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IEC TC 88 : WIND ENERGY GENERATION SYSTEMS	
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TITLE:

Wind energy generation systems - Part 1: Design requirements

PROPOSED STABILITY DATE: 2021

NOTE FROM TC/SC OFFICERS:

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND ENERGY GENERATION SYSTEMS –

Part 1: Design requirements

FOREWORD

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International Standard IEC 61400-1 has been prepared by IEC technical committee 88: Wind energy generation systems.

This fourth edition cancels and replaces the third edition published in 2005 and Amendment 1:2010. This edition constitutes a technical revision.

This edition includes the following significant technical changes with respect to the previous edition:

a) general update and clarification of references and requirements;
b) extension of wind turbine classes to allow for tropical cyclones and high turbulence;
c) Weibull distribution of turbulence standard deviation for normal turbulence model (NTM);
d) updated design load cases (DLCs), in particular DLC 2.1 and 2.2;
e) revision of partial safety factor specifications;
f) major revision of Clauses 8, 10 and 11;
g) introduction of cold climate requirements, Clause 14;

h) new Annex B on design load cases for site-specific or special class S wind turbine design or site suitability assessment;

i) new Annex J on prediction of the extreme wind speed of tropical cyclones by using Monte Carlo simulation method;

j) new Annex K on calibration of structural material safety factors and structural design assisted by testing;

k) new Annex L on assessment and effects of icing climate;

l) new Annex M on medium wind turbines.

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

FDIS	Report on voting
88/XX/FDIS	88/XX/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.

This document 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.

Future standards in this series will carry the new general title as cited above. Titles of existing standards in this series will be updated at the time of the next edition.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

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- withdrawn,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

A bilingual version of this publication may be issued at a later date.

IMPORTANT – The 'colour inside' logo on the cover page of this publication indicates that it contains colours which are considered to be useful for the correct understanding of its contents. Users should therefore print this document using a colour printer.

INTRODUCTION

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

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. This provision, however, does not apply to the classification and the associated definitions of external conditions in Clause 6. Compliance with this document does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

This document is not intended to give requirements for wind turbines installed offshore, in particular for the support structure. For offshore installations, reference is made to the IEC 61400-3 series.

WIND ENERGY GENERATION SYSTEMS –

Part 1: Design requirements

1 Scope

This part of IEC 61400 specifies essential design requirements to ensure the structural integrity of wind turbines. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.

This document is concerned with all subsystems of wind turbines such as control and protection functions, internal electrical systems, mechanical systems and support structures.

This document applies to wind turbines of all sizes. For small wind turbines, IEC 61400-2 can be applied. IEC 61400-3-1 provides additional requirements to offshore wind turbine installations.

This document is intended to be used together with the appropriate IEC and ISO standards mentioned in Clause 2.

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 60034 (all parts), *Rotating electrical machines*

IEC 60038, *IEC standard voltages*

IEC 60071-1, *Insulation co-ordination – Part 1: Definitions, principles and rules*

IEC 60071-2, *Insulation co-ordination – Part 2: Application guidelines*

IEC 60076 (all parts), *Power transformers*

IEC 60204-1, *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*

IEC 60204-11:2000, *Safety of machinery – Electrical equipment of machines – Part 11: Requirements for HV equipment for voltages above 1 000 V AC or 1 500 V DC and not exceeding 36 kV*

IEC 60364 (all parts), *Low voltage electrical installations*

IEC 60529, *Degrees of protection provided by enclosures (IP Code)*

IEC 60664-1, *Insulation coordination for equipment within low-voltage systems – Part 1: Principles, requirements and tests*

IEC 60664-3, *Insulation coordination for equipment within low-voltage systems – Part 3: Use of coating, potting or moulding for protection against pollution*

IEC 60721 (all parts), *Classification of environmental conditions*

IEC 61000-6-2, *Electromagnetic compatibility (EMC) – Part 6-2: Generic standards – Immunity standard for industrial environments*

IEC 61400-3, *Wind turbines – Part 3: Design requirements for offshore wind turbines*

IEC 61400-4, *Wind Turbines – Part 4: Design requirements for wind turbine gearboxes*

IEC 61400-24, *Wind turbines – Part 24: Lightning protection*

IEC 61439 (all parts), *Low-voltage switchgear and controlgear assemblies*

IEC 61800-4, *Adjustable speed electrical power drive systems – Part 4: General requirements – Rating specifications for AC power drive systems above 1 000 V AC and not exceeding 35 kV*

IEC 61800-5-1, *Adjustable speed electrical power drive systems – Part 5-1: Safety requirements – Electrical, thermal and energy*

IEC 62271 (all parts), *High-voltage switchgear and controlgear*

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

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

IEC 62477-1:2012, *Safety requirements for power electronic converter systems and equipment – Part 1: General*

ISO 76, *Rolling bearings – Static load ratings*

ISO 281, *Rolling bearings – Dynamic load ratings and rating life*

ISO 2394, *General principles on reliability for structures*

ISO 2533, *Standard Atmosphere*

ISO 4354, *Wind actions on structures*

ISO 6336-2, *Calculation of load capacity of spur and helical gears – Part 2: Calculation of surface durability (pitting)*

ISO 6336-3:2006, *Calculation of load capacity of spur and helical gears – Part 3: Calculation of tooth bending strength*

ISO 12494:2001, *Atmospheric icing on structures*

ISO 13850, *Safety of machinery – Emergency stop function – Principles for design*

ISO/TS 16281, *Rolling bearings – Methods for calculating the modified reference rating life for universally loaded bearings*

3 Terms and definitions

For the purposes of this document, the following terms and definitions 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
annual average
mean value of a set of measured data of sufficient size and duration to serve as an estimate of the expected value of the quantity

Note 1 to entry: The averaging time interval should be a whole number of years (e.g. 10) to average out non-stationary effects such as seasonality.

3.2
annual average wind speed
$V_{\mathbf{ave}}$
wind speed averaged according to the definition of annual average

3.3
auto-reclosing cycle
event with a time period, varying from approximately 0,01 s to a few seconds, during which a breaker released after a grid fault is automatically reclosed and the line is reconnected to the network

3.4
blocking
<wind turbines> use of a mechanical pin or other device (other than the ordinary mechanical brake) that cannot be released accidentally to prevent movement, for instance of the rotor shaft or yaw mechanism

3.5
brake
<wind turbines> device capable of reducing the rotor speed or stopping rotation

Note 1 to entry: The brake may operate on, for example, aerodynamic, mechanical or electrical principles.

3.6
characteristic value
value having a prescribed probability of not being attained (i.e. an exceedance probability of less than or equal to a prescribed amount)

3.7
complex terrain
surrounding terrain that features significant variations in topography and terrain obstacles that may cause flow distortion

3.8
control functions
<wind turbines> functions of the control system that, based on information about the condition of the wind turbine and/or its environment, adjust the turbine in order to maintain it within its operating limits

3.9
control system
<wind turbines> system implementing the turbine control functions, including sensors, logic elements, actuators, communication networks, and power supplies

Note 1 to entry: The intent of the control system is to control operation of the turbine by active and passive means and keep the operating parameters within the limits assumed in the structural design. The control system is likely to include control loops for normal operation as well as alarms and shutdown mechanisms to ensure that limits are not exceeded.

3.10
cut-in wind speed
$V_{\mathbf{in}}$
lowest 10 min average wind speed at hub height at which the wind turbine starts to produce power in the case of steady wind without turbulence

3.11
cut-out wind speed
$V_{\mathbf{out}}$
highest 10 min average wind speed at hub height at which the wind turbine is designed to produce power in the case of steady wind without turbulence

3.12
design limits
maximum or minimum values used in a design

3.13
dormant failure
failure of a component or system which remains undetected during normal operation

3.14
downwind
in the direction of the main wind vector

3.15
electrical power network
particular installations, substations, lines or cables for the transmission and distribution of electricity

Note 1 to entry: The boundaries of the different parts of this network are defined by appropriate criteria, such as geographical situation, ownership, voltage.

3.16
emergency stop
<wind turbines> rapid shutdown of the wind turbine triggered by manual intervention

3.17
environmental conditions
characteristics of the environment (wind, altitude, temperature, humidity, etc.) which may affect the wind turbine behaviour

3.18
external conditions
<wind turbines> factors affecting operation of a wind turbine, including the environmental conditions (temperature, snow, ice, etc.) and the electrical network conditions

3.19
extreme wind speed
value of the highest wind speed, averaged over t in seconds, with an annual probability of exceedance of $1/N$ ("return period": N years)

Note 1 to entry: In this document, return periods of N = 50 years and N = 1 year and averaging time intervals of t = 3 s and t = 10 min are used. In popular language, the less precise term, survival wind speed, is often used. In this document, however, the turbine is designed using extreme wind speeds for design load cases.

3.20
fail-safe
design property of an item which prevents its failures from resulting in critical faults

3.21
gust
temporary change in the wind speed

Note 1 to entry: A gust may be characterized by its rise time, its magnitude and its duration.

3.22
horizontal axis wind turbine
wind turbine whose rotor axis is substantially horizontal

3.23
hub
<wind turbines> fixture for attaching the blades or blade assembly to the rotor shaft

3.24
hub height
z_{hub}
<wind turbines> height of the centre of the swept area (3.57) of the wind turbine rotor above the terrain surface

3.25
idling
<wind turbines> condition of a wind turbine that is rotating slowly and not producing power

3.26
inertial sub-range
frequency interval of the turbulence spectrum, where eddies – after attaining isotropy – undergo successive break-up with negligible energy dissipation

Note 1 to entry: At a typical 10 m/s wind speed, the inertial sub-range is roughly from 0,2 Hz to 1 kHz.

3.27
limit state
state of a structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirement

Note 1 to entry: The purpose of design calculations (i.e. the design requirement for the limit state) is to keep the probability of a limit state being reached below a certain value prescribed for the type of structure in question (see ISO 2394).

3.28
mean wind speed
statistical mean of the instantaneous value of the wind speed averaged over a given time period which can vary from a few seconds to many years

3.29
medium wind turbine
wind turbine with a rotor swept area or, in the case of a ducted or shrouded turbine, the larger of the duct or shroud entry and exit areas greater than 200 m^2 and less than or equal to 1 000 m^2

3.30
nacelle
housing which contains the drive-train and other elements on top of a horizontal axis wind turbine tower

3.31
network connection point
<wind turbines> cable terminals of a single wind turbine or, for a wind power station, the connection point to the electrical bus of the site power collection system

3.32
network loss
loss of electrical network (grid) for a period exceeding any ride through provision in the turbine control system

3.33
normal shutdown
<wind turbines> shutdown in which all stages are under the control of the control system

3.34
operating limits
set of conditions defined by the wind turbine designer that governs the activation of the turbine control functions

3.35
parked wind turbine
turbine being either in a standstill or an idling condition, depending on the design of the wind turbine

3.36
performance level
PL
discrete level used to specify the ability of safety-related parts of control systems to perform a safety function under foreseeable conditions

3.37
power collection system
<wind turbines> electric system that collects the power from one or more wind turbines

Note 1 to entry: It includes all electrical equipment connected between the wind turbine terminals and the network connection point.

3.38
power output
power delivered by a device in a specific form and for a specific purpose

Note 1 to entry: For a wind turbine, it is the electric power it delivers.

3.39
primary layer protection function
protection function (3.40) in a protection system with two or more independent layers which may be implemented as a part of the wind turbine control system and is separate from a secondary layer protection function (3.52) with a similar purpose

3.40
protection functions
<wind turbine> functions of the control system which ensure that a wind turbine remains within the design limits

3.41
rated power
quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment

Note 1 to entry: For a wind turbine, it is the maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating and external conditions.

3.42
rated wind speed
V_r
minimum wind speed at hub height at which a wind turbine's rated power is achieved in the case of steady wind without turbulence

3.43
Rayleigh distribution
P_R
probability distribution function

Note 1 to entry: See 3.68.

3.44
reference wind speed
V_{ref}
basic parameter for wind speed used for defining wind turbine classes

Note 1 to entry: Other design related climatic parameters are derived from the reference wind speed and other basic wind turbine class parameters (see Clause 6).

Note 2 to entry: A turbine designed for a wind turbine class with a reference wind speed V_{ref} is designed to withstand climates for which the extreme 10 min average wind speed with a return period of 50 years at turbine hub height is lower than or equal to V_{ref}.

3.45
resistance partial safety factor
γ_M
factor which takes account of possible unfavourable deviations/uncertainties of the material strength parameters and of the resistance model including bias in the resistance model

3.46
rotationally sampled wind velocity
wind velocity experienced at a fixed point of the rotating wind turbine rotor

Note 1 to entry: The turbulence spectrum of a rotationally sampled wind velocity is distinctly different from the normal turbulence spectrum. While rotating, the blade cuts through a wind flow that varies in space. Therefore, the resulting turbulence spectrum will contain sizeable amounts of variance at the frequency of rotation and harmonics of the same.

3.47
rotor speed
<wind turbines> rotational speed of a wind turbine rotor about its axis

3.48
roughness length
z_0
extrapolated height at which the mean wind speed becomes zero if the vertical wind profile is assumed to have a logarithmic variation with height

3.49
safe-life
design property for a critical system which is either very difficult to repair or may cause severe damage to life and property

Note 1 to entry: Such systems are designed to work for the full system lifetime without requirement of any repairs or inspections.

3.50
safety integrity level
SIL
discrete level (one out of a possible four), corresponding to a range of safety integrity values for the control functions, where 4 and 1 belong to the highest and lowest levels, respectively

Note 1 to entry: Target failure measures for the four safety integrity levels are defined in Tables 2 and 3 of IEC 61508-1:2010. These levels can be used for specifying safety integrity requirements of safety functions allocated to the systems. A SIL is not a property of a system, subsystem, element or component. As defined in IEC 61508-1, the phrase "SIL n safety-related system" (where n is 1, 2, 3, or 4) means that the system is potentially capable of supporting safety functions with a safety integrity level up to n.

3.51
scheduled maintenance
preventive maintenance carried out in accordance with an established schedule

3.52
secondary layer protection function
dedicated protection function which operates using a layer of monitoring and logic separate from a primary layer protection function (3.39) with a similar purpose

3.53
site data
environmental, seismic, soil and electrical network data for the wind turbine site

Note 1 to entry: Wind data shall be the statistics of 10 min samples unless otherwise stated.

3.54
standstill
condition of a wind turbine that is stopped

3.55
support structure
<wind turbines> part of a wind turbine comprising the tower and foundation

3.56
survival wind speed
maximum wind speed that a construction is designed to withstand

Note 1 to entry: This is a popular expression that is not used in this document. Design conditions instead refer to extreme wind speed (3.19).

3.57
swept area
projected area perpendicular to the wind direction that a rotor will describe during one complete rotation

3.58
turbulence intensity
I
ratio of the wind speed standard deviation to the mean wind speed, determined from the same set of measured data samples of wind speed, and taken over a specified period of time

3.59
turbulence scale parameter
Λ_1
wavelength where the non-dimensional, longitudinal power spectral density is equal to 0,05

Note 1 to entry: The wavelength is thus defined as $\Lambda_1 = V_{hub}/f_0$, where $f_0 S_1(f_0)/\sigma_1^2 = 0{,}05$.

3.60
turbulence standard deviation
σ_1
standard deviation of the longitudinal component of the turbulent wind velocity at hub height

3.61
ultimate limit state
limit states which generally correspond to maximum load carrying capacity

3.62
unscheduled maintenance
maintenance carried out, not in accordance with an established time schedule, but after receipt of an indication regarding the state of an item

3.63
upwind
in the direction opposite to the main wind vector

3.64
vertical axis wind turbine
wind turbine whose rotor axis is vertical

3.65
Weibull distribution
P_W
probability distribution function

Note 1 to entry: See 3.68.

3.66
wind power station
wind farm
group or groups of wind turbines

3.67
wind profile
wind shear law
mathematical expression for assumed wind speed variation with height above ground

Note 1 to entry: Commonly used profiles are the logarithmic profile (Equation (1)) or the power law profile (Equation (2)).

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

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

where

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

z is the height above ground;

z_r is a reference height above ground used for fitting the profile;

z_0 is the roughness length;

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

3.68
wind speed distribution
probability distribution function, used to describe the distribution of wind speeds over an extended period of time

Note 1 to entry: Often used distribution functions are the Rayleigh, $P_R(V_0)$, and the Weibull, $P_W(V_0)$, functions.

$$\begin{aligned} P_R(V_0) &= 1 - \exp\left[-\pi\left(V_0 / 2V_{ave}\right)^2\right] \\ P_W(V_0) &= 1 - \exp\left[-\left(V_0 / C\right)^k\right] \end{aligned} \tag{3}$$

$$\text{with } V_{ave} = \left\{ \begin{array}{c} C\,\Gamma(1+\frac{1}{k}) \\ C\sqrt{\pi}\,/\,2, \text{ if } k = 2 \end{array} \right\}. \tag{4}$$

where

$P(V_0)$ is the cumulative probability function, i.e. the probability that $V < V_0$;

V_0 is the wind speed (limit);

V_{ave} is the average value of V;

C is the scale parameter of the Weibull function;

k is the shape parameter of the Weibull function;

Γ is the gamma function.

Both C and k can be evaluated from real data. The Rayleigh function is identical to the Weibull function if k = 2 is chosen and C and V_{ave} satisfy the condition stated in Equation (4) for k = 2.

The distribution functions express the cumulative probability that the wind speed is lower than V_0. Thus $(P(V_1) - P(V_2))$, if evaluated between the specified limits V_1 and V_2, will indicate the fraction of time that the wind speed is within these limits. Differentiating the distribution functions yields the corresponding probability density functions.

3.69
wind shear
variation of wind speed across a plane perpendicular to the wind direction

3.70
wind speed
V
speed of motion of a minute amount of air surrounding a specified point in space

Note 1 to entry: It is also the magnitude of the local wind velocity (vector) (see 3.73).

3.71
wind turbine generator system
<wind turbine> system which converts kinetic energy in the wind into electrical energy

3.72
wind turbine site
location of an individual wind turbine either alone or within a wind farm

3.73
wind velocity
vector pointing in the direction of motion of a minute amount of air surrounding the point of consideration, the magnitude of the vector being equal to the speed of motion of this air "parcel" (i.e. the local wind speed)

Note 1 to entry: The vector at any point is thus the time derivative of the position vector of the air "parcel" moving through the point.

3.74
wind turbine electrical system
electrical equipment internal to the wind turbine, up to and including the wind turbine terminals, including equipment for earthing, bonding and communications

Note 1 to entry: Conductors local to the wind turbine, which are intended to provide an earth termination network specifically for the wind turbine, are included.

3.75
wind turbine terminals
point or points identified by the wind turbine supplier at which the wind turbine may be connected to the power collection system

Note 1 to entry: This includes connection for the purposes of transferring energy and communications.

3.76
yawing
rotation of the rotor axis about a vertical axis

Note 1 to entry: For horizontal axis wind turbines only.

3.77
yaw misalignment
horizontal deviation of the wind turbine rotor axis from the wind direction

4 Symbols and abbreviated terms

4.1 Symbols and units

C	scale parameter of the Weibull distribution function	[m/s]
C_{CT}	turbulence structure correction parameter	
C_{T}	thrust coefficient	[-]
Coh	coherence function	[-]
D	rotor diameter	[m]
$D_{\mathrm{TV},i}$	standard deviation of terrain variation Δz in ith 30° sector	[m]
$D_{\mathrm{TV,360}}$	standard deviation of terrain variation Δz of the 360° circle area	[m]
f	frequency	[s^{-1}]
f_{d}	design value for material strength	[-]
f_{k}	characteristic value for material strength	[-]
F_{d}	design value for loads	[-]

F_k	characteristic value for loads	[-]
I_ref	reference value of the turbulence intensity corresponding to the 70 % quantile at 15 m/s	[-]
I_eff	effective turbulence intensity	[-]
k	shape parameter of the Weibull distribution function	[-]
k_1	empirical adjustment factor for TSI360, k_1 = 5/3	[-]
k_2	empirical adjustment factor for TVI360, k_2 = 3	[-]
K	modified Bessel function	[-]
L	isotropic turbulence integral scale parameter	[m]
L_e	coherence scale parameter	[m]
L_k	velocity component integral scale parameter	[m]
m	Wöhler curve exponent	[-]
n_i	counted number of fatigue cycles in load bin i	[-]
N(.)	number of cycles to failure as a function of the stress (or strain) indicated by the argument (i.e. the characteristic S-N curve)	[-]
N	return period for extreme situations	[years]
p	air pressure	[N/m^2]
$P(V_0)$	probability distribution, i.e. the probability that $V < V_0$	[-]
$P_\mathrm{R}(V_0)$	Rayleigh probability distribution, i.e. the probability that $V < V_0$	[-]
P_s	survival probability	[-]
$P_\mathrm{W}(V_0)$	Weibull probability distribution	[-]
r	magnitude of separation vector projection	[m]
R	radius of circle segment	[m]
R_0	gas constant	[J/(kg·K)]
S	load function	[-]
s_i	the stress (or strain) level associated with the counted number of cycles in bin i	[-]
$S_1(f)$	power spectral density function for the longitudinal wind velocity component	[m^2/s]
$S_\mathrm{F,min}$	minimum value of safety factor for tooth breakage	[-]
$S_\mathrm{H,min}$	minimum value of safety factor for pitting	[-]
$S_k(f)$	one-sided power spectral density function for wind velocity component k: k = 1 longitudinal component k = 2 lateral component k =3 vertical component	[m^2/s]
T	gust characteristic time	[s]
t	time	[s]
V	wind speed	[m/s]
$V(z)$	wind speed at height z	[m/s]

V_{ave}	annual average wind speed at hub height	[m/s]
V_{cg}	extreme coherent gust magnitude over the whole rotor swept area	[m/s]
V_{eN}	expected extreme wind speed (averaged over three seconds), with a recurrence time interval of N years. V_{e1} and V_{e50} for 1 year and 50 years, respectively	[m/s]
V_{gust}	largest gust magnitude with an expected return period of 50 years	[m/s]
V_{hub}	wind speed at hub height	[m/s]
V_{in}	cut-in wind speed	[m/s]
V_0	limit wind speed in wind speed distribution model	[m/s]
V_{50}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 50 years	[m/s]
V_{100}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 100 years	[m/s]
V_{out}	cut-out wind speed	[m/s]
V_r	rated wind speed	[m/s]
V_{ref}	reference wind speed	[m/s]
$V_{ref,T}$	reference wind speed for tropical-like conditions	[m/s]
$V(y,z,t)$	longitudinal wind velocity component to describe transient horizontal wind shear	[m/s]
$V(z,t)$	longitudinal wind velocity component to describe transient variation for extreme gust and shear conditions	[m/s]
x, y, z	co-ordinate system used for the wind field description; along wind (longitudinal), across wind (lateral) and height respectively	[m]
Z_{NT}	life factor for contact stress for reference test conditions	[-]
z_{hub}	hub height of the wind turbine	[m]
z_r	reference height above ground	[m]
z_0	roughness length for the logarithmic wind profile	[m]
α	wind shear power law exponent	[-]
β	parameter for extreme direction change model	[-]
δ	coefficient of variation	[-]
Γ	gamma function	[-]
γ_f	partial safety factor for loads	[-]
γ_M	partial safety factor for resistances	[-]
γ_n	partial safety factor for consequences of failure	[-]
$\theta(t)$	wind direction change transient	[deg]
θ_{cg}	angle of maximum deviation from the direction of the average wind speed under gust conditions	[deg]
θ_{eN}	extreme direction change with a return period of N years	[deg]
θ_i	slope of fitted plane for ith 30° sector	[deg]
θ_{360}	slope of the fitted 360° plane	[deg]

$\theta_{1\text{year,min}}$	minimum ambient temperature to be expected in hourly average	[K]
$\theta_{\text{min,operation}}$	minimum allowable ambient temperature for wind turbine operation	[K]
Λ_1	turbulence scale parameter defined as the wavelength where the non-dimensional, longitudinal power spectral density, $fS_1(f)/\sigma_1^2$, is equal to 0,05	[m]
ρ	air density	[kg/m^3]
$\hat{\sigma}$	estimated wind speed standard deviation	[m/s]
$\hat{\sigma}_c$	representative ambient turbulence standard deviation	[m/s]
$\hat{\sigma}_{\text{eff}}$	effective estimated wind speed standard deviation	[m/s]
σ_{wake}	wind speed standard deviation in the wake	[m/s]
$\hat{\sigma}_T$	maximum centre-wake wind speed standard deviation	[m/s]
$\hat{\sigma}_\sigma$	standard deviation of estimated wind speed standard deviation $\hat{\sigma}$	[m/s]
$\hat{\sigma}_{1,\text{ETM}}$	extreme ambient turbulence standard deviation	[m/s]
σ_1	hub-height longitudinal wind velocity standard deviation	[m/s]
σ_2	hub-height lateral wind velocity standard deviation	[m/s]
σ_3	hub-height upward wind velocity standard deviation	[m/s]
Φ	standardized normal probability function	[-]
E[ ]	expected value of parameter inside brackets	[-]
Var[ ]	variance of parameter inside brackets	[-]

4.2 Abbreviated terms

A	abnormal (for partial safety factors)
AC	alternating current
DC	direct current
CC	cold climate
COV	coefficient of variation
DLC	design load case
DWM	dynamic wake meandering
ECD	extreme coherent gust with direction change
EDC	extreme wind direction change
EOG	extreme operating gust
ETM	extreme turbulence model
EWM	extreme wind speed model
EWS	extreme wind shear
F	fatigue
FMEA	failure mode and effect analysis
HV	high voltage
IAC	internal arc classification
IC	icing climate

LTC	low temperature climate
LVRT	low voltage ride through
N	normal and extreme (for partial safety factors)
NWP	normal wind profile model
NTM	normal turbulence model
S	special IEC wind turbine class
T	transport and erection (for partial safety factors)
TSI	terrain slope index
TVI	terrain variation index
U	ultimate
ULS	ultimate limit state

5 Principal elements

5.1 General

The engineering and technical requirements to ensure the safety of the structural, mechanical, electrical and control systems of the wind turbine are given in the following clauses. This specification of requirements applies to the design, manufacture, installation and manuals for operation and maintenance of a 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 wind turbine, are taken into account.

5.2 Design methods

This document requires the use of an aeroelastic dynamics model to predict design loads. Such a model shall be used to determine the loads over a range of wind speeds, using the turbulence conditions and other wind conditions defined in Clause 6 and design situations defined in Clause 7. All relevant combinations of external conditions and design situations shall be analysed. A minimum set of such combinations has been defined as load cases in this document.

Data from full scale testing of a wind turbine shall be used to increase confidence in predicted design values and to verify structural dynamics models and design situations as specified in 7.2.

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.

5.3 Safety classes

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

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

Partial safety factors, for normal safety class wind turbines, are specified in 7.6.

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

5.4 Quality assurance

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

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

5.5 Wind turbine markings

The following information, as a minimum, shall be prominently and legibly displayed on the indelibly marked turbine nameplate:

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

6 External conditions

6.1 General

The external conditions described in Clause 6 shall be considered in the design of a wind turbine.

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

The environmental conditions are further divided into wind conditions and other environmental conditions. The electrical conditions refer to the electrical power network conditions. Soil properties are relevant to the design of wind turbine foundations.

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.

Wind conditions are the primary external conditions affecting structural integrity. Other environmental conditions also affect design features such as control system function, durability, corrosion.

The normal and extreme conditions, which are to be considered for design according to wind turbine classes, are prescribed in 6.2 to 6.4.

6.2 Wind turbine classes

The external conditions to be considered for design are dependent on the intended site or site type for a wind turbine installation. Wind turbine classes are defined in terms of wind speed, wind turbine class I, II and III, and turbulence parameters, turbulence category A+, A, B, and C. The intention of the classes is to cover most applications. The values of wind speed and turbulence parameters are intended to represent many different sites and do not give a precise representation of any specific site, see 11.3. The wind turbine classification offers a range of robustness clearly defined in terms of the wind speed and turbulence parameters. In order to allow the use of wind turbine classes for areas, which may experience very high extreme winds in an otherwise moderate wind climate, a T class reference wind speed is included. Such conditions may be found in areas subject to tropical cyclones. This reference wind speed may be used with the average wind speed in class I to III and turbulence categories A+ to C[1]. Table 1 specifies the basic parameters, which define the wind turbine classes.

Table 1 – Basic parameters for wind turbine classes

Wind turbine class		I	II	III	S
V_{ave}	(m/s)	10	8,5	7,5	Values specified by the designer
V_{ref}	(m/s)	50	42,5	37,5	
	Tropical (m/s) $V_{ref,T}$	57	57	57	
A+	I_{ref} (-)	0,18			
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

The parameter values apply at hub height and

V_{ave} is the annual average wind speed;

V_{ref} is the reference wind speed average over 10 min;

$V_{ref,T}$ is the reference wind speed average over 10 min applicable for areas subject to tropical cyclones;

A+ designates the category for very high turbulence characteristics;

A designates the category for higher turbulence characteristics;

B designates the category for medium turbulence characteristics;

C designates the category for lower turbulence characteristics; and

I_{ref} is a reference value of the turbulence intensity (see 6.3.2.3).

Class T assumes all wind model parameters to be the same and allows the combination of $V_{ref,T}$ with all turbulence categories. It does not cover all the areas prone to tropical cyclones. A site assessment based on Clause 11 is needed, as a minimum assessing that V_{50} is below V_{ref} of class T ($V_{ref,T}$).

An optional wind turbine class CC, which may be used for areas with cold climate, is defined in Clause 14. The optional wind turbine class specifies additional requirements and parameters to what is given in Clause 6.

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

1 A turbine class using for example the annual average wind speed of class II and turbulence category B together with the T class reference wind speed is designated class IIB,T.

The design values for the wind turbine class S shall be chosen by the designer and specified in the design documentation. For such special designs, the values chosen for the design conditions shall reflect an environment at least as severe as is anticipated for the use of the wind turbine.

Wind turbines to be designed for site-specific or very extreme conditions may require wind turbine class S design.

In addition to the basic parameters showed in Table 1, several other important parameters are required to completely specify the external conditions to be used in wind turbine design. In the case of the wind turbine classes I_{A+} through III_C, later referred to as the standard wind turbine classes, the values of these additional parameters are specified in 6.3, 6.4 and 6.5.

The design lifetime for wind turbine classes I to III shall be at least 20 years.

For the wind turbine class S the manufacturer shall, in the design documentation, describe the models used and values of design parameters. Where the models in Clause 6 are adopted, statement of the values of the parameters will be sufficient. The design documentation of wind turbine class S shall contain the information listed in Annex A. Guidance on turbine class S design load cases is given in Annex B.

The abbreviations added in parentheses in the subclause headings in 6.3.2.2 to 6.3.3.7 are used for describing the wind conditions for the design load cases defined in 7.4.

6.3 Wind conditions

6.3.1 General

A wind turbine shall be designed to safely withstand the wind conditions defined by the selected wind turbine class.

The design values of the wind conditions shall be clearly specified in the design documentation.

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

The wind conditions include a constant mean flow combined, in many cases, with either a varying deterministic gust profile or with turbulence. In all cases, the influence of an inclination of the mean flow with respect to a horizontal plane of 8° shall be considered. This flow inclination angle shall be assumed to be invariant with height.

The expression "turbulence" denotes random variations in the wind velocity from 10 min averages. The turbulence model, when used, shall include the effects of varying wind speed, shears and direction and allow rotational sampling through varying shears. The three vector components of the turbulent wind velocity are defined as

- longitudinal – along the direction of the mean wind velocity,
- lateral – horizontal and normal to the longitudinal direction, and
- upward – normal to both the longitudinal and lateral directions, i.e. tilted from the vertical by the mean flow inclination angle.

For the standard wind turbine classes, the random wind velocity field for the turbulence models shall satisfy the Kaimal model together with the coherence model described in Annex C. This model satisfies the following requirements.

a) The turbulence standard deviation, σ_1, with values given in the following subclauses, shall be assumed to be invariant with height. The components normal to the mean wind direction shall have the following minimum standard deviations[2]:

   – lateral component: $\sigma_2 \geq 0{,}7\sigma_1$;

   – upward component: $\sigma_3 \geq 0{,}5\sigma_1$;

b) The longitudinal turbulence scale parameter, Λ_1, at hub height z shall be given by

$$\Lambda_1 = \begin{cases} 0{,}7z & z \leq 60m \\ 42m & z \geq 60m \end{cases} \tag{5}$$

The power spectral densities of the three orthogonal components, $S_1(f)$, $S_2(f)$, and $S_3(f)$ shall asymptotically approach the following forms as the frequency in the inertial sub-range increases:

$$S_1(f) = 0{,}05\sigma_1^2(\Lambda_1 / V_{\text{hub}})^{-2/3} f^{-5/3} \tag{6}$$

$$S_2(f) = S_3(f) = \tfrac{4}{3} S_1(f) \tag{7}$$

c) A recognized model for the coherence, defined as the magnitude of the co-spectrum divided by the auto-spectrum for the longitudinal velocity components at spatially separated points in a plane normal to the longitudinal direction, shall be used.

As an alternative, the corresponding Mann model may be applied as described in Annex C.

Other turbulence models may be applied; however, for the standard wind turbine classes (I to III), the turbulence model shall satisfy the requirements a) to c) and also result in fatigue loads that are higher or equal to the fatigue loads generated using the models in Annex C. For Class S, a validated turbulence model may be applied.

6.3.2 Normal wind conditions

6.3.2.1 Wind speed distribution

The wind speed distribution is significant for wind turbine design because it determines the frequency of occurrence of individual load conditions for the normal design situations. The mean value of the wind speed for an averaging period of 10 min shall be assumed to follow a Rayleigh distribution at hub height given by

$$P_{\text{R}}(V_{\text{hub}}) = 1 - \exp\left[-\pi\left(V_{\text{hub}} / 2V_{\text{ave}}\right)^2\right] \tag{8}$$

where, in the standard wind turbine classes, V_{ave} shall be chosen from Table 1.

6.3.2.2 Normal wind profile model (NWP)

The wind profile, $V(z)$, denotes the average wind speed as a function of height, z, above the ground. In the case of the standard wind turbine classes, the normal wind speed profile shall be given by the power law:

2 The actual values can depend on the choice of turbulence model and the requirements in b).

$$V(z) = V_{\text{hub}} (z/z_{\text{hub}})^{\alpha} \tag{9}$$

The power law exponent, α, shall be assumed to be 0,2.

The assumed wind profile is used to define the average vertical wind shear across the rotor swept area.

6.3.2.3 Normal turbulence model (NTM)

For the normal turbulence model, the representative value of the turbulence standard deviation, σ_1, shall be given by the 90 % quantile for the given hub height wind speed. This value for the standard wind turbine classes shall be given by

$$\sigma_1 = I_{\text{ref}} (0{,}75 V_{\text{hub}} + b); \quad b = 5{,}6 \text{ m/s} \tag{10}$$

Values for the turbulence standard deviation σ_1 and the turbulence intensity σ_1/V_{hub} are shown in Figure 1.

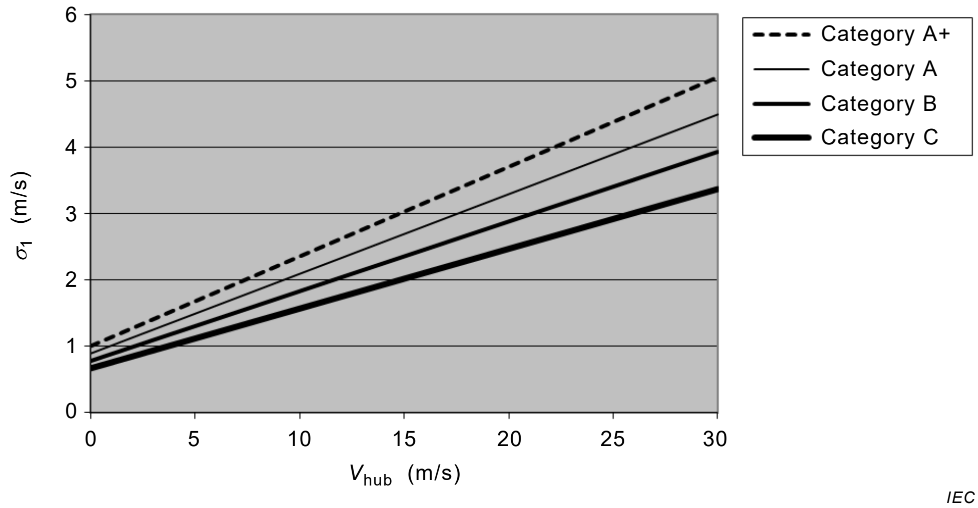

Figure 1a – Turbulence standard deviation

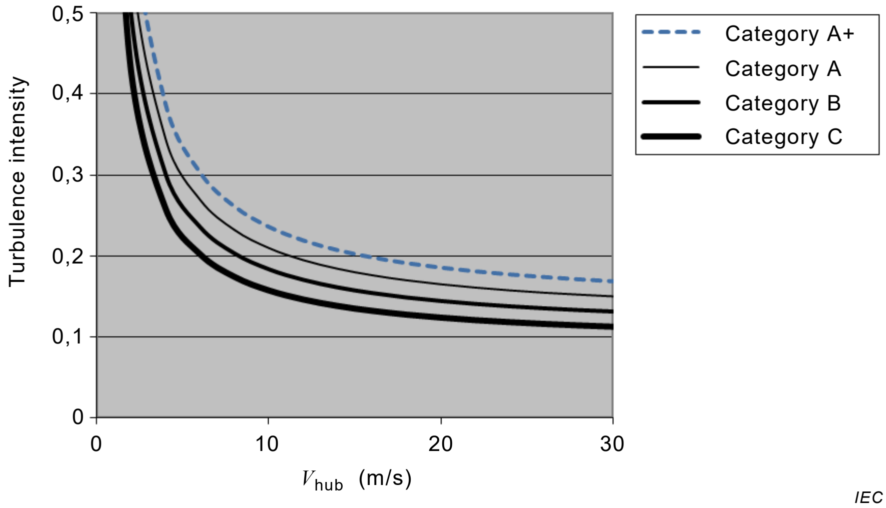

Figure 1b – Turbulence intensity

Figure 1 – Turbulence standard deviation and turbulence intensity for the normal turbulence model (NTM)

Values for I_{ref} are given in Table 1.

As an alternative to Equation (10), a Weibull distribution shall be assumed for σ_1 with Weibull scale and shape parameters:

$$P_W(\sigma_1 < \sigma_0) = 1 - \exp\left[-\left(\frac{\sigma_0}{C}\right)^k\right] \tag{11}$$

where

$$k = 0{,}27\ V_{hub}(\mathrm{s/m}) + 1{,}4$$

$$C = I_{ref}\left(0{,}75 V_{hub} + 3{,}3\ \mathrm{m/s}\right) \tag{12}$$

6.3.3 Extreme wind conditions

6.3.3.1 General

The extreme wind conditions include wind shear events, as well as peak wind speeds due to storms and rapid changes in wind speed and direction.

6.3.3.2 Extreme wind speed model (EWM)

The EWM shall be either a steady or a turbulent wind model. The wind models shall be based on the reference wind speed, V_{ref}, and a fixed turbulence standard deviation, σ_1. If the wind turbine type is designed for a T class reference wind speed, V_{ref} shall be replaced by $V_{ref,T}$ in the extreme wind speed model while keeping other parameters.

For the steady extreme wind model, the extreme wind speed, V_{e50}, with a return period of 50 years, and the extreme wind speed, V_{e1}, with a return period of 1 year, shall be computed as a function of height, z, using the following equations:

$$V_{e50}(z) = 1{,}4\,V_{ref}\left(\frac{z}{z_{hub}}\right)^{0{,}11} \tag{13}$$

and

$$V_{e1}(z) = 0{,}8\,V_{e50}(z) \tag{14}$$

In the steady extreme wind model, allowance for short-term deviations from the mean wind direction shall be made by assuming constant yaw misalignment in the range of ±15°.

For the turbulent extreme wind speed model, the 10 min average wind speeds as functions of z with return periods of 50 years and 1 year, respectively, shall be given by

$$V_{50}(z) = V_{ref}\left(\frac{z}{z_{hub}}\right)^{0{,}11} \tag{15}$$

$$V_1(z) = 0{,}8\,V_{50}(z) \tag{16}$$

The longitudinal turbulence standard deviation[3] shall be

$$\sigma_1 = 0{,}11\,V_{hub} \tag{17}$$

6.3.3.3 Extreme operating gust (EOG)

The hub height gust magnitude V_{gust}[4] shall be given for the standard wind turbine classes by the following relationship:

$$V_{gust} = \mathrm{Min}\left\{ 1{,}35\,(V_{e1} - V_{hub});\quad 3{,}3\left(\frac{\sigma_1}{1+0{,}1\left(\frac{D}{\Lambda_1}\right)}\right)\right\} \tag{18}$$

where

σ_1 is given in Equation (10);

Λ_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The wind speed shall be defined by Equation (19):

$$V(z,t) = \begin{cases} V(z) - 0{,}37\,V_{gust}\sin(3\pi t/T)\big(1-\cos(2\pi t/T)\big) & \text{for } 0 \le t \le T \\ V(z) & \text{otherwise} \end{cases} \tag{19}$$

where

$V(z)$ is defined in Equation (9);

---

3 The turbulence standard deviation for the turbulent extreme wind model is not related to the normal (NTM) or the extreme turbulence model (ETM). The steady extreme wind model is related to the turbulent extreme wind model by a peak factor of approximately 3,5.

4 The gust magnitude is calibrated, together with the probability of an operation event such as starts and stops, to give a return period of 50 years.

T = 10,5 s.

An example of the extreme operating gust (V_{hub} = 25 m/s, Class I_A, D = 42 m) is shown in Figure 2.

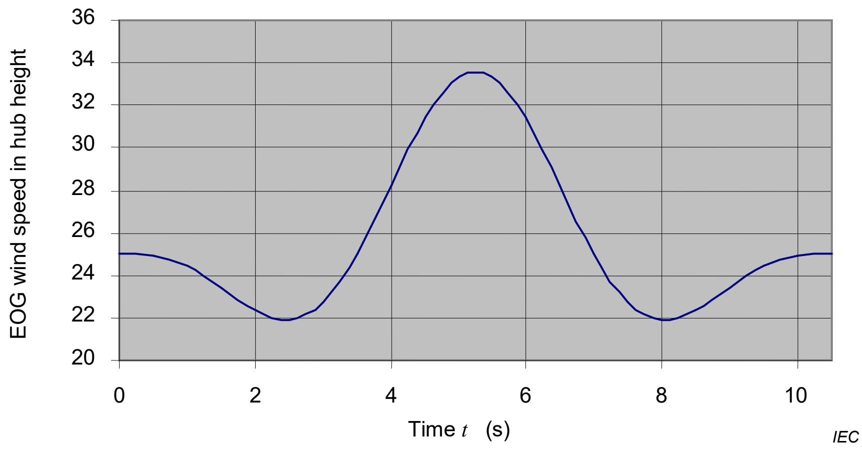

Figure 2 – Example of extreme operating gust

6.3.3.4 Extreme turbulence model (ETM)

The extreme turbulence model shall use the normal wind profile model in 6.3.2.2 and turbulence with longitudinal component standard deviation given by

$$\sigma_1 = c\ I_{ref}\left(0{,}072\left(\frac{V_{ave}}{c}+3\right)\left(\frac{V_{hub}}{c}-4\right)+10\right);\quad c = 2\ \text{m/s}. \tag{20}$$

6.3.3.5 Extreme direction change (EDC)

The extreme direction change magnitude, θ_e, shall be calculated using the following relationship:

$$\theta_e = \pm 4\ \arctan\left(\frac{\sigma_1}{V_{hub}\left(1+0{,}1\left(\frac{D}{\Lambda_1}\right)\right)}\right) \tag{21}$$

where

σ_1 is given by Equation (10) for the NTM;

θ_e is limited to the interval ±180°;

Λ_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The extreme direction change transient, $\theta(t)$, shall be given by

$$\theta(t) = \begin{cases} 0^\circ & \text{for} \quad t < 0 \\ \pm 0{,}5\theta_e (1 - \cos(\pi t / T)) & \text{for} \quad 0 \le t \le T \\ \theta_e & \text{for} \quad t > T \end{cases} \tag{22}$$

where T = 6 s is the duration of the extreme direction change. The sign shall be chosen so that the worst transient loading occurs. At the end of the direction change transient, the direction is assumed to remain unchanged. The wind speed shall follow the normal wind profile model in 6.3.2.2.

As an example, the magnitude of the extreme direction change with turbulence category A, D = 42 m, z_{hub} = 30 m is shown in Figure 3 for varying V_{hub}. The corresponding transient for V_{hub} = 25 m/s is shown in Figure 4.

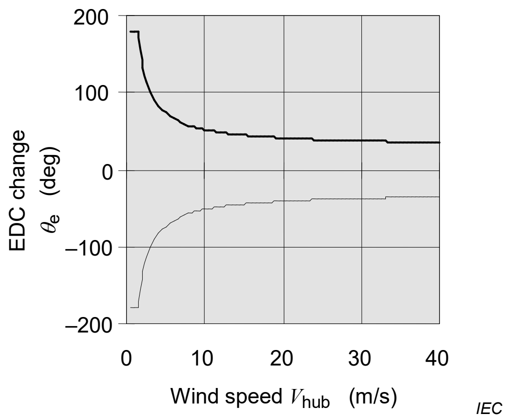

Figure 3 – Example of extreme direction change magnitude

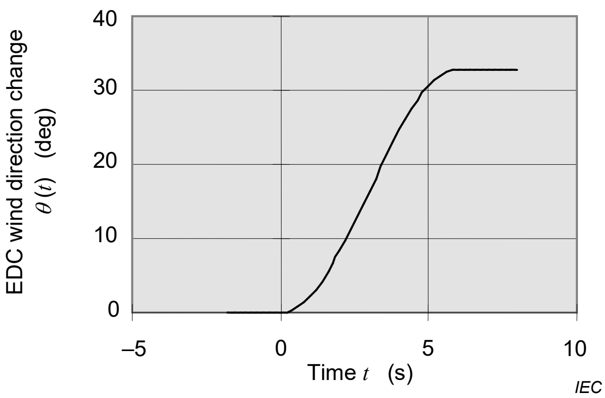

Figure 4 – Example of extreme direction change transient

6.3.3.6 Extreme coherent gust with direction change (ECD)

The extreme coherent gust with direction change shall have a magnitude of

$$V_{cg} = 15 \text{ m/s} \tag{23}$$

The wind speed shall be defined by

$$V(z,t) = \begin{cases} V(z) & \text{for} \quad t \le 0 \\ V(z) + 0{,}5 V_{cg} \left(1 - \cos(\pi t / T)\right) & \text{for} \quad 0 \le t \le T \\ V(z) + V_{cg} & \text{for} \quad t \ge T \end{cases} \tag{24}$$

where T = 10 s is the rise time and the wind speed $V(z)$ is given by the normal wind profile model in 6.3.2.2. The rise in wind speed during the extreme coherent gust is illustrated in Figure 5 for V_{hub} = 25 m/s.

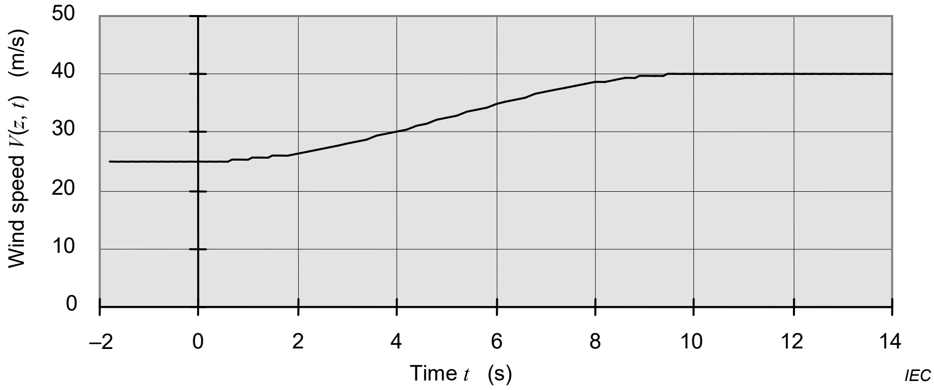

Figure 5 – Example of extreme coherent gust amplitude for ECD

The rise in wind speed shall be assumed to occur simultaneously with the direction change θ from 0° up to and including θ_{cg}, where the magnitude θ_{cg} is defined by

$$\theta_{cg}(V_{hub}) = \begin{cases} 180^\circ & \text{for } V_{hub} < 4\,\text{m/s} \\ \dfrac{720^\circ\,(\text{m/s})}{V_{hub}} & \text{for } 4\,\text{m/s} < V_{hub} < V_{ref} \end{cases} \tag{25}$$

The simultaneous direction change is then given by

$$\theta(t) = \begin{cases} 0^\circ & \text{for} \quad t < 0 \\ \pm 0{,}5\theta_{cg}\left(1 - \cos(\pi t / T)\right) & \text{for} \quad 0 \le t \le T \\ \pm\theta_{cg} & \text{for} \quad t > T \end{cases} \tag{26}$$

where T = 10 s is the rise time.

The direction change magnitude, θ_{cg}, and the direction change $\theta(t)$ are shown in Figures 6 and 7, as a function of V_{hub} and as a function of time for V_{hub} = 25 m/s, respectively.

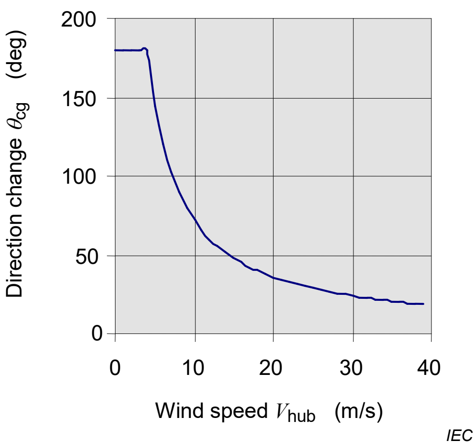

Figure 6 – Direction change for ECD

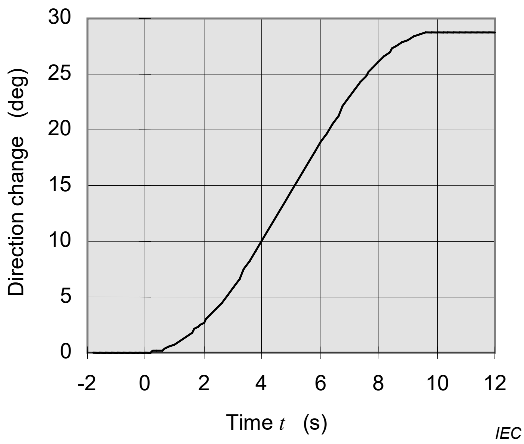

Figure 7 – Example of direction change transient

6.3.3.7 Extreme wind shear (EWS)

The extreme wind shear shall be accounted for using the following wind speed transients.

Transient (positive and negative) vertical shear:

$$V(z,t) = \begin{cases} V_{\text{hub}}\left(\dfrac{z}{z_{\text{hub}}}\right)^{\alpha} \pm \left(\dfrac{z - z_{\text{hub}}}{D}\right)\left(2{,}5[\text{m/s}] + 0{,}2\beta\sigma_1\left(\dfrac{D}{\Lambda_1}\right)^{1/4}\right)\left(1 - \cos\left(2\pi t/T\right)\right) & \text{for } 0 \le t \le T \\ V_{\text{hub}}\left(\dfrac{z}{z_{\text{hub}}}\right)^{\alpha} & \text{otherwise} \end{cases} \quad (27)$$

Transient horizontal shear:

$$V(y,z,t) = \begin{cases} V_{\text{hub}}\left(\dfrac{z}{z_{\text{hub}}}\right)^{\alpha} \pm \left(\dfrac{y}{D}\right)\left(2{,}5[\text{m/s}] + 0{,}2\beta\sigma_1\left(\dfrac{D}{\Lambda_1}\right)^{1/4}\right)\left(1 - \cos\left(2\pi t/T\right)\right) & \text{for } 0 \le t \le T \\ V_{\text{hub}}\left(\dfrac{z}{z_{\text{hub}}}\right)^{\alpha} & \text{otherwise} \end{cases} \quad (28)$$

where for both vertical and horizontal shear:

α = 0,2; β = 6,4; T = 12 s;

σ_1 is given by Equation (10) for the NTM;

Λ_1 is the turbulence scale parameter, according to Equation (5);

D is the rotor diameter.

The sign for the horizontal wind shear transient shall be chosen so that the worst transient loading occurs. The two extreme wind shears are not applied simultaneously.

As an example, the extreme vertical wind shear (turbulence category A, z_{hub} = 30 m, V_{hub} = 25 m/s, D = 42 m) is illustrated in Figure 8, which shows the wind profiles before onset of the extreme event (t = 0 s) and at maximum shear (t = 6 s). Figure 9 shows the wind speeds at the top and the bottom of the rotor, to illustrate the time development of the shear (assumptions as in Figure 8).

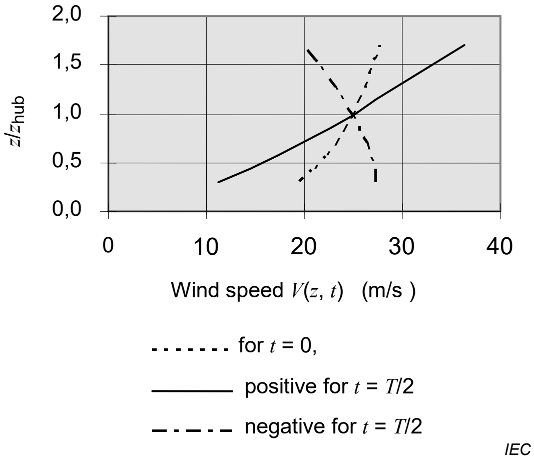

Figure 8 – Examples of extreme positive and negative vertical wind shear, wind profile before onset (t = 0, dashed line) and at maximum shear (t = 6 s, full line)

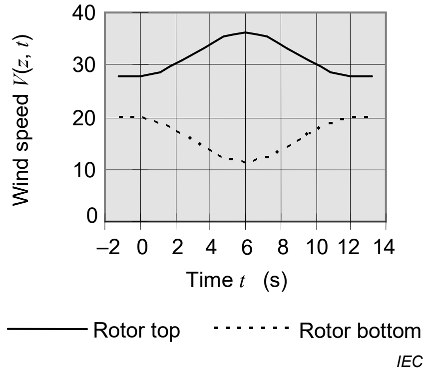

Figure 9 – Example of wind speeds at rotor top and bottom, respectively, which illustrate the transient positive wind shear

6.4 Other environmental conditions

6.4.1 General

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

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

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

An offshore environment requires additional consideration, as per IEC 61400-3.

An optional cold climate class is defined in Clause 14.

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 climatic conditions within the normal limits corresponding to a 1-year return period shall not interfere with the designed normal operation of a wind turbine.

Unless correlation exists, other extreme environmental conditions according to 6.4.3 shall be combined with normal wind conditions according to 6.3.2. A general description on how to combine design situations with external conditions is given in 7.4.

6.4.2 Normal other environmental conditions

The normal other environmental condition values that shall be taken into account are the following:

- ambient temperature range of –10 °C to +40 °C;
- relative humidity up to 95 %;
- atmospheric content equivalent to that of a non-polluted inland atmosphere (see IEC 60721-2-1);
- solar radiation intensity of 1 000 W/m^2;
- air density of 1,225 kg/m^3.

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

6.4.3 Extreme other environmental conditions

6.4.3.1 General

The extreme other environmental conditions that shall be considered for wind turbine design are temperature, lightning, ice and earthquakes (see 11.6 for assessment of earthquake conditions).

6.4.3.2 Temperature

The extreme temperature range for the standard wind turbine classes shall be at least –20 °C to +50 °C.

6.4.3.3 Lightning

The provisions of lightning protection required in 10.7 may be considered as adequate for turbine designs for the standard wind turbine classes.

6.4.3.4 Ice

No minimum ice requirements are given for the standard wind turbine classes. For cold climate, ice requirements are given in Clause 14 and Annex L.

6.4.3.5 Earthquakes

No minimum earthquake requirements are given for the standard wind turbine classes. For consideration of earthquake conditions and effects, see 11.6 and Annex D.

6.5 Electrical power network conditions

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

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

- Voltage – nominal value (according to IEC 60038) ± 10 %.
- Frequency – nominal value ± 2 %.

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

7 Structural design

7.1 General

The integrity of the load-carrying components of the 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 a 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 to the safety factors appropriate for the characteristic loads according to 7.6.

Tower, 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 category C design turbulence for DLC 1.2, see 7.4.2. 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 recognized codes.

The design methodology assumes that the aeroelastic simulation model used for the specific design calculations is subsequently validated by measurements. Such measurements shall be made on a wind turbine that is dynamically and structurally similar to, but may differ in detail (such as alternative tower designs) 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 7.3.5 shall be considered for the design calculations.

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

7.3.2 Gravitational and inertial loads

Gravitational and inertial loads are static and dynamic loads that result 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 or inverter or both, 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 Other loads

Other loads such as wake loads, impact loads, ice loads, tower loads resulting for example from vortex-induced vibrations might occur and shall be considered where appropriate. For other loads associated with cold climate, see Clause 14 and Annex L.

7.4 Design situations and load cases

7.4.1 General

Subclause 7.4 describes the design load cases for a wind turbine and specifies a minimum number to be considered.

For design purposes, the life of a wind turbine can be represented by a set of design situations covering the most significant conditions that the 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 a 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, electrical and other external conditions.

If the wind turbine controller can, during design load cases with a deterministic wind model, cause the 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.

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 the activation of system protection functions. The type of design situation, N or A, determines the partial safety factor γ_f to be applied to the ultimate loads. These factors are given in Table 3.

Table 2 – Design load cases (DLC)

Design situation	DLC	Wind condition		Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM	$V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM	$V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD	$V_{hub} = V_r – 2$ m/s, V_r, $V_r + 2$ m/s		U	N
	1.5	EWS	$V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM	$V_{in} < V_{hub} < V_{out}$	Normal control system fault or loss of electrical network or primary layer control function fault (see 7.4.3)	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Abnormal control system fault or secondary layer protection function related fault (see 7.4.3)	U	A
	2.3	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM	$V_{in} < V_{hub} < V_{out}$	Control system fault, electrical fault or loss of electrical network	F	*
	2.5	NWP	$V_{in} < V_{hub} < V_{out}$	Low voltage ride through	U	N
3) Start-up	3.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC	$V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
4) Normal shutdown	4.1	NWP	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency stop	5.1	NTM	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM	50-year return period		U	N
	6.2	EWM	50-year return period	Loss of electrical network connection	U	A
	6.3	EWM	1-year return period	Extreme yaw misalignment	U	N
	6.4	NTM	$V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM	1-year return period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	N
	8.2	EWM	1-year return period		U	A

Key	
DLC	Design load case
ECD	Extreme coherent gust with direction change (see 6.3.3.6)
EDC	Extreme direction change (see 6.3.3.5)
EOG	Extreme operating gust (see 6.3.3.3)
EWM	Extreme wind speed model (see 6.3.3.2)
EWS	Extreme wind shear (see 6.3.3.7)
NTM	Normal turbulence model (see 6.3.2.3)
ETM	Extreme turbulence model (see 6.3.3.4)
NWP	Normal wind profile model (see 6.3.2.2)
V_r ± 2 m/s	Sensitivity to all wind speeds in the range shall be analysed
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
*	Partial safety for fatigue (see 7.6.3)

When a wind speed range is indicated in Table 2, wind speeds leading to the most adverse condition for wind turbine design shall be considered. The range of wind speeds may be represented by a set of discrete values, in which case the resolution shall be sufficient to assure accuracy of the calculation[6]. In the definition of the design load cases, reference is made to the wind conditions described in Clause 6.

In the further specifications of design load cases (DLCs) in 7.4.2 to 7.4.9, some DLCs allow alternative formulations. Where alternatives are mentioned, the party designing to this document shall decide which alternative shall be used throughout the analysis of the DLC.

7.4.2 Power production (DLC 1.1 to 1.5)

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

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

Design load cases (DLCs) 1.1 and 1.2 embody the requirements for loads resulting from atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime (NTM). DLC 1.3 embodies the requirements for ultimate loading resulting from extreme turbulence conditions. DLC 1.4 and 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine.

The statistical analysis of DLC 1.1 simulation data, see 7.6.2.2 and Annex G, shall include at least the calculation of extreme values of the blade root in-plane moment and out-of-plane moment and tip deflection. If the extreme design values of the blade root moments derived from DLC 1.1 are exceeded by the extreme design values derived for DLC 1.3, the further analysis of DLC 1.1 may be omitted.

If the extreme design values of the blade root moments derived from DLC 1.1 are not exceeded by the extreme design values derived for DLC 1.3, the factor c in Equation (20) for the extreme

6 In general, a resolution of 2 m/s is considered sufficient. However, in the wind speed range where the power curve rises quickly, 2 m/s steps may be too large to assure accuracy.

turbulence model used in DLC 1.3 may be increased until the extreme design values of the blade root moments computed in DLC 1.3 are equal to or exceed the relevant extremes. The characteristic values of the loads relevant for other turbine components may be determined from this analysis based on DLC 1.3 with the increased c value. As an alternative to this analysis, the appropriate characteristic values of all load components relevant for each specific turbine component may be directly determined or extrapolated from the simulation.

7.4.3 Power production plus occurrence of fault or loss of electrical network connection (DLC 2.1 to 2.5)

7.4.3.1 General

This design situation involves a transient event triggered by a fault or by the loss of electrical network connection while the turbine is producing power. Any fault in the control system, or internal fault in the electrical system, significant for wind turbine loading (such as generator short circuit) shall be considered. This design situation is considered to be relevant for fatigue analysis as well, see DLC 2.4.

A failure mode and effect analysis (FMEA) or equivalent fault analysis shall be carried out to determine fault events relevant for the wind turbine loading.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random.

Faults in the control system shall be considered in DLC 2.1 and DLC 2.2 as described in 7.4.3.2. For architectures where turbine safety is ensured by two independent sets of functions (via primary layer control functions and secondary layer protection functions, respectively), the method described in 7.4.3.3 may be used. See Clause 8 for guidance on identification of failure modes, assessment of failure mode return periods, fault exclusions, and measures to avoid common-cause failures.

7.4.3.2 Control system failure (DLC 2.1 and DLC 2.2) – Quantitative approach

For DLC 2.1, the following shall be considered as normal events:

a) control system failure related events that have an expected failure mode return period that is equal to or less than 50 years;
b) control system failure related events where the expected failure mode return period cannot be obtained;
c) loss of electrical network connection.

For events with expected failure mode return periods between 10 and 50 years, the partial load factor applied is found as function of the failure mode return period as stated in Table 3.

For DLC 2.2, control system failure events or internal electrical and mechanical system faults with expected failure mode return period greater than 50 years shall be considered as abnormal.

Fault events with a return period in excess of 2 000 years and fault events that are not relevant for wind turbine loading may be disregarded. The fault event return period is based on the statistical calculation of the probability of an event whereby a control or internal electrical system part is in or enters a failed state such that a structural failure could occur.

7.4.3.3 Control system failure (DLC 2.1 and DLC 2.2) – Two-layer approach

This approach can be used for control system architectures consisting of two or more independent layers. Within this approach,

a) primary layer control and protection functions aim to keep the turbine operating parameters within their normal operating limits and their design limits, respectively, and

b) secondary layer protection functions aim to keep the turbine operating parameters within their design limits. These shall be activated as a result of failure of the primary layer control functions or as a result of the effects of an internal or external failure or dangerous event.

For DLC 2.1, primary layer control function faults, activation of primary layer protection functions or loss of electrical network connection shall be considered as normal events. Control function faults which lead to exceedance of the limits and the activation of the secondary layer protection functions shall be included in DLC 2.2.

Primary layer control function faults considered in DLC 2.1 typically include faults relating to rotor speed, yaw angle, and blade pitch angles.

For DLC 2.2, rare events that have relevance for the wind turbine loading, including faults relating to activation of secondary layer protection functions, shall be considered as abnormal. Such faults may include erroneous activation of actuators, non-activation of braking systems, and blocking of the pitch system. This load case shall at least address the following: independent overspeed protection, generator overload/fault protection, uncontrolled blade pitch protection (blade pitch runaway), uncontrolled yaw protection and excessive vibration or shock protection.

7.4.3.4 Other power production plus occurrence of fault or loss of electrical network connection (DLC 2.3 to 2.5)

For DLC 2.3, the potentially significant wind event, the extreme operating gust (EOG), is combined with loss of one or more phases in a multiphase electrical network connection and considered as an abnormal event. In this case, the timing of these two events shall be chosen to achieve the worst loading.

As an alternative to the specification of DLC 2.3 above and in Table 2, DLC 2.3 may instead be considered as a normal event (i.e. a partial safety factor for load of 1,35) to be analysed using stochastic wind simulations (NTM – $V_{in} < V_{hub} < V_{out}$) combined with an internal or external electrical system fault (including loss of electrical network connection). In this case, 12 response simulations shall be carried out for each considered mean wind speed. For each response simulation, the extreme response after the electrical fault has occurred is sampled. The fault shall be introduced after the effect of initial conditions has become negligible. For each mean wind speed, a nominal extreme response is evaluated as the mean of the 12 sampled extreme responses plus three times the standard deviation of the 12 samples. The characteristic response value for DLC 2.3 is determined as the extreme value among the nominal extreme responses.

If a fault or loss of electrical network connection does not cause an immediate shutdown and the subsequent loading can lead to significant fatigue damage, the likely duration of this situation along with the resulting fatigue damage in normal turbulence conditions (NTM) shall be evaluated in DLC 2.4. The manufacturer shall estimate the expected frequency/duration for the events[7].

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[7] If there is no relevant data/information available, the following frequency/duration can be applied for the below listed events:

- 10 shut-downs per year for overspeed event;
- 24 hours per year of operation for events with yaw error;
- 24 hours per year of operation for events with pitch error;
- 20 times per year with loss of electrical network connection.

For DLC 2.5, the event of low voltage ride through (LVRT)[8] is considered as normal. The design low voltage ride through event shall be specified by voltage drop and duration.

7.4.4 Start-up (DLC 3.1 to 3.3)

This design situation includes all the events resulting in loads on a wind turbine during the transients from any standstill or idling situation to power production. The number of occurrences shall be estimated based on the control system behaviour.[9]

For DLC 3.2, at least four different timing events between the EOG and the start-up event shall be considered for each wind speed. The first timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 50 % of maximum power. The last timing shall be chosen so that the beginning of the EOG occurs when the power production reaches 95 % of maximum power. At least two additional timings shall be chosen, evenly distributed within the interval from 50 % to 95 % of maximum power.

For each wind speed, the characteristic value of the load may be computed as the average value of the extreme computed transient value for the four defined distinct points of time.

As an alternative to the EOG gust, the DLC 3.2 may instead be analysed using at least 12 stochastic wind simulations for each mean wind speed with the ETM. For each mean wind speed, a nominal extreme response is evaluated as the mean of the simulated extremes.

7.4.5 Normal shutdown (DLC 4.1 to 4.2)

This design situation includes all the events resulting in loads on a wind turbine during normal transient situations from a power production situation to a standstill or idling condition. The number of occurrences shall be estimated based on the control system behaviour.[10]

For DLC 4.2, the timing of the gust and the shutdown event shall be chosen such that the EOG gust starts at different times relative to the shutdown, with minimum six events evenly distributed from 10 s before the beginning of the shutdown, till the power reaches 50 % of the initial power production level.

At least four evenly distributed rotor azimuth positions shall be applied for each distinct point of time. For each wind speed, the characteristic value of the load may be computed as the mean value of the extreme computed loads among all timings and azimuth positions considered.

If, due to the safety and control system, a shutdown event is automatically triggered during the EOG gust, that event shall also be considered in the analysis.

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8 Low voltage ride through situations are normally defined by the electrical utilities as situations with grid disturbances or failures the wind turbine should be able to handle without shutting down. The reason for a demand for riding through these situations is that if the wind turbines (especially in wind farms) shut down it can result in a collapse of the grid.

9 If historical data on start-ups for similar wind turbines are unavailable, the following annual frequencies for DLC 3.1 can be assumed:

- 1000 start-up procedures at V_{in};
- 50 start-up procedures at V_r;
- 50 start-up procedures at maximum start-up wind speed.

10 If historical data on shutdowns for similar wind turbines are unavailable, the following annual frequencies for DLC 4.1 can be assumed:

- 1000 shut-down procedures at V_{in};
- 50 shut-down procedures at V_r;
- 50 shut-down procedures at V_{out}.

As an alternative to the EOG gust, the DLC 4.2 may instead be analysed using at least 12 stochastic wind simulations for each mean wind speed with the ETM. For each mean wind speed, a nominal extreme response is evaluated as the mean of simulated extremes.

7.4.6 Emergency stop (DLC 5.1)

Loads arising from activation of the emergency stop button shall be considered.

The azimuth position for the rotor at the time of a fault may have significant influence on the load level. The azimuth position at time of occurrence for the fault should be random.

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

In this design situation, the rotor of a parked wind turbine is either in a standstill or idling condition. In DLC 6.1, 6.2 and 6.3, this situation shall be considered with the extreme wind speed model (EWM). For DLC 6.4, the normal turbulence model (NTM) shall be considered.

For design load cases, where the wind conditions are defined by EWM, either the steady extreme wind model or the turbulent extreme wind model may be used. If the turbulent extreme wind model is used, the response shall be estimated using either a full dynamic simulation or a quasi-steady analysis with appropriate corrections for gusts and dynamic response using the formulation in ISO 4354. If the steady extreme wind model is used, the effects of resonant response shall be estimated from the quasi-steady analysis above. If the ratio of resonant to background response (R/B) is less than 5 %, a static analysis using the steady extreme wind model may be used. If slippage in the wind turbine yaw system can occur at the characteristic load, the largest possible unfavourable slippage shall be added to the mean yaw misalignment. If the wind turbine has a yaw system where yaw movement is expected in the extreme wind situations (e.g. free yaw, passive yaw or semi-free yaw), the turbulent wind model shall be used and the yaw misalignment will be governed by the turbulent wind direction changes and the turbine yaw dynamic response. Also, if the wind turbine is subject to large yaw movements or change of equilibrium during a wind speed increase from normal operation to the extreme situation, this behaviour shall be included in the analysis.

In DLC 6.1, for a wind turbine with an active yaw system, a yaw misalignment of up to ±15° using the steady extreme wind model or a mean yaw misalignment of ±8° using the turbulent extreme wind model shall be imposed, provided restraint against slippage in the yaw system can be assured.

In DLC 6.2, a loss of the electrical power network at an early stage in a storm containing the extreme wind situation shall be assumed. Unless power back-up is provided for the control and yaw system with a capacity for yaw alignment for a period of at least 6 h, the effect of a wind direction change of up to ±180° shall be analysed.

The partial safety factors for loads for DLC 6.1 and DLC 6.2 in Table 3 are derived by assuming that the coefficient of variation of the annual maximum wind speed is smaller than 15 %; for other COV, see footnote 31 in 11.3.2.

In DLC 6.3, the extreme wind with a 1-year return period shall be combined with an extreme yaw misalignment. An extreme yaw misalignment of up to ±30° using the steady extreme wind model or a mean yaw misalignment of ±20° using the turbulent wind model shall be assumed.

If for the cases DLC 6.1 with steady extreme wind model, DLC 6.2 and DLC 6.3, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades.

In DLC 6.4, the expected number of hours of non-power production time at a fluctuating load appropriate for each wind speed where significant fatigue damage can occur to any components (e.g. from the weight of idling blades) shall be considered.

7.4.8 Parked plus fault conditions (DLC 7.1)

Deviations from the normal behaviour of a parked wind turbine, resulting from faults on the electrical network or in the wind turbine, shall require analysis. As a minimum, failures in the following systems shall be evaluated: brake system, pitch system, and yaw system. The fault condition shall be combined with EWM for a return period of one year. Those conditions shall be either turbulent or quasi-steady with correction for gusts and dynamic response.

In case of a fault in the yaw system, yaw misalignment of ±180° shall be considered. If for the cases DLC 7.1 with fault in the yaw system, yaw misalignment is evaluated using discrete values, the increment in yaw misalignment shall be not more than 10° in the sector of the maximum lift force on the blades. For any other fault, yaw misalignment shall be consistent with DLC 6.1.

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

7.4.9 Transport, assembly, maintenance and repair (DLC 8.1 and 8.2)

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

In addition, DLC 8.2 shall include all transport, assembly, maintenance and repair turbine states which may persist for longer than one week. This shall, when relevant, include a partially completed tower, the tower standing without the nacelle and the turbine without one or more blades. In the case of a tower standing without a nacelle, appropriate means shall be taken to avoid critical wind speeds for vortex generated transverse vibrations, or the appropriate fatigue design load case shall be added[11]. It shall be assumed that the electrical network is not connected in any of these states. Measures may be taken to reduce the loads during any of these states as long as these measures do not require the electrical network connection.

Blocking devices shall be able to sustain the loads arising from relevant situations in DLC 8.1. Non-redundant blocking devices shall be designed in component class 3. In particular, application of maximum design actuator forces shall be taken into account. It is recommended that standards for lifting appliances including safety factors/influence factors are additionally applied when relevant. Unless permanently installed, the lifting appliance itself is not covered by this document and should be designed and tested according to relevant standards for lifting appliances.

7.5 Load calculations

Loads as described in 7.3.2 through 7.3.5 shall be taken into account for each design load case. Where relevant, the following shall also be taken into account:

- wind field perturbations due to the wind turbine itself (wake induced velocities, tower shadow, etc.);
- the influence of three dimensional flow on the blade aerodynamic characteristics (e.g. three dimensional stall and aerodynamic tip loss);
- unsteady aerodynamic effects;
- structural dynamics and the coupling of vibration modes;

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[11] Guidance for tower loads from vortex-induced vibrations can be found in IEC 61400-6 (under preparation; stage at the time of publication: IEC CDV 61400-6:2017).

- aeroelastic effects;
- the behaviour of the control system of the wind turbine.

Dynamic simulations utilizing a structural dynamics model are usually used to calculate wind turbine loads. Certain load cases have a turbulent wind input. The total period of load data, for these cases, shall be long enough to ensure statistical reliability of the estimate of the characteristic load. At least six 10-min stochastic realizations (or a continuous 60 min period) shall be required for each mean, hub-height wind speed used in the simulations. However, for DLC 2.1, 2.2 and 5.1, at least 12 simulations shall be carried out for each event at the given wind speed. Since the initial conditions used for the dynamic simulations typically have an effect on the load statistics during the beginning of the simulation period, the first 5 s of data (or longer if necessary) shall be eliminated from consideration in any analysis interval involving turbulent wind input.

It shall be ensured that during application of a cycle count on the load time series, the remaining residuals from each time series shall be taken into consideration by half-cycles for fatigue failure mode evaluation. Furthermore, the discretization of the load range shall ensure a sufficient resolution.

When turbulent winds are used for dynamic simulations, attention should be given to the grid resolution regarding the spatial[12] and time resolution.

In many cases, the local strains or stresses for critical locations in a given wind turbine component are governed by simultaneous multi-axial loading. In this case, time series of orthogonal loads that are output from simulations are sometimes used to specify design loads. When such orthogonal component time series are used to calculate fatigue and ultimate loads, they shall be combined to preserve both phase and magnitude. Thus, the direct method is based on the derivation of the significant stress as a time history. Extreme and fatigue prediction methods can then be applied to this single signal, avoiding load combination issues.

Ultimate load components may also be combined in a conservative manner assuming the extreme component values occur simultaneously. In case this option is pursued, both minimum and maximum extreme component values shall be applied in all possible combinations to avoid introducing non-conservatism.

Guidance for the derivation of extreme design loads from contemporaneous loads taken from a number of realizations is given in Annex I.

7.6 Ultimate limit state analysis

7.6.1 Method

7.6.1.1 General

Partial safety factors account for the uncertainties and variability in loads and resistances, the uncertainties in the analysis methods and the importance of structural components with respect to the consequences of failure.

For the ultimate limit state analysis of the wind turbine, the following four types of analysis shall be performed where relevant:

- analysis of ultimate strength (see 7.6.2);

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12 Concerning the spatial resolution, the maximum distance between adjacent points should be smaller than 25 % of Λ_1 (Equation (5)) and no larger than 15 % of the rotor diameter. This distance is meant to be the diagonal distance between points in each grid cell defined by four points. In the case of a non-uniform grid, an average value over the rotor surface of the distance between grid points can be considered as the representative spatial resolution, but this distance typically decreases towards the blade tip.

- analysis of fatigue failure (see 7.6.3);
- stability analysis (e.g. buckling) (see 7.6.4);
- critical deflection analysis (mechanical interference between blade and tower, etc.) (see 7.6.5).

Each type of analysis requires a different formulation of the limit state function and deals with different sources of uncertainties through the use of safety factors.

7.6.1.2 Partial safety factors for loads and resistance

The uncertainties and variability in loads and resistances (including variability in materials) are taken into account by partial safety factors as defined in Equations (29) and (30) in order to assure safe design values.

$$F_\mathrm{d} = \gamma_\mathrm{f} F_\mathrm{k} \tag{29}$$

where

F_d is the design value for the aggregated internal load or load response to multiple simultaneous load components from various sources for the given design load case;

γ_f is the partial safety factor for loads;

F_k is the characteristic value for the load.

$$R_\mathrm{d} = \frac{1}{\gamma_\mathrm{M}} R_\mathrm{k} \tag{30}$$

where

R_d are the design values for resistances, see Annex K;

γ_M are the partial safety factors[13] accounting for uncertainties in the material parameters and resistance models, see Annex K;

R_k are the characteristic values of resistances including load duration effects, scale effects, etc. accounted for by a conversion factor, see Annex K.

The partial safety factors for loads used in this document take account of

a) possible unfavourable deviations/uncertainties of the load from the characteristic value, and
b) uncertainties in the loading model.

The partial safety factors for resistances γ_M used in this document, as in ISO 2394, take account of

- possible unfavourable deviations/uncertainties of the strength of material from the characteristic value,
- possible inaccurate assessment of the resistance of sections or load-carrying capacity of parts of the structure,
- uncertainties in the geometrical parameters,
- uncertainties in the relation between the material properties in the structure and those measured by tests on control specimens, and

[13] Alternatively, the partial safety factor for resistance γ_M can be included as a partial safety factor related to uncertainty in material parameters and a partial safety factor related to uncertainty in the resistance model, see Annex K.

- uncertainties in conversion factors.

These different uncertainties are sometimes accounted for by means of individual partial safety factors; but in this document, as in most others, the load related factors are combined into one factor, γ_f, and the material and resistance related factors into one factor, γ_M. Values of γ_f and γ_M are given in 7.6.2 to 7.6.5. However, these values may be replaced if it can be documented that assumptions leading to these values are conservative, in which case a calibration of load and resistance safety factors may be performed to meet the intended safety level in this document[14].

7.6.1.3 Partial safety factor for consequence of failure and component classes

A consequence of failure factor, γ_n, is introduced to distinguish between:

a) component class 1: used for "fail-safe" structural components whose failure does not result in the failure of a major part of a wind turbine, for example replaceable bearings with monitoring;
b) component class 2: used for "safe-life" structural components whose failures may lead to the failure of a major part of a wind turbine;
c) component class 3: used for "safe-life" mechanical components that link actuators and brakes to main structural components for the purpose of implementing non-redundant wind turbine protection functions. Regarding blocking devices, see 7.4.9.

Partial safety factors for consequences of failure:

- component class 1: γ_n = 0,9;
- component class 2: γ_n = 1,0;
- component class 3: γ_n = 1,2.

The consequences of failure factor shall be included in the test load when performing tests such as, for example, full scale blade testing.

Other values of γ_n apply for critical deflection analysis, see 7.6.5.

7.6.1.4 Application of recognized material codes

When determining the structural integrity of elements of a wind turbine, national or international design codes for the relevant material may be employed. Special care shall be taken when partial safety factors from national or international design codes are used together with partial safety factors from this document. It shall be ensured that the resulting safety level is not less than the intended safety level in this document.

Different codes subdivide the partial safety factors for resistance, γ_M, into several material factors accounting for separate types of uncertainty, for example inherent variability of material strength, extent of production control or production method. If the code gives partial safety factors or uses reduction factors on the characteristic values to account for other uncertainties, these shall also be taken into account.

Individual codes may choose different factorizations of partial safety factors on the load and the material parts of the design verification. The division of factors intended here is the one defined in ISO 2394. If the division of factors in the code of choice deviates from that of ISO 2394, the necessary adjustments in the code of choice shall be taken into account in verifications according to this document.

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[14] Annex K provides a guideline for calibration of material partial safety factors.

7.6.2 Ultimate strength analysis

7.6.2.1 General

The limit state function can be separated into load and resistance functions S and R so that the condition becomes

$$\gamma_n \cdot S\left(F_d\right) \leq R_d \tag{31}$$

The function S for ultimate strength analysis is usually defined as the highest value of the structural response, hence $S(F_d) = F_d$. The equation then becomes

$$\gamma_n \gamma_f F_k \leq \frac{1}{\gamma_M} R_k \tag{32}$$

Note that γ_n is a consequence of failure factor and shall not be treated as a safety factor on materials.

For each wind turbine component assessed and for each load case in Table 2 where ultimate strength analysis is appropriate, the limit state condition in Equation (32) shall be verified for the most critical limit state, identified on the basis of having the least margin.

7.6.2.2 Partial safety factors for loads

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

a) The characteristic value is obtained as the largest (or smallest) among the average values of the 10 min extremes determined for each wind speed in the given range, multiplied by 1,35. This method can only be applied for the calculation of the blade root in-plane moment and out-of-plane moment and tip deflection.
b) The characteristic value is obtained as the largest (or smallest) among the 99th percentile (or 1st percentile in the case of minima) values of the 10 min extremes determined for each wind speed in the given range, multiplied by 1,2.
c) The characteristic value is obtained as the value corresponding to a 50 year return period, based on load extrapolation methods, considering the wind speed distribution given in 6.3.2.1 and the normal turbulence model in 6.3.2.3. Guidance about load extrapolation is given in Annex G.

The design load will be then obtained by multiplying the characteristic loads according to any of these alternatives by the partial safety factor for DLC 1.1 defined in Table 3.

For all three alternatives above, data used in the statistical analysis shall be extracted from time series of turbine simulations of at least 10 minutes in length over the operating range of the turbine for DLC 1.1. A minimum of 15 simulations is required for each wind speed from (V_r – 2 m/s) to cut-out, and six simulations are required for each wind speed below (V_r – 2 m/s). When extracting data, the designer shall consider the effect of independence between peaks on the statistical analysis and minimize dependence when possible. For guidance on dependency checks, see Annex G.

For load cases with specified deterministic wind field events, the characteristic value of the load shall be the worst case computed transient value. If more simulations are performed at a given wind speed, representing the rotor azimuth, the characteristic value for the load case is taken as the average value of the worst case computed transient values at each azimuth. Guidance for the derivation of the contemporaneous load can be found in Annex I. When turbulent inflow is used, the mean value among the worst case computed loads for different 10 min stochastic realizations shall be taken, except for DLC 2.1, 2.2 and 5.1, where the characteristic value of the load shall be the mean value of the largest half of the maximum loads.

Partial safety factors for loads shall be at least the values specified in Table 3.

The approach in 7.6.1.2, where the partial safety factor for loads is applied to the load response, assumes that a proper representation of the dynamic response is of prime concern. Where a proper representation of non-linear material behaviour or geometrical nonlinearities (such as, for example, for foundations) or both are of primary concern, the design load response S_d shall be obtained from a structural analysis for the combination of the design loads F_d, where the design load is obtained by multiplication of the characteristic loads F_k by the specified partial load factor γ_f for favourable and unfavourable loads:

$$F_d = \gamma_f F_k \tag{33}$$

The load responses in the tower at the interface (shear forces and bending moments) factored with γ_f from Table 3 shall be applied as boundary conditions.

Table 3 – Partial safety factors for loads γ_f

Unfavourable loads		Favourable loads[15]
Type of design situation (see Table 2)		All design situations
Normal (N)	Abnormal (A)	
1,35[a]	1,1	0,9

[a] For design load case DLC 1.1, the partial load factor shall be γ_f = 1,25.

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

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

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

For design load case DLC 2.1, the partial load factor may be calculated from the following expression if the mean time between failures (MTBF), in years, for the considered failure mode has been evaluated (see 7.4.3.2):

$$\gamma_f = \begin{cases} 1{,}35 & \text{MTBF} \le 10 \\ 1{,}71 - 0{,}155\ln(\text{MTBF}) & 10 < \text{MTBF} \le 50 \\ 1{,}10 & \text{MTBF} > 50 \end{cases}$$

For design load case DLC 2.5, the partial load factor shall be 1,2.

Use of the partial safety factors for loads for normal and abnormal design situations specified in Table 3 requires that the load calculation model is validated by load measurements. These

15 Pretension and gravity loads that significantly relieve the total load response are considered favourable loads. In the case of both favourable and unfavourable loads, Equation (32) becomes

$$\gamma_n S(\gamma_{f,unfav} F_{k,unfav}, \gamma_{f,fav} F_{k,fav}) \le R(f_d)$$

measurements shall be made on a wind turbine that is similar to the wind turbine design under consideration with respect to aerodynamics, control and dynamic response.

7.6.2.3 Partial safety factors for gravity foundations

For gravity foundations, the limit states considering overall stability (rigid body motion with no failure in soil) and bearing capacity of soil and foundation shall be regarded and calculated according to a recognized standard. In general, a partial safety factor of $\gamma_f = 1,1$ for unfavourable gravity loads and $\gamma_f = 0,9$ for favourable gravity loads shall be applied for foundation load, backfilling and buoyancy. If it can be demonstrated by respective quality management and surveillance that the foundation material densities specified in the design documentation are met on site, a partial safety factor for gravity foundation load $\gamma_f = 1,0$ can be used for the limit states regarding bearing capacity of soil and foundation. If buoyancy is calculated equal to a terrain water level, a partial safety factor for buoyancy $\gamma_f = 1,0$ can be applied.

Alternatively, the check of capacity of soil and foundation can be based on a partial safety factor $\gamma_f = 1,0$ for both favourable and unfavourable gravity loads, and the check of overall stability can be based on a partial safety factor of $\gamma_f = 1,1$ for unfavourable gravity loads and $\gamma_f = 0,9$ for favourable gravity loads, using in all cases conservative estimates of weights or densities defined as 5 %/95 % fractiles. The lower fractile is to be used when the load is favourable. Otherwise the upper fractile is to be used.

7.6.2.4 Partial safety factors for resistances where recognized design codes are not available

Partial safety factors for resistances shall be selected in relation to the adequacy of the available material properties test data. The safety level in this document corresponds to a partial safety factor for resistances, $\gamma_M = 1,2$ when applied to characteristic material properties of 95 % survival probability.[16] This value assumes no bias (typically systematic conservatism in the resistance model) and small uncertainty related to the resistance model (coefficient of variation less than 5 %), see Annex K; and applies to components with ductile behaviour whose failure may lead to the failure of a major part of a wind turbine.

To derive the design values for resistances, it is necessary to account for scale effects, tolerances and degradation due to external actions, for example, ultraviolet radiation or humidity. These effects can be taken into account through additional factors on the partial safety factor for resistance or through a conversion factor used to obtain the characteristic value of the resistance, see Annex K.

In the following cases with ductile failure modes, the partial safety factor for resistance, γ_M, shall be not less than

- 1,1 for materials with a well-defined elastic limit (yield strength is 90 % or less of the ultimate strength), and
- 1,1 for bolt rupture in a connection with sufficient number of bolts to ensure a ductile failure mode.

For "safe-life" mechanical/structural components with non-ductile behaviour whose failures lead rapidly to the failure of a major part of a wind turbine, the partial safety factor for resistance, γ_M, shall be not less than

16 Alternatively, the characteristic strength parameters can be selected as the 95 % fractile using the Bayesian approach, see Annex K and ISO 2394. The characteristic strength parameters should be selected as the 95 % fractile (determined with 75 % confidence) or the certificate value for materials with established routines for testing of representative samples.

– 1,3 when materials with no well-defined elastic limit (yield strength is more than 90 % of the tensile or compression strength) are used, and
– 1,2 for global buckling of curved shells such as tubular towers and blades.[17]

7.6.2.5 Partial safety factors for materials where recognized design codes are available

The combined partial safety factors for loads, resistance and the consequences of failure, γ_f, γ_M, and γ_n, shall be not less than those specified in 7.6.1.3, 7.6.2.2 and 7.6.2.4.

7.6.3 Fatigue failure

7.6.3.1 General

Fatigue damage shall be estimated using an appropriate fatigue damage calculation. For example, in the case of Miner's rule, the limit state is reached when the accumulated damage exceeds 1. Thus, in this case, the accumulated damage over the design lifetime of a turbine shall be less than or equal to 1. Fatigue damage calculations shall consider the formulation, including effects of both cyclic range and mean strain (or stress) levels. All partial safety factors (load, material and consequences of failure) shall be applied to the cyclic strain (or stress) range for assessing the increment of damage associated with each fatigue cycle. An example formulation is given for Miner's rule in Annex H.

7.6.3.2 Partial safety factor for loads

The partial safety factor for loads, γ_f, shall be 1,0.

7.6.3.3 Partial safety factors for resistances where recognized codes are not available

The partial safety factor for resistances, g_M, shall be at least 1,7 provided that the SN-curve is based on 50 % survival probability and coefficient of variation < 15 %. For components with large coefficient of variation for fatigue strength[18], i.e. 15 % to 20 % (such as for many components made of composites, for example reinforced concrete or fibre composites), γ_M shall be increased accordingly and at least to 2,0.

The fatigue strengths shall be derived from a statistically significant number of tests and the derivation of characteristic values shall account for scale effects, tolerances, degradation due to external actions, such as ultraviolet radiation, and defects that would not normally be detected.

For welded and structural steel, traditionally the 97,7 % survival probability is used as basis for the SN-curves. In this case, γ_M may be taken as 1,25, corresponding to a safe-life assessment approach, see Annex K. In cases where it is possible to detect critical crack development through introduction of a periodic inspection programme, a lower value of g_M may be used, corresponding to a damage tolerant assessment approach, see Annex K. In all cases, γ_M shall be larger than 1,0.

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[17] The parametric formulas based on membrane theory in Eurocode 3 Part 6 (EN 1993-1-6) for shell buckling applicable to tubular steel towers with D/t < 300 include a bias that can be accounted for by reducing γ_M for buckling to 1,1.

[18] Fatigue strength is defined here as stress ranges associated with given numbers of cycles.

For fibre composites, the strength distribution shall be established from test data for the actual material. The 95 % survival probability shall be used as a basis for the SN-curve. In that case, g_M may be taken as 1,35. The same approach may be used for other materials.

7.6.3.4 Partial material factors where recognized design codes are available

The combined partial safety factors for loads, materials and consequences of failure shall not be less than those specified in 7.6.3.2 and 7.6.3.3, with due consideration of the quantiles specified in the code.

7.6.4 Stability

The load-carrying parts of "non fail-safe" components shall not buckle under the design load. For all other components, elastic buckling under the design load is acceptable. Buckling shall not occur in any component under the characteristic load.

A minimum value for the partial safety factor for loads, γ_f, shall be chosen in accordance with 7.6.2.2 to obtain the design value. The material partial safety factors shall be not less than those specified in 7.6.2.4.

7.6.5 Critical deflection analysis

7.6.5.1 General

It shall be verified that no deflections affecting structural integrity occur in the design conditions detailed in Table 2. The maximum elastic deflection in the unfavourable direction shall be determined for the load cases detailed in Table 2. A characteristic value for the resulting deflections is determined in a manner consistent with the other load components. The resulting characteristic deflection is then multiplied by the combined partial safety factor for loads, materials and consequences of failure.

7.6.5.2 Partial safety factor for loads

The values of γ_f shall be chosen from Table 3.

7.6.5.3 Partial safety factor for the elastic properties of materials

The value of γ_M shall be 1,1 except when the elastic properties of the component in question have been determined by testing and monitoring, in which case it may be reduced. Particular attention shall be paid to geometrical uncertainties and the accuracy of the deflection calculation method.

7.6.5.4 Partial safety factor for consequences of failure

The partial safety factor for consequences of failure, γ_n, shall be 1,0.

The elastic deflection shall then be added to the un-deflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference.

7.6.5.5 Blade (tip) deflection

One of the most important considerations is to verify that no mechanical interference between blade and tower will occur. The combined safety factor, $\gamma_f\gamma_n\gamma_m$, for blade-tower clearance shall be at least 1,15.

In general, blade deflections have to be calculated for the ultimate load cases. The deflections caused by the ultimate load cases can be calculated based on beam models, finite element models or the like. All relevant load cases from Table 2 have to be taken into account with the relevant partial load safety factors.

Moreover, for DLC 1.1 a statistical analysis of maximum tip deflection or minimum tower clearance is mandatory according to 7.4.2. Here, direct dynamic deflection or tower clearance analysis can be used. The probability in the most unfavourable direction shall be the same for this characteristic value as for the characteristic blade loading. For a deflection analysis, the characteristic deflection is then to be multiplied by the combined partial factors for loads, materials and consequences of failure and be added to the undeflected position in the most unfavourable direction and the resulting position compared to the requirement for non-interference. In the case of direct dynamic tower clearance analysis, the minimum allowable clearance is determined by multiplying the nominal undeflected tower clearance by the ratio of the combined partial factors for loads, materials and consequences of failure minus one to the combined partial factor (i.e. $\frac{\gamma_f \gamma_n \gamma_m - 1}{\gamma_f \gamma_n \gamma_m}$).

7.6.6 Special partial safety factors

Lower partial safety factors for loads may be used where the magnitudes of loads have been established by measurement or by analysis confirmed by measurement to a higher than normal degree of confidence. The values of all partial safety factors used shall be stated in the design documentation.

8 Control system

8.1 General

Wind turbine operation shall be governed by a control system that meets the requirements of Clause 8.

The scope of Clause 8 is limited to ensuring that the control system provides an appropriate level of protection against structural failure of the turbine main components.[19]

For special cold climate requirements, see 14.6.

8.2 Control functions

The control functions of a wind turbine shall control the operation by active or passive means and keep the operating parameters within the envelope assumed in the structural design.

The control functions may govern or otherwise limit functions or parameters such as

- power,
- rotor speed,
- connection of the electrical load,
- start-up and shutdown procedures,
- cable twist,
- excessive vibrations,
- alignment to the wind, and
- blade pitch angle.

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[19] Risk assessments may result in requirements for additional control system functionality needed for ensuring personnel safety. These functions should be designed and evaluated according to recognized methods and design principles, such as those specified in ISO 13849 or IEC 62061.

The ability of the control functions to control the turbine during failure-free operation of the control functions shall be demonstrated in the design load cases (but excluding the DLC 2.1 and 2.2 load cases).

When a control function failure occurs, the wind turbine must maintain a safe mode of operation, which may include maintaining operation or bringing the wind turbine to a shutdown.

Turbine behaviour following a fault in the control functions shall be clearly defined, including any procedures for automatic or manual restart, see 8.7.

8.3 Protection functions

The control system shall make use of protection functions in order to prevent turbine structural overloading due to failure modes. These protection functions may be implemented as either control functions that apply inherently safe design measures[20], or as separate secondary layer protection functions.

Where a secondary layer protection function is used to bring the turbine to a safe mode of operation, it shall overrule the primary layer control function.

Functions protecting against structural overloading shall be implemented by means of multi-channel architectures[21] with diagnostic coverage to yield sufficiently high mean time between failure.

The ability of protection functions to protect against structural overloading shall be demonstrated in design load cases DLC 2.1 and 2.2, cf. 7.4.3.

8.4 Control system failure analysis

8.4.1 General

Faults or errors in the systems implementing the control and protection functions may lead to a number of failure modes, where the failure mode is defined as the behaviour of the control system in case of a fault or error. Such failure modes may lead to events affecting the turbine structure.

EXAMPLE A sensor fault may lead to erroneous pitch action (the failure mode), which may lead to excessive rotor speed (the event).

Failure modes of the control system shall be identified according to the requirements in this clause and evaluated according to the requirements given in 7.4.3.

FMEA or equivalent fault analysis shall be carried out to determine fault events relevant for wind turbine loading. This may include fault-tree analysis or similar methods to identify any common cause failures.

The set of events addressed in the fault analysis shall include at least the following:

a) excessive rotor speed;

b) excessive vibrations;

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20 ISO 12100:2010, 6.2.11 and 6.2.12 provides guidance on applying inherently safe design measures to control systems.

21 Multichannel architectures include but are not limited to the use of redundancy. A single functional channel with high diagnostic coverage provided by a separate test channel may suffice if the resulting mean time to dangerous failure is sufficiently high. The designated architecture for Category 2 systems as per ISO 13849-1 constitutes such architecture.

c) excessive power production;

d) actuator faults, e.g. pitch and yaw actuation faults.

8.4.2 Independence and common-cause failures

It may be assumed that independent faults do not occur simultaneously. If independent faults are assumed, measures against common-cause failures shall be implemented, and there shall be sufficient diagnostic coverage to protect against dormant failures.[22]

8.4.3 Fault exclusions

Control system failures subject to fault exclusions[23] as described in recognized standards can be omitted.

All mechanical components of the control system where fault exclusions are applied shall be considered in component class 3 with an appropriate consequences-of-failure partial safety factor (as defined in 7.6). All such critical components shall be analysed for ultimate strength, fatigue, buckling and critical deflection.

8.4.4 Failure mode return periods

If failure mode return periods are claimed in the load calculations (see 7.4.3.2) then these shall be demonstrated by recognized methods.[24]

For mechanical components, failure mode return periods need only to be established if fault exclusions do not apply.

8.4.5 Systematic failures

For protection functions and for control functions where failure mode return periods higher than 10 years are claimed, measures for avoiding systematic failures[25] (including software failures) described by recognized standards shall be applied.

8.5 Manual operation

Manual or automatic intervention shall not compromise the control system's ability to keep the turbine within limits. Any device allowing manual intervention shall be clearly visible and identifiable, by appropriate marking where necessary.

Where selection of control mode can be exercised, for example for maintenance, the mode selection shall be governed by a selector, which can be locked in each position corresponding with a single mode.

Settings of the control system shall be protected against unauthorized interference.

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[22] ISO 13849-1 may be used to judge whether the measures against common cause failures are sufficient.

[23] Fault exclusions are described in standards such as ISO 13849-2. For mechanical components, fault exclusions are relevant for "safe-life" components.

[24] See IEC 61508-6 or IEC 62061 for suitable methods for demonstrating failure rates, e.g. fault trees, Markov models, etc. Also, ISO 13849-1 provides simplified methods for assessing the failure rates, including generic values for components.

[25] Measures to avoid systematic failures and software failures are covered within 6.4, 6.10 and 6.11 of IEC 62061:2005, IEC 62061:2005/AMD1:2012 and IEC 62061:2005/AMD2:2015, or 4.6, Annex G and Annex J of ISO 13849-1:2015.

8.6 Emergency stop button function

An emergency stop button function shall be implemented using recognized methods and design principles, such as those specified in ISO 13850, which gives guidance on emergency stop button availability, location, choice of stop functionality, and reset behaviour.

It shall be specified which stop category is chosen. Further, any functionality required from the control system when the emergency stop button is activated shall be clearly specified.[26]

The behaviour of all systems impacting the structural loading upon activation of the emergency stop button shall be clearly specified.

EXAMPLE 1 Disconnection of electrical systems may impact the loading of the drive train.

When the emergency stop function behaviour depends on operating conditions, these dependencies shall be clearly defined.

EXAMPLE 2 Application of the mechanical disc brake in case of emergency button activation may be conditioned on the rotational speed and/or wind speed, etc.

Effects of activation of the emergency stop button shall be evaluated under DLC 5.1 for all relevant operating scenarios (see 7.4).

8.7 Manual, automatic, and remote restart

Mechanisms for restarting the turbine following a stop shall be clearly defined and meet the following requirements.

Turbine restart behaviour and restart procedures[27] following a control function failure shall be defined based on a failure mode analysis (for example via a fault tree analysis).

If failures in functions that define if a restart can occur could influence turbine loads then these faults should be considered to be control system fault events as defined in 8.4.1.

The behaviour following a control function failure may be defined by automatic or manual procedures, performed locally or remotely. In the case of remote restart, this shall include any remote inspection needed (for example, via the use of remote cameras and/or SCADA data), and suitable criteria that need to be met before it is deemed safe to allow remote restart.

Automatic restart shall not be allowed unless automatic diagnostics and criteria necessary to ensure that the turbine will remain safe (i.e. within an acceptable risk of turbine damage) after restart have been defined.

EXAMPLE Such diagnostics may consist of automatic substantiation that the structural design limits for rotor speed and tower top acceleration have not been exceeded.

The risks and consequences of an unintended remote restart (for example, due to a communications system error) shall be considered.

A turbine with automatic or remote restart capability shall be provided with a means to locally disable and lock out the automatic restart function and the remote restart function.

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26 This requirement is particularly important when stop category 1 (controlled stop) is chosen.

27 A restart procedure needs to consider the reasons why the turbine shut down to in order to justify that it is safe to restart the turbine. For example, a restart might not be considered safe without an inspection taking place if the turbine has been shut down due to excessive mechanical shock.

The turbine shall not incorrectly restart as a result of external factors such as loss (and reinstatement) of grid power or external loads or due to maintenance actions.

The number and frequency of remote or automatic restarts that are permissible shall be clearly defined based on the shutdown assumptions contained in the design loads assessment. The restart function shall ensure that these limits are not exceeded.

The design loads assessment shall consider the consequences of repeated restarts up to the limits defined above.

The functionality to control the number and frequency of remote or automatic restarts that are permissible shall not be incorrectly affected by external factors such as loss (and reinstatement) of grid power or external loads or due to maintenance actions.

8.8 Braking system

It shall be possible to bring the rotor to idling mode or complete standstill from any operation condition, including loss of power.

Means shall be provided for bringing the rotor to a complete standstill in any wind speed less than the wind speed limit defined for maintenance and repair, see 7.4.9, unless this is explicitly discounted based on the results of a risk assessment.

It is recommended that at least one braking system operate on an aerodynamic principle, as such acting directly on the rotor. If this recommendation is not met, at least one braking system shall act on the shaft directly connected to the rotor or on the rotor of the wind turbine.

If a braking system is designed to bring the rotor to standstill upon emergency stop activation, it shall be able to keep the rotor in standstill for the defined wind conditions for at least one hour after it is applied.

9 Mechanical systems

9.1 General

A mechanical system for the purposes of this document is any system which does not consist solely of static structural components, or electrical components, but uses or transmits relative motion through the combination of shafts, links, bearings, slides, gears and other devices. Within a wind turbine, these systems may include elements of the drive train such as gearboxes, shafts and couplings, and auxiliary items such as brakes, blade pitch controls, yaw drives. Auxiliary items may be driven by electrical, hydraulic or pneumatic means.

All mechanical systems in the drive train and in the control system shall be designed according to IEC or ISO standards wherever available. Otherwise, recognized standards shall be used. Partial safety factors shall be consistent with component class 2 in 7.6.1.3, unless the systems falls into component class 3.

Particular care shall be taken to ensure that cooling and filtration systems can maintain the relevant operating conditions throughout the operating temperature range when the specified maintenance procedures are followed.

The remaining life of any component subject to wear in the brake system shall be monitored automatically and subject to regular inspection. The turbine shall be parked when there is insufficient material for further emergency stops. All brake devices shall be designed and maintained to keep the response time within acceptable levels.

Load calculation shall be based on simulations including both the mean braking level and a minimum braking level that allows for minimum friction and application pressure predicted for the design. If the brake is able to slip at the minimum braking level, when the brake is applied, it shall be designed to avoid overheating and brake performance impairment and to avoid risk of fire.

For cold climate requirements, see 14.7.

9.2 Errors of fitting

Errors likely to be made when fitting or refitting certain parts that could be a source of risk shall be made impossible by the design of such parts or, failing this, by information given on the parts themselves and/or housings. The same information shall be given on the moving parts and/or their housings where the direction of movement shall be known to avoid a risk. Any further information that may be necessary shall be given in the operator's instruction and maintenance manuals.

Where a faulty connection can be a source of risk, incorrect connections shall be made impossible by the design or, failing this, precautions shall be taken to avoid faulty connection by information given on the pipes, hoses and/or connector blocks.

9.3 Hydraulic or pneumatic systems

Where auxiliary items are powered by hydraulic or pneumatic energy, the systems shall be so designed, constructed and equipped as to avoid all potential hazards associated with these types of energy. Means of isolating or discharging accumulated energy shall be included in such systems. All pipes and/or hoses carrying hydraulic oil or compressed air and their attachments shall be designed to withstand or be protected from foreseen internal and external stresses. Precautions shall be taken to minimize risk of injury arising as a consequence of rupture.

9.4 Main gearbox

The main gearbox shall be designed according to IEC 61400-4.

9.5 Yaw system

The yaw system may consist of means to maintain a fixed yaw orientation (e.g. hydraulic brakes), means to change that orientation (e.g. electric motors, gearboxes and pinions) and means to guide the rotation (e.g. a bearing).

Any motors shall comply with relevant parts of Clause 10.

Non-redundant parts of the gear system such as the final yaw gear shall be considered as component class 2. When multiple yaw drives ensure sufficient redundancy in the yaw gear system, and easy replacement is possible, the reduction gearbox and the final drive pinion may be considered to be in component class 1.

The safety against pitting shall be determined in accordance with ISO 6336-2. The application of the upper limit curve (1) for life factor Z_{NT}, which allows limited pitting, is permissible. Sufficient tooth bending strength shall be proven in accordance with ISO 6336-3. The reverse bending loads on gear teeth shall be considered in accordance with ISO 6336-3:2006, Annex B. Minimum values for S_{F} and S_{H} are specified in Table 4. These values shall be achieved by using characteristic loads F_{k}. Hence, S_{F} and S_{H} include the partial safety factor for consequences, γ_{n}, materials, γ_{M} and loads, γ_{f}.

Table 4 – Minimum safety factor $S_{H,min}$ and $S_{F,min}$ for the yaw gear system

	Component class 1	Component class 2
Surface durability (pitting)	$S_{H,min}$ = 1,0	$S_{H,min}$ = 1,1
Tooth bending fatigue strength	$S_{F,min}$ ≥ 1,1	$S_{F,min}$ = 1,25
Static bending strength	$S_{F,min}$ ≥ 1,0	$S_{F,min}$ = 1,2

However, lower safety factors, S_F and $S_{H,}$ may be applicable in cases where efficient monitoring is implemented. If safety factors below 1,0 are applied, then the maintenance manual shall reflect anticipated replacement intervals.

9.6 Pitch system

The pitch system may consist of means to adjust blade pitch angle (e.g. hydraulic actuators, electric motors, gearboxes, brakes and pinions) and means to guide the rotation (e.g. a bearing).

Any motors shall comply with relevant parts of Clause 10. For pitch systems with individual pitch drives/actuators ensuring sufficient redundancy, these may be considered to be in component class 2.

For component class 2, gearboxes and gears shall comply with relevant parts of 9.5.

9.7 Protection function mechanical brakes

Where mechanical brakes are used for a protection function (see 7.4.3.3), they are generally friction devices applied by hydraulic or mechanical spring pressure. The remaining life of any wearing components, for example friction pads, shall be monitored by the control system, which shall place the turbine in parked mode when insufficient material is available for a further emergency stop or braking.

Load calculation shall be based on simulations including an appropriate range of the braking level. If the brake is able to slip in the standstill state at the minimum braking level, whenever the brake is to maintain the wind turbine in a stationary state, the period of slip in a turbulent wind shall be sufficiently short to avoid overheating and brake performance impairment and to avoid a risk of fire.

9.8 Rolling element bearings

9.8.1 General

The basis of rating analysis of rolling bearings shall be ISO 76, ISO 281 and ISO/TS 16281. The calculation shall consider the actual operating and lubrication conditions as well as the bearing environment. Any life adjustment factor according to ISO 281 and ISO/TS 16281 shall be applied with care.

The design loads shall reflect the loads determined in the various load cases in 7.4 and appropriate safety factors in 7.6. The bearing design shall consider the expected amount of rotation during its lifetime and whether the rotations are continuous or discontinuous.

9.8.2 Main shaft bearings

The modified reference rating life L_{10mr} (90 % survival probability) of main shaft bearings shall meet or exceed the specified design life of the wind turbine.

9.8.3 Generator bearings

The modified reference rating life L_{10mr} (90 % survival probability) of generator bearings shall meet or exceed the specified design life of the wind turbine.

Generator bearings that can be replaced in the wind turbine without special tools may be specified for a shorter design life.

9.8.4 Pitch and yaw bearings

For pitch and yaw bearings, the ratio of static rating to design load shall be at least 1,0 according to ISO 76. The load distribution due to flexibility of the connected parts shall be carefully considered.

Bearings used in the pitch and yaw systems are exposed to a discontinuous, oscillatory motion. Therefore, consideration shall be given to the potential effect of insufficient lubrication due to small movement.

10 Electrical system

10.1 General

The electrical system of a wind turbine installation comprises all electrical equipment installed in each individual wind turbine up to and including the wind turbine terminals; referred to below as the "wind turbine electrical system".

Clause 10 includes electrical components specific to wind turbine designs that have features and functions not typically addressed in other system or component standards. Clause 10 also addresses common wind turbine components but it is not intended to be all inclusive. Specific components are dictated by the turbine design and these components and assemblies shall be evaluated for the electrical, mechanical and environmental installation locations and application as defined in 10.2.

The power collection system is not covered by this document.

10.2 General requirements for the electrical system

The design of the electrical system shall ensure minimal hazards to people and livestock as well as minimal potential damage to the wind turbine and external electrical system during operation and maintenance under all normal and extreme electrical and environmental conditions (as defined in 6.4.2 and 6.4.3) for the specific area where the equipment operates, including additional effects related to the overall turbine and its environmental ratings. Electrical components and subassemblies shall be rated for their electrical conditions and operating environment.

Electrical equipment should be designed to provide protection from potential arc flashes using recognized national or international standards and risk assessment methodologies.

For cold climate requirements, see 14.8.

Unless otherwise specified in this document, the design of a wind turbine electrical system shall comply with the requirements of IEC 60204-1. For equipment that have input and or output circuits at nominal voltages greater than 1 000 V AC or 1 500V DC, the applicable requirements of IEC 60204-11 shall be applied. The manufacturer shall state the design standard(s) used. The design of the electrical system shall take into account the fluctuating nature of power generation from wind turbines.

10.3 Internal environmental conditions

The environmental conditions internal to the turbine are likely to be different from the external environmental conditions.

Environmental conditions shall be determined for the locations in which all major components and subassemblies within the wind turbine are located and shall be conducted in accordance with IEC 60721 (all parts). The locations for consideration normally include, but are not limited to, the hub, tower sections, nacelle, tower base, tower basement.

The internal environmental conditions are dependent upon the specific environmental control systems and foreseeable environmental pollution included in a specific turbine design. Heating, cooling and active ventilation shall be considered.

The manufacturer shall specify the following service conditions for operation, storage and transportation for each of the turbine subassemblies and major components. Where applicable, the classifications from IEC 60721 (all parts) shall be used:

- coolant temperature (min./max.);
- ambient temperature (min./max.);
- humidity (min./max.);
- pollution degree;
- vibration;
- OVC (overvoltage category);
- altitude for thermal consideration, if rated for operation above 1 000 m;
- altitude for insulation coordination considerations, if rated for operation above 2 000 m.

These environmental condition determinations are the basis for the insulation coordination defined in 10.3.

IEC 60664-1 and IEC 60664-3 for equipment having a rated voltage up to 1 000 V AC and IEC 60071-1 and IEC 60071-2 for equipment having a rated voltage above 1 000 V AC shall be used for evaluating the insulation coordination requirements for the specific wind turbine equipment unless otherwise specified by specific component requirements within this document. This insulation coordination evaluation shall address the overvoltage category, pollution degree, and environmental conditions for the electrical equipment within the turbine.

Minimum environmental conditions within the turbine are to be considered pollution degree 3. Specific areas where conductive pollution such as slip ring brush dust and brake dust are present shall be considered pollution degree 4.

The pollution degree may be reduced within certain areas of the equipment by the use of encapsulation, conformal coating, etc. Reduction of pollution degree within the overall equipment may also be achieved by the use of enclosures providing protection in accordance with IEC 60529. Steps may be taken to control and reduce the pollution degree at the creepage location by design features or the consideration of the operating characteristics of the component or equipment.

Pollution degree 2 can be achieved by reducing the possibilities of debris accumulation (filtered ventilation) and condensation or high humidity at the creepage locations. Continuous application of heat, through the use of heaters or continuous energizing of the equipment when it is in use, can be used to control condensation. Continuous energizing is considered to exist when the equipment is operated without interruption every day and 24 hours per day or when the equipment is operated with interruptions of duration which do not permit cooling to the point that condensation occurs.

Pollution degree 1 can be achieved by potting, moulding the equipment or circuit or by enclosing it in an IP 67 enclosure.

Overvoltage category IV shall be applied to determine clearance spacings in general locations within a wind turbine. Surge protectors that are relied upon to protect control and protection circuits and other circuits relied upon for the safe operation of the turbine shall include monitoring circuits or other automatic means to indicate a surge protective device has failed. Use of surge suppression protection may be used to locally reduce the overvoltage category to below IV for specific equipment or circuits.

Direct or nearby lightning strikes can induce high overvoltage conditions in the external electrical systems and wind turbine electrical systems including equipment circuits throughout the hub, nacelle and tower. Surge protective devices, if used, shall be installed in close proximity to the equipment being protected.

10.4 Protective devices

A wind turbine electrical system shall, in addition to the requirements of IEC 60364 (all parts), include suitable devices that ensure protection against malfunctioning either within the wind turbine, equipment, subassemblies and components or as consequence of the external electrical system malfunction that may lead to an unsafe condition or state. These protective device functions include: short circuit, overcurrent, ground fault, over temperature and arc fault.

10.5 Disconnection from supply sources

Lockable disconnect device or devices shall be provided to disconnect the equipment from each electrical source of supply that has a hazardous live voltage or exceeds the values for hazardous energy or from which a hazardous live voltage or energy is derived. The levels of hazardous voltage and energy are defined in IEC 60204-1 and IEC 60204-11.

The emergency stop is not intended to provide a routine disconnect function for this purpose.

Semiconductor switching devices without additional air gap disconnect contacts are not suitable to meet the requirements of 10.4.

Where lighting or other electrical systems are necessary for safety during maintenance, auxiliary circuits shall be provided with their own disconnect devices, such that these circuits may remain energized while all other circuits are de-energized.

Circuits and equipment rated more than 1 000 V AC or 1 500 V DC shall comply with Clause 5 of IEC 60204-11:2000.

10.6 Earth system

A wind turbine shall be provided with a local earth electrode system to meet the requirements of IEC 60364 (all parts) (for the correct operation of the electrical installation) and IEC 62305-3 (for lightning protection).[28] The range of soil conditions for which the earth electrode system is adequate shall be stated in the design documentation, together with recommendations should other soil conditions be encountered.

The choice and installation of the equipment of the earthing arrangement (earth electrodes, earthing conductors, main earthing terminals and bars) shall be made in accordance with IEC 60364-5-54.

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[28] Additional considerations are included in IEC 61400-24:2010, Clause 9.

Provisions shall be made in any electrical system operating above 1 000 V AC or 1 500 V DC for earthing during maintenance in accordance with IEC 60204-11.

10.7 Lightning protection

The lightning protection system of a wind turbine shall be designed in accordance with IEC 61400-24. A risk-based approach shall be applied during the lightning protection system design with respect to the risk of damage and personnel safety.

The design shall consider the protection of the following areas:

- rotor blades;
- hub/spinner;
- nacelle;
- tower.

Additional system components such as external transformers and switchgear outside the scope of this document may also need to be connected and or included in the lightning protection system.

The protection of electrical systems within the turbine shall follow a lightning protection approach as set out in IEC 62305-4, with the design incorporating a combination of bonding, shielding and surge protection devices.

Design requirements of the lightning protection system are provided in IEC 61400-24.

10.8 Electrical cables

Electrical cables shall be rated for the electrical, flammability, mechanical and environmental applications where they are used and shall be installed in a manner for which they are rated. Where there is a probability of rodents or other animals damaging cables, armoured cables or conduits shall be used.

- Cables shall be protected or rated to mitigate the possible risk of fire in the event of the fault.
- Control cables shall be segregated and or protected from power cables unless insulation failures are specifically addressed in the fault analysis.
- Cable clamps, supports and strain reliefs shall be suitable for the cable type so as to prevent damage to the cable insulation.
- Cables shall be protected or suitably located to prevent damage from abrasion and wear.

10.9 Self-excitation

Any electrical system that can alone self-excite a wind turbine shall be disconnected and remain safely disconnected in the event of loss of network power.

If a capacitor bank is connected in parallel with an induction generator (i.e. for power factor correction), a suitable switch is required to disconnect the capacitor bank whenever there is a loss of network power, to avoid self-excitation of the generator. Alternatively, if capacitors are fitted, it shall be sufficient to show that the capacitors cannot cause self-excitation.

10.10 Protection against lightning electromagnetic impulse

The overvoltage protection shall be designed in accordance with the requirements of IEC 62305-4.

The limits of the protection shall be so designed that any lightning electromagnetic impulse transferred to the electrical equipment will not exceed the limits governed by the equipment insulation levels.

10.11 Power quality

The procedures in IEC 61400-21 can be used to demonstrate compliance with the requirements of the operator of the public distribution or transmission network.

10.12 Electromagnetic compatibility

For immunity to radiated and conducted disturbances, all electrical components installed in the wind turbine shall meet the requirements of the relevant product standards and shall not be less than the greater of requirements of IEC 61000-6-2 or the requirements defined during the functional safety evaluation of the control system in Clause 8.

10.13 Power electronic converter systems and equipment

The converter shall be evaluated for the environment in which it is installed as defined by Table 18 of IEC 62477-1:2012. The interior of a turbine is not considered to be a conditioned space. If the converter is installed within a conditioned space, it shall be evaluated for that environment. The pollution degree shall be chosen with respect to ingress of moisture from humidity and condensation due to extended durations of de-energization. The environmental service conditions defined in IEC 62477-1 may be modified to accommodate the specific end application within the turbine.

IEC 61800-4 shall be applied for converters operating above 1 000 V AC or 1 500 V DC.

Converter controls and protection shall additionally comply with the applicable requirements in Clause 8.

10.14 Twist/drip loop

Wiring that is subject to movement, flexing, or twisting during operation of the wind turbine shall be investigated for suitability in the application conditions of use and rated life.

If operation of the wind turbine may result in twisting of flexible cables, such as the connecting cables between rotating parts (nacelle) and parts of the fixed structure (tower or foundation), the operational conditions of use shall not cause damage to the conductors or their insulation. The evaluation shall address service life, electrical and environmental operating conditions of the subassembly.

Controls that prevent damage to conductors or their insulation including rotational limits shall be considered part of the control system.

Where multiple cables are grouped or tied together, the assembly loading shall be distributed such that the individual cables are not subjected to loads that exceed their individual ratings.

The cable support assemblies shall be designed for the mechanical loading and torsional forces of operation.

Cable size and temperature rating shall be evaluated based upon the operating temperature of the assembly including representative size and number of cables fully twisted, carrying maximum normal current and including electrical terminations similar in distance in the end application.

10.15 Slip rings

Slip rings shall comply with 10.2 and the applicable portions of IEC 60204-1 and shall be rated for the electrical and environmental conditions to which they are subjected within the turbine. The slip rings shall be rated for normal operating and abnormal (overload) conditions to which they may be subjected. The normal rating of a slip ring is based upon the circuit electrical loads. The overload rating shall be based upon source circuit fault current capacity and may account for overcurrent protection if provided.

Slip rings used in safety critical power and control circuits shall be provided with means to address failure and wear.

10.16 Vertical power transmission conductors and components

Vertical power transmission systems that are run up the tower, such as bus bar-based systems and cable-based systems, shall comply with the respective component standards. These are IEC 61439-1 and IEC 61439-6 for bus bar-based systems and IEC 60364-5-52 for cable-based systems.

The conductors and components shall comply with their applicable standard with regards to: operating temperature range, environmental conditions, electrical isolation, electrical impulse withstand and short circuit withstand capabilities as necessary for the electrical and environmental conditions within the turbine.

Vertical power transmission equipment shall be constructed with sufficient mechanical strength to withstand the foreseeable mechanical forces (deflection, movement and loading) for its use as determined from the results of the design load cases for the specific component within the specific turbine. Sections of vertical power transmission conductors and components shall be suitably attached to the tower or to components of the tower intended to support the assembly.

The evaluation of these vertical power transmission systems shall account for the following conditions:

a) static loading on system components;
b) expected deflection and forces on the transmissions assemblies and support structure resulting from bending of the tower under anticipated extreme conditions;
c) expected force direction and magnitude of displacement of the assembly;
d) component fatigue, loosening of fasteners;
e) degradation, wear, deformation and creep of polymeric electrical insulating materials;
f) loss of electrical conductivity or electrical isolation;
g) operation for the intended turbine life span or specified maintenance period for the assembly.

The assembly may be evaluated by testing, analysis or a combination of the two.

Scaled testing may be used to represent the complete system.

The mechanical and structural suitability of the power transmission assembly and supporting members may be addressed via analysis per the design load case evaluation. The design load cases shall specifically include and address the forces on the assembly, subassemblies and components including insulating and conducting materials.

Consideration of short circuit conditions for vertical power transmission systems should include electrical, thermal and mechanical effects on components as well as installed systems.

If the analysis method does not include effects of abrasion/wear and material creep on the polymeric electrical insulation, testing may be necessary.

10.17 Motor drives and converters

Motor drives and converters shall comply with the applicable portions of IEC 61800-5-1.

Pitch and yaw motor drive and converter controls shall additionally comply with the applicable requirements in Clause 8.

10.18 Electrical machines

Electrical machines shall comply with relevant parts of IEC 60034 and shall have a duty rating suitable for the intended application[29].

The turbine generator shall be rated for continuous operation (duty S1 according to IEC 60034-1).

The combination of an electrical machine powered by a frequency converter drive shall have coordinated electrical and isolation ratings.

10.19 Power transformers

Power transformers included within or as part of a turbine system shall comply with IEC 60076 (all parts).

Low voltage transformers within the wind turbine shall either be fully enclosed, including all terminations, or they shall be located in dedicated areas behind barriers or panels as required in recognized national or international standards and codes. High voltage (HV) transformers within the wind turbine shall comply with the requirements for restricted accessibility and lock out as defined in 10.21.

10.20 Low voltage switchgear and controlgear

Low voltage switchgear and controlgear operating up to 1 000 V AC or 1 500 V DC shall comply with IEC 61439-1 and other parts of the IEC 61439 series and shall be rated for the electrical and environmental conditions to which it is subjected within the turbine.

All enclosures for switchgear and controlgear shall be provided with cautionary markings required by IEC 61439-1 and other applicable parts of the IEC 61439 series.

10.21 High voltage switchgear

High voltage (HV) switchgear operating above 1 000 V AC or 1 500 V DC shall comply with IEC 62271 (all parts) and shall be rated for the electrical and environmental conditions to which it is subjected within the turbine.

HV switchgear shall be located in areas of the turbine only accessible by authorized personnel. Cautionary markings shall be posted on the turbine access, hatch or door to wear appropriate personnel protection equipment for the hazards inside the area beyond the access, hatch or door.

HV switchgear installed in areas accessible to normal maintenance personnel shall be metal enclosed and specified for internal arc containment classification (IAC). The IAC shall be classification A as defined in IEC 62271-200 for all equipment sides where personnel may reasonably have access.

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29 Consideration should be given to interconnection cable length, the drive voltage waveform, the use of insulated bearings and shaft earthing arrangements.

HV switchgear shall be tested, rated and marked for the IAC fault current with a duration of not less than 1 s.

HV switchgear shall be installed in accordance with the manufacturer's ratings and instructions. Pressure relief vents shall output without obstruction and without risk to personnel or equipment.

Switchgear configured for automatic operation shall be switchable to lock out and disable the automatic operation.

As required by 10.4, HV switchgear and associate controls shall be provided with a means to be locked in a safe state.

SF6 switchgear shall be installed in areas with sufficient ventilation so as to avoid hazard to personnel in the event of a leak.

10.22 Hubs

Equipment within the hub shall be provided with enclosures rated for the electrical and environmental application in accordance with IEC 60529 to protect electrical components from damage. Electrical cabinets and enclosures shall be provided with doors or covers that are securely fastened.

Wiring associated with the control systems shall be mechanically protected from damage due to hub rotation, service personnel interaction and unintended impacts within the hub.

11 Assessment of a wind turbine for site-specific conditions

11.1 General

Wind turbines are subject to environmental and electrical conditions including the influence of nearby turbines, which may affect their loading, durability and operation. In addition to these conditions, account has to be taken of the seismic, topographic and soil conditions at the wind turbine site. It shall be shown that the site-specific conditions do not compromise the structural integrity. The demonstration requires an assessment of the site complexity, see 11.2, and an assessment of the wind conditions at the site, see 11.3. For assessment of structural integrity, two approaches may be used:

a) a demonstration that all these conditions are not more severe than those assumed for the design of the wind turbine, see 11.9;
b) a demonstration of the structural integrity for conditions, each equal to or more severe than those at the site, see 11.10.

If any conditions are more severe than those assumed in the design, the structural and electrical compatibility shall be demonstrated using the second approach.

The partial safety factors for loads in 7.6.2.2 assume that the site assessment of the normal and extreme wind conditions has been carried out according to the minimum requirements in Clause 11.

11.2 Assessment of the topographical complexity of the site and its effect on turbulence

11.2.1 Assessment of the topographical complexity

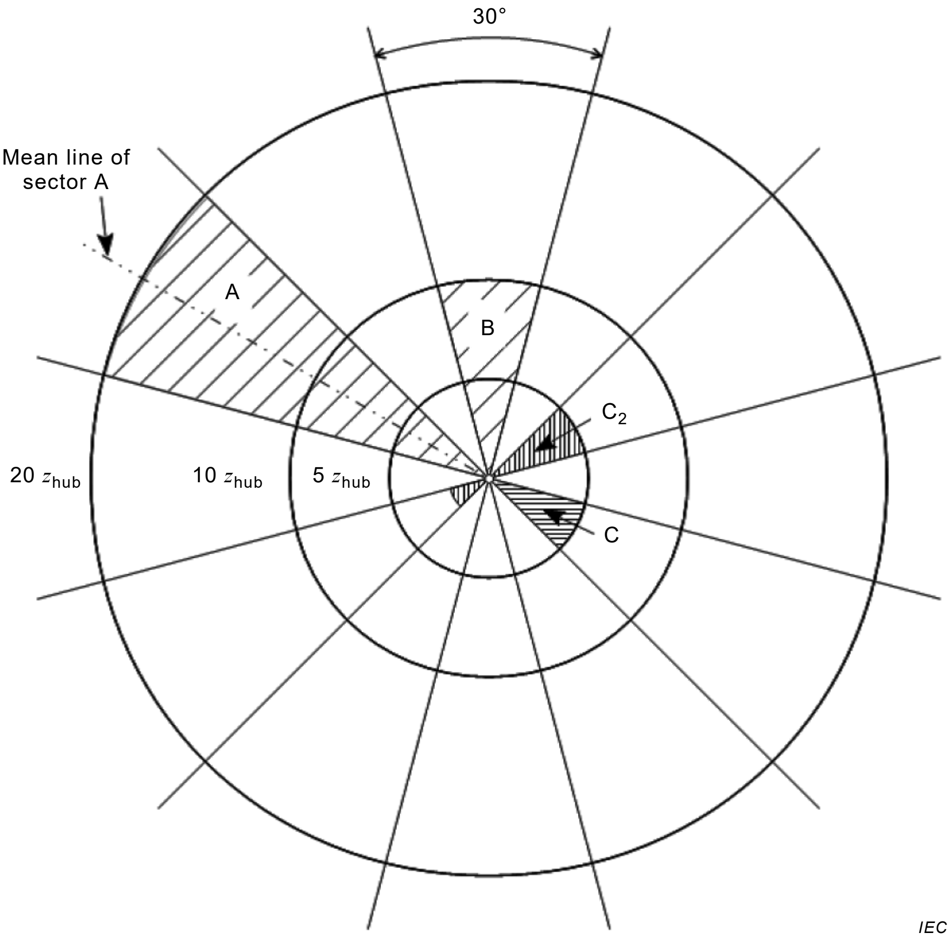
A site shall be assessed for the topographical complexity of the terrain, since it may cause distortion, and hence deviation, of the turbulence structure from the design conditions.

The complexity of the site is characterized by the slope of the terrain and variations of the terrain topography from a plane, and it may be assessed according to the following procedure.

To obtain the slope of the terrain, planes are defined that fit the terrain within specific distances and sector amplitudes for all wind direction sectors around the wind turbine, see Figures 10 and 11. The fitted planes do not need to pass through the tower base. The slope denotes the angle between a horizontal line and the different mean lines of sectors projected vertically on the fitted planes. Accordingly, the terrain variation from the fitted plane denotes the distance, along a vertical line, between the fitted plane and the terrain at the surface points.

The resolution of surface grid and its original source map used for terrain complexity assessment should not exceed 50 m.

The circle sectors shall be 30°. For the circle sectors with radius $5z_{\text{hub}}$ the area used to fit the plane may be extended $2z_{\text{hub}}$ downwind of the wind turbine position, see Figure 10.



Key

A radius $20z_{\text{hub}}$

B radius $10z_{\text{hub}}$

C radius $5z_{\text{hub}}$

C_2 radius $5z_{\text{hub}}$ extended $2z_{\text{hub}}$ behind the wind turbine position

Figure 10 – Examples of 30° sectors for fitting the terrain data

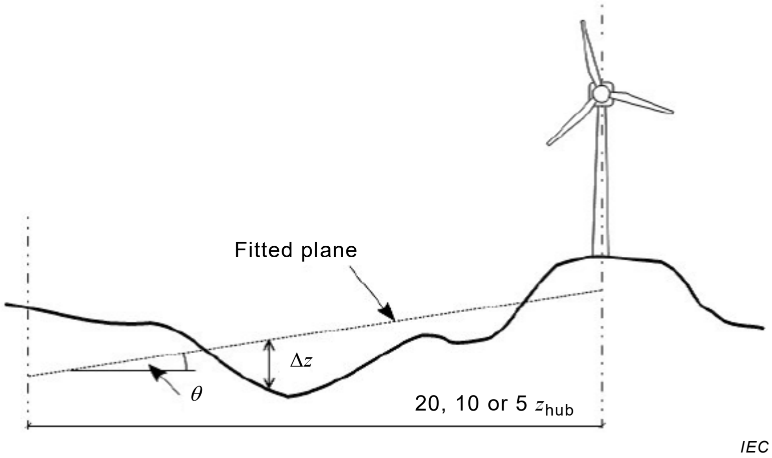


Figure 11 – Terrain variation (Δz) and terrain slope (θ)

Using thus defined slope and terrain variation, terrain slope indices (TSI) and terrain variation indices (TVI) for each circle area are given by the following equations:

$$
\begin{aligned}
TSI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot |\theta(i)| \\
TVI_{30} &= \sum_{i=1}^{12} f_{\text{Energy}}(i) \cdot \frac{D_{\text{TV}}(i)}{R} \\
TSI_{360} &= k_1 \cdot \theta_{360} \\
TVI_{360} &= \frac{D_{\text{TV360}}}{k_2 \cdot R}
\end{aligned}
\tag{34}
$$

where

TSI_{30}, TSI_{360}	are the terrain slope indices calculated from 30° sectors and 360° circle area, respectively;
TVI_{30}, TVI_{360}	are the terrain variation indices calculated from 30° sectors and 360° circle area, respectively;
i	is the wind sector index (1, 2, ..., 12);
$f_{\text{Energy}}(i)$	is the percentage of the wind energy coming through ith 30° sector, $\sum f_{\text{Energy}}(i) = 1$;
$\theta(i)$	is the slope of fitted plane for ith 30° sector;
θ_{360}	is the slope of the fitted 360° circle plane;
$D_{\text{TV}}(i)$	is the standard deviation of terrain variation in ith 30° sector;
D_{TV360}	is the standard deviation of terrain variation of the 360° circle area;
R	is the radius of the circle area;
k_1	is the empirical adjustment factor for TSI_{360}, k_1 = 5/3;
k_2	is the empirical adjustment factor for TVI_{360}, k_2 = 3.

TSI_{30} is the mean absolute value of the slopes of the twelve sector-wise fitted planes weighted by energy inflow. Similarly, TVI_{30} is the mean value of the twelve sector-wise standard deviations of terrain variation normalized by the circle radius, weighted by the energy inflow.

TSI_{360} is the slope of the fitted 360° circle plane adjusted by an empirical factor k_1.

TVI_{360} is the standard deviation of terrain variation in 360° circle area, normalized by the circle radius and adjusted by an empirical factor k_2.

Terrain is assessed for terrain complexity by means of two indices TSI and TVI for each of the three circle areas ($5z_{hub}$, $10z_{hub}$, and $20z_{hub}$). For both indices, three complexity categories low (L), medium (M) and high (H) are defined, see Table 5. If the TSI_{30} and TVI_{30} values as well as the TSI_{360} and TVI_{360} values for all three circle areas are below the threshold value for category L, the site is assessed as not complex. If not, the site is assessed as complex and assigned one of the three complexity categories, L, M or H, depending on the highest category TSI or TVI for any of the circle areas.

Table 5 – Threshold values of the terrain complexity categories L, M and H

<table>
<tr><th rowspan="3">Radius of circle area</th><th rowspan="3">Sector amplitude of fitted plane</th><th colspan="6">Threshold values (lower limit)</th></tr>
<tr><th colspan="3">Terrain slope index (TSI)</th><th colspan="3">Terrain variation index (TVI)</th></tr>
<tr><th>L</th><th>M</th><th>H</th><th>L</th><th>M</th><th>H</th></tr>
<tr><td>$5z_{hub}$</td><td>360°</td><td rowspan="4">10°</td><td rowspan="4">15°</td><td rowspan="4">20°</td><td rowspan="4">2 %</td><td rowspan="4">4 %</td><td rowspan="4">6 %</td></tr>
<tr><td>$5z_{hub}$</td><td rowspan="3">30°</td></tr>
<tr><td>$10z_{hub}$</td></tr>
<tr><td>$20z_{hub}$</td></tr>
</table>

11.2.2 Assessment of turbulence structure at the site

The turbulence structure, i.e. the ratios of the three components of turbulence, of a site shall be determined primarily from measurements at the site. When there are no site data, it may be estimated by an appropriate flow model.

Alternatively, it may be estimated from the complexity of the site. Values shown in Table 6 may be assigned depending on the complexity category defined according to the procedure described in 11.2.1.

Table 6 – Values of lateral and vertical turbulence standard deviations relative to the longitudinal component depending on terrain complexity category L, M and H

	Category		
	L	M	H
σ_2/σ_1	0,85	0,93	1,00
σ_3/σ_1	0,60	0,65	0,70

The turbulence structure correction parameter C_{CT}, which may be used in the assessment of the structural integrity by reference to wind data in 11.9, may be defined by the following equation[30]:

30 If C_{CT} is less than 1, C_{CT} = 1,0 shall be used.

$$C_{CT} = \sqrt{1+\left(\hat{\sigma}_2 / \hat{\sigma}_1\right)^2 + \left(\hat{\sigma}_3 / \hat{\sigma}_1\right)^2} \;/\; \sqrt{1+\left(\sigma_2 / \sigma_1\right)^2 + \left(\sigma_3 / \sigma_1\right)^2}$$

in which σ_1, σ_2 and σ_3 are values of the three components of turbulence, at hub height and at wind turbine location, averaged over a wind speed range between 0,6 V_r and 1,6 V_r. The design values for the Kaimal and Mann models can be obtained from Annex C.

When there are no measured site data, the values in Table 7 may be used for C_{CT} depending on the complexity category of the site.

Table 7 – Values of turbulence structure correction parameter depending on terrain complexity category L, M and H

	Category		
	L	**M**	**H**
C_{CT}	1,05	1,10	1,15

Interpolation between the values in Table 6 and Table 7 is allowed.

11.3 Wind conditions required for assessment

11.3.1 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). Simulation models shall be validated against representative data.

11.3.2 Wind condition parameters

The following parameters shall be derived for the position of the wind turbine at hub height:

- extreme 10 min average wind speed[31], V_{50}, at hub height with a return period of 50 years;
- wind speed probability density function, $p(V_{hub})$;
- 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 all wind speeds required in 11.9 or 11.10;

[31] The load partial safety factors for DLC 6.1 and DLC 6.2 are derived by assuming that the coefficient of variation of the annual maximum wind speed, COV, is smaller than 15 %. If COV is larger than 15 %, they can be increased linearly by a factor η from 1,0 at COV = 15 % to 1,15 at COV = 30 %. If η > 1,0 an adjusted value of the extreme 10 min average wind speed of $\tilde{V}_{50} = \sqrt{\eta}\; V_{50}$ can be used in the assessment of the structural integrity, see 11.9 and 11.10. COV of the annual maximum wind speed can approximately be obtained assuming a Gumbel distribution and assuming that for example 50 year and 100 year return values of the wind speed, V_{50} and V_{100}, are available. The parameters α and β are obtained from:

$$\alpha = \frac{V_{100} - V_{50}}{p_{100} - p_{50}}, \quad \beta = V_{50} - \alpha\, p_{50} \quad \text{with} \quad p_{100} = -\ln\left(-\ln\left(1-\frac{1}{100}\right)\right) \quad \text{and} \quad p_{50} = -\ln\left(-\ln\left(1-\frac{1}{50}\right)\right)$$

COV is determined from

$$\text{COV} = \frac{\sigma}{\mu} = \frac{\pi}{\sqrt{6}} \frac{1}{\frac{\beta}{\alpha} + 0,5772}$$

- extreme ambient wind speed standard deviation[32], $\hat{\sigma}_{1,\text{ETM}}$, with a return period of 50 years;
- flow inclination;
- wind shear[33];
- air density.

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

The bin width of any wind speed used in the above shall be 2 m/s or less, and the wind direction sectors shall be 30° or less. All measurements, except air density, shall be available as function of wind direction, given as a 10 min average.

Attention should be given to wakes from significant structures and orographic obstacles within a distance from the wind turbine of 20 times the characteristic length of the structure or the orographic obstacle. The influence can be neglected if the bottom edge of the rotor is at least four times higher than the height of the structure or the orographic obstacle.

In regions prone to hurricanes, cyclones and typhoons, the extreme wind speed shall be evaluated by appropriate methods, for example as given in Annex J.

For cold climate, additional parameters should be derived for the position of the wind turbine. Icing condition may be assessed according to Annex L.

11.3.3 Measurement setup

The requirement for and use of measurements for wind turbine site suitability assessment and wind resource assessments differ in many respects, and therefore a balance needs to be found between the amount and the quality of measurements.[34] Furthermore, for the purposes of a wind turbine site suitability measurement campaign, additional criteria should be taken into consideration.

- The measurement system should be installed in locations broadly representative of the majority of site areas (e.g. forest, ridge lines, plains, valleys, slopes and obstacles).
- The exact number and location of measuring systems recommended is very site-specific and depends upon the terrain, extent and ground cover of the proposed wind farm as well as the expected complexity of the flow regime and the on-site validation of the flow model to be used in the analysis.
- The wind condition measurement heights as well as the number of sensors should be chosen to be representative. Measurements should be performed at a range of heights within the proposed turbine rotor's swept area. Consideration should be given to surrounding terrain and vegetation.
- The vertical separation distance between the sensors should enable a robust analysis of the vertical wind shear, for example a separation of at least one third of the rotor diameter.
- A temperature as well as pressure sensor should be installed.

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32 The extreme ambient wind speed standard deviation $\hat{\sigma}_{1,\text{ETM}}$ may be derived using an appropriate extrapolation method, for example, the IFORM method, or estimated by:

$$\hat{\sigma}_{1,\text{ETM}} = \hat{\sigma} + k_\text{p}\hat{\sigma}_\sigma ;\quad k_\text{p} = 0{,}01\left(\frac{V_\text{ave}}{(\text{m/s})} - 21\right)\left(\frac{V_\text{hub}}{(\text{m/s})} - 5\right) + 5$$

33 Shear values with high variability have been reported for certain areas in connection with highly stratified flow, complex terrain or severe roughness changes. In this case using the average wind shear may not be sufficient.

34 IEC 61400-12-1 and IEA Recommendation 11 illustrate best-practice guidelines for measurement equipment installation and setup.

- 10 minutes averaging time, based on at least 1 Hz (mean, standard deviation and maximum wind speed, mean of wind direction and mean temperature) should be used.
- If measurements are performed in a cold climate zone, then additional heated sensors should be used and their performance relative to unheated sensors considered.
- In complex terrain, all wind components should be measured, for example with a 3D-ultrasonic anemometer.

11.3.4 Data evaluation

The recommendations with respect to data coverage and period are the following.

- The measurement period can deviate depending on the quality of data and the reliability of the correlation to a reference long term source. Where seasonal variations contribute significantly to the wind conditions, the monitoring period should be long enough to include these effects (the minimum to capture seasonal effects would be 12 months).
- The data coverage in each month should be sufficiently high to adequately represent the monthly variation in wind conditions.

During data evaluation, a quality check and filtering should be performed and documented. A measure-correlate-predict (MCP) procedure may be performed to extend the data.

The average value of the wind speed standard deviation $\hat{\sigma}$, i.e. the standard deviation of the longitudinal turbulence component, and its standard deviation $\hat{\sigma}_\sigma$ shall be determined using appropriate statistical techniques applied to measured and preferably linearly de-trended data.

A long-term assessment is normally required for the estimation of the extreme wind speed, long-term mean wind speed as well as air density, but only if the available long term source is appropriate and sufficiently reliable.

Alternative methods can be used. These methods should aim to improve the representativeness of the measurements for the site.

The above mentioned methods and procedures shall be documented.

11.4 Assessment of wake effects from neighbouring wind turbines

Wake effects from neighbouring wind turbines during power production shall be considered. The assessment of the suitability of the wind turbine at a site in a wind farm shall take into account the deterministic and turbulent flow characteristics associated with single or multiple wakes from upwind machines, including the effects of the spacing between the machines, for all ambient wind speeds and wind directions relevant to power production.

The increase in loading generally assumed to result from wake effects may be accounted for by the use of an added turbulence approach, or by using more detailed wake models. In either case, the wake model shall include adequate representation of the effect on loading of ambient turbulence and discrete and turbulent wake effects.

For fatigue calculations, the effective turbulence intensity I_{eff} may be derived according to Annex E.

The added turbulence for fatigue and ultimate loads may be assumed to be the same.

The DWM model described in Annex E is generally applicable to both fatigue and extreme load cases.

11.5 Assessment of other environmental conditions

The following environmental conditions shall be assessed for comparison with the assumptions made in the design of a wind turbine:

- normal and extreme temperature ranges;
- icing, hail and snow;
- humidity;
- lightning;
- solar radiation;
- chemically active substances;
- salinity.

11.6 Assessment of earthquake conditions

There are no earthquake resistance requirements for standard class turbines because such events are only design driving in a few regions of the world. No earthquake assessment analysis is required for sites already excluded by the applicable local seismic code due to their weak seismic action. For locations where the seismic load cases described below are critical, the engineering integrity shall be demonstrated for the wind turbine site conditions. The assessment may be based on Annex D. The evaluation of load shall take into account the combination of seismic loading with other significant, frequently occurring operational loads.

The seismic loading shall depend on ground acceleration and response spectrum requirements as defined in local codes. If a local code is not available or does not give the ground acceleration and response spectrum, an appropriate evaluation of these parameters shall be carried out.

The ground acceleration shall be evaluated for a 475-year return period.

The earthquake loading shall be superposed with operational load that shall be the largest of

a) mean loads during normal power production determined at V_{r},

b) loads during emergency stop at V_{r}, and

c) loads during idling or parked condition at no wind and V_{out}.

The partial safety factor for load for all load components shall be 1,0. The material safety factor for steel can be set to 1,0.

The seismic load evaluation may be carried out through response spectrum methods, in which case the operational load is added using the SRSS (square-root-sum-of-squares) or equivalent load combination arising from the seismic loading.

The seismic load evaluation may be carried out through time-domain methods, in which case sufficient simulations shall be undertaken to ensure that the operational load is representative of the time averaged values referred to above.

The number of tower natural vibration modes used in either of the above evaluations shall be selected in accordance with a recognized seismic code. In the absence of such a code, consecutive modes with a total modal mass of 85 % of the total mass shall be used.

The evaluation of the resistance of the structure may assume elastic response only, or ductile energy dissipation. However, it is important that the latter is assessed correctly for the specific type of structure in use, in particular for lattice structures and bolted joints.

The acceleration response spectrum at the engineering bedrock and seismic response evaluation method are described in Annex D. The response spectrum method shall not be used if it is possible that seismic action will cause significant loading of structures other than the tower.

11.7 Assessment of electrical network conditions

The external electrical conditions at the wind turbine terminals at a proposed site shall be assessed to ensure compatibility with the electrical design conditions. The external electrical conditions shall include the following[35]:

- normal voltage and range including requirements for remaining connected or disconnecting through specified voltage range and duration;
- normal frequency, range and rate of change, including requirements for remaining connected or disconnecting through specified frequency range and duration;
- voltage imbalance specified as a percentage negative phase-sequence voltage for symmetric and unsymmetrical faults;
- method of neutral grounding;
- method of ground fault detection/protection;
- annual number of network outages;
- auto-reclosing cycles;
- required reactive compensation schedule;
- fault currents and duration;
- phase-phase and phase-ground short-circuit impedance at the wind turbine terminals;
- background harmonic voltage distortion of the network;
- presence of power line carrier signalling if any and frequency of same;
- fault profiles for ride-through requirements;
- power factor control requirements;
- ramp rate requirements; and
- other grid compatibility requirements.

11.8 Assessment of soil conditions

The soil properties at a proposed site shall be assessed by a professionally qualified geotechnical engineer, with reference to available local building codes.

11.9 Assessment of structural integrity by reference to wind data

11.9.1 General

It is possible to complete the assessment of structural integrity by comparison of the wind parameter values for the site to those used in design. The assessment can be performed separately for the fatigue load suitability and the ultimate load suitability.

11.9.2 Assessment of the fatigue load suitability by reference to wind data

A wind turbine is suitable for a site with respect to fatigue loading when the following conditions are all satisfied.

[35] The turbine designer may need to take account of grid compatibility conditions. The list represents a set of minimum requirements. Local and national grid compatibility requirements need to be anticipated at the design stage.

a) The site value of the wind speed probability density function at hub height $p(V_{\text{hub}})$ shall be less than or equal to the design probability density function at all values of V_{hub} between the wind speeds V_{ave} and $2V_{\text{ave}}$. If the turbine has been designed with the wind speed distribution in 6.3.2.1 and the shape parameter k of the site-specific Weibull wind speed distribution is greater than or equal to 1,4, then, k shall fulfil the following equation, which depends on the site-specific mean wind speed at hub height normalized by the design mean wind speed, see Figure 12:

$$6{,}5 \times \frac{V_{\text{ave,site}}}{V_{\text{ave,design}}} - 4{,}5 \leq k \leq -6{,}0 \times \frac{V_{\text{ave,site}}}{V_{\text{ave,design}}} + 8{,}0 \qquad (35)$$

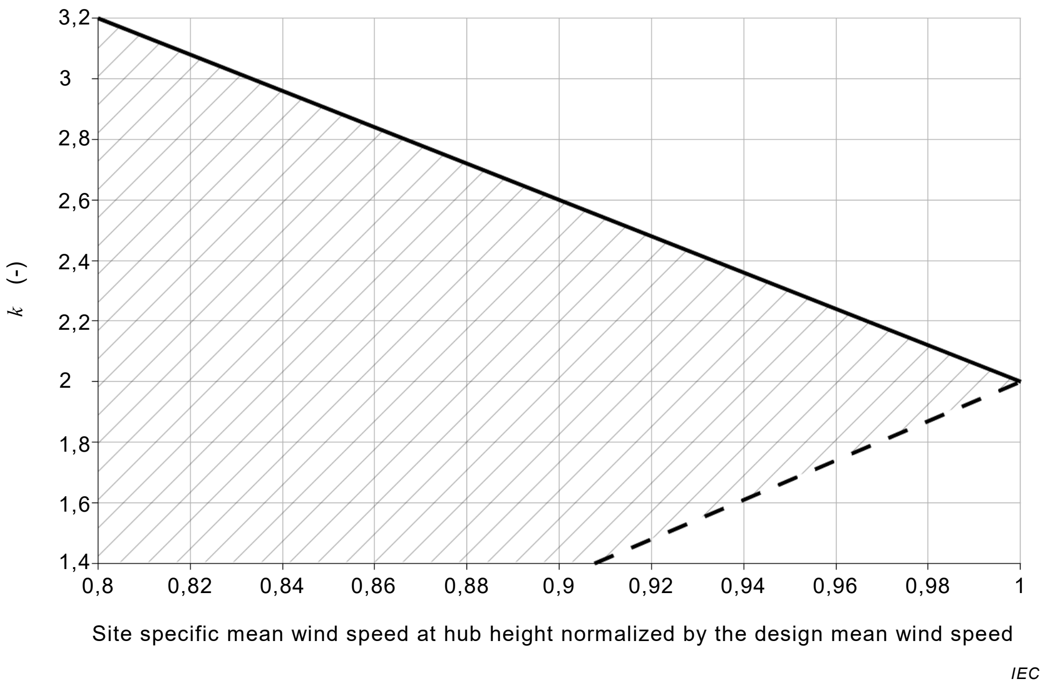

Figure 12 – Possible combinations of normalized mean wind speed and Weibull shape parameter *k* (shaded area)

b) An adequate assessment of the ambient turbulence intensity and wake effects can be performed by verifying that the wind speed standard deviation σ_1 from the normal turbulence model (NTM) used in design is greater than or equal to the effective wind speed standard deviation $\hat{\sigma}_{\text{eff}}$ (see Annex E) between the wind speeds V_{ave} and $2V_{\text{ave}}$, i.e.

$$\sigma_1 > \hat{\sigma}_{\text{eff}} \left(= I_{\text{eff}} V_{\text{hub}}\right) \qquad (36)$$

Guidance for calculating I_{eff} can be found in Annex E. In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation, i.e. $\hat{\sigma}_{\text{c}}$, shall be increased in order to account for the distortion of the turbulent flow. This can be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

c) The site flow inclination, taken as the wind energy weighted mean from all directions, shall be between –8° and +8°. Where there are no site data or calculations for the flow inclination, it shall be assumed that the flow inclination is equal to the slope, θ, for the 30° sector within a distance of $5z_{\text{hub}}$ or the $5z_{\text{hub}}$ area extended by $2z_{\text{hub}}$ downwind of the wind turbine position from the wind turbine, see 11.2.

d) The energy weighted average over all wind directions and wind speeds during power production of the vertical site wind shear exponent α shall be in the range of 0,05 to 0,25.

Where there are no site data for the wind shear, it shall be calculated taking topography and roughness of the surrounding terrain into account.

e) The average site air density shall be less than the one specified in 6.4.2 for wind speeds greater than or equal to V_r. As an alternative, for an air density greater than the one specified in 6.4, it shall be demonstrated that the following condition applies:

$$\rho_{design} \times V^2_{ave,design} \geq \rho_{site} \times V^2_{ave,site} \tag{37}$$

11.9.3 Assessment of the ultimate load suitability by reference to wind data

A wind turbine is suitable for a site with respect to ultimate loading when the following conditions are all satisfied.

a) The design value of the wind speed standard deviation, σ_1, (see Equation (10)) shall be greater than or equal to the site value of the estimated 90 % quantile[36] of the wind speed standard deviation at all values of V_{hub} between the wind speeds 0,6 V_r and 1,6 V_r, i.e.

$$\sigma_1 \geq \hat{\sigma} + 1{,}28\ \hat{\sigma}_\sigma \tag{38}$$

In case of complex terrain, the estimated 90 % quantile of the wind speed standard deviation shall be increased in order to account for the distortion of the turbulent flow. This may be done by additional multiplication with a turbulence structure correction parameter C_{CT} as defined in 11.2.

b) The site estimate of the extreme 10-min average wind speed V_{50} at hub height with a return period of 50 years shall be less than or equal to V_{ref}. Alternatively, the wind turbine site central estimate of extreme 3 s average wind speed at hub height with a return period of 50 years shall be less than V_{e50}. For Class S turbines, both the extreme 3 s average wind speed and the extreme 10 min average wind speed shall be assessed. V_{50} shall be modified according to Footnote 24 when the coefficient of variation of the annual maximum wind speed is larger than 15 %. If the average site air density is different from the one specified in 6.4.2, it shall be demonstrated that the following condition applies:

$$\rho_{design} \times V^2_{ref} \geq \rho_{site} \times V^2_{50,hub} \tag{39}$$

c) It shall be demonstrated that the site-specific extreme ambient wind speed standard deviation does not exceed the ETM model in 6.3.3.4.

d) In case of wake situations, it shall be demonstrated that the maximum centre-wake wind speed standard deviation in the most severe direction does not exceed the ETM model in 6.3.3.4. Alternatively, it can be demonstrated that the ambient site-specific extreme turbulence does not exceed the ETM model used for DLC 1.6 in Annex B and that the minimum site-specific inter-turbine distance does not fall below S_{min} from DLC 1.6. For determination of the site-specific turbulence, the site-specific conditions, the frequency of the wake situations and the wind farm layout shall be accounted for.

11.10 Assessment of structural integrity by load calculations with reference to site-specific conditions

The demonstration shall comprise a comparison of loads and deflections calculated for the specific wind turbine site conditions with those calculated during design, taking account of the reserve margins and the influence of the environment on structural resistance. The calculations shall account for variations of wind conditions with mean wind direction and speed as well as for wake effects, vertical wind shear, mean wind flow angle, etc.

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[36] The right hand side of Equation (38) represents an approximation of the 90 % quantile.

For the fatigue loading, a comparison of damage equivalent moments and damage equivalent load of the load duration distribution of the driving torque is sufficient for verification of components. For ultimate loading a comparison of contemporaneous loads is not required.

Turbulence structure shall be based on site-specific values. Where there are no site data for the components of turbulence and the terrain is complex, values for the ratios of the components assigned for each complexity category in 11.2 may be used. As an alternative, the longitudinal turbulence intensity may be increased by the C_{CT} factor.

In the case of wake effects, it shall be verified that structural integrity is not compromised. This may be performed using a wake model, for example see Annex E, with the turbulence model adjusted to the site-specific parameters.

Since for fatigue load calculations, I_{eff} as defined in Annex E depends on the Wöhler curve exponent m of the material of the considered component, the loads on structural components with other material properties shall either be recalculated or assessed with the appropriate value of m.

Fatigue load calculations shall be performed, if one of the criteria in 11.9.2 fails.

Ultimate limit state analyses shall be performed if one of the criteria in 11.9.3 fails. As a minimum, the following ultimate design load cases shall be assessed: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. If the design load cases for the standard classes are adequate, no further evaluations need to be performed.

Annex B provides definitions of the aforementioned ultimate and fatigue load cases for site-specific conditions. If relevant, other load cases in design situations 1), 6), and 7) in Table B.1 should be considered. Design situations 2), 3), 4), 5), and 8) in Table B.1 only need to be considered when the control system behaviour and transport, assembly, maintenance and repair procedures are site-dependent.

12 Assembly, installation and erection

12.1 General

The manufacturer of a wind turbine shall provide an installation manual clearly describing installation requirements for the wind turbine structure and equipment. The installation of a wind turbine shall be performed by personnel trained or instructed in these activities.

The site of a wind turbine facility shall be prepared, maintained, operated and managed so that work can be performed in a safe and efficient manner. This should include procedures to prevent unauthorized access where appropriate. The operator should identify and eliminate existing and potential hazards.

Checklists of planned activities shall be prepared, and logs of completed work and results of that work should be kept.

When appropriate, installation personnel shall use approved eye, foot, hearing, and head protection. All personnel climbing towers, or working above ground or water level, should be trained in such work and shall use approved safety harnesses, safety climbing aids or other safety devices. When appropriate, a buoyancy aid should be used around water.

All equipment shall be kept in good repair and be suitable for the task for which it is intended. Cranes, hoists and lifting equipment, including all slings, hooks and other apparatus, shall be adequate for safe lifting.

Particular consideration should be given to installation of the wind turbine under unusual conditions, such as hail, lightning, high winds, earthquake, icing.

In the case of a tower standing without a nacelle, appropriate means shall be taken to avoid critical wind speeds for vortex-generated transverse vibrations unless the appropriate fatigue design load case has been analysed, or the resulting loads shall be included in the fatigue analysis. The critical wind speeds and precaution measures shall be included in the installation manual.

12.2 Planning

The assembly, erection and installation of wind turbine and associated equipment shall be planned in order that the work is carried out safely and in accordance with local and national regulations. In addition to procedures for quality assurance, the planning shall include, where appropriate, consideration of the following:

- rules for safe execution of excavation work;
- detailed drawings and specifications of the work and inspection plan;
- rules for the proper handling of embedded items, such as foundations, bolts, anchors and reinforcement steel;
- rules for concrete composition, delivery, sampling, pouring, finishing and placement of conduits;
- safety rules for blasting;
- procedures for installation of towers and other anchors.

12.3 Installation conditions

During the installation of a wind turbine, the site shall be maintained in such a state that it does not present safety risks.

12.4 Site access

Access to a site shall be safe and the following shall be taken into account:

- barriers and routes of travel;
- traffic;
- road surface;
- road width;
- clearance;
- access weight bearing capacity;
- movement of equipment at the site.

12.5 Environmental conditions

During installation, environmental limits specified by the manufacturer shall be observed. Items such as the following should be considered:

- wind speed;
- snow and ice;
- ambient temperature;
- blowing sand;
- lightning;
- visibility;

- rain.

12.6 Documentation

The manufacturer of a wind turbine shall provide drawings, specifications and instructions for assembly procedures, installation and erection of the wind turbine. The manufacturer shall provide details of all loads, weights, lifting points and special tools and procedures necessary for the handling and installation of the wind turbine.

12.7 Receiving, handling and storage

Handling and transport of wind turbine generator equipment during installation shall be performed with equipment confirmed to be suitable to the task and in accordance with the manufacturer's recommended practice.

Wind turbines are often sited on hilly terrain. Therefore, heavy equipment shall be set down in such a manner that it cannot shift. A suitably-sized, level lay-down area is preferred for all handling and assembly operations. Where this cannot be provided, all heavy equipment shall be securely blocked in a stable position.

Where there is risk of movement caused by the wind with risk of consequent damage, blades, nacelles, other aerodynamic parts and light crates shall be secured with ropes and stakes, or ground anchors.

12.8 Foundation/anchor systems

Where specified by the manufacturer for safe installation or assembly, special tools, jigs and fixtures and other apparatus shall be used.

12.9 Assembly of wind turbine

A wind turbine shall be assembled according to the manufacturer's instructions. Inspection shall be carried out to confirm proper lubrication and pre-service conditioning of all components.

12.10 Erection of wind turbine

A wind turbine shall be erected by personnel trained and instructed in proper and safe erection practices.

No part of a wind turbine electrical system shall be energized during erection unless it is necessary for the erection process. In this case, the energization of such equipment shall be carried out in accordance with a written procedure to be provided by the wind turbine supplier.

All elements where motion (rotation or translation) may result in a potential hazard shall be secured from unintentional motion throughout the erection process.

12.11 Fasteners and attachments

Threaded fasteners and other attachment devices shall be installed according to the wind turbine manufacturer's recommended torque and/or other instructions. Fasteners identified as critical shall be checked and procedures for confirming installation torque and other requirements shall be obtained and used.

In particular, inspection shall be carried out to confirm the following:

- proper assembly and connection of guys, cables, turn buckles, gin poles and other apparatus and devices;
- proper attachment of lifting devices required for safe erection.

12.12 Cranes, hoists and lifting equipment

Cranes, hoists and lifting equipment, including all hoisting slings, hooks and other apparatus required for safe erection, shall be adequate for safe lifting and final placement of the loads. Manufacturer's instructions and documentation with respect to erection and handling should provide information on expected loads and safe lifting points for components and/or assemblies. All hoisting equipment, slings and hooks shall be tested and certified for safe load.

13 Commissioning, operation and maintenance

13.1 General

The commissioning, operation, inspection, and maintenance procedures shall be specified in the wind turbine manual with due consideration of the safety of personnel.

The design shall incorporate provisions for safe access for inspection and maintenance of all components.

The requirements of Clause 10 also cover electrical measurement equipment temporarily installed in the wind turbine for the purpose of measurements.

When appropriate, operation and maintenance personnel shall use approved eye, foot, hearing and head protection. All personnel climbing towers, or working above ground or water level, shall be trained in such work and shall use approved safety belt, safety climbing aids or other safety devices. When appropriate, a buoyancy aid should be used around water.

13.2 Design requirements for safe operation, inspection and maintenance

The normal operation of a wind turbine by the operating personnel shall be possible at ground level. A tagged, local, manual override on the automatic/remote control system shall be provided.

External events detected as faults but not critical for the future safety of a wind turbine, such as loss and reinstatement of the electrical load, may allow automatic return to normal operation after completion of the shutdown cycle.

Guards designed to protect personnel from accidental contact with moving components shall be fixed, unless frequent access is foreseen where they may be movable.

Guards shall

a) be of robust construction,
b) not be easy to by-pass, and
c) where possible, enable essential maintenance work to be carried out without their dismantling.

Provisions shall be made in the design for use of diagnostic fault-finding equipment.

In order to ensure the safety of inspection and maintenance personnel, the design shall incorporate

- safe access paths and working places for inspection and routine maintenance,
- adequate means to protect personnel from accidental contact with rotating components or moving parts,
- provision for securing lifelines and safety harnesses or other approved protection devices when climbing or working above ground level,

- provisions for blocking rotation of the rotor and yawing mechanism or other mechanical motion, such as blade pitching, during servicing according to wind conditions and design situations specified in DLC 8.1, as well as provisions for safe unblocking,
- warning signs for live conductors,
- suitable devices for the discharge of accumulated electricity,
- suitable fire protection for personnel, and
- an alternative escape route from the nacelle.

Maintenance procedures shall require safety provisions for personnel entering any enclosed working space, such as hub or blade interior, that ensure any dangerous situation will be known by standby personnel to immediately initiate rescue procedures if necessary.

13.3 Instructions concerning commissioning

13.3.1 General

The manufacturer shall provide instructions for commissioning.

13.3.2 Energization

The manufacturer's instructions shall include a procedure for initial energization of the wind turbine electrical system.

13.3.3 Commissioning tests

The manufacturer's instructions shall include the procedures for wind turbine testing after installation, to confirm proper, safe and functional operation of all devices, controls and apparatus. These shall include, but not be limited to,

- safe start-up,
- safe shutdown,
- safe emergency stop,
- safe shutdown from overspeed or representative simulation thereof, and
- test of protection functions, see Clause 8.

13.3.4 Records

The manufacturer's instructions shall include the instruction that proper records shall be kept describing testing, commissioning, control parameters and results.

13.3.5 Post commissioning activities

At the completion of installation, and following operation for the manufacturer recommended running-in period, the specific actions that may be required by the manufacturer shall be completed.

These can include, but are not limited to, preloading of fasteners, changing of lubrication fluids, checking other components for proper setting and operation and proper adjustment of control parameters.

The wind turbine site should be refurbished to remove hazards and prevent erosion.

13.4 Operator's instruction manual

13.4.1 General

An operator's instruction manual shall be supplied by the wind turbine manufacturer and augmented with information on special local conditions at the time of commissioning as appropriate. The manual shall include, but not be limited to

- any requirements that the operation shall be performed by personnel suitably trained or instructed in this activity,
- safe operating limits and system descriptions,
- start-up and shutdown procedures,
- an alarms action list,
- emergency procedures plan, and
- stated requirements that
  - when appropriate, approved eye, feet, hearing and head protection shall be used,
  - when appropriate, all personnel climbing towers, or working above ground or water level, shall be trained in such work and shall use approved safety harness, safety climbing aids or other safety devices,
  - when appropriate, a buoyancy aid should be used around water, and
  - the manual shall be available to the operation and maintenance personnel in a language that can be read and understood by the operator.

13.4.2 Instructions for operations and maintenance records

The manual shall state that operations and maintenance records shall be kept and should include the following:

- wind turbine identification;
- energy produced;
- operating hours;
- shutdown hours;
- date and time of fault reported;
- date and time of service or repair;
- nature of fault or service;
- action taken;
- parts replaced.

13.4.3 Instructions for unscheduled automatic shutdown

The manual shall require that following any unscheduled automatic shutdown caused by a fault or malfunction, unless specified otherwise in the operations manual or instructions, the operator shall investigate the cause before a wind turbine is restarted. All unscheduled automatic shutdowns should be recorded.

13.4.4 Instructions for diminished reliability

The manual shall require that action shall be taken to eliminate the root cause of any indication or warning of abnormality or diminished reliability.

13.4.5 Work procedures plan

The manual shall require that the wind turbine shall be operated according to safe working procedures, taking account of the following:

- electrical systems operation;
- co-ordination of operation and maintenance;
- utility clearance procedures;
- tower climbing procedures;
- equipment handling procedures;
- activity during bad weather;
- communications procedures and emergency plans.

13.4.6 Emergency procedures plan

Probable emergency situations shall be identified in the operations manual and the required actions of the operating personnel prescribed.

The manual shall require that where there is a fire or apparent risk of structural damage to the wind turbine or its components, no one should approach the wind turbine unless the risk is specifically evaluated.

In preparing the emergency procedures plan, it shall be taken into account that the risk for structural damage may be increased by situations such as the following:

- overspeeding;
- icing conditions;
- lightning storms;
- earthquakes;
- broken or loose guy-wires;
- brake failure;
- rotor imbalance;
- loose fasteners;
- lubrication defects;
- sandstorms;
- fire, flooding;
- other component failures.

13.5 Maintenance manual

Each wind turbine model shall have a maintenance manual, which at a minimum consists of the maintenance requirements and emergency procedures specified by the wind turbine manufacturer. The manual shall also provide for unscheduled maintenance.

The maintenance manual shall identify parts subject to wear and indicate criteria for replacement.

Subjects which should also be covered in the manual include the following:

- any requirement that inspection and maintenance shall be carried out by personnel suitably trained or instructed in this activity, at the intervals specified in and in compliance with the instructions in the wind turbine maintenance manual;
- description of the subsystems of the wind turbine and their operation;
- lubrication schedule prescribing frequency of lubrication and types of lubricants or any other special fluids;
- recommissioning procedure;

- maintenance inspection periods and procedures;
- procedures for functional check of protection subsystems;
- complete wiring and interconnection diagram;
- guy cable inspection and re-tensioning schedules and bolt inspection and preloading schedules, including tension and torque loadings;
- diagnostic procedures and trouble-shooting guide;
- recommended spare parts list;
- set of field assembly and installation drawings;
- tooling list.

14 Cold climate

14.1 General

Cold climate (CC) weather conditions are defined as icing climate (IC) and/or low temperature climate (LTC). LTC is for temperatures below the normal environmental conditions (6.4.2). IC is defined as meteorological icing leading to rime and/or glaze ice accretion on the wind turbine. For ice type definitions, see ISO 12494. For simplicity, cold climate conditions will be treated here as IC and LTC conditions unless stated otherwise.

The impact of cold climate on the structural integrity or safety systems of the wind turbine shall be assessed.

14.2 Low temperature and icing climate

As a minimum, the following effects on a wind turbine from a LTC shall be considered:

a) component materials;
b) air density;
c) start-up procedures;
d) viscosity of oils and lubricants.

As a minimum, the following effects from an IC shall be considered:

- reduced turbine performance due to iced blades;
- inhomogeneous ice distribution on wind turbine blades;
- ice shedding from blades;
- icing effects on wind measurements;
- increased sound levels;
- prolonged standstills.

14.3 External conditions for cold climate

14.3.1 General

The external conditions for cold climate deviate from normal climate external conditions (6.4.2) in terms of ambient temperature, air density, and icing.

14.3.2 Wind turbine class for cold climate

The external conditions to be considered for design are dependent on the intended site or site type for a wind turbine installation. As a consequence of LTC effects in cold climate conditions, minimum ambient temperature conditions shall be assumed which are intended to represent many different sites and do not give a precise representation of any specific site. Wind turbine class for cold climate is defined in terms of ambient temperature as follows:

$\theta_{min,operation}$ = –30 °C	Minimum allowable ambient temperature for wind turbine operation (instantaneous value)
$\theta_{1year,min}$ = –40 °C	Minimum ambient temperature to be expected in hourly average (return period 1 year) = minimum dimensioning temperature
θ_{mean} = –5 °C	Yearly mean ambient temperature

Other environmental conditions are according to normal environmental conditions (6.4.2).

14.4 Structural design

For LTC, the air density of 1,225 kg/m^3 shall be used for structural design in order to allow the use of wind turbines designed according to standard wind turbine classes.

The effect of the actual air density at the site[37], as influenced by temperature and altitude, shall be considered during the site suitability analysis.

14.5 Design situations and load cases

14.5.1 General

Cold climate conditions result in specific design situations for a wind turbine. In IC, the effect of ice accretion on blade aerodynamic coefficients and on the blade mass distribution needs to be considered. In LTC, low ambient temperatures (14.3.2) resulting in higher air densities than in normal climate conditions (6.4.2), selection of suitable materials (14.5.3) and the resulting consequences shall be taken into account in turbine design.

Ice accretion on rotor blades often occurs for temperatures higher than minimum ambient temperatures (14.3.2).

In cold climate conditions, altered turbine performance resulting to a shift in turbine operational point shall be assessed. As a minimum, the following shall be considered:

- unfavourable turbine controller behaviour, for example, due to incorrect generator torque and pitch setpoints caused by different aerodynamic performances of the blades;
- increase in start-stop cycles;
- change in stall behaviour of turbine blades;
- eigenfrequency changes due to additional blade ice mass.

Higher loading may be a consequence of aforementioned effects. Higher loading during icing may also be a consequence of imbalances resulting from altered rotor aerodynamics and additional ice mass. Further guidance can be found in Annex L.

14.5.2 Load calculations

For cold climate conditions, the turbine controller behaviour and loads are primarily affected by IC effects resulting from ice accretion on the rotor blades and LTC effects resulting from increased air density. Further guidance can be found in Annex L.

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37 An air density of 1,3 kg/m^3 may be more representative for sea-level sites.

14.5.3 Selection of suitable materials

For LTC effects in cold climate, all load calculation shall be matched to the modified temperature range to take material properties into account. One air density according to 14.4 may be used for all cold climate temperature ranges.

Ultimate strength verifications for components[38] that are exposed to the ambient temperature shall be considered for $\theta_{\mathrm{min,operation}}$ except for loads derived from DLC 7.1, 8.1 and 8.2 to be considered with $\theta_{\mathrm{1year,min}}$. Alternatively, the minimum temperature for DLC 8.1 may also be defined by the manufacturer. Fatigue strength verifications shall be considered for θ_{mean}.

14.6 Control systems

In addition to normal climate requirements for control systems stated in Clause 8, the components of the control system shall be designed under consideration of a shift in turbine operational point due to icing of the turbine, the specified ambient temperatures during operation and standstill as defined in 14.3.2. Cold climate conditions are especially to be considered in the following situations:

- when ensuring safety of the turbine controller behaviour during cold climate conditions;
- when a start procedure shall be implemented to set the wind turbine safely back on-line after an event leading to the turbine being cooled off to minimum ambient operation temperature $\theta_{\mathrm{min,operation}}$ or below (due to grid failure, maintenance, or other);
- when the effect on wind turbine dynamics of different air density values shall be taken into account;
- in case of safety critical energy storages, for example in the hub;
- in case of ice/low temperature effects on sensors and data processing.

If operation of the iced turbine is not considered in the load assumptions, measures have to be taken to prevent operation of the iced turbine. These measures need to be redundant; a single failure shall not lead to unintended operation of an iced turbine.

14.7 Mechanical systems

In addition to normal climate requirements for mechanical systems stated in Clause 9, the mechanical systems of the wind turbine shall be designed under consideration of the ambient temperatures during operation and standstill as defined in 14.3.2.

It shall be assured that the oil temperature in the gearbox has reached a temperature to avoid damage before power can be transmitted. For a cold start procedure, see 14.6.

14.8 Electrical systems

In addition to normal climate requirements for electrical systems stated in Clause 10, the electrical installation of the wind turbine shall be designed under consideration of the ambient temperatures during operation and standstill as defined in 14.3.2.

Cold climate conditions are especially to be considered in the following areas:

- materials in the electrical components;
- grid return at minimum standstill ambient temperature $\theta_{\mathrm{1year,min}}$, as defined in 14.3.2;
- start procedure as defined in 14.6.

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38 Minimum temperature and corresponding load cases for components that are not exposed to the ambient conditions shall be defined by the manufacturer.

Annex A
(normative)

Design parameters for external conditions

A.1 Design parameters for describing wind turbine class S

A.1.1 General

For wind turbines designed to site-specific or special conditions, i.e. class S turbines, the following information shall be given in the design documentation for all conditions that differ from conditions for the wind turbine classes as defined in 6.2. Remaining conditions may be stated by reference to the appropriate wind turbine class.

A.1.2 Machine parameters

Rated power	[kW]
Hub height operating wind speed range $V_{\text{in}} - V_{\text{out}}$	[m/s]
Design life time	[years]

A.1.3 Wind conditions

General:

Air density	[kg/m^3]
Hub height extreme wind speeds V_{e1} and V_{e50}	[m/s]

Turbulence model and parameters

Turbulence intensity mean and standard deviation as a function of mean wind speed

Extreme gust model and parameters for 1- and 50-year return periods

Extreme direction change model and parameters for 1- and 50-year return periods

Extreme coherent gust model and parameters

Extreme coherent gust with direction change model and parameters

Extreme wind shear model and parameters

Aggregated or sector-wise (30° or less):

Annual average wind speed	[m/s]
Flow inclination	[°]

Wind speed distribution (Weibull, Rayleigh, measured, other)

Wind profile model and parameters

Sector turbulence intensity mean and standard deviation as a function of mean wind speed

Wake effect model and parameters (effective turbulence intensity or dynamic wake meandering)

A.1.4 Electrical network conditions

Normal supply voltage and range	[V]
Normal supply frequency and range	[Hz]
Voltage imbalance	[V]

Method of neutral grounding

Method of ground fault detection/protection

Annual number and maximum duration of network outages

Auto-reclosing cycles

Required reactive compensation schedule

Fault currents and duration

Phase-phase and phase-ground short-circuit impedance at the wind turbine terminals

Background harmonic voltage distortion of the network

Presence of power line carrier signalling if any and frequency of same

Fault profiles for ride-through requirements

Power factor control requirements

Ramp rate requirements

Other grid compatibility requirements

A.1.5 Other environmental conditions (where taken into account)

Normal and extreme temperature ranges [°C]
Relative humidity of the air [%]
Solar radiation [W/m^2]
Rain, hail and snow
Icing model and parameters
Chemically active substances
Mechanically active particles
Lightning, including description of lightning protection system
Salinity [g/m^3]

Foundation:

Foundation stiffness and damping

Earthquake model and parameters:

A.2 Additional design parameters for describing cold climate wind turbine class S (CC-S)

See Table A.1.

Table A.1 – Design parameters for describing cold climate wind turbine class S (CC-S)

External conditions		
Symbol	**Unit**	**Description**
$\theta_{min,operation}$	[K]	Minimum allowable ambient temperature for wind turbine operation
$\theta_{1year,min}$	[K]	Minimum ambient temperature to be expected in hourly average
$\rho(\theta_{min,operation})$	[kg/m^3]	Air density for cold climate design load cases associated with the minimum allowable ambient temperature for wind turbine operation $\theta_{min,operation}$
$\rho(\theta_{1year,min})$	[kg/m^3]	Air density for cold climate design load cases associated with the minimum ambient temperature to be expected in hourly average $\theta_{1year,min}$

The air densities used for load calculation and in the determination of the power curve should be calculated by applying the ideal gas law[39].

The following equation applies:

$$\rho(\theta) = \frac{p}{R_0 \times \theta} \tag{A.1}$$

with

p = 101 325 N/m^2 (at sea level);

R_0 = 287 J/(kg·K);

$\theta = \theta_{1\text{year,min}}$ + 35 K to calculate $\rho(\theta_{1\text{year,min}})$;

$\theta = \theta_{\text{min,operation}}$ + 25 K to calculate $\rho(\theta_{\text{min,operation}})$.

Corrections for different altitudes can be applied.

The air density of 1,225 kg/m^3 can be used for structural design in order to allow the use of wind turbines designed according to standard wind turbine classes

The effect of the actual air density at the site, as influenced by temperature and altitude, shall be considered during the site suitability analysis

39 The temperature value $\theta_{1\text{year,min}}$ can be set to $\theta_{1\text{year,min}}$ + 35 K and $\theta_{\text{min,operation}}$ can be set to $\theta_{\text{min,operation}}$ + 25 K for determining the air density accordingly. This increase by +35 K and +25 K, respectively, is equivalent to definitions of the normal climate conditions in 6.4.2 and 6.4.3.2. The standard air density for normal climate conditions is 1,225 kg/m^3 referring to +15 °C. The ambient temperature range for normal climate is –10 °C to +40 °C, being +15 °C ± 25 K. The extreme temperature range for normal climate is –20 °C to +50 °C, being +15 °C ± 35 K.

Annex B
(informative)

Design load cases for special class S wind turbine design or site suitability assessment

B.1 General

The design load cases for special class S wind turbine design or site suitability assessment are determined from the combination of operational modes or design situations with the applicable class S external conditions with design parameters as specified in Annex A.

In design situation power production, the analysis for NTM_S and ETM_S may be performed for each sector with wind conditions determined for each sector or for all sectors using aggregated wind conditions. For other design situations, the analysis is performed for all sectors using aggregated wind conditions. The aggregation of wind conditions shall be carried out such that proper fatigue and extreme loads are maintained, or the design parameters shall be chosen conservatively. Consideration should be given to the potential variation in wind shear, density and other parameters that can affect fatigue loading on the wind turbine.

Wake effects, earthquake loading and icing shall be considered in load cases as specified for other conditions, if appropriate.

When a wind speed range is indicated in Table B.1, wind speeds leading to the most adverse condition for wind turbine design shall be considered. The range of wind speeds may be represented by a set of discrete values, in which case the resolution shall be sufficient to assure accuracy of the calculation.[40] In the definition of the design load cases, reference is made to the wind conditions described in Clause 6.

As stated in 11.10, for site suitability assessment, the following ultimate design load cases shall be assessed as minimum: DLC 1.1, DLC 1.3, DLC 6.1, and DLC 6.2. If the design load cases for the standard classes are adequate, no further evaluations need to be performed. If relevant, other load cases in design situations 1), 6), and 7) in Table B.1 should be considered. Design situations 2), 3), 4), 5), and 8) in Table B.1 only need to be considered when the control system behaviour and transport, assembly, maintenance and repair procedures are site-dependent.

B.2 Power production (DLC 1.1 to 1.9)

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

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

Design load cases (DLC) 1.1 and 1.2 embody the requirements for loads resulting from site-specific atmospheric turbulence that occurs during normal operation of a wind turbine throughout its lifetime (NTM). For DLC 1.2, wake effects are additionally considered – see Annex E for guidance. DLC 1.3 embodies the requirements for ultimate loading resulting from

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[40] In general, a resolution of 2 m/s is considered sufficient.

extreme site-specific turbulence conditions. DLC 1.4 and 1.5 specify transient cases that have been selected as potentially critical events in the life of a wind turbine.

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

If the extreme design values of the blade root moments derived from DLC 1.1 are not exceeded by the extreme design values derived for DLC 1.3, the factor c in Equation (20) for the extreme turbulence model used in DLC 1.3 may be increased until the extreme design values of the blade root moments computed in DLC 1.3 are equal to or exceed the relevant extremes. The characteristic values of the loads relevant for other turbine components may be determined from this analysis based on DLC 1.3 with the increased extreme turbulence. As an alternative to this analysis, the appropriate characteristic values of all load components relevant for each specific turbine component determined from the simulation may be directly extrapolated.

Table B.1 – Design load cases

Design situation	DLC	Wind condition[41]	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM_s $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM_s $V_{in} < V_{hub} < V_{out}$	Wake effects	F	*
	1.3	ETM_s $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD_s $V_{hub} = V_r$ – 2 m/s, V_r, V_r +2 m/s		U	N
	1.5	EWS_s $V_{in} < V_{hub} < V_{out}$		U	N
	1.6	ETM_s $V_{hub} = V_r \pm 2$ m/s and V_{out}	Wake effects	U	N
	1.7	NTM_s $V_{in} < V_{hub} < V_{out}$	Ice formation Wake effects	U	N
	1.8	NTM_s $V_{hub} = V_r$	Earthquake plus grid loss	U	N
2) Power production plus occurrence of fault	2.1	NTM_s $V_{in} < V_{hub} < V_{out}$	Normal control system fault or loss of electrical network or primary layer control function fault (see 7.4.3)	U	N
	2.2	NTM_s $V_{in} < V_{hub} < V_{out}$	Abnormal control system fault or secondary layer protection function related fault (see 7.4.3)	U	A
	2.3	EOG_s $V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM_s $V_{in} < V_{hub} < V_{out}$	Control system fault, electrical fault or loss of electrical network	F	*
	2.5	NWP $V_{in} < V_{hub} < V_{out}$	Low voltage ride through	U	N

41 For Class S design, the wind conditions (gust amplitudes, turbulence intensity, etc.) are defined by the designer, as stated in Annex A.

Design situation	DLC	Wind condition[42]		Other conditions	Type of analysis	Partial safety factors
3) Start-up	3.1	NWP_s	$V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG_s	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC_s	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
4) Normal shutdown	4.1	NWP_s	$V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG_s	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency stop	5.1	NTM_s	$V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM_s	50-year return period		U	N
	6.2	EWM_s	50-year return period	Loss of electrical network connection	U	A
	6.3	EWM_s	1-year return period	Extreme yaw misalignment	U	N
	6.4	NTM_s	$V_{hub} < 0{,}7\ V_{ref}$		F	*
	6.4	NTM_s	$V_{hub} < 0{,}7\ V_{ref}$	Ice formation	U	N
	6.6	NTM_s	$V_{hub} < 0{,}7\ V_{ref}$	Extreme temperature range	U	N
	6.7	NTM_s	$V_{hub} < 0{,}7\ V_{ref}$	Earthquake plus grid loss	U	N
7) Parked and fault conditions	7.1	EWM_s	1-year return period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM_s	V_{maint} to be stated by the manufacturer		U	N
	8.2	EWM_s	1-year return period		U	A

The following abbreviations are used:

DLC Design load case

ECD_s Site-specific extreme coherent gust with direction change. When site-specific values are not available, it may be assumed to be identical to the ECD defined in 6.3.3.6.

EDC_s Site-specific extreme direction change. When site-specific values are not available, Equations (21) and (22) in 6.3.3.5 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1.

EOG_s Site-specific extreme operating gust. When site-specific values are not available, Equations (18) and (19) in 6.3.3.3 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1.

EWM_s Site-specific extreme wind speed. When site-specific values are not available, Equations (13) through (17) in 6.3.3.2 may be used, with site-specific extreme wind speed with 50 years return period in place of V_{ref}.

EWS_s	Site-specific extreme wind shear. When site-specific values are not available, Equations (27) and (28) in 6.3.3.7 may be used, using site-specific representative ambient turbulence standard deviation $\hat{\sigma}_c$ in place of σ_1 and site-specific wind shear exponent in place of α = 0,2.
NTM_s	Site-specific representative ambient turbulence intensity, as a function of hub height wind speed, $\hat{\sigma}_c / V_{hub}$ (see 6.3.2.3).
ETM_s	Site-specific extreme ambient turbulence intensity as a function of hub height wind speed $\hat{\sigma}_{1,ETM} / V_{hub}$ (see 6.3.2.3 and footnote 25).
NWP_s	Site-specific wind profile model. When site-specific wind speed profile is not available, Equation (9) in 6.3.2.2 may be used with the site-specific wind shear exponent at hub height in place of α = 0,2.
V_r ± 2 m/s	Sensitivity to all wind speeds in the range shall be analysed.
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
*	Partial safety for fatigue (see 7.6.3)

In DLC 1.6, the assessment of loads resulting from the ambient site-specific ETM_s model in combination with an inter-turbine wake condition shall be assessed. The inter-turbine spacing S shall cover the worst loading conditions between a minimum spacing S_{min} (to be defined by the manufacturer) and S = 20D, where D is the turbine rotor diameter.

Annex E provides guidance on the use of appropriate wake models for DLC 1.6. If an added wake turbulence model is used, the maximum centre-line wake turbulence intensity shall be applied. The use of a meandering wake model (e.g. DWM) shall consider at least five mean wake offset angles θ_{wake} = 0°; ± $\theta_{hub\text{-}tip}$; ± $\theta_{hub\text{-}tip}$ × 1,5, where $\theta_{hub\text{-}tip} = \sin^{-1}\left(\frac{D}{2S}\right)$.

The number of transient events for DLC 2.4, DLC 3.1 and DLC 4.2 may be site-dependent, and that should be considered in the analysis of site-specific loads. If there is no information available, the number of events suggested in 7.4.3, 7.4.4 and 7.4.5 (footnotes 7, 9 and 10) may be used.

Annex C
(informative)

Turbulence models

C.1 General

Two turbulence models are given here for design load calculations. The turbulent velocity fluctuations are assumed to be a stationary, random vector field whose components have zero-mean Gaussian statistics. The first model is recommended.

1) Mann uniform shear model.
2) Kaimal spectral and exponential coherence model.

Parameters for the models have been selected to satisfy the general turbulence requirements given in 6.3.

C.2 Mann [3] uniform shear turbulence model

The description of this model differs somewhat from the previous models in that a three-dimensional velocity spectral tensor is defined. The model assumes that the isotropic von Karman [2] energy spectrum is rapidly distorted by a uniform, mean velocity shear. The resulting spectral tensor components are given by

$$\Phi_{11}(k_1,k_2,k_3) = \frac{E(k_0)}{4\pi k_0^4}\left(k_0^2 - k_1^2 - 2k_1(k_3+\beta(k)k_1)\zeta_1 + (k_1^2+k_2^2)\zeta_1^2\right) \quad \text{(C.1)}$$

$$\Phi_{22}(k_1,k_2,k_3) = \frac{E(k_0)}{4\pi k_0^4}\left(k_0^2 - k_2^2 - 2k_2(k_3+\beta(k)k_1)\zeta_2 + (k_1^2+k_2^2)\zeta_2^2\right) \quad \text{(C.2)}$$

$$\Phi_{33}(k_1,k_2,k_3) = \frac{E(k_0)}{4\pi k^4}\left(k_1^2+k_2^2\right) \quad \text{(C.3)}$$

$$\Phi_{12}(k_1,k_2,k_3) = \frac{E(k_0)}{4\pi k_0^4}\left(-k_1k_2 - k_1(k_3+\beta(k)k_1)\zeta_2 - k_2(k_3+\beta(k)k_1)\zeta_1 + (k_1^2+k_2^2)\zeta_1\zeta_2\right) \quad \text{(C.4)}$$

$$\Phi_{13}(k_1,k_2,k_3) = \frac{E(k_0)}{4\pi k_0^2 k^2}\left(-k_1(k_3+\beta(k)k_1) + (k_1^2+k_2^2)\zeta_1\right) \quad \text{(C.5)}$$

$$\Phi_{23}(k_1,k_2,k_3) = \frac{E(k_0)}{4\pi k_0^2 k^2}\left(-k_2(k_3+\beta(k)k_1) + (k_1^2+k_2^2)\zeta_2\right) \quad \text{(C.6)}$$

where

$$\Phi_{ij}\left(k_1,k_2,k_3\right) = \Phi_{ji}^{*}\left(k_1,k_2,k_3\right) = \frac{1}{8\pi^3}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} R_{ij}\left(\delta_1,\delta_2,\delta_3\right)e^{-\iota k_1\delta_1}e^{-\iota k_2\delta_2}e^{-\iota k_3\delta_3}\,d\delta_1 d\delta_2 d\delta_3 \ ;$$

$$R_{ij}\left(\delta_1,\delta_2,\delta_3\right)=\frac{1}{\sigma_{\text{iso}}{}^2}E\left\langle u_i\left(x_1,x_2,x_3\right)u_j\left(x_1+\ell\delta_1,x_2+\ell\delta_2,x_3+\ell\delta_3\right)\right\rangle$$

= a non-dimensional correlation tensor;

u_1,u_2,u_3 = the longitudinal, lateral, and upward velocity components, respectively;

$\delta_1,\delta_2,\delta_3$ = the non-dimensional spatial separation vector components;

k_1,k_2,k_3 = the non-dimensional spatial wave numbers for the three component directions;

$k=\sqrt{k_1{}^2+k_2{}^2+k_3{}^2}$ = the magnitude of the non-dimensional wave number vector;

$k_0=\sqrt{k^2+2\beta\left(k\right)k_1k_3+\left(\beta\left(k\right)k_1\right)^2}$ = the magnitude before shear distortion;

$$\zeta_1=C_1-\frac{k_2}{k_1}C_2,\ \zeta_2=\frac{k_2}{k_1}C_1+C_2;$$

$$C_1=\frac{\beta\left(k\right)k_1{}^2\left(k_1{}^2+k_2{}^2-k_3\left(k_3+\beta\left(k\right)k_1\right)\right)}{k^2\left(k_1{}^2+k_2{}^2\right)};$$

$$C_2=\frac{k_2k_0{}^2}{\left(k_1{}^2+k_2{}^2\right)^{3/2}}\arctan\left(\frac{\beta\left(k\right)k_1\sqrt{k_1{}^2+k_2{}^2}}{k_0{}^2-\left(k_3+\beta\left(k\right)k_1\right)k_1\beta\left(k\right)}\right);$$

$E(k)=\dfrac{1{,}453\,k^4}{\left(1+k^2\right)^{17/6}}$ = the non-dimensional, von Karman isotropic energy spectrum;

$$\beta\left(k\right)=\frac{\gamma}{k^{\frac{2}{3}}\sqrt{{}_2F_1\left(\frac{1}{3},\frac{17}{6},\frac{4}{3},-k^{-2}\right)}}$$

= a non-dimensional distortion time inversely proportional to $\sqrt{k^2\int_k^{\infty}E\left(p\right)dp}$;

${}_2F_1$ = Hypergeometric function;

$\sigma_{\text{iso}}^2,\ell$ = the unsheared, isotropic variance and scale parameters respectively;

γ = a non-dimensional shear distortion parameter.

While this model is more complex than the von Karman isotropic model, it contains only one additional parameter, namely the shear distortion parameter, γ. When this parameter is zero, the isotropic model is recovered. As this parameter is increased, the longitudinal and lateral velocity component variances increase while the upward velocity component variance decreases. The resulting turbulent eddy structure is stretched in the longitudinal direction and tilted relative to the 1-2 plane.

Assuming that the random velocity field generated by the model is convected past the turbine at the hub-height wind speed, the velocity component spectra observed at a point may be computed by integrating the spectral tensor components. In particular, the non-dimensional, one-sided spectra are given by

$$\frac{f\,S_i(f)}{\sigma_i^2}=\frac{\sigma_{\text{iso}}^2}{\sigma_i^2}\left(\frac{4\pi\ell f}{V_{\text{hub}}}\right)\Psi_{ii}\left(\frac{2\pi\ell f}{V_{\text{hub}}}\right) \qquad \text{(C.7)}$$

where

$$\Psi_{ij}\left(k_1\right)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Phi_{ij}\left(k_1,k_2,k_3\right)dk_2dk_3$$

= the one-dimensional, wave number autospectrum for $i=j$, or cross-spectrum for $i\neq j$, and

$\sigma_i^2=\sigma_{\text{iso}}^2\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\Phi_{ii}\left(k_1,k_2,k_3\right)dk_1dk_2dk_3$ = the component variance.

Similarly, for spatial separations normal to the longitudinal direction the coherence is given by

$$\text{Coh}_{ij}(f,\ell\delta_2,\ell\delta_3)=\frac{\left|\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Phi_{ij}\left(\frac{2\pi\ell f}{V_{\text{hub}}},k_2,k_3\right)\mathrm{e}^{-ik_2\delta_2}\,\mathrm{e}^{-ik_3\delta_3}dk_2dk_3\right|}{\sqrt{\Psi_{ii}\left(\frac{2\pi\ell f}{V_{\text{hub}}}\right)\Psi_{jj}\left(\frac{2\pi\ell f}{V_{\text{hub}}}\right)}} \tag{C.8}$$

Unfortunately, the resulting integrals do not have known analytical forms and shall be carried out numerically for a specific value of the parameter, γ. Mann [4] carried out such integrations and compared the results to the Kaimal spectral model. A least squares fit to the Kaimal model gave the shear parameter

$$\gamma=3{,}9 \tag{C.9}$$

with the resulting variance relations

$$\left.\begin{aligned}\sigma_1^2&=3{,}25\,\sigma_{\text{iso}}^2\\ \sigma_2^2&=1{,}65\,\sigma_{\text{iso}}^2\\ \sigma_3^2&=0{,}85\,\sigma_{\text{iso}}^2\end{aligned}\right\}\Rightarrow\left\{\begin{aligned}\frac{\sigma_2}{\sigma_1}&\approx0{,}7\\ \frac{\sigma_3}{\sigma_1}&\approx0{,}5\end{aligned}\right. . \tag{C.10}$$

Note the resulting lateral variance is slightly less than given in Table C.1. The scale parameter may be found by equating the asymptotic, inertial-sub-range longitudinal spectra. Thus,

$$S_1(f)\rightarrow0{,}475\sigma_{\text{iso}}^2\left(\frac{2\pi\ell}{V_{\text{hub}}}\right)^{-2/3}f^{-5/3}=0{,}05\,\sigma_1^2\left(\frac{\Lambda_1}{V_{\text{hub}}}\right)^{-2/3}f^{-5/3}\Rightarrow\ell\approx0{,}8\,\Lambda_1 \tag{C.11}$$

In summary, the three parameters required in the Mann model are given by

$$\begin{aligned}&\gamma=3{,}9\\ &\sigma_{\text{iso}}=0{,}55\,\sigma_1\\ &l=0{,}8\,\Lambda_1\end{aligned} \tag{C.12}$$

where σ_1 and Λ_1 are specified in 6.3.

For three dimensional turbulent velocity simulations, the velocity components are determined from a decomposition of the spectral tensor and an approximation by the discrete Fourier transform. Thus, the three-dimensional spatial domain is divided into equally spaced discrete points and the velocity vector at each point is given by

$$\begin{bmatrix} u_1(x,y,z) \\ u_2(x,y,z) \\ u_3(x,y,z) \end{bmatrix} = \sum_{k_1,k_2,k_3} e^{i\frac{xk_1+yk_2+zk_3}{\ell}} \begin{bmatrix} C(k_1,k_2,k_3) \end{bmatrix} \begin{bmatrix} n_1(k_1,k_2,k_3) \\ n_2(k_1,k_2,k_3) \\ n_3(k_1,k_2,k_3) \end{bmatrix} \quad \text{(C.13)}$$

where

$$\begin{bmatrix} C\left(k_1,k_2,k_3\right) \end{bmatrix} \approx \sigma_{\text{iso}} \sqrt{\frac{2\pi^2 \ell^3 E\left(k_0\right)}{N_1 N_2 N_3 \Delta^3 k_0{}^4}} \begin{bmatrix} k_2\zeta_1 & k_3 - k_1\zeta_1 + \beta k_1 & -k_2 \\ k_2\zeta_2 - k_3 - \beta k_1 & -k_1\zeta_2 & k_1 \\ \frac{k_0{}^2 k_2}{k^2} & -\frac{k_0{}^2 k_1}{k^2} & 0 \end{bmatrix}$$

u_1, u_2, u_3 = complex vector components whose real and imaginary parts are independent realizations of the turbulent velocity field;

n_1, n_2, n_3 = complex Gaussian random values that are independent for each different wave number and have real and imaginary parts with unit variance;

x, y, z = coordinates of the spatial grid points;

N_1, N_2, N_3 = the number of spatial grid points in the three directions;

Δ = the spatial grid resolution.

In this expression, the notation $\sum_{k_1,k_2,k_3}$ means the summation over all dimensionless wave numbers in the grid and may be accomplished using FFT techniques. In cases when the spatial domain is smaller than 8ℓ in any dimension, an adjustment is recommended for the spectral tensor factorization, $\left[C\left(k_1,k_2,k_3\right)\right]$. This procedure is detailed in Mann [4].

The Mann model parameters derived herein to represent the Mann sheared turbulence model are based on conforming to the external conditions defined in Clause 6 and whereby the resulting wind spectra are equivalent to the Kaimal spectra.

For site-specific analysis, the shear distortion (anisotropy) parameter γ, dissipation factor, $\alpha\epsilon^{2/3}$ and the length scale, l, may be determined based on high frequency site-specific measurements of the wind spectra $F_{\text{u}}(kl)$, $F_{\text{v}}(kl)$, $F_{\text{w}}(kl)$ and $F_{\text{uw}}(kl)$ at one fixed point. The Mann model turbulent wind field needs to be then generated based on the three model parameters derived from the measured spectra.

C.3 Kaimal [1][42] spectrum and exponential coherence model

The component power spectral densities are given in non-dimensional form by Equation (C.14):

42 Note that the turbulence component variance ratios in Table C.1 and the equation form for the upward velocity component differ somewhat from the original Kaimal spectral model. The longitudinal scale has been chosen to approximate the original Kaimal spectrum and, for the lateral and upward scales, to satisfy the spectral requirements in 6.3 for the asymptotic inertial subrange and the variance ratios given in Table C.1.

$$\frac{f\,S_k(f)}{\sigma_k^2} = \frac{4f\,L_k\,/\,V_{\text{hub}}}{\left(1+6f\ \ L_k\,/\,V_{\text{hub}}\right)^{5/3}} \tag{C.14}$$

where

- f is the frequency, in hertz;
- k is the index referring to the velocity component direction (i.e. 1 = longitudinal, 2 = lateral, and 3 = upward);
- S_k is the single-sided velocity component spectrum;
- σ_k is the velocity component standard deviation;
- L_k is the velocity component integral scale parameter;

and with

$$\sigma_k^2 = \int_0^\infty S_k\left(f\right)\,df \tag{C.15}$$

The turbulence spectral parameters are given in Table C.1.

Table C.1 – Turbulence spectral parameters for the Kaimal model

	Velocity component index, *k*		
	1	2	3
Standard deviation, σ_k	σ_1	0,8 σ_1	0,5 σ_1
Integral scale, L_k	8,1 Λ_1	2,7 Λ_1	0,66 Λ_1
σ_1 and Λ_1 are the standard deviation and scale parameters, respectively, of the turbulence as specified in 6.3.			

The following exponential coherence model may be used in conjunction with the Kaimal autospectrum to account for the spatial correlation structure of the longitudinal velocity component:

$$\text{Coh}(r,f) = \exp\left[-12\left(\left(f\,r\,/\,V_{\text{hub}}\right)^2 + \left(0{,}12\,r\,/\,L_{\text{c}}\right)^2\right)^{0{,}5}\right] \tag{C.16}$$

where

- Coh(r,f) is the coherence function defined by the complex magnitude of the cross-spectral density of the longitudinal wind velocity components at two spatially separated points divided by the autospectrum function;
- r is the magnitude of the projection of the separation vector between the two points on to a plane normal to the average wind direction;
- f is the frequency, in hertz;
- $L_{\text{c}} = 8{,}1\Lambda_1$ is the coherence scale parameter.

C.4 Reference documents

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Annex D
(informative)

Assessment of earthquake loading

D.1 General

There are two approaches to evaluate the seismic loading on wind turbine. One approach is the dynamic simulation in time domain and the other approach is the response spectrum method (RSM). In time domain approach, the ground acceleration at the surface is estimated from the response spectrum at the engineering bedrock, or the time history of the ground motion specified in the local building codes. The site-specific parameters of the response spectrum may be based on local building codes [1-7]. Special care is required when response spectrum method is used for wind turbine support structures due to its low damping ratio [8]. In Annex D, the design response spectrum is first presented in Clause D.2 followed by the description of the structure model in Clause D.3, seismic load evaluation methods in Clause D.4 and additional load in Clause D.5. An example of time domain simulation is described in [9-10].

D.2 Design response spectrum

The acceleration response spectrum shall be selected at the engineering bedrock for a 475-year return period. In general, the response spectrum is given by local codes.

The acceleration response spectrum may be defined according to Equation (D.1):

$$S_{a0}(T)=\begin{cases} a_0\left[1+(\beta_0-1)\dfrac{T}{T_B}\right] & (0\le T<T_B) \\ a_0\beta_0 & (T_B\le T<T_C) \\ a_0\beta_0\left(\dfrac{T_C}{T}\right)^{K_1} & (T_C\le T<T_D) \\ a_0\beta_0\left(\dfrac{T_C}{T_D}\right)^{K_1}\left(\dfrac{T_D}{T}\right)^{K_2} & (T_D\le T) \end{cases} \tag{D.1}$$

where a_0 is the peak ground acceleration at the engineering bedrock for a 475-year return period; β_0 is the acceleration response magnification ratio for the region where acceleration response becomes constant and may be taken as 2 to 3; T is the fundamental natural period of the structure; T_B, T_C, K_1 and K_2 are dependent on tectonic, geological and soil condition. T_B may be taken as 1/5 to 1/2 of T_C. T_C can be taken as 0,3 s to 0,5 s for stiff and hard soil conditions, 0,5 s to 0,8 s for intermediate soil conditions and 0,8 s to 1,2 s for loose and soft soil conditions. K_1 and K_2 are the exponents that can vary between 1/3 and 2. These parameters can be determined by local design codes as shown in references [2], [3], [4].

The design response spectrum can be written as in Equation (D.2) [2].

$$S_a(T,\zeta)=\begin{cases} a_0 G_s\left[1+\left(F_\zeta \beta_0-1\right)\dfrac{T}{T_B}\right] & \left(0 \le T < T_B\right) \\ a_0 G_s F_\zeta \beta_0 & \left(T_B \le T < T_C\right) \\ a_0 G_s F_\zeta \beta_0 \left(\dfrac{T_C}{T}\right)^{K_1} & \left(T_C \le T < T_D\right) \\ a_0 G_s F_\zeta \beta_0 \left(\dfrac{T_C}{T_D}\right)^{K_1}\left(\dfrac{T_D}{T}\right)^{K_2} & \left(T_D \le T\right) \end{cases} \tag{D.2}$$

where G_s is the soil amplification factor and F_ζ is the damping correction factor of the structure. These parameters are described in Clause D.2.

Soil amplification factor G_s explains the difference of seismic wave amplification during its propagation through the soil where a structure is built. Local design codes usually define typical soil types and their amplification factor. Those valued in local design code may be used for the seismic load evaluation of the wind turbine.

The following damping correction factor may be used for the seismic response analysis of wind turbine [8]:

$$\begin{cases} F_\zeta(\zeta,T,\gamma)=\left(\dfrac{7}{2+100\zeta}\right)^{(-0{,}07T+0{,}7r+0{,}5)} & (\zeta \le 5\%) \\ F_\zeta(\zeta,T,\gamma)=\left(\dfrac{2}{-3+100\zeta}\right)^{\left(0{,}15\log_{10}\frac{T}{1{,}5\gamma}+0{,}3\right)} & (\zeta > 5\%) \end{cases} \tag{D.3}$$

where γ is a value to consider uncertainty in seismic loading, and a value between 0,5 and 0,85 can be used considering local requirement.

D.3 Structure model

For the estimation of seismic load on wind turbine, simplified N degree of freedom model (Figure D.1) can be used in which the mass and the inertia moment of rotor, gear box and generator are lumped at the top of tower (node N), and tower mass is distributed along the tower. The bottom of the tower can be fixed to the ground for the load estimation of tower. More complicated model may be needed for the load estimation of the foundation, which is out of scope of Annex D.

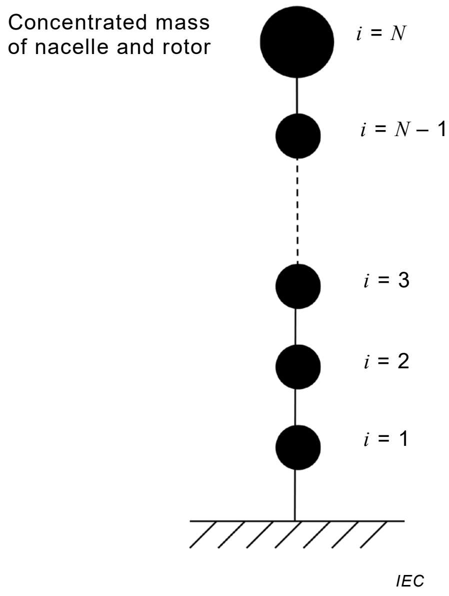

Figure D.1 – Structure model for response spectrum method

D.4 Seismic load evaluation

Using the response spectrum, maximum acceleration (A_{ij}), force (F_{ij}) and displacement (D_{ij}) corresponding to j^{th} mode at i^{th} node can be calculated as follows.

$$A_{ij} = \gamma_j X_{ij} S_a\left(T_j, \zeta_j\right) \tag{D.4}$$

$$F_{ij} = \gamma_j X_{ij} S_a\left(T_j, \zeta_j\right) m_i \tag{D.5}$$

$$D_{ij} = \gamma_j X_{ij} S_a\left(T_j, \zeta_j\right)\left(\frac{T_j}{2\pi}\right)^2 \tag{D.6}$$

where X_{ij} is the j^{th} mode shape obtained from eigenvalue analysis, $S_a\left(T_j, \zeta_j\right)$ is the amplitude of response spectrum for natural period T_j and damping ratio ζ_j of j^{th} mode, and γ_j is the modal participation factor for j^{th} mode.

$$\gamma_j = \frac{\sum_{i=1}^{N} X_{ij}}{\sum_{i=1}^{N} X_{ij}^2} \tag{D.7}$$

where N is the number of nodes in the model.

The total acceleration (A_i^{total}), displacement (D_i^{total}), shear force (Q_i^{total}) and bending moment (M_i^{total}) considering all the relevant modes at i^{th} node can be calculated by using complete quadratic combination (CQC) method [Equations (D.8) to (D.11)].

$$A_i^{\text{total}} = \sqrt{\sum_{j=1}^{M}\sum_{l=1}^{M}\rho_{jl} A_{ij} A_{il}} \tag{D.8}$$

$$D_i^{\text{total}} = \sqrt{\sum_{j=1}^{M}\sum_{l=1}^{M}\rho_{jl} D_{ij} D_{il}} \tag{D.9}$$

$$Q_i^{\text{total}} = \sqrt{\sum_{j=1}^{M}\sum_{l=1}^{M}\rho_{jl} \left(\sum_{k=i}^{N} F_{kj}\right)\left(\sum_{k=i}^{N} F_{kl}\right)} \tag{D.10}$$

$$M_i^{\text{total}} = \sqrt{\sum_{j=1}^{M}\sum_{l=1}^{M}\rho_{jl} \left[\sum_{k=i}^{N} F_{kj}\left(z_N - z_k\right)\right]\left[\sum_{k=i}^{N} F_{kl}\left(z_N - z_k\right)\right]} \tag{D.11}$$

where

$$\rho_{jl} = \frac{8\sqrt{\zeta_j \zeta_l}\left(\zeta_j + X_{jl}\zeta_l\right) X_{jl}^{3/2}}{\left(1 - X_{jl}^2\right)^2 + 4\zeta_j \zeta_l X_{jl}\left(1 + X_{jl}^2\right) + 4\left(\zeta_j^2 + \zeta_l^2\right) X_{jl}^2} \tag{D.12}$$

where ζ_j and ζ_l are the damping ratios for j^{th} and l^{th} modes, respectively, and X is the ratio of the j^{th} mode natural frequency to the l^{th} mode natural frequency.

D.5 Additional load

The torsional moment of the tower (M^{t}) can be calculated by using Equation (D.13) [8].

Additional bending moment caused by geometrical non-linearity, such as $p - \Delta$ effect, can be calculated by using maximum displacement, see [8].

$$M^{\text{t}} = 1{,}1 M_n A_n L_e \tag{D.13}$$

where M_n is the mass of the nacelle and rotor, A_n is the maximum acceleration at the nacelle and L_e is the distance between rotor centre and centre of gravity of the nacelle and rotor.

D.6 Reference documents

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Annex E
(informative)

Wake and wind farm turbulence

E.1 Added wake turbulence method

Wake effects from neighbouring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity I_{eff}, [1]. The effective turbulence intensity – conditioned on hub height mean wind speed V_{hub} – may be defined as

$$I_{\text{eff}}(V_{\text{hub}}) = \left\{ \int_0^{2\pi} p(\theta | V_{\text{hub}}) I^m (\theta | V_{\text{hub}}) d\theta \right\}^{\frac{1}{m}} \tag{E.1}$$

where

p is the probability density function of wind direction;

I is the turbulence intensity of the combined ambient and wake flows from wind direction θ, and

m is the Wöhler curve exponent corresponding to the material of the considered structural component.

The approach is applicable for regular as well as irregular wind farm layouts.

In the following, a uniform distribution $p\left(\theta | V_{\text{hub}}\right)$ and a regular rectangular wind farm layout are assumed. It is acceptable to adjust the formulas for other layouts and other than uniform distribution.[43] No reduction in mean wind speed inside the wind farm shall be assumed.

If $\min\{d_{\text{I}}\} \geq 10D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_{\text{c}}}{V_{\text{hub}}} \tag{E.2}$$

If $\min\{d_{\text{I}}\} < 10D$:

$$I_{\text{eff}} = \frac{\hat{\sigma}_{\text{eff}}}{V_{\text{hub}}} = \frac{1}{V_{\text{hub}}} \left[\left(1 - N\, p_{\text{w}}\right) \hat{\sigma}_{\text{c}}^m + p_{\text{w}} \sum_{i=1}^{N} \hat{\sigma}_{\text{T}}^m \left(d_i\right) \right]^{\frac{1}{m}} ;\ p_{\text{w}} = 0{,}06 \tag{E.3}$$

where

D is turbine diameter;

$\hat{\sigma}_{\text{c}} = \hat{\sigma} + 1{,}28 \hat{\sigma}_{\sigma}$ is the representative ambient turbulence standard deviation;

$\hat{\sigma}$ is the estimated ambient turbulence standard deviation;

---

43 In the case of non-uniform distribution or non-grid wind farm layout, the formula should be modified accordingly, maintaining the concept implied in the more general Formula (E.1). It should be taken into consideration for each neighbour affecting wind turbine, the sector disturbed and their associated probability of occurrence conditioned on hub height mean wind speed.

$\hat{\sigma}_\sigma$ is the estimated standard deviation of the ambient turbulence standard deviation;

$\hat{\sigma}_T = \sqrt{\dfrac{V_{hub}^2}{\left(1{,}5 + \dfrac{0{,}8 d_i}{\sqrt{C_T}}\right)^2} + \hat{\sigma}_c^2}$ is the representative value of the maximum centre-wake, hub height turbulence standard deviation ($\hat{\sigma}_c$ shall not account for farm generated ambient turbulence);

C_T is the characteristic value of the wind turbine thrust coefficient for the corresponding hub height wind velocity. If the thrust coefficient for the neighbouring wind turbines are not known, a generic value $C_T = 7\ c\ /V_{hub}$, can be used;

d_i is the distance, normalized by rotor diameter, to neighbouring wind turbine no. i;

c is a constant equal to 1 m/s;

I_{eff} is the effective turbulence intensity;

N is the number of neighbouring wind turbines, see Table E.1.

Wake effects from wind turbines "hidden" behind other machines need not be considered, for example in a row only wakes from the two units closest to the machine in question are to be taken into account. Dependent on wind farm configuration, the number of nearest wind turbines to be included in the calculation of I_{eff} is as given in Table E.1.

Table E.1 – Number (N) of neighbouring wind turbines

Wind farm configuration	N
2 wind turbines	1
1 row	2
2 rows	5
Inside a wind farm with more than 2 rows	8

The wind farm configuration is illustrated in Figure E.1 for the case "Inside a wind farm with more than 2 rows" and a regular layout.

Inside large wind farms, wind turbines tend to generate their own "wind farm ambient" turbulence. Thus, when

a) the number of wind turbines from the considered unit to the "edge" of the wind farm is more than 5, or

b) the spacing in the rows perpendicular to the predominant wind direction is less than $3D$,

then the following representative wind farm ambient turbulence shall be assumed instead of $\hat{\sigma}_c$ except in the expression for $\hat{\sigma}_T$:

$$\hat{\sigma}_c' = \frac{1}{2}\left(\sqrt{\hat{\sigma}_w^2 + \hat{\sigma}^2} + \hat{\sigma}\right) + 1{,}28\ \hat{\sigma}_\sigma \qquad \text{(E.4)}$$

where

$$\hat{\sigma}_w = \frac{0{,}36 V_{hub}}{1 + 0{,}2\sqrt{d_r d_f / C_T}} \qquad \text{(E.5)}$$

in which d_r and d_f are separations in rotor diameters in rows and separation between rows, respectively.

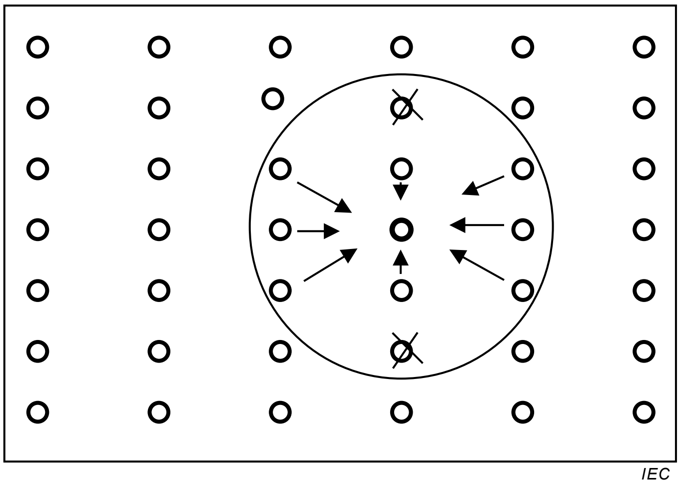

Figure E.1 – Configuration – Inside a wind farm with more than 2 rows

E.2 Dynamic wake meandering model

E.2.1 General

Wake effects from neighboring wind turbines may be taken into account for fatigue and ULS calculations by application of the Dynamic Wake Meandering (DWM) model [2], [3] and [4]. It describes the changes in the mean flow field over the wind farm as well as the changes in the turbulence intensity and turbulence structure compared to ambient conditions.

The DWM model is composed of three parts, see Figure E.2:

1) a model of the wake deficit formulated in the meandering frame of reference;
2) a stochastic model of the downstream wake meandering process;
3) a model of the self-induced wake turbulence described in the meandering frame of reference.

A summary description of recommended sub-models, their synthesis and their extension to the multiple wake case are given in the following.

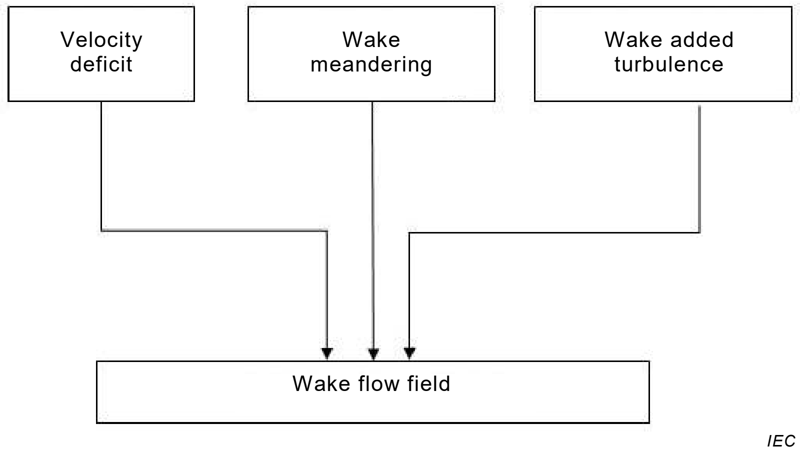

Figure E.2 – The three fundamental parts of the DWM model

E.2.2 Wake deficit

The mean wake deficit expands and attenuates with downstream distance from the wake generating rotor. The recommended modelling of the wake deficit is based on the thin shear layer approximation of the Navier-Stokes equations in their rotational symmetric form with the pressure term disregarded. Taking an eddy viscosity approach for the Reynolds stresses, the system of equations to be solved is:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rV\left(r,x\right)\right)+\frac{\partial U\left(r,x\right)}{\partial x}=0 \tag{E.6}$$

$$U\frac{\partial U\left(r,x\right)}{\partial x}+V\left(r,x\right)\frac{\partial U\left(r,x\right)}{\partial r}=\frac{\nu_{\mathrm{T}}}{r}\frac{\partial}{\partial r}\left(r\frac{\partial U\left(r,x\right)}{\partial r}\right) \tag{E.7}$$

where U and V denote the mean wake velocities in the axial and radial directions, respectively. The eddy viscosity, ν_{T}, includes contributions from both the ambient turbulence and the wake self-generated wake turbulence:

$$\frac{2\nu_{\mathrm{T}}}{DV_{\mathrm{hub}}}=0{,}023\ F_1\left(\tilde{x}\right)\left(\frac{\sigma}{V_{\mathrm{hub}}}\right)^{0{,}3}+0{,}016\ F_2\left(\tilde{x}\right)\frac{R_{\mathrm{w}}\left(\tilde{x}\right)}{D}\left(1-\frac{U_{\mathrm{min}}\left(\tilde{x}\right)}{V_{\mathrm{hub}}}\right) \tag{E.8}$$

where normalized spatial variables are introduced as

$$\tilde{r}=\frac{2r}{D}\ ;\ \tilde{x}=\frac{2x}{D} \tag{E.9}$$

and F_1 and F_2 are filter functions depending on the axial coordinate, R_{w} is the wake radius, and U_{min} is the minimum wake velocity. The empirical filter functions, accounting for the near field pressure influence (i.e. F_2) and the lack of equilibrium between the mean shear flow field and the turbulence field in the near and intermediate wake regime (i.e. F_1), are given by

$$F_1(\tilde{x}) = \begin{cases} \left(\dfrac{\tilde{x}}{8}\right)^{3/2} - \dfrac{\mathrm{Sin}\left(2\pi\,\tilde{x}^{3/2} / 8^{3/2}\right)}{2\pi} & ; 0 \le \tilde{x} < 8 \\ 1 & ; \tilde{x} \ge 8 \end{cases} \tag{E.10}$$

$$F_2(\tilde{x}) = \begin{cases} 0{,}0625 & ; 0 \le \tilde{x} < 4 \\ 0{,}025\,\tilde{x} - 0{,}0375 & ; 4 \le \tilde{x} < 12 \\ 0{,}00105\,(\tilde{x} - 12)^3 + 0{,}025\,\tilde{x} - 0{,}0375 & ; 12 \le \tilde{x} < 20 \\ 1 & ; 20 \le \tilde{x} \end{cases} \tag{E.11}$$

The pressure influence is implicitly taken into account by the introduction of F_2 and further by including the part of the wake expansion dictated by the pressure recovery in the boundary conditions associated with the system of differential Equations (E.6) and (E.7). Thus, the initial wake radius is approximated by

$$R_{\mathrm{w}}(0) = D\left(1 - 0{,}45\,a_{\mathrm{m}}^2\right)\sqrt{\frac{1+m}{8}} \tag{E.12}$$

where a_{m} denotes the mean induction over the rotor, and

$$m = \frac{1}{\sqrt{1 - C_{\mathrm{T}}}} \tag{E.13}$$

with C_{T} being the rotor thrust coefficient. The initial wake deficit to be developed downstream using Equations (E.6) and (E.7) is thus obtained from a blade element momentum far-field induction prediction combined with the radial scaling given by Equation (E.12).

E.2.3 Meandering

The wake meandering part is based on the fundamental presumption that the transport of wakes in the atmospheric boundary layer can be modelled by considering the wakes to act as passive tracers driven by the large-scale turbulence structures. Modelling of the meandering process consequently includes considerations of a suitable description of the "carrier" stochastic transport media (i.e. the large scale turbulence field) as well as of a suitable definition of the cut-off frequency defining large-scale turbulence structures in this context.

The stochastic modelling of wake meandering is established by considering a cascade of wake deficit releases "emitted" at consecutive time instants in agreement with the passive tracer analogy. The propagation of each "emitted" wake deficit is subsequently modelled, and the collective description of these constitutes the wake meandering model in space and time.

Adopting Taylor's hypothesis, the downstream advection of each wake deficit "release" is dictated by a suitable advection velocity often taken as the ambient mean wind speed. As for the dynamics in the lateral and vertical directions, each considered wake cascade-element is successively displaced according to the large scale lateral and vertical turbulence velocities at the instantaneous wake deficit position. In mathematical terms, the wake deficit dynamics in the lateral direction, y, and in the vertical direction, z, are thus described by the following differential equation system:

$$\frac{dy}{dt} = v_{\mathrm{c}}(y,z,t) \tag{E.14}$$

$$\frac{dz}{dt} = w_{\text{c}}\left(y,z,t\right) \tag{E.15}$$

where v_{c} and w_{c} are the spatially dependent large scale turbulent velocities at time t.

The recommended spatial averaging, defining the large scale part of the turbulence, may be expressed in terms of a cut off frequency using Taylor's frozen hypothesis:

$$f_{\text{c}} = \frac{U_{\text{u}}}{4R} \tag{E.16}$$

Note that with this formulation the large scale part of the turbulence is assumed unaffected by the presence of the wind farm.

E.2.4 Wake induced turbulence

Wake induced turbulence includes contributions from conventional mechanically generated turbulence, caused by the wake shear, as well as from the blade shed and trailed vortices mainly in terms of tip and root vortices gradually breaking down downstream of the wake generating rotor. Thus, this turbulence contribution is considered independent of the ambient turbulence.

With a length scale comparable with the characteristic size of the wake deficit, the basic DWM split in scales implies that the wake induced turbulence meanders with the wake deficit. The induced small scale turbulence is consequently formulated in the meandering frame of reference. Although violating the second order statistics (i.e. the cross correlation), the in-homogeneity of the induced turbulence is approximated by simple scaling of a homogeneous and isotropic turbulence field with a length scale equal to one rotor diameter and a turbulence standard deviation equal to 1 m/s. Rotational symmetry of the induced wake turbulence intensity is assumed, resulting in a scaling coefficient that for a given downstream distance only depends on the radial coordinate. The empirical scaling factor, k_{wt}, depends on the deficit depth, ($V_{\text{hub}} - U_{\text{min}}$), at the considered downstream distance, as well as on the wake deficit radial gradient $\partial U / \partial r$:

$$k_{\text{wt}}\left(\tilde{x},\tilde{r}\right) = 0{,}6\left|1-\frac{U\left(\tilde{x},\tilde{r}\right)}{V_{\text{hub}}}\right| + \frac{0{,}35}{V_{\text{hub}}}\left|\frac{\partial U\left(\tilde{x},\tilde{r}\right)}{\partial \tilde{r}}\right| \tag{E.17}$$

E.2.5 Wake superposition

Wake superposition is important when dealing with wind farm flow fields. This is a complicated process that calls for simplification. Wakes (including associated small scale wake induced turbulence) from the turbines in question are treated individually, and their correlated meandering is then subsequently modelled. Referring to ambient wind speed conditions, two different approaches are applied for the wind regimes corresponding to below and above rated power, respectively.

- *Below rated wind speed*: For a turbine with the rotor centre located at the spatial position, x, within the wind farm, the temporally varying flow field at the rotor polar coordinate (r,θ) is determined by the dominating wake among contributions from all upstream turbines at any time:

$$U_{\text{t}}\left(r,\theta,t\middle|x\right) = \underset{i}{\text{MIN}}\left(U_{\text{t},i}\left(r,\theta,t\middle|x\right)\right) \tag{E.18}$$

  where $(r,\theta,t|x)$ denotes a temporal coordinate combined with a spatial coordinate in a polar frame of reference centred at the spatial position x, and where each individual wake flow field is given by $U_{t,i}$ = $(U_i + u_i)e_1 + v_i e_2 + w_i e_3$, with e_j, j = 1, 2, 3, being unit normal vectors in the longitudinal, transversal and vertical flow directions. The parameter i includes all upstream turbines relative to the spatial position x for a given mean wind direction. Note that with the recipe formulated in Equation (E.18), the induced small scale turbulence, associated with the wakes contributing to U_t, is aggregated in a non-consistent manner. However, since the induced turbulence contributions are small scale this does not compromise the present application.

- *Above rated wind speed*: Using the nomenclature introduced above, Equation (E.18) is replaced by a summation of the deficit contributions of all upstream turbines:

$$U_t\left(r,\theta,t\middle|x\right) = \sum_i U_{t,i}\left(r,\theta,t\middle|x\right) \tag{E.19}$$

E.2.6 Model synthesis

For each rotor in a wind farm, the inflow wind field is composed of the ambient, undisturbed wind field with relevant (see Equation (E.18)) wake deficits and wake induced small scale turbulence linearly superimposed. The undisturbed wind field is the site-specific mean wind speed consisting of a deterministic part (i.e. the mean wind shear) and the conventional turbulent part with ambient turbulence characteristics. The resulting inflow wake effects to be superimposed consist of stochastically moving wake deficits, ($V_{hub} - U$), and associated wake induced turbulence contributions, respectively, and added according to the recipe formulated in Equation (E.18). Note that the wake deficit meandering is by far the dominating wake effect.

E.3 Reference documents

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Annex F
(informative)

Prediction of wind distribution for wind turbine sites by measure-correlate-predict (MCP) methods

F.1 General

The assessment of the suitability of a wind turbine for a specific site requires the evaluation of the design-critical wind speed parameters at a site. Frequently, there is insufficient data even at a single point within a wind farm to carry out the evaluation. However, the extended data record can be synthesized by extrapolation based on a long-term record for another location. The MCP methods are a means to create that extended record. The following explanation is taken from [2]. Further information can be found in [3], [4] and [5].

F.2 Measure-correlate-predict (MCP)

The MCP method takes a number of forms in which the averaging period and directional nature of the data vary. One version is described here, based upon the concurrent hourly data from the wind turbine site and a nearby reference meteorological station (Met. Station). These data are cross-plotted and used to derive sector-wise linear regression equations; the sectors being consistent with those used by the Met. Station, typically 30° sectors. The data sets used for deriving the regression equations should be as long as possible, at least conservatively covering the conservative part of any seasonal variations.

F.3 Application to annual mean wind speed and distribution

The above regression equations are applied to the long-term Met. Station record sector by sector, for a period sufficiently long to eliminate short-term variations, probably at least seven years. The result is an hourly mean record for the site, which may be processed into a probability distribution for site assessment.

F.4 Application to extreme wind speed

The classical method for the prediction of the extreme wind speed is a Gumbel analysis modified to improve accuracy (e.g. Best Leiblein Unbiased Estimators (BLUE) method described in [1]). The minimum recommended length of data set is ten years.

It is also possible to apply the method of independent storms (MIS), a derivative of the Gumbel method, which utilizes more than one data point per year from a data set, also described by Cook [1]. This method can be used for data sets that are as short as four years. MIS selects individual storms' peak wind speeds by application of thresholds and time filters to ensure that all values are from independent events.

The sector-specific regression coefficients are applied to a table of the maximum hourly wind speed at the Met. Station, by year for basic Gumbel and by storm event for MIS, and by sector. A similar table is therefore built up for the wind turbine site. The maximum value in each year for the candidate site is extracted for use in a Gumbel analysis.

The use of the coefficients is appropriate here since they have been formed from hourly mean data and are being applied to hourly mean data. In this method, there is no assumption that the maximum value at the candidate site occurs in the same sector as the maximum at the reference site. By using the sector-specific regression coefficients, the maximum at the candidate site can be more accurately determined, taking account of the inter-site relationships.

The selection of the relevant return period in the extreme value analysis should account for the number of events per annum.

The gust factors should be estimated from the site-measured data, or by theoretical methods.

Users of these methods for estimation of extreme wind speed should note that the resulting accuracy depends significantly on data quality and actual local conditions compared to the reference station. As a result, correlations from a regression analysis may be poor. In cases where existing local codes are recognized as applicable by authorities having jurisdiction, the extreme values obtained using such codes should be considered as minimum values for design in preference to MCP.

F.5 Reference documents

[1] N.J. Cook, The designers guide to wind loading of building structures, Butterworths, 1995

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[4] D.C. Quarton, Wind Farms in Hostile Terrain, Final Report, A report prepared under ETSU contract W/43/00501/00/00, July 1999

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Annex G
(informative)

Statistical extrapolation of loads for ultimate strength analysis

G.1 General

Failure of a structure occurs when the stress at a critical location exceeds the resistance capacity of the component material. Assuming that local stresses are related to the loading so that the stress progressively increases with increased loading, the strength of a structural component can be defined in terms of an ultimate load that causes failure. Given the service loading, the adequacy of the structure can be assessed by comparing the extreme values of the loading with the ultimate load resistance, applying suitable factors of safety.

For wind turbines, loading depends on the turbulent wind inflow for a variety of wind conditions. Thus, it is necessary to analyse the extreme values of the loading on a statistical basis in order to determine a suitable characteristic load.

For a given wind condition, it is reasonable to model the short-term load response as a stationary random process. Given that loads can be represented as such processes, methods are described in the following for the extraction of data for extrapolation and load extrapolation. Convergence criteria also are proposed and an alternative for estimating the long-term loads using the inverse first-order reliability method (IFORM) is given.

The methods have been tested for a 3-bladed horizontal-axis upwind turbine. Special attention may be necessary for other wind turbine concepts and/or control schemes including load feedback. More information and guidance can be found in [1].

G.2 Data extraction for extrapolation

Data used in extrapolation methods are extracted from time series of turbine simulation over the operating range of the turbine in specified wind conditions. Data may be extracted by choosing the global individual response extremes from each simulation or some subset created by breaking the simulation into blocks of equal time or ensuring a minimum time separation between extremes.

Establishing independence among the individual load response extremes is important for some methods of extrapolation. When extracting, the designer should consider the effect of independence between peaks on the extrapolation and minimize dependence when possible. If the method chosen for extrapolation is sensitive to independence assumption (e.g. the method involves transforming probability functions between time bases), the designer should attempt to statistically test for independence.

A simple approach to ensure independence is to assume that the global extreme in each ten-minute simulation or local extremes from intervals no shorter than three response cycles are independent and thus require a minimum time separation between individual response extremes of three response cycles (defined by three mean crossings over the block size). If a systematic statistical approach is desired, the designer may test for independence using standard estimation techniques (e.g. [5], [6]) and then minimize dependence in a controlled manner.

Peak over threshold methods may also be employed, but the designer should be careful that truncation errors and correlation introduced by the threshold do not influence the shape of the empirical distribution dramatically.

G.3 Load extrapolation methods

G.3.1 General

The 50-year return period load of a wind turbine may be defined as the extreme loading that has an annual probability of exceedance of $\frac{1}{50\text{ years}} = 0{,}02$ per year.

The suggested approaches of extrapolation of extreme events for determination of the 50-year load can be divided into the following procedures.

1) Parametric fitting and aggregation afterwards
   - Subdivide the operational range of the turbine into discrete wind speeds and perform time domain simulations at the normal turbulence (NTM) level.
   - Estimate an extreme value (parametric) distribution [2] for every wind speed realization.
   - Aggregate all distributions according to the long-term distribution function of the mean wind speed.
   - Predict the 50-year value of the aggregated distribution function.

     For global extreme from ten-minute simulations, the probability of the 50-year load is approximately $3{,}8 \times 10^{-7}$.
2) Data aggregation first and fitting afterwards
   - Subdivide the operational range of the turbine into discrete wind speeds and performance of time domain simulations at normal turbulence (NTM) level.
   - Aggregate all relevant extremes from all time series according to the long-term distribution function of the mean wind speed within the operational range of the turbine.
   - Estimate one (aggregated) distribution function for all extremes.
   - Predict the 50-year value from the resulting distribution function.

     Two different cases are regarded for aggregation of simulated short-term distributions of extremes for a specific observation period T into an empirical distribution of the long-term extremes for the same period: extrapolation from global extremes, and from local extremes.

G.3.2 Global extremes

The short-term distribution of global extremes in the observation period, T, is denoted

$$F_{\text{short-term}}\left(s \middle| V;T\right) \tag{G.1}$$

where s stands for load response and V is the mean wind speed for the observation period. Using the long-term distribution of the mean wind speeds, the long-term distribution of extreme values is obtained:

$$F_{\text{long-term}}\left(s;T\right) = e^{\int_{V_{\text{in}}}^{V_{\text{out}}} \ln\left(F_{\text{short-term}}(s|V;T)\right) f(V)\, dV} \tag{G.2}$$

This equation is derived assuming that the exceedances of the value s form a composite Poisson point process with independent increments. The extreme load response, s_{r}, of the desired return period, T_{r}, is obtained from Equation (G.3):

$$F_{\text{long-term}}\left(s;T\right)=\left(1-\frac{1\text{yr}}{T_{\text{r}}}\right)^{\frac{T}{1\text{yr}}}\approx 1-\frac{T}{T_{\text{r}}} \tag{G.3}$$

for sufficiently small values of $\frac{T}{T_{\text{r}}}$.

The practical implementation of these formulas would typically be to use discrete wind speed values. Then one has

$$F_{\text{long-term}}\left(s;T\right)\approx\prod_{k=1}^{M}\left(F_{\text{short-term}}\left(s|V_k;T\right)\right)^{p_k},$$

$$p_k=f\left(V_k\right)\Delta V_k,\ V_{\text{in}}\leq V_1<\ldots<V_{\text{M}}\leq V_{\text{out}} \tag{G.4}$$

For small short-term exceedance probabilities, this may be conservatively approximated as

$$F_{\text{long-term}}\left(s;T\right)\approx 1-\sum_{k=1}^{M}\left(1-F_{\text{short-term}}\left(s|V_k;T\right)\right)p_k$$

$$=\sum_{k=1}^{M}F_{\text{short-term}}\left(s|V_k;T\right)p_k \tag{G.5}$$

The latter equivalence results because the exceedance probability outside the operating range is assumed to be zero.

The distribution $F_{\text{short-term}}$ may be obtained by fitting to the empirical distribution

$$\hat{F}_{\text{short-term}}\left(s_{ki}\left|V_k\right.\right)=\frac{r_i}{n_k+1},i=1,\ldots,n_k \tag{G.6}$$

where s_{ki} denotes the ith extreme value sample from wind speed k and r_i is s_{ki}'s rank among the n_k extremes arising from wind speed k. For the following developments, it is worth noting that an equivalent expression for the empirical distribution by use of a summation is

$$\hat{F}_{\text{short-term}}\left(s_{ki}\left|V_k\right.\right)=\sum_{j=1}^{n_k}\frac{1}{n_k+1}I\left(s_{kj}-s_{ki}\right),\ i=1,\ldots,n_k \tag{G.7}$$

where an indicator function $I(x)$ has the expression

$$I(x)=\begin{cases}1 \text{ for } x\leq 0\\ 0 \text{ for } x>0\end{cases} \tag{G.8}$$

The task of the indicator function is to pick out all values less than or equal to s_{ki} in order that they can contribute to the empirical probability of having values less than or equal to s_{ki}. Note that the specific definition of the indicator function ensures that the event that identical extreme values should be realized is accounted for.

G.3.3 Local extremes

Now the short-term distribution of global extremes in the observation period, T, is obtained from $n(V)$ independent local extreme values in the period (assuming the extremes are positive, otherwise a change of sign may be made):

$$F_{\text{short-term}}\left(s\middle|V;T\right) = F_{\text{local}}\left(s\middle|V;T\right)^{n(V)} \tag{G.9}$$

The long-term distribution, defined in Equation (G.9), and the extreme load response, s_{r}, of the desired return period, T_{r}, are established as described in G.3.2. Strictly, n should be a random number for which a distribution (dependent on V) should be assumed. However, n has for wind turbine applications limited variation compared to its mean value. Consequently, replacing n by its mean value (conditional on V), as implicitly done above, is sufficiently accurate. The approximation may be accepted if, when applying the formulas proposed in the following, one uses an s-value representative of the wind speeds that contribute most to the specific load response under consideration. Based on the approximation, one has the following expression:

$$F_{\text{long-term}}\left(s;T\right) = e^{\int_{V_{\text{in}}}^{V_{\text{out}}} n(V)\ln\left(F_{\text{local}}(s|V;T)\right)f(V)dV} \tag{G.10}$$

G.3.4 Long-term empirical distributions

There are advantages to aggregating data from all wind speeds and then fitting a distribution to the combined data. One method for accomplishing this is to compute a number of simulations, where the number of simulations per bin is determined by the Weibull (or appropriate) distribution of wind speed.

$$N_{\text{sims}}\left(V_k\right) \approx N_{\text{total}}p_k, \quad p_k = f\left(V_k\right)\Delta V_k, V_{\text{in}} \le V_1 < \ldots < V_{\text{M}} \le V_{\text{out}} \tag{G.11}$$

Once simulations are completed and maxima are extracted, all maxima from all wind speeds are combined into a single distribution and ranked such that

$$\hat{F}_{\text{long-term}}\left(s_i\right) = \frac{r_i}{n_k+1}, i = 1,\ldots,n_{\text{total}} \tag{G.12}$$

where s_i denotes the ith extreme value sample over all wind speeds and r_i is s_i's rank among the n_{total} extremes arising from the combined distribution.

One potential disadvantage of this method is that loads that are dominated by high wind speeds may have very few simulations from which to extract large extreme values in the tail of the empirical distribution. To address this issue, additional long-term distributions can be calculated using additional simulations for the low probability wind speed bins. The total simulation time per bin should follow the original wind speed distribution. But, a number of new long-term empirical distributions can be formed using randomly bootstrapped data from all bins, in which a large number of simulations are available. Once a number of long-term distributions are formed, they can be averaged to form a single aggregate long-term distribution that can be used for extrapolation to lower probability levels.

G.4 Convergence criteria

G.4.1 General

In the context of turbine extreme loads, the importance of different wind speeds varies depending on the load that is being extrapolated. Some loads are dominated by wind speeds near rated while others are dominated near cut-out or other wind speeds. It is important that the designer examine the dominant wind speeds closely to ensure that a sufficient number of simulations are carried out to ensure stability of the method. A minimum of 15 simulations is necessary for each wind speed from (V_r – 2 m/s) to cut-out and six simulations are necessary for each wind speed with V below (V_r – 2 m/s).

In addition to a minimum number of simulations for the wind speeds (V_r – 2 m/s) to cut-out, an additional convergence criterion shall also be applied according to 7.6.2. The recommended number of simulations is determined by calculating a confidence interval for the resulting empirical distribution. The number of simulations deemed sufficient is that for which the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile. This interval may be estimated using bootstrapping methods [3], the binomial estimation method [4], or it may be inherently estimated as a part of the extrapolation method employed.

If the extremes are obtained using any other method (e.g. block maxima) that results in m extremes per 10-minute simulation, on average, then the 84 % fractile above needs to be replaced by p^* where

$$p^* = (0{,}84)^{1/m} \tag{G.13}$$

The convergence criterion[44] should be applied individually to each short-term load distribution whether the long-term distribution is to be established using aggregation of wind speed data before fitting or whether fitting parametric distributions to data from each wind speed is carried out before aggregation.

In the procedure that involves aggregation before fitting, empirical long-term distributions for the loads following aggregation of all wind speed bins can be established by making use of similar convergence criteria as proposed above for short-term distributions. The appropriate fractile at which to impose the convergence criterion should be higher than the fractile corresponding to any apparent "knee" (often observed) in the empirical long-term distribution to ensure that convergence is checked closer to the tail of this empirical distribution.

G.4.2 Load fractile estimate

The desired load fractile, $\hat{L}_p$, corresponding to a non-exceedance probability, P, is estimated as follows.

Rank order all the loads data such that $S_1 \le S_2 \le \ldots \le S_m$ if we have m such values from simulations. Note that m will be equal to the number of simulations if global maxima are used.

For any specified p, make sure it is possible to find some integer i (where $2 \le i \le m$), such that

44 The criterion should only be evaluated where the 84 % fractile is much larger than 0. For example, blade flap moments away from tower for outboard sections might be problematic at certain wind speeds; i.e. criterion should be handled with a certain engineering judgement.

$$\frac{i-1}{m+1} \le p \le \frac{i}{m+1} \quad \text{(G.14)}$$

A sufficient number of extremes, m, should be available (for which a sufficient number of simulations will have to be run) so that the above inequality results and a value of i found.

The load fractile estimate is then computed by (linear) interpolation as follows:

$$\hat{S}_p = S_{i-1} + [p(m+1)-(i-1)](S_i - S_{i-1})\text{; where } 2 \le i \le m \quad \text{(G.15)}$$

G.4.3 Confidence bounds

Confidence bounds are estimated such that the 90 % confidence interval on the 84 % fractile, $\hat{S}_{0{,}84}$, is as follows:

$$\frac{\hat{S}_{0{,}84;0{,}05} - \hat{S}_{0{,}84;0{,}95}}{\hat{S}_{0{,}84}} < 0{,}15 \quad \text{(G.16)}$$

The interval, $\left\langle \hat{S}_{0{,}84;0{,}05}, \hat{S}_{0{,}84;0{,}95} \right\rangle$, represents the desired 90 % confidence interval.

G.4.4 Confidence intervals based on bootstrapping

Using the bootstrap procedure to form confidence intervals [3, 7] begins with taking the initial set of data on p global maxima ($m_1, m_2, m_3, m_4, m_5 \ldots m_p$) and randomly resampling these data with replacement to form a new set ($m_1^*, m_2^*, m_3^*, m_4^*, m_5^* \ldots m_p^*$) or a bootstrap resampling of the same size as the original sample. Note that bootstrap resamplings will be composed of repeated values from the original sample since, for each resampling, data are sampled randomly with replacement. The process is repeated so as to form a large number, N_b, of bootstrap resamplings. From each of these sets of p data, individual estimates of the 84 % fractile can be obtained. From these N_b estimates, constituting the set, ($l_1, l_2, l_3, l_4, l_5, \ldots, l_{Nb}$), confidence intervals can be found in the usual manner by ordering the data. These can then be used for the numerator of Equation (G.16). The estimate of the 84 % fractile that is obtained from the original data represents the denominator of Equation (G.16).

A minimum number of 25 bootstrap resamplings may be sufficient to determine a reasonable estimate of confidence bounds. However, a larger number closer to 5 000 will lead to more reliable estimates.

G.4.5 Confidence intervals based on the binomial distribution

Confidence intervals based on the binomial distribution [7] are computationally less intensive than those computed using the bootstrap procedure. This saving is simplified by tabulating parameters for calculating a binomial confidence interval that will result for most common situations. For the load fractile equal to 0,84 and 90 % confidence interval, Table G.1 provides values of k^* and l^* as well as two other values, A and B, needed for interpolating the estimate confidence bounds in Equation (G.17), below. The number of simulations is of the order of 15 to 35 for each wind speed bin.

Table G.1 – Parameters needed to establish binomial-based confidence intervals

	No. of sims.	k^*	l^*	A	B
For 90 % confidence interval on the 84th percentile load	15	9	14	0,50	0,32
	16	10	15	0,27	0,19
	17	11	16	0,10	0,03
	18	11	16	0,87	0,96
	19	12	17	0,58	0,90
	20	13	18	0,35	0,83
	21	14	19	0,16	0,76
	22	14	20	1,00	0,69
	23	15	21	0,69	0,60
	24	16	22	0,45	0,50
	25	17	23	0,25	0,39
	26	18	24	0,08	0,26
	27	18	25	0,85	0,12
	28	19	25	0,58	0,98
	29	20	26	0,36	0,91
	30	21	27	0,18	0,83
	31	22	28	0,02	0,75
	32	22	29	0,75	0,66
	33	23	30	0,51	0,56
	34	24	31	0,31	0,44
	35	25	32	0,13	0,32

The parameters in Table G.1 are used with a design equation that is tailored to give the 90 % confidence interval for the 84th percentile ten-minute maximum. The design equation can be written as follows:

$$\left(x_l - x_k\right) = \left(x_{l^*} - x_{k^*}\right) + B\left(x_{(l+1)^*} - x_{l^*}\right) - A\left(x_{(k+1)^*} - x_{k^*}\right) \tag{G.17}$$

where l^*, k^*, A, and B are as given in Table G.1 as a function of the number of simulations run and x_{l^*}, $x_{(l+1)^*}$, x_{k^*}, and $x_{(k+1)^*}$ are obtained from the rank-ordered simulated extremes. This estimate can then be inserted into Equation (G.16) to determine if the convergence criteria are met, where

$$\hat{S}_{0,84;0,05} - \hat{S}_{0,84;0,95} \approx x_l - x_k \tag{G.18}$$

G.5 Inverse first-order reliability method (IFORM)

An alternative to typical loads extrapolation methods is the use of IFORM to estimate long-term loads. In this method, turbulence and wind turbine response simulations are carried out for NTM conditions. A minimum of 15 simulations should be carried out for wind speeds (V_r – 2 m/s) to cut-out. The wind speed(s) that yields the highest load is (are) then identified.

Extrapolation of the short-term load distributions to a probability level consistent with the definition of a 50-year return period yields the 50-year load for use with DLC 1.1.

The convergence criteria for IFORM should be the same as for the other extrapolation methods, except that the designer need only estimate confidence intervals for the load distributions from identified important wind speeds (often only one).

The theory for the use of the inverse FORM (IFORM) technique (which relies on transformation of physical random variables to standard normal random variables [8]) is well-documented, see for example [9], and can be applied to estimate long-term wind turbine loading under NTM conditions.

In order to implement IFORM for wind turbine extreme loads, use the following steps.

a) Carry out 15 simulations for the wind speed bins (V_r – 2 m/s) to cut-out.
b) Identify which bins yield the largest load maxima.
c) Refine the search by performing another 15 simulations for the bins identified in step b). Again, identify the design dominating wind speed(s), v^*, which produce the largest loads. Ensure that the number of simulations at the important wind speed(s) is sufficient such that the width of the 90 % confidence interval on the 84 % fractile of the empirical load distribution of global maxima is smaller than 15 % of the estimate of the 84 % fractile.
d) Perform short-term analysis only for the bin(s) identified in step c). The desired fractile of the load distribution for this bin is derived and depends on the target probability level.
   - Using Rayleigh CDF, compute $U_1 = \Phi^{-1}[P_R(v^*)]$.
   - For probability of exceedance in 10 min once in 50 years, $p_T = 3{,}8 \times 10^{-7}$. This corresponds to $\beta = 4{,}95$.
   - Solve $U_2 = [\beta^2 - U_1{}^2]^{1/2}$.
   - Derive the load fractile $P_S = \Phi(U_2)$, see Table G.2.
   - The long term load is the P_S fractile of the short-term distribution for the wind speed bin, v^*. To reach the appropriate fractile, extrapolation may be required.

Table G.2 – Short-term load exceedance probabilities as a function of hub-height wind speed for different wind turbine classes for use with the IFORM procedure

v* [m/s]	1-P_S,class I	1-P_S,class II	1-P_S,class III
5	5,91E-07	4,95E-07	4,42E-07
6	4,86E-07	4,24E-07	3,94E-07
7	4,26E-07	3,90E-07	3,80E-07
8	3,94E-07	3,80E-07	3,91E-07
9	3,81E-07	3,90E-07	4,24E-07
10	3,83E-07	4,17E-07	4,84E-07
11	3,97E-07	4,64E-07	5,78E-07
12	4,24E-07	5,35E-07	7,20E-07
13	4,66E-07	6,38E-07	9,33E-07
14	5,26E-07	7,85E-07	1,26E-06
15	6,08E-07	9,97E-07	1,75E-06
16	7,20E-07	1,30E-06	2,54E-06
17	8,71E-07	1,75E-06	3,82E-06
18	1,08E-06	2,43E-06	5,93E-06
19	1,36E-06	3,46E-06	9,54E-06
20	1,75E-06	5,06E-06	1,59E-05
21	2,31E-06	7,60E-06	2,74E-05
22	3,10E-06	1,17E-05	4,89E-05
23	4,25E-06	1,86E-05	9,02E-05
24	5,93E-06	3,03E-05	1,73E-04
25	8,45E-06	5,06E-05	3,42E-04

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Annex H
(informative)

Fatigue analysis using Miner's rule with load extrapolation

H.1 Fatigue analysis

Fatigue failure results from an accumulation of damage due to fluctuating loads. For this kind of macroscopic view of fatigue, there is general agreement that an increment of damage results from each hysteresis cycle displayed in the local stress-strain diagram. Thus, each local maximum of the load time history is paired with the local minimum that completes a full cycle (rain-flow cycle counting, see [1] or [2]). Each of these cycles is characterized by the paired extreme values (or equivalently by the range and midpoint values, i.e. the difference between and the mean of the two paired cycle extremes). If the damage accumulates linearly and independently for each cycle [5, 3] then the total damage, D, will be given by[45]

$$D = \sum_i \frac{1}{N(S_i)} \tag{H.1}$$

where S_i is the load range for the ith cycle, and $N(\ )$ is the number of cycles to failure for a constant amplitude loading with the range given by the argument (i.e. the S-N curve). In this expression, it has been further assumed that the local stress at the failure location is linearly related to the loading. Typically, for fatigue analysis, the S-N curve selected for design is associated with a given survival probability (often 95 %) and level of confidence (often 95 %) in determining the curve from materials data. Thus, the desired minimum level of reliability may be expected when the damage sums to unity.

For the life of a wind turbine, there will be many cycles of varying sizes resulting from a broad range of wind conditions. Therefore, for design purposes, a load spectrum should be estimated. The largest cycles for this spectrum will be estimated from a smooth fit to the data obtained from simulations or testing of a duration that is significantly shorter than the turbine lifetime. For each wind condition, it may be assumed that the load is modelled by a stationary random process. Thus, the expected damage for a given wind speed, V, and a specific time period, T, will be given by

$$E\langle D|V,T\rangle = \int_0^\infty \frac{n_{\mathrm{ST}}(S|V,T)}{N(S)} dS \tag{H.2}$$

where $n_{\mathrm{ST}}(S|V,T)$ is the short term load spectrum defined as a density function for the number of cycles. In this case, the expected number of cycles in any load range interval (S_{A},S_{B}) during the time period T is given by $\int_{S_{\mathrm{A}}}^{S_{\mathrm{B}}} n_{\mathrm{ST}}(S|V,T)\,dS$. The expected damage from normal operating loads for the whole turbine life is then given by extending the time interval to the full lifetime and integrating over the range of operating wind speeds, so that

45 For ease of presentation, the effect of variation in the midpoint load level for each cycle is neglected. This restriction is eliminated later when the issue of varying midpoint levels is addressed through the use of an equivalent cyclic range.

$$E\langle D\rangle = \frac{\text{Lifetime}}{T}\int_{V_{\text{in}}}^{V_{\text{out}}} E\langle D|V,T\rangle\, p(V)\,dV = \frac{\text{Lifetime}}{T}\int_{V_{\text{in}}}^{V_{\text{out}}}\int_{0}^{\infty} \frac{n_{\text{ST}}(S|V,T)}{N(S)}\, p(V)\,dS\,dV \tag{H.3}$$

where $p(V)$ is the probability density function for the hub-height wind speed prescribed for the standard wind turbine classes in 6.3.2.1.

Now, defining the long-term load spectrum

$$n_{\text{LT}}(S) = \frac{\text{Lifetime}}{T}\int_{V_{\text{in}}}^{V_{\text{out}}} n_{\text{ST}}(S|V,T)\,p(V)\,dV \tag{H.4}$$

then gives

$$E\langle D\rangle = \int_{0}^{\infty} \frac{n_{\text{LT}}(S)}{N(S)}\,dS \tag{H.5}$$

In many cases, it is convenient, for practical purposes, to divide the ranges of load and wind speed values into discrete bins. In this case, the expected damage can be approximated by

$$E\langle D\rangle \approx \sum_{j,k} \frac{n_{jk}}{N(S_k)} \tag{H.6}$$

where n_{jk} is the expected number of lifetime load cycles in the j^{th} wind speed and the k^{th} load bins, and S_k is the centre value for the k^{th} load bin. Thus, from the above definition,

$$n_{jk} = \frac{\text{Lifetime}}{T}\int_{V_j - \Delta V_j/2}^{V_j + \Delta V_j/2}\ \int_{S_k - \Delta S_k/2}^{S_k + \Delta S_k/2} n_{\text{ST}}(S|V,T)\,p(V)\,dS\,dV \tag{H.7}$$

where ΔV_j is the width of the j^{th} wind speed bin and ΔS_k is the width of the k^{th} load bin.

Utilizing these results, and considering the requirement from 7.6.3 that the safety factors be applied to the load, the limit state relation for fatigue analysis becomes

$$\int_{0}^{\infty} \frac{n_{\text{LT}}(S)}{N(\gamma S)}\,dS \le 1 \tag{H.8}$$

where $\gamma = \gamma_{\text{f}}\gamma_{\text{m}}\gamma_{\text{n}}$ is the product of all three general partial safety factors for load, materials, and consequences of failure, respectively. In discrete terms, this equation results in

$$\sum_{j,k} \frac{n_{jk}}{N(\gamma S_k)} \le 1 \tag{H.9}$$

In cases where significant damage occurs in more than one load case from Table 2, the damage fractions for all the load cases, computed using the left side of Equation (H.9), should sum to be less than or equal to one.

The formulation up to this point has ignored the effect of the variability in the midpoint levels for each load cycle. One simple way of dealing with this variability is to define damage equivalent load cycles with a fixed midpoint value. In this case, the damage done by the equivalent cycles is exactly the same as that done by the cycles with varying midpoints. Thus, failure will occur (on average) for the same number of constant amplitude cycles for the equivalent cyclic range, S_{eq}, as for cycles at any given cyclic range and midpoint value. Thus, defining a family of S-N curves for varying midpoint values, $N(S,M)$, the equivalent damage equation

$$N\left(S_{\text{eq}},M_0\right)=N\left(S,M\right) \tag{H.10}$$

is solved for S_{eq} given values for S,M and the selected constant midpoint level M_0. In mathematical terms, this can be stated as

$$S_{\text{eq}}=N^{-1}\left(N\left(S,M\right),M_0\right) \tag{H.11}$$

where the inverse refers to solution for the first argument in the function, N, given the second argument. Typically, M_0 is chosen to give R values (the ratio of maximum load to minimum load) for the equivalent load cycles that are in the middle of the range of values observed directly in the load data. Often, an acceptable value is the mean load considering all operating wind speeds. Fortunately, in most cases where the S-N curves are defined analytically (e.g. power law or exponential forms), the equivalent cyclic load range is easily computed. Care should be taken, however, as the range becomes large. Depending on the midpoint value, the maximum or minimum load value for the given cycle can get close to the static strength, in which case the simple, high-cycle S-N curve may not be applicable. Also, for larger range values, the local stress or strain may transition from a compression-compression or tension-tension dominated case to a tension-compression case, which could have a different analytical S-N curve representation. It is important to utilize the proper S-N relation in determining the equivalent cyclic range. For a given load time history, the rain flow cycles are first identified. Then a set of equivalent constant-midpoint cycles is computed considering the proper S-N relation for each cycle. The distribution of these equivalent cycles is then estimated giving a new short-term equivalent load spectrum. This new spectrum is then used to define the number of cycles used for the damage fraction for each load and wind speed bin. The main advantage of using this method is that the estimation of the equivalent spectrum is statistically more robust than tracking the midpoint levels as an independent variable. This advantage results because many more load cycles are counted from typical time series load data for each load and wind speed bin than when midpoint bins are also tracked separately.

An additional practical issue that arises in determining the short-term load spectrum is the large number of small cycles determined by the rain-flow method. These small cycles can often occur at nearby points in time and may therefore be correlated. The small cycles can also distort the shape of analytical approximations to the tail of the distribution. It is therefore recommended to only consider cycles above a threshold when approximating the tail of the short-term distribution. A threshold value of at least the 95th percentile typically works well in practice. Lower threshold values may be appropriate if the small cycles have been eliminated or if the increased number of data points used for the fitting process is expected to yield significant additional statistical reliability.

For practical wind turbine design applications, it is necessary to estimate the short-term equivalent load spectrum from dynamic simulation data and then compute the lifetime damage. One method of accomplishing this task is given by the following procedure.

a) Select the reference midpoint level as the mean load level considering all wind speeds.

From the simulation data for a given wind speed, extract the sequence of local maxima and minima. The sequences of local maxima and minima from multiple time series for the same wind conditions may be concatenated into a single series.

b) Use the rain flow method to identify the midpoint and range for each simulated load cycle.

c) Determine the equivalent range for each load cycle in relation to the selected reference midpoint level.

d) Determine an analytical fit for the short-term probability distribution of equivalent load cycles, $F_{\mathrm{ST}}\left(S \middle| V,T\right)$ for the data above the selected threshold. Guidance for one method for fitting the distribution may be found in [4]. The distribution type selected should be checked to see if the fit to the data is acceptable and whether there is sufficient data for reliable estimation of the behaviour of the tail compared to the data.

e) Determine the expected number of lifetime cycles in each bin using the data when the load bin is below the threshold and the fitted load distribution when the load bin is above the threshold. This results in

$$n_{jk} \approx \left(\frac{\text{Lifetime}}{T}\right) P_j \left\{ \begin{array}{ll} m_{jk} & \text{if } S_k \text{ is below the } j^{\text{th}} \text{ threshold} \\ M_j \left(F\left(S_k + \frac{\Delta S_k}{2} \middle| V_j, T \right) - F\left(S_k - \frac{\Delta S_k}{2} \middle| V_j, T \right) \right) & \text{if } S_k \text{ is above the } j^{\text{th}} \text{ threshold} \end{array} \right\} \quad \text{(H.12)}$$

where m_{jk} is the number of simulation fatigue cycles counted in the data for the j^{th} wind speed bin and k^{th} load bin below the threshold, M_j is the number of fatigue cycles counted in the simulation above the threshold, and

$$P_j = e^{-\pi\left(\frac{V_j - \Delta V_j/2}{2V_{\text{ave}}}\right)} - e^{-\pi\left(\frac{V_j + \Delta V_j/2}{2V_{\text{ave}}}\right)}$$

is the fraction of time the wind speed is in bin j for the assumed Rayleigh wind speed distribution.

1) Sum the damage using the left hand side of Equation (G.9).

2) Sum the total lifetime damage from all fatigue load cases.

In using this procedure, care should be taken that

- the resolution of the wind speed and load range bins is sufficient for the desired numerical precision, and
- sufficiently large values of load range are used to adequately represent the tail of the long-term load distribution.

The first issue may be addressed by approximating the error as half the difference between results computed by two different bin resolutions skipping data from every other wind speed or load range. An alternative would be to compute the damage summation using the endpoints for the bin values instead of the central values to bound the result. The second issue may be addressed by progressively increasing the highest load range bin value until a negligible increase in the lifetime damage is observed. Note because the ratio $\frac{\text{Lifetime}}{T}$ is a large number, the largest required load bin may be significantly larger than the largest cycle observed in the simulation data. This results because the total simulated load time history is much smaller than the turbine lifetime, and statistical extrapolation is required to accurately estimate damage from the tail of the long-term load distribution.

H.2 Reference documents

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Annex I
(informative)

Contemporaneous loads

I.1 General

Detailed structural analyses of wind turbine components commonly use a finite element or other suitable model for determination of the local stress or strain resulting from the loading applied to the component. Such analyses often define a suitable interface plane where the applied loads are acting (e.g. the yaw bearing interface, defining the tower top loading). In this case, there are six load components defining the boundary conditions for loading, three forces, F_x, F_y, and F_z, and three moments, M_x, M_y, and M_z. For convenience here, the x,y axes are taken to be in the loading plane and the z axis normal to the plane. To describe the extreme loading situations, a load matrix is often defined as shown in Table I.1.

Table I.1 – Extreme loading matrix

	F_x	F_y	F_z	M_x	M_y	M_z	F_R	θ_F	M_R	θ_M
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Min.										
Max.										
Max.										

In this table, each column represents a load component value delineated by the heading at the top. Each row represents contemporaneous values (i.e. all values occurring at the same time) and the shaded cell shows the specific component that has either a maximum or minimum value as indicated on the left. These maximum and minimum values are intended to cover the full range of values for that particular load component. The detailed structural model is then exercised using each of the rows to determine resulting local stress or strain values, which are compared to an appropriate failure criterion. When the structural stiffness and strength in response to loading in the plane is similar for the different loading directions, the most extreme loading can result when both x and y components are large in magnitude but not at their very largest values. Thus, the in-plane vector resultant values are also displayed in the additional columns on the right and the rows at the bottom. These in-plane resultants are defined as

$$F_R = \sqrt{F_x^2 + F_y^2} \text{ and } M_R = \sqrt{M_x^2 + M_y^2} \qquad (I.1)$$

The angular directions of these resultants are also defined as

$$\theta_F = \arctan\left(F_x / F_y\right) \text{ and } \theta_M = \arctan\left(M_x / M_y\right) \tag{I.2}$$

The values in the table are determined by post-processing analysis of the time series for the six load components determined as the outputs from the complete wind turbine dynamic simulation code. In this analysis, the time series are searched for the maximum and minimum values for each component as well as the maxima for the resultants. The contemporaneous values associated with each of these corresponding time points are then inserted in the rows of the table. Each of the load cases defined in Clause 7 are analysed in this way and the most extreme loading in each row from the different load cases is then used to define an overall loads envelope for that part of the wind turbine.

In Clauses I.2 and I.3, two approaches are given. Note that caution should be exercised in order to obtain conservative contemporaneous loads.

I.2 Scaling

- For each cross section and load component, one bin of the considered load case delivers the largest among candidate characteristic loads.
- A time series from this bin being close with its maximum within ±5 % to this characteristic load is selected.
- The maximum of this time series is scaled to the characteristic load. The obtained scaling factor is then also applied to all contemporaneous load components to this selected maximum of this time series.
- For each load component, one load case series is obtained to be used for extreme design load analysis.
- For minimum values, a corresponding procedure is applied considering appropriate scaling of magnitude.

I.3 Averaging

- For a load case consisting of more than one realization, the candidate characteristic maximum load is calculated as the mean of the maximum of all realizations.
- Contemporaneous loads are calculated as the mean of the absolute contemporaneous values of each realization. Signs on the contemporaneous loads are applied in accordance with the signs of the contemporaneous loads of the realization with the highest load.
- The candidate characteristic minimum load is calculated as the mean of the minimum of each realization. Contemporaneous loads are calculated in the same manner as in the positive case.
- The ultimate maximum and minimum characteristic loads are determined as the maximum and minimum, respectively, of the candidate characteristic loads described above with the corresponding contemporaneous values.

Annex J
(informative)

Prediction of the extreme wind speed of tropical cyclones by using Monte Carlo simulation method

J.1 General

In the areas where the strong wind is dominated by extratropical cyclones, the extreme wind speed can be estimated by using the Gumbel method for extended data obtained from a nearby reference meteorological station with the measure-correlate-predict (MCP) approach as described in Annex F. On the other hand, tropical and subtropical regions, where both tropical and extratropical cyclones are dominant, are known as mixed climates and the examination of each significant wind-producing meteorological phenomenon is required as mentioned by [2]. It was noticed that the MCP method without consideration for different type of storms underestimates the extreme wind speed in mixed climate regions.

Annex J describes a Monte Carlo simulation (MCS) method for the prediction of tropical cyclone induced extreme wind speeds. Refer to [1] for the detail of the MCS method.

J.2 Prediction of tropical cyclone induced extreme wind speeds

J.2.1 General

Monte Carlo simulation of tropical cyclones has been proposed (e.g. [3]) in order to obtain reliable statistical wind speed induced by tropical cyclones. The prediction of strong wind induced by tropical cyclones should be performed as follows.

J.2.2 Evaluation of tropical cyclone parameters

The number of tropical cyclones per year at specific site λ can be defined as the number of the tropical cyclones whose passes are included within the simulation circle (usually, the radius of which is 500 km) per year and obtained from the track records of past tropical cyclones. For each tropical cyclone, four tropical cyclone parameters, namely, the central pressure p_c, the translation speed C, the translation angle q measured counterclockwise positive from east and the minimum distance d_min when the cyclone approached the site of the interest most closely, are obtained from the historical track record of the tropical cyclones. The other tropical cyclone parameter is the radius of maximum wind speed R_m, which can be identified by the pressure field model proposed by [4].

$$\frac{p(r)-p_\mathrm{c}}{p_\infty - p_\mathrm{c}} = \exp\left(-\frac{R_\mathrm{m}}{r}\right)^B \tag{J.1}$$

where $p(r)$ is the sea surface pressure at the distance r from the centre of the tropical cyclone. R_m can be identified by the least square method using the measured sea surface pressure at the meteorological stations, and periphery pressure p_∞ can be assumed to be 1 013 hPa or identified simultaneously. The central pressure difference is defined as Δ or $i_\infty - p_\mathrm{c}$. In the case of B = 1,0, this relationship becomes the formulae proposed by [5].

These six parameters are approximated by analytical functions: Δh, R_m and C can be approximated by mixed probability density functions based on lognormal and Weibull distribution (e.g. [6]), q by normal or bi-normal distribution (e.g. [7]), d_min by a polynomial function and λ by Poisson's distribution. The correlations between these parameters except for λ should also be calculated.

J.2.3 Generation of synthetic tropical cyclones

Synthetic tropical cyclones are generated for long period to satisfy the modelled probability distribution functions and the correlations. The change in the pressure field of the tropical cyclones can be neglected since the wind speed and direction are estimated only when the tropical cyclone is located inside the simulation circle with the radius of 500 km.

A modified orthogonal decomposition (MOD) method should be used to satisfy the statistical distribution functions of the tropical cyclone parameters and the correlations between them at the same time, as proposed by [6]. The detailed procedure of the MOD method is described below.

Five parameters describing a tropical cyclone are normalized and written in vector form as follows.

$$\mathbf{x}^T = \left\{ \ln(\Delta p), \ \ \ln(R_\mathrm{m}), \ \ \ln(C), \ \ \theta, \ \ d_\mathrm{min} \right\} \tag{J.2}$$

The covariance matrix of x is defined as $\mathbf{S}$. The eigenvalues $\lambda^{(\mathrm{k})}$ and the eigenvectors $\mathbf{\Phi}^{(\mathrm{k})}$ are calculated by solving the following equation.

$$\left[\mathbf{S} - \lambda^{(\mathrm{k})}\mathbf{E} \right] \mathbf{\Phi}^{(\mathrm{k})} = 0 \tag{J.3}$$

The independent parameters $\mathbf{z}_\mathrm{i}$ with five components are then generated following the approximated distributions to the intended ones for specified years and the number of the generated vectors following the estimated annual occurrence rate. The correlated parameters $\mathbf{x}_\mathrm{i}$ can be obtained by the following equation.

$$\mathbf{x}_\mathrm{i} = \left[\mathbf{\Phi}^{(1)} \quad \mathbf{\Phi}^{(2)} \quad \cdots \quad \mathbf{\Phi}^{(5)} \right]^{-1} \mathbf{z}_\mathrm{i} \tag{J.4}$$

These vectors $\mathbf{x}_\mathrm{i}$ should be considered as the set of parameters for tropical cyclones. Note that although the correlations between each component of $\mathbf{x}_\mathrm{i}$ satisfy the intended correlations, the probability distributions of them do not follow the intended ones.

Finally, $\mathbf{x}_\mathrm{i}$ should be rearranged in an ascending order and modified so that its probability distribution follows the intended probability distributions. This operation hardly affects the correlations because it does not change the set of parameters.

J.2.4 Prediction of wind speeds in the tropical cyclone boundary

A tropical cyclone induced wind at the site of interest $\vec{\mathbf{x}}$ is affected by local topography. Wind speed $u_\mathrm{T}(\vec{\mathbf{x}})$ and direction $\theta_\mathrm{T}(\vec{\mathbf{x}})$ at the hub height can be written as

$$u_\mathrm{T}(\vec{\mathbf{x}}) = S_\mathrm{t} E_\mathrm{p} u_\mathrm{g}(\vec{\mathbf{x}}) \tag{J.5}$$

$$\theta_\mathrm{T}(\vec{\mathbf{x}}) = \theta_\mathrm{g}(\vec{\mathbf{x}}) - \gamma_\mathrm{p} + D_\mathrm{t} \tag{J.6}$$

where $u_\mathrm{g}(\vec{\mathbf{x}})$ and $\theta_\mathrm{g}(\vec{\mathbf{x}})$ are the gradient wind speed and direction (clockwise positive from south), E_p and γ_p are the wind profile factor and the inflow angle measured counterclockwise positive from the gradient wind velocity vector, S_t and D_t are the speed up ratio and the difference in wind direction due to local topography as functions of the wind direction ($\theta_g(\vec{\mathbf{x}}) - \gamma_p$) over flat terrain.

The gradient wind speed and direction at the site $\vec{\mathbf{x}}(r, \phi)$ can be calculated from the pressure field of the tropical cyclone assuming the balance among pressure gradient force, centrifugal force and Coriolis force.

$$u_g(\vec{\mathbf{x}}) = \frac{-C \sin(\phi - \theta) - fr}{2} + \sqrt{\left(\frac{-C \sin(\phi - \theta) - fr}{2}\right)^2 + \frac{r}{\rho}\frac{\partial p(r)}{\partial r}} \tag{J.7}$$

$$\theta_g(\vec{\mathbf{x}}) = \pi - \phi \tag{J.8}$$

where r is the distance from the centre of the tropical cyclone, ϕ is the angle measured counterclockwise positive from east, f is the Coriolis parameter, u_g and θ_g are the functions of time due to the motion of tropical cyclones.

The wind profile factor E_p and the inflow angle γ_p are used to calculate the wind speed at the hub height above the ground, which can be estimated by semi-theoretical formulae (e.g. [6]) or computational fluid dynamics (CFD). The speed up ratio S_t and the difference in wind direction D_t show the effect of local topography on the wind speed and direction. These factors are defined as functions of the wind direction over flat terrain and can be calculated by CFD (e.g. [8]).

Ten-minute average wind speed can be predicted by adding random values to the wind speed estimated by the wind field models. These random values are assumed to follow the lognormal distribution with the mean value of zero and the standard deviation of σ_a, which can be modelled as

$$\sigma_a = \gamma \times u_T(\vec{\mathbf{x}}) \tag{J.9}$$

Here, 0,1 was used for γ as proposed by [9].

J.3 Prediction of extreme wind speed in mixed climate regions

J.3.1 General

The relation between the return period R and the probability distribution of annual maximum wind speed $F(u)$ can be written as follows:

$$F(u) = 1 - 1/R \tag{J.10}$$

In mixed climate regions, the probability distributions should be evaluated separately for extratropical cyclones and tropical cyclones, and then combined probability distribution should be predicted.

J.3.2 Extreme wind distributions of extratropical cyclones by the MCP method

The extreme wind distribution (i.e. the probability distribution of annual maximum wind speed) of extratropical cyclones can be estimated by the MCP method from limited length of measurement data for N years at nearby reference meteorological station as follows.

a) First, the time series of the wind speed at the site for N years can be obtained from wind records at nearby reference station by using the MCP method or CFD method.

b) Next, the maximum wind speed $u_{\mathrm{E,i}}$ caused by extratropical cyclones in each calendar year at the site is extracted and ranked in ascending order from $u_{\mathrm{E,1}}$ to $u_{\mathrm{E,N}}$, for which a probability distribution of annual maximum wind speed induced by extratropical cyclones defined as Equation (J.11) is assigned.

$$F_{\mathrm{E}}(u_{\mathrm{E,i}}) = \frac{i}{N+1} \tag{J.11}$$

c) Then, $u_{\mathrm{E,i}}$ is plotted against a reduced variate $y_{\mathrm{E,i}}$, expressed as

$$y_{\mathrm{E,i}} = -\ln(-\ln(F_{\mathrm{E}}(u_{\mathrm{E,i}}))) \tag{J.12}$$

A best fitting function can be obtained by the least square method, and the extreme wind speed with specified return period can be predicted from this function.

J.3.3 Extreme wind distributions of tropical cyclones by the MCS method

The extreme wind distribution of tropical cyclones can be estimated from the M years of Monte Carlo simulation described in Clause J.2. The procedure is as follows:

a) From M years of Monte Carlo simulation of tropical cyclones, annual maximum wind speed can be extracted and ranked in the ascending order from $u_{\mathrm{T,1}}$ to $u_{\mathrm{T,M}}$. A probability distribution $F_{\mathrm{T}}(u_{\mathrm{T}})$ is assigned, and reduced variate $y_{\mathrm{T,i}}$ is calculated similarly.

b) Then, $u_{\mathrm{T,i}}$ is plotted against the reduced variate $y_{\mathrm{T,i}}$. In case of the MCS method, extrapolation of $F_{\mathrm{T}}(u_{\mathrm{T}})$ by the best fitting is not necessary since sufficient data are obtained.

J.3.4 Determination of extreme wind speed in a mixed climate region

The combined probability distribution of annual maximum wind speed can be obtained considering both extratropical and tropical cyclones. Assuming that wind speeds induced by extratropical cyclones and tropical cyclones are independent events, the combined probability distribution can be estimated by

$$F_{\mathrm{C}}(u_{\mathrm{C}}) = F_{\mathrm{E}}(u_{\mathrm{E}})F_{\mathrm{T}}(u_{\mathrm{T}}) \tag{J.13}$$

where $F_{\mathrm{C}}(u_{\mathrm{C}})$ denotes the combined probability distribution. It should be made sure that the predicted extreme wind speeds have comparable values with the measurement.

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Annex K
(informative)

Calibration of structural material safety factors and structural design assisted by testing

K.1 Overview and field of application

Annex K provides guidance on selection of partial safety factors for materials in Clauses K.2 to K.6 and on statistical analysis of tests for material parameters and resistances in Clauses K.7 to K.12.

K.2 Target reliability level

For calibration of partial safety factors, a measure of reliability should be identified with the survival probability $P_S = (1 - P_F)$, where P_F is the probability of failure[46] for the considered failure mode within an appropriate reference period. If the calculated failure probability is larger than a pre-set target value P_0, the structure should be considered to be unsafe.

An alternative measure of reliability is conventionally defined by the reliability index β which is related to P_F by

$$P_F = \Phi(-\beta) \quad \text{(K.1)}$$

where $\Phi(\ )$ is the cumulative distribution function of the standardized normal distribution.

A target value for the nominal failure probability for structural design for extreme and fatigue failure modes for a reference period of one year is

$$P_F^t = 5 \times 10^{-4} \quad \text{(K.2)}$$

The corresponding target value for the reliability index is $\beta^t = 3,3$. Application of this target value assumes that the risk to human lives is negligible in case of failure of a structural element, see [5]. The target reliability level is assumed to correspond to component class 2.

K.3 Safety formats

The resistance model is assumed to be obtained by the following general model:

$$R = b\,\delta\,R(X,a) \quad \text{(K.3)}$$

where

$R(X,a)$ is the resistance model as defined in a relevant structural and materials standard;

46 The probability of failure and its corresponding reliability index are notional values that do not necessarily represent the actual failure rates but are used as operational values for code calibration purposes and comparison of reliability levels of structures.

X is the strength (and stiffness) material parameter(s). Each of the strength parameters is modelled as a lognormal stochastic variable with coefficient of variation V_X;

a is the geometrical parameter(s);

δ is the model uncertainty related to resistance model (can be determined using the method in Clause K.12). δ is modelled as a lognormal stochastic variable with mean value 1 and coefficient of variation V_δ;

b is the bias in resistance model. b can be determined using the method in Clause K.12.

The design value of the resistance, R_d can be determined by different models[47].

a) Model 1 where design values are determined for the material strength parameters:

$$R_\text{d} = \frac{R(X_\text{d}, a_\text{d})}{\gamma_\Delta} \tag{K.4}$$

where

a_d is the design value for geometrical data;

X_d is the design values for strength parameters;

γ_Δ is the partial safety factor related to the model uncertainty for the resistance model including bias in resistance model.

If more than one strength parameter is used in the resistance model, then design values are applied for each strength parameter in Equation (K.4).

The design value of a strength parameter(s) X_d is determined by

$$X_\text{d} = \eta \frac{X_\text{k}}{\gamma_\text{m}} \tag{K.5}$$

where

η is the conversion factor taking into account load duration effects, moisture, temperature, scale effects;

X_k is the characteristic value of strength parameter generally defined by the 5 % quantile;

γ_m is the partial safety factor for strength parameter depending on the coefficient of variation V_X.

If the resistance model is linear in the strength parameters, then $R_\text{d} = R(X_\text{d}, a_\text{d})$ and X_d for each of the strength parameters is obtained using a partial safety factor $\gamma_\text{M} = \gamma_\text{m}\gamma_\Delta$.

The partial safety factor γ_Δ depends on the uncertainty of the resistance model, including bias:

$$\gamma_\Delta = \frac{\gamma_\delta}{b} \tag{K.6}$$

where

γ_δ is the partial safety factor depending on the model uncertainty with coefficient of variation V_δ without taking into account bias in the resistance model.

47 The following three models correspond to the basic resistance models in the Eurocodes [2].

b) Model 2 where a characteristic resistance is obtained using characteristic values of the material strength parameters, and the design value of the resistance is obtained from:

$$R_\mathrm{d} = \frac{R(\eta\, X_\mathrm{k}, a_\mathrm{k})}{\gamma_\mathrm{M}} \tag{K.7}$$

where

γ_M is the partial safety factor for the resistance related to the uncertainty of the resistance including uncertainty in material parameters, uncertainty in resistance model and bias.

The total uncertainty of the resistance depends on the model uncertainty δ, the bias of the resistance model and the uncertainty related to the strength parameters X though the resistance function $R(X,a)$. The material partial safety factors are correspondingly obtained from

$$\gamma_\mathrm{M} = \frac{\gamma_\delta \gamma_\mathrm{Rm}}{b} \tag{K.8}$$

where

γ_Rm is the partial safety factor depending on the resistance uncertainty with coefficient of variation V_Rm from the strength parameters though the resistance function $R(X,a)$;

γ_δ is the partial safety factor depending on the model uncertainty with coefficient of variation V_δ.

c) Model 3 where a characteristic resistance is estimated based on tests:

$$R_\mathrm{d} = \frac{R_\mathrm{k}}{\gamma_\mathrm{M}} \tag{K.9}$$

where

R_k is the characteristic resistance estimated based on tests, see Clause K.12. R_k is generally defined by the 5 % quantile;

γ_M is the partial safety factor for the resistance related to uncertainty of the resistance obtained based on tests, V_R.

The material partial safety factors should be calibrated such that failure probabilities for the relevant failure modes are close to the target reliability level in Equation (K.2) – see Clause K.4 – where relevant statistical uncertainty and uncertainty related to transformation from laboratory to real structure should be included.

K.4 Reliability-based calibration

The partial safety factors for loads and resistances are determined such that the failure probability obtained using the limit state function

$$g = R - S \tag{K.10}$$

is less than the target failure probability P_F^t. In Equation (K.10), the resistance is modelled by Equation (K.3) and S is the load effect. The corresponding design equation is

$$R_\mathrm{d} - \gamma_\mathrm{f} S_\mathrm{k} \geq 0 \tag{K.11}$$

where R_d is the design value of the resistance and S_k is the characteristic value of the load effect defined usually as the 98 % quantile in the distribution function for the annual maximum load effect corresponding to a 50 year return period. Other reference periods might also be used in some cases. γ_f is the load partial safety factor.

Table K.1 – Partial safety factor for model uncertainty, γ_δ [48]

Coefficient of variation for model uncertainty for resistance model in model 1, V_δ	≤ 5 %	10 %	15 %	20 %
γ_δ	1,20	1,25	1,35	1,45

If the load partial safety factors for ULS in 7.6 are used, then the partial safety factors are calibrated for a failure mode such that the reliability level becomes equal to the target reliability level P_F^t specified by Equation (K.2), see [5]. The recommended partial safety factors for Models 1 and 2 are γ_m = 1,0, γ_{Rm} = 1,0 and γ_δ as shown in Table K.1[49] [50]. For Model 3, the recommended partial safety factor is γ_M = 1,2, corresponding to the value of γ_δ for V_δ ≤ 5 % in Table K.1.

K.5 Calibration using the design value format

Alternatively, to the reliability-based method in Clause K.4 for calibration of partial safety factors, the design value format can be applied, see ISO 2394.

K.6 Partial safety factors for fatigue for welded details in steel structures

The SN-approach is assumed to be used together with the Miner's rule for linear fatigue accumulation[51].

For linear SN-curves, the number of cycles, N, to failure with constant stress range, $\Delta\sigma$, is written

$$N(\Delta\sigma) = \left(\frac{\Delta\sigma}{\Delta\sigma_C}\right)^{-m} 2 \times 10^6 = K\Delta\sigma^{-m} \tag{K.12}$$

48 The partial safety factors in Table K.1 are calibrated without taking into account the bias b and with the characteristic value for the model uncertainty equal to 1.

49 The reason that γ_m = 1,0 and γ_{Rm} = 1,0 is that the partial safety factor for resistance becomes independent of the uncertainty of the strength parameters because the 5 % quantile used to define the characteristic values covers the influence of this uncertainty. The characteristic value of the model uncertainty is defined as the mean value and therefore γ_δ depends on V_δ. V_δ should be determined from tests, see Clause K.12 (design assisted by testing) or from the literature.

50 The partial safety factor for a steel component with a yielding failure criteria becomes γ_M = 1,1 using coefficients of variation for yield strength equal to 5 % and for resistance model equal to 5 %, and bias equal to 1,1 (yield strength is less than 90 % of the tensile or compression strength).

The parametric formulas based on membrane theory in [6] for shell buckling applicable to tubular steel towers with D/t < 300 include a bias (design buckling curve is 85 % of the mean value of experimental values) and a model uncertainty with a coefficient of variation equal to 13 % implying that γ_M for buckling becomes 1,1.

51 Fatigue failure of welded details is considered in Clause K.6. The same principles could be used for fatigue failure of other fatigue critical details made by other materials such as composites and cast steel where the mean value of the fatigue load can be important.

where

$\Delta\sigma_C$ is the characteristic fatigue strength defined as the 5 % quantile;

m is the slope of SN-curve (Wöhler exponent);

K is the SN-curve parameter.

For variable amplitude fatigue loading, the design value of the Miner's sum should fulfil

$$\sum_i \frac{n_i}{2\times 10^6}\left(\frac{\gamma_n \gamma_{Ff} \Delta\sigma_i}{\Delta\sigma_C / \gamma_{Mf}}\right)^m \leq 1 \tag{K.13}$$

where

γ_n is the consequence of failure factor, see 7.6.1.3;

γ_{Ff} is the partial factor for fatigue load depending on uncertainties related to fatigue stresses;

γ_{Mf} is the partial factor for fatigue strength depending on uncertainties related to the SN-curve and the Miner's rule;

n_i is the number of cycles with fatigue stress range $\Delta\sigma_i$.

For non-linear SN-curves, the design value of the Miner's sum should fulfil

$$\sum_i \frac{n_i}{N\left(\gamma_n \gamma_{Mf} \gamma_{Ff} \Delta\sigma_i\right)} \leq 1 \tag{K.14}$$

The partial safety factors γ_{Mf} and γ_{Ff} in Tables K.2 and K.3 are calibrated such that failure probabilities for the relevant failure modes are close to the target reliability level in Clause K.2 for a welded structural detail in component class 2. The partial safety factor γ_{Ff} depends on the coefficient of variation, V_{Ff}, for the fatigue stresses.

The fatigue strength parameter, $\log K$, can be assumed normal distributed with coefficient depending on the actual SN-curve, but typically 0,2 for welded details. The Miner sum can be assumed lognormal distributed with coefficient of variation equal to 0,3. The uncertainty for the fatigue stress ranges can be assumed lognormal distributed with a coefficient of variation representing the uncertainty for the assessment of the fatigue load and the uncertainty for the calculation of stress ranges given the fatigue loading, see [5]. Normally, the coefficient of variation V_{Ff} can be taken as 0,15 to 0,20, see [5].

The required reliability can be achieved as follows.

a) Damage tolerant method:
   - selecting details, materials and stress levels so that in the event of the formation of cracks a low rate of crack propagation and a long critical crack length would result;
   - provision of multiple load path;
   - provision of crack-arresting details;
   - provision of readily inspectable details during regular inspections.

b) Safe-life method:
   - selecting details and stress levels resulting in a fatigue life sufficient to achieve the target value β^t at the end of the design service life. No inspections are required.

Table K.2 – Recommended values for partial safety factor for fatigue strength, γ_{Mf}

Assessment method	γ_{Mf}
Damage tolerant	1,10
Safe-life	1,25

Table K.3 – Recommended partial safety factor for fatigue stresses, γ_{Ff}

Coefficient of variation, V_{Ff}, for fatigue stress ranges	15 % to 20 %	20 % to 25 %	25 % to 30 %
γ_{Ff}	1,00	1,10	1,20

K.7 Types of tests for materials[52]

A distinction needs to be made between the following types of tests:

a) tests to establish directly the ultimate resistance or serviceability properties of structures or structural members for given loading conditions;

b) tests to obtain specific material properties using specified testing procedures; for instance, coupon tests for material properties for blades;

c) tests to reduce uncertainties in parameters used in resistance models; for instance by subcomponent and full-scale tests.

K.8 Planning of tests

K.8.1 General

Prior to the carrying out of tests, a test plan should be agreed with the testing organization. This plan should contain the objectives of the test and all specifications necessary for the selection or production of the test specimens, the execution of the tests and the test evaluation. The test plan should cover the following:

- objectives and scope;
- prediction of test results;
- specification of test specimens and sampling;
- loading specifications;
- testing arrangement;
- measurements;
- evaluation and reporting of the tests.

K.8.2 Objectives and scope

The objective of the tests should be clearly stated, for example the required properties, the influence of certain design parameters varied during the test and the range of validity. Limitations of the test and required conversions (e.g. scaling effects) should be specified.

52 Clauses K.8 to K.11 are based on ISO 2394:2015 [3] and EN 1990:2002 [2].

K.8.3 Prediction of test results

All properties and circumstances that can influence the prediction of test results should be taken into account, including

- geometrical parameters and their variability,
- geometrical imperfections,
- material properties,
- parameters influenced by fabrication and execution procedures, and
- scale effects of environmental conditions taking into account, and if relevant, any sequencing.

The expected modes of failure and/or calculation models, together with the corresponding variables should be described. If there is a significant doubt about which failure modes might be critical, then the test plan should be developed on the basis of accompanying pilot tests.[53]

K.8.4 Specification of test specimen and sampling

Test specimens should be specified, or obtained by sampling, in such a way as to represent the conditions of the real structure.

Factors to be taken into account include

- dimensions and tolerances,
- material and fabrication of prototypes,
- number of test specimens,
- sampling procedures, and
- restraints.

The objective of the sampling procedure should be to obtain a statistically representative sample. Attention should be drawn to any difference between the test specimens and the product population that could influence the test results.

K.8.5 Loading specifications

The loading and environmental conditions to be specified for the test should include

- loading points,
- loading history,
- restraints,
- temperatures,
- relative humidity,
- loading by deformation or force control, etc.

Load sequencing should be selected to represent the anticipated use of the structural member, under both normal and severe conditions of use. Interactions between the structural response and the apparatus used to apply the load should be taken into account where relevant.

Where structural behaviour depends upon the effects of one or more actions that will not be varied systematically, then those effects should be specified by their representative values.

53 Attention needs to be given to the fact that a structural member can possess a number of fundamentally different failure modes.

K.8.6 Testing arrangement

The test equipment should be relevant for the type of tests and the expected range of measurements. Special attention should be given to measures to obtain sufficient strength and stiffness of the loading and supporting rigs, and clearance for deflections, etc.

K.8.7 Measurements

Prior to the testing, all relevant properties to be measured for each individual test specimen should be listed. Additionally, a list should be made

a) of measurement-locations, and
b) of procedures for recording results, including if relevant,
   1) time histories of displacements,
   2) velocities,
   3) accelerations,
   4) strains,
   5) forces and pressures,
   6) required frequency,
   7) accuracy of measurements, and
   8) appropriate measuring devices.

K.8.8 Evaluation and reporting the test

For specific guidance, see Clause K.9. Any standards on which the tests are based should be reported.

K.9 General principles for statistical evaluations

When evaluating test results, the behaviour of test specimens and failure modes should be compared with theoretical predictions. When significant deviations from a prediction occur, an explanation should be sought: this might involve additional testing, perhaps under different conditions, or modification of the theoretical model.

The evaluation of test results should be based on statistical methods, with the use of available (statistical) information about the type of distribution to be used and its associated parameters. The methods given in Annex K may be used only when the following conditions are satisfied:

a) the statistical data (including prior information) are taken from identified populations which are sufficiently homogeneous; and
b) a sufficient number of observations is available.

At the level of interpretation of test results, three main categories can be distinguished.

- Where one test only (or very few tests) is (are) performed, no classical statistical interpretation is possible. Only the use of extensive prior information, associated with hypotheses about the relative degrees of importance of this information and of the test results, make it possible to present an interpretation as statistical (Bayesian procedures, see ISO 12491 [4]).
- If a larger series of tests is performed to evaluate a parameter, a classical statistical interpretation might be possible. This interpretation will still need to use some prior information about the parameter; however, this will normally be less than above.
- When a series of tests is carried out in order to calibrate a model (as a function) and one or more associated parameters, a classical statistical interpretation is possible.

The result of a test evaluation should be considered valid only for the specifications and load characteristics considered in the tests. If the results are to be extrapolated to cover other design parameters and loading, additional information from previous tests or from theoretical bases should be used.

K.10 Derivation of characteristic values

The derivation of a characteristic value from tests should take into account

a) the scatter of test data,

b) statistical uncertainty associated with the number of tests, and

c) prior statistical knowledge.

If the response of the structure or structural member or the resistance of the material depends on influences not sufficiently covered by the tests such as

- time and duration effects,
- scale and size effects,
- different environmental, loading and boundary conditions, and
- resistance effects,

then the calculation model should take such influences into account as appropriate.

K.11 Statistical determination of characteristic value for a single property

Clause K.11 gives expressions for deriving characteristic values from (a) test types and (b) a single property (for example, a strength)[54].

NOTE The expressions presented here, which use Bayesian procedures with "vague" prior distributions, lead to almost the same results as classical statistics with confidence levels equal to 75 %.

The table and expressions below are based on the following assumptions:

a) all variables follow either a normal or a lognormal distribution;

b) there is no prior knowledge about the value of the mean;

c) for the case "V_X unknown", there is no prior knowledge about the coefficient of variation;

d) for the case "V_X known", there is full knowledge of the coefficient of variation.

In practice, it is often preferable to use the case "V_X known" together with a conservative upper estimate of V_X, rather than to apply the rules given for the case "V_X unknown". Moreover, V_X, when unknown, should be assumed to be not smaller than 0,10.

The characteristic value of a property X should be found by using

$$X_k = m_X\left(1 - k_n V_X\right) \tag{K.15}$$

where m_X is the sample mean and the value of k_n can be found from Table K.4.

When using Table K.4, one of two cases should be considered as follows.

54 Adopting a lognormal distribution for certain variables has the advantage that no negative values can occur as for example for geometrical and resistance variables.

- The row "V_X known" should be used if the coefficient of variation, V_X, or a realistic upper bound of it, is known from prior knowledge[55].
- The row "V_X unknown" should be used if the coefficient of variation V_X is not known from prior knowledge and so needs to be estimated from the sample as:

$$m_x = \frac{1}{n}\sum x_i \tag{K.16}$$

$$s_X^2 = \frac{1}{n-1}\sum\left(x_i - m_X\right)^2 \tag{K.17}$$

$$V_X = \frac{s_X}{m_X} \tag{K.18}$$

Table K.4 – Values of k_n for the 5 % characteristic value

N	1	2	3	4	5	6	8	10	20	30	∞
V_X known	2,31	2,01	1,89	1,83	1,80	1,77	1,74	1,72	1,68	1,67	1,64
V_X unknown	-	-	3,37	2,63	2,33	2,18	2,00	1,92	1,76	1,73	1,64

Table K.4 is based on the normal distribution. With a lognormal distribution expression, Equation (K.15) becomes:

$$X_k = \exp\left(m_y - k_n s_y\right)$$

where

$$m_y = \frac{1}{n}\sum \ln\left(x_i\right)$$

If V_X is known from prior knowledge, $s_y = \sqrt{\ln\left(V_X^2 + 1\right)} \cong V_X$

If V_X is unknown from prior knowledge, $s_y = \sqrt{\frac{1}{n-1}\sum\left(\ln x_i - m_y\right)^2}$

K.12 Statistical determination of characteristic value for resistance models

K.12.1 General

Clause K.12 is mainly intended to define procedures (methods) for calibrating resistance models and for deriving design values from test type c), see Clause K.7. Use will be made of available prior information (knowledge or assumptions).

55 Prior knowledge can come from the evaluation of previous tests in comparable situations. What is "comparable" needs to be determined by engineering judgement.

Based on the observation of actual behaviour in tests and on theoretical considerations, a "design model" should be developed, leading to the derivation of a resistance function. The validity of this model should then be checked by means of a statistical interpretation of all available test data. If necessary, the design model is adjusted until sufficient correlation is achieved between the theoretical values and the test data.

Deviation in the predictions obtained by using the design model should also be determined from the tests. This deviation will need to be combined with the deviations of the other variables in the resistance function in order to obtain an overall indication of deviation. These other variables include:

- deviation in material strength and stiffness;
- deviation in geometrical properties.

The characteristic resistance should be determined by taking account of the deviations of all the variables.

The method is presented as a number of discrete steps, and some assumptions regarding the test population are made and explained; these assumptions are to be considered to be no more than recommendations covering some of the most common cases.

For the standard evaluation procedure, the following assumptions are made:

a) the resistance function is a function of a number of independent variables X;
b) a sufficient number of test results is available;
c) all relevant geometrical and material properties are measured;
d) there is no correlation (statistical dependence) between the variables in the resistance function;
e) all variables follow either a normal or a lognormal distribution[56].

The standard procedure comprises seven steps, see K.12.2 to K.12.8.

K.12.2 Step 1: Develop a design model

Develop a design model for the theoretical resistance r_{t} of the member or structural detail considered, represented by the resistance function:

$$r_{\mathrm{t}} = g_{r_{\mathrm{t}}}\left(\underline{X}\right) \tag{K.19}$$

The resistance function should cover all relevant basic variables $\underline{X}$ that affect the resistance at the relevant limit state.

All basic parameters should be measured for each test specimen and should be available for use in the evaluation.

K.12.3 Step 2: Compare experimental and theoretical values

Substitute the actual measured properties into the resistance function so as to obtain theoretical values $r_{\mathrm{t}i}$ to form the basis of a comparison with the experimental values $r_{\mathrm{e}i}$ from the tests.

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56 Adopting a lognormal distribution for a variable has the advantage that no negative values can occur.

The points representing pairs of corresponding values (r_{ti}, r_{ei}) should be plotted on a diagram, as indicated in Figure K.1.

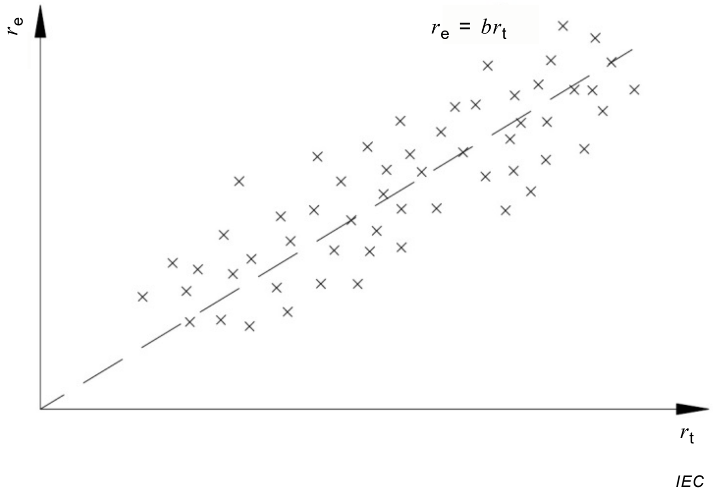

Figure K.1 – r_e-r_t diagram

If the resistance function is exact and complete, then all of the points will lie on the line with b = 1. In practice, the points will show some scatter, but the causes of any systematic deviation from that line should be investigated to check whether this indicates errors in the test procedures or in the resistance function.

K.12.4 Step 3: Estimate the mean value correction factor (bias) b

Represent the probabilistic model of the resistance r in the format

$$r = b\, r_t\, \delta \tag{K.20}$$

where

b is the least squares best-fit to the slope, given by

$$b = \frac{\sum r_{ei} r_{ti}}{\sum r_{ti}^2} \tag{K.21}$$

The mean value of the theoretical resistance function, calculated using the mean values $\underline{X}_m$ of the basic variables, can be obtained from

$$r_m = b\, r_t\left(\underline{X}_m\right)\, \delta = b\, g_{r_t}\left(\underline{X}_m\right)\, \delta \tag{K.22}$$

K.12.5 Step 4: Estimate the coefficient of variation of the errors

The error term δ_i for each experimental value r_{ei} should be determined from the expression

$$\delta_i = \frac{r_{ei}}{b\, r_{ti}} \tag{K.23}$$

From the values of δ_i an estimated value for V_δ should be determined by defining

$$\Delta_i = \ln(\delta_i) \tag{K.24}$$

The estimated value $\bar{\Delta}$ for $E(\Delta)$ should be obtained from

$$\bar{\Delta} = \frac{1}{n}\sum \Delta_i \tag{K.25}$$

The estimated value s_Δ^2 for σ_Δ^2 should be obtained from

$$s_\Delta^2 = \frac{1}{n-1}\sum\left(\Delta_i - \bar{\Delta}\right)^2 \tag{K.26}$$

The expression

$$V_\delta = \sqrt{\exp\left(s_\Delta^2\right) - 1} \tag{K.27}$$

may be used as the coefficient of variation V_δ of the δ_i error terms.

K.12.6 Step 5: Analyse compatibility

The compatibility of the test population with the assumptions made in the resistance function should be analysed.

If the scatter of the (r_{ti}, r_{ei}) values is too high to give economical design resistance functions, this scatter may be reduced in one of the following ways:

a) by correcting the design model to take into account parameters which had previously been ignored;
b) by modifying b and V_δ by dividing the total test population into appropriate subsets for which the influence of such additional parameters may be considered to be constant.

To determine which parameters have most influence on the scatter, the test results may be split into subsets with respect to these parameters.[57]

When determining the fractile factors k_n (see step 7), the k_n value for the subsets may be determined on the basis of the total number of the tests in the original series.

K.12.7 Step 6: Determine the coefficients of variation V_{Xi} of the basic variables

If it can be shown that the test population is fully representative of the variation in reality, then the coefficients of variation V_{Xi} of the basic variables in the resistance function may be determined from the test data. However, since this is not generally the case, the coefficients of variation V_{Xi} will normally need to be determined on the basis of some prior knowledge.

57 The purpose is to improve the resistance function per subset by analysing each subset using the standard procedure. The disadvantage of splitting the test results into subsets is that the number of test results in each subset can become very small.

K.12.8 Step 7: Determine the characteristic value r_k of the resistance

If the resistance function is of the form

$$r = b\, r_t\, \delta = b\, g_{r_t}\left(\underline{X_1,\ldots,X_j}\right)\delta \tag{K.28}$$

the mean value may be obtained from

$$E(r) = b\, g_{r_t}\left(E(X_1),\ldots,E(X_j)\right)\delta = b\, g_{r_t}\left(\underline{X}_m\right)\delta \tag{K.29}$$

and the coefficient of variation V_r may be approximated by

$$V_r^2 \cong V_\delta^2 + V_{r_t}^2 \tag{K.30}$$

where V_δ is obtained from Equation (K.30)[58] and the coefficient of variation V_{r_t} may be obtained from

$$V_{r_t}^2 = \frac{1}{g_{r_t}\left(\underline{X}_m\right)^2}\sum_{i=1}^{j}\left(\frac{\partial g_{r_t}\left(\underline{X}\right)}{\partial X_i}\sigma_i\right)^2 \tag{K.31}$$

where

σ_i is the standard deviation of X_i.

If the number of tests is limited (say n < 100), allowance should be made in the distribution of Δ for statistical uncertainties. The distribution should be considered as a central t-distribution with the parameters $\bar{\Delta}$, V_Δ and n.

The characteristic (5 % fractile) resistance r_k should be obtained from

$$r_k = b\, g_{r_t}\left(\underline{X}_m\right)\exp\left(-k_\infty\alpha_{\ln r_t}\sigma_{\ln r_t} - k_n\alpha_{\ln\delta}\sigma_{\ln\delta} - 0{,}5\sigma_{\ln r}^2\right) \tag{K.32}$$

with

$$\sigma_{\ln r} = \sqrt{\ln\left(V_r^2+1\right)}$$

$$\sigma_{\ln r_t} = \sqrt{\ln\left(V_{r_t}^2+1\right)}$$

$$\sigma_{\ln\delta} = \sqrt{\ln\left(V_\delta^2+1\right)}$$

58 The value of V_δ is estimated from the test sample under consideration.

$$\alpha_{\ln r_t} = \frac{\sigma_{\ln r_t}}{\sigma_{\ln r}}$$

$$\alpha_{\ln \delta} = \frac{\sigma_{\ln \delta}}{\sigma_{\ln r}}$$

where

k_n is the characteristic fractile factor from Table 5 with V_X unknown;

k_∞ is the value of k_n for $n \to \infty$ [k_∞ = 1,64];

$\alpha_{\ln r_t}$ is the weighting factor for $\sigma_{\ln r_t}$;

$\alpha_{\ln \delta}$ is the weighting factor for $\sigma_{\ln \delta}$.

K.13 Reference documents

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[5] Safety Factors – IEC 61400-1 ed. 4 – background document DTU Wind Energy-E-Report-0066(EN) (ISBN: 978-87-93278-08-0) November 2014 John Dalsgaard Sørensen, Henrik Stensgaard Toft

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Annex L
(informative)

Cold climate: assessment and effects of icing climate

L.1 Assessment of icing climate conditions

L.1.1 General

In icing climate conditions, meteorological icing is defined as the accretion of ice or snow on structures which are exposed to the atmosphere. In general, two different types of atmospheric icing that impact wind turbines can be distinguished: in-cloud icing (rime ice or glaze ice) and precipitation icing (freezing rain or drizzle, wet snow, see [1]). Typically in-cloud icing is more common and in many cases the frequency of in-cloud icing increases with increasing altitude. This is due to a higher probability of a structure being inside clouds and due to lower temperature.

Icing climate conditions can be assessed using various methods and measurement sensors. In order to assess icing climate effects for a wind turbine, the severity and duration of expected long-term rotor icing needs to be assessed. Clause L.1 describes some methods that can be used to assess expected rotor icing effects.

It is recommended to assess icing near blade tip or hub height (if necessary, extrapolate assessed icing to representative rotor icing height as presented in Equation (L.1)), use multiple ice detection methods in parallel for increased availability and reliability and use long-term site-specific data (preferably 10 years or more) to assess icing whenever possible as observed icing frequency may have a high inter-annual variation.

Additional information for guidance can be found in [3], [4], [5] and [6].

L.1.2 Icing climate

In general, an icing event can be described with the following expressions applicable to wind turbines exposed to meteorological icing (see Figure L.1).

- Meteorological icing: Period during which the meteorological conditions for ice accretion are favourable (active ice formation).
- Rotor icing[59]: Period during which a wind turbine rotor is disturbed by ice.
- Incubation time: Delay between the start of meteorological icing and the start of rotor icing (dependent on the surface, the temperature of the structure and the wind turbine operating point).
- Recovery time: Delay between the end of meteorological icing and the end of rotor icing (period during which the ice remains but is not actively formed).

59 The term "rotor icing" is used in this document instead of typical literature term "instrumental icing" because "rotor icing" specifies the phenomenon more accurately in case ice is affecting a rotating turbine rotor. For the rotating turbine rotor, high flow velocity and blade vibrations result to typically shorter incubation and recovery times than for stationary instruments.

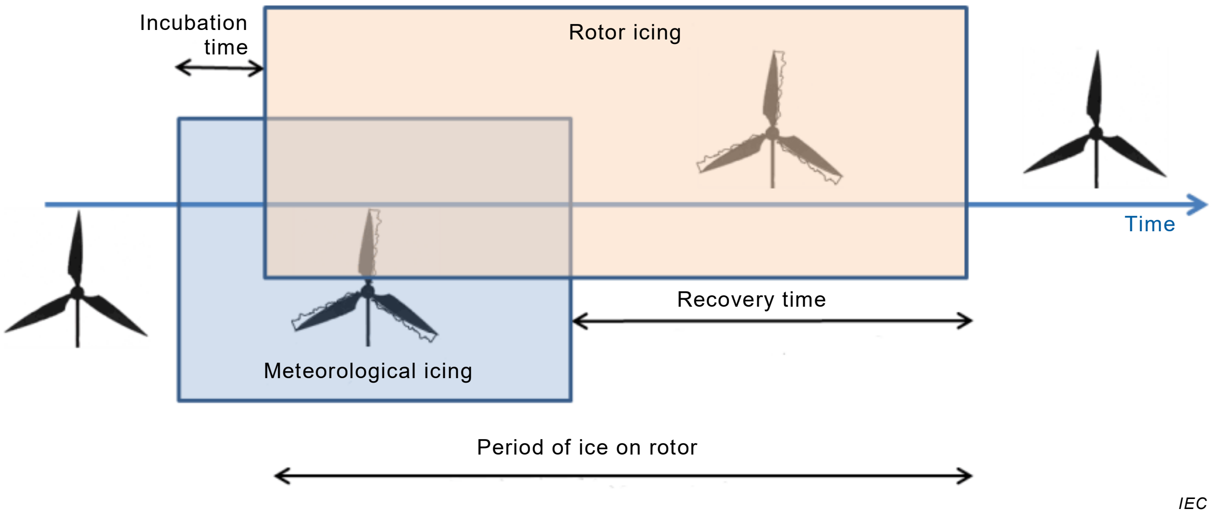

Figure L.1 – Definition of meteorological icing and rotor icing

L.1.3 Rotor icing

Rotor icing is defined as the period during which the wind turbine rotor is disturbed by ice. Ice is accreted continuously on a wind turbine rotor until the meteorological conditions for icing are not present anymore (end of the meteorological icing). Ice will remain at the wind turbine for a certain time – the recovery time – until ice erodes, sublimates, melts or sheds away from the rotor (end of the rotor icing).

In general, the frequency of meteorological in-cloud icing conditions increases significantly with altitude, thus a representative height above ground level for a wind turbine rotor is required to take these effects in to account. This representative height, rotor icing height (h_{ri}), is defined as:

$$h_{\mathrm{ri}} = z_{\mathrm{hub}} + \frac{1}{3}D \tag{L.1}$$

where

z_{hub} is hub height of the wind turbine [m];

D is the rotor diameter [m].

Figure L.2 illustrates the definition of rotor icing height. For cloud heights below the rotor icing height, it may be assumed that the complete rotor above is in cloud.

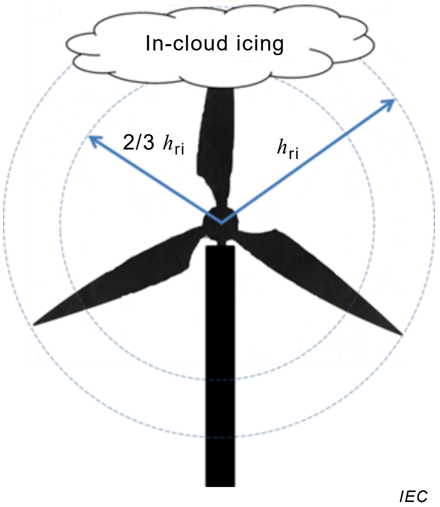

Figure L.2 – Representative ice affected rotor area as defined by rotor icing height

L.1.4 Measurement methods

Icing climate conditions may be assessed with following methods:

- use of dedicated ice detectors that measure severity and/or duration of meteorological and/or instrumental icing conditions;
- use pair of heated/unheated cup anemometers, which can be used to approximate the duration of instrumental icing;
- synoptic or camera system on stationary, for example met mast, or rotating component such as blades;
- measurements or observations via cloud base height and/or visibility and temperature;
- other validated method to assess meteorological icing.

Measurement equipment and/or the wind turbine may also be affected by a phenomenon called secondary icing. Secondary icing is formed through the process of ice accretion, melting and refreezing. Secondary icing may affect, for example, instrument availability and reliability.

Finally assessment of icing climate (IC) effects for wind turbines in terms of expected long-term rotor icing is needed. Typical severity and duration of IC effects on rotor blades presented in Clauses L.2 and L.3 may be used if no further data is available.

L.1.5 Profile coefficients modification for ice

Ice accretion on rotor blades deteriorates the airfoil aerodynamic performance characteristics versus clean airfoil performance. To account for the changes in airfoil performance, the following procedure for modifying the static airfoil characteristics may be used. It should be noted that the below mentioned range is arbitrary and should be chosen and evaluated according to the specific polar. Especially the merging into the background polar should be handled with care.

Airfoil penalty factors are to be multiplied with clean airfoil lift (C_L) and drag (C_D) coefficients for angles of attack from –2° to $\alpha = \alpha_{\mathrm{Clmax}}$. Coefficients outside this range may be extrapolated e.g. by Viterna [2] or similar method. The lift and drag penalties are a function of airfoil angle of attack as follows:

$$C_{\mathrm{L,pen}}(\alpha) = -0{,}0014\,\alpha^2 - 0{,}0017\,\alpha + 0{,}9509 \qquad \text{(L.2)}$$

$$C_{\mathrm{D,pen}}(\alpha) = 0{,}0191\,\alpha + 3{,}1151;$$

$$C_{\mathrm{L,Iced}} = C_{\mathrm{L,pen}} \times C_{\mathrm{L,clean}}$$

$$C_{\mathrm{D,Iced}} = \mathrm{C}_{\mathrm{D,pen}} \times C_{\mathrm{D,clean}}$$

where

$C_{\mathrm{L,pen}}$ is the clean airfoil lift coefficient penalty factor [-];

$C_{\mathrm{D,pen}}$ is the clean airfoil drag coefficient penalty factor [-];

α is the angle of attack [°].

There is no modification applied for moment coefficient (C_{m}). It should be noted that the angle of attack range from –2° is arbitrary and should be adjusted according to angle of attack definition. This value could be adjusted to approximately the mid-point between α_{Clmax} and α_{Clmin}.

Figure L.3 illustrates the penalty factors for iced airfoils. In the figure equations, x refers to the angle of attack, α, and y to the penalty factor.

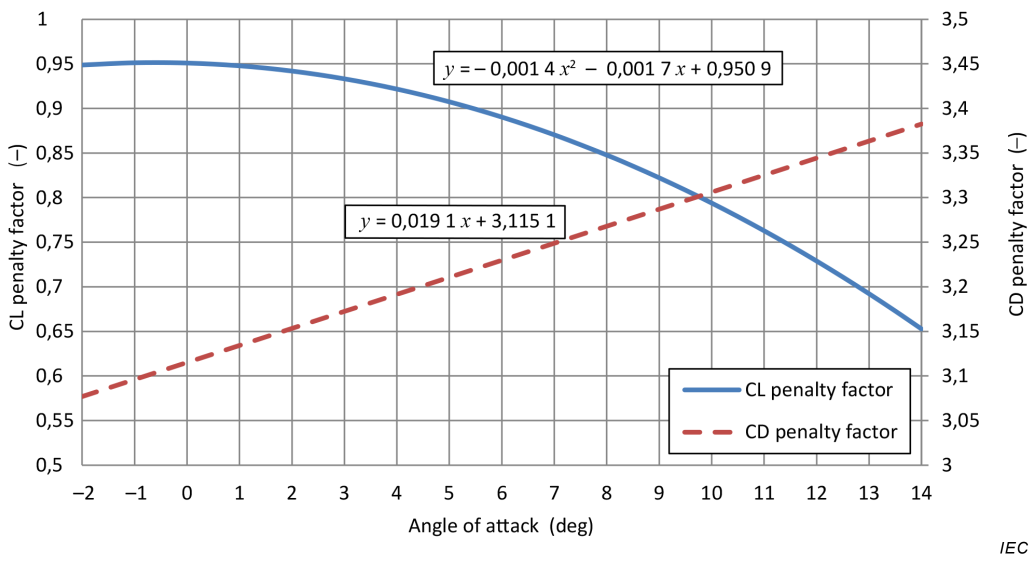

Figure L.3 – Iced airfoil lift and drag penalty factors

L.2 Ice mass effects on wind turbine blades

The duration ice remains on a rotor varies significantly geographically and from one year to another. It is recommended to assess the icing climate effects for a wind turbine with site measurements, see more guidance in Clause L.1. If no other information is available, 750 h of annual expected long-term rotor icing may be assumed.

The ice mass distribution (mass / unit length) for a wind turbine blade shall be assumed at the leading edge. It increases linearly from zero in the rotor axis to the maximum value at the rotor tip. The ice load distribution is calculated as follows:

$$M(r) = A \times C_{85\,\%} \times r \tag{L.4}$$

where

M is the mass distribution on the leading edge of the rotor blade [kg/m];

A is 0,125 [kg/m^3];

$C_{85\,\%}$ is the chord length at 85 % rotor radius [m];

r is the radial position from rotor axis [m].

L.3 Cold climate design situations and load case

L.3.1 General

Additional load cases according to cold climate conditions are listed in Table L.1.

Table L.1 – Cold climate design load cases

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1. Power production	1.6	NTM $V_{in} < V_{hub} < V_{out}$	Ice formation	F / U	N
6. Parked (standstill or idling)	6.5	NTM $V_{hub} < 0{,}7\ V_{ref}$	Ice formation	F / U	N
7. Parked and fault conditions	7.1	EWM 1-year return period	Ice formation	U	A

The duration ice remains on a rotor varies significantly geographically and from one year to another. It is recommended to assess the icing climate effects for a wind turbine with site measurements, see more guidance in Clause L.1. If no other information is available, 750 h of annual expected long-term rotor icing may be assumed.

L.3.2 Power production (DLC 1.1 to 1.6)

If icing of the blades can be expected and not actively prevented, safety of the turbine controller behaviour and turbine performance (Clause L.2) due to iced blades needs to be evaluated.

L.3.3 Parked (standstill or idling) (DLC 6.1 to 6.5)

For DLC 6.5 iced turbine idling, safety of the turbine controller behaviour needs to be evaluated.

L.3.4 Parked and fault conditions (DLC 7.1)

If no autonomous energy supply exists for the wind turbine, a cooling of the wind turbine down to $\theta_{1\text{year,min}}$ is to be assumed in case of grid failure. It shall be observed that low oil sump temperatures lead to significantly increased power train losses and damping, which obstruct free idling of the rotor. Iced turbine idling safety regarding turbine controller behaviour needs to be evaluated.

L.4 Cold climate load calculations

All load calculations are mainly for investigations regarding the behaviour and safety of turbine controller. Simulations with aerodynamic penalties according to Clause L.2 and ice induced rotor masses according to Clause L.3 may be implemented in the absence of other information. For ultimate load analysis, ice mass formation on all rotor blades except one and aerodynamic penalties on all rotor blades should be investigated. For fatigue analysis, ice mass on all rotor blades except one rotor blade where 50 % of the ice mass should be considered, in addition to aerodynamic penalties on all rotor blades, should be investigated. Increased air density according to 14.4 shall be used.[60] The approach is summarized in Table L.2.

For fatigue load analysis, ice mass distribution according to Equation (L.4) may be used. For ultimate load analysis, Formula (L.4) is to be increased by a factor of two.

Table L.2 – Blade ice mass and airfoil penalty factors used in different analysis types

Analysis Type	Blade No. 1	Blade No. 2	Blade No. N	Airfoil penalty factor, applied for all blades
Ultimate	Equation (L.4)	Equation (L.4)	-	Equations (L.2) and (L.3)
Fatigue	Equation (L.4)	Equation (L.4)	Equation (L.4) – 50 %	Equations (L.2) and (L.3)

L.5 Reference documents and bibliography

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[2] D.J. Larry Viterna, "Theoretical and Experimental Power From Large Horizontal Axis Wind Turbines," NASA, 1982

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60 Special care should be taken to investigate different lateral (perpendicular to main wind direction) stiffness and damping coefficients especially for foundations. Variations in these properties might significantly influence the effects of rotor mass imbalances.

Annex M
(informative)

Medium wind turbines

M.1 Overview

There is a significant market for the deployment of turbines in a size category smaller than typical utility size and larger than the category dealt with in IEC 61400-2. This category is referred to as "medium wind turbines". Depending on the application, it may be appropriate to use design requirements that differ from those in the main text.

Annex M provides information on design requirements that may be appropriate to medium wind turbines as defined in 3.29. All requirements described in this document shall be met with the following optional additions and clarifications for medium wind turbine systems.

M.2 External conditions

M.2.1 General

External conditions as defined in Clause 6 apply to medium wind turbine systems with the following clarifications.

Medium wind turbines may be installed in more complex terrain and/or near industrial areas. Therefore, it may be more appropriate to use a turbulence intensity class A+ or A for wind turbines in these environments.

M.2.2 Wind shear

On some medium wind turbine sites, higher shear exponents can arise in combination with high turbulence levels at such sites. Therefore, for a medium wind turbine, it may be appropriate to use a shear exponent, α, larger than 0,2. A shear exponent of $\alpha = 0{,}3$ provides a more conservative value of the wind profile for such sites.

A generic class wind turbine may also be designated with an "M" sub-class. If a value of $\alpha > 0{,}2$ is needed, the value shall be stated in the design documentation and the load analysis shall be executed with this value.

M.3 Assembly, installation and erection

Assembly, installation and erection of medium wind turbine systems shall meet the requirements described in Clause 12 with the following optional additional paragraphs.

12.6 Documentation

Additional paragraphs:

Information on the how to install, assemble and erect the turbine shall be specified in the documentation provided to the installer. This could include, but is not be limited to:

- details on the correct sequencing and assembly of the turbine installation;
- any general or specific training or competence standards recommended or mandated to enable contractors to undertake the installation safely and in accordance with local rules;
- technical and health and safety information regarding foundation installation, in case the turbine manufacturer is responsible for the foundation – if not, turbine loads and turbine-

foundation interface details, as well as any other turbine requirement to be taken into account for the correct foundation design and construction;

- technical and health and safety information regarding tower, blade and nacelle installation;
- technical and health and safety information regarding any other structure or system being installed (e.g. gearbox);
- technical and health and safety information regarding the installation of anchors or any equivalent systems;
- advice on site management, site access and the receiving handling and storage of the turbine and associate equipment to enable the protection of workers and others including the turbine and its components during the installation of the turbine;
- any specified loads or environmental conditions (e.g. wind speeds), including specified limits that need to be observed or not exceeded with specific reference to the installation of the tower and blades;
- technical and health and safety information necessary to enable the safe use of any specified equipment (e.g. cranes and lifting equipment) as part of the installation of the turbine;
- any additional or alternative requirements to safely decommission the turbine; and
- all necessary information to record and communicate the final as installed information to customers or end users.

Unless specific installation equipment is supplied by the manufacturer, the final selection of any equipment used or systems of work applied shall be the responsibility of the installer.

Any specific regulatory requirements or obligations relevant to the turbine and any duties mandated to fulfil national regulations in the jurisdiction supplied may be specified in the documentation provided.

Any specific standards or codes relevant to the turbine and any duties mandated to fulfil national standards and codes in the jurisdiction supplied may be specified in the documentation provided.

M.4 Commissioning, operation and maintenance

Commissioning, operation and maintenance of medium wind turbine systems shall meet the requirements described in Clause 13 with the following optional paragraphs.

13.1 General

Additional paragraphs:

Information and instruction on the how to operate and maintain the turbine shall be specified in the documentation provided to the operator. This shall include, but not be limited to:

- drawings, diagrams, descriptions and explanations necessary for the operation, maintenance, repair and testing of the wind turbine;
- instructions for training of operators and maintenance personnel, which shall indicate important aspects to be covered – as a minimum, description of access and egress to the wind turbine, climbing instructions, use of the lift, instructions about safe access to electrical installations and emergency escape procedures, maximum maintenance wind speed and the maximum number of persons allowed inside the nacelle or working on it;
- information about the maximum number of people allowed in different parts of the wind turbine at the same time;
- information about the protective measures to be taken by the operator including, where appropriate, the personal protective equipment (PPE) to be provided;

- requirements for maintenance, inspection and testing of safety critical components and systems;
- details of control and operating modes of the turbine control system;
- specification of rescue equipment;
- list of potential danger zones and specification of hazards associated with each potential danger zone;
- specification of fire extinguishers and their location;
- description of essential special tools to be used during maintenance and repair; and
- recommended service intervals for the turbine and the key components and systems;
- limits of stability during operation, maintenance, repair and breakdown. This includes description of the environmental limits to enter the turbine for maintenance work.

13.2 Design requirements for safe operation, inspection and maintenance

Additional paragraphs:

The protective measures that have been incorporated into the turbine shall be documented. This could include, but not be limited to:

– a description of significant hazards that may exist;
– specification of the limits of the wind turbine, including
  - the intended use of the wind turbine including different operating modes and intervention procedures for the operators,
  - the space limits defining working areas and access to them, operator-machine interfaces and machine-power supply interfaces,
  - any time limits specifying the design life of components critical to safety;
– details of the safety requirements and protective measures including the control systems that the turbine design has taken into account; and
– details of any residual risks that need to be brought to the attention of the buyer or operator of the turbine.

M.5 Documentation

All necessary manuals, diagrams, specifications, instructions, drawings or safety instructions sufficient to enable the safe and correct supply, assembly, installation, operation and maintenance of the wind turbine structure and equipment shall be provided as appropriate. The final scope and content of all information provided shall take into account:

a) risk assessments performed by the manufacturer;
b) the size and configuration of the turbine;
c) the applicable class and load characteristics of the turbine as supplied; and
d) site and environmental conditions for which the turbine is appropriate.

Documentation provided to the buyer shall be written in the English language and one or more official languages of the country in which the turbine is to be installed if English is not one of them. It shall include:

- the name of the manufacturer and its local representative, if a separate organization;
- the designation of the wind turbine, including name, model and class;
- any specified declarations of conformity; and
- a clear statement regarding the limitations regarding the operations that can be carried out by the buyer/user and those which should be entrusted to specialized/authorized

companies/technicians and the evidences these companies/technicians shall show to be allowed to carry out these operations.

All the documentation shall be arranged in a logical order and it shall be updated when new information becomes available. The content of the documentation shall also cover reasonably foreseeable misuse.

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62 Under preparation. Stage at the time of publication: IEC CDV 61400-6:2017.

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