysis of individual storm data, the independence of storm events shall be ensured by the choice of a sufficient time gap between two data points that are considered maxima for the analysis. The separation time between two maxima that is necessary to ensure individual storm consideration may be influenced by the particular type of storm.

Special attention shall be paid to the impact that the choice of the threshold for the determination of the maxima has upon the extreme value analysis outcome.

It shall be ensured that the maxima used for extrapolation are sufficiently separated and thus independent.

The extrapolated extreme wind values that are concluded for the design shall be listed. Existing uncertainties shall be addressed by an appropriate confidence level and reported.

Requirements based on national or local building codes shall be considered.

Guidance note 1:
As an example, the minimum measurement period for extrapolation of V_{ref} (50-year return period) should not be lower than 12 years. In case the method of independent storm events is used, a measurement period of more than 7 years should be used. See [ESDU 87034], [E.J. Gumbel] and [J.P. Palutikof],for the references see Table 1-5.

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Guidance note 2:
A description of various types of storms may be found in [ESDU 87043].

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Guidance note 3:
For non-tropical storms, a separation of more than three days is assumed to be sufficient to consider independence.

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3.4 Site specific marine conditions

3.4.1 General

In the design and at the specific site, the basic parameters for the marine conditions listed below shall be determined as a minimum:

— mean sea level (MSL)
— tidal ranges (LAT and HAT)
— storm surge (1- and 50-year recurrence period)
— highest still water level (HSWL)
— lowest still water level (LSWL)
— maximum water elevation
— water density (upper bound)
— normal and extreme sea temperature ranges
— salinity
— significant wave height (50-year and 1-year recurrence period)
— design wave height (50-year and 1-year recurrence period)
— design wave period range (50-year and 1-year recurrence period)
— current speed (50-year and 1-year recurrence period)
— wave spectrum and parameters
— deterministic wave model and parameters

— breaking wave type model and parameters (height, period)
— sea ice occurrence (if occurring: annual & extreme ice thickness, ice strength & compliance parameters, description of ice-structure interaction, static and dynamic ice loads)
— marine growth thickness (profile)
— marine growth density
— sea icing and atmospheric icing.

Furthermore, the relation between wind and waves has to be established for the design load cases in Table 4-3:

— wind and wave joint distribution (H_s, T_p, V)
— wind and wave joint directional distribution (wind-wave misalignment).

If non-accredited oceanographic measurements are used (e.g. in case of historical measurements) the quality of data shall be state-of-the-art. Safety margins shall be added, if the data accuracy is reduced compared with measurements fulfilling the requirements of ISO 17025.

3.4.2 Wave data

Wave statistics are to be used as a basis for the representation of the long-term and short-term wave conditions. Empirical statistical data used as a basis for the design shall cover a sufficiently long period of time, preferably 10 years or more.

Guidance note 1:

Wave data obtained on site should be preferred over wave data observed at an adjacent location. Good quality data are measured data and hindcast data. Continuous records of data should be preferred over records with gaps. Longer periods of observation should be preferred over shorter periods.

When no site-specific wave data are available and data from adjacent locations should be capitalised on instead, proper transformation of such other data should be performed to account for possible differences due to different water depths and different seabed topographies. Such transformation should take effects of shoaling and refraction into account.

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The estimation of oceanographic parameters at the site should be supported by hindcast studies. Hindcast of wave data may be used to extend measured time series, or to interpolate to places where measured data have not been collected. The hindcast model shall be validated against measured data to ensure that the hindcast results comply with available measured data.

The long-term distributions of the significant wave height (H_S) and the spectral peak period (T_P) should preferably be based on statistical data for the same reference period for the waves as the reference period which is used for the determination of loads. If a different reference period than 3 or 6 hours is used for the determination of loads, the wave data may be converted by application of appropriate adjustment factors.

Guidance note 2:

When the long-term distribution of the arbitrary significant wave height H_S is given by a Weibull distribution,

$$F_{H_s}(h) = 1 - e^{-\left(\frac{h}{h_0}\right)^{\beta}} \tag{3.2}$$

the significant wave height H_S, T_S for a reference period of duration T_S may be obtained from the significant wave height H_S, T_{S0} for a reference period of duration T_{S0} according to the following relationship,

$$H_{s,T_s} = H_{s,T_{s0}}\left(1 + \frac{\ln(T_{S0}/T_S)}{\ln(N_0 T_R)}\right)^{\frac{1}{\beta}} \tag{3.3}$$

in which N_0 is the number of sea states of duration T_{S0} in one year and T_R is the specified return period of the significant wave height, which should be converted. N_0 = 2920 when T_{S0} = 3 hours. T_R is given in units of years.

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Wave climate and wind climate are correlated, because waves are usually wind-generated. The correlation between wave data and wind data shall be accounted for in design.

Guidance note 3:

Simultaneous observations of wave and wind data in terms of simultaneous values of H_S and V_{hub} should be obtained. It is recommended that directionality of wind and waves are recorded. Extreme waves may not always come from the same direction as extreme winds. This may in particular be so when the fetch in the direction of the extreme winds is short.

Within a period of stationary wind and wave climates, short term wind speeds and individual wave heights may be assumed to be independent and uncorrelated.

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3.4.3 Current data

Sea current statistics shall be used as a basis for the representation of the long-term and short-term current conditions. Empirical statistical data used as a basis for design shall cover a sufficiently long period of time.

Tidal currents and wind driven currents shall be considered, the variation of the current with the water depth shall be considered when relevant.

3.4.4 Water level data

Water level statistics shall be used as a basis for representation of the long-term and short-term water level conditions. Empirical statistical data used as a basis for design shall cover a sufficiently long period of time.

Guidance note:

Simultaneous observations of water level and wind data in terms of simultaneous values of water level and V_{hub} should be obtained.

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3.4.5 Sea ice

The ice thickness forms an important parameter for calculation of ice loads. The ice thickness shall be based on local ice data, e.g. as available in an *Ice Atlas* or as derived from frost index data.

Besides the ice thickness, the following data of the sea ice shall be determined:

— ice bulk salinity
— ice brine volume
— ice porosity
— ice temperature
— ice density
— ice strength
— ice flow velocity.

3.4.6 Marine growth

The thickness and type of marine growth shall be determined. Guidance values given in [2.4.11] should be confirmed by measurements or local experience.

3.4.7 Seabed movement and scour

For local scour around a pile placed in non-cohesive sediment DNVGL-ST-0126 App.D provides further guidance. For other structures (for example gravity-based structures, jacket structures etc.), or structures placed on cohesive sediment or in a wave dominated environment the scour development shall be predetermined by full scale or model scale experiences of comparable sites and geometries. Sufficient safety shall be added depended on the uncertainties (environmental conditions, soil conditions etc.).

In regions where bottom material is likely to erode, special studies of current conditions near the sea bottom may be required.

3.5 Determination of other environmental conditions

3.5.1 Foundation/soil properties

The soil properties at the intended site shall be assessed in accordance with the local situation (subsoil, building codes) by a geotechnical report. For this, DNVGL-ST-0126 shall be taken into account.

3.5.2 Influence of earthquakes

The loading caused by earthquakes shall be taken into account in regions at risk from earthquakes. In the absence of any locally applicable regulations, a procedure based on Eurocode 8 and/or API 2RP may be applied.

The investigation of the earthquake-generated loads is based on the combination of the wind loads and earthquake accelerations with a recurrence period of 475 years.

3.5.3 Complex terrain

At onshore wind farms special forms of terrain, particularly elevations, may produce velocity and turbulence distributions over the height which differ from those described in the standard class definition and shall be taken into consideration accordingly.

The complexity of such terrain may be determined through a sector wise analysis of the deviation of the orography from a plane. The sector amplitude for analysing the site complexity shall not be larger than 30° for distances larger than 5 times the wind turbines hub height.

The inclination of the plane Φ shall be set so that it represents the best possible approximation of the terrain from the wind turbine (base point) to the viewpoint per sector. The maximum deviation Δh of the terrain from the plane shall be determined in the vertical direction; see also Figure 3-1.

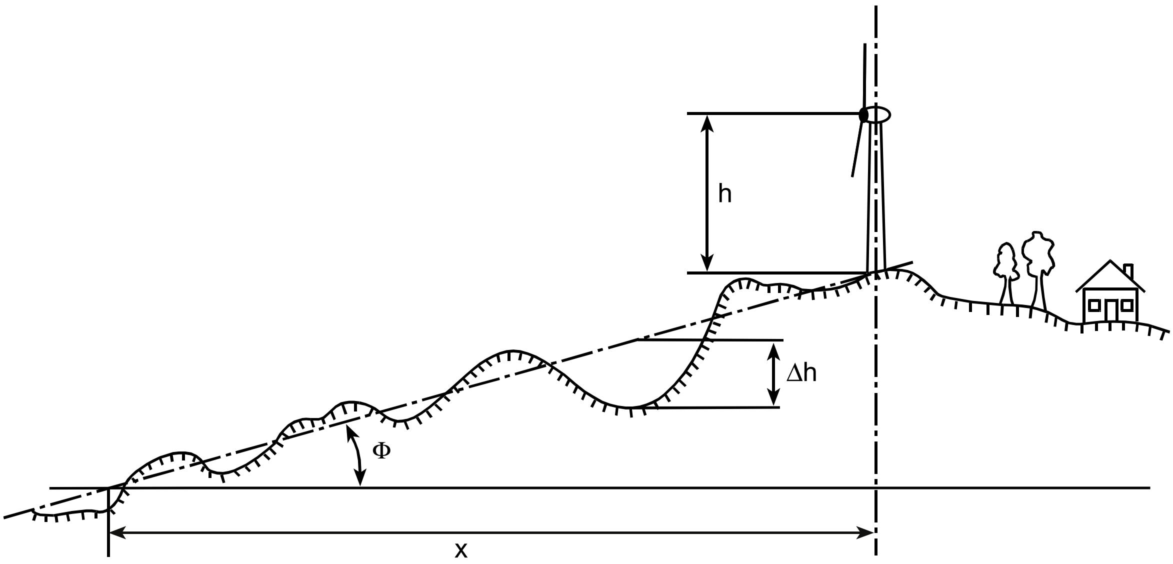

Figure 3-1 Cross section of complex terrain

Table 3-1 Conditions for the definition of complex terrain

Distance (x) from the turbine	*Sector amplitude*	*Inclination (Φ) of the plane*	*Deviation of the terrain from the plane (Δh)*
< 5 *h*	360°	< 10°	< 0,3 *h*
< 10 *h*	30°		< 0,6 *h*
< 20 *h*	30°		< 1,2 *h*
where *h* is the hub height.			

For wind turbine locations that do not meet the conditions listed in Table 3-1 the level of complexity shall be analysed.

The terrain complexity of a wind turbine location is divided in three categories:

— **non-complex terrain;** all conditions of Table 3-1 are fulfilled or one or more condition from Table 3-1 are not being met and less or equal than 5% of the estimated annual energy production of the wind turbine comes from a sector not meeting the conditions in Table 3-1.

- **terrain of intermediate complexity;** one or more conditions of Table 3-1 are not being met and less than 15% of the estimated annual energy production of the wind turbine comes from a sector not meeting the conditions in Table 3-1.
- **complex terrain;** one or more conditions of Table 3-1 are not being met and 15% or more of the estimated annual energy production of the wind turbine comes from a sector not meeting the conditions in Table 3-1.

In complex terrain, the turbulence intensity with its three turbulence components shall be determined with special care. The inclination of the airflow at the wind turbine shall be assumed to be equal to the maximum inclination of the sector wise fitted planes.

Alternatively to the complex terrain definition according to the present standard, the methods described in IEC 61400-1, 11.2 may be applied.

3.5.4 Corrosive and/or abrasive effects

It shall be investigated, if special conditions exist, which lead to increased risk of corrosion or erosion.

3.5.5 Electrical network conditions

The electrical conditions shall be determined at the grid connection point between the wind turbine or farm and the existing electrical grid, in order to ensure compatibility between the turbine and, where necessary, all electrical equipment located between the turbine and the grid. This shall include at least the following items:

- normal supply voltage and fluctuations
- normal supply frequency and fluctuations
- voltage symmetry
- symmetrical and asymmetrical faults
- number and type of the electrical grid outages and their average duration
- special features of the electrical grid at the site as well as requirements of the local grid operator shall be taken into account. These may be:
  - auto-reclosing cycles
  - short-circuit impedance at the connection points of the wind turbine
  - harmonic voltage distortion of the turbine’s power system.

3.5.6 Weather window and weather down time

Transport, installation and maintenance of offshore wind turbines are only possible during certain weather conditions. The weather windows suitable for transport, installation and maintenance as well as the associated weather downtime shall be determined and considered in the design.

SECTION 4 CALCULATION OF LOADS

4.1 Fundamentals

4.1.1 General

This standard gives guidance and requirements for the determination of loads for onshore and offshore wind turbines. Fundamentals and paragraphs within this section are in general valid for both, onshore and offshore, if not an explicitly exclusivity is given in the headline of the respective paragraph.

The calculation of design loads for floating offshore wind turbines will be described in a separate DNV GL standard based on DNV-OS-J103.

The following sections define the requirements for the determination of the loads resulting from the environmental conditions in conjunction with the operational behaviour of the wind turbine.

Guidance note:
Type certification may be performed for the RNA without support structure, in this case an exemplary support structure and in the case of an offshore type certification corresponding oceanographic conditions should be considered in the load analysis.

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Special requirements for loads during transport and installation of the wind turbines are given in Section [4.5.8].

The standard is applicable to all types of wind turbines, however, it is most comprehensive for two or three bladed and grid connected horizontal axis wind turbines with active pitch and yaw systems. When this standard is applied for other turbine types, the standard shall be applied analogously rather than literally, with the target of reaching the same level of safety.

4.1.2 Assessment documents

For the assessment of the load assumptions of a wind turbine or a wind farm, the design basis and all information needed to perform a complete load analysis are required. If relevant, documents containing the following information according to a) to q) shall be submitted in type certification:

a) Drawings with principal dimensions and a compilation of the masses, mass moments of inertia, and centres of gravity. For the rotor blades, rotor-nacelle assembly (RNA), the tower and sub-structure, complete details of the geometry and mass distribution are needed. For the geometry of the rotor blade, this includes in particular twist, chord length, profile thickness and profile type distributions.
b) Aerodynamic data for the profile types used (lift, drag and moment coefficients) in relation to the angle of attack over 360° for the Reynolds numbers and profile thicknesses in question. A 3D correction shall be performed for load cases with the wind turbine in operation.
c) A power curve as the result of the calculations in normal operation between V_{in} and V_{out} with application of a steady wind model.
d) For all main structural components (e.g. rotor blade, drive train, support structure etc.), the mass distributions, stiffnesses, natural frequencies and damping values used for the calculation shall be specified.
e) The characteristic quantities of those electrical components (e.g. positioning drives, generator etc.) which have an influence on the dynamic behaviour of the turbine (see also DNVGL-ST-0076 and DNVGL-ST-0361).
f) Detailed descriptions/assumptions of the pitch actuator details and blade pitch bearing friction parameters, e.g. pitch rate limits min/max, pitch torque limits min/max, ratio of pitch system (pitch drive gear box and pitch bearing mesh), gear box efficiency, rotational inertia of the pitch drive, pitch bearing friction parameters relevant for the pitch system dynamics, blade pitching inertia.
g) The braking torque curve of the mechanical brake and respective min/max values of braking torque.
h) The assessment documents shall be accompanied by a description of the functional principle of the wind turbine and of all parts of the control and safety systems which exert an influence on the load response of the wind turbine. The scope and informational content of the documents to be submitted in this regard are given in DNVGL-ST-0438. App.I of this standard provides tables that summarize the relevant main load assessment parameters as an expedient for data submission. The use of the tables is optional.

i) Documents for transport and installation procedures: details on special turbine states, and specification of the corresponding maximum permissible average wind speeds and significant wave heights for installation and maintenance. Here the dimensioning loads for the locking of moving components (e.g. blade, rotor and yaw bearing lock) shall be specified.
j) Documentation of the controller including an executable controller DLL, see also DNVGL-ST-0438.
k) A resonance diagram (e.g. Campbell diagram) shall be given, containing the natural frequencies to be considered (e.g. rotor blade, drive train, support structure) and the relevant excitations (e.g. rotor speed 1P, 3P, 6P etc.).
l) For operation within the resonance range of the support structure (refer to DNVGL-ST-0126), the description of the functional principle and criteria for the application of vibration monitoring as well as the prescribed triggering values shall be specified (see also [4.2.14] and DNVGL-ST-0126).
m) A table of the wind speeds used in the calculations.
n) Physical environmental parameters (e.g. air density, dynamic viscosity, water density, salinity etc.) at the intended installation site. At locations with extreme temperatures DNVGL-RP-0363 shall be observed.
o) A description and, if applicable, a sketch of the coordinate systems used, with the position of coordinate origins (see App.A).
p) A detailed description of the calculated load cases and the evaluation of extreme and fatigue loads (see App.C).
q) Requirements for the evaluation and presentation of the calculation results are defined in App.C.

The following assessment documents are optional in type certification but are normally needed for site-specific evaluation/project certification:

r) Wind farm configuration charts with the position of turbines, site elevation or bathymetry, as well as the natural frequencies of the turbines depending on their position.
s) Site data, such as environmental conditions, information on the characteristics of the sea floor, geotechnical data, electrical conditions etc., shall be defined for the site or taken according to the requirements defined by the manufacturer and/or the generic wind turbine class. The design documentation of the specific data shall at least contain the information listed in App.E or App.F.
t) If the models given in this standard are used, a statement of the method and the design parameters derived therefrom is sufficient. If the models given in this standard are not adopted or if other methods are being used, the reasoning for doing so and the models used shall be explicitly described.
u) Wind conditions at the site as well as a description of the methods and the database used to derive them, including consideration of terrain roughness and complex terrain and the analysis of the mutual interaction of the wind turbines.
v) General specifications shall be included to specify the design life, environment, place(s) and period of construction and the main stages of construction up to final assembly and/or installation.
w) Description of the soil conditions assumed for design and derived values used for load analysis, e.g. p-y curves.
x) Interface between wind turbine and support structure.

The following assessment documents are only needed for offshore projects:

y) Description of marine conditions influencing the structures' loading and their behaviour as well as the methods taken into account to reduce or exclude them, i.e. scour and scour protection, marine growth, corrosion protection and corrosion allowance.
z) Marine operations may impose additional loads on the structures or structural members. The size and displacement of the maintenance boat shall be specified.
aa) Description of the methods to derive the hydrodynamic behaviour of the support structure and the derived values, e.g. the hydrodynamic coefficients. The influence of the appurtenances shall be considered within the determination of the hydrodynamic behaviour and for the load analysis as well as for the design.
ab) If tank tests are used to derive hydrodynamic properties, tank test reports and scaling analysis shall be provided.

4.1.3 Design methods

This standard is the basis for determining design load values (design loads) to be used in the structural analysis.

If the design loads are determined by computation, an integrated structural dynamics model shall be used. Calculations may generally be based on linear elastic theory. However, non-linear relationships between loads and load effects shall be properly accounted for, where they are found to be important (e.g. non-linear soil behaviour for high deflections). This model shall be used to determine the loads over a range of wind speeds, with due consideration of the aeroelastic coupling. Here, as a minimum, the turbulence conditions and other extreme wind conditions, as defined in [2.3] and [3.1.1], shall be applied. All relevant combinations of external conditions and design situations shall be analysed. A minimum set of such combinations is defined as load cases in [4.4].

A structure may become unsafe or unfit for use by damage or other changes of state according to different criteria. They may be defined by "limit states". The limit states are classified in section [4.3].

The load cases are drawn up for general strength and fatigue strength analysis. If appropriate, the dynamic behaviour of the system (e.g. resonances, dynamic instabilities) shall be taken into account in both cases. The fatigue load analysis shall include the effect of the distribution of wind speed over the rotor swept area in an appropriate manner. This distribution is the result of deterministic (vertical wind-speed gradient, tower shadow) and stochastic influences (partial gusts, turbulence). Load cases shall include cases where the specific design of the turbine leads to special conditions for the actual turbine.

Verification of the adequacy of the design shall be proven by calculation and/or by measurements. If measured results are used in this verification, the environmental conditions prevailing during the test shall be analysed to reflect the design situations defined in this standard. The selection of measurement conditions, including the test loads, shall take account of the relevant partial safety factors to be applied.

4.1.4 Safety classes

A wind turbine shall be designed according to one of the following two safety classes:

— the normal safety class which applies when a failure results in risk of personal injury and/or economic, environmental or social consequences
— the special safety class which applies when the safety requirements are determined by local regulations and/or the safety requirements are agreed between the designer and the customer.

Partial safety factors for the loads acting upon a wind turbine of the normal safety class are specified in [4.3] of the present standard. Partial safety factors for wind turbines of the special safety class may deviate based on an assessment of the safety level if estimates of environmental design parameters are a better estimate and documented than those specified in the standard. A wind turbine designed according to the special safety class is a class S turbine.

4.2 Calculation of loads

4.2.1 General

The structural design of wind turbines shall be based on verification of the structural integrity of the load-carrying components. The ultimate and fatigue strength of structural members shall be verified by calculations and/or tests to demonstrate the structural integrity of the wind turbine with the appropriate safety level.

Calculations shall be performed using appropriate methods. Descriptions of the analysis methods shall be provided in the design documentation. These descriptions shall include evidence of the validity of the analysis methods or references to suitable verification studies.

The analysis methods to be used shall depend on the type of loading and the structural response. Time history analysis, e.g. by direct integration, shall be used for dynamic problems of a non-linear nature.

The calculation model (idealization) used shall take account of all main load bearing and stiffening components, and of the relevant supporting and constraining effects. The degree of subdivision (detailing) shall take account of the geometry of the structure and its influence on the load distribution and load introduction.

For offshore wind turbines, wind conditions are the primary external conditions for the structural integrity of the RNA structure, although the marine conditions including wave conditions may also have an influence in some cases, depending on the dynamic properties of the support structure. During the design of the RNA structure, the structural integrity shall be demonstrated, taking proper account of the marine conditions. The demonstration of the suitability of the RNA structure for a specific offshore site shall be based on or verified against the requirements defined in Sec.2 and Sec.3.

The design of the support structure of an offshore wind turbine shall be based on environmental conditions at the site, including the marine conditions.

Account shall be taken of the soil properties at the site, including the timely variations of such properties due to scour, sand waves etc. In the dynamic analysis of the loads, the change in the stiffness properties of the soil conditions at the site and the change in the masses during the design lifetime of the turbine shall be considered in the load case definitions; see also [4.4].

Marine conditions, such as humidity, corrosion and marine fouling, may vary during the turbine lifetime and influence the dynamic properties of the turbine. The load cases shall be defined in such a way that conservative loads are obtained for the entire lifetime of the offshore turbine.

For the site-specific load case definitions, the meteorological and oceanographic data relevant for the installation site shall apply. If the actual external conditions are not sufficiently known, the wind turbine may be designed according to one of the wind turbine classes specified in [2.2.3] and adequate assumptions regarding the parameters not defined by classes. Before the installation of the turbine, it shall be ensured that the design conditions adequately cover the prevailing external conditions at the site that shall be specified according to Sec.3. For turbines erected within a wind farm, the mutual influence shall be taken into account. This manifests itself in an increased turbulence and non-uniform inflow. Guidance is given in App.H.

Guidance note:
Usually, a preliminary load analysis is based on site assumptions or a wind turbine class in combination with assumed marine conditions. Since the model dynamics and the soil behaviour depend on the loads, they may vary during design process. A final load evaluation or analysis should be performed for the critical load cases of all support structure configurations, and the original assumptions should be reconciled.

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4.2.2 Loads

The loads described in [4.2] shall be considered for the design calculations. Prototype tests and model investigations (tests) may also be used to support the load calculations. Tests shall be based on approved test plans. Any test shall be supervised by an accredited institute or a certification body. In special cases, model tests may be required.

In general, a dynamic analysis of the wind turbine, considering the dynamic response for external and operating conditions, is required.

Guidance note:
If justified a quasi-static analysis may be carried out in some exceptional cases in agreement with DNV GL. Dynamic amplification factors (DAF) should then be determined such that the quasi-static analysis does not lead to a reduction of the safety level.

Response spectrum analysis may be applied for structures with a linear elastic response to random loading, e.g. due to non-deterministic wind and/or wave loads, provided a linearization of the non-linear load effects is possible. The method may be appropriate to determine the dynamic amplification effects due to extreme wind and wave loads or loads on fixed jacket structures and also to perform fatigue damage accumulations.

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4.2.3 Operational loads

Operational loads result from the operation and control of the wind turbine. They shall be assigned to several categories. These are the control of rotor speed and the torque control by pitching of blades or other aerodynamic devices. Other operational loads are the mechanical braking and transient loads arising during the starting and stopping of the rotor, connection and disconnection of the generator, and yaw movements. The following influences shall also be taken into account:

— static and load-dependent bearing friction moments (especially blade pitch bearing, yaw bearing)

— behaviour of the control and safety systems of the wind turbine.

4.2.4 Inertia and gravitation loads

Inertia and gravitation loads are static and dynamic loads acting on the wind turbine. They result from vibration, rotation, gravity and seismic activity.

In a dynamic analysis, structural dynamics and the coupling of vibrational modes shall be considered. The following items shall be taken into account:

- the elasticity of the blades
- elasticity of the drive train and generator (drive train dynamics)
- elasticity of the support structure, including interaction with the soil
- global motions of the structure
- helideck dynamics (if relevant).

The elastic mounting of the machinery, vibration dampers, the stiffness of the support structure and the influence of the foundation shall also be included, if their influence cannot be neglected. For structural components supporting rotating equipment, resonance shall be avoided.

Interaction between the structure and soil should in general be modelled non-linearly. For piled foundations, the non-linear behaviour of axial and lateral pile-soil support should be modelled explicitly to ensure load deflection compatibility between the structure and pile-soil system.

For the rotor, the actual mass eccentricity shall be taken into account.

Besides all effective structural and appurtenance masses, the hydrodynamic masses accounting for increased member thickness due to marine growth and water enclosed in submerged members shall be taken into account.

Second-order motions shall be considered, if they have a relevant impact on the loading, e.g. for very soft support structure designs resulting in large inclination angles.

4.2.5 Aerodynamic loads

The aerodynamic loads are subdivided into quasi-static and dynamic loads which are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.

The aerodynamic loads are dependent (among other factors) upon the rotational speed of the rotor, the average wind speed across the rotor plane, the three-dimensional turbulence intensity, the wind shear, wind direction changes, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including the aeroelastic effects.

The following influences shall be taken into account when wind loads on the wind turbine are analysed:

- wind field perturbations due to the wind turbine itself (wake-induced velocities, tower shadow, tower upwind effect etc.)
- the influence of three-dimensional flow on the blade aerodynamic characteristics (e.g. three-dimensional stall and aerodynamic tip loss)
- dynamic stall effects of the airflow on the profiles used
- unsteady aerodynamic effects
- aeroelastic effects
- aerodynamic asymmetries that may arise through production or assembly tolerances of the rotor blades. A verified tolerance shall be observed. If this is not (or not yet) known, a deviation of the blade angle of attack of ± 0,3° (i.e. for a three-blade turbine: blade 1 at 0°, blade 2 at –0,3°, blade 3 at +0,3°) shall be assumed.
- aerodynamic loads (lift, drag and torsion, if applicable) on structural members.

The aerodynamic force coefficient c_f for structural parts shall be determined in accordance with EN 1991-1-4 or in accordance with equivalent international standards.

4.2.6 Hydrodynamic loads

Hydrodynamic loads are subdivided into stationary and non-stationary loads which are caused by the water flow and its interaction with the support structure of the offshore wind turbine.

The hydrodynamic loads are dependent on the kinematics of the water flow, the density of the water, the water depth, the shape of the support structure and their interactive effects, including hydroelastic effects.

Depending on the support structure type and stiffness, the structure response shall be considered in hydrodynamic analysis. Vortex-induced vibrations may need consideration for slender structures.

The importance of radiation and diffraction effects shall be considered in the hydrodynamic model. This shall be agreed with DNV GL.

4.2.6.1 Wave loads

For calculation of wave loads, a recognised wave theory for representation of the wave kinematics shall be applied. The wave theory shall be selected with due consideration of the water depth and of the range of validity of the theory.

Methods for wave load prediction shall be applied that properly account for the size, shape and type of structure.

For large volume structures, for which the wave kinematics are disturbed by the presence of the structure, wave diffraction analysis shall be performed to determine local (pressure force) and global wave loads.

Both viscous effects and potential flow effects may be important in determining the wave-induced loads on a wind turbine support structure. Wave diffraction and radiation are included in the potential flow effects.

Guidance note 1:

Figure 4-1 may be used as a guidance to establish if viscous effects or potential flow effects are important. Figure 4-1 refers to horizontal wave-induced forces on a vertical cylinder, which stands on the seabed and penetrates the free water surface, and which is subject to incoming regular waves.

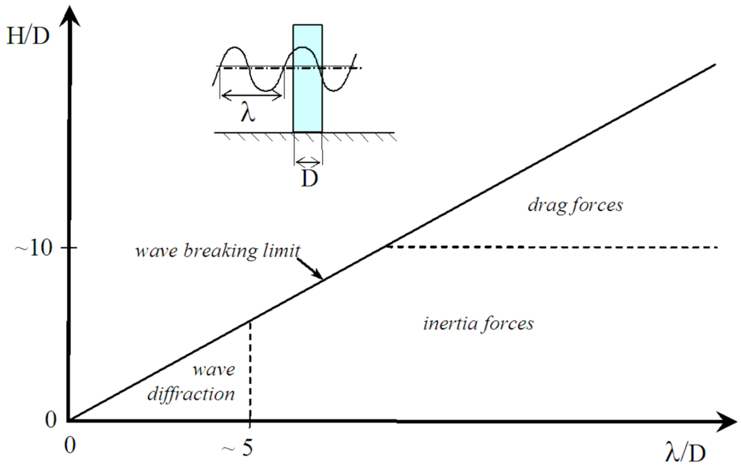

Figure 4-1 Relative importance of inertia, drag and diffraction wave forces

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Wave forces on slender structural members, such as a cylinder submerged in water, may be predicted by Morison's equation. In this equation, the horizontal force on a vertical element *dz* of the structure at level *z* is expressed as:

$$\begin{aligned} dF &= dF_M + dF_D \\ &= C_M \rho \pi \frac{D^2}{4} \ddot{x}\, dz + C_D \rho \frac{D}{2} |\dot{x}| \dot{x}\, dz \end{aligned} \tag{4.1}$$

where the first term is an inertia force and the second term is a drag force. Here, C_M and C_D are inertia and drag coefficients, respectively, D is the diameter of the cylinder, ρ is the density of water, $\dot{x}$ is the horizontal wave-induced velocity of water, and $\ddot{x}$ is the horizontal wave-induced acceleration of water. The level z is measured from still water level, and the z axis points upwards. Thus, at seabed $z = -d$, when the water depth is d.

Guidance note 2:

The drag and inertia coefficients are in general functions of the Reynolds number, the Keulegan-Carpenter number and the relative roughness. The coefficient also depends on the cross-sectional shape of the structure and of the orientation of the body. For a cylindrical structural member of diameter D, the Reynolds number is defined as Re = $u_{max}D/\nu$ and the Keulegan-Carpenter number as KC = $u_{max}T_i/D$, where u_{max} is the maximum horizontal particle velocity at still water level, ν is the kinematic viscosity of seawater, and T_i is the (intrinsic) period of the waves. Re and KC, and in turn C_D and C_M, may attain different values for the extreme waves that govern the ULS and for the moderate waves that govern the FLS.

The drag coefficient C_{DS} for steady-state flow may be used as a basis for the calculation of C_M and C_D. The drag coefficient C_{DS} for steady-state flow depends on the roughness of the surface of the structural member and may be taken as

$$C_{DS} = \begin{cases} 0{,}65 & \text{for } k/D < 10^{-4} \text{ (smooth)} \\ \dfrac{29 + 4\log_{10}(k/D)}{20} & \text{for } 10^{-4} < k/D < 10^{-2} \\ 1{,}05 & \text{for } k/D > 10^{-2} \text{ (rough)} \end{cases} \tag{4.2}$$

in which k is the surface roughness and D is the diameter of the structural member. New uncoated steel and painted steel may be assumed to be smooth. For concrete and highly rusted steel, k = *0,003 m* may be assumed. For marine growth, k = *0,005* to *0,05 m* may be assumed.

The drag coefficient C_D depends on C_{DS} and on the KC number and may be calculated as

$$C_D = C_{DS} * \psi(C_{DS}, KC) \tag{4.3}$$

in which the wake amplification factor ψ may be taken from Figure 4-2. For intermediate roughness between smooth and rough, linear interpolation is allowed between the curves for smooth and rough cylinder surfaces in Figure 4-2.

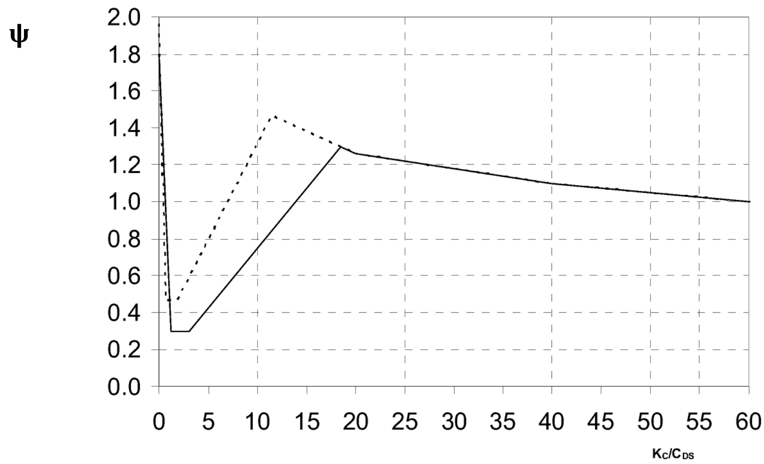

Figure 4-2 Wake amplification factor ψ as function of KC number Kc/C_{DS} for roughness smooth (solid line) and rough (dotted line)

For KC < *3*, potential theory is valid with C_M = *2,0*. For KC > *3*, the inertia coefficient C_M may be taken as

$$C_M = \max\{2{,}0 - 0{,}044(KC - 3); 1{,}6 - (C_{DS} - 0{,}65)\} \tag{4.4}$$

where C_{DS} depends on the surface roughness of the structural member as specified above.

As an example, in 30 to 40 m of water depth in the southern and central parts of the North Sea, C_D = *0,8* and C_M = *1,6* may be applied for diameters less than 2,2 m for use in load calculations for fatigue limit states.

For structures in shallow waters near coastlines where there is a significant current in addition to the waves, C_M should not be taken less than 2,0.

For long waves in shallow water, the depth variation of the water particle velocity is usually not large. Hence it is recommended to use force coefficients based on the maximum horizontal water particle velocity u_{max} at the free surface.

When waves are asymmetric, which may in particular be the case in shallow waters, the front of the wave has a different steepness than the rear of the wave. Since the wave force on a structure depends on the steepness of the wave, caution should be exercised to apply the asymmetric wave to the structure in such a manner that the wave load impact is calculated with that of the two wave steepnesses which will produce the largest force on the structure.

For more detailed information about the definition of hydrodynamic coefficients refer to DNV-RP-C205.

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The resulting horizontal force F on the cylinder may be found by integration of Morison's equation for values of z from $-d$ to the wave crest, $\eta(t)$.

Guidance note 3:
For non-breaking waves, the resulting horizontal force becomes:

$$\begin{aligned} F &= F_M + F_D \\ &= \int_{-d}^{\eta(t)} C_M \rho \pi \frac{D^2}{4} \ddot{x}\, dz + \int_{-d}^{\eta(t)} C_D \rho \frac{D}{2} |\dot{x}| \dot{x}\, dz \end{aligned} \tag{4.5}$$

The integration from $-d$ to 0 ignores contributions to the force from the wave crest above the still water level at $z = 0$. This is a minor problem when the inertia force F_M is the dominating force component in F, since F_M has its maximum when a nodal line at the still water level passes the structure. The drag force F_D has its maximum when the crest or trough passes the structure. If this force is the dominating force component in F, a significant error may be introduced by ignoring the contribution from the wave crest.

The relative magnitude of the inertia force component F_M and the drag force component F_D may be expressed by the ratio of their amplitudes, $A = A_M/A_D$. Figure 4-3 may be used to quickly establish whether the inertia force or the drag force is the dominating force, once the ratios H/D and d/λ have been calculated. Structures having relative magnitudes of inertia and drag forces above the curve marked $A = 1$ in Figure 4-3 experience drag-dominated loads, whereas structures having relative magnitudes below this curve experience inertia-dominated loads.

Morison's equation is only valid when the dimension of the structure is small relative to the wave length, i.e. when $D < 0{,}2\lambda$. The integrated version of Morison's equation given here is only valid for non-breaking waves. However, Morison's equation as formulated for a vertical element dz is valid for the calculation of wave forces from both breaking and non-breaking waves as long as the element is fully submerged. In deep water, waves break when H/λ exceeds a value of about 0,14. In shallow water, waves break when H/d exceeds a value of about 0,78.

Figure 4-3 is based on linear wave theory and should be used with caution, since linear wave theory may not always be an adequate wave theory for the prediction of wave forces in particularly shallow waters. 5th order stream function theory is usually considered the best wave theory for representation of wave kinematics in shallow waters. For prediction of wave forces for fatigue assessment, higher order stream function theory may be applied for water depths less than approximately 15 m, whereas Stokes 5th order theory is recommended for water depths in excess of approximately 30 m.

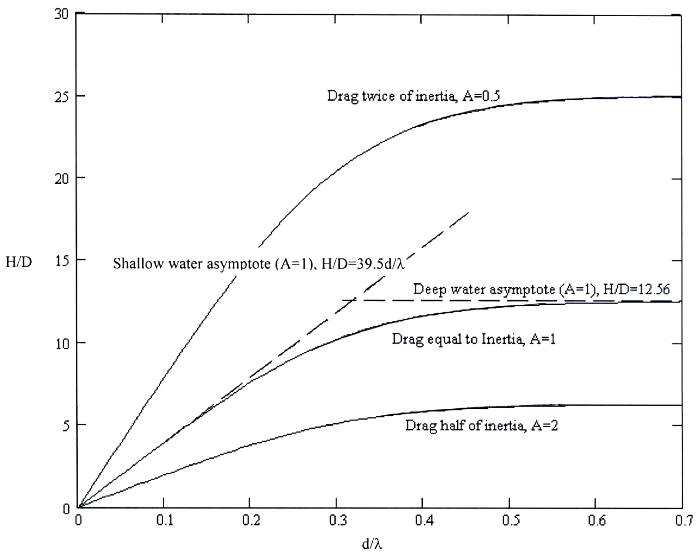

Figure 4-3 Relative magnitude of inertia and drag forces for cylinders with $D/\lambda < 0{,}2$

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When the dimension of the structure is large compared to the wave length, typically when $D > 0{,}2\lambda$, Morison's equation is not valid. The inertia force is dominating and may be predicted by diffraction theory.

Guidance note 4:
For linear waves, the maximum horizontal force $F_{X,\max}$ on a vertical cylinder of radius $R = D/2$ installed in water of depth d and subjected to a wave with an amplitude A_W, may be calculated as

$$F_{X,\max} = \frac{4\rho g A}{k^2} \frac{\sinh\big(k(d + A\sin\alpha)\big)}{\cosh(kd)} \xi \tag{4.6}$$

and its lever arm h_F measured from the seabed is

$$h_F = d\frac{kd\sinh(kd) - \cosh(kd) + 1}{kd\sinh(kd)} \tag{4.7}$$

The coefficients ξ and α are given in Table 4-1.

The diffraction solution for a vertical cylinder given above is referred to as the *MacCamy-Fuchs* solution. The terms given represent essentially a corrected inertia term which may be used in Morison's equation together with the drag term.

The formulae given in this guidance note are limited to vertical circular cylinders with constant diameter *D*. For other geometries of the support structure, such as when a conical component is present in the wave-splash zone to absorb or reduce ice loads, diffraction theory is still valid, but the resulting force and moment arm will come out differently from the vertical cylinder solutions given here.

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For the evaluation of load effects from wave loads, possible ringing effects shall be included in the considerations. When a steep, high wave encounters a monopile, high frequency nonlinear wave load components may coincide with natural frequencies of the structure causing resonant transient responses of the global bending modes of the pile. Such ringing effects are only of significance in combination with extreme first order wave frequency effects. Ringing should be evaluated in time domain with due consideration of higher order wave load effects. The magnitude of the first ringing cycles is governed by the magnitude of the wave impact load and its duration is related to the structural resonance period.

Guidance note 5:

Ringing may occur if the lowest natural frequencies of the structure do not exceed three to four times the typical wave frequency. In case that the natural frequency exceeds about five to six times f_p, where f_p denotes the peak frequency, ringing may be ruled out. When a dynamic analysis is carried out, any ringing response will automatically appear as part of the results of the analysis, provided the wave forces are properly modelled and included in the analysis.

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Table 4-1 Coefficients ξ and α

kR	ξ	$\alpha(°)$	*kR*	ξ	$\alpha(°)$
0,02	0,00063	0,018	0,2	0,06433	1,816
0,04	0,00252	0,072	0,4	0,25808	6,972
0,06	0,00568	0,162	0,6	0,54230	13,618
0,08	0,01012	0,289	0,8	0,83373	18,734
0,10	0,01586	0,453	1,0	1,07726	20,504
0,12	0,02290	0,653	1,2	1,26842	18,940
0,14	0,03126	0,889	1,4	1,42148	14,804
0,16	0,04095	1,162	1,6	1,54958	8,844
0,18	0,05197	1,471	1,8	1,66133	1,611
0,20	0,06433	1,816	2,0	1,76191	-6,522
0,22	0,07802	2,195	2,2	1,85448	-15,306
0,24	0,09304	2,609	2,4	1,94099	-24,572
0,26	0,10937	3,056	2,6	2,02275	-34,201
0,28	0,12701	3,534	2,8	2,10063	-44,112
0,30	0,14591	4,043	3,0	2,17526	-54,245
0,32	0,16606	4,581	3,2	2,24705	-64,555
0,34	0,18740	5,145	3,4	2,31641	-75,009
0,36	0,20989	5,733	3,6	2,38360	-85,581
0,38	0,23347	6,343	3,8	2,44882	-96,253
0,40	0,25808	6,972	4,0	2,51228	-107,007
0,42	0,28364	7,617	4,2	2,57411	-117,832
0,44	0,31008	8,276	4,4	2,63444	-128,717
0,46	0,33732	8,944	4,6	2,69340	-139,654
0,48	0,36526	9,619	4,8	2,75107	-150,637

Table 4-1 Coefficients ξ and α (Continued)

kR	ξ	$\alpha(°)$	*kR*	ξ	$\alpha(°)$
0,50	0,39381	10,298	5,0	2,80754	-161,659
0,52	0,42287	10,976	5,2	2,86288	-172,716
0,54	0,45234	11,650	5,4	2,91717	176,196
0,56	0,48214	12,318	5,6	2,97045	165,081
0,58	0,51216	12,975	5,8	3,02280	153,941
0,60	0,54230	13,618	6,0	3,07425	142,779
0,62	0,57249	14,245	6,2	3,12485	131,598
0,64	0,60263	14,852	6,4	3,17465	120,399
0,66	0,63263	15,438	6,6	3,22368	109,183
0,68	0,66244	15,998	6,8	3,27197	97,953
0,70	0,69197	16,532	7,0	3,31956	86,710
0,72	0,72118	17,036	7,2	3,36648	75,454
0,74	0,75000	17,510	7,4	3,41275	64,188
0,76	0,77839	17,952	7,6	3,45841	52,910
0,78	0,80631	18,360	7,8	3,50348	41,624
0,80	0,83373	18,734	8,0	3,54797	30,328
0,82	0,86062	19,073	8,2	3,59192	19,025
0,84	0,88697	19,376	8,4	3,63533	7,714
0,86	0,91276	19,643	8,6	3,67824	-3,604
0,88	0,93797	19,874	8,8	3,72064	-14,929
0,90	0,96261	20,068	9,0	3,76258	-26,260
0,92	0,98667	20,226	9,2	3,80405	-37,596
0,94	1,01016	20,349	9,4	3,84508	-48,938
0,96	1,03308	20,435	9,6	3,88567	-60,284
0,98	1,05545	20,487	9,8	3,92585	-71,635
1,00	1,07726	20,504	10,0	3,96562	-82,991

4.2.6.2 Breaking wave loads

When waves are likely to break close to the structure, loads and shock pressures from breaking waves shall be considered. Wave loads from breaking waves depend on the type of the breaking wave. A distinction is made between spilling, plunging and surging waves. The kinematics are different for these three types of breaking waves.

For details about loads due to breaking waves, see DNV-RP-C205.

4.2.6.3 Sea current loads

A design value of sea current pressure on structural elements at the depth *z* below still water level is defined as

$$q_D(z) = \frac{\rho_W}{2} U_D^2(z) \tag{4.8}$$

where:

$q_D(z)$ = design sea current pressure at the level z

ρ_W = density of the water

$U_D(z)$ = design sea current speed at the level z

z = distance from still water level, positive upwards, $0 \geq z \geq -d$

In this formula, the design sea current speed $U_D(z)$ is the component of the current speed $U_C(z)$ (see [2.4.8]) directed perpendicularly to the cylinder axis at the height z.

Using $q_D(z)$ as defined above, design sea current loads $F_D(z)$ may be estimated by:

$$F_D(z) = C_D q_D(z) D(z) \tag{4.9}$$

where:

$F_D(z)$	=	design sea current load at the level z
C_D	=	drag coefficient
$q_D(z)$	=	design sea current pressure at the level z
$D(z)$	=	projected width of the structure perpendicular to $u_D(z)$ at the height z

The direction of $F_D(z)$ is equal to the direction of $U_D(z)$. For circular cylinders, $D(z)$ is the diameter at the height z.

The drag coefficient C_D may be taken from textbooks or model tests and has to be corrected for the effects of marine fouling and the influence of appurtenances.

4.2.7 Hydrostatic loads

Hydrostatic loads, whether external or internal, may occur if a member or compartment is wet only from one side. Hydrostatic forces act in a direction normal to the surface. For large structures with empty spaces, hydrostatic forces may have a considerable influence.

4.2.8 Sea ice loads

Static and dynamic sea ice loads acting on an offshore wind turbine are caused by the current- and wind-induced motion of ice flows and their failure in contact with the support structure. The relevance of sea ice loads for the design of the support structure depends on the specific location and characteristics of the site at which the offshore wind turbine will be installed. Forces exerted on a structure by ice shall be evaluated for their effect on local structural elements and for global effects on the structure as a whole.

Ice loads shall be evaluated for a range of interactions between ice and structure. The range of interactions is determined by the ice environment and may include:

- pressure from continuous first or multi-year level ice
- collision with first- and/or multi-year ridges within the ice field
- impact by drifting ice floes (sea ice or glacial ice)
- impact by icebergs
- dynamic ice loading.

Ice load evaluations shall include the forces exerted by ice on rubble ice or other ice pieces which are in firm contact with or held by the structure. This is of particular concern for multi-legged structures and for structures designed to cause ice failure in modes other than crushing.

The maximum compressive strength of the ice shall be considered as a characteristic of the local loading of the structure by ice. In selecting the appropriate compressive strength, the following factors shall be considered:

- temperature or temperature gradient in the ice
- orientation of the ice crystals
- salinity
- total porosity of the ice (brine volume, gas pockets and voids)
- strain rate
- loading rate
- scale effects (size of structure/ice thickness).

The brittle nature of ice may lead to periodic dynamic loading, even during interactions between ice and structure where this is not initially apparent. Dynamic amplification of the structure’s response in its natural vibratory modes shall be analysed.

Model tests are recommended for the evaluation of global loads and confirmation of expected ice failure modes.

The methods to analyse sea ice loading on offshore wind turbine foundations are given in ISO 19906. Extra investigations and analysis shall be performed for dynamic ice loading.

Guidance note:
The dynamic ice-structure interaction process is influenced by the ice velocity and the waterline displacement of the structure. Three modes of interaction are known:

— *Intermittent ice crushing* may arise if a compliant structure is exposed to ice action at a low speed. The interaction involves a loading phase and an unloading phase. In the loading phase, the structure moves in the same direction as the ice. The ice edge experiences ductile deformations and the ice action gradually increases. The external ice action and the internal forces of the structure are usually in a static equilibrium when the ice action reaches a maximum value. At the peak value of ice action, brittle crushing starts at the ice edge, leading to relaxation vibrations in the structure that decay during the unloading phase. The rate of decay depends on the total damping provided by the soil and the structure.
— *Frequency lock-in* may occur at intermediate ice speeds, ranging typically from 0,04 m/s to 0,1 m/s, as the time-varying ice actions adapt to the frequency of the waterline displacements of the structure. The vibrations of the structure are typically sinusoidal in this condition. Similar to intermittent crushing the ice-structure interaction exhibits alternating phases of ductile loading and brittle unloading. The time history of the ice action depends on the characteristics of the ice and the structure.
— *Continuous brittle crushing* occurs at higher ice speeds, typically at speeds above 0,1 m/s. Both the ice action and the response are random.

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4.2.9 Seismic loads

The analysis of the dynamic response shall be performed using recognized procedures such as:

— response spectrum analysis
— time history analysis.

A three-dimensional model of the structure should be used for the analysis. The combination of earthquake loads with other loads is described in Table 4-4 and [4.6.3]. The seismic response spectrum is generally given in local building codes. When applying the seismic response spectrum, it shall be ensured, that the recurrence period is the same as that the chosen analysis method is based on.

When the response spectrum analysis is applied for the combination of the modal maxima, the use of the complete quadratic combination (CQC) method as described in EN 1998 is recommended.

When time domain simulations are used, the ground acceleration at the surface of the seabed shall be derived from the seismic response spectrum taking into account the soil properties. A sufficient number of stochastic acceleration time series of sufficient duration shall be taken into account.

Further information may be found in IEC 61400-1, 11.6 and the corresponding Annex.

4.2.10 Boat impact loads

The primary structures, boat landings, ladders and other secondary structures in and near the water line, shall be designed for service vessel impacts as a normal event. The primary structure in and near the waterline shall additionally be designed for supply vessel impacts as an abnormal event as described below.

For the normal design load case, the following applies:

— Only service vessels which are actually approaching boat landings (or other access systems) need to be considered.
— The characteristic impact energy shall be taken as the expected energy caused by the maximum authorised service vessel approaching in the most severe sea state to be considered for operation of the service vessel.
— A vessel-specific speed shall be assumed. The speed shall not be assumed less than 0.5 m/s.
— Effects of wind, wave and current shall be included as well as effects of added mass, which contributes to the kinetic energy of the vessel.
— The secondary structural parts shall be designed such that the vertical movement of the service vessel is not restrained.
— The secondary structural parts shall be able to withstand 1/2 of the operational impact load applied vertically.

Guidance note 1:

If specific loads are not available for a service vessel impact, the contact area may be designed for an impact force of $F = 2.5 \cdot \Delta$, where F is the impact force in kN and Δ is the displacement of the fully loaded service vessel in *Mg*.

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For the abnormal design load case, the following applies:

— Supply vessels (e.g. hotel ships) which operate within the wind farm, but do not approach wind turbines, do not need to be considered for impact scenarios.

— The characteristic impact energy shall be taken as the impact energy caused by unintended collision by the maximum authorised service vessel which is approaching the turbines.

— For this purpose, the service vessel shall be assumed to be drifting laterally. The speed of the drifting vessel shall not be less than 2.0 m/s.

— Effects of added mass shall be included. Effects of fendering of the maximum authorised service vessel shall be considered.

— Secondary structural parts are allowed to become torn off, e.g. by including weak points or by local strengthening of supporting structural parts, thereby to avoid excessive damage to these supporting parts.

Guidance note 2:

The energy absorbed by the support structure will depend on its strength and stiffness in comparison to that of the impacting component of the vessel. In the case of a very stiff and strong support structure, the energy will be absorbed primarily by the vessel. Following a vessel impact, it is important to examine any damage of the support structure caused by the impact force and determine any necessary repair work to be undertaken to ensure that the required load carrying capacity of the support structure is preserved.

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Guidance note 3:

The impact energy transferred into elastic deformation yields the impact condition (both for the normal and abnormal case):

$$E_{kin} = E_{spring} \tag{4.10}$$

The impact energy is given by:

$$E_{kin} = \frac{1}{2} a m v_{impact}^2 \tag{4.11}$$

where:

m = vessel displacement [t]

a = added mass coefficient; $a = 1.25$ for bow or stern collision; $a = 1.4$ for sideways collision

v_{impact} = impact speed [m/s]

The impact speed may be assumed by the following, assuming the operation of the vessel compensates for current:

$$v_{impact} = v_{boat} + \begin{cases} \frac{1}{2}\sqrt{\frac{g}{d}} H_s & \text{for shallow water} \\ \dfrac{\pi H_s}{T_p} & \text{for deep water} \end{cases} \tag{4.12}$$

Assuming linear elasticity the spring energy relates to spring force and stiffness:

$$E_{spring} = \frac{1}{2} \frac{F_{boat,impact}^2}{c} \tag{4.13}$$

where:

$F_{boat,impact}$ = impact force [kN/m]

E_{spring} = spring energy [kN/m]

c = total spring stiffness of the structure at the impact point [kN/m]

The total spring stiffness c may be calculated by:

$$\frac{1}{c} = \frac{1}{c_1} + \cdots + \frac{1}{c_n} \tag{4.14}$$

The stiffness values c_1 to c_n are representing the different components of the total flexibility at the point of contact such as:

— local stiffness of the boat landing structure
— global stiffness of the offshore structure (including foundation)
— shock cells, rub strips etc. at the boat landing side
— fender and local structural flexibility of the vessel side.

In general it is conservative for the offshore turbine to assume that the service vessel is rigid and the total energy is transferred into the support structure.

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4.2.11 Combination of external conditions

For the load analysis of offshore wind turbines, scatter diagrams (long-term statistics) including wave height, wave period and wind speed should be used to determine the wind/wave combinations to be considered. The directional distribution of wind and waves shall be evaluated and should be included in the scatter diagrams considered.

The combination of extreme external conditions (wind, wave, current, sea ice and water level) is performed in a way that results in the global extreme environmental action on the structure and the resulting response with the specified return period (50-year or 1-year). The geometric and dynamic properties of the support structure may make it necessary to specify several combined events.

In the absence of information of the long-term probability distribution of combined extreme external conditions, it may be assumed that the extreme external conditions occur during the same 3-hour storm event, i.e. the specified return period sea state is combined with the mean wind speed and the current velocity with the same specified return period, all determined independently by extrapolation of the individual parameters.

4.2.12 Combination of loads

Load time series for offshore wind turbines from combined external conditions include all components required, [4.1.3]. No further combination is needed.

4.2.13 Load impact due to extreme temperatures

In the case of extreme temperatures and temperature influences for site-specific designs, reference is made to DNVGL-RP-0363.

4.2.14 Variation of support structure natural frequency and operation within the resonance range

During the wind turbine's lifetime, the mass and stiffness of the structure and the soil may change considerably. Scour, corrosion, marine growth, soil settlings and sand movement may influence the turbine's natural frequencies.

In the load analysis, the change of the support structure's natural frequencies shall be considered, i.e. by applying the most adverse conditions for load analysis. Mean values may be applied for fatigue analysis if no resonant operational modes can appear.

If the operation of a wind turbine is desired within the resonance range of the support structure with a tolerance of ± 5% of the support structure's natural frequency (see DNVGL-ST-0126, [3.6]), suitable vibration monitoring systems shall be provided (see DNVGL-ST-0438, [3.8]). Within the load calculation, suitable threshold values for permissible vibrations shall be defined and taken into account.

4.2.15 Load-relevant control and safety system functions

Load relevant control and safety systems functions are given in detail within the load case tables for on- and offshore wind turbines for the load cases of the load cases DLC2.x. The evaluation of safety system and control algorithms is described in DNVGL-ST-0438.

4.2.16 Other loads

Other loads (such as maintenance loads, extreme temperature etc.) may occur and shall be included where appropriate. Special conditions of the installation site shall be considered.

Loads resulting from installation and removal actions shall be considered in the structural design. These loads may result from:

— buoyancy aids, self-floating
— lifting of parts or the whole structure
— piling
— launching
— submerging.

4.3 Partial safety factors for loads

The partial safety factors for the loads shall have at least the values given in Table 4-2.

Table 4-2 Partial safety factors for loads γ_F

Functional and environmental loads					Permanent loads*		
ULS		**FLS**	**ALS**	**SLS**	**ULS**		**FLS, ALS, SLS**
Normal	Abnormal				Favourable	Unfavourable	
N 1,35***	A 1,1	F 1,0	F 1,0	F 1,0	0,9**	1,1**	1,0

* Permanent loads include dead loads and pretension loads for the support structure design.

For submerged sub-structures, for example a GBS placed on the seabed, the Permanent load is the total weight minus the buoyancy determined at the still water level

** Factors for permanent loads in ULS may be taken as 1,0 if appropriate measures are taken.

*** For DLC 1.1 the partial load factor shall be γ_F = 1,25; for DLC 2.5 the partial load factor shall be γ_F = 1,2

The following formulation according to IEC 61400-1, Table 3 may be applied:

If for normal design situations the characteristic value of the load response $F_{gravity}$ due to gravity may be calculated for the design situation in question, and gravity is an unfavourable load, the partial load factor for combined loading from gravity and other sources may have the value

$$\gamma_f = 1{,}1 + \varphi\varsigma^2 \text{ and } \varphi = \begin{cases} 0{,}15 \text{ for DLC 1.1} \\ 0{,}25 \text{ otherwise} \end{cases}$$

$$\zeta = \begin{cases} 1 - \left|\dfrac{F_{gravity}}{F_k}\right| ; & |F_{gravity}| \leq |F_k| \\ 0; & |F_{gravity}| > |F_k| \end{cases}$$

where F_k = characteristic value for loads

The partial safety factors for loads are given below in accordance with the limit state design method. Where relevant, different safety factors are defined for the same limit state based on the failure mechanism.

The following limit states are considered in this standard:

Ultimate limit states (ULS) corresponding to the ultimate resistance for carrying loads.

Fatigue limit states (FLS) related to the possibility of failure due to the effect of cyclic loading. Due their importance FLS are treated separately from the ULS in this standard.

Accidental limit states (ALS) corresponding to damage of components due to an accidental event or operational failure.

Serviceability limit states (SLS) corresponding to the criteria applicable to normal use or durability.

Guidance note:

The maximum deflection of the rotor blade towards the tower is within this standard and DNVGL-ST-0376 considered a serviceability limit state (SLS). Due to the possible contact between blade tip and tower under ultimate blade deflection, this could also constitute an ultimate limit state and should be avoided under all conditions. Care should be taken when applying this standard in combination with standards other than DNVGL-ST-0376 to ensure a consistent consideration of safety factors regarding the deflection analysis.

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4.3.1 Partial safety factors for the loads in the analysis of the ultimate limit state/ultimate strength

4.3.1.1 Wind turbine loads

The partial safety factor for the loads in ultimate limit states (ULS)/ultimate strength for normal conditions is γ_F = 1,35, except for DLC 1.1, where the partial load factor shall be γ_F = 1,25 and except for DLC 2.5, where the partial load factor shall be γ_F = 1,20. For further application of load extrapolation alternatives and the applicable additional factors see [4.7].

The partial safety factor for the loads in ultimate limit states (ULS)/ultimate strength for abnormal conditions is γ_F = 1,1. Abnormal operating conditions denote situations with serious failures and/or combinations of more than one unlikely environmental condition. For example failures of the safety system or the combination of extreme wind speed with simultaneous grid failure are considered as abnormal operating conditions.

4.3.1.2 Permanent loads

Permanent loads include for example dead loads and pretension loads. Favourable loads for the ULS analysis are pretension and gravity loads, which lower the total response significantly.

4.3.2 Partial safety factors in the analysis of the fatigue limit state/ fatigue strength

The partial safety factor for the loads in the fatigue limit state (FLS) is γ_F = 1,0 for all normal and abnormal design situations. It is assumed that the coefficient of variation of the fatigue load stress ranges is less than 20%.

4.3.3 Partial safety factors in the analysis of the accidental limit states

The safety factor for the loads resulting from accidental limit state (ALS) conditions is γ_F = 1,0. These conditions include e.g. earthquakes.

4.3.4 Serviceability limit states

4.3.4.1 Partial safety factors for the loads in the analysis of the serviceability limit states

For the analysis of the serviceability limit states (SLS, see [C.3]), a partial safety factor for loads of γ_F = 1.0 shall be used for all load components.

4.3.4.2 Partial safety factors for the loads for the blade deflection analysis

It shall be verified that no blade deflections endangering the safety of the wind turbine occur under the design conditions listed in Table 4-3 and, if applicable, Table 4-4. One of the important considerations is that no contact is permitted to occur between the rotor and the support structure. The maximum elastic deflection in the most unfavourable direction shall be determined for the load cases listed in Table 4-3 and, if applicable, Table 4-4.

Methods of statistical extreme value analysis (see e.g. E. J. Gumbel) may also be used for the blade deflection analysis. An extrapolation to 50-years shall be applied. For sites where this requirement may be fulfilled by extrapolation of the more severe directions (wind/turbulence), with the fraction of the time where the wind is in the actual direction, if the wind is in this severe direction 1/5 of the lifetime, e.g. 1/5 times 50-years (10 years).

The partial safety factor for the loads shall be γ_F = 1,0 in all cases. For the minimum requirements concerning the clearance between blade and support structure see DNVGL-ST-0376, [2.5.11].

4.3.5 Special partial safety factors

Different partial safety factors for loads may be applied based on an assessment of the safety level after agreement with DNV GL, if the loads were determined by measurements, or by analyses verified by measurements, with a higher level of confidence than is normally the case. The values of all partial safety factors shall be stated in the design documentation.

4.4 Load case tables for onshore and offshore loads

For each design situation in the normal operational speed range, several design load cases shall be considered to verify the structural integrity of wind turbine components. As a minimum, the design load cases in Table 4-3 shall be considered. This table specifies the design load cases for each design situation through the description of the wind, marine, electrical and other external conditions. If other realistic combinations lead to more severe loading, these shall be considered. Table 4-4 contains the extended design load cases described in more detail in [4.6].

Other design load cases relevant for safety shall be considered, if required by the specific wind turbine design or by the control concept.

For each design load case, the appropriate type of analysis is stated by F and U in Table 4-3 and Table 4-4. F refers to analysis of fatigue loads, to be used in the assessment of fatigue strength. U refers to the analysis of ultimate loads, such as the analysis of exceeding the maximum material strength, analysis of tip deflection, and stability analysis.

In the definition of the design load cases, reference is made to the wind and marine conditions described in Sec.2. If a wind speed range is indicated in Table 4-3, the wind speeds leading to the most adverse condition for the wind turbine design shall be considered. For the analysis of ultimate strength (U), at least the wind speeds $V_{r-2m/s}$, V_r, $V_{r+2m/s}$ and V_{out} shall be investigated in the wind range $V_{in} \leq V_{\text{hub}} \leq V_{\text{out}}$ (e.g. DLC 1.1), and at least $V_{r-2m/s}$ and V_r in the wind range $V_{in} \leq V_{\text{hub}} \leq V_r$ (e.g. DLC 1.4). For the analysis of the fatigue strength (F), the range may be divided into a number of sub-ranges; each sub-range shall be allocated the corresponding proportion of the turbine's operating life.

If the use of a mechanical brake by the control or safety system is prescribed in a load case, both the minimum and the maximum braking torque shall be taken into account. The occurrence of each braking torque in the range between the minimum and the maximum braking torque is regarded as a normal condition and not as a fault condition. The suitability of the brakes (minimum braking torque) shall be verified for load case DLC 8.1.

Where the assessment of site-specific external conditions determines wind and wave conditions resulting in higher loads than those computed on the basis of the preceding generic assumptions, the site-specific data shall be taken into account.

For offshore wind turbines, the multi-directionality of wind and waves may, in some cases, have an important influence on the loads acting on the support structure. For some design load cases, the load calculations may be undertaken by assuming that wind and waves are acting from a single, worst-case direction. In these cases, however, the structural integrity shall be verified by application of the calculated worst-case loads to the relevant directional orientations of the support structure.

For fatigue investigations, a simulation time length of 10 minutes is assumed to be adequate if the overall simulation time in every wind speed bin is not less than one hour. The simulations for the estimation of extreme events using stochastic wind fields and/or irregular sea states require a simulation time of 1 hour; the sum of different realizations shall be at least 5 hours. Each simulation shall be carried out with a different seed.

Guidance note:

Simulations shorter than 1 hour may be applied for the estimation of extreme events if this does not compromise extreme load statistics, e.g. six 10-min simulations. Constrained wave methods may be used in this case; see IEC 61400-3. If a deterministic constrained wave is used, a minimum of 6 realizations should be considered instead of the 5 hours' simulation length.

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Table 4-3 Design load cases

Design Situation	DLC	Wind Condition	Marine Condition				Other Conditions:	Type of Analysis		Partial safety factor
			Waves	Wind and wave directionality	Sea Currents	Water Level		Onshore	Offshore	
1) Power Production:	1.1	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	For extrapolation of extreme loads (offshore – only RNA)	U	U	N (1.25)
	1.2	NTM $V_{in} < V_{hub} < V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	MIS, MUL	No Currents	NWLR or ≥ MSL		F/U	F/U	F/N
	1.3	ETM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL		U	U	N
	1.4	ECD $V_{hub} = V_r - 2$ m/s, V_r, $V_r + 2$ m/s	NSS $H_s = E[H_s \vert V_{hub}]$	MIS, wind direction change	NCM	MSL		U	U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL		U	U	N
	1.6	NTM $V_{in} < V_{hub} < V_{out}$	SSS $H_s = H_{s,SSS}$	COD, UNI	NCM	NWLR		-	U	N
	1.7	NTM $V_{in} < V_{hub} < V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	MIS, MUL	No Currents	NWLR or ≥ MSL	Ice formation	F/U	F/U	F/N
2) Power Production + occurrence of fault:	2.1	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	Normal control system fault or primary layer control function fault	U	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	Abnormal control system fault or secondary layer protection function fault	U	U	A
	2.3	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	External or internal electrical fault including loss of electrical network	U	U	A
	2.3 alternatively	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	External or internal electrical fault including loss of electrical network	U	U	N
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	No currents	NWLR or ≥ MSL	Normal control system fault or loss of electrical network or primary layer control function fault	F/U	F/U	F/N
	2.5	NWP $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \vert V_{hub}]$	COD, UNI	NCM	MSL	Fault ride through	U	U	N (1.20)

Table 4-3 Design load cases (Continued)

Design Situation	DLC	Wind Condition	Marine Condition				Other Conditions:	Type of Analysis		Partial safety factor
			Waves	Wind and wave directionality	Sea Currents	Water Level		Onshore	Offshore	
3) Start up	3.1	NWP $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	No currents	NWLR or ≥ MSL		F/U	F/U	F/N
	3.2	EOG $V_{hub} = V_{in}$, $V_r \pm 2$ m/s, and V_{out} or ETM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	The timing of the gust and the start-up event chosen for minimum 4 distinct points	U	U	N
	3.3	EDC $V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	MIS, wind direction change	NCM	MSL		U	U	N
4) Normal shutdown	4.1	NWP $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	No currents	NWLR or ≥ MSL		F/U	F/U	F/N
	4.2	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out} or ETM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	The timing of the gust and the shutdown event chosen for minimum 6 distinct points	U	U	N
5) Emergency stop	5.1	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out}	NSS $H_s = E[H_s \| V_{hub}]$	COD, UNI	NCM	MSL	Azimuth position at the time of the emergency stop shall be randomly selected	U	U	N
6) Parked (standing still or idling)	6.1	EWM $V_{hub} = V_{ref}$	ESS $H_s = H_{s,50}$	MIS, MUL	ECM $U = U_{50}$	EWLR	Yaw misalignment of ±8 deg Possible yaw slippage	U	U	N
	6.2	EWM $V_{hub} = V_{ref}$	ESS $H_s = H_{s,50}$	MIS, MUL	ECM $U = U_{50}$	EWLR	Loss of electrical network Yaw misalignment of ±180°	U	U	A
	6.3	EWM $V_{hub} = V_1$	ESS $H_s = H_{s,1}$	MIS, MUL	ECM $U = U_1$	NWLR	Extreme yaw misalignment Yaw misalignment of ±20 deg	U	U	N
	6.4	NTM $V_{hub} < V_{in}$ and $V_{out} < V_{hub} < 0{,}7\,V_{ref}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL	Investigation of natural frequencies during idling	F/U	F/U	F/N
	6.5	EWM $V_{hub} = V_1$	ESS $H_s = H_{s,1}$	MIS, MUL	ECM $U = U_1$	NWLR	Ice formation on structure	-	U	N

Table 4-3 Design load cases (Continued)

Design Situation	DLC	Wind Condition	Marine Condition				Other Conditions:	Type of Analysis		Partial safety factor
			Waves	Wind and wave directionality	Sea Currents	Water Level		Onshore	Offshore	
7) Parked and fault conditions:	7.1	EWM $V_{hub} = V_1$	ESS $H_s = H_{s,1}$	MIS, MUL	ECM $U = U_1$	NWLR	Fault that produces deviations from the normal turbine behaviour while parked; including loss of electrical network	U	U	A
	7.2	NTM $V_{hub} < V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL		-	F/U	F/N
8) Transport, installation, maintenance and repair	8.1	NTM $V_{hub} = V_T$ *to be stated by the manufacturer*	NSS $H_s = H_{sT}$ *to be stated by the manufacturer*	COD, MUL	No currents	NWLR	Design conditions shall be stated by the manufacturer	U	U	N
	8.2	EWM $V_{hub} = V_1$	ESS $H_s = H_{s,1}$	COD, MUL	No currents	NWLR	Transport, installation, maintenance and repair	U	U	A
	8.3	EWM $V_{hub} = V_1$	ESS $H_s = H_{s,1}$	COD, UNI	ECM $U = U_1$	NWLR	Vortex-induced vibrations due to wind, waves or currents	F/U	F/U	F/N
	8.4	NTM $V_{hub} < 0{,}7V_{ref}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or ≥ MSL	No grid during installation period	-	F/U	F/N
	8.5	NTM $V_{hub} = V_T$	ESS $H_s = H_{sT}$	COD, MUL	ECM $U = U_1$	NWLR	Service vessel impact and helicopter loads – normal event	-	U	N
	8.6	NTM $V_{hub} = V_T$	ESS $H_s = H_{sT}$	COD, MUL	ECM $U = U_1$	NWLR	Supply vessel impact – abnormal event	-	U	A

4.5 Design situations and load cases for wind turbines

4.5.1 Power production (DLC 1.1 to 1.7)

In this design situation, the wind turbine is in operation and connected to the electrical grid. No fault situation occurs and the control system is active. The assumed wind turbine configuration shall take into account any rotor imbalance. The maximum mass and aerodynamic imbalances (e.g. blade pitch and twist deviations) specified for rotor manufacturing shall be applied in the design calculations.

Deviations from theoretical optimum operating situations, such as yaw misalignment and control system delays, shall be taken into account in the analyses of operational loads.

Yaw misalignment and hysteresis shall be considered in the yaw movement. If values for the turbine type cannot be specified, yaw misalignment of -8°, 0° and +8° evenly distributed in ± 8° shall be applied (DLC 1.1 to 1.3 and 1.5 to 1.7).

The deterministic wind and wave conditions have to be combined in a conservative manner. The phase angle between the wave and gust peaks may be arbitrary.

Design load cases DLC 1.1 to 1.3 embody the requirements for loads resulting from atmospheric turbulence. DLC 1.4 specifies a transient load case which has been selected as potentially critical event in the life of a wind turbine.

DLC 1.1 and 1.2: The discretization of the wind speed intervals (bins) within the wind speed ranges to be investigated shall not be chosen to be larger than 2 m/s.

DLC 1.1: Analysis of this load case is required only for calculation of the ultimate loads acting on the RNA and on tower and foundation of onshore wind turbines. The calculations of the extreme loads shall be based on statistical extrapolation of the load response of multiple simulations for a range of mean wind speeds. For further information on the calculation procedure and requirements see [4.7] and App.C.

DLC 1.2: Misalignment of wind, wave and current shall be considered in this load case. In addition, the multi-directionality of metocean conditions shall be taken into account.

DLC 1.2: In the fatigue load calculation, 700 generator switching operations (high speed/low speed and vice versa) per year shall be included, if applicable. Additionally, in the case of horizontal-axis turbines with active yaw control, operation of the yaw system shall be considered if the yaw speed exceeds $15/R$ in $°/s$ or if the yaw acceleration exceeds $450/R^2$ in $°/s^2$ (where R is the rotor radius in m). Operation of the yaw system shall be considered during 10% of the service life. Furthermore, 300 changes per year in the mean wind speeds from V_{in} to V_r and back to V_{in} shall be taken into account. 50 changes per year in the mean wind speeds from V_r to V_{out} and back to V_r shall be taken into account.

DLC 1.3 embodies the requirements for the ultimate loading resulting from extreme turbulence conditions. These conditions include both environmental turbulence as well as turbine wake extreme turbulence. For the analysis, it is sufficient to assume that mean wind and wave directions coincide.

DLC 1.4 and 1.5: Different rotor azimuth positions shall be considered. Evenly distributed rotor azimuth positions (with intervals be at most 30° for three-bladed turbines and 45° for two-bladed turbines) shall be simulated for each wind speed. For each wind speed, the characteristic load value may be determined as the average of all these distinct rotor azimuth positions.

DLC 1.6: The offshore wind turbine shall be considered in the event of a combination with a severe sea state. The significant wave height of each individual sea state shall be calculated according to [2.4.4.2].

DLC 1.7: This design load case considers humid weather conditions with ice formation on the rotor blades. Until a DNV GL standard on icing is published, the following assumptions shall be applied: The conditions ice formation on all rotor blades and ice formation on all rotor blades except one shall be assumed. In the analysis of the fatigue loads, the manufacturer shall define assumptions regarding the duration of operation with ice formation. At least one day per year ice formation on all rotor blades except one shall be assumed for standard wind turbine classes; unless it is shown that ice formation on rotor blades cannot occur during operation. The ice formation shall be modelled according to [2.5.4].

For DLC 1.1 to DLC 1.7, irregular sea state conditions shall be assumed. The significant wave height, peak spectral period and direction for each sea state shall be selected, together with the associated mean wind speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site. The designer shall ensure that number and resolution of the sea states considered are sufficient to account for the fatigue damage associated with the full long-term distribution of metocean parameters.

4.5.2 Power production plus occurrence of fault (DLC 2.1 to 2.5)

Any fault in the control or safety systems or any internal fault in the electrical system that is significant for wind turbine loading (such as generator short circuit) shall be assumed to occur during power production.

It may be assumed that independent faults do not occur simultaneously.

Guidance note:
The definitions of DLC 2.1 and 2.2 should be based on failure mode and effect analysis (FMEA) (or similar) and mean time between failures (MTBF) should be provided by control and safety system assessment.

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DLC 2.1: The occurrence of a fault in the control system which is considered a normal event shall be analysed in DLC 2.1. Exceedance of the limiting values of the control system, e.g. $n \geq n_4$ (see DNVGL-ST-0438), yaw error, pitch deviation of the blades to each other) shall be investigated.

If a fault causes an immediate shut-down or the consequent loading may lead to significant fatigue damage, the probable number of shut-downs, or the duration of this extraordinary design situation, shall be considered in DLC 2.4. At least 10 shut-downs per year due to over-speed n_4 and 24 hours of operation with an extreme yaw error (value equal to the maximum permissible oblique inflow) shall be considered.

DLC 2.2: The occurrence of faults in the safety system or in the internal electrical system which are considered to be rare events shall be analysed in DLC 2.2. Exceedance of the limiting values of the safety system (e.g. $n \geq n_A$, $P \geq P_A$, vibrations, shock, runaway of the blade pitch, failure of a braking system or runaway of yaw) shall be investigated, see also DNVGL-ST-0438. Furthermore, faults in the power system (including generator short circuit, see App.D) shall be investigated. In the case of collective pitch control DNVGL-ST-0438 shall be observed.

In DLC 2.3 transitional events due to external faults and loss of electrical grid shall be considered. The transient switching operations of the wind turbine triggered by grid loss shall be considered with regard to the analysis of fatigue and extreme loads. Additionally in this load case, peculiarities arising from connection to an energy consumer (e.g. power limitations, frequency, voltage and load fluctuations in a weak grid, operation of mechanically powered machinery, grid failure) shall be taken into account as applicable. Examples of influences on a wind turbine are:

— power limitation for the wind farm/turbine
— major frequency, voltage and load fluctuations
— interference voltages
— short circuit in the grid.

For DLC 2.3 two alternatives for the simulations exist. Only one alternative needs to be simulated:

For alternative 1 the grid loss may occur at any time during the course of the gust. The most unfavourable combinations shall be considered. At least the following three combinations of grid loss and gust (EOG) shall be examined for each wind speed considered:

— the grid loss occurs at the time of the lowest wind speed
— the grid loss occurs at the time of the highest gust acceleration
— the grid loss occurs at the maximum wind speed.

For alternative 2 at least 12 simulations with different seeds for each considered mean wind speed applying the NTM combined with grid loss shall be carried out. For each mean wind speed the extreme load is calculated as the mean of the 12 simulations plus three times the standard deviations of these 12 simulations.

DLC 2.4: The manufacturer shall specify the number and/or duration of fault or loss of electrical network conditions. As a minimum requirement for the determination of fatigue loading, at least 10 shut-downs per year due to first overspeed value n_4, 24 hours per year of operation with extreme yaw error (value equal to the maximum permissible oblique inflow) and 20 grid losses per year shall be considered.

DLC 2.5 considers low voltage ride through events combined with normal external conditions. The events shall be specified by voltage drop and duration. This includes also any special requirements of a grid operator, as e.g. fault ride-through capabilities, auto-reclosing cycles.

For DLC 2.1 to 2.5 an irregular sea state with the significant wave height $H_s(V)$ corresponding to the mean wind speed shall be assumed.

4.5.3 Start-up (DLC 3.1 to 3.3)

This design situation includes all the events resulting in loads on the wind turbine during the transitions from any standstill or idling situation to power production.

DLC 3.1: At least 1000 start-up procedures at V_{in}, 50 start-up procedures at V_r and 50 start-up procedures at maximum start-up wind speed shall be considered per year. If applicable, further start-up procedures shall be taken into account for site-specific requirements, such as shadow criteria or conditions for installation within a wind farm (curtailment strategy).

DLC 3.2: The start-up may occur at any time during the course of the EOG. At least the following four combinations of gust (EOG) and start-up shall be examined for each wind speed considered:

— the gust occurs at about 50% of the power according to the power curve at the considered wind speed
— the gust occurs at about 95% of the power according to the power curve at the considered wind speed
— two approximately equally spaced points in between the two above.

As an alternative, the extreme turbulence model ETM may be applied in 12 simulations for each mean wind speed considered.

DLC 3.3: The start-up may occur at any time during the course of the EDC. At least the same four combinations of direction changes (EDC) and start-up shall be examined as for DLC 3.2 for each wind speed considered.

For DLC 3.2 (applying EOG) and DLC 3.3 different evenly distributed rotor azimuth positions (with intervals be at most 30° for three-bladed turbines and 45° for two-bladed turbines) shall be simulated for each wind speed and distinct point of time. For each wind speed, the characteristic load value may be determined as the average of all these distinct rotor azimuth positions and distinct points of time.

For DLC 3.1 to 3.3, an irregular sea state or regular wave with the significant wave height $H_s(V)$ corresponding to the mean wind speed shall be assumed.

4.5.4 Normal shut-down (DLC 4.1 and 4.2)

This design situation includes all the events resulting in loads on the wind turbine during normal transitions from power production to stand-by condition (standstill or idling).

DLC 4.1: At least 1000 shut-down procedures at V_{in}, 50 shut-down procedures at V_r and 50 shut-down procedures at V_{out} shall be considered per year for fatigue load analysis. If applicable, further shut-down procedures shall be taken into account for site-specific requirements, such as shadow criteria or conditions for installation within a wind farm (curtailment strategy).

DLC 4.2: The shut-down may occur at any time during the course of the EOG gust. At least the following six combinations of shut-down and gust shall be examined:

— EOG starts 10 seconds before beginning of the shutdown
— EOG starts when about 50% of the power according to the power curve is reached
— four approximately equally spaced points in between the two above.

As an alternative, the extreme turbulence model ETM may be applied in 12 simulations for each mean wind speed considered.

For DLC 4.2 (applying EOG) different evenly distributed rotor azimuth positions (with intervals be at most 30° for three-bladed turbines and 45° for two-bladed turbines) shall be simulated for each wind speed and distinct point of time. For each wind speed, the characteristic load value may be determined as the average of all these distinct rotor azimuth positions and distinct points of time.

For DLC 4.1 and 4.2, an irregular sea state or regular wave with the significant wave height $H_S(V)$ corresponding to the mean wind speed shall be assumed.

4.5.5 Emergency shut-down (DLC 5.1)

This load case covers manual actuation of the emergency stop pushbutton. For this load case, the rotor shall be brought to a standstill.

For DLC 5.1, an irregular sea state or a regular wave with the significant wave height $H_S(V)$ corresponding to the mean wind speed shall be assumed.

4.5.6 Parked (DLC 6.1 to 6.5)

For this design situation, the rotor of a parked wind turbine in stand-by mode is at standstill or idling.

In the design load cases DLC 6.1, 6.2, 6.3 and 6.5, the extreme wind speed model (EWM) shall be applied. In DLC 6.4, the normal turbulence model (NTM) shall be used.

If the wind turbine has a yaw system where the yaw braking capacity will be exceeded during extreme wind situations (e.g. free or semi-free yawing), the turbulent extreme wind speed model shall be applied.

If the wind turbine is subject to large yaw movements, changes in the operating condition or stand-by condition may occur during the increase in the wind speed from normal operation to the extreme condition. This behaviour shall be considered in the calculation.

For the simulation of offshore wind turbines, design situations in DLC 6.1 to 6.3 and 6.5 shall be modelled using the turbulent extreme wind model in combination with a stochastic wave model and the response shall be computed by using a full dynamic simulation.

DLC 6.1: An average oblique inflow of ± 8° shall be assumed, if it is ensured that the average yaw misalignment does not lead to larger values and that slippage of the yaw system can be excluded (in this case, an additional yaw error need not be considered). If this cannot be excluded, a yaw error of up to ± 180° shall be applied.

DLC 6.2: A grid failure in an early stage of the storm with the extreme wind situation shall be assumed. A yaw error of up to ± 180° shall be assumed if no independent power supply is available. The independent power supply shall ensure at least 7 days of operation of the control and safety system and 6 hours of operation of the yaw system.

DLC 6.3: The extreme wind speed with a recurrence period of one year shall be assumed together with an extreme oblique inflow or average extreme oblique inflow. An average oblique inflow of up to ± 20° shall be assumed. An additional yaw error needs not to be considered.

In DLC 6.4, the expected number of hours of non-power production time at a fluctuating load appropriate for each wind speed where significant fatigue damage may occur at any component shall be considered. Yaw system misalignment and the hysteresis shall be considered for yaw movement. If values for the turbine type cannot be specified, an average yaw misalignment of ± 8° shall be applied.

DLC 6.5: This design load case includes weather conditions with ice formation on the offshore wind turbine structure. The ice formation shall be modelled according to [2.5.4]. Yaw system misalignment and the hysteresis shall be considered for yaw movement. If values for the turbine type cannot be specified, an average yaw misalignment of ± 8° shall be applied.

For DLC 6.1 and 6.2, the turbulent wind model shall be taken together with irregular sea state conditions. In this case, the 50-year recurrence value of the significant wave height and the 50-year recurrence value of the mean wind speed or a set of combined values with joint recurrence period of 50-years shall be taken. The averaging values of the significant wave height and the mean wind shall be adjusted to the simulation time length.

For DLC 6.3, the turbulent wind model shall be taken together with irregular sea state conditions. In this case, the 1-year recurrence value of the significant wave height and the 1year recurrence value of mean wind speed shall be taken. The averaging values of the significant wave height and the mean wind shall be adjusted to the simulation time length.

In DLC 6.1, 6.2 and 6.3, a misalignment of up to ± 30° shall be considered for the mean wind direction associated with the turbulent wind model relative to the mean wave direction. In the case that a steady wind model is used, an additional 7° of misalignment of the short-term wind direction shall be considered relative to the wave direction.

In DLC 6.1, 6.2 and 6.3, the occurrence of the extreme design wave as defined in [2.4.4.4] shall be taken into account. The extreme wave kinematics of non-linearity, wave breaking and possible slap and slam loads shall be taken into account; see DNV-RP-C205.

For DLC 6.4 and 6.5, irregular sea state conditions shall be assumed. The significant wave height, peak spectral period and direction for each sea state shall be selected, together with the associated mean wind speed, based on the long-term joint probability distribution of metocean parameters appropriate for the anticipated site. The designer shall ensure that for DLC 6.4 the number and resolution of the normal sea states considered are sufficient to account for the fatigue damage associated with the full long-term distribution of metocean parameters.

4.5.7 Parked plus fault conditions (DLC 7.1 and 7.2)

This design situation considers the non-stand-by state (standstill or idling) resulting from the occurrence of a fault. Deviations from the normal behaviour of a parked wind turbine, whether resulting from faults in the electrical network or within the wind turbine, shall require analysis. If any fault other than a grid failure produces deviations from the normal behaviour of the wind turbine in parked situations, the possible consequences shall be considered. Grid failures in this case shall be regarded as fault conditions and therefore need not be considered together with any other fault of the wind turbine.

In design load case DLC 7.1, the extreme wind speed model (EWM) shall be applied. In DLC 7.2, the normal turbulence model (NTM) shall be used.

For DLC 7.1, the fault condition shall be combined with the extreme wind speed model (EWM) and a recurrence period of one year. In this load case, transient oblique inflow of up to ± 15° for the steady extreme wind speed model shall be assumed and ± 8° for the turbulent extreme wind speed model. An additional yaw error needs not to be considered here, unless a failure of the yaw system itself is being investigated. In such a case, a yaw error of up to ± 180° shall be applied. If slippage of the yaw system cannot be excluded, a yaw error of up to ± 180° shall be applied.

If a grid failure with duration up to 1 week (see [2.5.10]) may occur and no backup energy system or redundant electricity supply is provided, the behaviour of the mechanical brake, the safety system and yaw system shall be considered adequately in the load assumptions. At minimum, faults in the following shall be considered: yaw system, pitch system and brake system.

In the case of a braking system failure (erroneous activation or non-activation), the most unfavourable braking torque (min. or max.) shall be considered.

For DLC 7.1, the irregular sea state with 1-year recurrence value of the significant wave height and the 1-year recurrence value of mean wind speed shall be taken. The averaging values of the significant wave height and the mean wind shall be adjusted to the simulation time length.

In DLC 7.1, a misalignment of up to ± 30° shall be considered for the mean wind direction associated with the turbulent wind model relative to the mean wave direction.

In DLC 7.2, the expected number of hours of non-power-production time due to faults of the electrical network or in the offshore wind turbine shall be considered for each wind speed where significant fatigue damage may occur in any component. The duration of non-power-production time due to faults shall be determined as part of assessment of the site for the offshore wind turbine.

Guidance note:
An availability of max 90% should be considered in addition to the optimum case of 100% availability. Special care should be given to large yaw errors and accompanying vibrations of the turbine. The whole range of wind speeds should be considered. A failure of the pitch system need not be accounted for. It should be assumed that the yaw system is not active.

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For DLC 7.1 and 7.2, irregular sea state conditions shall be assumed. The significant wave height, peak spectral period and direction for each sea state shall be selected, together with the associated mean wind speed, based on the long-term joint probability distribution of metocean parameters appropriate to the anticipated site. The designer shall ensure for DLC 7.2 that number and resolution of the normal sea states considered are sufficient to account for the fatigue damage associated with the full long-term distribution of metocean parameters.

4.5.8 Transport, installation, maintenance and repair (DLC 8.1 to 8.5)

DLC 8.1: The manufacturer shall state all wind and marine conditions and design situations relevant for transport, installation, maintenance and repair of the wind turbine, and especially up to which maximum average wind speed (10-min mean), for which significant wave height and for which oblique inflow the turbine may be erected and maintained. The maximum wind speed V_T and the significant wave height H_{sT} specified by the manufacturer apply for active work on the wind turbine. If the wind and marine conditions exceed the specified limiting values, the work shall be halted. For the load assumptions and determination of the safety factors in respect of lifting operations, it is recommended that standards for lifting appliances including safety factors/influence factors are additionally applied when relevant. Unless permanently installed, the lifting appliance itself is not covered by this standard and should be designed and tested according to relevant standards for lifting appliances.

During the setup of the conditions for maintenance, particular consideration shall be given to the effect of the various locking devices (e.g. blade pitching, rotor and yaw drive) and the maintenance position which may have been adopted. Even with the rotor locked, the blade pitching system shall be able to move through its entire control range. Verification of standstill without the rotor lock activated shall be provided up to an oblique inflow of ± 10°.

For the verification of the mechanical brake (situation after actuation of the emergency stop pushbutton), a transient oblique inflow of up to ± 30° shall be assumed for this load case. The rotor positions which lead to the most unfavourable conditions for the wind turbine shall be considered. The intervals between the rotor positions shall be at most 30 ° for three bladed wind turbines and 45 ° for two bladed wind turbines. The most unfavourable braking torque (min or max) shall be applied.

DLC 8.2: All situations for transport, installation, maintenance and repair turbine states which may persist for longer than one week shall be considered. This shall, when relevant, include a partially completed tower, the tower standing without the nacelle and the turbine without one or more blades. It shall be assumed that the electrical network is not connected in any of these states. Measures may be taken to reduce the loads during any of these states as long as these measures do not require the electrical network connection. The case that the turbine shall be left behind in locked condition (for yaw/rotor/pitch systems) is taken into account in case the control and protection system and the respective manuals allow this. In this load case, transient oblique inflow of up to ± 15° for the steady extreme wind speed model, or an average oblique inflow of ± 8° for the turbulent extreme wind speed model, shall be assumed, if it is ensured that the yaw system is ready for operation during the entire period and that no slippage can be assured. In this case, an additional yaw error need not be considered. If a slippage cannot be excluded or an operational yaw system is not available (locked or not powered), a yaw error of up to ± 180° shall be applied.

Non-redundant blocking devices, based on loads from DLC 8.1 shall be designed considering a safety factor for the consequence of failure of at least γ_N = 1.2, see also DNVGL-ST-0361, [7.5.4]. Note that the consequence of failure factor shall not be treated as a safety factor for materials.

DLC 8.3: Transverse oscillations due to vortex shedding shall be investigated in the verifications for the support structure. Vortex shedding due to current and wave loading shall be considered, too. Possible vortex shedding conditions due to wind, current and waves may be assumed as non-correlated and may be analysed as separated events. See also DNVGL-ST-0126, [3.6].

DLC 8.4: Long periods with a not fully erected or assembled offshore wind turbine, or without grid connection, shall be considered in the fatigue and ultimate load analysis. The period to be considered shall be defined with due care but shall not be less than 3 months during the turbine lifetime.

DLC 8.5: An operational boat impact may arise during operation of vessels in the vicinity. An impact with the dedicated maintenance boat shall be considered. The size of the maintenance vessel (displacement) shall be stated by the manufacturer and/or operator of the offshore wind farm project, see [4.2.10] (normal case).

DLC 8.6: In addition to the operational boat impact from DLC 8.5, an accidental boat impact shall be considered for the case of the drifting maintenance boat, see [4.2.10] (abnormal case).

The environmental conditions to be applied in conjunction with the operational boat impact shall correspond to the most severe conditions under which the maintenance boat is allowed to approach the turbine. For the analysis, it may be assumed that the turbine may be stopped or brought to maintenance condition by remote control.

The maximum permissible significant wave height for vessel operations near the offshore wind turbine installation shall be stated in the operation manual. Any areas where vessels are not permitted to operate in close proximity should be specified in the operation manual.

Guidance note:
Accidental collision with drifting ships after an average (accident) may be omitted. In case it is desired to consider such events a risk assessment according to section [2.5.8] may be performed.

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Functional loads occurring during installation and maintenance of the offshore wind turbine shall be considered. These may be:

— weight of tools and mobile equipment
— loads from operation of cranes and other conveyance equipment
— loads from transport operations, e.g. helicopter
— mooring/fendering loads from vessels serving the offshore wind turbine.

Loads and the weight of tools and equipment shall be specified by the owner/designer. The specifications shall also contain indications regarding permissible load combinations and limitations. Any such limitations shall be stated in the operating manual. The operating manual shall cover all relevant procedures and limiting conditions.

The limiting operating conditions, i.e. environmental conditions tolerable during specified operations, will generally be defined by the operator or designer. The regulations of the competent authorities/ administrations shall be observed, particularly regarding collisions and helicopter operations.

The environmental conditions, together with the turbine operating status and largest helicopter type expected, shall be stated by the manufacturer. The safety aspects of helicopter operations regarding structural safety of landing platforms, clearance, fire protection, marking etc. shall be treated according to the relevant national and international regulations and codes.

The helicopter load shall be combined with the loads from wind and wave conditions in accordance with the maximum helicopter operation conditions allowed.

4.5.9 General influences

The following general influences shall be considered in the load calculations:

— wind field perturbations due to the wind turbine itself (wake-induced velocities, tower shadow, tower upwind effect etc.)
— the influence of three-dimensional flow on the blade aerodynamic characteristics (e.g. three-dimensional stall and aerodynamic tip loss)
— dynamic stall effects of the airflow for the profiles used
— unsteady aerodynamic effects
— aeroelastic effects
— aerodynamic asymmetries, which may arise through production or assembly tolerances of the rotor blades. A verified tolerance shall be observed. If this is not (or not yet) known, a deviation of the blade angle of attack of 0,3° (i.e. for a three-bladed rotor: blade 1 at 0°, blade 2 at −0,3°, blade 3 at +0,3°) shall be assumed.
— structural dynamics and the coupling of vibrational modes: The elasticity of the blades, elasticity of drive train and generator (drive train dynamics) as well as the tower bending shall be considered. The elastic mounting of machinery, vibration dampers, the torsional stiffness of the tower and the influence of the foundation shall also be included, if their influence cannot be neglected.
— eccentricity: For at least the blades, the hub and all relevant components of the drive train, the actual mass eccentricity according to the manufacturer’s specifications shall be taken into account.

— dynamic response when parked (standstill or idling) and application of the EWM with steady wind model by a gust reaction factor to the tower loads.

4.5.10 Operational influences

The following operational influences shall be considered in the load calculations:

— static and load-dependent bearing friction moments (especially blade pitch bearing, yaw bearing)
— the behaviour of the control and safety systems of the wind turbine in the load case definitions and during all load simulations performed
— in case the control system provides active features for load reduction, it shall be ensured that they are in operation over the whole lifetime of the wind turbine. Possible malfunctions of these features shall be detected and consequences considered. The influence of the malfunctions of the control system features, including corrective actions, shall be considered in load analysis as load case DLC 2.1. In case any errors are detected with delay, this delay shall also be considered in the extreme and fatigue load analysis.

4.6 Design load cases for extended design situations

In addition to Table 4-3, the extended design load cases listed in Table 4-4 shall be considered where applicable.

Table 4-4 Extended design load cases

Design Situation	DLC	Wind Condition	Marine Condition				Other Conditions:	Type of Analysis		Partial safety factor
			Waves	Wind and wave directionality	Sea Currents	Water Level		Onshore	Offshore	
Drifting sea ice (power production)	9.1	NTM $V_{in} < V_{hub} < V_{out}$	No waves	n/a	NCM	NWLR	Ice load in horizontal direction from moving ice at relevant velocities. $h = h_{50}$ or largest value of moving ice Dynamic effects from ice loading – frequency lock-in effects	-	U	N
	9.2	NTM $V_{in} < V_{hub} < V_{out}$	No waves	n/a	NCM	NWLR	Ice load in horizontal direction from moving ice at relevant velocities *Use values of h corresponding to expected history of moving ice occurring* Dynamic effects from ice loading – frequency lock-in effects	-	F/U	F/N
Drifting sea ice (parked, standing still or idling)	9.3	Turbulent - EWM $V_{hub} = V_1$	No waves	n/a	NCM	NWLR	Pressure from hummocked ice and ice ridges	-	U	N
	9.4	NTM $V_{hub} < 0.7\, V_{50}$	No waves	n/a	NCM	NWLR	Horizontal load from moving ice at relevant velocities *Use values of h corresponding to expected history of moving ice occurring*) Dynamic effects from ice loading – frequency lock-in effects	-	F/U	F/N
	9.5	Turbulent - EWM $V_{hub} = V_1$	No waves	n/a	NCM	NWLR	Horizontal load from moving ice at relevant velocities. $h = h_{50}$ or largest value of moving ice Dynamic effects from ice loading – frequency lock-in effects	-	U	N
Temperature effects (power production)	10.1	NWP $V_{in} \le V_{hub} \le V_{out}$	$H=H_s(V)$	COD, UNI	NCM	MSL	Temperature effects	F/U	F/U	F/N

Table 4-4 Extended design load cases (Continued)

Design Situation	DLC	Wind Condition	Marine Condition: Waves	Marine Condition: Wind and wave directionality	Marine Condition: Sea Currents	Marine Condition: Water Level	Other Conditions:	Type of Analysis: Onshore	Type of Analysis: Offshore	Partial safety factor
Temperature effects (parked, standing still or idling)	10.2	NWP $V_{hub} = V_1$	$H=H_s(V)$	COD, UNI	NCM	MSL	Temperature effects	U	U	N
Earthquake (power production)	11.1	NTM $V_{in} \leq V_{hub} \leq V_{out}$	$H=H_s(V)$	COD, UNI	NCM	NWLR	Earthquake	U	U	See [4.3.4]
Earthquake plus grid loss (power production)	11.2	NWP $V_{in} \leq V_{hub} \leq V_{out}$	$H=H_s(V)$	COD, UNI	NCM	NWLR	Earthquake plus grid loss	U	U	See [4.3.4]
Earthquake plus grid loss (parked, standing still or idling)	11.3	NWP $V_{hub} = V_1$	$H=H_s(V)$	COD, UNI	NCM	NWLR	Earthquake plus grid loss	U	U	See [4.3.4]
Wind farm influence (power production)	12.1	NTM $V_{in} \leq V_{hub} \leq V_{out}$	$H=H_s(V)$	COD, UNI	NCM	NWLR	Wind farm influence	F/U	F/U	F/N

4.6.1 Drifting sea ice (DLC 9.1 to 9.5)

DLC 9.1: 50-year sea ice conditions shall be investigated during power production according to [2.4.10] and [4.2.8].

DLC 9.2: It shall be analysed that the dynamic interaction between the structure and the moving sea ice cover leads to a lock-in situation during power production. The conditions according to [2.4.10] and [4.2.8] shall be investigated.

DLC 9.3: 50-year sea ice conditions shall be investigated during standstill/idling according to [2.4.10] and [4.2.8].

DLC 9.4: it shall be analysed that the dynamic interaction between the structure and the moving sea ice cover leads to a lock-in situation during standstill/idling. The conditions according to [2.4.10] and [4.2.8] shall be investigated. For details refer to ISO 19906.

DLC 9.5: Static loads from ice ridges, rubble fields, large rafted ice features etc. within the ice cover shall be considered. For details refer to ISO 19906.

4.6.2 Temperature effect (DLC 10.1 and 10.2)

DLC 10.1 and DLC 10.2: In the case of extreme temperatures and temperature influences for site-specific designs, refer to DNVGL-RP-0363. The certification of wind turbines to be erected at sites with a temperature higher than + 50°C shall be performed according to an approved design basis.

4.6.3 Earthquakes (DLC 11.1 to 11.3)

DLC 11.1 assumes the occurrence of an earthquake during normal operation.

DLC 11.2 comprises a superposition of the earthquake and a shut-down procedure possibly triggered by the earthquake. A grid failure as well as the activation of the safety system by a vibration sensor triggered by the earthquake shall be considered.

DLC 11.3 considers a superposition of the earthquake and a previously occurred grid loss.

See also [4.2.9] of this standard and IEC 61400-1, 11.6 and the corresponding Annex.

4.6.4 Wind farm influence (DLC 12.1)

DLC 12.1: Influences of a wind farm configuration on the loads due to wind field perturbations in the wake shall be considered. This shall be considered for both a simple shadow effect and for superimposed wake interaction. For large wind farms, an increase in the environmental turbulence or terrain roughness shall be taken into account.

The mutual influence of wind turbines through the wake interaction behind the rotor shall be considered in a wind farm configuration up to a distance of 10 D (D = rotor diameter).

Calculation models (e.g. S. Frandsen or "Dynamic Loads in Wind Farms II" (DLWF II)) may be applied under consideration of their limits of applicability. One model is given in App.H. The models shall be validated.

For the installation of the turbines within a wind farm, the influence on the extreme and fatigue loads shall be determined.

See also IEC 61400-1 Section 11.4 and the corresponding Annex, as well as [4.8.2] of this standard.

4.7 Evaluation of loads

4.7.1 General

The evaluation of the loads shall be performed according to IEC 61400-1 and IEC 61400-3. The procedure is summarized here.

4.7.2 Evaluation of load cases applying deterministic gusts

For load cases with specified deterministic gusts, the characteristic value of the loads shall be the worst case computed transient values. If more simulations are performed at a given wind speed, representing the rotor azimuth, the characteristic value for the load case is taken as the average value of the worst case computed transient values at each azimuth.

4.7.3 Evaluation of load cases applying turbulent wind

For load cases with turbulent wind fields the total period of load data shall be long enough to ensure statistical reliability of the estimate of the characteristic loads. At least six 10 min stochastic realizations with different turbulent seeds shall be required for each mean hub-height wind speed used in the simulations. However, for DLC 2.1, 2.2 and 5.1 at least 12 simulations shall be carried out for each event at the given wind speed.

When turbulent inflow is applied, the mean value among the worst case computed loads for different 10 min stochastic realisations shall be taken, except for DLC 2.1, 2.2 and 5.1, where the characteristic value of the load shall be the mean value of the largest half of the maximum loads.

The same method shall be used for determining characteristic values of other properties such as deflections and accelerations.

4.7.4 Evaluation of DLC 1.1 and DLC1.3

For DLC 1.1, the characteristic values of the loads shall be determined by a statistical analysis of the extreme loading that occurs for normal design situations and shall correspond to one of the following alternatives:

a) The characteristic values are obtained as the largest (or smallest) among the average values of the 10-min extremes determined for each wind speed in the given range, multiplied by 1.35. This method may only be applied for the calculation of the blade root in-plane bending moment, the blade root out-of-plane bending moment and the tip deflection.
b) The characteristic values are obtained as the largest (or smallest) among the 99th percentile (or 1st percentile in the case of minima) values of the 10-min extremes determined for each wind speed in the given range, multiplied by 1.2.
c) The characteristic values are obtained as the value corresponding to a 50-year return period, based on load extrapolation methods, considering the applied wind speed distribution and the normal turbulence model (NTM).

The design load shall then be obtained by multiplying the characteristic loads according to any of these alternatives by the partial safety factor for DLC1.1 defined in Table 4-2.

For all three alternatives above, data used in the statistical analysis shall be extracted from time series of turbine simulations of at least 10 min in length over the operating range of the turbine for DLC 1.1. A minimum of 15 simulations is required for each wind speed from $V_{r-2m/s}$ to V_{out} and six simulations are required for each wind speed below $V_{r-2\,m/s}$. When extracting data, the designer shall consider the effect of independence between peaks on the statistical analysis and minimize dependence when possible. For guidance on dependency checks, see the respective Annex of IEC 61400-1.

The statistical analysis of the simulation data of DLC 1.1 shall include at least the calculation of the blade root in-plane bending moment, the blade root out-of-plane bending moment and the tip deflection. If the extreme design values of the blade root moments derived from the DLC 1.1 analysis are exceeded by the extreme design values derived from the DLC 1.3 analysis, the continuation of the analysis of DLC 1.1 may be omitted.

If the extreme design values of the blade root moments derived from the DLC 1.1 analysis are not exceeded by the extreme design values derived from the DLC 1.3 analysis, the turbulence intensity in the extreme turbulence model used in DLC 1.3 may be increased until the extreme design values of the blade root moments computed in DLC 1.3 are equal to or exceed the relevant extremes. This turbulence intensity of the ETM is increased by increasing the factor "*c*" in the equation for the ETM according to IEC 61400-1 for onshore applications, respectively increasing the factor "*b*" in the equation for the ETM according to [2.3.3] of this standard for offshore applications. The characteristic values of the loads relevant for other turbine components may be determined from this analysis based on DLC 1.3 with the increased *c* or *b* value. As an alternative to this analysis, the appropriate characteristic values of all load components relevant for each specific turbine component may be directly extrapolated from the simulation.

Guidance about load extrapolation is given in App.B of this standard and in the respective Annex of IEC 61400-1.

4.8 Site specific evaluation

4.8.1 Site specific evaluation through comparison of site wind conditions and design class conditions

Under certain conditions, the design of a wind turbine may be evaluated for a specific site through comparison of the site wind conditions and the design class conditions. The conditions listed below refer to onshore sites, in case that the method shall be used for an offshore site, additional considerations are required.

A wind turbine design may be evaluated for a specific onshore site, if the following wind conditions at the site are more favourable than the design class conditions used for the load assumptions of the wind turbine's design:

(a) The 50-year recurrence wind speed $V_{ref,site}$ is less or equal $V_{ref,design}$.
(b) The annual average wind speed $V_{ave,site}$ is less or equal $V_{ave,design}$.
(c) Between the wind speeds min($V_{ave,site}$, V_{rated}) and P(95)site, the probability density function of the wind speed at hub height is equal to or smaller than the probability density function of the design class conditions.
(d) Between the wind speeds 0,6 V_{rated} and V_{out} the characteristic turbulence intensity occurring at the site, estimated as the 90% quantile is equal to or lower than the one considered in the design class conditions. The effective turbulence intensity shall be considered where relevant.
(e) The normal and the extreme wind shear is equal or lower for all wind directions than those considered in the design class conditions.
(f) The average air density at the site should be lower than the design air density. If this is not fulfilled, a correction as outlined in the guidance note below may be performed.
(g) In case of complex terrain all three components of the turbulence intensity, longitudinal, horizontal and vertical are equal to or lower than the ones assumed for the certification.
(h) The site specific extreme turbulence wind speed standard deviation does not exceed the extreme turbulence model (ETM) used in the design. Appropriate methods shall be used for the determination of the site specific extreme turbulence wind speed standard deviation and be documented.

Guidance note 1:

$P(95)_{,site}$ represents the 95% quantile of the wind speed distribution at hub height at the site. In case of a Rayleigh distribution and a V_{ref}/V_{ave} ratio of 5, as defined in the wind turbine classes I,II and III, the range between V_{ave} and $P(95)$ coincides the interval from 0,2 V_{ref} to 0,4·V_{ref}.

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Guidance note 2:

For comparisons of site specific wind speeds to design wind speeds, average air density corrections may be performed according to the following formula:

$$V_{\text{site,corrected}}^2 = \frac{\rho_{\text{site}}}{\rho_{\text{design}}} V_{\text{site}}^2 \tag{4.15}$$

Where $V_{site,corrected}$ is the average air density corrected wind speed and ρ_{design} and ρ_{site} are the design and site average air density respectively.

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For the site versus certification comparison through wind data alternatively the methods described in IEC 614001, 11.9 may be applied.

4.8.2 Site specific evaluation through load calculations

Alternative to the method described in [4.8.1] or in cases where a site specific evaluation through wind data is not applicable, the design of a wind turbine may be evaluated for a specific site by comparison of the site specific loads with the design loads.

The wind turbine design may be confirmed, if the site specific loads are below the class loads, which form the basis for the wind turbine design. In case site specific loads are larger than the design loads, the affected components and systems shall be verified for the site specific loads. Furthermore a geotechnical investigation is required in order to confirm if the foundation design is suitable for the site, see DNVGL-ST-0126.

Site specific loads shall be calculated for the most severely affected wind turbine position(s). At least the following load sensors shall be considered,

— tower sectional loads for at least the tower base and tower top
— blade sectional loads for blade root and two further sections, one at or close to the maximum chord length and one further along the blade
— hub loads, rotating and non-rotating.

If wind conditions listed in [3.3] affecting the fatigue loading are more severe than documented in the type certification, a site specific fatigue load analysis shall be performed.

The fatigue load analysis shall comprise damage equivalent fatigue loads for all relevant S/N values considering the site conditions and the load case definitions of the design loads assumptions. If the site specific load case definitions deviate from the load case definitions of the design load assumptions the deviations shall be documented and explained. The fatigue load analysis shall take the turbulence intensity magnification due to wake effects into account and if measurements or reliable estimations are available, the site specific three components of the turbulence intensity. If only the longitudinal turbulence component is available, then for the lateral and vertical components the relation according to the standard values from IEC 61400-1 shall be used.

For non-direct drive wind turbines, the load duration distribution of the driving toque shall be analysed with site specific input data and compared with the load duration distribution of the wind turbine design. Furthermore for pitch controlled wind turbines with electrical pitch drives the load duration distribution of the torque at the pinions of the pitch drives shall be analysed with site input data and compared with the load duration distribution of the wind turbine design.

If the wind conditions listed in [3.3] affecting the extreme loading are more severe than those documented in the type certification, a site specific extreme analysis shall be performed.

The extreme load analysis shall comprise extreme load cases considering site conditions and the load case definitions of the design load assumptions. As a minimum, the following ultimate design load cases shall be assessed: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. Table 4-4 of Sec. 4 provides definitions of ultimate and fatigue load cases for site specific conditions. The type class design load cases DLC 2.x, DLC 3.x, DLC 4.x, DLC 5.x, and DLC 8.x of Table 4-3 shall be considered when site-specific support structures or other design modifications versus the type certificate have been made or when the control system behaviour and transport, installation, maintenance and repair procedures are site-dependent. If the site specific load case definitions deviate from the load case definitions of the design load assumptions the deviations shall be documented and explained. The normal turbulence model for extreme loads in wind farms may be set to the characteristic ambient turbulence intensity at the site. In large wind farms, the wake corrected characteristic turbulence intensity shall be considered where relevant. If measurements or reliable estimations are available, the site specific three components of the turbulence intensity shall be used.

If measurements or calculations of greater accuracy are not available for complex terrain and terrain of intermediate complexity, the lateral component of the turbulence intensity for the load calculations shall be set to 1 times the longitudinal component and the vertical component shall be set to 0.7 times the longitudinal component.

For wind turbines with distances lower than $3D$, special care regarding partial wake effects shall be taken.

Changes in the safety and control system compared to the type certified system effecting fatigue and extreme loading shall be documented and appropriately considered in the site specific load calculation.

If site specific changes to turbine components are considered, all design relevant load cases shall be taken into account with site specific input data and documented. The extent and realisation of the site specific changes to the turbine design shall be documented.

The critical blade deflection, maximum rotor speed and maximum tower top acceleration analyses shall be re-evaluated based on the site specific load time series if the load cases to be calculated are design driving load cases for the subsequent analysis or if site specific changes of the wind turbine design or of the dynamic behaviour have been made.

SECTION 5 MEASUREMENTS

5.1 General

The complete list of measurements needed for a new turbine type within the scope of a prototype testing are listed in DNVGL–SE-0441, measurements within the scope of a project certification are listed in DNVGL–SE-0190.

This standard gives guidance and requirements for the certification of loads for onshore- and offshore wind turbines. Sec.1 to Sec.4 guide through the theoretical part of load evaluation. This section deals with the verification of theoretical loads respectively of the simulation model via measurements. Relevant measurements for verifying loads are power curve measurements, load measurements and the test of turbine behaviour.

The test of turbine behaviour is covered in DNVGL-ST-0438. Power curve and load measurements are dealt with in the present standard.

All measurements should be carried out and documented by a testing laboratory accredited for these measurements. Alternatively, the load measurements may be carried out by the manufacturer after compliance of the manufacturers testing laboratory with the applicable parts of ISO/IEC 17025 has been confirmed through an audit performed by a testing laboratory accredited for these measurements or by the accredited certification body verifying the measurements. In all cases where an accredited laboratory is involved, this laboratory shall be responsible for compliance with the fundamental standards and with the requirements of this standard.

Based on an approved test plan, the scope of the prototype test may be reduced for turbine variants or modified turbines after agreement with DNV GL, provided that the prototype test was performed in its entirety for a predecessor turbine. The test plan specifying measurement points, the planned scope of the measurements, and their assessment shall be agreed with DNV GL before installation of the measurement equipment commences. The influence of a turbine variant on the measurement result shall be documented by the manufacturer. When introducing a new rotor blade design, rotor diameter, increase of rated power output by more than 5%, or a new rated rotational rotor speed, new measurements shall be carried out.

The testing laboratory performing the measurements shall record the identifications and data on the nameplates of the surveyed plant and on the nameplates of the primary components (at least the rotor blades, gearbox, generator and tower) and shall include them in the measurement report.

On completion of the measurements the following activities shall be performed by the laboratory doing the tests.

— evaluation and documentation of the measurements
— plausibility check of the measurement results.

A load validation by comparison of the measured results with corresponding load simulations using the aero-elastic model from design calculations shall be performed by the manufacturer/designer.

The respective documents shall be submitted for assessment.

5.2 Requirements for the wind turbine to be tested

The prototype tests performed at a prototype test turbine onshore may be regarded as being sufficient for the offshore turbine with respect to the requirements for prototype testing. The compliance of the design of the test turbine with the design on which the offshore certification is based shall be shown.

If a prototype turbine onshore is used for the prototype tests, then it is advisable to select a site close to the sea coast to achieve the highest possible similarity with marine atmospheric and wind conditions e.g. low turbulence.

The onshore wind turbines at which the measurements are carried out should conform to the design or variety of designs on which the offshore certification is based. Compliance shall be confirmed in a declaration by the manufacturer. Any deviations in design shall be reported before the measurements take place. This shall be described in a separate document, discussing, reasoning and listing all deviations. This document shall be submitted by the manufacturer. If the compliance is adequate for the corresponding test purpose, the measurement may be used for the certification.

5.3 Power curve measurements

The measurement of the power performance of the wind turbine shall be carried out in accordance with IEC 61400-12-1.

Deviations from this standard shall be justified and agreed with DNV GL. Furthermore, the deviations shall be listed in detail within a separate chapter in the test report.

Any deviations in the design of the test turbine from the design within the process of type certification shall be reported before the measurement takes place. Deviations from the design shall be justified and agreed with DNV GL. This shall be described in a separate document, discussing, reasoning and listing all deviations. This document shall be submitted by the manufacturer. If an already certified test report shall be used for the type certification of a variant, this test report shall be listed in the document, too.

On completion of the measurements, the measured power curve shall be compared with the power curve assumed in the design documentation. Here special attention shall be paid to sufficient correspondence with the assumed values for rated wind speed and rated power.

The measurement report of the accredited testing laboratory, as well as all relevant data logs and the comparison with the power curve assumed in the design documentation shall be submitted for assessment.

5.4 Load measurements

Load measurements shall be carried out in accordance with latest version of IEC 61400-13.

Deviations from this standard shall be justified and agreed with DNV GL. Furthermore, the deviations shall be listed in detail within a separate chapter in the test report.

The measurement report of the accredited test institute shall be submitted for assessment.

Any deviations in the design of the test turbine from the design within the process of type certification shall be reported before the measurement takes place. Deviations from the design shall be justified and agreed with DNV GL. This shall be described in a separate document, discussing, reasoning and listing all deviations. This document shall be submitted by the manufacturer. If an already certified test report shall be used for the type certification of a variant, this test report shall be listed in the document, too.

5.4.1 Measurement of mechanical loads according IEC 61400-13

Before the measurements are conducted, the measurement parameter plan and the extent of the measurements shall be documented in a measurement specification, which should be approved by the certifying body prior to commencement of the measurements.

In IEC 61400-13 emphasises has been out on on describing the minimum required measurement load cases (MLC) needed for proper model validation in order to validate the loads presented in the Statement of Compliance for the A-level design. Where applicable the MLCs shall be defined in relation to the DLCs, described in IEC 61400-1.

As IEC 61400-13 contains a minimum requirement, deviations are generally not accepted.

Guidance note:
Loads solely measured according to IEC 61400-13 are not suitable for designing the turbine, as they do not reflect complete requirements according to IEC 61400-1.

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5.4.2 Verification of design loads via model verification by comparing simulation and measurement results

After completion of the measurements, a load calculation shall be carried out. For the load calculation, the same simulation model used for achieving the load assumption certified with the statement of compliance for the A-level design shall be applied. If necessary the model shall be adopted to site conditions (e.g. tower design). With this model, measured load cases shall be simulated, taking into account the wind conditions

– and if applicable wave conditions – as documented in the measurements. In the simulation, both fatigue and ultimate loads shall be investigated.

In order to have comparable wind conditions, the measured wind data sets shall be analysed with respect to mean value, standard deviation, trends (wind speed and direction) and wind direction changes. These shall be applied in the simulation accordingly.

Fatigue load analysis:

Only power production (MLC/DLC 1.1) load cases shall be considered. The MLC/DLC 1.1 shall be investigated by applying two different turbulence intensities, as measured with the capture matrix defined in IEC TS 61400-13 respectively IEC 61400-13. As the result two-dimensional load spectra and scatter plots shall be evaluated at the cross-sections, as measured in compliance with IEC TS 61400-13 respectively IEC 61400-13.

Ultimate load analysis shall consider:

— at least two turbulence bands of MLC/DLC 1.1 considering two different turbulence intensities according to the capture matrix
— idling/parked at wind speed above rated wind speed (MLC1.2/DLC6.4)
— transient loads as defined in IEC TS 61400-13 respectively IEC 61400-13.

The statistics of the measured and calculated loads shall be compared. The time series of measurements and simulations, considering loads as well as all parameters defining the turbine status and operational mode, shall be compared.

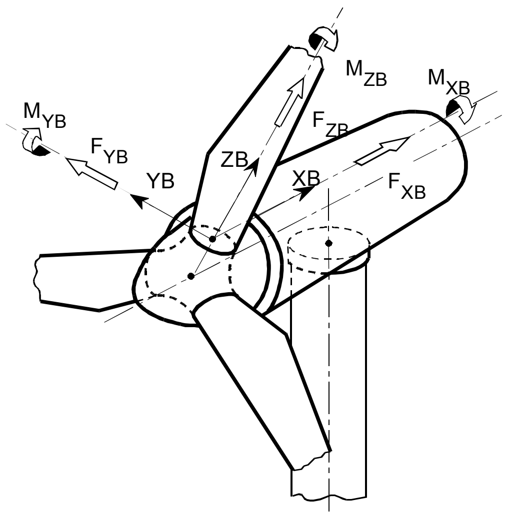
The results of the comparison shall be discussed and justified. The measurements shall show that, under consideration of technical tolerances, the assumptions made for the design were conservative. In case of significant deviations, corrective measures shall be taken (i.e. new analysis and/or redesign of affected structure).

APPENDIX A COORDINATE SYSTEMS

In general, the coordinate systems may be chosen freely. By way of recommendation, possible coordinate systems, together with their origin and orientation, are shown in the following diagrams. As a simplification, the representations of the rotor axis tilt angle and the cone angle were omitted.

A.1 Blade coordinate system

The blade coordinate system has its origin at the blade root and rotates with the rotor. Its orientation to the rotor hub is fixed.



XB   in direction of the rotor axis

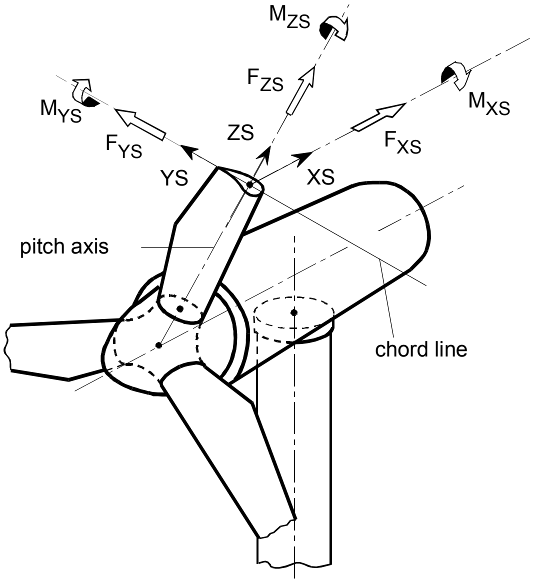
ZB   radially

YB   so that XB, YB, ZB rotate clockwise

Figure A-1 Blade coordinate system

A.2 Chord coordinate system

The chord coordinate system has its origin at the intersection of the corresponding chord line and the blade pitch axis. It rotates with the rotor and the local pitch angle adjustment.

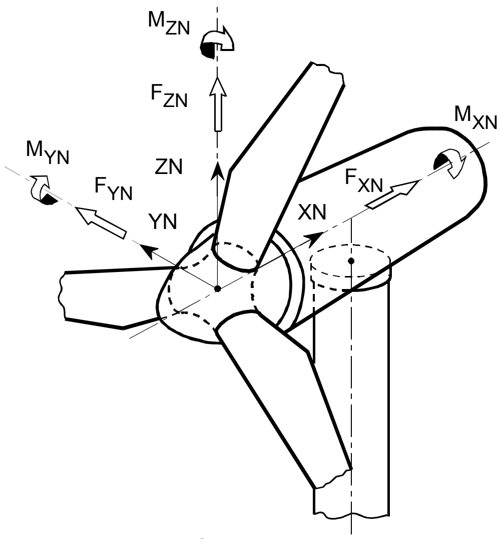


YS in direction of the chord, orientated to blade trailing edge
ZS in direction of the blade pitch axis
XS perpendicular to the chord, so that XS, YS, ZS rotate clockwise

Figure A-2 Chord coordinate system

A.3 Hub coordinate system

The hub coordinate system has its origin at the rotor centre (or any other position on the rotor axis, e.g. hub flange or main bearing) and does not rotate with the rotor.

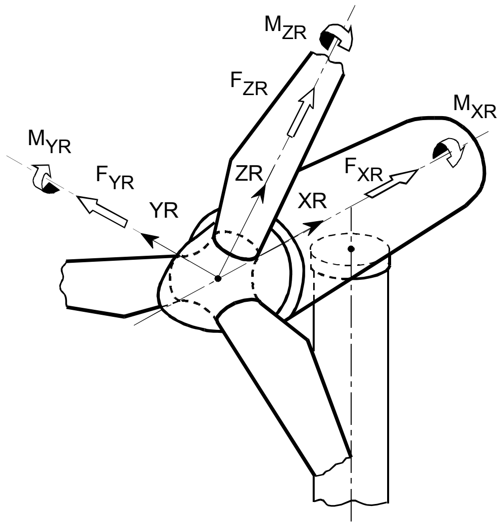


XN in direction of the rotor axis
ZN upwards perpendicular to XN
YN horizontally sideways, so that XN, YN, ZN rotate clockwise

Figure A-3 Hub coordinate system

A.4 Rotor coordinate system

The rotor coordinate system has its origin at the rotor centre (or any other position on the rotor axis, e.g. hub flange or main bearing) and rotates with the rotor.

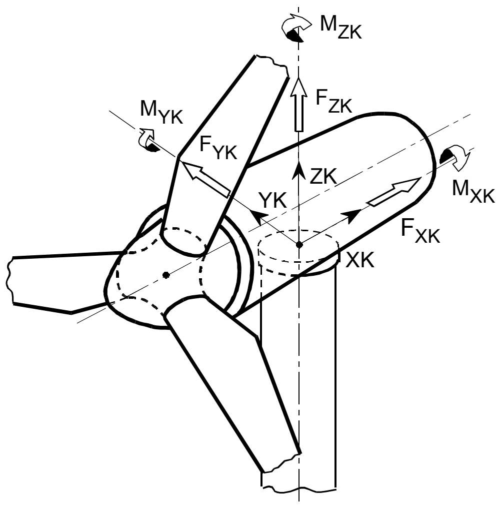


XR in direction of the rotor axis
ZR radially, orientated to rotor blade 1 and perpendicular to XR
YR perpendicular to XR, so that XR, YR, ZR rotate clockwise

Figure A-4 Rotor coordinate system

A.5 Tower top coordinate system

The tower top coordinate system has its origin at the intersection of the tower axis and the upper edge of the yaw bearing and rotates with the nacelle.

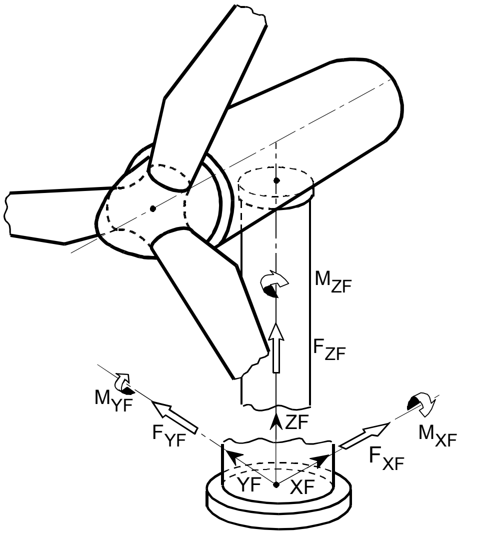


XK horizontal in direction of the rotor axis, fixed to nacelle
ZK vertically upwards
YK horizontally sideways, so that XK, YK, ZK rotate clockwise

Figure A-5 Yaw bearing coordinate system

A.6 Support structure (tower) coordinate system

The support structure coordinate system has its origin between mudline/respective upper edge of foundation for onshore wind turbines and tower top at the intersection with the support system axis and does not rotate with the nacelle. The orientation corresponds with the tower top coordinate system. In addition, other locations on the support system axis are also possible.



XF horizontal
ZF vertically upwards in direction of the tower axis
YF horizontally sideways, so that XF, YF, ZF rotate clockwise

Figure A-6 Support structure coordinate system

A.7 Water levels

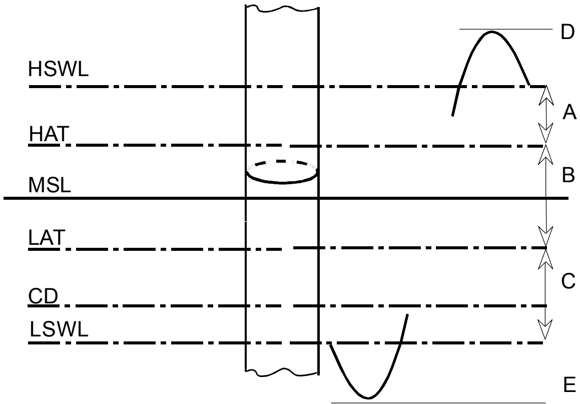


Figure A-7 Water levels

HSWL	highest still water level
HAT	highest astronomical tide
MSL	mean sea level
LAT	lowest astronomical tide
CD	chart datum (often equal to LAT)
LSWL	lowest still water level
A	positive storm surge
B	tidal range
C	negative storm surge
D	maximum crest elevation
E	minimum

APPENDIX B STATISTICAL EXTRAPOLATION PROCEDURE

B.1 Requirements for extrapolation procedure

The following list states comments and requirements for the evaluation of loads based on statistical extrapolation:

— In some cases all blades may be considered to be independent. It shall be shown that the maxima are separated by a minimum time distance, which shall be defined such that statistical independence is ensured. As a first value a minimum time distance of Δt = 10 seconds might be taken.
— For local maxima, derived by a block maxima method, the peak-over threshold method, or other local maxima methods, the independence of maxima of the same time domain simulation shall be checked.
— It shall be verified that the size of the data base is large enough, i.e. that there are enough points to produce reliable and stable results. The convergence test described in the respective Annex of IEC 61400-1 may be used, i.e. by boot a strapping method calculating the 90% confidence interval of the 84 % fractile and verifying that it is less than 15% of the estimate of the 84% fractile.
— Minimum required data base: for each wind speed bin between $V_{r\text{-}2m/s}$ and V_{out} at least 15 seeds each 10 min, for each wind speed bin below $V_{r\text{-}2m/s}$ at least six seeds each 10 min; or, in case of peak-over-threshold (POT) method, at least 150 min for each wind speed bin between $V_{r\text{-}2m/s}$ and V_{out} and at least 60 min for each wind speed bin below $V_{r\text{-}2m/s}$. In general as many runs as possible should be realized.
— The yaw angle and inclination angle may be distributed evenly over the number of simulations, e.g.

  — 1/6 with positive yaw error and with vertical inclination
  — 1/6 with positive yaw error and without vertical inclination
  — 1/6 without yaw error and with vertical inclination
  — 1/6 without yaw error and without vertical inclination
  — 1/6 with negative yaw error and with vertical inclination
  — 1/6 with negative yaw error and without vertical inclination.

— Each simulation run shall be realized with a different seed.
— Outliers shall be retained in the data; it should be checked if they are valid data values rather than modelling errors; it should be examined if they belong to different processes (e.g. turbine status) and thus to different populations which may have to be considered independently.
— Data (maxima/minima) may be extrapolated separately for each wind speed bin to form a short-term distribution and be aggregated afterwards by their long-term probability distribution to form an extreme distribution ('fitting before aggregation'). Data may also be aggregated first by their long-term probability distribution and extrapolated afterwards to form an extreme distribution ('aggregation before fitting'); for details see IEC 61400-1. At least the following values shall be extrapolated: blade root out-of-plane bending moment, blade root in-plane bending moment, blade tip deflection (max deflection or deflection at min tower clearance).
— Tail fitting might be practical method to achieve good results; in this case a justification for data to be fitted shall be provided; a robustness analysis by changing the tail size shall be provided as well.

B.2 Requirements for documentation

The following list constitutes the minimum requirements for the analysis carried out and documented:

— description of the method
— data base, separated for each wind bin
— aggregated data base in case of aggregation before fitting
— distribution type parameters, plot of distribution for each wind speed bin in case of fitting before aggregation, plot of final extrapolation and results for the 1-year and 50-year extrapolation periods
— the size of the data base needs to be explained, and shown to be large enough to provide reliable and stable results
— check of independency of single maxima in case of application of data of different blades.

— for local maxima methods, as block maxima method or POT or other local maxima method: adjustment of threshold (for POT), check of independency of single maxima.
— if all channels are extrapolated, the client needs to explain how the contemporaneous loads are calculated for the extrapolation driven load components. For the determination of contemporaneous loads the respective Annex of IEC 61400-1 may be applied.

APPENDIX C EVALUATION OF THE LOADS

C.1 Presentation of load case definitions

All calculated load cases shall be listed. For each load case, the principal simulation parameters (wind shear, wind model, wave model, current, water level, possible ice loads, upflow, simulation duration etc.) as well as a description of the control and safety system parameters that are necessary for the load cases in question (braking procedures, shut-down procedures, yawing manoeuvres, delay times etc.) shall be specified.

The variations of the load cases in relation to the principal data of the load case definitions shall be listed together with the filenames of the time series with the associated parameters (e.g. wind speed, gust characteristics, oblique inflow, criteria for the activation of control or safety actions, etc.).

C.2 Presentation of the results

C.2.1 General

A distinction is made between extreme loads and fatigue loads when presenting the results. As a matter of principle, all loads used for the analyses of the component dimensioning shall be specified. The loads shall be presented in the same way as applied in the design process.

All time series of the calculated extreme and fatigue load cases and an appropriate viewer programme shall be supplied on computer storage media (e.g. hard drive, DVD, CD-ROM, USB stick) in a universal readable format (e.g. ASCII, XLS) or including appropriate conversion tools.

The relevant deflections and clearances of the structure from the water and the tower shall be stated.

C.2.2 Extreme loads

The results of the extreme load evaluations, including the partial safety factors, shall be presented in tabular form for the positions investigated (e.g. blade sections, blade root, rotor shaft rotating, rotor shaft not rotating, etc.). This shall contain a brief description of the load cases with statements of the partial safety factors used. The following presentation format is recommended. The extreme values (maxima and minima) of the corresponding load components are located on the diagonal. The simultaneous loads of the other load components shall be given in the rows (see Table C-1).

For the extreme loads in the chord coordinate system, a table of the loads including the partial safety factors and a table of the loads excluding them shall be given for each blade section examined.

For the extreme loads at the support structure, a column shall be added to the table for the wind speed and wind direction, as well as the wave direction belonging to the extreme load situation (the sign of the wind and wave direction shall be indicated in a sketch or stated in accordance with the coordinate systems listed in App.A). A table of the loads including the partial safety factors and a table of the loads excluding them shall be given for each load case.

Guidance note:

From the evaluation of the extreme loads with or without partial safety factors, differing load cases may be relevant.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

The extreme loads of the pitch drive actuator torque (min/max) shall be given for all load cases without pitch activity (braked pitch) and separately for all load cases with pitch activity. The simulation of the pitch drive actuator torque shall include effects of the aerodynamic pitch torque, the blade bearing and pitch gearbox friction and the pitching inertia of rotor blade and pitch drive.

For the maximum loads in the blade coordinate system, a table shall be compiled with all the corresponding loads of all the blade connections.

For the maximum bending moment in the hub coordinate system, a table shall be compiled with all the corresponding loads of all the blade connections.

C.2.3 Fatigue loads

In addition to the time series required in [C.2.1], all results of the evaluation shall be submitted in formats which may be accessed by computer.

For the evaluation of the fatigue loads, all design load cases of the fatigue strength shall be included, see Table 4-3.

The assumptions made in the calculation of the fatigue loads shall be specified. These include e.g. the mean annual wind speed, the parameters of the wind speed distribution and the wave height distribution as well as their correlation, the operating life etc.

For all load components, accumulated fatigue spectra within the simulated operating life shall be given in tabular, and if necessary graphic, form. In addition, equivalent constant-range spectra shall be computed from the accumulated fatigue spectra and also be specified. Here the reference load cycle number n_{ref} shall be stated. Equivalent fatigue loads may be presented in tabular form for all material-relevant slope parameters of the S/N curves, in accordance with Table C-2.

For dynamically loaded components made from fibre-reinforced plastics (GRP/CRP) or concrete materials, such as the rotor blade or concrete foundations, the Markov matrices (range-mean matrix) shall be given at the sections investigated.

In particular, for the evaluation of the fatigue loads at the blade root, the following procedure shall be observed:

— Apart from the evaluation for the bending moments in the flapwise and edgewise directions (Mx and My), the angular sector between these bending moments and the subsequent sector up to 90° shall be examined, so that a total sector of 180° is obtained. These bending moments shall be computed in angular intervals not larger than 15°.
— Without further proof one may abstain from this examination if the fatigue loads for the flapwise and edgewise directions are multiplied by a factor of 1,2.

For the components of the blade pitching system, the drive train (main bearing, gearing, coupling etc.) and the yaw system, the average values of the fatigue loads as well as the distribution of the load duration distribution (LDD) shall be specified for the relevant load components.

For the components of the blade pitching system, the root mean square value (RMS) of the 600 sec time series of the sensor “pitch actuator torque” is requested additionally for all load cases of DLC 1.1.

For tower and foundation resp. support structure, the investigated load components shall be verified with a statement of the mean values and the amplitudes, e.g. through specification of the Markov matrices.

C.3 Further evaluations

C.3.1 Maximum blade deflection

In the case of wind turbines with a horizontal axis, the maximum blade deflection in the tower direction (determined for all load cases) and the minimum clearance between rotor blade and tower or other relevant parts of the turbine shall be specified for the deformation analysis. Here the deformations of all blades shall be taken into account. The decisive load case shall be specified.

C.3.2 Maximum tower top acceleration

The maximum tower top acceleration in the tower longitudinal direction and in the tower lateral direction (x and y directions acc. to Figure A-5) shall be specified for the strength analysis. All load cases shall be considered. The acceleration values shall be multiplied with the partial safety factor for the loads γ_F according to Table 4-3 and Table 4-4. Also acceleration values (thresholds) shall be specified for the setting of the shock sensor and the operational vibration monitoring.

C.3.3 Maximum rotational speed

Statement of the maximum rotational speed of the rotor and generator n_{max} occurring in all load case simulations, and the corresponding load case shall be stated. All rotational speeds shall be multiplied with the partial safety factor for the loads of $\gamma_F = 1{,}0$.

C.3.4 Braking load cases

Graphic representation of the time series of a braking load case with application of the mechanical brake or of the braking system bringing the turbine to standstill, in which the maximum torque occurs (rotor torque versus simulation time) shall be given.

A statement of the maximum rotor braking time that is required when the mechanical brake is applied shall be given.

C.3.5 Operation within the support structure resonance range

If the wind turbine is operated within the support structure resonance range and significant amplifications can be expected, the corresponding evaluation and definition of the limiting values shall be stated and explained.

C.3.6 Design loads for locking devices

For the dimensioning of the locking devices for the blade pitching, rotor and yaw systems, the relevant loads shall be specified with consideration of the partial safety factors. This concerns the load cases DLC 8.1 and DLC 8.2. Non-redundant blocking devices, based on loads from DLC 8.1, shall be designed considering a safety factor for the consequence of failure of at least γ_N = 1,2, see also DNVGL-ST-0361, [7.5.4]. Note that the consequence of failure factor shall not be treated as a safety factor on materials. See also [4.5.8].

C.3.7 Serviceability limit state design of the support structure

For the serviceability limit state design of the support structure the following three environmental loads (combination of actions) are required (see also DNVGL-ST-0126):

- Characteristic extreme loads as maximum value of the groups N, E and DLC8.1 according to [4.4].
- LDD 10^{-4} (i.e. the load level exceeding 0,01% of the time equivalent to 17.5 h in 20 years), being evaluated for DLC 1.2 and DLC 6.4 according to Sec.4.
- LDD 10^{-2} (i.e. the load level exceeding 1% of the time equivalent to 1750 h in 20 years), being evaluated for DLC 1.2 and DLC 6.4 according to Sec.4.

For verifications in the serviceability limit states, the partial safety factor for the loads shall be γ_F = 1,0.

The following load evaluations are required:

- For the appearance of a ground gap, together with crack control and stress level limitation in the concrete, in the case of onshore wind turbines with slab foundations, the three load components are required at the tower bottom.
- For special tower designs the three load components may also be needed at higher elevations. This will for example be the case for concrete towers and concrete/steel hybrid towers. Specific levels shall be agreed with the tower designer.
- The loads shall be executed in tabular form in accordance with the table for extreme load evaluation, including statement of the wind speeds and wind direction for the corresponding load situation.

C.3.8 Minimum clearance

The minimum clearance of the rotor from the water surface as well as the air gap between water level and access platform shall be given for offshore wind turbines

C.3.9 Movement of the wind turbine

The maximum deflections and rotations of the turbine shall be analysed and reported. The corresponding load cases and time series shall be provided.

Table C-1 Recommended presentation of the calculation results of extreme loads (F_{res} – resulting transverse force, M_{res} – resulting bending moment)

Results of the extreme load evaluation											
		Load case	γ_F	F_x	F_y	F_z	F_{res}	M_x	M_y	M_z	M_{res}
F_x	**Max**										
	Min										
F_y	**Max**										
	Min										
F_z	**Max**										
	Min										
F_{res}	**Max**										
	Min										
M_x	**Max**										
	Min										
M_y	**Max**										
	Min										
M_z	**Max**										
	Min										
M_{res}	**Max**										
	Min										

Table C-2 Recommended presentation of the calculation results of equivalent fatigue loads for various slope parameters of the S/N curve

Results of the fatigue load evaluation							
n_{Ref}	*slope parameter*	F_x	F_y	F_z	M_x	M_y	M_z
Slope parameter of the S/N curve m	m_a						
	m_b						
	m_c						
	m_d						
	m_e						
	m_f						
	m_g						
	m_h						
	m_i						
	m_j						

APPENDIX D GENERATOR SHORT-CIRCUIT

The loads of a generator short-circuit may also be initiated by short-circuits in main parts of the internal electrical system. The worst case of a short-circuit concerning the loads is in or near the generator or directly connected power circuits. Such short-circuits shall be investigated, since this may result in very high transient loads. In the absence of any proven values that are more precise, the equations given below shall be applied.

A two-phase short-circuit generally leads to higher maximum torques than a three-phase short-circuit, so that the two-phase case is decisive. For a two-phase short-circuit at the terminals of a synchronous generator, the following electromagnetic torque (M) shall be analysed:

$$M = \frac{1.3 M_n}{x''_d} \tag{D.1}$$

where:

M_n = rated synchronous generator torque

x''_d = subtransient reactance of the synchronous generator per unit value, as stated by the generator manufacturer.

If x''_d is unknown, the occurrence of 10.5 times the rated torque shall be taken into account.

If the synchronous generator is equipped with devices or measures for short-circuit limitation, the resulting electromagnetic torque (*M*) shall be analysed by simulations. The generator model shall be submitted for assessment. See DNVGL-ST-0076.

For a two-phase short-circuit at the stator terminals of an induction generator, the following electromagnetic torque (*M*) shall be analysed:

$$M = -\frac{M_K}{1-\sigma}\cos\alpha + \frac{M_K}{1-\sigma}\cos\left(2\omega_g t - \alpha\right) - 2\frac{M_K}{1-\sigma}\sin\left(\omega_g t\right) e^{-\frac{t}{T_1}} \tag{D.2}$$

where:

M_K = breakdown torque of the induction generator

σ = leakage coefficient

α = angle for two-phase short-circuit with α = arctan(ω_g T_1)

ω_g = angular frequency at the generator stator terminals

t = time

T_1 = time constant of the stator.

The values of M_K, σ and T_1 shall be applied in accordance with the information supplied by the generator manufacturer. If the required values are unknown, then 8 times the rated torque shall be applied.

For induction generators, a three-phase short-circuit shall also be investigated. Here the following electromagnetic torque (*M*) shall be analysed:

$$M = 2M_K \sin\left(\omega_g t\right) e^{-2 s_K \omega_g t} \tag{D.3}$$

where:

ω_g = angular frequency at the generator stator terminals

M_K = breakdown torque of the induction generator

s_K = breakdown slip of the induction generator, as stated by the generator manufacturer.

The maximum torque is attained when the following applies:

$$\omega_g t = \arctan\left(\frac{1}{2 s_K}\right) \tag{D.4}$$

APPENDIX E DESIGN PARAMETERS FOR THE DESCRIPTION OF AN ONSHORE WIND TURBINE CLASS S

For class S onshore wind turbines, at least the following design parameters shall be given in the design documentation:

E.1 Turbine parameters

Description of planned wind turbine type		
Description of wind turbine coordinate systems		
Design lifetime		[a]
Rated power		[kW]
Operating wind speed range at hub height	V_{in} to V_{out}	[m/s]
Rated wind speed		[m/s]
Rotational speed range		[rpm]
Hub height		[m]
Rotor diameter		[m]

E.2 Wind conditions, representative at hub height

Representative turbulence intensity as a function of the mean wind speed	[-]
Annual average wind speed at hub height	[m/s]
Wind direction distribution (wind rose) Average inclination of flow	[°]
Distribution function for the wind speed (Weibull, Rayleigh, measured, other)	
Wind profile model and parameters	
Turbulence model and parameters	
Reference wind speed V_{ref} and V_1 (10-min average)	[m/s]
Extreme wind speeds V_{e1} and V_{e50} at hub height	[m/s]
Maximum wind speed VT (1-h average value)	[m/s]

E.3 Conditions of the electrical power network

Normal supply voltage and fluctuation	[V]
Normal supply frequency and fluctuation	[Hz]
Voltage imbalance	[V]
Maximum duration of electrical network outages	[d]
Number of electrical network outages	[1/a]
Auto-reclosing cycles (description)	
Behaviour during symmetrical and asymmetrical external faults (description)	
Location where electrical conditions are applicable	

E.4 Other environmental conditions (where necessary)

Normal and extreme temperature ranges (1-h average value)	[°C]
Humidity	[%]
Air density	[kg/m³]
Intensity of the solar radiation	[W/m²]
Rain, hail, snow and ice	
Chemically active substances	
Mechanically active particles	
Salinity	[g/m³]
Description of the lightning protection system	
Earthquake model and parameters	
Foundation stiffness and damping	

E.5 Deviations to standard parameters and models

Applied standard(s) in hierarchical order

Deviations to standard parameters and models

APPENDIX F DESIGN PARAMETERS FOR THE DESCRIPTIONOF AN OFFSHORE WIND TURBINE AND WIND FARM

For class S offshore wind turbines, at least the following design parameters shall be given in a summary included in the design documentation:

F.1 Turbine parameters

Description of planned wind turbine type(s)		
Description of wind turbine coordinate systems		
Design lifetime		[a]
Rated power		[kW]
Operating wind speed range at hub height	V_{in} to V_{out}	[m/s]
Rated wind speed		[m/s]
Rotational speed range		[rpm]
Hub height (above reference level, e.g. MSL or LAT)		[m]
Rotor diameter		[m]
Minimum rotor clearance above highest water level		[m]
Allowed natural frequency range for the complete system (support structure with turbine in soil) considering the operational range of the turbine		[Hz]
Natural frequencies of main components		[Hz]

F.2 Support structure parameters

Description of planned support structure type(s)	
Description of support structure coordinate system(s)	
Description of transition piece concept and, if planned, description of grouted connection	
Description of bolted connection	
Structure total displacement	[m]
Design lifetime	[a]
Installation mass of support structure type(s)	[t]
Interface level, platform level, splash zone levels	[m LAT or MSL]
Nominal draft, max. and min. draft (if applicable)	[m]
Natural frequencies (support structure with turbine in soil) for each location (table format)	[Hz]

F.3 Wind farm parameters

Farm location description with indication of environment peculiarities, period of intended construction, main stages of construction up to final assembly and/or installation at sea	
Number of turbines and transformer platforms	
Coordinates of each turbine and transformer location	
Design water depth of each turbine and transformer location	[m]

F.4 Geotechnical information and seismic conditions

Bathymetry	
Description of soil conditions (soil classification)	
Sea bed variations (bedslope movement expected due to seismic hazards, currents or waves?)	
Long term variation of sandbank characteristics, if applicable (global scour)	
Scour allowance (local)	
Scour protection (description)	
Earthquake model and parameters, if applicable	

F.5 Wind conditions, representative at hub height

Representative turbulence intensity as a function of the mean wind speed, including wake effects (effective turbulence intensity)	
Annual average wind speed at hub height (10-min average)	[m/s]
Wind direction distribution (wind rose)	
Distribution function for the wind speed (Weibull, Rayleigh, measured, other)	
Wind profile model and parameters	
Turbulence model and parameters	
Reference wind speed V_{ref} and V_1 (10-min average)	[m/s]
Extreme wind speeds V_{e50} and V_{e1} at hub height (3s average)	[m/s]
Normal and extreme atmospheric temperature ranges	[°C]

F.6 Marine conditions

Mean sea level (MSL)	[m]
Tidal ranges (LAT and HAT)	[m]
Storm surge (1-year and 50-year recurrence periods)	[m]
Highest still water level (HSWL, 50-year recurrence period)	[m]
Lowest still water level (LSWL, 50-year recurrence period)	[m]
Maximum water elevation	[m]
Water density	[kg/m³]
Normal and extreme sea temperature ranges	[°C]
Salinity	[%]
Significant wave height (50-year and 1-year recurrence periods)	[m]
Design wave height (50-year and 1-year recurrence periods)	[m]
Design wave period range (50-year and 1-year recurrence periods)	[s]
Current speed (50-year and 1-year recurrence periods)	[m/s]
Wind and wave joint distribution (H_s, T_p, V)	
Wind and wave joint directional distribution	
Wave spectrum and parameters	
Deterministic wave parameters	
Breaking wave type and parameters (height, period)	
Sea ice occurrence (if occurring: annual & extreme ice thickness, ice strength & compliance parameters, description of ice-structure interaction, static and dynamic ice loads)	
Marine growth thickness	[mm]
Marine growth density	[kg/m³]

F.7 Conditions of the electrical power network

Normal supply voltage and fluctuation	[V]
Normal supply frequency and fluctuation	[Hz]
Voltage imbalance	[V]
Maximum duration of electrical network outages	[d]
Number of electrical network outages	[1/a]
Auto-reclosing cycles (description)	
Behaviour during symmetrical and asymmetrical external faults (description)	
Location where electrical conditions are applicable	

F.8 Other environmental conditions (where necessary)

Normal and extreme atmospheric temperature ranges (1-h average value)	[°C]
Humidity	[%]
Air density	[kg/m^3]
Intensity of the solar radiation	[W/m^2]
Rain, hail, snow and ice	
Chemically active substances	
Mechanically active particles	
Salinity	
Tsunami waves prediction, if applicable	
Description of the lightning protection system	
Corrosion allowance	[mm]
Corrosion protection (description)	
Displacement of supply vessel	[t]

F.9 Limiting conditions for maintenance, transport and installation

Maximum wind speed V_T (1-h average value)	[m/s]
Maximum significant wave height H_{sT}	[m]
Maximum water level variation	[m]
Permitted atmospheric temperature	[°C]

F.10 Deviations to standard parameters and models

Applied standard(s) in hierarchical order

Deviations to standard parameters and models

APPENDIX G DIRECTIONAL DISTRIBUTION OF WAVES IN A SEA STATE

The directional characteristics are often assumed to be independent of frequency, allowing a separation of variables so that the directional wave spectrum may be expressed as the product of a wave directional spreading function, independent of frequency, and a wave frequency spectrum, which is independent of direction. The directional distribution of the waves in a given sea state is considered by:

$$S_\zeta(\omega, \mu_e) = S_\zeta(\omega) \cdot G(\mu_e) \tag{G.1}$$

where:

$G(\mu_e)$ = directional distribution function

μ_e = deviation from mean wave direction

and

$$\int_{-\pi/2}^{\pi/2} G(\mu_e)\, d\mu_e = 1. \tag{G.2}$$

Parametric forms for the wave directional spreading function are given in the literature. Often the function has the form:

$$\begin{aligned} G_1(\mu_e) &= k_n \cdot \cos^n(\mu_e) \quad \text{for} \quad -\frac{\pi}{2} \le \mu_e \le \frac{\pi}{2} \\ G_1(\mu_e) &= 0 \qquad\qquad\qquad\quad \text{else} \end{aligned} \tag{G.3}$$

The factor k_n takes values to comply with the boundary condition i.e. $k_2 = 2/\pi$ or $k_4 = 8/(3\pi)$.

$$k_n = \frac{\Gamma(n/2+1)}{\sqrt{\pi}\,\Gamma(n/2+1/2)} \tag{G.4}$$

The values for n to be used are site specific, depending among others on the seabed bathymetry. For wind seas with large spreading n is typically taken to be n=2, for medium spreading n is typically taken to be n= 4 and for long crested swell seas n= 6 is normally used. Alternative methods may be applied if shown to be applicable for the specific site.

APPENDIX H WAKE AND WIND FARM TURBULENCE

Wake effects from neighbouring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity I_{eff}, as defined by S. Frandsen. The effective turbulence intensity – conditioned on hub height mean wind speed - may be defined as

$$I_{eff}(V_{amb}) = \left\{ \int_0^{2\pi} p(\theta|V_{amb}) I^m (\theta|V_{amb}) d\theta \right\}^{\frac{1}{m}} \quad \text{(H.1)}$$

where

p = probability density function of the wind direction

I = turbulence intensity combined of ambient and wake flow from wind direction θ

m = Wöhler (S/N-curve) exponent for the material considered

V_{amb} = ambient 10-minute average wind speed at hub height

A uniform distribution $p(\theta|V_{amb})$ is assumed. It is also acceptable to adjust the formula for other than uniform distributions. No reduction in mean wind speed inside the wind farm shall be assumed.

If $min\{d_i\} \geq 20\,D$:

$$I_{eff} = \frac{\sigma_c}{V_{amb}} \quad \text{(H.2)}$$

If $min\{d_i\} \leq 20\,D$:

$$I_{eff} = \frac{\sigma_{eff}}{V_{amb}} = \frac{1}{V_{amb}} \left[(1 - N \cdot p_w) \sigma_c^m + \dots \dots + p_w \sum_{i=1}^{N} \sigma_T^m (d_i) \right]^{\frac{1}{m}} ; \; pw = 0{,}06 \quad \text{(H.3)}$$

where:

σ_c = characteristic ambient turbulence standard deviation under consideration of the influence of neighbouring wind farms or large wind farms, see equations (H.5)

$\bar{\sigma}$ = mean ambient estimated turbulence standard deviation

σ_σ = standard deviation of the ambient turbulence standard deviation

$$\sigma_T = \sqrt{\frac{V_{amb}^2}{\left(1.5 + \frac{0.8 d_i}{\sqrt{C_T}}\right)^2} + \sigma_c^2} \quad \text{(H4)}$$

σ_T = characteristic value of the maximum centre-wake, hub height turbulence standard deviation

C_T = thrust coefficient of the neighbouring wind turbines for the corresponding wind velocity at hub height. If the thrust coefficients are unknown, $C_T = 7/V_{amb}$ may be used

d_i = distance to neighbouring wind turbine, normalised by the rotor diameter

I_{eff} = effective turbulence intensity

N = number of neighbouring turbines

m = Wöhler (SN-curve) exponent for the material considered

Wake effects from wind turbines hidden behind other turbines need not be considered, e.g. in a row only wakes from the two units closest to the turbine in question are to be taken into account. Depending on the wind farm configuration, the number of the nearest wind turbines to be included in the calculation of I_{eff} is given in the Table H-1.

Table H-1 Wind farm configurations

Wind farm configuration	N
2 wind turbines	1
1 row	2
2 rows	5
Inside a wind farm with more than 2 rows	8

The wind farm configurations are illustrated in the Table H-1 for the case inside a wind farm with more than 2 rows.

Inside large wind farms, or in the wake of neighbouring wind farms the wind turbines tend to generate their own ambient turbulence. Thus, when

— the number of wind turbines from the considered unit to the edge of the wind farm is more than 5, or
— the spacing in the rows perpendicular to the predominant wind direction is less than *3D*, then the following characteristic ambient turbulence shall be assumed instead of σ_C:

$$\sigma_c = \frac{1}{2}\left(\sqrt{\sigma_w^2 + \bar{\sigma}^2} + \bar{\sigma}\right) + 1.28\sigma_\sigma \tag{H.5}$$

Where

$$\sigma_w = \frac{0.36 V_{amb}}{1 + 0.2\sqrt{d_r d_f / C_T}} \tag{H.6}$$

in which d_r and d_f are separations in rotor diameters in rows and separation between rows, respectively.

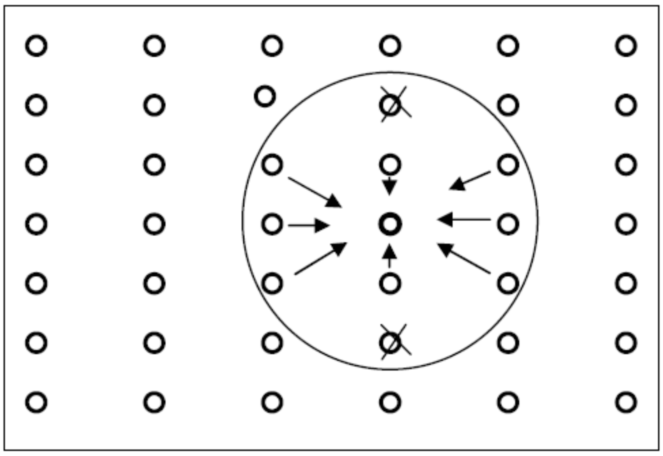


Figure H-1 Configuration - inside a wind farm with more than 2 rows

APPENDIX I LOAD ASSESSMENT RELEVANT DATA

The tables below provide a summary of the main load assessment relevant parameters as defined in Sec. 4. They are meant as an expedient for data submission for the load assessment. The use of the tables is optional.

Table I-1 Turbine data relevant to load assessment to be combined with Table I-2

	Item no.		*Item*	*Unit*	*Value(s)*	*Reference (in case of external documentation)*
Rotor speed, referred to * LSS * HSS	1.1		Gearbox ratio	-		
	1.2		Operating range n_1 – n_3	1/min		
	1.3		Rated rotor speed Set value of speed controller n_r/n_2	1/min		
	1.4		Cut-out rotor speed n_4	1/min		
	1.5		Activation speed n_A	1/min		
	1.6		Max. overspeed, n_{max}	1/min		
Electrical power output and torque	2.1		Rated electrical power output, P_r	kW		
	2.2		Over-power, P_T	kW		
	2.3		Activation power, P_A	kW		
	2.4		Slip torque of slip coupling incl. tolerance	kNm		
	2.5		Maximum generator torque during short-circuit	kNm		
Wind speed	3.1		Rated wind speed, V_r	m/s		
	3.2		Cut-out wind speed, V_{out}	m/s		
	3.3		Short-term cut-out wind speed, V_A	m/s		
	3.4		Max. 10min-mean wind speed for maintenance V_T	m/s		
Mechanical brake	4.1		Min. required/max. braking torque, M_{Bmin}/ $M_{Bmax.}$	kNm		
	4.2		Time delay for activation of the mechanical brake	s		
	4.3		Ramp time (time constant) for braking torque	s		
Aerodynamic brake, pitch system	5.1		Min/max pitch or blade-tip angle (hardware stop)	°		
	5.2		Pitch angle after normal stop/grid loss	°		
	5.3		Max. difference between pitch angles of blades before shut-down	°		
	5.4		Max. pitch-/tip-speed at emergency stop	°/s		
	5.5		Max. pitch speed during operation	°/s		
	5.6		Time delay for activation of pitch movement	s		
Wind tracking	6.1		Min./max. yaw-braking torque	kNm		
	6.2		Max. yawing speed	°/s		
	6.3		Max. yaw error for shut down φ_A	°		
	6.4		Max. allowed yaw error at V_T	°		
	6.5		Min. yaw error for triggering yawing activity	°		
	6.6		Averaging time of yaw error for triggering yaw activity	s		
	6.7		Uninterruptible power supply (UPS) for yaw system	yes/no		
Temperature	7.1		Min./max. ambient temperature during operation	°C		
Nacelle vibration	8.1		Max. acceleration	m/s²		

Table I-2 Shut-down parameters relevant to load assessment

Quantity[1]	*Referring to item no.*	*Value or status*[2]	*Averaging time for triggering*[3]	*Time delay for action*[4]	*Action*				*Reference for external documentation (if applicable)*
					Pitch state[5]	*Generator state*[6]	*Mechanical brake state*[7]	*Yaw state*[8]	
Rotor speed	1.4 1.5	n_4 = n_A = n_x =							
Power	2.2 2.3	P_T = P_A = P_x = [9]							
Wind	3.2 3.3	V_{out} = V_A =	(e.g. "3 sec mean" or "immediately" ...)	(e.g. "0,2 sec")	(e.g. "8°/s to position of 90°" ...)	(e.g. "generator switched off immediately" or "stays online until ...")	(e.g. "mech. brake applied at rotor speed < = >... rpm")	(e.g. "still enabled" or "disabled" or "yaw rate = ...")	
Pitch system	5.3	Pitch runaway Pitch angle difference between blades Difference between actual pitch angle and scheduled value (Other possible pitch failures ...)							
Yaw	6.3	φ_A= (Further yaw failure(s), ...)							
Electrical system	2.5	Grid loss Generator short-circuit							
Emergency stop		Em. stop button							
Nacelle vibration	8.1								

Footnotes to Table I-2:

1 quantity should be filled according to the safety and control system of the turbine

2 trigger value or failure according to GL Guideline plus definitions by the manufacturer

3 averaging time as appropriate, e.g. immediately, 3 sec mean, 10-min mean, ...

4 time delay for action as appropriate, e.g. immediately or 0,2 sec ...

5 pitch state should include the appropriate pitch rate and the final pitch position

6 generator state should specify whether the generator remains online or is switched off, electrical power is ramped down (how?) etc.

7 mechanical brake state should specify whether the mechanical brake is activated immediately, delayed, ramped up, not activated, ...

8 yaw state should specify whether the yaw system is still active, disabled, shows any defined action …

9 subscript x means to be specified, if applicable, by the manufacturer

DNV GL
Driven by our purpose of safeguarding life, property and the environment, DNV GL enables organizations to advance the safety and sustainability of their business. We provide classification and technical assurance along with software and independent expert advisory services to the maritime, oil and gas, and energy industries. We also provide certification services to customers across a wide range of industries. Operating in more than 100 countries, our 16 000 professionals are dedicated to helping our customers make the world safer, smarter and greener.

SAFER, SMARTER, GREENER