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Wind turbines –

Part 1:
Design requirements

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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WIND TURBINES –

Part 1: Design requirements

FOREWORD

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

This third edition cancels and replaces the second edition published in 1999. It constitutes a technical revision.

The main changes with respect to the previous edition are listed below:

– the title has been changed to "Design requirements" in order to reflect that the standard presents safety requirements rather than requirements for safety or protection of personnel;
– wind turbine class designations have been adjusted and now refer to reference wind speed and expected value of turbulence intensities only;
– turbulence models have been expanded and include an extreme turbulence model;
– gust models have been adjusted and simplified;

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– design load cases have been rearranged and amended;
– the inclusion of turbulence simulations in the load calculations is emphasised and a scheme for extreme load extrapolation has been specified;
– the partial safety factors for loads have been adjusted and simplified;
– the partial safety factors for materials have been amended and specified in terms of material types and component classes;
– the requirements for the control and protection system have been amended and clarified in terms of functional characteristics;
– a new clause on assessment of structural and electrical compatibility has been introduced with detailed requirements for assessment, including information on complex terrain, earthquakes and wind farm wake effects.

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

FDIS	Report on voting
88/228/FDIS	88/232/RVD

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

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

IEC 61400 consists of the following parts under the general title *Wind turbine generator systems:*

Part 1: Design requirements

Part 2: Design requirements for small wind turbines

Part 11: Acoustic noise measurement techniques

Part 12: Wind turbine power performance testing

Part 13: Measurement of mechanical loads

Part 14: Declaration of apparent sound power level and tonality values

Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines

Part 23: Full-scale structural testing of rotor blades

Part 24: Lightning protection

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

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

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

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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 standard 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 standard does not relieve any person, organization, or corporation from the responsibility of observing other applicable regulations.

The standard is not intended to give requirements for wind turbines installed offshore, in particular for the support structure. A future document dealing with offshore installations is under consideration.

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WIND TURBINES –

Part 1: Design requirements

1 Scope

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

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

This standard applies to wind turbines of all sizes. For small wind turbines IEC 61400-2 may be applied.

This standard should be used together with the appropriate IEC and ISO standards mentioned in Clause 2.

2 Normative references

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

IEC 60204-1:1997, *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 a.c. or 1 500 V d.c. and not exceeding 36 kV*

IEC 60364 (all parts), *Electrical installations of buildings*

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

IEC 61000-6-1:1997, *Electromagnetic compatibility (EMC) – Part 6: Generic standards – Section 1: Immunity for residential, commercial and light-industrial environments*

IEC 61000-6-2:1999, *Electromagnetic compatibility (EMC) – Part 6: Generic standards – Section 2: Immunity for industrial environments 15*

IEC 61000-6-4:1997, *Electromagnetic compatibility (EMC) – Part 6: Generic standards – Section 4: Emission standard for industrial environments*

IEC 61024-1:1990, *Protection of structures against lightning – Part 1: General principles*

IEC 61312-1:1995, *Protection against lightning electromagnetic impulse – Part 1: General principle*

IEC 61400-21:2001, *Wind turbine generator systems – Part 21: Measurement and assessment of power quality characteristics of grid connected wind turbines*

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IEC 61400-24: 2002, *Wind turbine generator systems – Part 24: Lightning protection*

ISO 76:1987, *Rolling bearings – Static load ratings*

ISO 281:1990, *Rolling bearings – Dynamic load ratings and rating life*

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

ISO 2533:1975, *Standard Atmosphere*

ISO 4354:1997, *Wind actions on structures*

ISO 6336 (all parts), *Calculation of load capacity of spur and helical gears*

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

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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. The averaging time interval should be a whole number of years 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 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 and protection 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
cut-in wind speed
V_{in}
lowest wind speed at hub height at which the wind turbine starts to produce power in the case of steady wind without turbulence

3.10
cut-out wind speed
V_{out}
highest wind speed at hub height at which the wind turbine is designed to produce power in the case of steady wind without turbulence

3.11
design limits
maximum or minimum values used in a design

3.12
dormant failure
failure of a component or system which remains undetected during normal operation

3.13
downwind
in the direction of the main wind vector

3.14
electrical power network
particular installations, substations, lines or cables for the transmission and distribution of electricity

NOTE The boundaries of the different parts of this network are defined by appropriate criteria, such as geographical situation, ownership, voltage, etc.

3.15
emergency shutdown (wind turbines)
rapid shutdown of the wind turbine triggered by a protection function or by manual intervention

3.16
environmental conditions
characteristics of the environment (wind, altitude, temperature, humidity, etc.) which may affect the wind turbine behaviour

3.17
external conditions (wind turbines)
factors affecting operation of a wind turbine, including the environmental conditions (temperature, snow, ice, etc.) and the electrical network conditions

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3.18
extreme wind speed
value of the highest wind speed, averaged over t s, with an annual probability of exceedance of $1/N$ ("recurrence period": N years)

NOTE In this standard recurrence 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 standard, however, the turbine is designed using extreme wind speeds for design load cases.

3.19
fail-safe
design property of an item which prevents its failures from resulting in critical faults

3.20
gust
temporary change in the wind speed

NOTE A gust may be characterised by its rise-time, its magnitude and its duration.

3.21
horizontal axis wind turbine
wind turbine whose rotor axis is substantially horizontal

3.22
hub (wind turbines)
fixture for attaching the blades or blade assembly to the rotor shaft

3.23
hub height (wind turbines)
z_{hub}
height of the centre of the swept area of the wind turbine rotor above the terrain surface. (see 3.51, swept area)

3.24
idling (wind turbines)
condition of a wind turbine that is rotating slowly and not producing power

3.25
inertial sub-range
frequency interval of the turbulence spectrum, where eddies – after attaining isotropy – undergo successive break-up with negligible energy dissipation

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

3.26
limit state
state of a structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirement

[ISO 2394, modified]

NOTE 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).

3.27
logarithmic wind shear law
see 3.62

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

3.30
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

3.31
network loss
loss of network for period exceeding any ride through provision in the turbine control system

3.32
normal shutdown (wind turbines)
shutdown in which all stages are under the control of the control system

3.33
operating limits
set of conditions defined by the wind turbine designer that govern the activation of the control and protection system

3.34
parked wind turbine
depending on the design of the wind turbine, parked refers to the turbine being either in a standstill or an idling condition

3.35
power collection system (wind turbines)
electric system that collects the power from one or more wind turbines. It includes all electrical equipment connected between the wind turbine terminals and the network connection point

3.36
power law for wind shear
see 3.62

3.37
power output
power delivered by a device in a specific form and for a specific purpose

NOTE (wind turbines) The electric power delivered by a wind turbine

3.38
protection functions (wind turbine)
functions of the control and protection system which ensure that a wind turbine remains within the design limits

3.39
rated power
quantity of power assigned, generally by a manufacturer, for a specified operating condition of a component, device or equipment

NOTE (wind turbines) Maximum continuous electrical power output which a wind turbine is designed to achieve under normal operating and external conditions.

3.40
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

3.41
Rayleigh distribution
P_R
probability distribution function, see 3.63

3.42
reference wind speed
V_{ref}
basic parameter for wind speed used for defining wind turbine classes. Other design related climatic parameters are derived from the reference wind speed and other basic wind turbine class parameters (see Clause 6)

NOTE 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 recurrence period of 50 years at turbine hub height is lower than or equal to V_{ref}.

3.43
rotationally sampled wind velocity
wind velocity experienced at a fixed point of the rotating wind turbine rotor

NOTE 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.

3.44
rotor speed (wind turbines)
rotational speed of a wind turbine rotor about its axis

3.45
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

3.46
scheduled maintenance
preventive maintenance carried out in accordance with an established time schedule

3.47
site data
environmental, seismic, soil and electrical network data for the wind turbine site. Wind data shall be the statistics of 10 min samples unless otherwise stated

3.48
standstill
condition of a wind turbine that is stopped

3.49
support structure (wind turbines)
part of a wind turbine comprising the tower and foundation

3.50
survival wind speed
popular name for the maximum wind speed that a construction is designed to withstand

NOTE In this standard, the expression is not used. Design conditions instead refer to extreme wind speed (see 3.18).

3.51
swept area
projected area perpendicular to the wind direction that a rotor will describe during one complete rotation

3.52
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

3.53
turbulence scale parameter
Λ_1
wavelength where the non-dimensional, longitudinal power spectral density is equal to 0,05

NOTE The wavelength is thus defined as $\Lambda_1 = V_{hub}/f_0$, where $f_0 S_1(f_0)/\sigma_1^2 = 0{,}05$

3.54
turbulence standard deviation
σ_1
standard deviation of the longitudinal component of the turbulent wind velocity at hub height

3.55
ultimate limit state
limit states which generally correspond to maximum load carrying capacity

[ISO 2394, modified]

3.56
unscheduled maintenance
maintenance carried out, not in accordance with an established time schedule, but after reception of an indication regarding the state of an item

3.57
upwind
in the direction opposite to the main wind vector

3.58
vertical axis wind turbine
wind turbine whose rotor axis is vertical

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3.59
Weibull distribution
P_W
probability distribution function, see 3.63

3.60
wind farm
see 3.61

3.61
wind power station
group or groups of wind turbines, commonly called a wind farm

3.62
wind profile – wind shear law
mathematical expression for assumed wind speed variation with height above ground

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

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

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

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

3.63
wind speed distribution
probability distribution function, used to describe the distribution of wind speeds over an extended period of time

NOTE Often used distribution functions are the Rayleigh, $P_R(V_o)$, and the Weibull, $P_W(V_o)$, functions.

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

$$with\ V_{ave} = \begin{Bmatrix} C\,\Gamma(1+\frac{1}{k}) \\ C\sqrt{\pi}/2,\ if\ k = 2 \end{Bmatrix} \quad (4)$$

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;

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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 yield the corresponding probability density functions

3.64
wind shear
variation of wind speed across a plane perpendicular to the wind direction

3.65
wind shear exponent
α
also commonly known as power law exponent, see 3.62

3.66
wind speed
V
at a specified point in space it is the speed of motion of a minute amount of air surrounding the specified point

NOTE It is also the magnitude of the local wind velocity (vector) (see 3.69).

3.67
wind turbine generator system (wind turbine)
system which converts kinetic energy in the wind into electrical energy

3.68
wind turbine site
the location of an individual wind turbine either alone or within a wind farm

3.69
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 The vector at any point is thus the time derivative of the position vector of the air "parcel" moving through the point.

3.70
wind turbine electrical system
all electrical equipment internal to the wind turbine, up to and including the wind turbine terminals, including equipment for earthing, bonding and communications. Conductors local to the wind turbine, which are intended to provide an earth termination network specifically for the wind turbine, are included

3.71
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. This includes connection for the purposes of transferring energy and communications

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3.72
yawing
rotation of the rotor axis about a vertical axis (for horizontal axis wind turbines only)

3.73
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]
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}	expected value of hub-height turbulence intensity at a 10 min average wind speed of 15 m/s	[-]
I_{eff}	effective turbulence intensity	[-]
k	shape parameter of the Weibull distribution function	[-]
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	[-]
$N(.)$	is the 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	recurrence period for extreme situations	[years]
p	survival probability	[-]
$P_R(V_0)$	Rayleigh probability distribution, i.e. the probability that $V<V_0$	[-]
$P_W(V_0)$	Weibull probability distribution	[-]
r	magnitude of separation vector projection	[m]
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_k	one-sided velocity component spectrum	[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 recurrence 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_{out}	cut-out wind speed	[m/s]
V_r	rated wind speed	[m/s]
V_{ref}	reference wind speed	[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_{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 materials	[-]
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_e	extreme direction change with a recurrence period of N years	[deg]
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]
$\hat{\sigma}$	estimated turbulence standard deviation	[m/s]
$\hat{\sigma}_{eff}$	effective estimated turbulence standard deviation	[m/s]
σ_{wake}	wake turbulence standard deviation	[m/s]

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$\hat{\sigma}_T$	maximum centre-wake turbulence standard deviation	[m/s]
$\hat{\sigma}_\sigma$	standard deviation of estimated turbulence standard deviation $\hat{\sigma}$	[m/s]
σ_1	hub-height longitudinal wind velocity standard deviation	[m/s]
σ_2	hub-height vertical wind velocity standard deviation	[m/s]
σ_3	hub-height transversal wind velocity standard deviation	[m/s]
$E\langle\ \rangle$	expected value of parameter inside brackets	[-]
$Var\langle\ \rangle$	variance of parameter inside brackets	[-]

4.2 Abbreviations

A	abnormal (for partial safety factors)
a.c.	alternating current
d.c.	direct current
DLC	design load case
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
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)
U	ultimate

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 standard requires the use of a structural 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 standard.

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

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

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 of this standard.

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 is 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, $V_{in} - V_{out}$;
- 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 this clause 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, etc.

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

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 and turbulence parameters. 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. Table 1 specifies the basic parameters, which define the wind turbine classes.

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. 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.

The particular external conditions defined for classes I, II and III are neither intended to cover offshore conditions nor wind conditions experienced in tropical storms such as hurricanes, cyclones and typhoons. Such conditions may require wind turbine class S design.

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Table 1 – Basic parameters for wind turbine classes[1]

Wind turbine class		I	II	III	S
V_{ref}	(m/s)	50	42,5	37,5	Values specified by the designer
A	I_{ref} (-)	0,16			
B	I_{ref} (-)	0,14			
C	I_{ref} (-)	0,12			

In Table 1, the parameter values apply at hub height and

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

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 the expected value of the turbulence intensity[2] at 15 m/s.

In addition to these basic parameters, 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.

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

6.3 Wind conditions

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 recurrence period.

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[1] The annual average wind speed no longer appears in Table 1 as a basic parameter for the wind turbine classes in this edition of the standard. The annual average wind speed for wind turbine designs according to these classes is given in equation (9).

[2] Note that I_{ref} is defined as the mean value in this edition of the standard rather than as a representative value.

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 up to 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 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[3]:
   – 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

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

   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:

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

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

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.

The recommended turbulence model that satisfies these requirements is the Mann uniform shear turbulence model in Annex B. Another frequently used model that satisfy these requirements is also given in Annex B. Other models should be used with caution, as the choice may affect the loads significantly.

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

6.3.1 Normal wind conditions

6.3.1.1 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 over a time period of 10 min shall be assumed to follow a Rayleigh distribution at hub height given by

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

where, in the standard wind turbine classes, V_{ave} shall be chosen as

$$V_{\mathrm{ave}} = 0{,}2\ V_{\mathrm{ref}} \tag{9}$$

6.3.1.2 The 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:

$$V(z) = V_{\mathrm{hub}}\left(z/z_{\mathrm{hub}}\right)^{\alpha} \tag{10}$$

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.

6.3.1.3 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[4] for the given hub height wind speed. This value for the standard wind turbine classes shall be given by

$$\sigma_1 = I_{\mathrm{ref}}\left(0{,}75V_{\mathrm{hub}} + b\right); \quad b = 5{,}6\ \mathrm{m/s} \tag{11}$$

Values for the turbulence standard deviation σ_1 and the turbulence intensity $\sigma_1/V_{\mathrm{hub}}$ are shown in Figures 1a and 1b.

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

---

4 Note, if other quantiles are desired for additional optional load calculations, they may be approximated for the standard classes by assuming a log-normal distribution and

$$E\langle\sigma_1|V_{\mathrm{hub}}\rangle = I_{\mathrm{ref}}\left(0{,}75V_{\mathrm{hub}} + c\right); \ c = 3{,}8\ \mathrm{m/s}$$

$$Var\langle\sigma_1|V_{\mathrm{hub}}\rangle = \left(I_{\mathrm{ref}}\left(1{,}4\ \mathrm{m/s}\right)\right)^2$$

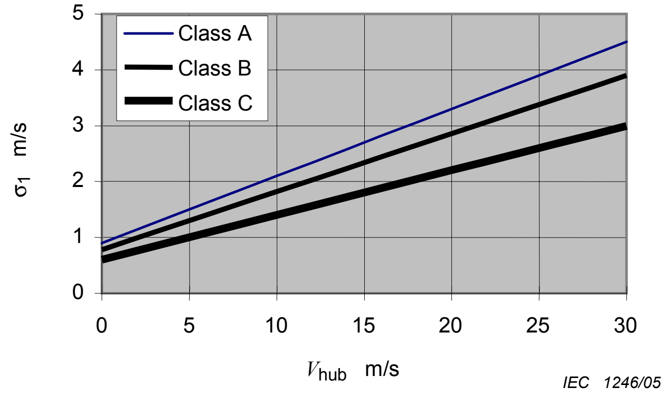

Figure 1a –Turbulence standard deviation for the normal turbulence model (NTM)

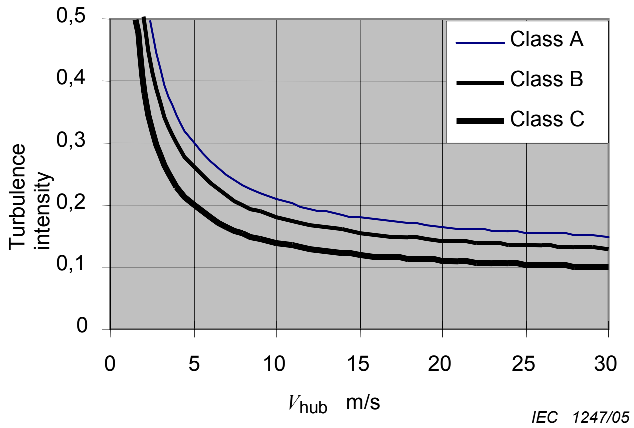

Figure 1b – Turbulence intensity for the normal turbulence model (NTM)

Figure 1 – Normal turbulence model (NTM)

6.3.2 Extreme wind conditions

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.

6.3.2.1 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.

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

$$V_{e50}(z) = 1{,}4\,V_{ref}\left(\frac{z}{z_{hub}}\right)^{0{,}11} \qquad (12)$$

and $V_{e1}(z) = 0{,}8\, V_{e50}(z)$ (13)

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 ±15º.

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

$$V_{50}(z) = V_{ref}\left(z / z_{hub} \right)^{0{,}11} \tag{14}$$

$$V_1(z) = 0{,}8\, V_{50}(z) \tag{15}$$

The longitudinal turbulence standard deviation[5] shall be:

$$\sigma_1 = 0{,}11\, V_{hub} \tag{16}$$

6.3.2.2 Extreme operating gust (EOG)

The hub height gust magnitude V_{gust}[6] shall be given for the standard wind turbine classes by the following relationship:

$$V_{gust} = \text{Min}\left\{ 1{,}35\,(V_{e1} - V_{hub});\quad 3{,}3\left(\frac{\sigma_1}{1 + 0{,}1\left(\frac{D}{\Lambda_1}\right)} \right) \right\} \tag{17}$$

where

σ_1 is given in equation (11);

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

D is the rotor diameter.

The wind speed shall be defined by the equation:

$$V(z,t) = \begin{cases} V(z) - 0{,}37\, V_{gust} \sin(3\pi t / T)\left(1 - \cos(2\pi t / T)\right) & \text{for } 0 \le t \le T \\ V(z) & \text{otherwise} \end{cases} \tag{18}$$

where

$V(z)$ is defined in equation (10)

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:

5 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.

6 The gust magnitude was calibrated to together with the probability of an operation event such as starts and stops to give a recurrence period of 50 years.

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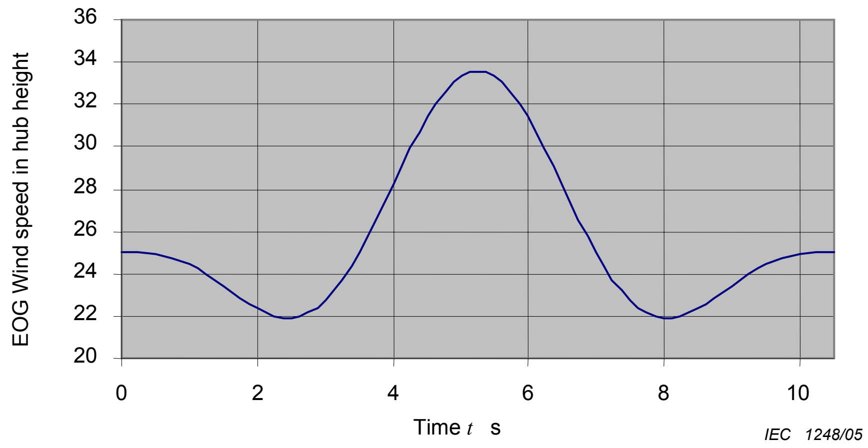

Figure 2 – Example of extreme operating gust

6.3.2.3 Extreme turbulence model (ETM)

The extreme turbulence model shall use the normal wind profile model in 6.3.1.2 and turbulence with longitudinal component standard deviation given by

$$\sigma_1 = c \quad I_{\text{ref}} \left(0{,}072 \left(\frac{V_{\text{ave}}}{c} + 3 \right) \left(\frac{V_{\text{hub}}}{c} - 4 \right) + 10 \right); \; c = 2 \;\; \text{m/s.} \tag{19}$$

6.3.2.4 Extreme direction change (EDC)

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

$$\theta_e = \pm 4 \arctan \left(\frac{\sigma_1}{V_{\text{hub}} \left(1 + 0{,}1 \left(\frac{D}{\Lambda_1} \right) \right)} \right) \tag{20}$$

where

σ_1 is given by equation (11) for the NTM;

θ_e is limited to the interval ±180°;

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

D is the rotor diameter.

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

$$\theta(t) = \begin{cases} 0^\circ & \text{for} \quad t < 0 \\ \pm 0{,}5\theta_e (1 - \cos(\pi t / T)) & \text{for} \quad 0 \le t \le T \\ \theta_e & \text{for} \quad t > T \end{cases} \tag{21}$$

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 6.3.1.2.

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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.

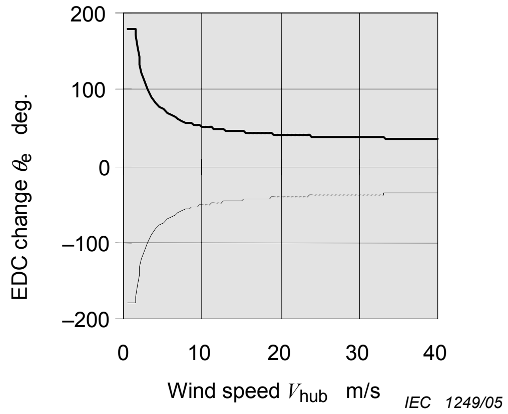

Figure 3 – Example of extreme direction change magnitude

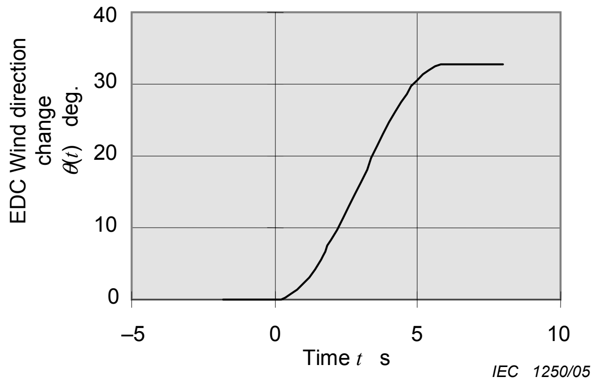

Figure 4 – Example of extreme direction change

6.3.2.5 Extreme coherent gust with direction change (ECD)

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

$$V_{cg} = 15 \text{ m/s} \tag{22}$$

The wind speed shall be defined by

$$V(z,t) = \begin{cases} V(z) & \text{for} \quad t \le 0 \\ V(z) + 0{,}5V_{cg}\left(1 - \cos(\pi t / T)\right) & \text{for} \quad 0 \le t \le T \\ V(z) + V_{cg} & \text{for} \quad t \ge T \end{cases} \tag{23}$$

where T = 10 s is the rise time and the wind speed $V(z)$ is given by the normal wind profile model in 6.3.1.2. The rise in wind speed during the extreme coherent gust is illustrated in Figure 5 for V_{hub} = 25 m/s.

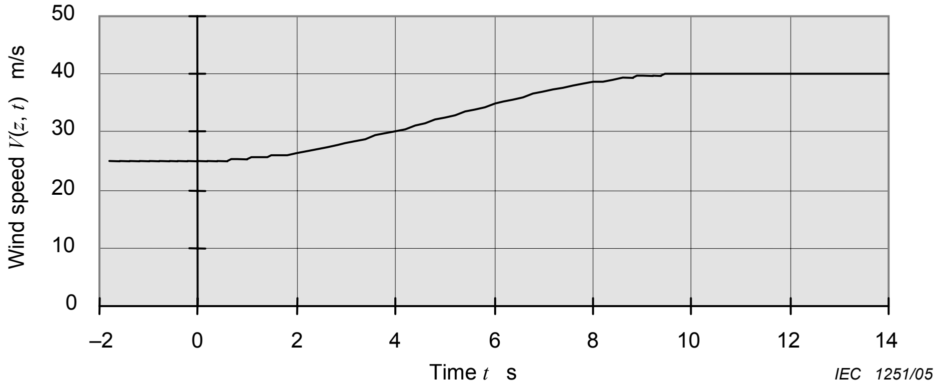

Figure 5 – Example of extreme coherent gust amplitude for ECD

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

$$\theta_{cg}(V_{hub}) = \begin{cases} 180^\circ & \text{for } V_{hub} < 4\,\text{m/s} \\ \dfrac{720^\circ\ \text{m/s}}{V_{hub}} & \text{for } 4\,\text{m/s} < V_{hub} < V_{ref} \end{cases} \tag{24}$$

The simultaneous direction change is then given by

$$\theta(t) = \begin{cases} 0^\circ & \text{for} \quad t < 0 \\ \pm 0{,}5\theta_{cg}\left(1 - \cos(\pi t / T)\right) & \text{for} \quad 0 \le t \le T \\ \pm\theta_{cg} & \text{for} \quad t > T \end{cases} \tag{25}$$

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.

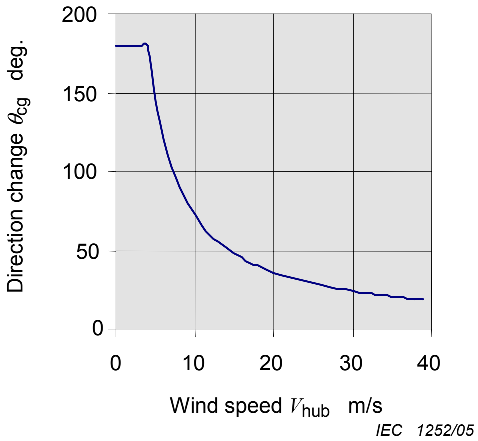

Figure 6 – Direction change for ECD

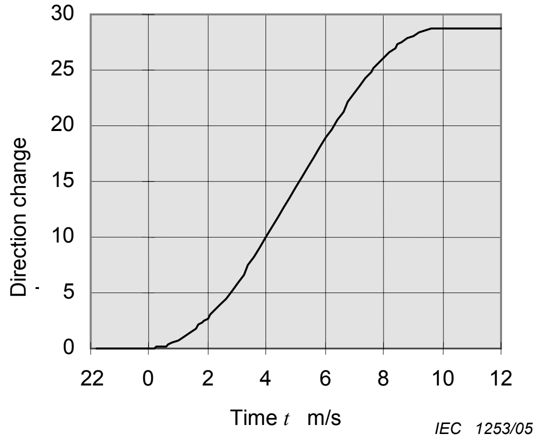

Figure 7 – Example of direction change transient

6.3.2.6 Extreme wind shear (EWS)

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

Transient (positive and negative) vertical shear:

$$V(z,t)=\begin{cases} V_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} \pm \left(\frac{z-z_{hub}}{D}\right)\left(2{,}5+0{,}2\beta\sigma_1\left(\frac{D}{\Lambda_1}\right)^{1/4}\right)\left(1-\cos\left(2\pi t/T\right)\right) & \text{for } 0\le t\le T \\ V_{hub}\left(\frac{z}{z_{hub}}\right)^{\alpha} & \text{otherwise} \end{cases} \tag{26}$$

Transient horizontal shear:

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

where for both vertical and horizontal shear:

α = 0,2; β = 6,4; T = 12 s;

σ_1 is given by equation (11) for the NTM;

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

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.

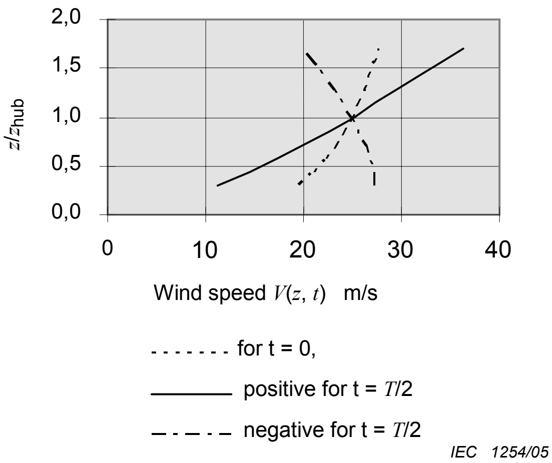

Figure 8 – Examples of extreme positive and negative vertical wind shear, wind profile before onset (t = 0, dashed line) and at maximum shear (t = 6 s, full line).

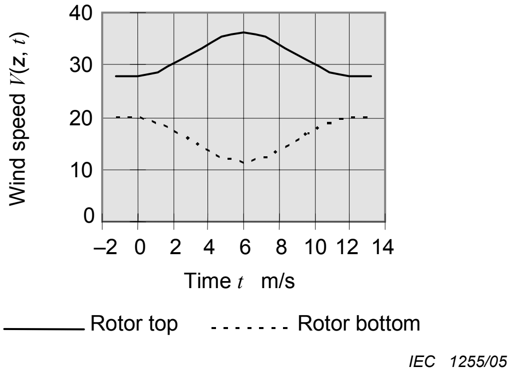

Figure 9 – Example of wind speeds at rotor top and bottom, respectively, illustrate the transient positive wind shear

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).

6.4 Other environmental conditions

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.

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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 recurrence period shall not interfere with the designed normal operation of a wind turbine.

Unless correlation exists, other extreme environmental conditions according to 6.4.2 shall be combined with normal wind conditions according to 6.3.1.

6.4.1 Normal other environmental conditions

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

- 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.

6.4.2 Extreme other environmental conditions

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).

6.4.2.1 Temperature

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

6.4.2.2 Lightning

The provisions of lightning protection required in 10.6, may be considered as adequate for turbine designs for the standard wind turbine classes.

6.4.2.3 Ice

No minimum ice requirements are given for the standard wind turbine classes.

6.4.2.4 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 C.

6.5 Electrical power network conditions

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

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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 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[7] 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 and/or tests 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 with the safety factors appropriate for the characteristic loads according to 7.6.

7.2 Design methodology

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

7.3 Loads

Loads described in 7.3.1 through 7.3.4, shall be considered for the design calculations.

7.3.1 Gravitational and inertial loads

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

7.3.2 Aerodynamic loads

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

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

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[7] Six hours of operation is assumed to correspond to the duration of the severest part of a storm.

7.3.3 Actuation loads

Actuation loads result from the operation and control of wind turbines. They are in several categories including torque control from a generator/inverter, yaw and pitch actuator loads and mechanical braking loads. In each case, it is important in the calculation of response and loading to consider the range of actuator forces available. In particular, for mechanical brakes, the range of friction, spring force or pressure as influenced by temperature and ageing shall be taken into account in checking the response and the loading during any braking event.

7.3.4 Other loads

Other loads such as wake loads, impact loads, ice loads, etc. may occur and shall be included where appropriate, see 11.4.

7.4 Design situations and load cases

This subclause 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 and protection system. The design load cases used to verify the structural integrity of a wind turbine shall be calculated by combining:

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

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

Within each design situation several design load cases shall be considered. As a minimum the design load cases in Table 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 could, during design load cases with a deterministic wind model, cause the wind turbine to shutdown prior to reaching maximum yaw angle and/or wind speed, then it must be shown that the turbine can reliably shutdown under turbulent conditions with the same deterministic wind condition change.

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

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

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Table 2 – Design load cases

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	$V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM	$V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	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, protection, or electrical system faults including loss of electrical network	F	*
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 shut down	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 shut down	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 recurrence period		U	N
	6.2	EWM	50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM	1-year recurrence 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 recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM	V_{maint} to be stated by the manufacturer		U	T
	8.2	EWM	1-year recurrence period		U	A

The following abbreviations are used in Table 2:

DLC	Design load case
ECD	Extreme coherent gust with direction change (see 6.3.2.5)
EDC	Extreme direction change (see 6.3.2.4)
EOG	Extreme operating gust (see 6.3.2.2)
EWM	Extreme wind speed model (see 6.3.2.1)
EWS	Extreme wind shear (see 6.3.2.6)
NTM	Normal turbulence model (see 6.3.1.3)
ETM	Extreme turbulence model (see 6.3.2.3)
NWP	Normal wind profile model (see 6.3.1.2)
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
T	Transport and erection
*	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[8]. In the definition of the design load cases reference is made to the wind conditions described in Clause 6.

7.4.1 Power production (DLC 1.1 – 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 (DLC) 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 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 these parameters are exceeded by the extreme design values derived for DLC 1.3, the further analysis of DLC 1.1 may be omitted.

If the extreme design values of these parameters are not exceeded by the extreme design values derived for DLC 1.3, the factor c in equation (19) for the extreme turbulence model used in DLC 1.3 may be increased until the extreme design values computed in DLC 1.3 are equal or exceed the extreme design values of these parameters computed in DLC 1.1.

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

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

This design situation involves a transient event triggered by a fault or the loss of electrical network connection while the turbine is producing power. Any fault in the control and protection system, or internal fault in the electrical system, significant for wind turbine loading (such as generator short circuit) shall be considered. For DLC 2.1 the occurrence of faults relating to control functions or loss of electrical network connection shall be considered as normal events. For DLC 2.2, rare events, including faults relating to the protection functions or internal electrical systems shall be considered as abnormal. For DLC 2.3 the potentially significant wind event, EOG, is combined with an internal or external electrical system fault (including loss of electrical network connection) and considered as an abnormal event. In this case, the timing of these two events shall be chosen to achieve the worst loading. If a fault or loss of electrical network connection does not cause an immediate shutdown and the subsequent loading can lead to significant fatigue damage, the likely duration of this situation along with the resulting fatigue damage in normal turbulence conditions (NTM) shall be evaluated in DLC 2.4.

7.4.3 Start up (DLC 3.1 – 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.

7.4.4 Normal shut down (DLC 4.1 – 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.

7.4.5 Emergency shut down (DLC 5.1)

Loads arising from emergency shut down shall be considered.

7.4.6 Parked (standstill or idling) (DLC 6.1 – 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.

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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.

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

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.

7.4.7 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. If any fault other than a loss of electrical power network produces deviations from the normal behaviour of the wind turbine in parked situations, the possible consequences shall be the subject of analysis. The fault condition shall be combined with EWM for a recurrence 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. 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.

7.4.8 Transport, assembly, maintenance and repair (DLC 8.1 – 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. It may be assumed that all blades are installed simultaneously. 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. In particular, application of maximum design actuator forces shall be taken into account.

7.5 Load calculations

Loads as described in 7.3.1 through 7.3.4 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;
- aero elastic effects;
- the behaviour of the control and protection 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.

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.

7.6 Ultimate limit state analysis

7.6.1 Method

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

7.6.1.1 Partial safety factors for loads and materials

To assure safe design values for the uncertainties and variability in loads and materials are taken into account by partial safety factors as defined in equations (28) and (29).

$$F_{\mathrm{d}} = \gamma_{\mathrm{f}} F_{\mathrm{k}} \tag{28}$$

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;

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γ_f is the partial safety factor for loads; and

F_k is the characteristic value for the load.

$$f_d = \frac{1}{\gamma_m} f_k \tag{29}$$

where

f_d are the design values for materials;

γ_m are the partial safety factors for materials; and

f_k are the characteristic values of material properties.

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

- possible unfavourable deviations/uncertainties of the load from the characteristic value;
- uncertainties in the loading model.

The partial safety factors for materials used in this standard, 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;
- uncertainties in conversion factors.

These different uncertainties are sometimes accounted for by means of individual partial safety factors but in this standard as in most others, the load related factors are combined into one factor γ_f and the material related factors into one factor γ_m.

7.6.1.2 Partial safety factor for consequence of failure and component classes

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

- 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.
- Component class 2: used for "non fail-safe" structural components whose failures may lead to the failure of a major part of a wind turbine.
- Component class 3: used for “non fail-safe” mechanical components that link actuators and brakes to main structural components for the purpose of implementing non-redundant wind turbine protection functions described in 8.3.

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);
- analysis of fatigue failure (see 7.6.3);
- stability analysis (buckling, etc.) (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.

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7.6.1.3 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 standard. It shall be ensured that the resulting safety level is not less than the intended safety level in this standard.

Different codes subdivide the partial safety factors for materials, 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. The material factors given in this standard correspond to the so-called "general partial safety factors for materials" accounting for the inherent variability of the strength parameters. 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 factorisations 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 standard.

7.6.2 Ultimate strength analysis

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

$$\gamma_n \cdot S(F_d) \leq R(f_d) \tag{30}$$

The resistance R generally corresponds with the maximum allowable design values of material resistance, hence $R(f_d) = f_d$, whilst 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

$$\gamma_f F_k \leq \frac{1}{\gamma_m \gamma_n} f_k \tag{31}$$

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 (31) shall be verified for the most critical limit state, identified on the basis of having the least margin.

In load cases involving turbulent inflow where a range of wind speeds is given, the exceedance probability for the characteristic load shall be calculated considering the wind speed distribution given in 6.3.1.1. Because many load calculations will involve stochastic simulations of limited duration, the characteristic load determined for the required recurrence period may be larger than any of the values computed in the simulation. Guidance for the calculation of characteristic loads using turbulent inflow is given in Annex F.

For DLC 1.1 the characteristic value of load shall be determined by a statistical load extrapolation and correspond to an exceedance probability, for the largest value in any 10-min period, of less than or equal to $3{,}8 \times 10^{-7}$, (i.e. a 50-year recurrence period) for normal design situations. For guidance see Annex F.

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For load cases with specified deterministic wind field events, the characteristic value of the load shall be the worst case computed transient value. When turbulent inflow is used, the mean value among the worst case computed loads for different 10-min stochastic realisations shall be taken, except for DLC 2.1, 2.2 and 5.1, where the characteristic value of the load shall be the mean value of the largest half of the maximum loads.

7.6.2.1 Partial safety factors for loads

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

Table 3 – Partial safety factors for loads γ_f

Unfavourable loads			Favourable[9] loads
Type of design situation (see Table 2)			All design situations
Normal (N)	Abnormal (A)	Transport and erection (T)	
1,35*	1,1	1,5	0,9

* For design load case DLC 1.1, given that loads are determined using statistical load extrapolation at prescribed wind speeds between V_{in} and V_{out}, the partial load factor for normal design situations 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

$$\gamma_f = 1{,}1 + \varphi \varsigma^2$$

$$\varphi = \begin{cases} 0{,}15 & \text{for DLC1.1} \\ 0{,}25 & \text{otherwise} \end{cases}$$

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

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 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.

7.6.2.2 Partial safety factors for materials where recognized design codes are not available

Partial safety factors for materials shall be determined in relation to the adequacy of the available material properties test data. The value of the general partial safety factor for materials, γ_m, and accounting for the inherent variability of the strength parameter shall be

$$\gamma_m \ge 1{,}1 \qquad (32)$$

9 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 (30) becomes

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

when applied to characteristic material properties of 95 % survival probability, p, with 95 % confidence limit[10]. This value applies to components with ductile behaviour[11] whose failure may lead to the failure of a major part of a wind turbine, for example welded tubular tower, tower flange connection, welded machine frame or blade connections. Failure modes may comprise:

- yielding of ductile materials;
- bolt rupture in a bolt connection with sufficient number of bolts to provide $1/\gamma_m$ of the strength following the failing of a single bolt.

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

- 1,2 for global buckling of curved shells such as tubular towers and blades, and
- 1,3 for rupture from exceeding tensile or compression strength.

To derive the global partial safety factors for materials from this general factor it is necessary to account for scale effects, tolerances and degradation due to external actions, for example ultraviolet radiation or humidity and defects that would not normally be detected.

Partial safety factors for consequences of failure:

Component class 1: $\gamma_n = 0,9$

Component class 2: $\gamma_n = 1,0$

Component class 3: $\gamma_n = 1,3$

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

The combined partial safety factors for loads, materials and the consequences of failure, γ_f, γ_m, and γ_n, shall be not less than those specified in 7.6.2.1 and 7.6.2.2.

7.6.3 Fatigue failure

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 G.

7.6.3.1 Partial safety factor for loads

The partial safety factor for loads, γ_f, shall be 1,0 for all normal and abnormal design situations.

10 The characteristic strength parameters should be selected as the 95 % fractile (determined with 95 % confidence) or the certificate value for materials with established routines for testing of representative samples.

11 Ductile behaviour includes not only ductile materials but also components which behave like ductile materials due to, for example internal redundancy.

7.6.3.2 Partial safety factors for materials where recognized codes are not available

The partial safety factor for materials γ_m shall be at least 1,5 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[12], i.e. 15 % to 20 % (such as for many components made of composites, for example reinforced concrete or fibre composites), the partial safety factor γ_m must be increased accordingly and at least to 1,7.

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 1,1. In cases, where it is possible to detect critical crack development through introduction of a periodic inspection programme, a lower value of γ_m may be used. In all cases, γ_m shall be larger than 0,9.

For fibre composites, the strength distribution shall be established from test data for the actual material. The 95 % survival probability with a confidence level of 95 % shall be used as a basis for the SN-curve. In that case γ_m may be taken as 1,2. The same approach may be used for other materials.

Partial safety factors for consequences of failure:

Component class 1: γ_n = 1,0

Component class 2: γ_n = 1,15

Component class 3: γ_n = 1,3.

7.6.3.3 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 7.6.3.1 and 7.6.3.2, 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 7.6.2.1 to obtain the design value. The material partial safety factors shall be not less than those specified in 7.6.2.2.

7.6.5 Critical deflection analysis

It shall be verified that no deflections affecting structural integrity occur in the design conditions detailed in Table 2. One of the most important considerations is to verify that no mechanical interference between blade and tower will occur.

The maximum elastic deflection in the unfavourable direction shall be determined for the load cases detailed in Table 2 using the characteristic loads. The resulting deflection is then multiplied by the combined partial safety factor for loads, material and consequences of failure.

12 Fatigue strength is defined here as stress ranges associated with given numbers of cycles.

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Partial safety factor for loads

The values of γ_f shall be chosen from Table 3.

Partial safety factor for the elastic properties of materials

The value of γ_m shall be 1,1 except when the elastic properties have been determined by full-scale testing in which case it may be reduced to 1,0. Particular attention shall be paid to geometrical uncertainties and the accuracy of the deflection calculation method.

Partial safety factor for consequences of failure

Component class 1: γ_n = 1,0

Component class 2: γ_n = 1,0

Component class 3: γ_n = 1,3.

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.

Direct dynamic deflection analysis may also be used. In this case, the characteristic deflection is determined in a manner consistent with the characteristic loads determined for each load case in Table 2. The exceedance probability in the most unfavourable direction shall be the same for the characteristic deflection as for the characteristic load. The characteristic deflection is then multiplied by the combined safety factor and added to the un-deflected position as described above.

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 and protection system

8.1 General

Wind turbine operation and safety shall be governed by a control and protection system that meets the requirements of this clause.

Manual or automatic intervention shall not compromise the protection functions. Any device allowing manual intervention must be clearly visible and identifiable, by appropriate marking where necessary.

Settings of the control and protection system shall be protected against unauthorised interference.

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 their normal limits. Where selection of control mode can be exercised, for example for maintenance, each mode shall override all other control, with the exception of the emergency stop button. Mode selection shall be governed by a selector, which can be locked in each position corresponding with a single mode. When certain functions are controlled numerically, access codes shall be provided to appropriately select the function.

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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;
- alignment to the wind.

8.3 Protection functions

The protection functions shall be activated as a result of failure of the control function or of the effects of an internal or external failure or dangerous event. The protection functions shall maintain the wind turbine in a safe condition. The activation levels for the protection functions shall be set in such a way that the design limits are not exceeded.

The protection functions shall have higher priority than control functions, but not higher than the emergency stop button, in accessing the braking systems and equipment for network disconnection when triggered.

The protection functions shall be activated in such cases as

- overspeed;
- generator overload or fault;
- excessive vibration;
- abnormal cable twist (due to nacelle rotation by yawing).

The protection functions shall be designed for fail-safe operation. The protection functions shall in general be able to protect the wind turbine from any single failure or fault in a power source or in any non-safe-life component within the systems implementing the protection functions. Any single failure in the sensing or non-safe-life structural parts of the systems implementing the control functions shall not lead to malfunction of the protection functions.

If two or more failures are interdependent or have a common cause, they shall be treated as a single failure.

Measures shall be taken to reduce the risk from dormant failures. Non-safe-life components within the systems implementing protection functions shall fail to a safe condition or their condition shall be automatically monitored; in either case their failure shall result in a machine shutdown. Safe-life designed components shall be inspected at adequate intervals.

All non-fail-safe components required for implementation of non-redundant protection functions shall be considered in component class 3 with an appropriate consequences of failure partial safety factor defined in 7.6. All such protection system critical components shall be analysed for ultimate strength, fatigue, buckling and critical deflection.

In cases of conflict, the protection function shall overrule the control function.

The automatic or remote restart of a wind turbine shall not be possible where the shutdown was initiated by an internal fault or trip that is critical to the turbine safety. If such a fault or trip is followed by electrical network interruption or loss of load, automatic restart shall not be possible after return of electrical network or load.

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An emergency stop button, which will override the control functions, shall bring the rotor to a complete stop in any wind speed less than the wind speed limit defined for maintenance and repair, see 7.4.8, and as a minimum to idling mode from any operation condition. In addition, activation of the emergency stop button shall de-energise the medium- and the high-voltage systems. Emergency stop buttons shall be provided at every major working place (e.g. nacelle and tower bottom). Disengagement of any emergency stop button following its use shall require an appropriate action. Following disengagement, automatic restart shall only be possible after manual clearance.

8.4 Braking system

The braking system shall be able to bring the rotor to idling mode or complete stop from any operation condition. Means shall be provided for bringing the rotor to a complete stop from a hazardous idling state in any wind speed less than the wind speed limit defined for maintenance and repair, see 7.4.8.

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 rotor shaft or on the rotor of the wind turbine.

Brakes shall be designed to function even if their external power supply fails. A brake shall be able to keep the rotor in the full stop position for the defined wind conditions for at least one hour after the brake is applied. During longer periods of grid loss, it shall be possible to apply the brake by either an auxiliary power supply or by manual operation.

9 Mechanical systems

9.1 General

A mechanical system for the purposes of this standard 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 and protection system shall be designed according to IEC/ISO standards wherever available. Otherwise, recognized standards shall be used. Partial safety factors shall be consistent with component class 2 in 7.6.1.2, 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.

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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 must 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 must 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 must 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 is to be considered as a class 2 component.

Gears shall be designed using appropriate calculation methods as described in ISO 6336-1 to ISO 6336-3. The material strength values shall be derived according to ISO 6336-5 and they shall at least correspond to the MQ quality. All relevant manufacturing tolerances and displacements shall be combined for the calculation of the face load distribution factor according to ISO 6336-1.

The safety factor S_H for pitting shall be calculated according to ISO 6336-2 using either method A or B. The direct Miner's rule shall be applied for the fatigue calculation. The calculated safety factor S_H shall be 1,2. This safety factor S_H includes the partial safety factor for consequence, material and load.

The safety factor S_F for tooth bending shall be calculated according ISO 6336-3 method A or B. The direct Miner's rule shall be used. The calculated safety factor S_F shall be at least 1,45. This safety factor S_F includes the partial safety factor for consequence, material and load.

For scuffing, fatigue loads have no significance, but even few high transient loads are able to initiate this failure especially with insufficient initial surface finish and at high lubricant temperature. The safety against scuffing shall be calculated using a relevant method, for example as described in ISO/TR 13989-1. The calculated safety factor S_S shall be at least 1,3.

Particular care shall be taken to ensure that the cooling and filtration systems can maintain the relevant lubrication state throughout the operating temperature range following the specified maintenance procedures.

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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. For yaw gear systems with multiple yaw drives ensuring sufficient redundancy, the gears may be considered to be in component class 1. The safety factors S_H and S_F may then be reduced to 1,1 and 1,25. Otherwise component class 2 shall be used.

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.

9.7 Protection function mechanical brakes

Where mechanical brakes are used for a protection function, 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 and protection system, which shall place the turbine in parked mode when insufficient material is available for a further emergency stop.

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 must be sufficiently short to avoid overheating and brake performance impairment and to avoid a risk of fire.

9.8 Rolling bearings

The basis of rating analysis of rolling bearings shall be ISO 76 and ISO 281. For shaft bearings, for example main shaft, gearbox, the bearing lives (90 % survival probability) shall be at least 20 years. The calculation method shall consider the operating conditions. Any adjustment factors (i.e. a-factors) according to ISO 281 shall be applied with care.

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

For bearings, 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 as in main shaft bearings or oscillating as in pitch and yaw bearings. Furthermore, consideration shall be given to the potential effect of insufficient lubrication due to small movement.

For slew 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.

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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".

The power collection system is not covered by this standard.

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 external conditions defined in Clause 6.

The electrical system, including all electrical equipment and components, shall comply with the relevant IEC standards. Specifically, the design of a wind turbine electrical system shall comply with the requirements of IEC 60204-1. For wind turbines that contain circuits at nominal voltages greater than 1000 V a.c. or 1500 V d.c. the design of a wind turbine electrical system shall comply with the requirements of IEC 60204-11. Fixed installations, not machine installations, shall comply with the requirements of IEC 60364. 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 Protective devices

A wind turbine electrical system shall, in addition to the requirements of IEC 60364, include suitable devices that ensure protection against malfunctioning of either the wind turbine or the external electrical system that may lead to an unsafe condition or state.

10.4 Disconnect devices

It shall be possible to disconnect a wind turbine electrical system from all electrical sources of energy as required for maintenance or testing.

Semiconductor devices shall not be used alone as disconnect devices.

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.

10.5 Earth system

The design of a wind turbine shall include a local earth electrode system to meet the requirements of IEC 60364 (for the correct operation of the electrical installation) and IEC 61024-1 (for lightning protection). 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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Provisions shall be made in any electrical system operating above 1 000 V a.c. or 1 500 V d.c. for earthing during maintenance.

10.6 Lightning protection

The lightning protection of a wind turbine shall be designed in accordance with IEC 61024-1. It is not necessary for protective measures to extend to all parts of the wind turbine, provided safety is not compromised. Guidance is given in IEC 61400-24.

10.7 Electrical cables

Where there is a probability of rodents or other animals damaging cables, armoured cables or conduits shall be used. Underground cables shall be buried at a suitable depth to avoid damage by service vehicles or farm equipment. Underground cables shall, if not protected by a conduit or duct, be marked by cable covers or suitable marking tape.

10.8 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.

10.9 Protection against lightning electromagnetic impulse

The over-voltage protection shall be designed in accordance with the requirements of IEC 61312-1.

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.

10.10 Power quality

The power quality characteristics of the wind turbine shall be assessed in accordance with IEC 61400-21.

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

10.11 Electromagnetic compatibility

Emissions of conducted disturbances are covered in 10.9.

Emissions of radiated disturbances shall meet the requirements of IEC 61000-6-4.

Immunity to conducted disturbances is covered in 10.6.

Immunity to radiated disturbances shall meet the requirements of IEC 61000-6-1 or IEC 61000-6-2. The turbine manufacturer shall state which of these two standards applies to the wind turbine design.

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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 no 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 7.6.2.1 assumes that the site assessment of the normal and extreme wind conditions has been carried out according to the minimum requirements in this clause.

11.2 Assessment of the topographical complexity of the site

The complexity of the site is characterised by the variations of the terrain topography from a plane. A site that fails to conform to all the restrictions of Table 4 is characterised as complex. The fitted plane slope, used in Table 4, denotes the slope of a plane that best fits the topographic variations within a specific distance from the wind turbine and passes through the wind turbine tower base. Accordingly, the terrain variation from the fitted plane denotes the distance, along a vertical line, between any surface point and the fitted plane. z_{hub} is the hub height of the wind turbine.

Table 4 – Terrain complexity indicators

Distance range from wind turbine	Max slope of fitted plane	Maximum terrain variation from a disc with radius 1,3 z_{hub} fitted to the terrain
< 5 z_{hub}	< 10°	< 0,3 z_{hub}
< 10 z_{hub}		< 0,6 z_{hub}
< 20 z_{hub}		< 1,2 z_{hub}

The resolution of surface grids used for terrain complexity assessment must not exceed z_{hub}.

11.3 Wind conditions required for assessment

Values at the wind turbine site of the following parameters shall be estimated:

- the extreme 10-min average wind speed at hub height with a recurrence period of 50 years;
- wind speed probability density function $p(V_{hub})$ in the range of V_{in} to V_{out};

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- ambient turbulence standard deviation $\hat{\sigma}$ (estimated as the mean value of the standard deviation of the longitudinal component[13]) and the standard deviation $\hat{\sigma}_\sigma$ of $\hat{\sigma}$ at V_{hub} between V_{in} and V_{out} and V_{hub} equal to V_{ref};
- flow inclination;
- wind shear[14];
- air density.

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

The interval of any wind speed bin used in the above shall be 2 m/s or less, and the wind direction sectors shall be 30º or less. All parameters, except air density, shall be available as functions of wind direction, given as a 10-min average.

The site wind parameters[15] shall be either

- measured in the range of 0,2 V_{ref} and 0,4 V_{ref} and extrapolated, or
- calculated from monitoring measurements made at the site, long-term records from local meteorological stations or from local codes or standards.

If measurements are used, the site conditions shall be correlated with long-term data from available local meteorological stations unless they can otherwise be shown to be conservative. The monitoring period shall be sufficient to obtain a minimum of six months of reliable data. Where seasonal variations contribute significantly to the wind conditions, the monitoring period shall be long enough to conservatively include these effects.

The value of the standard deviation of the longitudinal component shall be determined using appropriate statistical techniques applied to measured and preferably de-trended data. Where topographical or other local effects may influence the turbulence intensity, these effects shall be represented in the data. The characteristics of the anemometer, sampling rate and averaging time used to obtain measured data shall be considered when evaluating the turbulence intensity.

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 effective turbulence intensity, which 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 D.

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[13] The longitudinal component of turbulence may be approximated by the horizontal component.

[14] High shear values for extended periods of time have been reported for certain areas in connection with highly stratified flow or severe roughness changes. The external conditions in Clause 6 are not intended to cover such cases.

[15] Attention should be given to wakes from significant structures within a distance from the wind turbine of 20 times the characteristic length of the structure.

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For ultimate loads, I_{eff} may be assumed to be the maximum of wake turbulence intensities from neighbouring wind turbines as defined in Annex D.

$$I_{eff} = \frac{1}{V_{hub}} \max\{\hat{\sigma}_T\} \qquad (33)$$

It should be noted that for wind turbine spacing less than 3 diameters the validity of such models is uncertain and caution shall be exercised.

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 C. The evaluation of load shall take account of 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 recurrence period.

The earthquake loading shall be superposed with operational loading that shall be equal to the higher of

a) loads during normal power production by averaging over the lifetime;
b) loads during emergency shutdown for a wind speed selected so that the loads prior to the shutdown are equal to those obtained with a).

The partial safety factor for load for all load components shall be 1,0.

The seismic load evaluation may be carried out through frequency domain methods, in which case, the operational loads are added directly to the seismic load.

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.

A conservative approach to the calculation and the combination of loads on the tower is provided in Annex C. This procedure 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[16]:

- 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.

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

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11.9 Assessment of structural integrity by reference to wind data

It is possible to complete the assessment of structural integrity by comparison of the wind parameter values for the site with those used in design. A wind turbine is suitable for a site when the following conditions are all satisfied:

- the site estimate of extreme 10-min average wind speed at hub height with a recurrence period of 50 years shall be less than V_{ref}[17];
- the site value of the probability density function of V_{hub} shall be less than the design probability density function (see 6.3.1.1) at all values of V_{hub} between the wind speed 0,2 V_{ref} and 0,4 V_{ref};
- the representative value of the turbulence standard deviation, σ_1, (see equation (11)) shall be greater or equal to the site value of the estimated 90 % quantile of the turbulence standard deviation at all values of V_{hub} between the wind speed 0,2 V_{ref} and 0,4 V_{ref}, and i.e.

$$\sigma_1 \geq \hat{\sigma} + 1{,}28\,\hat{\sigma}_\sigma \tag{34}$$

When the terrain is complex, the estimate of the standard deviation of the longitudinal component of turbulence shall be increased in order to account for the distortion of the turbulent flow[18]. The site flow inclination, taken as the maximum of all directions, shall be less than that specified in 6.3. Where there are no site data or calculations for the flow inclination and the terrain is complex, it shall be assumed that the flow is always parallel to the fitted plane, see 11.2, within a distance of 5 z_{hub} from the wind turbine.

The site average vertical wind shear exponent α, for direction shall be less than that specified in 6.3.1.2 and larger than zero. Where there are no site data for the wind shear, it shall be calculated taking topography and roughness into account.

The average site air density shall be less than that specified in 6.4.1 for wind speeds greater than or equal to V_r.

An adequate assessment of wake effects can be performed by verifying that the turbulence standard deviation σ_1 from the normal turbulence model is greater or equal to the estimated 90 % quantile of the turbulence standard deviation (including both ambient and wake turbulence) between the wind speed 0,2 V_{ref} and 0,4 V_{ref} (or when the turbine properties are known, between 0,6 V_r and V_{out}), i.e.:

$$\sigma_1 \geq I_{eff} \cdot V_{hub} + 1{,}28\,\hat{\sigma}_\sigma \tag{35}$$

where I_{eff} for fatigue loads and extreme load calculations follows from 11.4.

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17 Alternatively, the wind turbine site central estimate of extreme 3 s average wind speed at hub height with a recurrence period of 50 years should be less than V_{e50}.

18 The effect of complex terrain may be included by an additional multiplication with a turbulence structure correction parameter C_{CT} defined as

$$C_{CT} = \frac{\sqrt{1 + (\hat{\sigma}_2 / \hat{\sigma}_1)^2 + (\hat{\sigma}_3 / \hat{\sigma}_1)^2}}{1{,}375}$$

where ratios of the estimated standard deviations, $\hat{\sigma}_i$, correspond to hub height values. Where there are no site data for the components of turbulence and the terrain is complex, results of modelling or C_{CT} = 1,15 may be used .

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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, wake effects, etc.

Where there are no site data for the components of turbulence and the terrain is complex, it shall be assumed that the longitudinal, lateral and upward turbulence component standard deviations are equal.

In case of wake effects it shall be verified that structural integrity is not compromised for DLC 1.1 and 1.2 in which σ_1 in the normal turbulence model is replaced by the actual wake turbulence. This may be estimated by

$$\sigma_{\text{wake}} = I_{\text{eff}} V_{\text{hub}} + 1{,}28\,\hat{\sigma}_{\sigma} \qquad (36)$$

where I_{eff} for fatigue load and extreme load calculations follows from 11.4.

Since for fatigue load calculations, I_{eff} as defined in Annex D 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.

For extreme load calculations, it is permitted to take into account the frequency of the wake situations and modify the load extrapolation in DLC 1.1 accordingly.

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 unauthorised 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, feet, 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 belts, 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.

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

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. 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.

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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.

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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 shut down 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

- be of robust construction;
- not be easy to by-pass;
- 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;

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- adequate means to protect personnel from accidental contact with rotating components or moving parts;
- provision for securing lifelines and safety belts 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;
- 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 ensures any dangerous situation will be known by standby personnel to immediately initiate rescue procedures if necessary.

13.3 Instructions concerning commissioning

The manufacturer shall provide instructions for commissioning.

13.3.1 Energization

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

13.3.2 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 shutdown;
- safe shutdown from overspeed or representative simulation thereof;
- function test of protection system.

13.3.3 Records

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

13.3.4 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.

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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;
- 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 belt, safety climbing aids or other safety devices,
  - when appropriate, a buoyancy aid should be used around water,
  - 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.

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Subjects which should also be covered in the manual include:

- 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.

Annex A
(normative)

Design parameters for describing wind turbine class S

For wind turbine class S turbines, the following information shall be given in the design documentation.

Machine parameters

Rated power	[kW]
Hub height operating wind speed range $V_{in} - V_{out}$	[m/s]
Design life time	[years]

Wind conditions

Turbulence intensity as a function of mean wind speed used for the NTM and ETM	
Annual average wind speed	[m/s]
Average inclined flow	[deg]
Wind speed distribution (Weibull, Rayleigh, measured, other)	
Wind profile model and parameters	
Turbulence model and parameters	
Hub height extreme wind speeds V_{e1} and V_{e50}	[m/s]
Extreme gust model and parameters for 1- and 50-year recurrence periods	
Extreme direction change model and parameters for 1- and 50-year recurrence periods	
Extreme coherent gust model and parameters	
Extreme coherent gust with direction change model and parameters	
Extreme wind shear model and parameters	

Electrical network conditions

Normal supply voltage and range	[V]
Normal supply frequency and range	[Hz]
Voltage imbalance	[V]
Maximum duration of electrical power network outages	[days]
Number of electrical network outages	[1/year]
Auto-reclosing cycles (description)	
Behaviour during symmetric and unsymmetrical external faults (description)	

Other environmental conditions (where taken into account)

Design conditions in case of offshore wind turbine (water depth, wave conditions, etc.)	
Normal and extreme temperature ranges	[°C]
Relative humidity of the air	[%]
Air density	[kg/m^3]
Solar radiation	[W/m^2]
Rain, hail, snow and icing	
Chemically active substances	
Mechanically active particles	
Description of lightning protection system	
Earthquake model and parameters	
Salinity	[g/m^3]

Annex B
(informative)

Turbulence models

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) The Mann uniform shear model, and
2) the Kaimal spectral and exponential coherence model.

Parameters for the models have been selected to satisfy the general turbulence requirements given in 6.3.

B.1 Mann (1994) 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 (1948) energy spectrum is rapidly distorted by a uniform, mean velocity shear. The resulting spectral tensor components are given by

$$\Phi_{11}(k_1,k_2,k_3)=\frac{E(k_0)}{4\pi k_0^4}\left(k_0^2-k_1^2-2k_1(k_3+\beta(k)k_1)\zeta_1+(k_1^2+k_2^2)\zeta_1^2\right) \quad \text{(B.1)}$$

$$\Phi_{22}(k_1,k_2,k_3)=\frac{E(k_0)}{4\pi k_0^4}\left(k_0^2-k_2^2-2k_2(k_3+\beta(k)k_1)\zeta_2+(k_1^2+k_2^2)\zeta_2^2\right) \quad \text{(B.2)}$$

$$\Phi_{33}(k_1,k_2,k_3)=\frac{E(k_0)}{4\pi k^4}\left(k_1^2+k_2^2\right) \quad \text{(B.3)}$$

$$\Phi_{12}(k_1,k_2,k_3)=\frac{E(k_0)}{4\pi k_0^4}\left(-k_1k_2-k_1(k_3+\beta(k)k_1)\zeta_2-k_2(k_3+\beta(k)k_1)\zeta_1+(k_1^2+k_2^2)\zeta_1\zeta_2\right) \quad \text{(B.4)}$$

$$\Phi_{13}(k_1,k_2,k_3)=\frac{E(k_0)}{4\pi k_0^2k^2}\left(-k_1(k_3+\beta(k)k_1)+(k_1^2+k_2^2)\zeta_1\right) \quad \text{(B.5)}$$

$$\Phi_{23}(k_1,k_2,k_3)=\frac{E(k_0)}{4\pi k_0^2k^2}\left(-k_2(k_3+\beta(k)k_1)+(k_1^2+k_2^2)\zeta_2\right) \quad \text{(B.6)}$$

where

$$\Phi_{ij}(k_1,k_2,k_3)=\Phi_{ji}^*(k_1,k_2,k_3)=\frac{1}{8\pi^3}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}R_{ij}(\delta_1,\delta_2,\delta_3)e^{-\iota k_1\delta_1}e^{-\iota k_2\delta_2}e^{-\iota k_3\delta_3}\,d\delta_1 d\delta_2 d\delta_3 \ ,$$

$$R_{ij}(\delta_1,\delta_2,\delta_3)=\frac{1}{{\sigma_{iso}}^2}E\left\langle u_i(x_1,x_2,x_3)u_j(x_1+\ell\delta_1,x_2+\ell\delta_2,x_3+\ell\delta_3)\right\rangle,$$

= 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,

$k_0 = \sqrt{k^2 + 2\beta(k)k_1k_3 + (\beta(k)k_1)^2}$ = the magnitude before shear distortion,

$$\zeta_1 = C_1 - \frac{k_2}{k_1}C_2, \quad \zeta_2 = \frac{k_2}{k_1}C_1 + C_2,$$

$$C_1 = \frac{\beta(k){k_1}^2\left({k_1}^2 + {k_2}^2 - k_3\left(k_3 + \beta(k)k_1\right)\right)}{k^2\left({k_1}^2 + {k_2}^2\right)},$$

$$C_2 = \frac{{k_2}^2{k_0}^2}{\left({k_1}^2 + {k_2}^2\right)^{3/2}}\arctan\left(\frac{\beta(k)k_1\sqrt{{k_1}^2 + {k_2}^2}}{{k_0}^2 - \left(k_3 + \beta(k)k_1\right)k_1\beta(k)}\right),$$

$E(k) = \dfrac{1{,}453\,k^4}{\left(1+k^2\right)^{17/6}}$ = the non-dimensional, von Karman isotropic energy spectrum,

$$\beta(k) = \frac{\gamma}{k^{\frac{2}{3}}\sqrt{{}_2F_1\left(\frac{1}{3}, \frac{17}{6}, \frac{4}{3}, -k^{-2}\right)}}$$

= a non-dimensional distortion time inversely proportional to $\sqrt{k^2 \int_k^\infty E(p)dp}$,

${}_2F_1$ = Hypergeometric function

$\sigma^2_{\mathrm{iso}}, \ell$ = the unsheared, isotropic variance and scale parameters respectively, and

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.

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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

$$\frac{f\,S_i(f)}{\sigma_i^2} = \frac{\sigma_{iso}^2}{\sigma_i^2}\left(\frac{4\pi\ell f}{V_{hub}}\right)\Psi_{ii}\left(\frac{2\pi\ell f}{V_{hub}}\right) \qquad \text{(B.7)}$$

where

$$\Psi_{ij}(k_1) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Phi_{ij}(k_1,k_2,k_3)\,dk_2\,dk_3$$

= the one-dimensional, wave number autospectrum for $i = j$, or cross-spectrum for $i \neq j$, and

$$\sigma_i{}^2 = \sigma_{iso}{}^2\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\Phi_{ii}(k_1,k_2,k_3)\,dk_1\,dk_2\,dk_3$$ = the component variance.

Similarly, for spatial separations normal to the longitudinal direction the coherence is given by

$$Coh_{ij}(f,\ell\delta_2,\ell\delta_3) = \frac{\left|\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\Phi_{ij}\left(\frac{2\pi\ell f}{V_{hub}},k_2,k_3\right)e^{-ik_2\delta_2}\,e^{-ik_3\delta_3}\,dk_2\,dk_3\right|}{\sqrt{\Psi_{ii}\left(\frac{2\pi\ell f}{V_{hub}}\right)\Psi_{jj}\left(\frac{2\pi\ell f}{V_{hub}}\right)}} \qquad \text{(B.8)}$$

Unfortunately the resulting integrals do not have known analytical forms and must be carried out numerically for a specific value of the parameter, γ. Mann (1998) 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

$$\gamma = 3{,}9 \qquad \text{(B.9)}$$

with the resulting variance relations

$$\left.\begin{aligned}\sigma_1^2 &= 3{,}25\,\sigma_{iso}^2\\ \sigma_2^2 &= 1{,}65\,\sigma_{iso}^2\\ \sigma_3^2 &= 0{,}85\,\sigma_{iso}^2\end{aligned}\right\} \Rightarrow \left\{\begin{aligned}\frac{\sigma_2}{\sigma_1} &\approx 0{,}7\\ \frac{\sigma_3}{\sigma_1} &\approx 0{,}5\end{aligned}\right. . \qquad \text{(B.10)}$$

Note the resulting lateral variance is slightly less than given in Table B.1. The scale parameter may be found by equating the asymptotic, inertial-sub-range longitudinal spectra. Thus,

$$S_1(f) \to 0{,}475\,\sigma_{iso}^2\left(\frac{2\pi\ell}{V_{hub}}\right)^{-2/3} f^{-5/3} = 0{,}05\,\sigma_1^2\left(\frac{\Lambda_1}{V_{hub}}\right)^{-2/3} f^{-5/3} \Rightarrow \ell \approx 0{,}8\,\Lambda_1 \qquad \text{(B.11)}$$

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In summary, the three parameters required in the Mann model are given by

$$\begin{aligned} \gamma &= 3,9 \\ \sigma_{iso} &= 0,55\sigma_1 \\ l &= 0,8\Lambda_1 \end{aligned} \tag{B.12}$$

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

$$\begin{bmatrix} u_1(x,y,z) \\ u_2(x,y,z) \\ u_3(x,y,z) \end{bmatrix} = \sum_{k_1,k_2,k_3} \mathrm{e}^{i\frac{xk_1+yk_2+zk_3}{\ell}} \begin{bmatrix} C(k_1,k_2,k_3) \end{bmatrix} \begin{bmatrix} n_1(k_1,k_2,k_3) \\ n_2(k_1,k_2,k_3) \\ n_3(k_1,k_2,k_3) \end{bmatrix} \tag{B.13}$$

where

$$\begin{bmatrix} C(k_1,k_2,k_3) \end{bmatrix} \approx \sigma_{\mathrm{iso}} \sqrt{\frac{2\pi^2\ell^3 E(k_0)}{N_1N_2N_3\Delta^3 {k_0}^4}} \begin{bmatrix} k_2\zeta_1 & k_3 - k_1\zeta_1 + \beta k_1 & -k_2 \\ k_2\zeta_2 - k_3 - \beta k_1 & -k_1\zeta_2 & k_1 \\ \frac{{k_0}^2 k_2}{k^2} & -\frac{{k_0}^2 k_1}{k^2} & 0 \end{bmatrix}$$

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, and

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, $[C(k_1,k_2,k_3)]$. This procedure is detailed in Mann (1998).

B.2 Kaimal (1972)[19] spectrum and exponential coherence model

The component power spectral densities are given in non-dimensional form by the equation:

$$\frac{f\,S_k(f)}{\sigma_k^2} = \frac{4f\,L_k/V_{hub}}{(1+6f\,L_k/V_{hub})^{5/3}} \tag{B.14}$$

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 (see equation (B.2));

L_k is the velocity component integral scale parameter,

and with

$$\sigma_k^2 = \int_0^\infty S_k(f)\,df \tag{B.15}$$

The turbulence spectral parameters are given in Table B.1.

Table B.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

where 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:

$$\mathrm{Coh}(r,f) = \exp\left[-12\left(\left(f\cdot r/V_{hub}\right)^2 + \left(0{,}12\,r/L_c\right)^2\right)^{0,5}\right] \tag{B.16}$$

where

$\mathrm{Coh}(r,f)$ 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;

---

19 Note that the turbulence component variance ratios in Table B.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 B.1.

f is the frequency in Hertz;

$L_c = 8{,}1\Lambda_1$ is the coherence scale parameter.

B.3 Reference documents

J.C. Kaimal, J.C. Wyngaard, Y. Izumi, and O.R. Cote, *Spectral characteristics of surface-layer turbulence*, Q.J.R. Meteorol. Soc., v. 98, 1972, pp. 563-598.

T. von Karman, *Progress in the statistical theory of turbulence*, Proc. Nat. Acad. Sci., v. 34, 1948, pp. 530-539.

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Annex C
(informative)

Assessment of earthquake loading

A simplified, conservative method for the calculation of seismic load is presented here for use when the need for a complex analysis cannot be readily established.

The principal simplifications are the ignoring of vibration modes higher than the first tower bending mode, and the assumption that the whole structure is subject to the same acceleration. Ignoring the second mode is a significant non-conservative simplification and is compensated for here by incorporating tower mass with the tower head mass and applying a conservative aerodynamic load.

The method for deriving the ground acceleration must still be consistent with 11.6. In the absence of detailed site data, conservative assumptions shall be made. ISO 3010 has been used as the basis of the terminology here.

The procedure includes the following steps:

- Evaluate or estimate the site and soil conditions required by the relevant local standard.
- Use the normalised design response spectrum and the seismic hazard-zoning factor to establish the acceleration at the first tower bending eigen-frequency assuming a damping of 1 % of critical damping.
- Calculate the load for a system subject to the above acceleration in which the total rotor, nacelle and 50 % of the tower mass is concentrated at the tower head.
- Add the result to the characteristic loads calculated for an emergency stop at rated wind speed.
- Compare the result against the design loads or the design resistance for the wind turbine

If the tower can sustain the resulting combined loading, no further investigation is needed. Otherwise, a thorough investigation shall be carried out according to 11.6.

Annex D
(informative)

Wake and wind farm turbulence

D.1 Wake effects

Wake effects from neighbouring wind turbines may be taken into account during normal operation for fatigue calculation by an effective turbulence intensity $I_{eff,}$, Frandsen (2003). The effective turbulence intensity – conditioned on hub height mean wind speed – may be defined as

$$I_{\mathrm{eff}}(V_{\mathrm{hub}}) = \left\{ \int_0^{2\pi} p(\theta|V_{\mathrm{hub}}) I^m(\theta|V_{\mathrm{hub}}) d\theta \right\}^{\frac{1}{m}} \quad \text{(D.1)}$$

where

p is the probability density function of wind direction;

I is the turbulence intensity combined of ambient and wake flow from wind direction θ, and

m is the Wöhler (SN-curve) exponent for the considered material.

In the following a uniform distribution $p(\theta|V_{hub})$ is assumed. It is also acceptable to adjust the formulas for other than uniform distribution[20]. No reduction in mean wind speed inside the wind farm shall be assumed.

if $\min\{d_i\} \geq 10\ D$:

$$I_{\mathrm{eff}} = \frac{\hat{\sigma}}{V_{\mathrm{hub}}} \quad \text{(D.2)}$$

if $\min\{d_i\} < 10\ D$:

$$I_{\mathrm{eff}} = \frac{\hat{\sigma}_{\mathrm{eff}}}{V_{\mathrm{hub}}} = \frac{1}{V_{\mathrm{hub}}} \left[(1 - N\, p_{\mathrm{w}}) \hat{\sigma}^m + p_{\mathrm{w}} \sum_{i=1}^{N} \hat{\sigma}_{\mathrm{T}}^m (d_i) \right]^{\frac{1}{m}} ; p_{\mathrm{w}} = 0{,}06 \quad \text{(D.3)}$$

where

$\hat{\sigma}$ is the ambient estimated turbulence standard deviation;

$\hat{\sigma}_{\mathrm{T}} = \sqrt{\dfrac{0{,}9 V_{\mathrm{hub}}^2}{(1{,}5 + 0{,}3 d_{\mathrm{i}} \sqrt{V_{\mathrm{hub}}/c})^2} + \hat{\sigma}^2}$ is the maximum centre-wake, hub height turbulence standard deviation;

d_{i} is the distance, normalised by rotor diameter, to neighbouring wind turbine no. i;

---

20 In the case of non-uniform wind direction distribution p_{w} may be adjusted by a factor equal to the ratio of the actual probability of the wind direction in the direction of the neighbouring turbines and the probability associated with uniform wind direction distribution.

c is a constant equal to 1 m/s;

I_{eff} is the effective turbulence intensity;

N is the number of neighbouring wind turbines, and

m is the Wöhler curve exponent corresponding to the material of the considered structural component.

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. Depending on the wind farm configuration, the number of nearest wind turbines to be included in the calculation of I_{eff} is given in the table below.

The wind farm configurations are illustrated in figure D.1 below for the case "Inside a wind farm with more than 2 rows".

Wind farm configuration	*N*
2 wind turbines	1
1 row	2
2 rows	5
Inside a wind farm with more than 2 rows	8

Inside large wind farms, the wind turbines tend to generate their own 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 ambient turbulence shall be assumed:

$$\hat{\sigma}' = \tfrac{1}{2}\left(\sqrt{\hat{\sigma}_w^2 + \hat{\sigma}^2} + \hat{\sigma}\right) \tag{D.4}$$

where

$$\hat{\sigma}_w = \frac{0,36\,V_{hub}}{1 + 0,2\sqrt{d_r d_f / C_T}} \tag{D.5}$$

C_T is the thrust coefficient, d_r and d_f are separations in rotor diameters in rows and separation between rows, respectively.

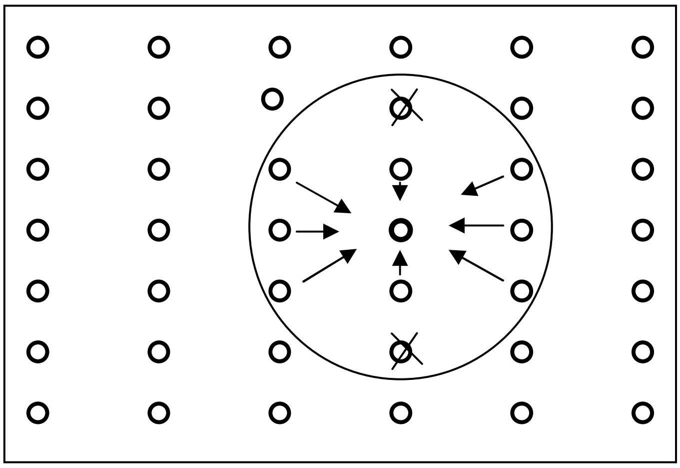

Figure D.1 – Configuration – Inside a wind farm with more than 2 rows

D.2 Reference documents

S. Frandsen (2003) *Turbulence and turbulence generated fatigue in wind turbine clusters*, Risø report R-1188.

Annex E
(informative)

Prediction of wind distribution for wind turbine sites by measure-correlate-predict (MCP) methods

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 synthesised 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 “Prediction of extreme wind speed at wind energy sites, a set of guidelines prepared under ETSU contract W/11/00427/00” by National Wind Power and Climatic Research Unit of the University of East Anglia.

E.1 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.

E.2 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 7 years. The result is an hourly mean record for the site, which may be processed into a probability distribution for site assessment.

E.3 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 “The designers guide to wind loading of building structures”, N J Cook, Butterworths, 1995.). 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 utilises more than one data point per year from a data set, also described by Cook. This method can be used for data sets that are as short as seven 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.

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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 recurrence 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.

E.4 Reference documents

N J Cook, *The designers guide to wind loading of building structures*, Butterworths, 1995.

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Annex F
(informative)

Statistical extrapolation of loads for ultimate strength analysis

F.1 Statistical extrapolation of loads

Failure of a structure occurs when the stress at a critical location exceeds the resistance capacity of the 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, one can assess the suitability of the structure by comparing the extreme values of the loading with the ultimate load resistance, applying suitable factors of safety.

For wind turbines, the 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. Further assuming that the largest load values occur at widely separated times and are thus statistically independent, the probability that the largest load F_{ext} exceeds a given load F in the observation time T is given by (see Gumbel, 1958, and Cramer, 1966)

$$\text{Prob}\left(F_{\text{ext}} \geq F \;\middle|V,T\right) = 1-\left(F_{\text{max}}\left(F\middle|V\right)\right)^{E\left(n\middle|V,T\right)} \tag{F.1}$$

where $F_{\text{max}}\left(F\middle|V\right)$ is the short-term probability distribution function of the local maxima for the load process, and $E(n|V,T)$ is the expected number of local maxima in the observation time period. As indicated, these statistical quantities are conditioned on the mean wind speed, V, and, where indicated, also depend on the observation time period, T.

Considering all the operating wind conditions, the long-term exceedance probability is then given by integrating overall operating wind speeds,

$$\text{Prob}\left(F_{\text{ext}} \geq F \;\middle|T\right) \equiv P_{\text{e}}(F,T) = \int_{V_{\text{in}}}^{V_{\text{out}}} \text{Prob}\left(F_{\text{ext}} \geq F \;\middle|V,T\right) p\left(V\right) dV \,, \tag{F.2}$$

where $p\left(V\right)$ is the probability density function for the hub-height wind speed and is prescribed for the standard wind turbine classes in 6.3.1.1. The acceptable probability of exceedance is the reciprocal of the number of time intervals of length T in the recurrence period T_{r} associated with the characteristic load. The resulting characteristic load, F_{k}, is then given by solving the equation

$$P_{\text{e}}(F_{\text{k}},T) = \frac{T}{T_{\text{r}}}\,. \tag{F.3}$$

The function $\text{Prob}\left(F_{\text{ext}} \geq F \middle| V, T\right)$ is determined from response simulations, from which extremes are taken in the following way:

- the extracted extremes must be selected so that they may be assumed to be independent;
- the number of extremes must be sufficient to determine the type of distribution (Gumbel, Weibull, or other) and provide reliable estimation of the behaviour of the tail;
- the wind speeds, where the highest loads due to turbulence are expected, must be included in the simulations.

The characteristic load may be estimated by the following procedure:

a) from the simulation data for a given wind speed, V_j, extract independent extreme values of the load. One method of doing this is to select the largest value between successive upcrossings of the mean plus 1,4 times the standard deviation of the load process;

b) fit a distribution to the selected extreme value data. Guidance for one method for fitting the distribution can be found in Moriarty, et. al. (2002). 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. A minimum of 300 min of time series data distributed over the range of significant wind conditions is recommended;

c) estimate the expected number of maxima for a typical 10 min observation period, T, from the equation

$$n_{\text{j}} = n_{\text{s}} \frac{T}{T_{\text{s}}} \tag{F.4}$$

where T_{s} is the total time period of all the simulation data for the given wind speed, V_j, and n_{s} is the total number of maxima extracted from the same simulation data;

d) compute the long term exceedance probability as a function of load level from the following equation (assuming the required Rayleigh wind speed distribution for the standard turbine classes given in 6.3.1.1):

$$P_{\text{e}}(F) = \sum_j \left(1 - \left(F_{\max}\left(F \middle| V_j\right)\right)^{n_j}\right) \left(e^{-\pi\left(\frac{V_j - \Delta V_j/2}{2V_{\text{ave}}}\right)^2} - e^{-\pi\left(\frac{v_j + \Delta V_j/2}{2V_{\text{ave}}}\right)^2} \right) \tag{F.5}$$

where V_j is the wind speed bin centre and ΔV_j is the bin width;

e) solve for the characteristic load either graphically or by using a numerical root finding technique:

$$P_{\text{e}}\left(F_{\text{k}}\right) = 3{,}8 \times 10^{-7} \tag{F.6}$$

for the 50-year recurrence period and the reference period of 10 min.

In using this procedure, care must be taken that an adequate number and resolution of wind speed bins is selected to approximate the integration in equation (F.2). Attention should be given to wind speeds around V_{r} and V_{out}. The accuracy of the discretization may be estimated by neglecting every other bin value and determining the resulting difference in the characteristic load.

Figure F.1 illustrates how the 1-year and 50-year extremes are determined from the computed long-term exceedance probability. The blade bending load has been normalized by the mean blade bending load at rated wind speed. Also shown on the plot is the largest computed blade bending load for all the simulations at the different mean wind speeds between cut-in and cut-out.

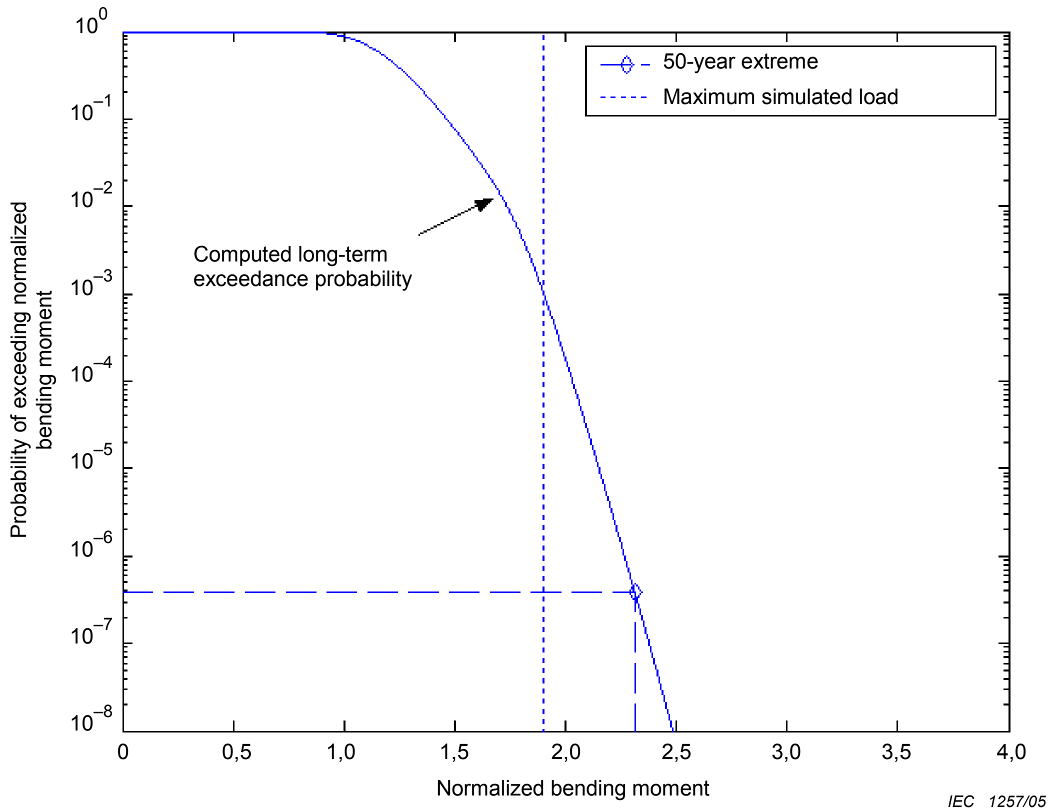

Figure F.1 – Exceedance probability for largest out-of-plane blade bending load in 10 min (normalized by mean bending load at rated wind speed).

F.2 Reference documents

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Annex G
(informative)

Fatigue analysis using Miner's rule with load extrapolation

G.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 Matsuishi & Endo, 1968, or Dowling, 1972). 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 (Palmgren, 1924, and Miner, 1945) then the total damage, D, will be given by[21]

$$D = \sum_i \frac{1}{N(S_i)}, \tag{G.1}$$

where S_i is the load range for the i[th] cycle, and $N(\cdot)$ 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 must 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

$$E\langle D|V,T\rangle = \int_0^\infty \frac{n_{\text{ST}}(S|V,T)}{N(S)} dS, \tag{G.2}$$

where $n_{\text{ST}}(S|V,T)$ 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 $\int_{S_A}^{S_B} n_{\text{ST}}(S|V,T)\,dS$. 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

$$E\langle D\rangle = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} E\langle D|V,T\rangle p(V)\,dV = \frac{\text{Lifetime}}{T} \int_{V_{\text{in}}}^{V_{\text{out}}} \int_0^\infty \frac{n_{\text{ST}}(S|V,T)}{N(S)} p(V)\,dS\,dV, \tag{G.3}$$

---

21 For ease of presentation, the effect of variation in the midpoint load level for each cycle is neglected. This restriction will be eliminated later when the issue of varying midpoint levels is addressed through the use of an equivalent cyclic range.

where $p(V)$ is the probability density function for the hub-height wind speed prescribed for the standard wind turbine classes in 6.3.1.1.

Now, defining the long-term load spectrum,

$$n_{\mathrm{LT}}(S) = \frac{\mathrm{Lifetime}}{T} \int_{V_{\mathrm{in}}}^{V_{\mathrm{out}}} n_{\mathrm{ST}}(S|V,T)\, p(V)\, dV \,, \tag{G.4}$$

then gives

$$E\langle D \rangle = \int_0^\infty \frac{n_{\mathrm{LT}}(S)}{N(S)} dS \,. \tag{G.5}$$

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

$$E\langle D \rangle \approx \sum_{j,k} \frac{n_{jk}}{N(S_k)} \,, \tag{G.6}$$

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,

$$n_{\mathrm{jk}} = \frac{\mathrm{Lifetime}}{T} \int_{V_{\mathrm{j}} - \Delta V_{\mathrm{j}}/2}^{V_{\mathrm{j}} + \Delta V_{\mathrm{j}}/2} \int_{S_{\mathrm{k}} - \Delta S_{\mathrm{k}}/2}^{S_{\mathrm{k}} + \Delta S_{\mathrm{k}}/2} n_{\mathrm{ST}}(S|V,T)\, p(V)\, dS dV \,, \tag{G.7}$$

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

$$\int_0^\infty \frac{n_{\mathrm{LT}}(S)}{N(\gamma \;\, S)} dS \le 1 \,, \tag{G.8}$$

where $\gamma = \gamma_{\mathrm{f}} \gamma_{\mathrm{m}} \gamma_{\mathrm{n}}$ 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

$$\sum_{j,k} \frac{n_{jk}}{N(\gamma \;\, S_k)} \le 1 \,. \tag{G.9}$$

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. (G.9), must 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

$$N(S_{\mathrm{eq}}, M_0) = N(S, M) \tag{G.10}$$

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

$$S_{eq} = N^{-1}\left(N(S,M),M_0\right) \tag{G.11}$$

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 must 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;
b) 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;
c) use the rain flow method to identify the midpoint and range for each simulated load cycle;
d) determine the equivalent range for each load cycle in relation to the selected reference midpoint level;
e) determine an analytical fit for the short-term probability distribution of equivalent load cycles, $F_{ST}\left(S|V,T\right)$ for the data above the selected threshold. Guidance for one method for fitting the distribution may be found in Moriarty and Holley, 2003. 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;

f) 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

$$n'_{jk} \approx \left(\frac{Lifetime}{T}\right) P_j \begin{Bmatrix} m_{jk} & \text{if } S_k \text{ is below the j}^{\text{th}} \text{ threshold} \\ M_j\left(F\left(S_k + \frac{\Delta S_k}{2} \middle| V_j, T\right) - F\left(S_k - \frac{\Delta S_k}{2} \middle| V_j, T\right)\right) & \text{if } S_k \text{ is above the j}^{\text{th}} \text{ threshold} \end{Bmatrix} \tag{G.12}$$

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 $P_j = e^{-\pi\left(\frac{V_j - \Delta V_j/2}{2V_{ave}}\right)} - e^{-\pi\left(\frac{V_j + \Delta V_j/2}{2V_{ave}}\right)}$ 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 must be taken that

a) the resolution of the wind speed and load range bins is sufficient for the desired numerical precision, and

b) 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 $\frac{Lifetime}{T}$ 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.

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The following standards are relevant to the design of wind turbines:

IEC 60034 (all parts), *Rotating electrical machines*

IEC 60038, *IEC standard voltages*

IEC 60146 (all parts), *Semiconductor converters*

IEC 60173:1964, *Colours of the cores of flexible cables and cords*

IEC 60227 (all parts), *Polyvinyl chloride insulated cables of rated voltages up to and including 450/750 V*

IEC 60245 (all parts), *Rubber insulated cables of rated voltages up to and including 450/750 V*

IEC 60269 (all parts), *Low-voltage fuses*

IEC 60287 (all parts), *Electric cables – Calculation of the continuous current rating (100 % load factor)*

IEC 60439 (all parts), *Low voltage switchgear and control gear assemblies*

IEC 60446:1999, *Basic and safety principles for man-machine interface, marking and identification- Identification of conductors by colours or numerals*

IEC 60529:1989, *Degrees of protection provided by enclosures (IP Code)*

IEC 60617, *Graphical symbols for diagrams*

IEC 60755:1983, *General requirements for residual current-operated protective devices*

IEC 60898:1995, *Electrical accessories – Circuit breakers for overcurrent protection for household and similar installations*

IEC 61310-1:1995, *Safety of machinery – Indication, marking and actuation – Part 1: Requirements for visual, auditory and tactile signals*

IEC 61310-2:1995, *Safety of machinery – Indication, marking and actuation – Part 2: Requirements for marking*

ISO 3010:2001, *Basis for design of structures – Seismic actions on structures*

ISO 8930:1993, *General principles on reliability for structures – List of equivalent terms*

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