

INTERNATIONAL STANDARD

NORME INTERNATIONALE

**Wind turbines –
Part 3: Design requirements for offshore wind turbines**

**Eoliennes –
Partie 3: Exigences de conception des éoliennes en pleine mer**



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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINES –

Part 3: Design requirements for offshore wind turbines

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International Standard IEC 61400-3 has been prepared by IEC technical committee 88: Wind turbines.

This part is to be read in conjunction with IEC 61400-1:2005, *Wind turbines – Part 1: Design requirements*.

The text of this standard is based on the following documents:

FDIS	Report on voting
88/329/FDIS	88/338/RVD

Full information on the voting for the approval of this standard can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

A list of all parts of IEC 61400 series, published under the general title *Wind turbines*, can be found on the IEC website.

The committee has decided that the contents of this publication will remain unchanged until the maintenance result date indicated on the IEC web site under "<http://webstore.iec.ch>" in the data related to the specific publication. At this date, the publication will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

INTRODUCTION

This part of IEC 61400 outlines minimum design requirements for offshore wind turbines and is not intended for use as a complete design specification or instruction manual.

Several different parties may be responsible for undertaking the various elements of the design, manufacture, assembly, installation, erection, commissioning, operation and maintenance of an offshore wind turbine and for ensuring that the requirements of this standard are met. The division of responsibility between these parties is a contractual matter and is outside the scope of this standard.

Any of the requirements of this standard may be altered if it can be suitably demonstrated that the safety of the system is not compromised. Compliance with this standard does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

WIND TURBINES –

Part 3: Design requirements for offshore wind turbines

1 Scope

This part of IEC 61400 specifies additional requirements for assessment of the external conditions at an offshore wind turbine site and it specifies essential design requirements to ensure the engineering integrity of offshore wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.

This standard focuses on the engineering integrity of the structural components of an offshore wind turbine but is also concerned with subsystems such as control and protection mechanisms, internal electrical systems and mechanical systems.

A wind turbine shall be considered as an offshore wind turbine if the support structure is subject to hydrodynamic loading. The design requirements specified in this standard are not necessarily sufficient to ensure the engineering integrity of floating offshore wind turbines.

This standard should be used together with the appropriate IEC and ISO standards mentioned in Clause 2. In particular, this standard is fully consistent with the requirements of IEC 61400-1. The safety level of the offshore wind turbine designed according to this standard shall be at or exceed the level inherent in IEC 61400-1. In some clauses, where a comprehensive statement of requirements aids clarity, replication of text from IEC 61400-1 is included.

2 Normative references

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60721-2-1:1982, *Classification of environmental conditions – Part 2-1: Environmental conditions appearing in nature. Temperature and humidity*
Amendment 1:1987

IEC 61400-1:2005, *Wind turbines – Part 1: Design requirements*

IEC 62305-3:2006, *Protection against lightning – Part 3: Physical damage to structures and life hazard*

IEC 62305-4:2006, *Protection against lightning – Part 4: Electrical and electronic systems within structures*

ISO 2394:1998, *General principles on reliability for structures*

ISO 2533:1975, *Standard Atmosphere*

ISO 9001:2000, *Quality management systems – Requirements*

ISO 19900:2002, *Petroleum and natural gas industries – General requirements for offshore structures*

ISO 19901-1:2005, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating conditions*

ISO 19901-4:2003, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 4: Geotechnical and foundation design considerations*

ISO 19902, *Petroleum and natural gas industries – Fixed steel offshore structures*

ISO 19903: 2006, *Petroleum and natural gas industries – Fixed concrete offshore structures*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply in addition to those stated in IEC 61400-1.

3.1

co-directional (wind and waves)

acting in the same direction

3.2

current

flow of water past a fixed location usually described in terms of a current speed and direction

3.3

design wave

deterministic wave with a defined height, period and direction, used for the design of an offshore structure. A design wave may be accompanied by a requirement for the use of a particular periodic wave theory

3.4

designer

party or parties responsible for the design of an offshore wind turbine

3.5

environmental conditions

characteristics of the environment (wind, waves, sea currents, water level, sea ice, marine growth, scour and overall seabed movement, etc.) which may affect the wind turbine behaviour

3.6

external conditions (wind turbines)

factors affecting operation of an offshore wind turbine, including the environmental conditions, the electrical network conditions, and other climatic factors (temperature, snow, ice, etc.)

3.7

extreme significant wave height

expected value of the highest significant wave height, averaged over 3 h, with an annual probability of exceedance of $1/N$ ("recurrence period": N years)

3.8

extreme wave height

expected value of the highest individual wave height (generally the zero up-crossing wave height) with an annual probability of exceedance of $1/N$ ("recurrence period": N years)

3.9

fast ice cover

rigid continuous cover of ice not in motion

3.10

fetch

distance over which the wind blows constantly over the sea with approximately constant wind speed and direction

3.11

foundation

part of an offshore wind turbine support structure which transfers the loads acting on the structure into the seabed. Different foundation concepts are shown in Figure 1 together with the other parts of an offshore wind turbine

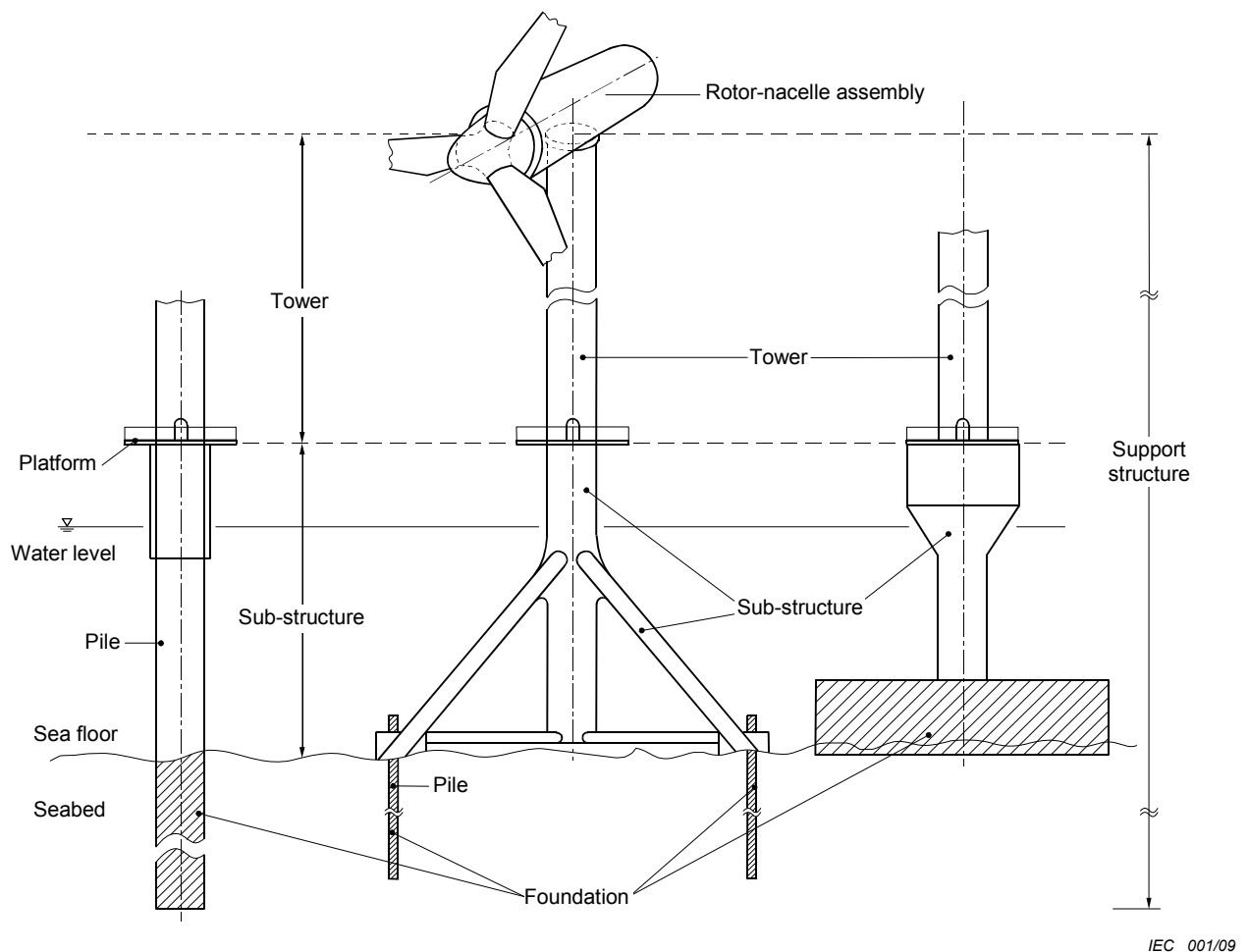


Figure 1 – Parts of an offshore wind turbine

3.12

highest astronomical tide

highest still water level that can be expected to occur under any combination of astronomical conditions and under average meteorological conditions. Storm surges, which are meteorologically generated and essentially irregular, are superimposed on the tidal variations, so that a total still water level above highest astronomical tide may occur

3.13**hindcasting**

method of simulating historical (metocean) data for a region through numerical modelling

3.14**hub height (wind turbines)**

height of the centre of the swept area of the wind turbine rotor above the mean sea level

3.15**hummocked ice**

crushed ice and ice floes piled up into ridges when large ice floes meet with each other or with a rigid obstacle, for example an offshore wind turbine support structure

3.16**ice floe**

sheet of ice in size from metres to several kilometres, not rigidly frozen to a shore, still or in motion

3.17**icing**

build-up of a cover of ice or frost on parts of an offshore wind turbine that can result in added loads and/or changed properties

3.18**land-locked waters**

waters almost or entirely surrounded by land

3.19**load effect**

effect of a single load or combination of loads on a structural component or system, for example internal force, stress, strain, motion, etc.

3.20**lowest astronomical tide**

lowest still water level that can be expected to occur under any combination of astronomical conditions and under average meteorological conditions. Storm surges, which are meteorologically generated and essentially irregular, are superimposed on the tidal variations, so that a total still water level below lowest astronomical tide may occur

3.21**manufacturer**

party or parties responsible for the manufacture and construction of an offshore wind turbine

3.22**marine conditions**

characteristics of the marine environment (waves, sea currents, water level, sea ice, marine growth, seabed movement and scour, etc.) which may affect the wind turbine behaviour

3.23**marine growth**

surface coating on structural components caused by plants, animals and bacteria

3.24**mean sea level**

average level of the sea over a period of time long enough to remove variations due to waves, tides and storm surges

3.25

mean zero crossing period

average period of the zero-crossing (up or down) waves in a sea state

3.26

metocean

abbreviation of meteorological and oceanographic

3.27

multi-directional (wind and/or wave)

distribution of directions

3.28

offshore wind turbine

wind turbine with a support structure which is subject to hydrodynamic loading

3.29

offshore wind turbine site

the location or intended location of an individual offshore wind turbine either alone or within a wind farm

3.30

pile penetration

vertical distance from the sea floor to the bottom of the pile

3.31

power collection system (wind turbines)

electric system that collects the power from one or more wind turbines. It includes all electrical equipment connected between the wind turbine terminals and the network connection point. For offshore wind farms, the power collection system may include the connection to shore

3.32

reference period

period during which stationarity is assumed for a given stochastic process, for example wind speed, sea elevation or response

3.33

refraction

process by which wave energy is redistributed as a result of changes in the wave propagation velocity due to variations in water depth and/or current velocity

3.34

residual currents

components of a current other than tidal current. The most important is often the storm surge current

3.35

rotor – nacelle assembly

part of an offshore wind turbine carried by the support structure, refer to Figure 1

3.36

sea floor

interface between the sea and the seabed

3.37**sea floor slope**

local gradient of the sea floor, for example associated with a beach

3.38**sea state**

condition of the sea in which its statistics remain stationary

3.39**seabed**

materials below the sea floor in which a support structure is founded

3.40**seabed movement**

movement of the seabed due to natural geological processes

3.41**scour**

removal of seabed soils by currents and waves or caused by structural elements interrupting the natural flow regime above the sea floor

3.42**significant wave height**

statistical measure of the height of waves in a sea state, defined as $4 \times \sigma_\eta$ where σ_η is the standard deviation of the sea surface elevation. In sea states with only a narrow band of wave frequencies, the significant wave height is approximately equal to the mean height of the highest third of the zero up-crossing waves

3.43**splash zone**

external region of support structure that is frequently wetted due to waves and tidal variations. This shall be defined as the zone between

- the highest still water level with a recurrence period of 1 year increased by the crest height of a wave with height equal to the significant wave height with a return period of 1 year, and
- the lowest still water level with a recurrence period of 1 year reduced by the trough depth of a wave with height equal to the significant wave height with a return period of 1 year

3.44**still water level**

abstract water level calculated by including the effects of tides and storm surge but excluding variations due to waves. Still water level can be above, at, or below mean sea level

3.45**storm surge**

irregular movement of the sea brought about by wind and atmospheric pressure variations

3.46**sub-structure**

part of an offshore wind turbine support structure which extends upwards from the seabed and connects the foundation to the tower, refer to Figure 1

3.47**support structure**

part of an offshore wind turbine consisting of the tower, sub-structure and foundation, refer to Figure 1

3.48

swell

sea state in which waves generated by winds remote from the site have travelled to the site, rather than being locally generated

3.49

tidal current

current resulting from tides

3.50

tidal range

distance between the highest astronomical tide and the lowest astronomical tide

3.51

tides

regular and predictable movements of the sea generated by astronomical forces

3.52

tower

part of an offshore wind turbine support structure which connects the sub-structure to the rotor – nacelle assembly, refer to Figure 1

3.53

tsunami

long period sea waves caused by rapid vertical movements of the sea floor

3.54

uni-directional (wind and/or waves)

acting in a single direction

3.55

water depth

vertical distance between the sea floor and the still water level

NOTE As there are several options for the still water level (see 3.44) there can be several water depth values.

3.56

wave crest elevation

vertical distance between the crest of a wave and the still water level

3.57

wave direction

mean direction from which the wave is travelling

3.58

wave height

vertical distance between the highest and lowest points on the water surface of an individual zero up-crossing wave

3.59

wave period

time interval between the two zero up-crossings which bound a zero up-crossing wave

3.60

wave spectral peak frequency

frequency of the peak energy in the wave spectrum

3.61**wave spectrum**

frequency domain description of the sea surface elevation in a sea state

3.62**wave steepness**

ratio of the wave height to the wave length

3.63**weather downtime**

one or more intervals of time during which the environmental conditions are too severe to allow for execution of a specified marine operation

3.64**weather window**

interval of time during which the environmental conditions allow for execution of a specified marine operation

3.65**wind profile – wind shear law**

mathematical expression for assumed wind speed variation with height above still water level

NOTE Commonly used profiles are the logarithmic profile (equation 1) and the power law profile (equation 2).

$$V(z) = V(z_r) \cdot \frac{\ln(z/z_0)}{\ln(z_r/z_0)} \quad (1)$$

$$V(z) = V(z_r) \cdot \left(\frac{z}{z_r} \right)^\alpha \quad (2)$$

where

$V(z)$ is the wind speed at height z ;

z is the height above the still water level;

z_r is a reference height above the still water level used for fitting the profile;

z_0 is the roughness length;

α is the wind shear (or power law) exponent.

3.66**zero up-crossing wave**

portion of a time history of wave elevation between zero up-crossings. A zero up-crossing occurs when the sea surface rises (rather than falls) through the still water level

4 Symbols and abbreviated terms

For the purposes of this document, the following symbols and abbreviated terms apply in addition to those stated in IEC 61400-1:

4.1 Symbols and units

A_C	Charnock's constant	[-]
d	water depth	[m]
f_p	wave spectral peak frequency	[s ⁻¹]
g	acceleration due to gravity	[m/s ²]

h	thickness of sea ice	[m]
h_N	thickness of sea ice with a recurrence period of N years	[m]
h_m	ice thickness equal to the long term mean value of the annual maximum ice thickness for winters with ice	[m]
H	individual wave height	[m]
H_B	breaking wave height	[m]
H_D	design wave height	[m]
H_N	individual wave height with a recurrence period of N years	[m]
H_s	significant wave height	[m]
H_{sN}	significant wave height with a recurrence period of N years	[m]
H_{redN}	reduced wave height with a recurrence period of N years	[m]
k	wave number	[-]
K_{max}	accumulated freezing degree-days	[°C]
s	sea floor slope	[°]
$p(V_{hub})$	probability density function of hub height wind speed	[-]
S_η	single sided wave spectrum	[m ² /Hz]
R_d	design value for component resistance	[-]
R_k	characteristic value for component resistance	[-]
S_d	design value for load effect	[-]
S_k	characteristic value for load effect	[-]
t	time	[s]
T	wave period	[s]
T_D	design wave period	[s]
T_p	peak spectral period	[s]
T_z	mean zero-crossing wave period	[s]
U_{ss}	sub surface current velocity	[m/s]
U_w	wind generated current velocity	[m/s]
U_{bw}	breaking wave induced surf current velocity	[m/s]
V_N	expected extreme wind speed (averaged over 10 min), with a recurrence period of N years	[m/s]
V_{redN}	reduced extreme wind speed (averaged over three seconds), with a recurrence period of N years	[m/s]
η	sea surface elevation relative to SWL	[m]
κ	von Karman's constant	[-]
λ	wave length	[m]
θ_w	wave direction	[°]
θ_{wm}	mean wave direction	[°]
θ_c	current direction	[°]
σ_η	sea surface elevation standard deviation	[m]
τ	temperature	[°C]

4.2 Abbreviations

COD co-directional

CPT	cone penetration test
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
EWLH	extreme wave height
EWLR	extreme water level range
EWM	extreme wind speed model
EWS	extreme wind shear
HAT	highest astronomical tide
LAT	lowest astronomical tide
MIC	microbiologically influenced corrosion
MIS	misaligned
MSL	mean sea level
MUL	multi-directional
NCM	normal current model
NSS	normal sea state
NTM	normal turbulence model
NWH	normal wave height
NWLR	normal water level range
NWP	normal wind profile model
RNA	rotor – nacelle assembly
RWH	reduced wave height
RWM	reduced wind speed model
SSS	severe sea state
SWH	severe wave height
SWL	still water level
UNI	uni-directional

5 Principal elements

5.1 General

The engineering and technical requirements to ensure the safety of the structural, mechanical, electrical and control systems of an offshore wind turbine are given in the following clauses. This specification of requirements applies to the design, manufacture, installation and manuals for operation and maintenance of an offshore wind turbine and the associated quality management process. In addition, safety procedures, which have been established in the various practices that are used in the installation, operation and maintenance of an offshore wind turbine, are taken into account.

5.2 Design methods

This standard requires the use of a structural dynamics model to predict design load effects. Such a model shall be used to determine the load effects for all relevant combinations of

external conditions and design situations as defined in Clause 6 and Clause 7 respectively. A minimum set of such combinations has been defined as load cases in this standard.

The design of the support structure of an offshore wind turbine shall be based on site-specific external conditions. These shall therefore be determined in accordance with the requirements stated in Clause 12. The conditions shall be summarized in the design basis.

In the case of the rotor – nacelle assembly, which may have been designed initially on the basis of a standard wind turbine class as defined in IEC 61400-1, 6.2, it shall be demonstrated that the offshore site-specific external conditions do not compromise the structural integrity. The demonstration shall comprise a comparison of loads and deflections calculated for the specific offshore wind turbine site conditions with those calculated during initial design, taking account of the reserve margins and the influence of the environment on structural resistance and the appropriate material selection. The calculation of loads and deflections shall also take account of the influence of site-specific soil properties on the dynamic properties of an offshore wind turbine, as well as potential long term time variation of these dynamic properties due to seabed movement and scour.

The design process for an offshore wind turbine is illustrated in Figure 2. The figure indicates the key elements of the design process and identifies the corresponding relevant clauses of this standard. The process is iterative and shall incorporate load and load effect calculations for the complete wind turbine comprising the integrated support structure and rotor – nacelle assembly. The structural design of an offshore wind turbine may be regarded as completed when its structural integrity has been verified based on the limit state analyses defined in 7.6.

Data from full scale testing may be used to increase confidence in predicted design values and to verify structural dynamics models and design situations. Guidance relating to the measurement of mechanical loads for full scale testing is available in IEC 61400-13.

Verification of the adequacy of the design shall be made by calculation and/or by testing. If test results are used in this verification, the external conditions during the test shall be shown to reflect the characteristic values and design situations defined in this standard. The selection of test conditions, including the test loads, shall take account of the relevant safety factors.

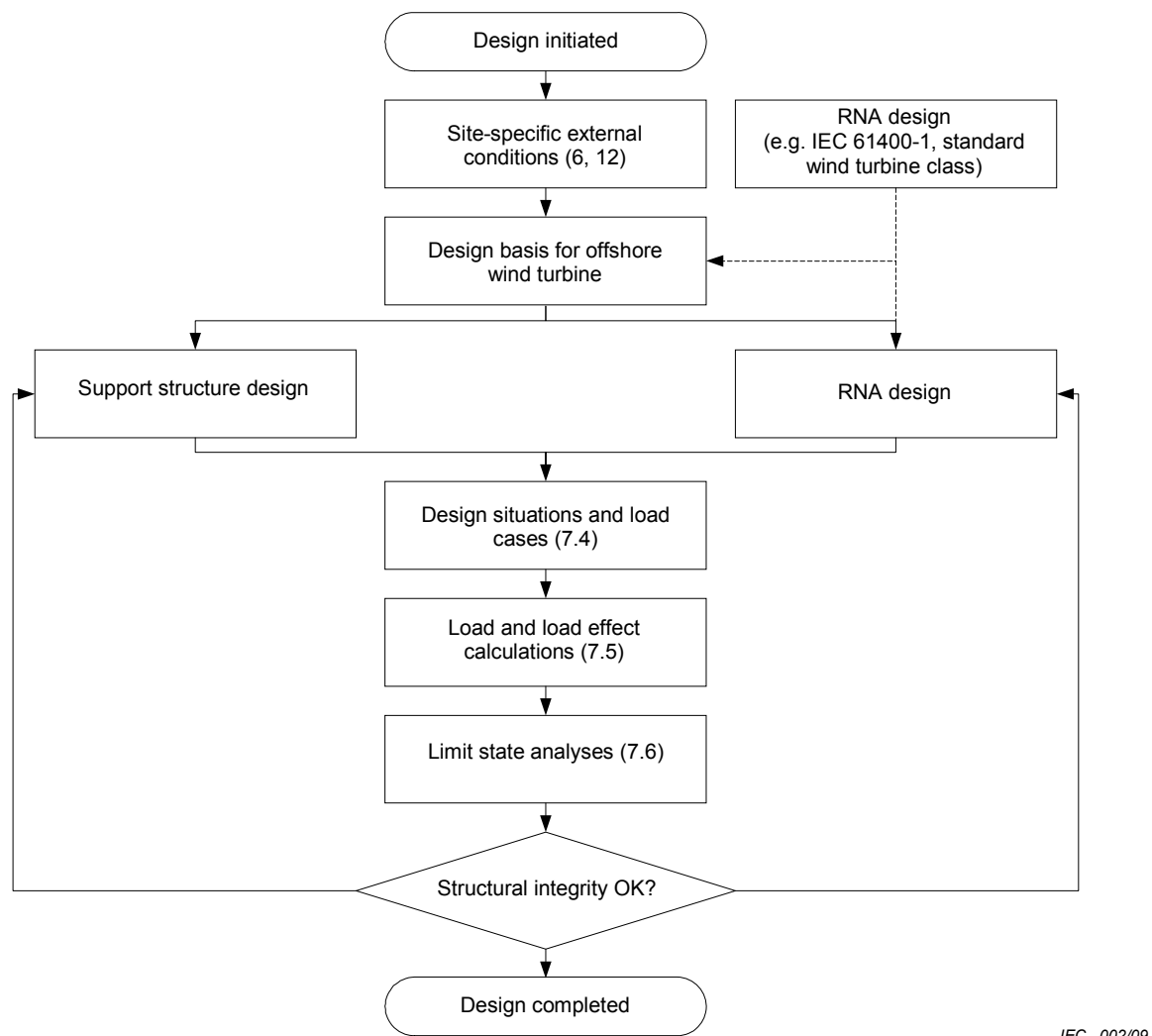


Figure 2 – Design process for an offshore wind turbine

5.3 Safety classes

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

- a normal safety class that applies when a failure results in risk of personal injury or other social or economic consequence;
- a special safety class that applies when the safety requirements are determined by local regulations and/or the safety requirements are agreed between the manufacturer and the customer.

Partial safety factors for normal safety class wind turbines are specified in 7.6 of this standard.

Partial safety factors for special safety class wind turbines shall be agreed between the manufacturer and the customer. An offshore wind turbine designed according to the special safety class is a class S turbine as defined in 6.2.

5.4 Quality assurance

Quality assurance shall be an integral part of the design, procurement, manufacture, installation, operation and maintenance of offshore wind turbines and all their components.

It is recommended that the quality system complies with the requirements of ISO 9001.

5.5 Rotor – nacelle assembly markings

The following information, as a minimum, shall be prominently and legibly displayed on the indelibly marked rotor – nacelle assembly nameplate:

- manufacturer and country;
- model and serial number;
- production year;
- rated power;
- reference wind speed, V_{ref} ;
- hub height operating wind speed range, $V_{\text{in}} - V_{\text{out}}$;
- operating ambient temperature range;
- IEC wind turbine class (see IEC 61400-1);
- rated voltage at the wind turbine terminals;
- frequency at the wind turbine terminals or frequency range in the case that the nominal variation is greater than 2 %.

6 External conditions

6.1 General

The external conditions described in this clause shall be considered in the design of an offshore wind turbine.

Offshore wind turbines are subjected to environmental and electrical conditions that may affect their loading, durability and operation. To ensure the appropriate level of safety and reliability, environmental, electrical and soil parameters shall be taken into account in the design and shall be explicitly stated in the design documentation.

The environmental conditions are divided into wind conditions, marine conditions (waves, sea currents, water level, sea ice, marine growth, seabed movement and scour) and other environmental conditions. The electrical conditions refer to the network conditions.

Account shall be taken of the soil properties at the site, including their time variation due to seabed movement, scour and other elements of seabed instability.

Wind conditions are the primary external consideration for the structural integrity of the rotor – nacelle assembly, although the marine conditions may also have an influence in some cases depending on the dynamic properties of the support structure. In all cases, including the case that the influence of marine conditions is shown to be of negligible importance during the design of the rotor – nacelle assembly, the structural integrity shall be demonstrated taking proper account of the marine conditions at each specific site at which the offshore wind turbine will be subsequently installed.

Other environmental conditions also affect design features such as control system function, durability, corrosion, etc.

The external conditions are subdivided into normal and extreme categories. The normal external conditions generally concern recurrent structural loading conditions, while the extreme external conditions represent rare external design conditions. The design load cases shall consist of potentially critical combinations of these external conditions with wind turbine operational modes and other design situations.

The normal and extreme conditions to be considered in design are prescribed in the following subclauses.

6.2 Wind turbine classes

The external conditions to be considered in design are dependent on the intended site or site type for an offshore wind turbine installation. In IEC 61400-1 wind turbine classes are defined in terms of wind speed and turbulence parameters. The intention of the classes is to cover most onshore applications.

For an offshore wind turbine the definition of wind turbine classes in terms of wind speed and turbulence parameters remains appropriate as the basis of design of the rotor – nacelle assembly.

A further wind turbine class, class S, is defined for use when special wind or other external conditions or a special safety class, (see 5.3), is required by the designer and/or the customer.

In addition to wind speed and turbulence intensity, which define the wind turbine classes, several other important parameters, notably marine conditions, are required to specify completely the external conditions to be used in the design of an offshore wind turbine. The values of these additional parameters are specified in 6.3, 6.4, 6.5 and 6.6.

The design lifetime shall be at least 20 years.

The manufacturer shall in the design documentation describe the models used and values of essential design parameters. Where the models in Clause 6 are adopted, a statement of the values of the parameters will be sufficient. The design documentation should contain the information listed for guidance in Annex A.

The abbreviations added in parentheses in the subclause headings in the remainder of this clause are used for describing the wind conditions for the design load cases defined in 7.4.

6.3 Wind conditions

An offshore wind turbine shall be designed to safely withstand the wind conditions adopted as the basis of design.

The wind regime for load and safety considerations is divided into the normal wind conditions which will occur more frequently than once per year during normal operation of an offshore wind turbine, and the extreme wind conditions which are defined as having a 1-year or 50-year recurrence period.

The design of the support structure of an offshore wind turbine shall be based on wind conditions which are representative of the offshore wind turbine site and which shall be assessed in accordance with the requirements stated in Clause 12.

For the rotor – nacelle assembly, the wind conditions assumed for design may be site-specific or as defined by the models and parameter values specified in IEC 61400-1, although in this latter case, it shall be demonstrated subsequently that site-specific external conditions do not compromise the structural integrity. In the case that the wind conditions specified in IEC 61400-1 are used as the basis of design of the rotor – nacelle assembly, the following exceptions to the models and parameter values may be assumed:

- the inclination of the mean flow with respect to a horizontal plane is zero;
- the wind profile, $V(z)$, denotes the average wind speed as a function of height, z , above the still water level. In the case of standard wind turbine classes, the normal wind speed profile is given by the power law:

$$V(z) = V_{\text{hub}} (z/z_{\text{hub}})^{\alpha} \quad (3)$$

where, for normal wind conditions, the power law exponent, α , is 0,14.

The occurrences of the extreme wind speed averaged over three seconds (V_{e50} , V_{e1}) and the extreme wave height (H_{50} , H_1) are assumed to be uncorrelated and their combination is conservative. The following reduced extreme wind speeds (RWM) shall therefore be used in combination with the extreme wave heights:

$$V_{\text{red50}}(z) = 1,1 V_{\text{ref}}(z/z_{\text{hub}})^{0,11} \quad (4)$$

and

$$V_{\text{red1}}(z) = 0,8 V_{\text{red50}}(z) \quad (5)$$

6.4 Marine conditions

An offshore wind turbine shall be designed to withstand safely the marine conditions adopted as the basis of design. The marine conditions described in this clause include waves, sea currents, water level, sea ice, marine growth, scour and seabed movement. Other external conditions relevant to the offshore environment are defined in 6.5.

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

The designer shall consider the influence of marine conditions on the rotor – nacelle assembly. In most cases, the rotor – nacelle assembly of an offshore wind turbine will be designed not for a specific site but rather to be suitable for a wide range of marine environments. The designer may therefore assume generic marine conditions which reflect an environment at least as severe as is anticipated for the use of the wind turbine. Depending on the dynamic properties of the support structure and the assumed design marine conditions, the designer may in some cases demonstrate by means of an appropriate analysis that the marine environment has a negligible influence on the structural integrity of the rotor – nacelle assembly.

The marine conditions for load and safety considerations are divided into the normal marine conditions which will occur more frequently than once per year during normal operation of an offshore wind turbine, and the extreme marine conditions which are defined as having a 1-year or 50-year recurrence period¹.

6.4.1 Waves

Waves are irregular in shape, vary in height, length and speed of propagation, and may approach an offshore wind turbine from one or more directions simultaneously. The features of a real sea are best reflected by describing a sea state by means of a stochastic wave model. The stochastic wave model represents the sea state as the superposition of many small individual frequency components, each of which is a periodic wave with its own amplitude, frequency and direction of propagation; the components have random phase relationships to each other. A design sea state shall be described by a wave spectrum, S_{η} , together with the significant wave height, H_s , a peak spectral period, T_p , and a mean wave direction, θ_{wm} . Where appropriate, the wave spectrum may be supplemented with a directional spreading function. Standard wave spectrum formulations are provided in Annex B.

¹ The normal range of water levels is, however, defined in this standard as the variation in water level with a recurrence period of 1 year, refer to 6.4.3.1.

In some applications, periodic or regular waves can be used as an abstraction of a real sea for design purposes. A deterministic design wave shall be specified by its height, period and direction.

The correlation of wind conditions and waves shall be taken into account for the design of an offshore wind turbine. This correlation shall be considered in terms of the long term joint probability distribution of the following parameters:

- mean wind speed, V ;
- significant wave height, H_s ;
- peak spectral period, T_p .

The joint probability distribution of these parameters is affected by local site conditions such as fetch, water depth, bathymetry, etc. The distribution shall therefore be determined from suitable long term measurements supported, where appropriate, by the use of numerical hindcasting techniques, refer to 12.4.

The correlation of normal wind conditions and waves may also include consideration of mean wind and wave directions. The distributions of wind and wave directions (multi-directional) may, in some cases, have an important influence on the loads acting on the support structure. The importance of this influence will depend on the nature of the wind and wave directionality and the extent to which the support structure is axi-symmetric. The designer may, in some cases, demonstrate by appropriate analysis that it is conservative and therefore acceptable to assume that the wind and waves are aligned (co-directional) and acting from a single, worst case direction (uni-directional). The assumptions regarding wind and wave directions are considered for each design load case in 7.4.

When taking account of the wind and wave misalignment, particular care shall be taken to ensure that the directional data and wind turbine modelling techniques are reliable, refer to 7.5.

Wave models are defined below in terms of both stochastic sea state representations and regular design waves. The stochastic sea state models shall be based on a wave spectrum appropriate to the site anticipated for the offshore wind turbine.

6.4.1.1 Normal sea state (NSS)

The significant wave height, peak spectral period and direction for each normal 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.

For fatigue load calculations, the designer shall ensure that 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.

For ultimate load calculations normal sea states shall, with the exception described in 7.4.1, be those sea states characterised by the expected value of the significant wave height, H_s , conditioned on a given value of mean wind speed. The designer shall take account of the range of peak spectral period, T_p , appropriate to each significant wave height. Design calculations shall be based on values of peak spectral period which result in the highest loads acting on the offshore wind turbine.

6.4.1.2 Normal wave height (NWH)

The height of the normal deterministic design wave, H_{NWH} , shall be assumed equal to the expected value of the significant wave height conditioned on a given value of the mean wind speed, $H_{s,NSS}$.

The designer shall take account of the range of wave period, T , appropriate to each normal wave height. The wave periods to be used in combination with the normal wave heights may be assumed to be within the range given by

$$11,1 \sqrt{H_{s,NSS}(V)/g} \leq T \leq 14,3 \sqrt{H_{s,NSS}(V)/g} \quad (6)$$

Design calculations based on NWH shall assume values of wave period within this range² that result in the highest loads acting on the offshore wind turbine.

6.4.1.3 Severe sea state (SSS)

The severe stochastic sea state model shall be considered in combination with normal wind conditions for calculation of the ultimate loading of an offshore wind turbine during power production. The severe sea state model associates a severe sea state with each wind speed in the range corresponding to power production. The significant wave height, $H_{s,SSS}(V)$, for each severe sea state shall in general be determined by extrapolation of appropriate site-specific metocean data such that the combination of the significant wave height and the wind speed has a recurrence period of 50 years³. For all wind speeds, the unconditional extreme significant wave height, H_{s50} , with a recurrence period of 50 years may be used as a conservative value for $H_{s,SSS}(V)$.

The designer shall take account of the range of peak spectral period, T_p , appropriate to each significant wave height. Within this range, design calculations shall be based on values of the peak spectral period that result in the highest loads acting on an offshore wind turbine.

6.4.1.4 Severe wave height (SWH)

The severe deterministic design wave shall be considered in combination with normal wind conditions for calculation of the ultimate loading of an offshore wind turbine during power production. The severe wave height model associates a severe wave height with each mean wind speed in the range corresponding to power production. The severe wave height $H_{SWH}(V)$ shall in general be determined by extrapolation of appropriate site-specific metocean data so that the combination of the significant wave height and the mean wind speed has a recurrence period of 50 years⁴. For all mean wind speeds the unconditional extreme wave height, H_{50} , with a recurrence period of 50 years may be used as a conservative value for $H_{SWH}(V)$.

The designer shall take account of the range of wave period, T , appropriate to each severe wave height. The wave periods to be used in combination with the severe wave heights may be assumed to be within the range given by

$$11,1 \sqrt{H_{s,SSS}(V)/g} \leq T \leq 14,3 \sqrt{H_{s,SSS}(V)/g} \quad (7)$$

Design calculations based on SWH shall assume values of wave periods within this range that result in the highest loads acting on an offshore wind turbine.

² The wave period has a depth-dependent lower limit which is determined from the breaking wave height limit, refer to Annex C.

³ It is recommended that the extrapolation of metocean data be undertaken using the so-called Inverse First Order Reliability Method (IFORM). This method is described in Annex G which also gives guidance on how to determine $H_{s,SSS}(V)$ from site-specific environmental conditions.

⁴ As for the severe sea state model, see 6.4.1.3, it is recommended to use IFORM described in Annex G, which also gives guidance on how to determine $H_{SWH}(V)$ from $H_{s,SSS}(V)$.

6.4.1.5 Extreme sea state (ESS)

The extreme stochastic sea state model shall be considered for both the extreme significant wave height, H_{s50} , with a recurrence period of 50 years and the extreme significant wave height, H_{s1} , with a recurrence period of 1 year. The values of H_{s50} and H_{s1} shall be determined from analysis of appropriate measurements and/or hindcast data for the offshore wind turbine site, refer to 12.4. The designer shall take account of the range of peak spectral period, T_p appropriate to H_{s50} and H_{s1} respectively. Design calculations shall be based on values of peak spectral period which result in the highest loads acting on an offshore wind turbine.

In the absence of information defining the long term joint probability distribution of extreme wind and waves, it shall be assumed that the extreme 10-min mean wind speed with a 50-year recurrence period occurs during the extreme 3-hour sea state with a 50-year recurrence period. The same assumption shall apply with regard to the combination of the extreme 10-min wind speed and the extreme 3-hour sea state each with a 1-year recurrence period.

6.4.1.6 Extreme wave height (EWH)

The extreme deterministic design wave shall be considered for both the extreme wave height, H_{50} , with a recurrence period of 50 years and the extreme wave height, H_1 , with a recurrence period of 1 year. The values of H_{50} , H_1 , and the associated wave periods may be determined from analysis of appropriate measurements at the offshore wind turbine site, refer to 12.4. Alternatively, assuming a Rayleigh distribution of wave heights, it may be assumed that:

$$H_{50} = 1,86 H_{s50} \quad (8)$$

and

$$H_1 = 1,86 H_{s1} \quad (9)$$

where the significant wave heights H_{s50} and H_{s1} are values for a 3-hour reference period.

The wave period to be taken in combination with these extreme wave heights may then be assumed to be within the range given by

$$11,1 \sqrt{H_{s,ESS}(V)/g} \leq T \leq 14,3 \sqrt{H_{s,ESS}(V)/g} \quad (10)$$

Design calculations based on EWH shall assume values of wave period within this range which result in the highest loads acting on the offshore wind turbine.

For shallow water sites the extreme wave heights H_{50} , H_1 and associated wave periods shall be determined from analysis of appropriate site-specific measurements. Where such measurements are not available, H_{50} and H_1 shall be assumed equal to the breaking wave height in cases where the latter is less than the values of H_{50} and H_1 determined from the Rayleigh distribution relationships above. Annex C provides guidance to determine the nature and dimensions of breaking waves based on site conditions. The informative annex also presents an empirical model of the distribution of wave heights for shallow foreshores.

6.4.1.7 Reduced wave height (RWH)

The reduced deterministic design wave shall be considered for both the reduced wave height, H_{red50} , for the definition of the 50-year return event and the reduced wave height, H_{red1} , for the definition of the 1-year return event. The values of H_{red50} , H_{red1} shall be determined so that the simultaneous combination with the extreme wind speed averaged over 3 s (V_{e50} , V_{e1}) leads to the same probability of a more unfavourable combination occurring as the combination of the extreme wave height (H_{50} , H_1) and the reduced extreme wind speeds (V_{red50} , V_{red1}).

The values of H_{red50} , H_{red1} , and the associated wave periods may be determined from analysis of appropriate measurements at the offshore wind turbine site, refer to 12.4. Alternatively, assuming a Rayleigh distribution of wave heights, it may be assumed that:

$$H_{red50} = 1,3 H_{s50} \quad (11)$$

and

$$H_{red1} = 1,3 H_{s1} \quad (12)$$

where the significant wave heights H_{s50} and H_{s1} are values for a 3-hour reference period.

These relationships have been derived from consideration of the joint probability statistics of the stochastic variations of wind speed from the 10-min average and the variation of individual wave heights. The derivation has assumed a Gaussian probability distribution of wind speed variations and a Rayleigh distribution of wave heights. The Rayleigh distribution of wave heights may not be valid for shallow water locations due to the occurrence of breaking waves. For shallow water sites, the reduced wave heights H_{red50} , H_{red1} and associated wave periods shall be determined from analysis of appropriate site-specific measurements. Where such measurements are not available, H_{red50} and H_{red1} shall be assumed equal to the breaking wave height in cases where the latter is less than the values of H_{red50} and H_{red1} determined from the Rayleigh distribution relationships above. Annex C presents an empirical model of the distribution of wave heights for shallow foreshores.

6.4.1.8 Breaking waves

The influence of breaking waves shall be assessed during the design of an offshore wind turbine. Breaking waves are classified as spilling, plunging or surging; the first two types being relevant to sites suitable for offshore wind turbines. The water depth, sea floor slope and wave period determine whether the breaker is spilling or plunging.

Annex C provides guidance relating to shallow water hydrodynamics and the influence of site characteristics on the nature and dimensions of breaking waves. Guidance is provided in Annex D relating to the calculation of the loading applied by a breaking wave to an offshore wind turbine support structure.

6.4.2 Sea currents

Although sea currents may, in principle, vary in space and time, they are generally considered as a horizontally uniform flow field of constant velocity and direction, varying only as a function of depth. The following components of sea current velocity shall be taken into account:

- sub-surface currents generated by tides, storm surge and atmospheric pressure variations, etc.;
- wind generated, near surface currents;
- near shore, wave induced surf currents running parallel to the coast.

The total current velocity is the vector sum of these components. Wave induced water particle velocities and current velocities shall be added vectorially. The influence of sea currents on the relationship between wave length and wave period is generally small and may therefore be neglected.

The influence of sea currents on the hydrodynamic fatigue loading of an offshore wind turbine may be insignificant in cases where the total current velocity is small compared to the wave induced water particle velocity in the wave crest and where vibrations of the support structure are unlikely to occur due to vortex shedding or moving ice floes. The designer shall determine

whether sea currents may be neglected for calculation of fatigue loads by means of an appropriate assessment of site-specific data.

6.4.2.1 Sub-surface currents

The sub-surface current profile may be characterised by a simple power law over the water depth d , where the current velocity $U_{ss}(z)$ is defined as a function of height z above SWL:

$$U_{ss}(z) = U_{ss}(0) [(z + d)/d]^{1/7} \quad (13)$$

The 1-year and 50-year recurrence values of the sea surface velocity $U_{ss}(0)$ may be determined from analysis of appropriate measurements at the offshore wind turbine site, refer to 12.5.

In general, it may be acceptable to assume that the sub-surface currents are aligned with the wave direction.

6.4.2.2 Wind generated, near surface currents

The wind generated current may be characterised as a linear distribution of velocity $U_w(z)$ reducing from the surface velocity $U_w(0)$ to zero at a depth of 20 m below SWL:

$$U_w(z) = U_w(0) (1 + z/20) \quad (14)$$

At sites where the water depth is less than 20 m, the wind generated current velocity at the sea floor will be non-zero.

The wind generated sea surface current velocity may be assumed to be aligned with the wind direction, and may be estimated from

$$U_w(0) = 0,01 V_{1\text{-hour}}(z = 10 \text{ m}) \quad (15)$$

where $V_{1\text{-hour}}(z = 10 \text{ m})$ is defined as the 1-hour mean value of wind speed at 10 m height above SWL.

The 1-year and 50-year recurrence values of $V_{1\text{-hour}}(z = 10 \text{ m})$ may be determined from analysis of appropriate measurements at the offshore wind turbine site. These wind speeds may then be used with equation (15) to estimate the 1-year and 50-year recurrence values of wind generated sea surface current velocity.

6.4.2.3 Breaking wave induced surf currents

In the case where an offshore wind turbine is to be sited near a coastal breaking wave zone, consideration shall be given to the surf currents generated by the shear forces of the breaking waves.

The magnitude of breaking wave induced surf currents may be determined using a suitable numerical model (e.g. Boussinesq) taking account of the fully coupled wave and current kinematics. However, for near shore surf currents which have a direction parallel to the shore line, the design velocity U_{bw} at the location of breaking wave may be estimated from

$$U_{bw} = 2s \sqrt{gH_B} \quad (16)$$

where

H_B is the breaking wave height;

s is the sea floor slope, and
 g is the acceleration due to gravity.

The breaking wave height may be estimated based on the site characteristics as described in Annex C.

6.4.2.4 Normal current model (NCM)

The normal current model is defined as the appropriate site-specific combination of wind generated currents and breaking wave surf induced currents (if any) associated with normal wave conditions. The normal current model excludes tide and storm-generated sub-surface currents.

The normal current model shall be assumed for those ultimate load cases involving normal and severe wave conditions (NSS, NWH, SSS, SWH) and for each load case the velocity of the wind generated currents may be estimated from the relevant mean wind speed, refer to 6.4.2.2.

6.4.2.5 Extreme current model (ECM)

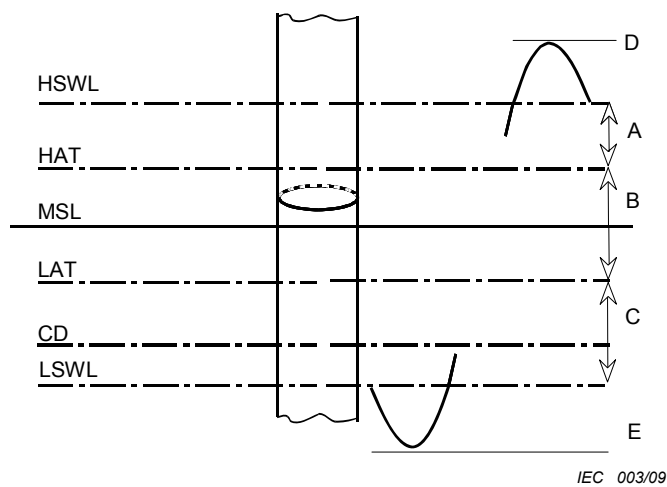
The extreme current model is defined as the appropriate site-specific combination of sub-surface currents, wind generated currents and breaking wave surf induced currents (if any) with recurrence periods of 1 and 50 years.

The extreme current model shall be assumed for those ultimate load cases involving extreme or reduced wave conditions (ESS, EWH, RWH). Sea currents with the same recurrence period as the waves shall be assumed for these load cases.

6.4.3 Water level

For the calculation of the hydrodynamic loading of an offshore wind turbine, the variation in water level (if significant) at the site shall be taken into account. A constant water level equal to the mean sea level (MSL) may, however, be assumed for ultimate load cases involving normal wave conditions (NSS, NWH) with the exception stated in 6.4.3.1 below.

Different water levels are illustrated in Figure 3.



Key:

HSWL	Highest still water level	A	Positive storm surge
HAT	Highest astronomical tide	B	Tidal range
MSL	Mean sea level	C	Negative storm surge
LAT	Lowest astronomical tide	D	Maximum crest elevation
CD	Chart datum (often equal to LAT)	E	Minimum trough elevation
LSWL	Lowest still water level		

Figure 3 – Definition of water levels

6.4.3.1 Normal water level range (NWLR)

The normal water level range shall be assumed equal to the variation in water level with a recurrence period of 1 year. In the absence of site-specific data to characterise the long term probability distribution of water levels, the normal water level range may be assumed to be equal to the variation between highest astronomical tide (HAT) and lowest astronomical tide (LAT).

The NWLR shall be assumed for those fatigue and ultimate load cases involving the normal sea state model (NSS) based on the joint probability distribution of sea state conditions and wind speed (H_s, T_p, V_{hub}). The NWLR range shall also be assumed for ultimate load cases associated with

- severe sea state (SSS) and severe wave height (SWH) models;
- wave conditions with a recurrence period of 1 year.

Ultimate load calculations shall be undertaken based on either the water level within the NWLR that results in the highest loads, or by appropriate consideration of the probability distribution of water levels within the NWLR.

For ultimate load cases associated with the severe stochastic sea state (SSS) and severe wave height (SWH) models, the water levels corresponding to NWLR may cause the wave heights to be depth-limited. If this is the case, and in order to avoid the wave heights being depth-limited, a higher water level within the extreme water level range (EWLR) shall then be assumed.

For the calculation of the hydrodynamic fatigue loads the designer may in some cases demonstrate by means of an appropriate analysis that the influence of water level variation on fatigue loads is negligible or can be accounted for in a conservative manner by assuming a constant water level greater than or equal to the mean sea level.

6.4.3.2 Extreme water level range (EWLR)

The extreme water level range shall be assumed for ultimate load cases associated with wave conditions with a recurrence period of 50 years. Load calculations shall be undertaken based on the water levels which result in the highest loads acting on an offshore wind turbine. The relevant design driving water levels shall be determined for calculation of the hydrodynamic loading, ice loading and buoyancy of the support structure.

In the absence of the long term joint probability distribution of metocean parameters including water level, the designer shall at least undertake calculations based on the following water levels:

- highest still water level with a recurrence period of 50 years, based on an appropriate combination of highest astronomical tide and positive storm surge;
- lowest still water level with a recurrence period of 50 years, based on an appropriate combination of lowest astronomical tide and negative storm surge;
- water level associated with the highest breaking wave load.

6.4.4 Sea ice

At some locations, loading of the support structure of an offshore wind turbine due to sea ice can be critical. The ice loads may be associated with static loading from a fast ice cover, or dynamic loading caused by wind and current induced motion of ice floes. Moving ice floes impacting the support structure over a considerable period of time may result in significant fatigue loading. A site-specific assessment of the occurrence and properties of the sea ice shall be undertaken as stated in 12.7.

Annex E provides guidance with regard to ice load calculations.

6.4.5 Marine growth

Marine growth influences the mass, the geometry, and the surface texture of the support structure of an offshore wind turbine. Consequently, marine growth may influence hydrodynamic loads, dynamic response, accessibility and corrosion rate of the structure.

Marine growth may be considerable at some locations and shall be taken into account in the design of the support structure.

Marine growth is broadly divided into “hard” (generally animal such as mussels and barnacles) and “soft” (seaweeds and kelps), where hard growth is generally thinner but rougher than soft growth. Marine organisms generally colonize a structure soon after installation but the growth rate tapers off after a few years.

The nature and thickness of marine growth depends on the structural member’s position relative to the sea level, orientation relative to dominant current, age and maintenance strategy; but also on other site conditions such as salinity, oxygen content, pH value, current, and temperature.

The corrosion environment is normally modified by marine growth in the upper submerged zone and the lower part of the splash zone of the support structure. Depending on the type of marine growth and other local conditions, the net effect may be either to enhance or retard corrosion attack. Enhancement of corrosion processes by marine growth (e.g. through corrosive metabolites) is commonly referred to as Microbiologically Influenced Corrosion (MIC). Marine

growth may further interfere with systems for corrosion control, including coatings/linings and cathodic protection.

Due to the uncertainties involved in assumptions regarding marine growth, a strategy for inspection and possible removal of marine growth should be planned as part of the support structure design. The frequency, inspection method and growth removal criteria shall be based on the impact of marine growth on the structural reliability of an offshore wind turbine, and the extent of experience with marine growth under the specific conditions prevailing at the site.

6.4.6 Seabed movement and scour

The support structure of an offshore wind turbine shall be designed taking account of the influence of seabed movement and scour. The analysis of seabed movement and scour, and the design of appropriate protection shall conform to the requirements of ISO 19901-4. Requirements regarding the assessment of seabed conditions are stated in 12.9.

6.5 Other environmental conditions

Environmental (climatic) conditions other than wind and marine conditions can affect the integrity and safety of an offshore wind turbine, by thermal, photochemical, corrosive, mechanical, electrical or other physical action. Moreover, combinations of the climatic parameters given may increase their effects.

The following other environmental conditions, at least, shall be taken into account and the action taken stated in the design documentation:

- air temperature;
- humidity;
- air density;
- solar radiation;
- rain, hail, snow and ice;
- chemically active substances;
- mechanically active particles;
- salinity causing corrosion;
- lightning;
- seismicity causing earthquakes;
- water density;
- water temperature;
- traffic.

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

Variations in the climatic conditions within the normal limits which correspond to a 1-year recurrence period or more often shall not interfere with the designed normal operation of an offshore wind turbine.

Unless correlation exists, other extreme environmental conditions according to 6.5.2 shall be combined with the normal wind conditions according to IEC 61400-1 and normal marine conditions according to 6.4.

6.5.1 Normal other environmental conditions

The normal other environmental condition values that should be taken into account, are:

- ambient air temperature range of $-10\text{ }^{\circ}\text{C}$ to $+40\text{ }^{\circ}\text{C}$;
- relative humidity of up to 100 %;
- solar radiation intensity of $1\,000\text{ W/m}^2$;
- air density of $1,225\text{ kg/m}^3$;
- water density of 1025 kg/m^3 ;
- water temperature range⁵ of $0\text{ }^{\circ}\text{C}$ to $+35\text{ }^{\circ}\text{C}$.

When additional external conditions are specified by the designer, the parameters and their values shall be stated in the design documentation and shall conform to the requirements of IEC 60721-2-1.

6.5.2 Extreme other environmental conditions

The extreme other environmental conditions that shall be considered for design of an offshore wind turbine are temperature, lightning, ice, and earthquakes.

6.5.2.1 Temperature

The extreme air temperature range for offshore wind turbines in the standard wind turbine classes should be at least $-20\text{ }^{\circ}\text{C}$ to $+50\text{ }^{\circ}\text{C}$.

6.5.2.2 Lightning

The provisions of lightning protection required in IEC 61400-1 may be considered as adequate for offshore wind turbines in the standard wind turbine classes.

6.5.2.3 Icing

No minimum ice requirements are given for offshore wind turbines in the standard wind turbine classes. Ice build-up on the wind turbine parts shall be considered from

- moisture and debris at temperatures around and below $0\text{ }^{\circ}\text{C}$;
- spray of the wave crest at temperatures below $0\text{ }^{\circ}\text{C}$.

6.5.2.4 Earthquakes

No minimum earthquake requirements are given for offshore wind turbines in the standard wind turbine classes. For consideration of earthquake conditions and effects see IEC 61400-1.

6.6 Electrical power network conditions

The normal conditions at the offshore wind turbine terminals to be considered are listed below.

Normal electrical power network conditions apply when the following parameters fall within the ranges stated below:

- voltage – nominal value (according to IEC 60038) $\pm 10\text{ }%$;
- frequency – nominal value $\pm 2\text{ }%$;

⁵ The ambient air and water temperatures shall be 1-hour average values.

- voltage imbalance – the ratio of the negative-sequence component of voltage not exceeding 2 %;
- auto-reclosing cycles – auto-reclosing cycle periods of 0,1 s to 5 s for the first reclosure and 10 s to 90 s for a second reclosure shall be considered;
- outages – electrical network outages shall be assumed to occur 20 times per year. An outage of up to 6 h⁶ shall be considered a normal condition. An outage of up to 3 months shall be considered an extreme condition.

7 Structural design

7.1 General

The integrity of the load-carrying components of an offshore wind turbine structure shall be verified and an acceptable safety level shall be ascertained. The ultimate and fatigue strength of structural members shall be verified by calculations and/or tests to demonstrate the structural integrity of an offshore wind turbine with the appropriate safety level.

The structural analysis shall be based on ISO 2394.

Calculations shall be performed using appropriate methods. Descriptions of the calculation methods shall be provided in the design documentation. The descriptions shall include evidence of the validity of the calculation methods or references to suitable verification studies. The load level in any test for strength verification shall correspond with the safety factors appropriate for the characteristic loads according to 7.6.

7.2 Design methodology

It shall be verified that limit states are not exceeded for a wind turbine design. Model testing and prototype tests may also be used as a substitute for calculation to verify the structural design, as specified in ISO 2394.

7.3 Loads

Loads described in 7.3.1, through 7.3.6, shall be considered for the design calculations.

7.3.1 Gravitational and inertial loads

Gravitational and inertial loads are static and dynamic loads resulting from gravity, vibration, rotation and seismic activity.

7.3.2 Aerodynamic loads

Aerodynamic loads are static and dynamic loads that are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.

The airflow is dependent upon the average wind speed and turbulence across the rotor plane, the rotational speed of the rotor, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including aeroelastic effects.

7.3.3 Actuation loads

Actuation loads result from the operation and control of wind turbines. They are in several categories including torque control from a generator/inverter, yaw and pitch actuator loads and mechanical braking loads. In each case, it is important in the calculation of response and

⁶ Six hours of operation is assumed to correspond to the duration of the severest part of a storm.

loading to consider the range of actuator forces available. In particular, for mechanical brakes, the range of friction, spring force or pressure as influenced by temperature and ageing shall be taken into account in checking the response and the loading during any braking event.

7.3.4 Hydrodynamic loads

Hydrodynamic loads are dynamic loads which are caused by the water flow and its interaction with the support structure of an offshore wind turbine.

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

Those parts of an offshore wind turbine support structure which are not designed to be exposed to hydrodynamic loads shall be positioned at a height with a minimum clearance relative to the expected value of the highest crest elevation with a recurrence period of 50 years, accounting for the highest astronomical tide, positive storm surge, the crest height of the extreme wave, and motion of the support structure. The minimum clearance, referred to as the air gap, shall be defined as $0,2 \times H_{s50}$ but with a minimum value of 1 m.

Hydrodynamic loads arising from wave “run-up” should be considered, particularly for the design of appurtenances.

7.3.5 Sea ice loads

Sea ice loads acting on an offshore wind turbine are both static and dynamic loads. Static loads have their origin either in temperature fluctuations or changes in water level in a fast ice cover. Dynamic loads are caused by wind and current induced motion of ice floes and their failure in contact with the support structure.

The relevance of ice loads, at sea or in lakes, to the design of the support structure depends on the specific location and characteristics of the offshore wind turbine site. Guidance with regard to ice load calculations is provided in Annex E.

7.3.6 Other loads

Other loads such as wake loads, impact loads, ice loads, etc., may occur and shall be included where appropriate.

Where relevant, earthquake loads shall be considered according to IEC 61400-1. In addition, hydrodynamic loads from waves resulting from sub-sea earthquakes (tsunamis) may need to be considered.

Hydrostatic loads acting on the support structure because of internal and external pressures and resulting buoyancy shall be taken into account where appropriate.

7.4 Design situations and load cases

This subclause describes the design load cases for an offshore wind turbine and specifies a minimum number to be considered.

For design purposes, the life of an offshore wind turbine can be represented by a set of design situations covering the most significant conditions that an offshore wind turbine may experience.

The load cases shall be determined from the combination of operational modes or other design situations, such as specific assembly, erection or maintenance conditions, with the load ha

conditions. All relevant load cases with a reasonable probability of occurrence shall be considered, together with the behaviour of the control and protection system. The design load cases used to verify the structural integrity of an offshore wind turbine shall be calculated by combining:

- normal design situations and appropriate normal or extreme external conditions;
- fault design situations and appropriate external conditions;
- transportation, installation and maintenance design situations and appropriate external conditions.

If correlation exists between an extreme external condition and a fault situation, a realistic combination of the two shall be considered as a design load case.

Within each design situation several design load cases shall be considered. As a minimum the design load cases in Table 1 shall be considered. In that table, the design load cases are specified for each design situation by the description of the wind, marine, electrical and other external conditions. Additionally, if the offshore wind turbine is to be installed at a site where sea ice is expected to occur, the design load cases presented in Table 2 shall be considered.

If the offshore wind turbine controller could, during design load cases with a deterministic wind model, cause a wind turbine to shutdown prior to reaching maximum yaw angle and/or wind speed, then it must be shown that the turbine can reliably shutdown under turbulent conditions with the same deterministic wind condition change.

Other design load cases shall be considered, if relevant to the structural integrity of the specific wind turbine design.

For each design load case, the appropriate type of analysis is stated by “F” and “U” in Table 1. “F” refers to analysis of fatigue loads, to be used in the assessment of fatigue strength. “U” refers to the analysis of ultimate loads, with reference to material strength, blade tip deflection and structural stability.

The design load cases indicated with “U”, are classified as normal (N), abnormal (A), or transport and erection (T). Normal design load cases are expected to occur frequently within the lifetime of a turbine. The turbine is in a normal state or may have experienced minor faults or abnormalities. Abnormal design situations are less likely to occur. They usually correspond to design situations with severe faults that result in activation of system protection functions. The type of design situation, N, A, or T, determines the partial safety factor γ_f to be applied to the ultimate loads. These factors are given in Table 3.

Table 1 – Design load cases

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$ RNA	NSS $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL	For extrapolation of extreme loads on the RNA	U	N (1,25)
	1.2	NTM $V_{in} < V_{hub} < V_{out}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or $\geq$ MSL		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL		U	N
	1.4	ECD $V_{hub} = V_r - 2 \text{ m/s}, V_r$ $V_r + 2 \text{ m/s}$	NSS (or NWH) $H_s = E[H_s V_{hub}]$	MIS, wind direction change	NCM	MSL		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL		U	N
	1.6a	NTM $V_{in} < V_{hub} < V_{out}$	SSS $H_s = H_{s,SSS}$	COD, UNI	NCM	NWLR		U	N
	1.6b	NTM $V_{in} < V_{hub} < V_{out}$	SWH $H = H_{SWH}$	COD, UNI	NCM	NWLR		U	N

Table 1 – Design load cases (continued)

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL	Control system fault or loss of electrical network	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL	Protection system or preceding internal electrical fault	U	A
	2.3	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	NSS (or NWH) $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	NSS $H_s = E[H_s V_{hub}]$	COD, UNI	No currents	NWLR or $\geq$ MSL	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s = E[H_s V_{hub}]$	COD, UNI	No currents	NWLR or $\geq$ MSL		F	*
	3.2	EOG $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}	NSS (or NWH) $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL		U	N
	3.3	EDC ₁ $V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and V_{out}	NSS (or NWH) $H_s = E[H_s V_{hub}]$	MIS, wind direction change	NCM	MSL		U	N

Table 1 – Design load cases (continued)

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
4) Normal shut down	4.1	NWP $V_{in} < V_{hub} < V_{out}$	NSS (or NWH) $H_s = E[H_s V_{hub}]$	COD, UNI	No currents	NWLR or $\geq$ MSL		F	*
	4.2	EOG $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	NSS (or NWH) $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL		U	N
5) Emergency shut down	5.1	NTM $V_{hub} = V_r \pm 2 \text{ m/s}$ and V_{out}	NSS $H_s = E[H_s V_{hub}]$	COD, UNI	NCM	MSL		U	N
	6.1a	EWM Turbulent wind model $V_{hub} = k_1 V_{ref}$	ESS $H_s = k_2 H_{s50}$	MIS, MUL	ECM	EWLR		U	N
6) Parked (standing still or idling)	6.1b	EWM Steady wind model $V(z_{hub}) = V_{e50}$	RWH $H = H_{red50}$	MIS, MUL	ECM	EWLR		U	N
	6.1c	RWM Steady wind model $V(z_{hub}) = V_{red50}$	EWLH $H = H_{50}$	MIS, MUL	ECM	EWLR		U	N
	6.2a	EWM Turbulent wind model $V_{hub} = k_1 V_{ref}$	ESS $H_s = k_2 H_{s50}$	MIS, MUL	ECM	EWLR	Loss of electrical network	U	A
	6.2b	EWM Steady wind model $V(z_{hub}) = V_{e50}$	RWH $H = H_{red50}$	MIS, MUL	ECM	EWLR	Loss of electrical network	U	A
	6.3a	EWM Turbulent wind model $V_{hub} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	MIS, MUL	ECM	NWLR	Extreme yaw misalignment	U	N
	6.3b	EWM Steady wind model $V(z_{hub}) = V_{e1}$	RWH $H = H_{red1}$	MIS, MUL	ECM	NWLR	Extreme yaw misalignment	U	N
6.4	NTM $V_{hub} < 0,7 V_{ref}$		NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or $\geq$ MSL		F	*

Table 1 – Design load cases (continued)

Design situation	DLC	Wind condition	Waves	Wind and wave directionality	Sea currents	Water level	Other conditions	Type of analysis	Partial safety factor
7) Parked and fault conditions	7.1a	EWM Turbulent wind model $V_{\text{hub}} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	MIS, MUL	ECM	NWLR		U	A
	7.1b	EWM Steady wind model $V(z_{\text{hub}}) = V_{e1}$	RWH $H = H_{\text{red1}}$	MIS, MUL	ECM	NWLR		U	A
	7.1c	RWM Steady wind model $V(z_{\text{hub}}) = V_{\text{red1}}$	EWB $H = H_1$	MIS, MUL	ECM	NWLR		U	A
	7.2	NTM $V_{\text{hub}} < 0,7 V_1$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or $\geq$ MSL		F	*
	8.1	To be stated by the manufacturer							
8) Transport, assembly, maintenance and repair	8.2a	EWM Turbulent wind model $V_{\text{hub}} = k_1 V_1$	ESS $H_s = k_2 H_{s1}$	COD, UNI	ECM	NWLR		U	A
	8.2b	EWM Steady wind model $V_{\text{hub}} = V_{e1}$	RWH $H = H_{\text{red1}}$	COD, UNI	ECM	NWLR		U	A
	8.2c	RWM Steady wind model $V(z_{\text{hub}}) = V_{\text{red1}}$	EWB $H = H_1$	COD, UNI	ECM	NWLR		U	A
	8.3	NTM $V_{\text{hub}} < 0,7 V_{\text{ref}}$	NSS Joint prob. distribution of H_s, T_p, V_{hub}	COD, MUL	No currents	NWLR or $\geq$ MSL	No grid during installation period	F	*

The following abbreviations are used in Table 1:

COD	co-directional (see 6.4.1)
DLC	design load case
ECD	extreme coherent gust with direction change (see IEC 61400-1)
ECM	extreme current model (see 6.4.2.5)
EDC	extreme direction change (see IEC 61400-1)
EOG	extreme operating gust (see IEC 61400-1)
ESS	extreme sea state (see 6.4.1.5)
EWH	extreme wave height (see, 6.4.1.6)
EWLR	extreme water level range (see 6.4.3.2)
EWM	extreme wind speed model (see IEC 61400-1)
EWS	extreme wind shear (see IEC 61400-1)
MIS	misaligned (see 6.4.1)
MSL	mean sea level (see 6.4.3)
MUL	multi-directional (see 6.4.1)
NCM	normal current model (see 6.4.2.4)
NTM	normal turbulence model (see IEC 61400-1)
NWH	normal wave height (see 6.4.1.2)
NWLR	normal water level range (6.4.3.1)
NWP	normal wind profile model (see IEC 61400-1)
NSS	normal sea state (see 6.4.1.1)
RWH	reduced wave height (see 6.4.1.7)
RWM	reduced wind speed model (see 6.3)
SSS	severe sea state (see 6.4.1.3)
SWH	severe wave height (see 6.4.1.4)
UNI	uni-directional (see 6.4.1)
$V_r \pm 2$ m/s	sensitivity to all wind speeds in the range shall be analysed
F	fatigue (see 7.6.3)
U	ultimate strength (see 7.6.2)
N	normal
A	abnormal
T	transport and erection
*	partial safety factor for fatigue (see 7.6.3)

When a wind speed range is indicated in Table 1, wind speeds leading to the most adverse condition for wind turbine design shall be considered. The range of wind speeds may be represented by a set of discrete values, in which case the resolution shall be sufficient to assure accuracy of the calculation⁷. In the definition of the design load cases, reference is made to the wind and marine conditions described in Clause 6.

⁷ In general a resolution of 2 m/s is considered sufficient.

For calculation of the loads acting on the RNA and with the exception of those design load cases (DLC 1.4 and 3.3) that involve a transient change in mean wind direction, it may generally be assumed that the waves are always co-directional with the wind, and that both the wind and waves act from a single direction (uni-directional)⁸.

In general, co-directionality of the wind and waves may be assumed for calculation of the loads acting on the support structure for all design load cases except those (DLC 1.4 and 3.3) involving a transient change in mean wind direction and those corresponding to the wind turbine in a parked (standing still or idling) design situation.

The multi-directionality of the wind and waves may, in some cases, have an important influence on the loads acting on the support structure depending primarily on the extent to which the support structure is non-axisymmetric. For some design load cases as indicated in Table 1, the load calculations may be undertaken by assuming that the wind and waves are acting from a single, worst case direction (uni-directional). In these cases, however, the structural integrity shall be verified by application of the calculated worst case loads to relevant directional orientations of the support structure.

The mean or extreme yaw misalignment to be considered for each design load case shall be as stated in IEC 61400-1. The yaw misalignment is defined as the horizontal deviation of the wind turbine rotor axis from the wind direction.

7.4.1 Power production (DLC 1.1 to 1.6)

In this design situation, an offshore wind turbine is running and connected to the electric load. The assumed wind turbine configuration shall take into account rotor imbalance. The maximum mass and aerodynamic imbalances (e.g. blade pitch and twist deviations) specified for rotor manufacture shall be used in the design calculations.

In addition, deviations from theoretical optimum operating situations such as yaw misalignment and control system tracking errors shall be taken into account in the analyses of operational loads.

DLC 1.1 and 1.2 embody the requirements for loads resulting from atmospheric turbulence (NTM) and stochastic sea states (NSS) that occur during normal operation of an offshore wind turbine throughout its lifetime.

Analysis of DLC 1.1 is required only for calculation of the ultimate loads acting on the RNA. The calculations for DLC 1.1 shall be based on statistical extrapolation of the load response results of multiple simulations of stochastic sea states and turbulent inflow for a range of mean wind speeds. The significant wave height for each individual sea state shall be taken as the expected value of the significant wave height conditioned on the relevant mean wind speed.

For DLC 1.2 a single value of significant wave height may be considered for each relevant mean wind speed. The designer shall, however, ensure that 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. The significant wave height, peak spectral period, wave direction and water level for each normal sea state shall be considered, together with the associated mean wind speed, based on the long term joint probability distribution of metocean parameters.

⁸ For DLC 1.4 and 3.3 the wind and waves may be assumed to be co-directional and uni-directional prior to the transient change in mean wind direction.

For DLC 1.2, normal sea state conditions (NSS) shall be assumed. The significant wave height, peak spectral period and direction for each normal 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 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.

DLC 1.3 embodies the requirements for ultimate loading resulting from extreme turbulence conditions. Normal sea state conditions (NSS) shall be assumed for this design load case and the significant wave height for each individual sea state shall be taken as the expected value of the significant wave height conditioned on the relevant mean wind speed.

DLC 1.4 and 1.5 specify transient cases which have been selected as potentially critical events in the life of an offshore wind turbine. For these load cases, normal sea state conditions (NSS) shall be assumed and the significant wave height for each individual sea state shall be taken as the expected value of the significant wave height conditioned on the relevant mean wind speed. Alternatively, the simulations may be performed using a normal deterministic design wave (NWH), where the height shall be assumed equal to the expected value of the significant wave height conditioned on the relevant mean wind speed.

For DLC 1.4 it may be assumed that the wind and waves are co-directional prior to the transient change in wind direction.

DLC 1.6a embodies the requirements for ultimate loading resulting from normal turbulence (NTM) and severe sea state (SSS) conditions. The significant wave height for each individual sea state shall be computed from the conditional distribution of significant wave heights for the relevant mean wind speed, as described in 6.4.1.3.

For DLC 1.6b, the height of the severe deterministic design wave (SWH) for each mean wind speed shall be computed as described in 6.4.1.4. Calculation of DLC 1.6b may be omitted if in the treatment of DLC 1.6a, the non-linear wave kinematics are properly represented in the dynamic simulations of the severe stochastic sea state.

For calculation of the loads acting on the RNA, the statistical analysis of DLC 1.1 simulation data shall include at least the calculation of extreme values of the blade root in-plane moment and out-of-plane moment and tip deflection. If the extreme values of these parameters are exceeded by the extreme design values derived for DLC 1.3, the further analysis of DLC 1.1 may be omitted. If the extreme design values of these parameters are not exceeded by the extreme design values derived for DLC 1.3, the factor c for the extreme turbulence model used in DLC 1.3 (see IEC 61400-1) may be increased until the extreme design values computed in DLC 1.3 are equal to or exceed the extreme design values of these parameters computed in DLC 1.1.

7.4.2 Power production plus occurrence of fault or loss of electrical network connection (DLC 2.1 - 2.4)

This design situation involves a transient event triggered by a fault or the loss of electrical network connection while the turbine is producing power. Any fault in the control and protection system, or internal fault in the electrical system, significant for wind turbine loading (such as generator short circuit) shall be considered. For DLC 2.1, the occurrence of faults relating to control functions or loss of electrical network connection shall be considered as normal events⁹. For DLC 2.2, rare events, including faults relating to the protection functions or internal electrical systems shall be considered as abnormal. For DLC 2.3, the potentially

⁹ For DLC 2.1, consideration should also be given to the design situation associated with ride-through of faults on the electrical network.

significant wind event, EOG, is combined with an internal or external electrical system fault (including loss of electrical network connection) and considered as an abnormal event. In this case, the timing of these two events shall be chosen to achieve the worst loading. If a fault or loss of electrical network connection does not cause an immediate shutdown and the subsequent loading can lead to significant fatigue damage, the likely duration of this situation along with the resulting fatigue damage in normal turbulence conditions (NTM) shall be evaluated in DLC 2.4.

For DLC 2.1, 2.2, 2.3 and 2.4, normal sea state conditions (NSS) shall be assumed and the significant wave height for each individual sea state shall be taken as the expected value of the significant wave height conditioned on the relevant mean wind speed. Alternatively, for DLC 2.3, the simulations may be performed using a normal deterministic design wave (NWH), where the height shall be assumed equal to the expected value of the significant wave height conditioned on the relevant mean wind speed.

7.4.3 Start up (DLC 3.1 to 3.3)

This design situation includes all the events resulting in loads on an offshore wind turbine during the transients from any standstill or idling situation to power production. The number of occurrences shall be estimated based on the control system behaviour.

For DLC 3.1, 3.2 and 3.3, normal sea state conditions (NSS) shall be assumed and the significant wave height for each individual sea state shall be taken as the expected value of the significant wave height conditioned on the relevant mean wind speed. Alternatively, the simulations for these load cases may be performed using a normal deterministic design wave (NWH), where the height shall be assumed equal to the expected value of the conditional distribution of significant wave heights for the relevant mean wind speed.

For DLC 3.3, it may be assumed that the wind and waves are co-directional prior to the transient change in wind direction.

7.4.4 Normal shut down (DLC 4.1 to 4.2)

This design situation includes all the events resulting in loads on an offshore wind turbine during normal transient situations from a power production situation to a standstill or idling condition. The number of occurrences shall be estimated based on the control system behaviour.

For DLC 4.1 and 4.2, normal sea state conditions (NSS) shall be assumed and the significant wave height for each individual sea state shall be taken as the expected value of the significant wave height conditioned on the relevant mean wind speed. Alternatively, the simulations may be performed using a normal deterministic design wave (NWH), where the height shall be assumed equal to the expected value of the significant wave height conditioned on the relevant mean wind speed.

7.4.5 Emergency shut down (DLC 5.1)

Loads arising from emergency shut down shall be considered.

For DLC 5.1, normal sea state conditions (NSS) shall be assumed and the significant wave height for each individual sea state shall be taken as the expected value of the significant wave height conditioned on the relevant mean wind speed.

7.4.6 Parked (standstill or idling) (DLC 6.1 to 6.4)

In this design situation, the rotor of a parked wind turbine is either in a standstill or idling condition. DLC 6.1, 6.2 and 6.3 shall be analysed to determine ultimate loads for this condition, whereas DLC 6.4 is concerned with fatigue loading.

For DLC 6.1 and 6.2, the combination of extreme wind and wave conditions shall be such that the global extreme environmental action has a combined recurrence period of 50 years. In the absence of information defining the long term joint probability distribution of extreme wind and waves, it shall be assumed that the extreme 10-min mean wind speed with 50-year recurrence period occurs during the extreme sea state with 50-year recurrence period. For DLC 6.3 the same assumption shall be applied with regard to the combination of the extreme 10-min mean wind speed and the extreme sea state each with a 1-year recurrence period.

DLC 6.1, 6.2 and 6.3 may be analysed using simulations of turbulent inflow and stochastic sea states, or by treatment of steady wind models in combination with deterministic design waves. Subsidiary load cases of DLC 6.1, 6.2 and 6.3 are defined in Table 1, based on these two approaches. For design load cases where the wind conditions are defined by EWM, either the steady extreme wind model or the turbulent extreme wind model shall be used as indicated in Table 1. If the steady extreme wind model or steady reduced wind model (RWM) is used, this shall be combined with a deterministic design wave and the response shall be estimated from a quasi-steady analysis with appropriate corrections for dynamic response, refer to Annex D.

In DLC 6.1, 6.2 and 6.3, misalignment of the wind and wave directions shall be considered for calculation of the loads acting on the support structure. Where appropriate site-specific measurements of wind and wave directions are available, these shall be used to derive the range of misalignment angles relevant to the combination of extreme wind and wave conditions associated with these design load cases. Load calculations shall then be based on values of misalignment within this range that result in the highest loads acting on the support structure.

In the absence of appropriate site-specific wind and wave directional data, the misalignment that results in the highest loads acting on the support structure shall be considered. If this misalignment exceeds 30°, the extreme wave height may be reduced due to the decay in severity of the sea state over the period associated with the change in wind direction which causes the misalignment¹⁰. The reduction of the extreme wave height shall be calculated taking account of the water depth, fetch and other relevant site-specific conditions.

If slippage in the wind turbine yaw system can occur at the characteristic load, the largest possible unfavourable slippage shall be added to the mean yaw misalignment. If the wind turbine has a yaw system where yaw movement is expected in the extreme wind situations (e.g. free yaw, passive yaw or semi-free yaw), the turbulent wind model shall be used and the yaw misalignment will be governed by the turbulent wind direction changes and the turbine yaw dynamic response. Also, if the wind turbine is subject to large yaw movements or change of equilibrium during a wind speed increase from normal operation to the extreme situation, this behaviour shall be included in the analysis.

In DLC 6.1, for an offshore wind turbine with active yaw system, a yaw misalignment of up to $\pm 15^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 8^\circ$ using the turbulent extreme wind model shall be imposed, provided that the absence of slippage in the yaw system can be assured.

¹⁰ The extreme wind and wave conditions may be assumed to be initially co-directional. As the storm passes over the site of the wind turbine, the wind direction may change causing a misalignment relative to the wave direction. During the time taken for a significant wind direction change, the severity of the wave conditions will have reduced.

For DLC 6.1a, the turbulent extreme wind model shall be taken together with the extreme sea state (ESS) conditions. The response shall be estimated using full dynamic simulation based on at least six 1-hour realizations for each combination of extreme wind speed and extreme sea state. In this case, the hub height mean wind speed, turbulence standard deviation and significant wave height shall be taken as 50-year recurrence values each referenced to a 1-hour simulation period. The 1-hour value of the 50-year recurrence mean wind speed may be obtained from the 10-min average by use of the conversion stated in Table 1:

$$V_{50,1\text{-hour}} = k_1 V_{50,10\text{-min}}; \quad k_1 = 0,95 \quad (17)$$

The 1-hour value of the turbulence standard deviation may be obtained from the 10-min value as follows:

$$\sigma_{i,1\text{-hour}} = \sigma_{i,10\text{-min}} + b; \quad b = 0,2 \text{ m/s} \quad (18)$$

The turbulence models given in IEC 61400-1 may be used together with the 1-hour values of 50-year recurrence mean wind speed and turbulence standard deviation given by equations (18) and (19).

The significant wave height for a 1-hour simulation period may be obtained from the value corresponding to a 3-hour reference period by the use of the conversion stated in Table 1 where, for deep water sites:

$$k_2 = 1,09 \quad (19)$$

At shallow water sites the value for k_2 given in equation (20) may be conservative and may be adjusted.

Realizations shorter than 1 h may be assumed if the designer is able to demonstrate that this will not reduce the estimated extreme response. Constrained wave methods may be used for this purpose, refer to Annex D. In the case of a constrained wave analysis based on a simulation period of 10 min, the hub height mean wind speed shall be taken as the 10 min value with a 50-year recurrence, the significant wave height shall be taken as the 3 h value with a 50-year recurrence and the embedded regular wave shall have the magnitude of the extreme wave height with a 50-year recurrence, H_{50} .

For DLC 6.1b, the steady extreme wind model shall be taken together with the reduced deterministic design wave (RWH) which has the reduced wave height, $H_{\text{red}50}$, with a recurrence period of 50 years.

For DLC 6.1c, the steady reduced wind model (RWM) shall be taken together with the extreme deterministic design wave (EDWH). In this case, the wind speed shall be assumed as $V_{\text{red}50}$ and the wave height shall be assumed equal to the extreme wave height, H_{50} , with a recurrence period of 50 years.

DLC 6.1b and 6.1c may be omitted if, in the treatment of DLC 6.1a, the non-linear wave kinematics are properly represented in the dynamic simulations of the extreme stochastic sea state.

In DLC 6.2, a loss of the electrical power network at an early stage in the storm containing the extreme wind situation, shall be assumed. Unless power back-up for the control and yaw system with a capacity of 6 h of wind turbine operation is provided, the effect of a wind direction change of up to $\pm 180^\circ$ shall be analysed.

For DLC 6.2a, the turbulent extreme wind model shall be taken together with the extreme sea state (ESS) conditions and the hub height mean wind speed and significant wave height shall be taken as 50-year recurrence values. The extreme response shall be estimated using the same methods as described above for DLC 6.1a.

For DLC 6.2b, the steady extreme wind model shall be taken together with the reduced deterministic design wave (RWH) which has the reduced wave height, H_{red50} , with a recurrence period of 50 years. DLC 6.2b may be omitted if in the treatment of DLC 6.2a, the non-linear wave kinematics are properly represented in the dynamic simulations of the extreme stochastic sea state.

In DLC 6.3, the extreme wind with a 1-year recurrence period shall be combined with an extreme yaw misalignment. An extreme yaw misalignment of up to $\pm 30^\circ$ using the steady extreme wind model or a mean yaw misalignment of $\pm 20^\circ$ using the turbulent wind model shall be assumed,

For DLC 6.3a, the turbulent extreme wind model shall be taken together with the extreme sea state (ESS) conditions and, in this case, the hub height mean wind speed and significant wave height shall be taken as 1-year recurrence values. The extreme response shall be estimated using the same methods as described above for DLC 6.1a.

For DLC 6.3b, the steady extreme wind model shall be taken together with the reduced deterministic design wave (RWH) which has the reduced wave height, H_{red1} , with a recurrence period of 1 year. DLC 6.3b may be omitted if, in the treatment of DLC 6.3a, the non-linear wave kinematics are properly represented in the dynamic simulations of the extreme stochastic sea state.

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 can occur to any component (e.g. from weight of idling blades) shall be considered. Particular account shall be taken of the resonant loading of the support structure due to excitation by the waves and influence by the low aerodynamic damping available from the rotor in a standstill or idling condition. Normal sea state conditions (NSS) shall be assumed. The significant wave height, peak spectral period and direction for each normal 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 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.

7.4.7 Parked plus fault conditions (DLC 7.1 to 7.2)

Deviations from the normal behaviour of a parked wind turbine, resulting from faults on the electrical network or in the wind turbine, shall require analysis. If any fault other than a loss of electrical power network produces deviations from the normal behaviour of the wind turbine in parked situations, the possible consequences shall be the subject of analysis.

In case of a fault in the yaw system, yaw misalignment of $\pm 180^\circ$ shall be considered. For any other fault, yaw misalignment shall be consistent with DLC 6.1.

In DLC 7.1, the fault condition shall be combined with extreme wind and wave conditions, so that the global extreme environmental action has a combined recurrence period of 1 year. In the absence of information defining the long term joint probability distribution of extreme wind and waves, it shall be assumed that the extreme 10-min mean wind speed with 1-year recurrence period occurs during the extreme sea state with 1-year recurrence period.

DLC 7.1 may be analysed using simulations of turbulent inflow and stochastic sea states, or by treatment of steady wind models in combination with deterministic design waves. Subsidiary load cases of DLC 7.1 are defined in Table 1 based on these two approaches. For design load cases, where the wind conditions are defined by EWM, either the steady extreme wind model or the turbulent extreme wind model shall be used, as indicated in Table 1. If the steady extreme wind model or steady reduced wind model (RWM) is used, this shall be combined with a deterministic design wave and the response shall be estimated from a quasi-steady analysis, with appropriate corrections for dynamic response, refer to Annex D.

In DLC 7.1, misalignment of the wind and wave directions shall be considered for calculation of the loads acting on the support structure. Where appropriate site-specific measurements of wind and wave directions are available, these shall be used to derive the range of misalignment angles relevant to the combination of extreme wind and wave conditions associated with this design load case. Load calculations shall then be based on values of misalignment within this range that result in the highest loads acting on the support structure.

In the absence of appropriate site-specific wind and wave directional data, the misalignment that results in the highest loads acting on the support structure shall be considered. If this misalignment exceeds 30°, the extreme wave height may be reduced due to the decay in severity of the sea state over the period associated with the change in wind direction which causes the misalignment. The reduction of the extreme wave height shall be calculated taking account of the water depth, fetch and other relevant site-specific conditions.

If slippage in the yaw system can occur at the characteristic load found in DLC 7.1, the largest unfavourable slippage possible shall be considered.

For DLC 7.1a, the turbulent extreme wind model shall be taken together with the extreme sea state (ESS) conditions. The extreme response shall be estimated using the same methods as described above for DLC 6.1a.

For DLC 7.1b, the steady extreme wind model shall be taken together with the reduced deterministic design wave (RWH) which has the reduced wave height, H_{red1} , with a recurrence period of 1 year.

For DLC 7.1c, the steady reduced wind model (RWM) shall be taken together with the extreme deterministic design wave (EWH). In this case, the wind speed shall be assumed as V_{red1} and the wave height shall be assumed equal to the extreme wave height, H_1 , with a recurrence period of 1 year.

DLC 7.1b and 7.1c may be omitted if in the treatment of DLC 7.1a the non-linear wave kinematics are properly represented in the dynamic simulations of the extreme stochastic sea state.

In DLC 7.2, the expected number of hours of non-power production time due to faults on the electrical network or in the wind turbine shall be considered for each wind speed and sea state where significant fatigue damage can occur to any components. Particular account shall be taken of the resonant loading of the support structure due to excitation by the waves and influenced by the low aerodynamic damping available from the rotor in a standstill or idling condition. Normal sea state conditions (NSS) shall be assumed. The significant wave height, peak spectral period and direction for each normal 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 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.

7.4.8 Transport, assembly, maintenance and repair (DLC 8.1 to 8.3)

For DLC 8.1, the manufacturer shall state all the wind conditions, marine conditions and design situations assumed for transport, assembly on site, access, maintenance and repair of an offshore wind turbine. The maximum stated wind conditions and marine conditions shall be considered in the design if they can produce significant loading on the wind turbine. The manufacturer shall allow sufficient margin between the stated conditions and the wind and marine conditions considered in design to give an acceptable safety level. Sufficient margin may be obtained by adding 5 m/s to the stated wind condition.

Loads occurring during transport, assembly, access, maintenance and repair of an offshore wind turbine shall be taken into account:

- weight of tools and mobile equipment;
- loads from operation of cranes;
- mooring and fendering loads from vessels serving the wind turbine;
- where relevant, loads associated with helicopter operations.

An impact of the support structure by the dedicated service vessel shall be considered and the analysis shall be performed in accordance with the requirements and guidelines of ISO 19902.

The design situation, the maximum size of the service vessel and the limiting external conditions for approach of an offshore wind turbine by the vessel shall be stated by the designer. The designer shall consider an impact not less than that caused by the service vessel coming into contact with the support structure at a speed of 0,5 m/s and considering an added mass coefficient of 1,4 for sideways collision and 1,1 for bow or stern collision. It shall be assumed, in this case, that all the kinetic energy associated with the impact is absorbed by the fendering installation. The loading associated with maximum wind and marine conditions allowed for service vessel access shall be combined with that due to the service vessel impact.

The energy absorbed by the support structure will depend on its stiffness in comparison to that of the impacting component of the vessel. In the case of a very stiff support structure, for example a concrete structure, the energy will be absorbed primarily by the vessel. Following a vessel impact, it is important to examine any damage to 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.

If information about the service vessel is not known by the designer, the impact force can normally be accounted for by applying 5 MN distributed as a horizontal line load over the whole width of the support structure. This load shall be considered to include dynamic amplification. The vertical extent of the collision zone shall be assessed on the basis of the vessel draft, and the maximum wave and tidal elevations allowed for service vessel access. In practice, the vertical position will vary between + 3 m to – 5 m relative to MSL. For local pressure calculation, a vertical extension of 2 m may be assumed.

Loading of an offshore wind turbine due to helicopter operations shall be considered where relevant. The design situation, the maximum size of helicopter and the limiting external conditions for approach of an offshore wind turbine by the helicopter shall be stated by the operator or designer and taken into account in the load calculations.

In addition, DLC 8.2 shall include all transport, assembly, maintenance and repair turbine states that may persist for longer than one week. This shall, when relevant, include a partially completed support structure, the support structure standing without the RNA, and the RNA 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.