

# INTERNATIONAL STANDARD

## NORME INTERNATIONALE



**Wind energy generation systems –  
Part 3-1: Design requirements for fixed offshore wind turbines**

**Systèmes de génération d'énergie éolienne –  
Partie 3-1: Exigences de conception des éoliennes en mer fixes**



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## INTERNATIONAL ELECTROTECHNICAL COMMISSION

**WIND ENERGY GENERATION SYSTEMS –****Part 3-1: Design requirements for fixed offshore wind turbines****FOREWORD**

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This edition cancels and replaces the first edition of IEC 61400-3 published in 2009. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the first edition of IEC 61400-3:

- a) Clause 12 has been merged with Clause 6 in order to acknowledge that the design of the wind turbine support structure is generally site specific for offshore projects;

- b) The design load table has been revised to simplify the approach to waves, both for several gust cases with the Normal Sea State, and for a number of cases with the Extreme Sea State. The guidance for load calculations has been altered accordingly;
- c) For load safety factors reference is now made directly to IEC 61400-1;
- d) Clause 8 on the control system has been aligned with the latest updates in IEC 61400-1;
- e) Annex B to edition one on wave spectra has been replaced by a reference to ISO 19901-1;
- f) The annex on ice loading has been revised and updated (now Annex D);
- g) Two informative annexes concerning tropical cyclones have been introduced: Annex H on wave height assessment and Annex I on safety level;
- h) Other parts of the text have been aligned with IEC 61400-1.

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

The text of this International Standard is based on the following documents:

|             |                  |
|-------------|------------------|
| FDIS        | Report on voting |
| 88/708/FDIS | 88/712/RVD       |

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

The French version of this standard has not been voted upon.

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

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

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<sup>1</sup> Under preparation. Stage at the time of publication: IEC/RFDIS 61400-1:2018.

## INTRODUCTION

This part of IEC 61400 outlines the minimum design requirements for fixed 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 document are met. The division of responsibility between these parties is a contractual matter and is outside the scope of this document.

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

The document is not intended to give requirements for floating offshore wind turbines. For floating installations, reference is made to IEC 61400-3-2.

## WIND ENERGY GENERATION SYSTEMS –

### Part 3-1: Design requirements for fixed 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 specifies essential design requirements to ensure the engineering integrity of fixed offshore wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.

This document 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 a fixed offshore wind turbine if the support structure is subject to hydrodynamic loading and it is founded on the seabed. The design requirements specified in this document are not sufficient to ensure the engineering integrity of floating offshore wind turbines. For floating installations, reference is made to IEC 61400-3-2. In the remainder of this document, the term “offshore wind turbine” is assumed to refer to those that are fixed to the seabed.

This document should be used together with the appropriate IEC and ISO standards mentioned in Clause 2. In particular, this document is fully consistent with the requirements of IEC 61400-1. The safety level of the offshore wind turbine designed according to this document 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 documents are referred to in the text in such a way that some or all of their content constitutes requirements 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 (all parts), *Classification of environmental conditions*

IEC 61400-1:2018, *Wind energy generation systems – Part 1: Design requirements*<sup>2</sup>

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

ISO 2533:1975, *Standard Atmosphere*

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

ISO 19901-1:2015, *Petroleum and natural gas industries – Specific requirements for offshore structures – Part 1: Metocean design and operating conditions*

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<sup>2</sup> Under preparation. Stage at the time of publication: IEC/RFDIS 61400-1:2018.

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

ISO 19902:2007, *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 terms and definitions given in IEC 61400-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

#### 3.1

##### **air gap**

clearance between the highest water surface that occurs during the extreme environmental conditions and the lowest exposed part not designed to withstand wave impingement

#### 3.2

##### **arch effect**

action of an arch ice (or its collapse) upon a substructure

#### 3.3

##### **arch ice**

ice build-up between substructures or between a substructure and shore that has an arch shape and eventually collapses

#### 3.4

##### **co-directional**

acting in the same direction

#### 3.5

##### **current**

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

#### 3.6

##### **diffraction**

phenomenon that describes the bending of waves around obstacles and spreading of waves past openings

#### 3.7

##### **design wave**

deterministic wave with a defined height, period and direction, used for the design of an offshore structure

Note 1 to entry: A design wave may be accompanied by a requirement for the use of a particular periodic wave theory.

#### 3.8

##### **designer**

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

### 3.9

#### **environmental conditions**

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

### 3.10

#### **external conditions**

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

### 3.11

#### **extreme significant wave height**

significant wave height of the sea state over the reference period with an annual probability of exceedance of  $1/N$  ("return period":  $N$  years), extrapolated from the extreme distribution of significant wave height at the site

### 3.12

#### **extreme wave height**

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

### 3.13

#### **fast ice cover**

rigid continuous cover of ice not in motion

### 3.14

#### **fetch**

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

### 3.15

#### **fixed offshore wind turbine**

wind turbine with a sub-structure that is subject to hydrodynamic loading and is founded on the seabed

### 3.16

#### **floating offshore wind turbine**

wind turbine with a sub-structure that is subject to hydrodynamic loading and is supported by buoyancy and a station-keeping system

### 3.17

#### **foundation**

part of an offshore wind turbine support structure which transfers the loads acting on the structure into the seabed

Note 1 to entry: Different foundation concepts are shown in Figure 1 together with the other parts of an offshore wind turbine support structure.

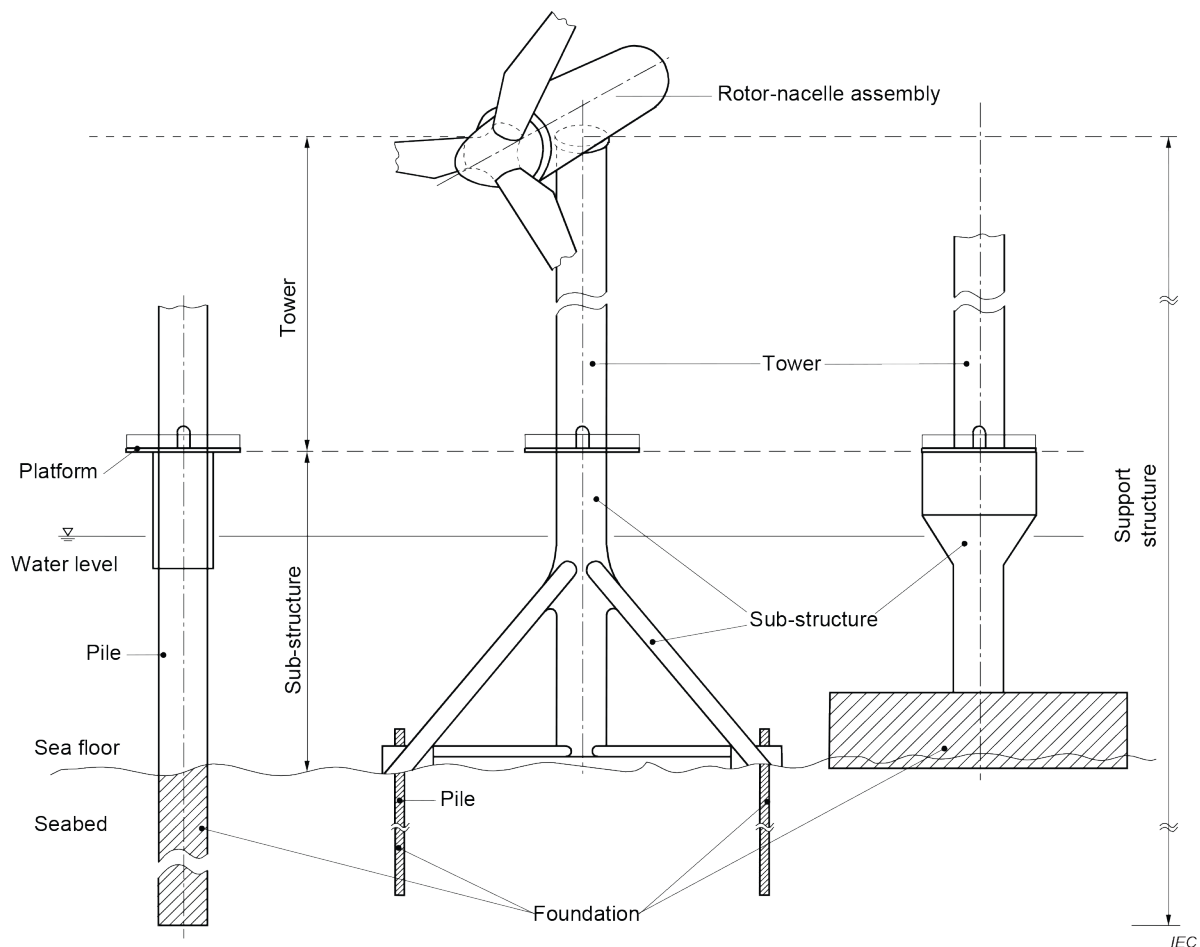


**Figure 1 – Parts of a fixed offshore wind turbine**

### 3.18

#### **highest astronomical tide**

highest still water level that can be expected to occur under any combination of astronomical conditions and under average meteorological conditions

Note 1 to entry: 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.

### 3.19

#### **hindcasting**

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

### 3.20

#### **hub height**

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

### 3.21

#### **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

### 3.22

#### **ice floe**

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

### **3.23**

#### **ice ridge**

angular ice blocks of various sizes that pile up on ice floes as they collide pushed by wind and currents

Note 1 to entry: The part of the ridge that is above the water surface is known as the sail; that below it as the keel. The upper part of the keel can be consolidated, consisting of refrozen ice blocks, refrozen rafted ice or a combination of these, and is known as the consolidated layer.

### **3.24**

#### **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

### **3.25**

#### **land-locked waters**

waters almost or entirely surrounded by land

### **3.26**

#### **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.

### **3.27**

#### **lowest astronomical tide**

lowest still water level that can be expected to occur under any combination of astronomical conditions and under average meteorological conditions

Note 1 to entry: 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.

### **3.28**

#### **manufacturer**

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

### **3.29**

#### **marine conditions**

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

### **3.30**

#### **marine growth**

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

### **3.31**

#### **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

### **3.32**

#### **mean zero crossing period**

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

Note 1 to entry: Relations exist between mean zero crossing period and peak period.

### **3.33**

#### **metocean**

abbreviation of meteorological and oceanographic

**3.34****moving ice**

portions of sea/lake ice that move under the action of wind and /or currents

**3.35****multi-directional**

acting in multiple directions

**3.36****offshore wind turbine site**

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

**3.37****peak wave period**

period of the peak energy in the wave spectrum

**3.38****pile penetration**

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

**3.39****power collection system**

electrical system that collects the power from one or more wind turbines

Note 1 to entry: The power collection system 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.

**3.40****rafted ice**

sea/lake ice sheet that converges toward another and slides on top of the other (overthrust) resulting in a local increase in ice thickness

**3.41****reference period**

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

**3.42****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

**3.43****rotor–nacelle assembly**

part of an offshore wind turbine carried by the support structure

**3.44****sea floor**

interface between the sea and the seabed

**3.45****sea floor slope**

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

### 3.46

#### **sea/lake ice**

frozen seawater or lake freshwater

### 3.47

#### **sea state**

condition of the sea in which its statistics remain stationary

### 3.48

#### **seabed**

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

### 3.49

#### **seabed movement**

movement of the seabed due to natural geological processes

### 3.50

#### **scour**

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

### 3.51

#### **shallow water**

depth in which the presence of the seabed has a pronounced effect on the wave hydrodynamics

Note 1 to entry: The distinction between shallow water and non-shallow water is defined in Figure B.1. For extreme sea states a site may have to be considered as shallow while for normal conditions it can be considered deep.

### 3.52

#### **significant wave height**

statistical measure of the height of waves in a sea state, defined as either the average height of the highest one third of the zero up-crossing waves or as  $4 \times \sigma_\eta$  where  $\sigma_\eta$  is the standard deviation of the sea surface elevation

Note 1 to entry: The former height is called the statistical significant wave height (usually denoted  $H_{1/3}$ <sup>3</sup>, while the latter height is called the spectral significant wave height (denoted by  $H_s$  or  $H_{m0}$ ).

### 3.53

#### **significant wave period**

statistical measure of the period of waves in a sea state, defined as the average period of the highest one third of the zero up-crossing waves, denoted  $T_{1/3}$

Note 1 to entry: Relations exist between the peak period  $T_p$  and  $T_{1/3}$ .

### 3.54

#### **splash zone**

external region of support structure that is frequently wetted due to waves and tidal variations

Note 1 to entry: This is defined as the zone between

- the highest still water level with a return 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 return 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.

<sup>3</sup> In deep water,  $H_{1/3} \approx 0,956H_s$  regardless of wave spectral form (ISO 21650:2007).

**3.55****still water level**

abstract water level calculated by including the effects of tides and storm surge but excluding variations due to waves

Note 1 to entry: Still water level can be above, at, or below mean sea level.

**3.56****storm surge**

change in water level caused by atmospheric change and/or wind associated with a storm

**3.57****sub-structure**

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

**3.58****support structure**

part of an offshore wind turbine consisting of the tower, sub-structure and foundation

**3.59****swell**

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

**3.60****tidal current**

current resulting from tides

**3.61****tidal range**

vertical distance between the highest astronomical tide and the lowest astronomical tide

**3.62****tides**

regular and predictable movements of the sea generated by astronomical forces

**3.63****tower**

part of an offshore wind turbine support structure which connects the sub-structure to the rotor-nacelle assembly

**3.64****tsunami**

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

**3.65****uni-directional (wind and/or waves)**

acting in a single direction

**3.66****water depth**

vertical distance between the sea floor and the still water level

Note 1 to entry: As there are several definitions for the still water level (see 3.55) there can be several water depth values.

### 3.67

#### **wave crest elevation**

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

### 3.68

#### **wave direction**

mean direction from which the wave is travelling

### 3.69

#### **wave height**

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

### 3.70

#### **wave period**

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

### 3.71

#### **wave spectral peak frequency**

frequency of the peak energy in the wave spectrum, the inverse of the wave peak period

### 3.72

#### **wave spectrum**

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

### 3.73

#### **wave steepness**

ratio of the wave height to the wave length

### 3.74

#### **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

### 3.75

#### **weather window**

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

### 3.76

#### **wind profile – wind shear law**

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

Note 1 to entry: 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;

$\alpha$  is the wind shear (or power law) exponent.

### 3.77

#### wind sea

sea state being generated by local winds

### 3.78

#### zero up-crossing wave

portion of a time history of wave elevation between zero up-crossings

Note 1 to entry: 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 symbols and abbreviated terms given in IEC 61400-1 and the following apply:

### 4.1 Symbols and units

|              |                                                                                                                |                      |
|--------------|----------------------------------------------------------------------------------------------------------------|----------------------|
| $A_C$        | Charnock's constant                                                                                            | [-]                  |
| $d$          | water depth                                                                                                    | [m]                  |
| $f_p$        | wave spectral peak frequency                                                                                   | [Hz]                 |
| $g$          | acceleration due to gravity                                                                                    | [m/s <sup>2</sup> ]  |
| $h$          | thickness of sheet sea/lake ice                                                                                | [m]                  |
| $h_c$        | thickness of sea/lake ice ridge consolidated layer or refrozen rafted layer                                    | [m]                  |
| $h_N$        | thickness of sea/lake ice with a return period of $N$ years                                                    | [m]                  |
| $h_m$        | ice thickness equal to the long-term mean value of the annual maximum ice sheet thickness for winters with ice | [m]                  |
| $H$          | individual wave height                                                                                         | [m]                  |
| $H_B$        | breaking wave height                                                                                           | [m]                  |
| $H_N$        | individual wave height with a return period of $N$ years                                                       | [m]                  |
| $H_s$        | spectral significant wave height                                                                               | [m]                  |
| $H_{sN}$     | spectral significant wave height with a return period of $N$ years                                             | [m]                  |
| $H_{1/3}$    | statistical significant wave height                                                                            | [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                                                          | [-]                  |
| $S_\eta$     | single sided wave spectrum                                                                                     | [m <sup>2</sup> /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]                  |
| $T_p$        | peak spectral period                                                                                           | [s]                  |
| $T_z$        | mean zero-crossing wave period                                                                                 | [s]                  |
| $U_N$        | current velocity, with a return period of $N$ years                                                            | [m/s]                |

|               |                                                                                          |       |
|---------------|------------------------------------------------------------------------------------------|-------|
| $U_{ss}$      | sub surface current velocity                                                             | [m/s] |
| $U_w$         | wind-generated current velocity                                                          | [m/s] |
| $V_N$         | expected extreme wind speed (averaged over 10 min),<br>with a return period of $N$ years | [m/s] |
| $V_{eN}$      | expected extreme wind speed (averaged over 3 s),<br>with a return period of $N$ years    | [m/s] |
| $z$           | vertical distance above SWL                                                              | [m]   |
| $\alpha$      | sea floor slope in radians                                                               | [rad] |
| $\eta$        | sea surface elevation relative to SWL                                                    | [m]   |
| $\kappa$      | von Karman's constant                                                                    | [-]   |
| $\lambda$     | wave length                                                                              | [m]   |
| $\theta_w$    | wave direction                                                                           | [°]   |
| $\theta_{wm}$ | mean wave direction                                                                      | [°]   |
| $\theta_c$    | current direction                                                                        | [°]   |
| $\sigma_\eta$ | sea surface elevation standard deviation                                                 | [m]   |
| $\tau$        | 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                           |
| EWLR | extreme water level range                   |
| EWM  | extreme wind speed model                    |
| EWS  | extreme wind shear                          |
| FMEA | failure modes and effects analysis          |
| 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                     |
| NWLR | normal water level range                    |
| NWP  | normal wind profile model                   |
| SSS  | severe sea state                            |
| 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 this document. 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 document 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 document.

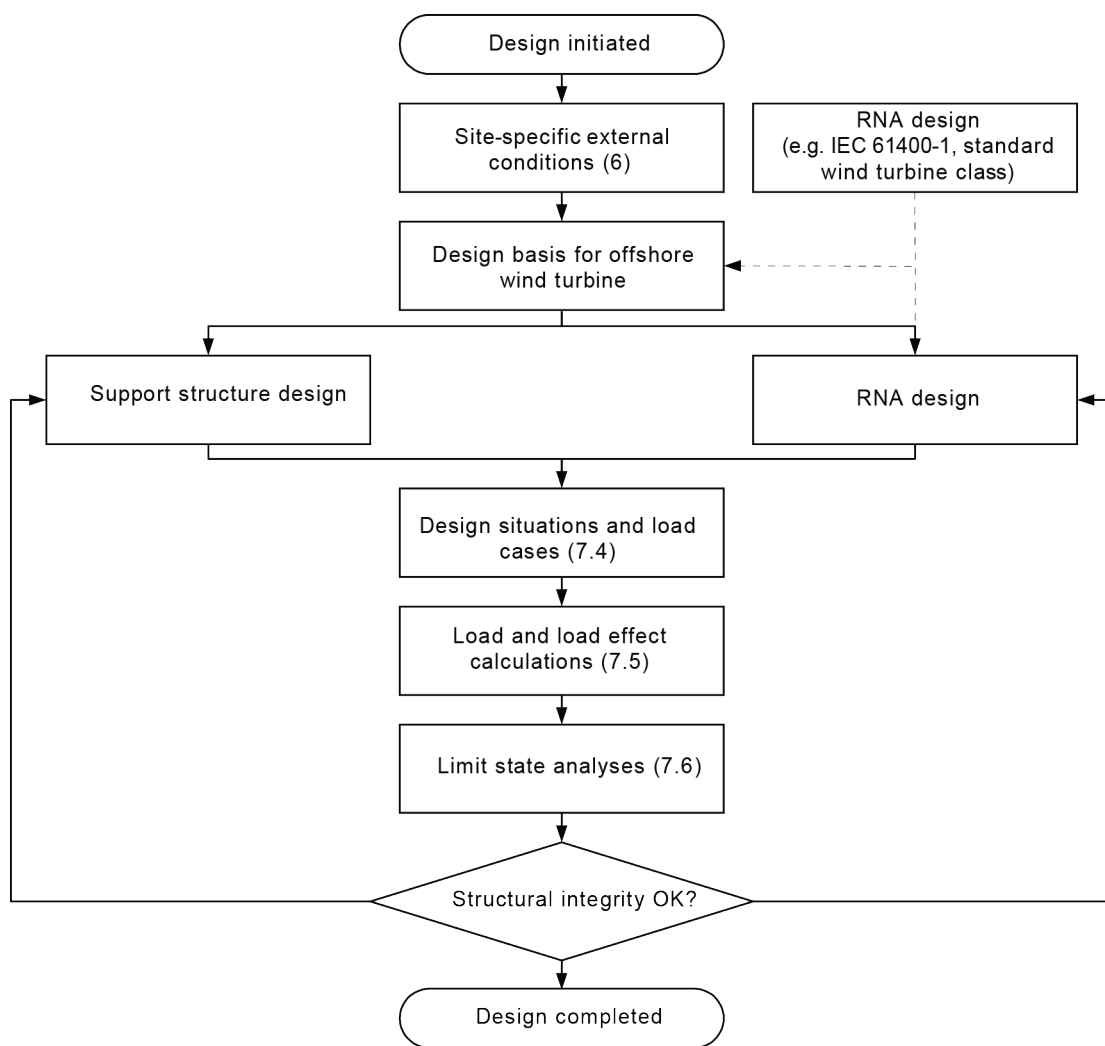
The design of the support structure of an offshore wind turbine shall be based on site-specific external conditions. These shall therefore be determined in accordance with the requirements stated in Clause 6. The conditions shall be summarized in the design basis.

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 61400-1:2018, 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 the 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 of the rotor-nacelle assembly shall be used to increase confidence in predicted design values and to verify structural dynamics models and design situations. Data from full-scale testing of the support structure may similarly be used. 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 document. The selection of test conditions, including the test loads, shall take account of the relevant safety factors.



IEC

**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 IEC 61400-1.

Partial safety factors for special safety class wind turbines shall be agreed upon 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 IEC 61400-1.

### 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.

## 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:

- wind turbine manufacturer and country;
- model and serial number;
- production year;
- rated power;
- reference wind speed,  $V_{\text{ref}}$ ;
- 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 – definition and assessment

### 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, including the influence of nearby turbines, 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/lake ice, marine growth, seabed movement and scour) and other environmental conditions. The electrical conditions refer to the electrical power network conditions. Soil properties are relevant to the design of offshore wind turbine foundations, 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.

The design process for an offshore wind turbine is shown in Figure 2. The assessment of site-specific external conditions is the first step in the design process and forms the basis for the design. This clause therefore specifies both the definition and assessment of the external conditions.

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 definition and assessment of the normal and extreme external conditions to be considered in design are specified in 6.2 to 6.4.

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

## 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. IEC 61400-1 includes a specific class for tropical cyclone conditions ("T class"). Additional guidance on tropical cyclone conditions is available in Annex H of this document.

There are some principal differences between offshore and onshore wind conditions. However, 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. As stated in 5.2 it shall be demonstrated subsequently that site-specific external conditions do not compromise the structural integrity of the rotor-nacelle assembly. Thus it is not a requirement that offshore rotor-nacelle assemblies be designed to IEC 61400-1 classes. There are no classes of external conditions defined for support structure design.

A further wind turbine class, class S, is defined for use when special wind conditions, other external conditions, a design lifetime other than 20 years, or a special safety class (see 5.3) is required by the designer and/or the customer.

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

## 6.3 Definition of external conditions at an offshore wind turbine site

### 6.3.1 General

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

The wind regime and marine conditions for load and safety considerations are divided into the normal conditions which occur frequently during normal operation of an offshore wind turbine, and the extreme conditions which are defined as having a 1-year or 50-year return period<sup>4</sup>.

The extreme conditions are intended to produce  $N$ -year ( $N = 1$  or 50) return period load effects (cross-sectional loads, deformations, etc.). Combining marginal  $N$ -year events directly will in general produce load effects of longer return period than  $N$  years. The more environmental parameters that are combined in this way, the more conservative the design potentially becomes. For the assessment of the combined wind and marine environment, several parameters are relevant for the load effects of offshore turbines. Thus for offshore wind turbine design, the assessment of joint environmental conditions by specifying associated conditions instead of direct combinations of marginal conditions of equal return

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<sup>4</sup> The normal range of water levels is, however, defined in this document as the variation in water level with a return period of 1 year, refer to 6.3.3.4.2.

period is appropriate. Offshore wind turbines can exhibit significant dynamic response. This shall be accounted for when establishing joint environmental conditions.

To determine joint environmental conditions for design, the approach of environmental contours can be used. The joint environmental conditions to be designed for are then defined as those among all conditions on the environmental contour that cause the most extreme response. The possible dynamic response shall be considered in the assessment. By this approach joint wind speeds, wave heights, wave periods, water levels, directional relations etc. may be established.

The application of the method of environmental contours, or other probabilistic methods, generally requires information defining the long-term joint probability distributions of wind and marine conditions. In practice not all environmental conditions are typically measured simultaneously. Environmental contours are instead developed for subsets of parameters – e.g. wave heights and water level, wave height and wave period, etc.

The following clauses define the predominant marginal extreme conditions to consider as a minimum, e.g.  $N$ -year return wind and marine conditions. Conditions to associate with these shall be established. In the absence of sufficient information to develop site-specific environmental contours, conservative alternatives are provided.

### **6.3.2 Wind conditions**

The wind parameters defined in IEC 61400-1 are appropriate for the offshore environment. Site-specific conditions representative of the offshore wind turbine site shall be assessed in accordance with the requirements stated in 6.4.3.

### **6.3.3 Marine conditions**

#### **6.3.3.1 General**

The marine conditions described in this subclause 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 6.3.5.

#### **6.3.3.2 Waves**

##### **6.3.3.2.1 General**

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,  $S_{\eta}$ , together with the significant wave height,  $H_s$ , a peak spectral period,  $T_p$ , and a mean wave direction,  $\theta_{wm}$ . Where appropriate, the wave spectrum may be supplemented with a directional spreading function. Standard wave spectrum formulations are provided in ISO 19901-1.

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 relevant parameters, e.g.:

- mean wind speed,  $V$ ;
- significant wave height,  $H_s$ ;
- peak spectral period,  $T_p$ ; and
- water depth,  $d$ .

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 and/or by the use of numerical hindcasting techniques whichever is appropriate, refer to 6.4.4.

The correlation of normal wind conditions and waves shall also consider wind-wave misalignment, i.e. consideration of mean wind and wave directions (separation of wind sea and swell may also be considered). The multi-directional distributions of wind and wave directions can 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 on properties of the support structure such as eigenfrequencies, modal damping, mode shapes and geometrical symmetry. 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.

The combined extreme event of wind, waves, water level, and other relevant parameters shall ensure that global extreme environmental actions with return periods of 1 year and 50 years are considered. The geometric and dynamic properties of the support structure may imply that several combined events shall be specified.

Wave models are defined in 6.3.3.2.2 to 6.3.3.2.5 in terms of sea state representations including stochastic linear wave models and regular non-linear design waves. The stochastic wave models shall be based on a wave spectrum appropriate to the site anticipated for the offshore wind turbine.

By definition  $H_s$  and  $T_p$  are independent of reference period. In order to determine the joint probability distribution of  $V_{hub}$ ,  $H_s$ , and  $T_p$ , a one hour averaging period shall be used to define the mean wind speed against which to correlate the significant wave height and peak spectral period.

#### **6.3.3.2.2 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, the normal sea states considered shall be those sea states characterised by the expected value of the significant wave height,  $H_s$ , and peak spectral period,  $T_p$ , 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.

#### 6.3.3.2.3 Severe sea state (SSS)

The severe 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 mean 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 mean wind speed has a return period of 50 years<sup>5</sup>. The severe sea state shall include the extreme individual wave height that, in combination with the associated wave period and the mean wind speed, has a return of 50 years. The designer shall take account of the range of wave period,  $T$ , appropriate to each extreme wave height. In the absence of a more sophisticated probabilistic assessment, design calculations shall assume values of wave periods within this range that result in the highest loads acting on an offshore wind turbine.

For all mean wind speeds, the unconditional extreme significant wave height,  $H_{s50}$ , with a return period of 50 years may be used as a conservative value for  $H_{s,SSS}(V)$ . Similarly, it is conservative to adopt the extreme individual wave height  $H_{50}$  for the extreme individual wave height in the severe sea state. This approach may be used in the absence of information defining the long-term joint probability distribution of wind and waves.

#### 6.3.3.2.4 Extreme sea state (ESS)

The extreme sea state model shall be considered for combined global environmental actions with return periods of 1 year and 50 years. The designer may need to investigate a number of extreme sea states combined with, for example, different water levels to determine the appropriate extreme sea state(s) for design, refer 6.3.3.4.3 and 6.3.3.3.5. Both the extreme significant wave height ( $H_{s50}$  or  $H_{s1}$ ) and the extreme individual wave height ( $H_{50}$  or  $H_1$ ) shall be included in the sea state. The designer shall take account of the range of wave period,  $T$ , appropriate to each extreme wave height. Design calculations shall assume values of wave periods within this range that result in the highest loads acting on an offshore wind turbine.

The extreme sea state(s) shall be determined from analysis of appropriate site-specific metocean data (i.e. measurements and/or hindcast data) for the offshore wind turbine site, refer to 6.4.4.

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 return period occurs during the extreme 3-hour sea state with a 50-year return 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 return period. The extreme individual wave height shall be assumed to occur at a random time during the simulation of the extreme sea state.

#### 6.3.3.2.5 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 form of the breaking wave is expected to be spilling or plunging.

Annex B 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

<sup>5</sup> 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 F which also gives guidance on how to determine  $H_{s,SSS}(V)$  from site-specific environmental conditions.

Annex C relating to the calculation of the loading applied by a breaking wave to an offshore wind turbine support structure.

### 6.3.3.3 Sea currents

#### 6.3.3.3.1 General

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.

The total current velocity is the vector sum of these components. Wave induced water particle velocities and current velocities shall similarly be added vectorially. The influence of sea currents on the relationship between wave length and wave period is generally small and may be neglected, refer to ISO 19901-1:2015, A.8.4.3 for further guidance. Other site-specific current components may exist, such as near shore, wave induced surf currents running parallel to the coast.

The influence of sea currents on the 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.

#### 6.3.3.3.2 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:

$$U_{ss}(z) = U_{ss}(0) \left[ (z + d) / d \right]^{1/7} \quad (3)$$

The 1-year and 50-year return period 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 6.4.4.3.

In general, it is conservative to assume that the sub-surface currents are aligned with the wave direction.

#### 6.3.3.3.3 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:

$$U_w(z) = U_w(0) (1 + z/20) \quad (4)$$

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

$$U_w(0) = 0,01 V_{1\text{-hour}}(z = 10 \text{ m}) \quad (5)$$

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 return period 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 (5) to estimate the 1-year and 50-year return values of wind-generated sea surface current velocity.

#### **6.3.3.3.4 Normal current model (NCM)**

The normal current model is defined as the appropriate site-specific combination of wind-generated currents and tidal currents. The normal current model excludes storm-generated sub-surface currents. Normal tidal currents shall be accounted for as the mean of tidal current speeds.

The normal current model shall be assumed for those ultimate load cases involving normal and severe wave conditions (NSS, SSS) and for each load case the velocity of the wind-generated currents may be estimated from the relevant mean wind speed, refer to 6.3.3.3.3.

#### **6.3.3.3.5 Extreme current model (ECM)**

The extreme current model shall be considered for those ultimate load cases associated with extreme wave conditions (ESS). Currents associated with ESS shall result in combined global environmental actions with return periods of 1 year and 50 years and are denoted by  $U_1$  and  $U_{50}$ , respectively. Load calculations shall be undertaken based on the currents which result in the highest loads acting on an offshore wind turbine.

These extreme values shall be determined from analysis of appropriate site-specific metocean data (i.e. measurements and/or hindcast data) for the offshore wind turbine site, refer to 6.4.4.

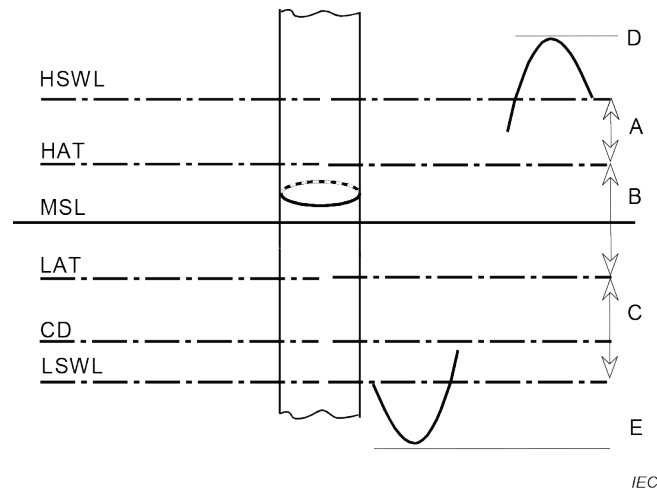
In the absence of information defining the long-term joint probability distribution of extremes it is conservative to apply currents with return period of 1 year and 50 years and to assume the current to be co-directional with the waves.

### **6.3.3.4 Water level**

#### **6.3.3.4.1 General**

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) with the exception stated in 6.3.3.4.2 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**

#### 6.3.3.4.2 Normal water level range (NWLR)

The normal water level range shall be assumed equal to the long-term difference 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);
- wave conditions with a return 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) model, 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.

#### 6.3.3.4.3 Extreme water level range (EWLR)

The extreme water level range shall be assumed for ultimate load cases associated with wave conditions with a return period of 50 years (ESS). Combination with ESS shall result in combined global environmental actions with a return period of 50 years. The designer may

need to investigate a number of representations of the ESS combined with different water levels. 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 return period of 50 years, based on an appropriate combination of highest astronomical tide and positive storm surge;
- lowest still water level with a return 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.

#### **6.3.3.5 Sea/lake ice**

At some locations, loading of the support structure of an offshore wind turbine due to sea/lake 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/lake ice shall be undertaken as stated in 6.4.4.5.

Annex D provides guidance with regard to ice load calculations.

#### **6.3.3.6 Marine growth**

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

#### **6.3.3.7 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 6.4.4.7.

#### **6.3.4 Electrical power network conditions**

The conditions at the offshore wind turbine terminals are to be determined for the specific installation as described in 6.4.6.

#### **6.3.5 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 may increase their effects.

The following other environmental conditions shall at least 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 and/or tsunamis;
- water density;
- water temperature.

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 return 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 6.4.5.3 shall be combined with the normal wind conditions according to IEC 61400-1 and normal marine conditions according to 6.3.3.

## 6.4 Assessment of external conditions at an offshore wind turbine site

### 6.4.1 General

The external conditions at an offshore wind turbine site shall be assessed as the basis of design and/or design verification in accordance with the requirements of the following subclauses.

The partial safety factors for loads referenced in 7.6.2.2 assume that the site assessment of the normal and extreme metocean conditions has been carried out according to the minimum requirements of this clause 6.4.

### 6.4.2 The metocean database

A site-specific metocean database shall be established containing information on

- wind speeds and directions;
- significant wave heights, wave periods and directions;
- correlation of wind and wave statistics;
- current speeds and directions;
- water levels;
- occurrence and properties of sea/lake ice and occurrence of their drift directions and drift speeds;
- occurrence of icing of the turbine and its support structure;
- other relevant metocean parameters such as air and water temperatures and densities, water salinity, site bathymetry, marine growth, etc.

The database may be established from site-specific measurements supported, where appropriate, by numerical simulations (hindcasts). If site-specific measurements are used, the results shall generally be correlated with data from a nearby location for which long-term measurements exist, unless the results can otherwise be shown to be conservative. The monitoring period for the site-specific measurements shall be sufficient to ensure reliable statistics for the individual parameters as well as the joint probability distribution of these parameters<sup>6</sup>. Long-term site-specific measurements shall not generally be required when correlation with suitable long-term data from a nearby location is undertaken or when numerical tools can be reliably applied for transposing the long-term data to the wind turbine site.

Time series measurements may be of particular importance in order to characterise wave heights, periods and wave spectra at shallow water sites.

When assessing the quality and quantity of data, special attention should be given to the adequacy of the data with respect to extrapolation to very infrequent events.

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<sup>6</sup> If only correlation analysis of measured data is to be undertaken, the location of the long-term measurements should be less than 50 km from the prospective offshore wind turbine site and the water depth, the fetch and the bathymetry should be similar at the two locations. When correlating the long-term data with the wind turbine site-specific short term data, care should be taken that the correlation is adequate and that the uncertainty of the correlation analysis can be estimated. Should the location of the long-term measurements be more than 50 km from the prospective wind turbine site, it is advisable also to undertake numerical simulations (hindcasts) to estimate the site's metocean statistics.

### 6.4.3 Assessment of wind conditions

#### 6.4.3.1 General

The site wind parameters shall be either measured and extrapolated, or calculated using appropriate methods (e.g. monitoring measurements made at the site, long-term records from local meteorological stations, simulation models or local codes and standards). The methods described in 11.3 of IEC 61400-1 apply with the deviations specified below.

Values of the following parameters shall be estimated at the wind turbine site in addition to those specified in IEC 61400-1:

- extreme 10-min average wind speed  $V_{1,\text{hub}}$  at hub height with a return period of 1 year;
- wind speed standard deviation  $\hat{\sigma}$  from the ambient turbulence (estimated as the mean value of the standard deviation of the longitudinal component) and the standard deviation  $\hat{\sigma}_\sigma$  of  $\hat{\sigma}$  at  $V_{\text{hub}}$  between  $V_{\text{in}}$  and  $V_{\text{out}}$  and  $V_{\text{hub}}$  equal to  $V_{\text{ref}}$ .

High values of wind shear have been reported for extended periods of time for certain areas in connection with highly stratified flow or severe roughness changes. However, for the gust models which employ the mean wind profile (i.e. EOG, ECD, EWS as defined in IEC 61400-1) the shear may be assumed equal to the mean wind shear. This is justified because these models are concerned with gusts generated by turbulence, which implies that shear values associated with high turbulence levels are appropriate.

The interval of any wind speed bin used in the above shall be 2 m/s or less, and the wind direction sectors shall be 30° or less. IEC 61400-1 requires that all parameters, except for air density, be available as functions of wind direction and given as 10-min averages. Because the offshore environment generally exhibits less directional variation than the onshore environment, providing omnidirectional information for parameters such as shear and turbulence is acceptable unless precluded by coastal effects for near-shore sites.

The site extreme wind parameters shall be either:

- measured in the range of 0,2  $V_{\text{ref}}$  to 0,4  $V_{\text{ref}}$  and extrapolated, or
- derived from a correlation analysis of short-term monitoring measurements made at the site and long-term records from local meteorological stations, or from local codes or standards, or
- based on experience of nearby sites. In this case the assumption of similarity between the sites is to be justified.

Where site-specific extreme average wind speeds are available only for averaging periods longer than 10 min, the conversion factors stated in Table 1 may be used to estimate the extreme 10-min average wind speed. The factors in this table give the ratio between the extreme wind speed for a given averaging period and the extreme 10-min average wind speed.

**Table 1 – Conversion between extreme wind speeds  
of different averaging periods**

| Averaging period                                                | 10 min | 1 h  | 3 h  |
|-----------------------------------------------------------------|--------|------|------|
| Correction factor relative to extreme 10-min average wind speed | 1,00   | 0,95 | 0,90 |

The long-term probability distribution of mean wind speed,  $V_{\text{hub}}$ , may be assumed to be independent of averaging period for periods in the range between 10 min and 3 h<sup>7</sup>.

#### 6.4.3.2 IEC 61400-1 wind conditions applied to rotor-nacelle assembly design

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 variations to the 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:

$$V(z) = V_{\text{hub}} (z/z_{\text{hub}})^{\alpha} \quad (6)$$

where, for normal wind conditions, the power law exponent,  $\alpha$ , is 0,14.

#### 6.4.3.3 Assessment of ambient free stream turbulence

The value of the ambient free stream turbulence standard deviation shall be determined using appropriate statistical techniques applied to measured and preferably de-trended data. Where topographical (shore line) or other local effects may influence the turbulence intensity, these effects shall be represented in the data. The characteristics of the anemometer, sampling rate and averaging time used to obtain measured data shall be taken into account when evaluating the turbulence intensity.

Where no site data for turbulence is available, the turbulence standard deviation  $\sigma_1$  may be estimated using the surface roughness parameter  $z_0$  derived from the Charnock expression for atmospheric conditions that are near-neutral:

$$z_0 = \frac{A_C}{g} \left[ \frac{\kappa \cdot V_{\text{hub}}}{\ln(z_{\text{hub}}/z_0)} \right]^2 \quad (7)$$

where

$g$  is the acceleration due to gravity;

$\kappa$  0,4 is von Karman's constant, and

$A_C$  is Charnock's constant.

$A_C$  0,011 is recommended for open sea and  $A_C = 0,034$  may be used for near-coastal locations<sup>8</sup>.

The roughness of the sea surface increases with wind speed and thus the turbulence intensity will increase as a function of wind speed in near-neutral conditions. At many offshore sites, it has been found that average turbulence intensity offshore is high at low wind speeds, decreases to a minimum at wind speeds of approximately 8 to 12 ms<sup>-1</sup> (at 10 m reference height) and then increases slowly with increasing wind speed.

<sup>7</sup> This assumption may not be valid at the tail of long-term probability distribution, for mean wind speeds exceeding  $V_{\text{out}}$ .

<sup>8</sup> The surface roughness parameter and resulting turbulence standard deviation calculated using the Charnock equation apply for open sea conditions. Care should be taken in cases where the influence of shore topology and onshore roughness may lead to higher values of turbulence standard deviation. Use of the higher value of the coefficient is recommended unless site specific data confirm otherwise.

The roughness parameter is found by solving the above implicit equation and, in turn, the standard deviation of the longitudinal wind speed component may be calculated from

$$\sigma_1 = \frac{V_{\text{hub}}}{\ln(z_{\text{hub}}/z_0)} + 1,28 \times d \times I_{15} \quad d = 4 \text{ m/s} \quad (8)$$

where  $I_{15}$  is the average value of hub height turbulence intensity determined at  $V_{\text{hub}} = 15 \text{ m/s}$ . The use of the assumption of near-neutral conditions (as equation (7)) will, in general, give low average values for the standard deviation of the longitudinal wind speed component and is not valid for representing tropical cyclone conditions.<sup>9</sup>

Models accounting for non-neutral atmospheric conditions offshore have been proposed. The models in "H. Wang, R. J. Barthelmie, S. C. Pryor and H. G. Kim, *A new turbulence model for offshore wind turbine standards*, Wind Energy, Volume 17, Issue 10, pages 1587–1604, October 2014" may be applied if no other information is available. They represent three different levels of turbulence spanning the range from far offshore to very near-shore with complex terrain onshore. Care shall be taken when justifying the level to adopt.

In the absence of suitable site-specific data to estimate the turbulence standard deviation with a 1-hour averaging period, this may be assumed to be related to the 10-min average turbulence standard deviation by

$$\sigma_{i,1\text{-hour}} = \sigma_{i,10\text{-min}} + b; \quad b = 0,2 \text{ m/s} \quad (9)$$

#### 6.4.3.4 Assessment of wake effects from neighbouring wind turbines

The assessment of wake effects from neighbouring wind turbines shall be undertaken in accordance with the requirements stated in IEC 61400-1. Guidance is provided in IEC 61400-1:2018, Annex E, regarding site-specific conditions.

#### 6.4.4 Assessment of marine conditions

##### 6.4.4.1 Assessment of extreme wave conditions

The following extreme sea state parameters shall be estimated:

- the significant wave height with a return period of 50 years assuming a 3-hour reference period,  $H_{s,50}$ ;
- the significant wave height with a return period of 1 year assuming a 3-hour reference period,  $H_{s,1}$ ;
- the extreme individual wave height with a return period of 50 years,  $H_{50}$  and the associated range of wave periods;
- the extreme individual wave height with a return period of 1 year,  $H_1$  and the associated range of wave periods;
- the extreme crest height with a return period of 50 years.

<sup>9</sup> The standard deviation  $4\text{m/s} \times I_{15}$  in equation (8) differs from  $1,44\text{m/s} \times I_{15}$  specified in IEC 61400-1 because significantly larger standard deviations have been recorded at some offshore locations. Hence, this parameter should be carefully evaluated for the specific site, accounting for available information from similar or neighbouring sites. Further, the specification of Weibull-distributed turbulence intensity in the IEC 61400-1 class definition is not generally valid offshore, which influences the assessment of ETM.

The extreme significant wave height and the extreme individual wave height may be determined in several ways. The most appropriate approach is based on statistical analysis of peak storm significant wave heights of the metocean database above a certain threshold. The extreme individual wave heights may be established by convolution of the long-term distribution of the significant wave height  $H_s$  and peak spectral period  $T_p$ , with the conditional short term distribution of individual wave height  $H$  given the significant wave height  $H_s$ . Reference is made to ISO 19901-1. The extreme wave heights may, however, be limited by water depth.

Breaking waves may occur at the site of an offshore wind turbine depending on the water depth, sea floor slope, wave height, period and steepness. Based on an assessment of these parameters, the guidance provided in Annex B may be followed to determine the nature and dimensions of breaking waves based on site conditions. This informative annex also presents an empirical model of the distribution of wave heights in shallow water areas.

Annex H provides guidance on assessment of extreme wave conditions during tropical cyclone conditions.

In the case that the metocean data is insufficient to assess the extreme wave height and the range of associated wave periods, for deep water it may be assumed that:

$$H = 1,86 H_s \quad (10)$$

which is obtained as the most probable maximum wave in a 3-hour reference period sea-state with significant wave height  $H_s$  assuming a Rayleigh distribution of wave heights and 1 000 waves, i.e. the 0,1 % exceedance quantile of the Rayleigh distribution. Associated with this wave height, the following wave period range can be applied

$$11,1 \sqrt{H_s/g} \leq T \leq 14,3 \sqrt{H_s/g} \quad (11)$$

For a given wave height, the wave period has a depth-dependent lower limit which is determined from the breaking wave height limit, refer to Annex B. Note that in deep water the ratios  $H_{50}/H_{s50}$  and  $H_1/H_{s1}$  are usually in the range 1,9 to 2,0. For shallow water sites where 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 2,0 times the value of the appropriate  $H_s$ .

#### 6.4.4.2 Assessment of normal wave conditions

For the normal sea states, the site-specific metocean database shall be analysed in order to establish the long-term joint probability distribution of the following parameters:

- mean wind speed at hub height,  $V_{hub}$ ;
- significant wave height,  $H_s$ ;
- peak spectral period,  $T_p$ .

In 6.3.3.2.2 defining NSS a 1-hour averaging period is required for the establishment of the long-term joint probability distribution of  $V_{hub}$ ,  $H_s$ , and  $T_p$ . If the available joint statistical data for  $V_{hub}$ ,  $H_s$ , and  $T_p$  are based on a different averaging period, the data shall be converted to be based on a 1-hour averaging period for the wind speed. The correlation between  $V_{hub}$ ,  $H_s$ , and  $T_p$  may increase with a longer averaging period because the build-up of waves under the influence of wind happens over a period of hours. However, depending on the specific characteristics of the site, the correlation may not change significantly with the averaging period and therefore it may be reasonable to assume that the long-term joint probability distribution of  $V_{hub}$ ,  $H_s$  and  $T_p$  is independent of averaging period.

If necessary, the joint probability distribution shall be extended to include wind and wave directions although site-specific measurements allowing the derivation of the joint occurrence of these five parameters are often not available<sup>10</sup>. The resolution of the joint probability distribution shall be such that the interval of any wind speed bin shall be 2 m/s or less, the interval of any significant wave height bin shall be 0,5 m or less, and the interval of any wave period bin shall be 0,5 s or less. If directional data are available, the widths of wind and wave direction sectors shall be 30° or less.

There is no requirement for assessment of site-specific wave spectra and directional spreading and the standard formulations provided in ISO 19901-1 may be assumed. Where appropriate and reliable measurements exist, site-specific wave spectra and the directional spreading function may, however, be assessed as the basis of design and/or design verification of an offshore wind turbine.

#### **6.4.4.3 Assessment of currents**

In addition to their impact on the loading of the support structure of an offshore wind turbine, currents affect the location and orientation of boat landings and fenders and may create seabed scouring.

Sea currents shall be assessed taking into account components associated with tidal, storm surge and wind-generated currents, where these are relevant to the wind turbine site. The velocity and directional characteristics of each significant component of sea current at the site shall be separately assessed.

Extreme sea surface current velocities having 1 year and 50 year return periods shall be determined from analysis of the site-specific metocean database.

There is no requirement for assessment of site-specific variation of current velocity with depth and the standard profiles provided in 6.3.3.3 may be assumed. Where appropriate and reliable measurements exist, site-specific current profiles may, however, be assessed as the basis of design and/or design verification of an offshore wind turbine.

#### **6.4.4.4 Assessment of water level, tides and storm surges**

The mean and fluctuation in water level at the wind turbine site shall be assessed in order to determine the following parameters:

- mean sea level (MSL);
- highest astronomical tide (HAT) and lowest astronomical tide (LAT);
- highest still water level (HSWL) including positive storm surge;
- lowest still water level (LSWL) including negative storm surge.

These parameters shall be determined from the site-specific metocean database. Accurate estimates of storm surge require a long data set. Long-term measurements or hindcasts available from a nearby location may be used together with correlation techniques to derive the site-specific storm surge characteristics.

#### **6.4.4.5 Assessment of sea/lake ice**

At sites where ice is expected to occur, its physical properties shall be taken into consideration for the design of support structures of offshore wind turbines.

The site-specific properties of the ice should be described in the design documentation.

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<sup>10</sup> It should be noted that an assumption of co-directionality of wind and waves may not be conservative for sites where large misalignment between wind and wave directions is common.

There are several parameters to be assessed, some of which can be measured, others calculated from empirical formulae and others determined from sources of historical data such as ice atlases.

The most relevant parameters are listed below:

- sheet ice thickness with a 50-year return period,  $h_{50}$ ;
- the dimensions of thick ice features of finite extent (such as ridges) entrained within the ice which may interact with the structure, including the consolidated layer thickness  $h_c$ , with a 50-year return period;
- ice strength coefficient  $C_R$ ;
- ice density;
- current speed at 1 m below ice lower surface;
- wind speed at 10 m above surface, acting on the ice sheets and ridges;
- water level fluctuation;
- water salinity;
- water density;
- air density;
- freezing degree-days;
- wind drag coefficient  $C_W$ ;
- current drag coefficient  $C_C$ ;
- frequency of ice concentrations.

Annex D provides definitions of the parameters needed to be assessed to calculate ice loads.

#### **6.4.4.6 Assessment of marine growth**

The thickness of marine growth and its dependence on depth below sea level shall be assessed based on applicable recommendations, local experience and existing measurements. Site-specific studies may be necessary to establish the nature, likely thickness and depth dependence of marine growth<sup>11</sup>.

#### **6.4.4.7 Assessment of seabed movement and scour**

The stability of the seabed shall be assessed. It shall be determined whether the bathymetry and soil configuration at the site require consideration of the possibility of slope failure, slides, cavity failure or erosion phenomena. Settlement and soil liquefaction shall in general be taken into account for the design of gravity base foundations.

Based on observations, sea floor variations can usually be characterised as a combination of the following:

- local scour characterised by steep sided scour pits around structural elements such as piles and pile groups;
- global scour characterised by shallow scoured basins of large extent around a structure, possibly caused by overall structure effects, multiple structure interaction, or wave-soil-structure interaction;
- overall seabed movement of sand waves, ridges and shoals which would occur in the absence of a structure. Such movements can result in the lowering or rising of the sea

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<sup>11</sup> Information regarding marine growth is available for some areas (North Sea, Persian Gulf, West African coast, Gulf of Mexico, coast of California, East coast of Canada), refer to ISO 19901-1.

floor, or repeated cycles of these. The addition of man-made structures may change the local sediment transport regime which can aggravate erosion, cause accumulation, or have no effect.

Seabed movement and scour can result in removal of vertical and lateral support for foundations, causing undesirable settlements and displacements of shallow foundations, overstressing of foundation elements and change of the dynamic properties of the wind turbine structure. Where scour is a possibility, it shall be taken into account in design and/or its mitigation shall be considered.

The extent of scour and the required scour protection at the wind turbine site shall be determined:

- on the basis of previous records from nearby sites or sites with similar sea floor characteristics;
- from model tests; or
- from calculations calibrated by prototype or model tests.

#### **6.4.5 Assessment of other environmental conditions**

##### **6.4.5.1 General**

The parameters specified in 6.3.5 shall be assessed.

##### **6.4.5.2 Other normal environmental conditions**

Normal values for the environmental parameters given below may be assumed as follows:

- ambient air temperature range of  $-10\text{ }^{\circ}\text{C}$  to  $+30\text{ }^{\circ}\text{C}$ ;
- 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  $1\,025\text{ kg/m}^3$ ;
- water temperature range of  $0\text{ }^{\circ}\text{C}$  to  $+30\text{ }^{\circ}\text{C}$ .

Where there are no site data for the air density, it shall be assumed that the air density is consistent with ISO 2533:1975, suitably corrected for annual average temperature.

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

##### **6.4.5.3 Other extreme environmental conditions**

###### **6.4.5.3.1 General**

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

###### **6.4.5.3.2 Temperature**

In the absence of site-specific data, the extreme ambient air temperature range for offshore wind turbines may be assumed to be  $-15\text{ }^{\circ}\text{C}$  to  $+40\text{ }^{\circ}\text{C}$ .

In the absence of site-specific data, the extreme water temperature range for offshore wind turbines may be assumed to be  $-2\text{ }^{\circ}\text{C}$  to  $+35\text{ }^{\circ}\text{C}$ .

#### **6.4.5.3.3 Lightning**

Lightning strikes of offshore wind turbines may be more frequent and more severe than onshore. The provisions for lightning protection required in IEC 61400-24 may be considered as adequate for offshore wind turbines.

#### **6.4.5.3.4 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 °C;
- spray of the wave crest at temperatures below 0 °C.

#### **6.4.5.3.5 Earthquakes**

Where relevant, assessment of earthquake conditions shall be performed according to 11.6 of IEC 61400-1:2018.

#### **6.4.6 Assessment of electrical network conditions**

For the assessment of electrical network conditions reference is made to Subclause 11.7 of IEC 61400-1:2018. In the absence of site data, a loss of electrical connection for a continuous period of 3 months shall be considered to be the extreme condition.

#### **6.4.7 Assessment of soil conditions**

Soil investigations shall be performed to provide adequate information to characterise soil properties throughout the depth and area that will affect or be affected by the foundation structure. The investigations shall in general include the following:

- geological survey of the site;
- bathymetric survey of the sea floor including registration of boulders, sand waves or obstructions on the sea floor;
- geophysical investigation;
- geotechnical investigations consisting of in-situ testing and laboratory tests.

In order to develop the required foundation design parameters, data obtained during the investigations shall be considered in combination with an evaluation of the shallow geology of the region. If practical, the soil sampling and testing program should be defined after reviewing the geophysical results.

Soil investigations shall include one or more soil borings to provide soil samples for in-situ tests and laboratory tests to determine data suitable for definition of engineering properties. The number and depths of borings required shall depend on the number and location of wind turbine foundations in the offshore wind farm, the soil variability in the vicinity of the site, the type of foundation, and the results of any preliminary geophysical investigations. Cone penetration tests (CPT) and shallow vibro-core borings may be used to supplement soil borings in the soil investigation. Site-specific soil data shall in principle be established for each foundation within the wind farm. CPTs may be used for this purpose at wind turbine locations where soil boring is not undertaken. For calibration of the CPTs, one CPT shall be performed in the vicinity of one of the soil borings.

The soil investigation shall provide the following data as the basis of the foundation design:

- data for soil classification and description of the soil;
- shear strength parameters, including soil degradation effects;
- deformation properties, including consolidation parameters;

- permeability;
- stiffness and damping parameters for prediction of the dynamic properties of the wind turbine structure.

For each soil layer, these engineering properties shall be thoroughly evaluated by means of appropriate in situ and laboratory testing.

The assessment of soil conditions shall also consider the potential for soil liquefaction, long-term settlement and displacement of the foundation structure as well as the surrounding soil, hydraulic stability and soil stability characteristics.

## **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, tests or both 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.

Support structure, rotor, and drive train resonances shall be identified for the frequency range up to and including 2 times the blade passing frequency excitation. Possible resonances shall be investigated at turbulence levels of 30 % of the NTM class C design turbulence for DLC 1.2. If high resonant loads are found at low turbulence, means shall be taken to avoid the resonances or they shall be included in the design loads.

### **7.2 Design methodology**

It shall be verified that limit states are not exceeded for the 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.

The design calculations shall be based on validated methods and recognised codes.

In accordance with IEC 61400-1, the design calculation model shall be validated by load measurements. Such measurements shall be made on an onshore or offshore wind turbine that is dynamically and structurally similar to, but may differ in detail (such as an alternative support structure) from the turbine designed. Requirements for load measurements can be found in IEC 61400-13.

### **7.3 Loads**

#### **7.3.1 General**

Loads described in 7.3.2 through 7.3.7, shall be considered for the design calculations.

#### **7.3.2 Gravitational and inertial loads**

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

The allowable tolerances in tower verticality shall be stated in the design documentation and shall include initial and long-term effects due to permanent soil subsidence. The effect of tower verticality on gravitational loads shall be taken into account separately during the structural analysis of tower and foundation.

### 7.3.3 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.

It is not required in the aerodynamic load calculations to account for geometric tolerances in tower verticality of less than or equal to 3°.

### 7.3.4 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 loading to consider the range of actuator forces available, including friction. 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.

### 7.3.5 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 an elevation which provides a clearance (air gap) relative to the expected value of the highest crest elevation with a return 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 air gap should be greater than or equal to  $0,2 \times H_{s50}$ , with a minimum value of 1 m. However, for sites where the extreme conditions are due to tropical cyclones, regional guidelines for determining the air gap shall be considered.

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

### 7.3.6 Sea/lake 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 D.

### 7.3.7 Other loads

Other loads such as wake loads, vessel impact loads, vortex-induced vibrations, etc., may occur and shall be included where appropriate. For other loads associated with cold climate, see IEC 61400-1:2018, Clause 14 and Annex L.

Where relevant, earthquake loads shall be considered according to IEC 61400-1:2018, 11.6. A time domain simulation is required for the load calculation of the support structures of offshore wind turbines. Appropriate modelling methods shall be used for specific support structure types, e.g. an interaction model is needed for a monopile support structure while a sway-rocking model can be used for a gravity base structure. See ISO 3010:2017, Annex H for more detail. 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

### 7.4.1 General

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

- 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 2 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/lake ice is expected to occur, the design load cases presented in Table 3 shall be considered.

If the offshore wind turbine controller can, during design load cases with a deterministic wind model, cause a wind turbine to shut down prior to reaching maximum yaw angle and/or wind speed, then it shall be shown that the turbine can reliably shut down 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.

The designer shall ensure that the load envelope includes the effects of all parameter variations that may lead to increased loads. This would include for example, azimuth angle, wave heights, variations in water depth, etc.

The designer shall consider the effect on loading of reducing the values of environmental and wind turbine status parameters below the limiting values defined here and in IEC 61400-1.

It is possible for the designer to show that variations in certain parameter values are not significant and thereby to exclude or reduce consideration of these parameters in the load case simulations. Typically this requires the use of a limited number of simulations to demonstrate that variations in the parameter are not significant. This may be extended to the elimination of certain external actions if these can be similarly shown to be insignificant. Such loading mechanisms may include currents, waves or elements of this process such as wave kinematics.

For bottom fixed support structures with a natural frequency of the first support structure eigenmode above 0,2 Hz, waves and currents may be ignored for DLCs 1.3, 1.4, 1.5, 2.1, 2.2, 2.3, 2.5, 3.2, 3.3, 4.2, and 5.1. The mass of water enclosed in sub-structure members should not be neglected.

For each design load case, the appropriate type of analysis is stated by “F” and “U” in Table 2. “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) or abnormal (A). Normal design load cases are expected to occur frequently. 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 or A, determines the partial safety factor  $\gamma_f$  to be applied to the ultimate loads. These factors are given in Table 3 of IEC 61400-1:2018.

For guidance on the required number and length of simulations refer to 7.5.6.

**Table 2 – 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<br>$V_{in} < V_{hub} < V_{out}$<br>rotor-nacelle assembly          | NSS<br>$H_s = E[H_s   V_{hub}]$                           | COD, UNI                     | NCM          | MSL                | For extrapolation of extreme loads on the rotor-nacelle assembly | U                | N<br>(1,25)           |
|                     | 1.2 | NTM<br>$V_{in} < V_{hub} < V_{out}$                                    | NSS Joint prob. distribution of $H_s$ , $T_p$ , $V_{hub}$ | MIS, MUL                     | No currents  | NWLR or $\geq$ MSL |                                                                  | F                | *                     |
|                     | 1.3 | ETM<br>$V_{in} < V_{hub} < V_{out}$                                    | NSS<br>$H_s = E[H_s   V_{hub}]$                           | COD, UNI                     | NCM          | MSL                |                                                                  | U                | N                     |
|                     | 1.4 | ECD<br>$V_{hub} = V_r - 2 \text{ m/s}$ , $V_r$ , $V_r + 2 \text{ m/s}$ | NSS<br>$H_s = E[H_s   V_{hub}]$                           | MIS, wind direction change   | NCM          | MSL                |                                                                  | U                | N                     |
|                     | 1.5 | EWS<br>$V_{in} < V_{hub} < V_{out}$                                    | NSS<br>$H_s = E[H_s   V_{hub}]$                           | COD, UNI                     | NCM          | MSL                |                                                                  | U                | N                     |
|                     | 1.6 | NTM<br>$V_{in} < V_{hub} < V_{out}$                                    | SSS<br>$H_s = H_{s,SSS}$                                  | COD, UNI                     | NCM          | NWLR               |                                                                  | U                | N                     |

| 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<br>$V_{in} < V_{hub} < V_{out}$                            | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | NCM          | MSL                | Normal control system fault or loss of electrical network or primary layer control function fault (see 7.4.3) | U                | N                     |
|                                              | 2.2 | NTM<br>$V_{in} < V_{hub} < V_{out}$                            | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | NCM          | MSL                | Abnormal control system fault or secondary layer protection function related fault (see 7.4.3)                | U                | A                     |
|                                              | 2.3 | EOG<br>$V_{hub} = V_r \pm 2 \text{ m/s}$ and $V_{out}$         | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | NCM          | MSL                | External or internal electrical fault including loss of electrical network                                    | U                | A                     |
|                                              | 2.4 | NTM<br>$V_{in} < V_{hub} < V_{out}$                            | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | No currents  | NWLR or $\geq$ MSL | Control system fault, electrical fault or loss of electrical network                                          | F                | *                     |
|                                              | 2.5 | NWP<br>$V_{in} < V_{hub} < V_{out}$                            | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | NCM          | MSL                | Low voltage ride through                                                                                      | U                | N                     |
| 3) Start up                                  | 3.1 | NWP<br>$V_{in} < V_{hub} < V_{out}$                            | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | No currents  | NWLR or $\geq$ MSL |                                                                                                               | F                | *                     |
|                                              | 3.2 | EOG<br>$V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and $V_{out}$ | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | NCM          | MSL                |                                                                                                               | U                | N                     |
|                                              | 3.3 | EDC<br>$V_{hub} = V_{in}, V_r \pm 2 \text{ m/s}$ and $V_{out}$ | NSS<br>$H_s = E[H_s   V_{hub}]$ | MIS, wind direction change   | NCM          | MSL                |                                                                                                               | U                | N                     |
| 4) Normal shut down                          | 4.1 | NWP<br>$V_{in} < V_{hub} < V_{out}$                            | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | No currents  | NWLR or $\geq$ MSL |                                                                                                               | F                | *                     |
|                                              | 4.2 | EOG<br>$V_{hub} = V_r \pm 2 \text{ m/s}$ and $V_{out}$         | NSS<br>$H_s = E[H_s   V_{hub}]$ | COD, UNI                     | NCM          | MSL                |                                                                                                               | U                | N                     |

| Design situation                               | DLC | Wind condition                                                                 | Waves                                               | Wind and wave directionality | Sea currents        | Water level        | Other conditions                   | Type of analysis | Partial safety factor |
|------------------------------------------------|-----|--------------------------------------------------------------------------------|-----------------------------------------------------|------------------------------|---------------------|--------------------|------------------------------------|------------------|-----------------------|
| 5) Emergency stop                              | 5.1 | NTM<br>$V_{hub} = V_r \pm 2 \text{ m/s}$ and $V_{out}$                         | NSS<br>$H_s = E[H_s   V_{hub}]$                     | COD, UNI                     | NCM                 | MSL                |                                    | U                | N                     |
| 6) Parked (standing still or idling)           | 6.1 | EWM Turbulent wind model<br>$V_{hub} = V_{ref}$                                | ESS<br>$H_s = H_{s50}$                              | MIS, MUL                     | ECM<br>$U = U_{50}$ | EWLR               |                                    | U                | N                     |
|                                                | 6.2 | EWM Turbulent wind model<br>$V_{hub} = V_{ref}$                                | ESS<br>$H_s = H_{s50}$                              | MIS, MUL                     | ECM<br>$U = U_{50}$ | EWLR               | Loss of electrical network         | U                | A                     |
|                                                | 6.3 | EWM Turbulent wind model<br>$V_{hub} = V_1$                                    | ESS<br>$H_s = H_{s1}$                               | MIS, MUL                     | ECM<br>$U = U_1$    | NWLR               | Extreme yaw misalignment           | U                | N                     |
|                                                | 6.4 | NTM<br>$V_{out} < V_{hub} < 0,7 V_{ref}$                                       | NSS Joint prob. distribution of $H_s, T_p, V_{hub}$ | COD, MUL                     | No currents         | NWLR or $\geq$ MSL |                                    | F                | *                     |
| 7) Parked and fault conditions                 | 7.1 | EWM<br>$V_{hub} = V_1$                                                         | ESS<br>$H_s = H_{s1}$                               | MIS, MUL                     | ECM<br>$U = U_1$    | NWLR               |                                    | U                | A                     |
|                                                | 7.2 | NTM<br>$V_{hub} < V_{out}$                                                     | NSS Joint prob. distribution of $H_s, T_p, V_{hub}$ | COD, MUL                     | No currents         | NWLR or $\geq$ MSL |                                    | F                | *                     |
| 8) Transport, assembly, maintenance and repair | 8.1 | See 7.4.9 for guidance. Design conditions shall be stated in the design basis. |                                                     |                              |                     |                    |                                    |                  | N                     |
|                                                | 8.2 | EWM<br>$V_{hub} = V_1$                                                         | ESS<br>$H_s = H_{s1}$                               | COD, UNI                     | ECM<br>$U = U_1$    | NWLR               |                                    | U                | A                     |
|                                                | 8.3 | NTM<br>$V_{hub} < 0,7 V_{ref}$                                                 | NSS Joint prob. distribution of $H_s, T_p, V_{hub}$ | COD, MUL                     | No currents         | NWLR or $\geq$ MSL | No grid during installation period | F                | *                     |
|                                                | 8.4 | See 7.4.9 for guidance. Design conditions shall be stated in the design basis. |                                                     |                              |                     |                    |                                    |                  | *                     |