

INTERNATIONAL STANDARD

NORME INTERNATIONALE



**Wind turbines –
Part 2: Small wind turbines**

**Eoliennes –
Partie 2: Petits aérogénérateurs**



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IEC Central Office
3, rue de Varembe
CH-1211 Geneva 20
Switzerland

Tel.: +41 22 919 02 11
Fax: +41 22 919 03 00
info@iec.ch
www.iec.ch

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

WIND TURBINES –

Part 2: Small wind turbines

FOREWORD

- 1) The International Electrotechnical Commission (IEC) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, IEC publishes International Standards, Technical Specifications, Technical Reports, Publicly Available Specifications (PAS) and Guides (hereafter referred to as “IEC Publication(s)”). Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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International Standard IEC 61400-2 has been prepared by IEC technical committee 88: Wind turbines.

This third edition cancels and replaces the second edition published in 2006.

This edition constitutes a technical revision. This edition includes the following significant technical changes with respect to the previous edition:

- the title has been modified to better reflect the scope;
- restructured into part I (design evaluation) and part II (type testing) to harmonise use with IEC 61400-22 conformity testing and certification;
- caution provided regarding the use of simplified equations;
- added annex on other wind conditions;
- added annex on tropical storms;
- added annex on extreme environmental conditions;

- added annex on EMC testing;
- added annex on dynamic behaviour;
- duration testing requirements modified;
- added annex on standardised format consumer label;
- many minor changes and all known errata corrected.

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

FDIS	Report on voting
88/465/FDIS	88/469/RVD

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

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

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

The committee has decided that the contents of this publication will remain unchanged until the stability 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.

The contents of the corrigendum of October 2019 have been included in this copy.

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WIND TURBINES –

Part 2: Small wind turbines

1 Scope

This part of IEC 61400 deals with safety philosophy, quality assurance, and engineering integrity and specifies requirements for the safety of small wind turbines (SWTs) including design, installation, maintenance and operation under specified external conditions. Its purpose is to provide the appropriate level of protection against damage from hazards from these systems during their planned lifetime.

This standard is concerned with all subsystems of SWTs such as protection mechanisms, internal electrical systems, mechanical systems, support structures, foundations and the electrical interconnection with the load. A small wind turbine system includes the wind turbine itself including support structures, the turbine controller, the charge controller / inverter (if required), wiring and disconnects, the installation and operation manual(s) and other documentation.

While this standard is similar to IEC 61400-1, it does simplify and make significant changes in order to be applicable to small wind turbines. Any of the requirements of this standard may be altered if it can be suitably demonstrated that the safety of the turbine 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, organisation, or corporation from the responsibility of observing other applicable regulations.

This standard applies to wind turbines with a rotor swept area smaller than or equal to 200 m², generating electricity at a voltage below 1 000 V a.c. or 1 500 V d.c. for both on-grid and off-grid applications.

This standard should be used together with the appropriate IEC and ISO standards (see Clause 2).

2 Normative references

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

IEC 60038:2009, *IEC standard voltages*

IEC 60204-1:2005, *Safety of machinery – Electrical equipment of machines – Part 1: General requirements*

IEC 60364-5-54, *Low-voltage electrical installations – Part 5-54: Selection and erection of electrical equipment – Earthing arrangements and protective conductors*

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

IEC 61400-11, *Wind turbines – Part 11: Acoustic noise measurement techniques*

IEC 61400-12-1:2005, *Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines*

IEC/TS 61400-13, *Wind turbine generator systems – Part 13: Measurement of mechanical loads*

IEC 61400-14:2005, *Wind turbines – Part 14: Declaration of apparent sound power level and tonality values*

IEC/TS 61400-23:2001, *Wind turbine generator systems – Part 23: Full-scale structural testing of rotor blades*

IEC 61643-11:2011, *Low-voltage surge protective devices – Part 11: Surge protective devices connected to low-voltage power distribution systems – Requirements and test methods*

ISO/IEC 17025, *General requirements for the competence of testing and calibration laboratories*

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

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

Note 1 to entry: The averaging time interval shall be an integer number of years to average out non-stationary effects such as seasonality.

3.2

annual average wind speed

V_{ave}

wind speed averaged according to the definition of annual average

3.3

auto-reclosing cycles

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

brake

device capable of reducing the rotor speed or stopping rotation of a wind turbine system

3.5

catastrophic failure

disintegration or collapse of a component or structure, that results in loss of vital function which impairs safety of a wind turbine system

3.6

characteristic value

value (of a material property) having a prescribed probability of not being attained in a hypothetical unlimited test series

3.7**consumer label**

a label for the benefit of consumers consisting of two parts: the label itself, and a test summary report made available by a web site

3.8**control system**

sub-system that receives information about the condition of the wind turbine system and/or its environment and adjusts the turbine in order to maintain it within its operating limits

3.9**cut-in wind speed** V_{in}

lowest mean hub height wind speed bin value at which the wind turbine system produces a net positive power output

3.10**cut-out wind speed** V_{out}

highest mean wind speed at hub height at which the wind turbine system is designed to produce power

3.11**declared sound power level**

the declared apparent sound power level in dB(A) as measured per IEC 61400-11 and as calculated per IEC 61400-14

3.12**design limit**

maximum or minimum value used in a design

3.13**design situation**

possible mode of wind turbine system operation, e.g. power production, parking, etc.

3.14**design wind speed**

wind speed at hub height used as input for the simple design equations (equal to $1,4 V_{ave}$)

3.15**downwind**

in the main direction of wind flow

3.16**emergency shutdown**

rapid shutdown of the wind turbine system triggered by a protection system or by manual intervention

3.17**environmental condition**

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

3.18**external condition**

factor affecting the operation of a wind turbine system including the environmental conditions (temperature, snow, ice, etc.) and the electrical network conditions that are not part of the wind turbine system

3.19

extreme wind speed

highest average wind speed, averaged over t seconds, that is likely to be experienced within a specified time period (recurrence period): of T years

Note 1 to entry: Recurrence periods of $T = 50$ years and $T = 1$ year and averaging time interval of $t = 3$ s and $t = 10$ min are used in a number of standards. In popular language the less precise term "survival wind speed" is often used. In practice, however, the wind turbine generator system is designed using the extreme wind speed for design load cases.

3.20

fail-safe

design property of an item which prevents its failures from resulting in critical faults

3.21

furling

a passive control mechanism by means of reducing the projected swept area, which can be used to e.g. control the wind turbine system power or rotational speed, etc.

3.22

gust

sudden and brief increase of the wind speed over its mean value

Note 1 to entry: A gust can be characterized by its rise-time, its amplitude and its duration.

3.23

horizontal axis wind turbine

wind turbine system whose rotor axis is substantially parallel to the wind flow

3.24

hub

fixture for attaching the blades or blade assembly to the rotor shaft of a wind turbine system

3.25

hub height

height of the geometric centre of the swept area of the wind turbine rotor above the terrain surface

3.26

idling

condition of a wind turbine that is rotating slowly and not producing power

3.27

limit state

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

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

[SOURCE: ISO 2394:1998, 2.2.9, modified to be precise to wind turbine systems]

3.28

load case

combination of a design situation and an external condition which results in structural loading

3.29**logarithmic wind shear law**

a mathematical law which expresses wind speed variations as a logarithmic function of height above ground

3.30**maximum output current**

maximum current (a.c. or d.c.) of the wind turbine system that can be taken from the connection facilities of the wind turbine system and which shall be specified as a 600 s average value, i_{600} , a 60 s average value, i_{60} and as a 0,2 s average value, $i_{0,2}$

Note 1 to entry: The maximum output current is ordinarily the rated current.

Note 2 to entry: The maximum output current is not to be confused with the current at the reference power.

3.31**maximum output power**

maximum power (a.c. or d.c.) that can be taken from the connection facilities of the wind turbine system and which shall be specified as a 600 s average value, P_{600} , a 60 s average value, P_{60} and as a 0,2 s average value, $P_{0,2}$

Note 1 to entry: The maximum output power is ordinarily the rated power.

Note 2 to entry: The maximum output power is not to be confused with the reference power.

3.32**maximum output voltage**

maximum voltage (a.c. or d.c.) that will be produced at the connection facilities of the wind turbine system and which shall be specified as a 600 s average value, U_{600} , a 60 s average value, U_{60} and as a 0,2 s average value, $U_{0,2}$

Note 1 to entry: The maximum output voltage may be exceeded within the wind turbine system itself.

3.33**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

3.34**nacelle**

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

3.35**noise label**

a defined graphical and textual representation of the acoustic noise data pertaining to a small wind turbine system

3.36**normal external conditions**

those external conditions which are encountered by the wind turbine system with less than one-year recurrence period

3.37**normal operation**

fault free operation complying with the description in the wind turbine manual

3.38**normal shutdown**

shutdown in which all stages are under the control of the wind turbine's control system

3.39

operating limits

set of conditions defined by the SWT designer that govern the activation of the control and protection system

3.40

overspeed control

the action of a control system, or part of such system, which prevents excessive rotor speed

3.41

parked wind turbine

depending on the construction of the wind turbine system, parked refers to the turbine being either in a stand-still or an idling condition

3.42

parking

situation to which a wind turbine system returns after a normal shutdown

3.43

power form

physical characteristics which describe the form in which power produced by the wind turbine system is made deliverable to the load (e.g. 230 V a.c., 50 Hz, 1 ph; or e.g. 48 V d.c.)

3.44

power law for wind shear

a mathematical law which expresses wind speed variations as a power law function of height above ground

3.45

power output

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

Note 1 to entry: The electric power delivered by a wind turbine system.

3.46

protection system

system which ensures that a wind turbine generator system remains within the design limits

3.47

rated power

maximum continuous electrical output power which a wind turbine system is designed to achieve at the connection facilities under normal operation

Note 1 to entry: The reference power is defined for the purposes of comparing wind turbine systems and is not to be confused with the rated power which may occur at much higher wind speeds. Rated power is an obsolete term that is better replaced by either maximum output power or reference power depending on context.

[SOURCE: IEC 61400-21:2008, 3.14, modified to be precise to wind turbine systems]

3.48

rated current

maximum continuous electrical output current which a wind turbine system is designed to achieve at the connection facilities under normal operation

Note 1 to entry: The reference current is defined for the purposes of comparing wind turbine systems and is not to be confused with the rated current which may occur at much higher wind speeds. Rated current is an obsolete term that is better replaced by maximum output current.

[SOURCE: IEC 61400-21:2008, 3.13, modified to be precise to wind turbine systems]

3.49**rated wind speed**

wind speed at which a wind turbine system's rated power is achieved

Note 1 to entry: Rated wind speed is an obsolete term. The reference power & reference annual energy are defined for the purposes of comparing wind turbine systems (see corresponding definitions) and are not to be confused with the maximum power which may occur at much higher wind speeds.

[SOURCE: IEC 61400-21:2008, 3.15, modified to be precise to wind turbine systems]

3.50**Rayleigh distribution**

probability distribution function often used for wind speeds

Note 1 to entry: The distribution depends on one adjustable parameter, the scale parameter, which controls the average wind speed.

Note 2 to entry: The Rayleigh distribution is identical to a Weibull distribution (see 3.73) with shape parameter 2.

3.51**reduced speed**

rotational speed such that the wind turbine system can be brought to a parked condition manually without any risk to personnel

3.52**reference annual energy**

calculated total energy that would be produced during a one-year period at an average wind speed of 5,0 m/s at hub height, assuming a Rayleigh wind speed distribution, 100 % availability, and the power curve derived from IEC 61400-12-1, where it is referred to as "Annual Energy Production" (AEP)

Note 1 to entry: The AEP from IEC 61400-12-1 is either the "AEP-measured" or the "AEP-extrapolated", and is either "sea-level normalised" or "site-specific".

Note 2 to entry: Within this standard reference annual energy is AEP-measured and sea-level normalised.

Note 3 to entry: The reference annual energy is defined for the purposes of comparing wind turbine systems.

3.53**reference power**

wind turbine system's power output at 11,0 m/s at hub height per the power curve from IEC 61400-12-1, or the maximum output power of the wind turbine system at a lower wind speed if this is a higher power output (again per the power curve from IEC 61400-12-1)

Note 1 to entry: The reference power is defined for the purposes of comparing wind turbine systems and is not to be confused with the maximum power which may occur at much higher wind speeds.

3.54**reference wind speed**

V_{ref}

basic parameter for wind speed used for defining SWT classes

Note 1 to entry: Other design related climatic parameters are derived from the reference wind speed and other basic SWT class parameters.

Note 2 to entry: A turbine designed for a SWT 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} (see 3.19).

3.55**resonance**

phenomenon appearing in an oscillating system, in which the period of a forced oscillation is very close to that of free oscillation

3.56

rotor centre

geometric centre of the wind turbine rotor

3.57

rotor speed

rotational speed of a wind turbine rotor about its axis

3.58

roughness length

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

3.59

safe life

prescribed service life with a declared probability of catastrophic failure

3.60

scheduled maintenance

preventive maintenance carried out in accordance with an established time schedule

3.61

shutdown

transitional state of a wind turbine between power production and standstill or idling

3.62

standstill

condition of a wind turbine generator system that is stopped

3.63

support structure

part of a wind turbine system comprising the tower and foundation

3.64

survival wind speed (deprecated)

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

Note 1 to entry: This term is not used in the IEC 61400 series; the design conditions instead refer to extreme wind speed (see 3.19), with extreme wind speed being the preferred term.

3.65

small wind turbine

SWT

system of 200 m² rotor swept area or less that converts kinetic energy in the wind into electrical energy.

Note 1 to entry: A small wind turbine system includes the wind turbine itself including support structures, the turbine controller, the charge controller / inverter (if required), wiring and disconnects, the installation and operation manual(s) and other documentation.

3.66

swept area

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

3.67

turbine test class

small wind turbine (SWT) class for which the duration test (13.4) has been completed

3.68**turbulence intensity**

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

3.69**ultimate limit state**

limit state which generally corresponds to maximum load carrying capacity (ISO 2394)

3.70**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

3.71**upwind**

in the direction opposite to the main direction of wind flow

3.72**vertical axis wind turbine**

wind turbine system whose rotor axis is substantially perpendicular to the wind flow

3.73**Weibull distribution**

probability distribution function often used for wind speeds

Note 1 to entry: This distribution function depends on two parameters, the shape parameter, which controls the width of the distribution and the scale parameter, which in turn controls the average wind speed (see wind speed distribution 3.75).

3.74**wind profile****wind shear law**

mathematical expression for assumed wind speed variation with height above ground

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

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

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

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.

3.75**wind speed distribution**

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

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

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

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

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 ;
- C is the scale parameter of the Weibull function;
- k is the shape parameter of the Weibull function;
- Γ is the gamma function.

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

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

3.76

wind shear

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

3.77

wind shear exponent

also commonly known as power law exponent (α), see 3.74, wind profile - wind shear law

3.78

wind speed

at a specified point in space, the speed of motion of a minute amount of air surrounding the specified point

Note 1 to entry: The wind speed is also the magnitude of the local wind velocity (vector) (see 3.79, wind velocity).

3.79

wind velocity

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

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

3.80

yawing

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

3.81

yaw rate

time rate of change of yaw angle, the rate of yawing

3.82

yaw misalignment

horizontal deviation of the wind turbine rotor axis from the wind direction

4 Symbols and abbreviated terms

4.1 General

NOTE Symbols and abbreviations can vary in some annexes, and if so they are defined internally within the annex.

4.2 Symbols

A	cross section area	[m ²]
A_{proj}	the component area projected on to a plane perpendicular or parallel to the wind direction	[m ²]
a	slope parameter for turbulence standard deviation model	[-]
B	number of blades	[-]
C	scale parameter of the Weibull distribution function	[m/s]
C_d	drag coefficient	[-]
C_f	force coefficient	[-]
C_l	lift coefficient	[-]
C_T	thrust coefficient	[-]
Coh	coherency function	[-]
D	rotor diameter	[m]
e_r	distance from the centre of gravity of the rotor to the rotation axis	[m]
F	force	[N]
F_{zB}	force on the blade at the blade root in the spanwise direction	[N]
$F_{x\text{-shaft}}$	axial shaft load	[N]
f	frequency	[Hz]
f_k	characteristic value for material strength	[-]
G	ratio between rated torque and short circuit torque for a generator	[-]
g	acceleration due to gravity: 9,81	[m/s ²]
i	electrical current	[A]
I_B	mass moment of inertia of the blade about the blade root flap axis	[kgm ²]
I_{15}	characteristic value of hub-height turbulence intensity at a 10-min average wind speed of 15 m/s	[-]
K	modified Bessel function	[-]
k	shape parameter of the Weibull distribution function	[-]
L	isotropic turbulence integral scale parameter	[m]
L_{lt}	distance between the lifting point and the top of the tower	[m]
L_{rt}	distance between the rotor centre and the yaw axis	[m]
L_{rb}	distance between rotor centre and first bearing	[m]
L_c	coherency scale parameter	[m]
L_k	velocity component integral scale parameter	[m]
M_{xB}, M_{yB}	blade root bending moments	[Nm]
M_{brake}	torque on the low speed shaft caused by the brake	[Nm]
$M_{x\text{-shaft}}$	torsion moment on the rotor shaft at the first bearing	[Nm]
M_{shaft}	combined bending moment for the shaft at the first bearing (nearest to rotor)	[Nm]
M_{tower}	the bending moment in the tower at the lifting point attachment	[Nm]

m_B	blade mass	[kg]
m_{overhang}	the mass of the tower between the lifting point and the top of the tower	[kg]
m_r	rotor mass being the mass of the blades plus the mass of the hub	[kg]
m_{towertop}	the mass of the nacelle and rotor combined	[kg]
$N(.)$	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	[yr]
n	rotor speed	[r/min]
n_{design}	design rotational speed	[r/min]
n_i	counted number of fatigue cycles in load bin i	[-]
n_{max}	maximum rotational speed	[r/min]
O	operational time fraction	[%]
P	electrical power	[W]
$P_R(V_0)$	Rayleigh cumulative probability distribution, i.e. the probability that $V < V_0$	[-]
$P_W(V_0)$	Weibull cumulative probability distribution	[-]
P_H	harmonic multiple of fundamental excitation frequency, being rotor speed	[Hz]
p	survival probability	[-]
Q	rotor torque	[Nm]
Q_{design}	design shaft torque	[Nm]
R	radius of the rotor	[m]
R_{cog}	radial distance between the centre of gravity of a blade and the rotor centre	[m]
r	magnitude of separation vector projection	[m]
$S_1(f)$	power spectral density function	[m ² /s ²]
S_k	single sided velocity component spectrum	[m ² /s ²]
s_i	the stress (or strain) level associated with the counted number of cycles in bin i	[-]
T	gust characteristic time	[s]
t	time	[s]
T_d	design life	[s]
T_E	excluded time	[h]
T_N	time during which the turbine was not operational	[h]
T_T	total time elapsed in the duration test	[h]
T_U	unknown time	[h]
U	electrical potential difference (voltage)	[V]
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_{design}	design wind speed	[m/s]
V_{eN}	expected extreme wind speed (averaged over 3 s), with a recurrence time interval of N years. V_{e1} and V_{e50} for 1 year and 50 years, respectively	[m/s]
V_{gustN}	largest gust magnitude with an expected recurrence period of N years.	[m/s]
V_{hub}	wind speed at hub height averaged over 10 min	[m/s]
V_{in}	cut-in wind speed	[m/s]

V_{maint}	wind speed (10-min average) below which safe shutdown of the SWT for performing inspections, service or maintenance is possible	[m/s]
$V_{\text{max,shutdown}}$	the maximum wind speed at which the manufacturer allows a normal shutdown	[m/s]
V_0	limit wind speed in wind speed distribution model	[m/s]
V_{out}	cut-out wind speed	[m/s]
V_{ref}	reference wind speed averaged over 10 min	[m/s]
V_{tip}	speed of the blade tip	[m/s]
$V(t,z)$	longitudinal wind velocity component to describe transient variation for extreme gust and shear conditions	[m/s]
W	section modulus used in stress calculations	[m ³]
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 and extreme operating gust model	[-]
Γ	gamma function	[-]
γ_f	partial safety factor for loads	[-]
γ_m	partial safety factor for materials	[-]
Δ	range	[-]
$\theta(t)$	wind direction change transient	[°]
θ_{cg}	angle of maximum deviation from the direction of the average wind speed under gust conditions	[°]
θ_{eN}	extreme direction change with a recurrence period of N years	[°]
η	efficiency of the components between the electric output and the rotor (typically generator, gearbox and conversion system)	[-]
Λ_1	turbulence scale parameter defined as the wave length where the non-dimensional, longitudinal power spectral density, $fS_1(f)/\sigma_1^2$, is equal to 0,05	[m]
λ	tip speed ratio	[-]
ρ	air density, here assumed 1,225	[kg/m ³]
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 lateral wind velocity standard deviation	[m/s]
σ_d	design stress	[MPa]
σ_k	k^{th} hub-height component wind velocity standard deviation ($k = 1, 2, \text{ or } 3$)	[m/s]
ω_n	rotational speed of the rotor	[rad/s]
ω_{yaw}	yaw rate	[rad/s]
$\omega_{\text{yaw,max}}$	maximum yaw rate	[rad/s]

Subscripts:

ave	average
B	blade

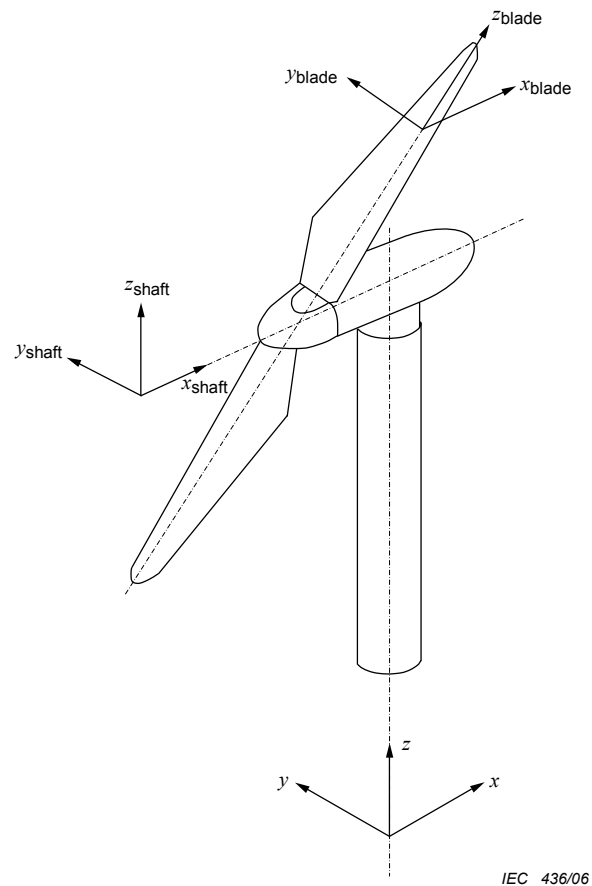
design	input parameter for the simplified design equations
e1	once per year extreme (averaged over 3 s)
e50	once per 50 year extreme (averaged over 3 s)
hub	hub
max	maximum
overhang	description of section of tower between lifting point and tower top
r	rotor
shaft	shaft
x	in the x -direction
y	in the y -direction
z	in the z -direction

Abbreviations:

asl	above sea level
AEP	Annual Energy Production
RAE	Reference Annual Energy
AC	Alternating current
DC	Direct current
CFD	Computational Fluid Dynamics
DLC	Design load case
ECD	Extreme coherent gust with direction change
ECG	Extreme coherent gust
EDC	Extreme wind direction change
EMC	Electromagnetic compatibility
EOG	Extreme operating gust
EWC	Extreme wind conditions
EWM	Extreme wind speed model
F	Fatigue
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode Effects and Criticality Analysis
GFCI	Ground fault circuit interrupter
HAWT	Horizontal axis wind turbine
NTM	Normal turbulence model
NWC	Normal wind conditions
NWP	Normal wind profile model
OWC	Other wind conditions
S	Special IEC wind turbine class
SWC	Standard wind conditions
SWT	Small wind turbine
U	Ultimate
UV	Ultra violet (radiation)
VAWT	Vertical axis wind turbine

4.3 Coordinate system

To define the directions of the loads of a horizontal axis wind turbine (HAWT), the system of axes shown in Figure 1 is used.



The following notes form part of the above figure:

Tower:

x is positive in the downwind direction, z is pointing up, y completes right hand coordinate system

the tower system is fixed

Shaft:

x_{shaft} is such that a positive moment about the x axis acts in the rotational direction

y_{shaft} and z_{shaft} are not used, only the combined moment is used

the shaft axis system rotates with the nacelle

Blade:

x_{blade} is such that a positive moment about the x-axis acts in the rotational direction

y_{blade} is such that a positive moment acts to bend the blade tip downwind

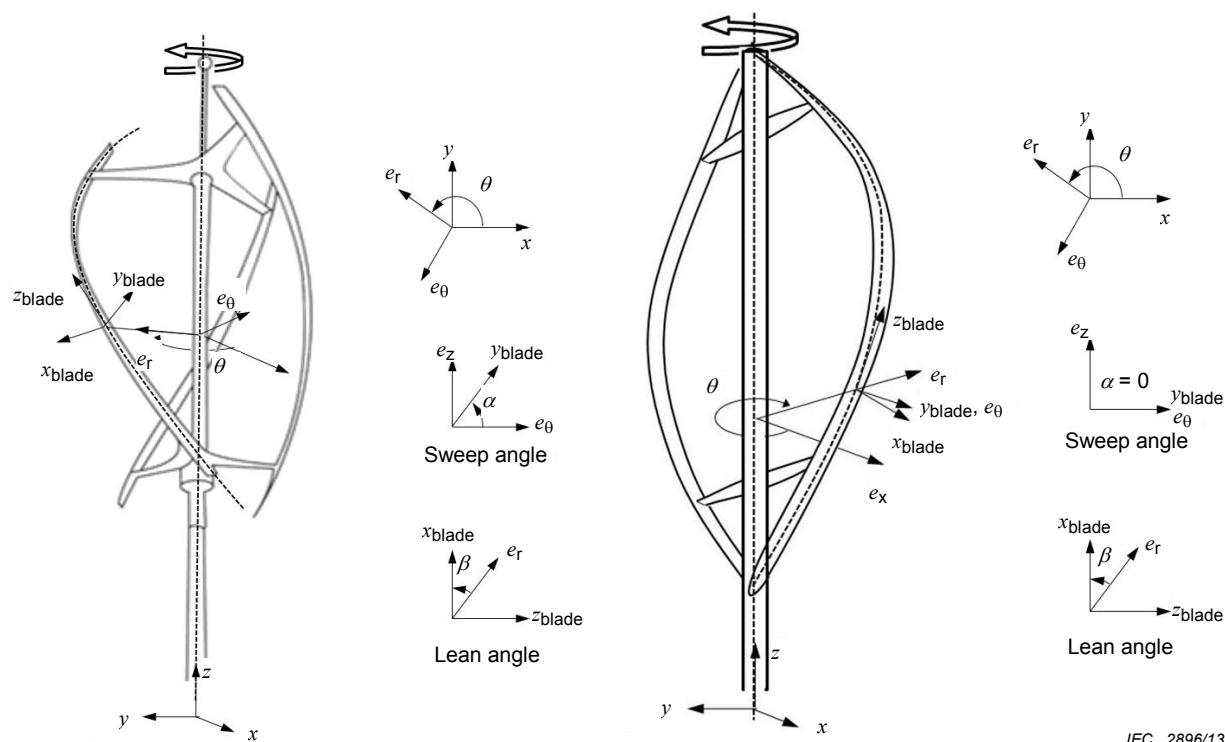
z_{blade} is positive towards blade tip

the blade coordinate system follows the right-hand convention for a rotor that spins clockwise and the left-hand convention for a rotor that spins counter clockwise when viewed from an upwind location.

the blade axis system rotates with the rotor

Figure 1 – Definition of the system of axes for HAWT

To define the directions of the loads of a vertical axis wind turbine (VAWT), the system of axes shown in Figure 2 is used.



IEC 2896/13

Tower:

x is positive in the downwind direction, z pointing up, y completes the right hand coordinate system.

Rotor:

The rotor coordinate system is cylindrical of axis z , the angle $\theta = (e_x, e_r)$ is positive from the downwind axis x . (e_r, e_θ, e_z) is a right hand coordinate system.

Blade:

z_{blade} is tangent to the reference line of the blade, and points upward.

y_{blade} is perpendicular to z_{blade} and to the radial vector e_r ; points in the opposite direction to the rotation

x_{blade} completes the right hand coordinate system (and is normal to the blade)

NOTE In the case of a rotor with planar straight blades (lean and sweep angle are both zero) spinning in the negative z direction, the blade coordinate system is coincident with the rotor coordinate system.

Figure 2 – Definition of the system of axes for VAWT

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 5 through 12. This specification of requirements applies to the design, manufacture, installation and maintenance of the wind turbine, and the associated quality management process, together with appropriate and sufficient documentation.

5.2 Design methods

The design method for turbines covered under this standard is depicted in Figure 3. A simplified approach is permitted for a variety of turbine configurations. For turbines with a swept rotor area of 2 m² or less only the sample support structure is considered part of the design (however see 11.2.3.2).

The design loads shall be obtained in one or a combination of the following three ways. The design loads shall be verified by measured “design data test” (See 13.2):

It is *recommended* that in-house tests for design data are conducted early in the development.

1) Simplified loads methodology

For certain turbine configurations a simplified calculation method is given. A limited set of load cases and configurations is given in 7.4 with simple formulas and simplified external conditions. The turbine data assumed within the simplified equations shall be verified by the “Tests to verify design data” (see 13.2).

2) Simulation model

A model shall be used to determine the loads over a range of wind speeds, using the turbulence conditions and other extreme wind conditions defined in 6.3.3, and design situations defined in 7.5. This approach uses a structural dynamics simulation model in combination with wind turbine and application adequate assumptions. The assumptions shall be verified by the “Tests to verify design data” (see 13.2).

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.

3) Full scale load measurement

Full scale load measurement with load extrapolation (see 7.6).

Each of these methods has different uncertainties. Therefore, different sets of safety factors shall be applied depending upon the load estimation method used (see 7.8).

For all turbines a static blade test is required (see 13.5.2). To verify the adequacy of other load carrying components, either calculations or testing is required or a combination of both. Test conditions shall reflect the design loads including the relevant safety factors.

Finally, for all turbines a safety and function test (see 13.6) and duration test (see 13.4) are required.

5.3 Quality assurance

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

It is recommended that the quality system complies with the requirements of the ISO 9000 series.

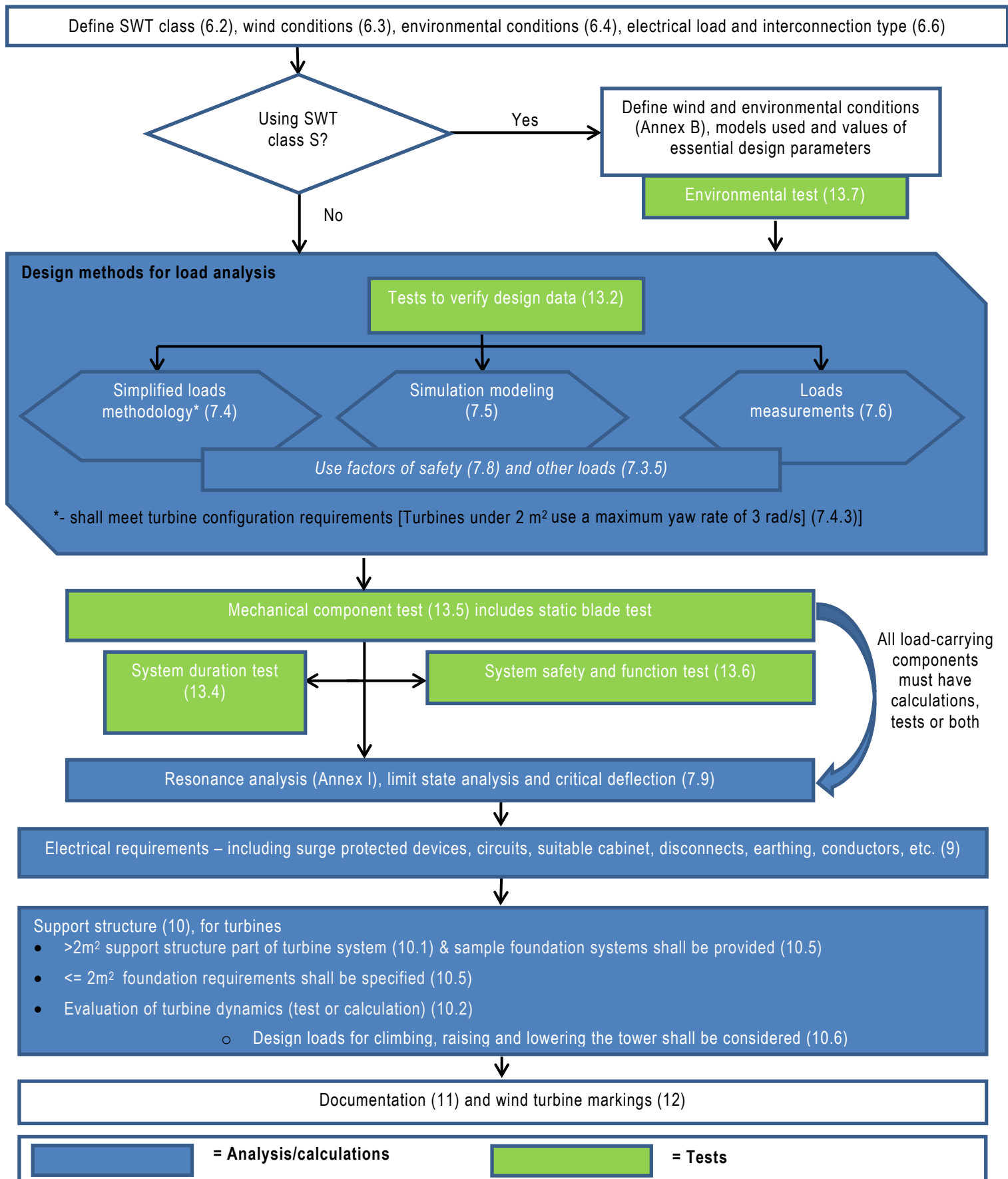


Figure 3 – IEC 61400-2 decision path

I Design evaluation

6 External conditions

6.1 General

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

The environmental conditions are divided into wind conditions and other environmental conditions. The electrical conditions refer to either network conditions or local electrical conditions like batteries, hybrid systems or local grid. Soil properties are relevant to the design of SWT foundations.

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

Each type of external condition may be subdivided into a normal external condition and an extreme external condition. The normal external conditions generally concern long-term structural loading and operating conditions, while the extreme external conditions represent the rare but potentially critical external design conditions. The design load cases shall consist of a combination of these external conditions with wind turbine operational modes.

6.2 SWT classes

The external conditions to be considered in design are dependent on the intended site or site type for a SWT installation. SWT classes are defined in terms of wind speed and turbulence parameters. The values of wind speed and turbulence parameters are intended to represent the characteristic values of many different sites and do not give a precise representation of any specific site. The goal is to achieve SWT classification with clearly varying robustness governed by the wind. Table 1 specifies the basic parameters, which define the SWT classes.

The intention of the classes is to cover most applications, and reference should be made to Annex L for other wind conditions that may be experienced. In cases where a special design (e.g. special wind conditions, or other wind conditions (per Annex L) or other external conditions or a special safety class) is necessary, a further SWT class, class S, is defined. The design values for the SWT class S shall be chosen by the designer and specified in the design documentation (see Annex B). For such special designs, the values chosen for the design conditions shall reflect a more severe environment than anticipated for the use of the SWT.

The particular external conditions defined for classes I, II, III and IV 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 (see Annex B, Annex K, and Annex L).

Table 1 – Basic parameters for SWT classes

SWT class	I	II	III	IV	S
V_{ref} (m/s)	50	42,5	37,5	30	Values to be specified by the designer
V_{ave} (m/s)	10	8,5	7,5	6	
I_{15} (Note 2) (-)	0,18	0,18	0,18	0,18	
a (-)	2	2	2	2	
NOTE					
1) the values apply at hub height, and;					
2) I_{15} is the dimensionless characteristic value of the turbulence intensity at 15 m/s, where 0,18 is the minimum value that shall be used, and noting that Annex M discusses observations regarding turbulence intensity;					
3) a is the dimensionless slope parameter to be used in Equation (7).					

In addition to these basic parameters, several important further parameters are required to completely specify the external conditions used in SWT design. In the case of the SWT classes I through IV later referred to as standard SWT classes, the values of these additional parameters are specified in 6.3, 6.4 and 6.6.

The abbreviations added in parentheses in the subclause headings in the remainder of Clause 6 are used for describing the wind conditions for the design load cases defined in 7.5, simulation modelling (note that for the simple load calculations, the wind conditions are simplified as well).

For the SWT class S the manufacturer shall in the design documentation describe the models used and values of essential design parameters. Where the models in the present subclause 6.2 are adopted, statement of the values of the parameters will be sufficient. The design documentation of SWT class S shall contain the information listed in Annex B.

The design lifetime shall be clearly specified in the design documentation.

6.3 Wind conditions

6.3.1 General

A SWT shall be designed to safely withstand the wind conditions defined by the selected SWT 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 (NWC) which will occur frequently during normal operation of a SWT, and the extreme wind conditions (EWC) which are defined as having a 1-year or 50-year recurrence period.

In this standard the combination of the NWC and EWC in conjunction with the four SWT classes I-IV define the standard wind conditions (SWC). In Annex L other wind conditions (OWC) are discussed.

In all cases the influence of an inclination of mean flow with respect to the horizontal plane of up to 8° shall be considered. The flow inclination angle may be assumed to be invariant with height. Note that oblique inflow can have an effect on furling if the furl direction is chosen poorly with respect to the rotational direction of the rotor.

6.3.2 Normal wind conditions

6.3.2.1 Wind speed distribution

The wind speed distribution at the site is significant for the SWT design because it determines the frequency of occurrence of the individual load conditions. In case of the standard SWT

classes, the mean value of the wind speed over a time period of 10 min shall be assumed to be Rayleigh distributed for the purposes of design load calculations. In this case, the cumulative probability distribution at hub height is given by:

$$P_R(V_{\text{hub}}) = 1 - \exp\left[-\pi(V_{\text{hub}} / 2V_{\text{ave}})^2\right] \quad (5)$$

6.3.2.2 Normal wind profile model (NWP)

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

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

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

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

6.3.2.3 Normal turbulence model (NTM)

The normal turbulence model shall include a wind shear as described under NWP, in 6.3.2.2. The expression "wind turbulence" denotes stochastic variations in the wind velocity from the 10-min average. The turbulence model shall include the effects of varying wind speed, varying direction, and rotational sampling. For the standard SWT classes, the power spectral densities of the random wind velocity vector field, whether used explicitly in the model or not, shall satisfy the following requirements:

- a) The characteristic value of the standard deviation of the longitudinal wind velocity component shall be given by¹:

$$\sigma_1 = I_{15}(15 + aV_{\text{hub}})/(a + 1) \quad (7)$$

Values for I_{15} and a are given in Table 1. The characteristic values of the standard deviation, σ_1 , and of the turbulence intensity, σ_1/V_{hub} , are shown below in Figure 4.

¹ To perform the calculations of load cases in addition to those specified in Table 4, it may be appropriate to use different percentile values. Such percentile values shall be determined by adding a value to Equation (7) given by:

$$\Delta\sigma_1 = 2(x - 1)I_{15}$$

where x is determined from the normal probability distribution function. For example, $x = 1,64$ for a 95th percentile value.

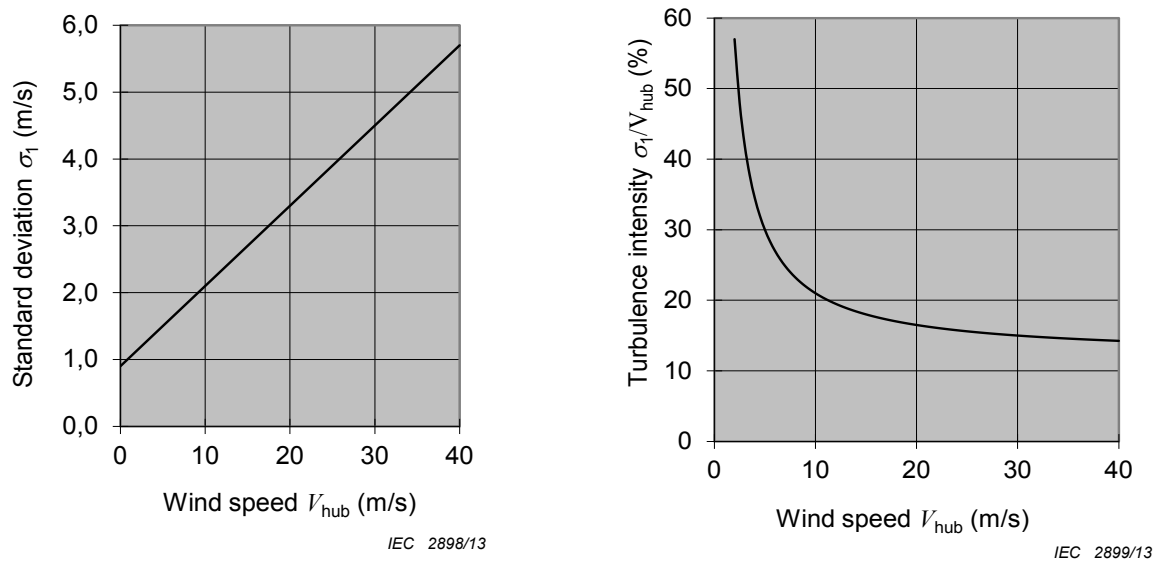


Figure 4 – Characteristic wind turbulence

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

$$S_1(f) = 0,05(\sigma_1)^2 (\Lambda_1 / V_{hub})^{-2/3} f^{-5/3} \quad (8)$$

- c) The turbulence scale parameter, Λ_1 , shall be given by:

$$\Lambda_1 = \begin{cases} 0,7 z_{hub} & \text{for } z_{hub} < 30 \text{ m} \\ 21 \text{ m} & \text{for } z_{hub} \geq 30 \text{ m} \end{cases} \quad (9)$$

Specifications for stochastic turbulence models, which satisfy these requirements, are given in Annex C. In Annex D a simplified deterministic model, which is based on a stochastic description of the turbulence, is given. This deterministic model may be used when it can be demonstrated that the turbine blade response to rotationally sampled wind velocity is sufficiently well damped. Guidance for this validation is also given in Annex D.

6.3.3 Extreme wind conditions

6.3.3.1 General

The extreme wind conditions are used to determine extreme wind loads on SWTs. These conditions include peak wind speeds due to storms and rapid changes in wind speed and direction. These extreme conditions include the potential effects of wind turbulence so that only the deterministic effects need to be considered in the design calculations.

6.3.3.2 Extreme wind speed model (EWM)

The 50-year extreme wind speed V_{e50} and the one year extreme wind speed V_{e1} shall be based on the reference wind speed V_{ref} . For SWT designs in the standard SWT classes, the 3-s gust V_{e50} and V_{e1} shall be computed using the following equations:

$$V_{e50}(z) = 1,4 V_{ref} (z / z_{hub})^{0,11} \quad (10)$$

$$V_{e1} = 0,75 V_{e50} \quad (11)$$

where z_{hub} is hub height, and 1,4 is the gust factor at hub height.

Short-term deviations from the mean wind direction of $\pm 15^\circ$ shall be assumed.

6.3.3.3 Extreme operating gust (EOG)

The hub height gust magnitude $V_{\text{gust}N}$ for a recurrence period of N years shall be given for the standard SWT classes by the following relationship:

$$V_{\text{gust}N} = \beta \left(\frac{\sigma_1}{1 + 0,1 \left(\frac{D}{A_1} \right)} \right) \quad (12)$$

where

- σ_1 is the standard deviation, according to Equation (7);
- A_1 is the turbulence scale parameter, according to Equation (9);
- D is the rotor diameter;
- $\beta = 4,8$ for $N = 1$; and
- $\beta = 6,4$ for $N = 50$.

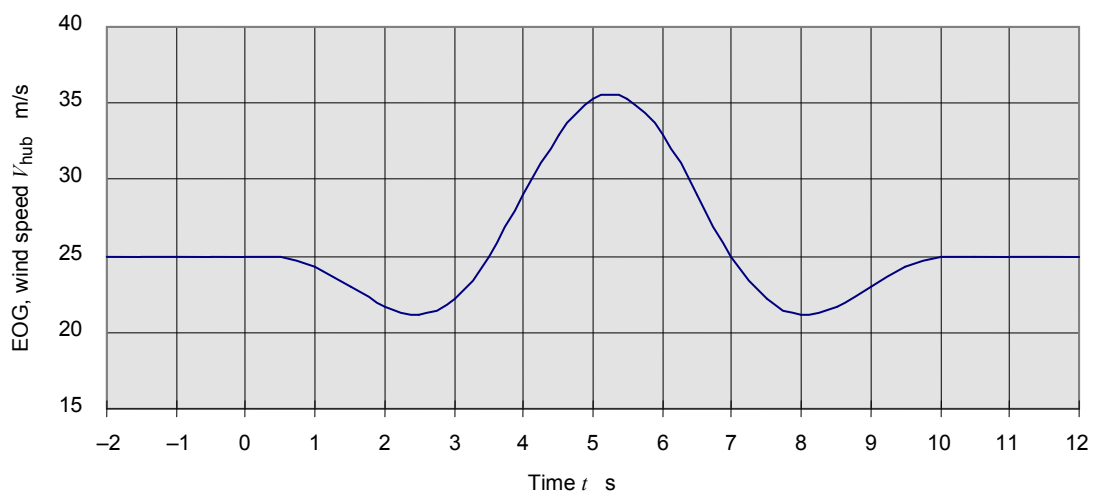
The wind speed shall be defined for a recurrence period of N years by the equation:

$$V(t) = \begin{cases} V(z) - 0,37 V_{\text{gust}N} \sin(3\pi t / T) (1 - \cos(2\pi t / T)) & \text{for } 0 \leq t \leq T \\ V(z) & \text{for } t < 0 \text{ and } t > T \end{cases} \quad (13)$$

where

- $V(z)$ is defined in Equation (6);
- $T = 10,5$ s for $N = 1$; and
- $T = 14,0$ s for $N = 50$.

As an example, the extreme operating gust with a recurrence period of one year and $V_{\text{hub}} = 25$ m/s is shown in Figure 5:



IEC 440/06

Figure 5 – Example of extreme operating gust ($N=1$, $V_{\text{hub}} = 25$ m/s)

The parameter values for both recurrence periods were selected to give the same maximum rise rate.

6.3.3.4 Extreme direction change (EDC)

The extreme direction change magnitude, θ_{eN} , for a recurrence period of N years shall be calculated using the following relationship:

$$\theta_{eN}(t) = \pm \beta \arctan \left(\frac{\sigma_1}{V_{hub} \left(1 + 0,1 \left(\frac{D}{A_1} \right) \right)} \right) \quad (14)$$

where

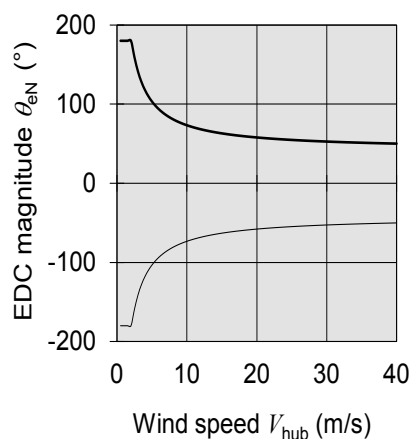
- θ_{eN} is limited to the interval $\pm 180^\circ$;
- A_1 is the turbulence scale parameter, according to Equation (9);
- D is the rotor diameter;
- $\beta = 4,8$ for $N = 1$; and
- $\beta = 6,4$ for $N = 50$.

The extreme direction change transient for a recurrence period of N years, $\theta_N(t)$, shall be given by:

$$\theta_N(t) = \begin{cases} 0 & \text{for } t < 0 \\ 0,5\theta_{eN}(1 - \cos(\pi t / T)) & \text{for } 0 \leq t \leq T \\ \theta_{eN} & \text{for } t > T \end{cases} \quad (15)$$

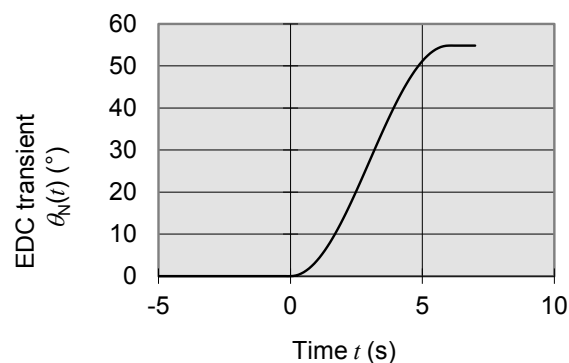
where $T = 6$ s is the duration of the extreme direction change transient. The sign shall be chosen so that the worst transient loading occurs. At the end of the direction change transient the direction is assumed to remain unchanged.

As an example, the extreme direction change with a recurrence period of 50 years and $V_{hub} = 25$ m/s is shown in Figure 6 and Figure 7.



IEC 2900/13

Figure 6 – Example of extreme direction change magnitude ($N = 50$, $D = 5$ m, $z_{\text{hub}} = 20$ m)



IEC 2901/13

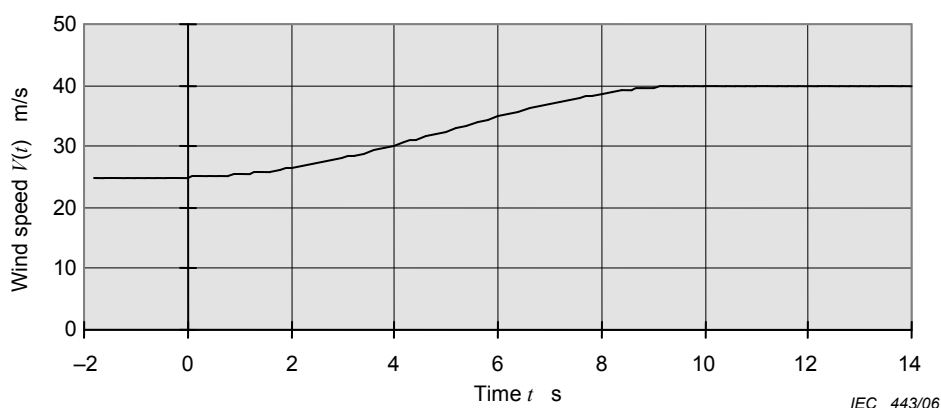
Figure 7 – Example of extreme direction change transient ($N = 50$, $V_{\text{hub}} = 25$ m/s)

6.3.3.5 Extreme coherent gust (ECG)

For wind turbine designs for the standard SWT classes, an extreme coherent gust with a magnitude of $V_{\text{cg}} = 15$ m/s shall be assumed. The wind speed shall be defined by the relations:

$$V(t, z) = \begin{cases} V(z) & \text{for } t < 0 \\ V(z) + 0,5 V_{\text{cg}}(1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ V(z) + V_{\text{cg}} & \text{for } t > T \end{cases} \quad (16)$$

where $T = 10$ s is the rise time. The normal wind profile model of wind speed as specified in Equation (6) shall be used. The extreme coherent gust is illustrated in Figure 8 for $V_{\text{hub}} = 25$ m/s.



IEC 443/06

Figure 8 – Extreme coherent gust ($V_{\text{hub}} = 25$ m/s) (ECG)

6.3.3.6 Extreme coherent gust with direction change (ECD)

In this case, the rise in wind speed (described by ECG, see Figure 8) shall be assumed to occur simultaneously with the direction change θ_{cg} , where θ_{cg} is defined by the relations:

$$\theta_{cg}(V_{hub}) = \begin{cases} 180^\circ & \text{for } V_{hub} < 4 \text{ m/s} \\ \frac{720^\circ}{V_{hub}} & \text{for } 4 \text{ m/s} \leq V_{hub} \leq V_{ref} \end{cases} \quad (17)$$

The direction change, θ_{cg} , as a function of V_{hub} and as a function of time for $V_{hub} = 25 \text{ m/s}$ is shown in Figure 9 and Figure 10, respectively.

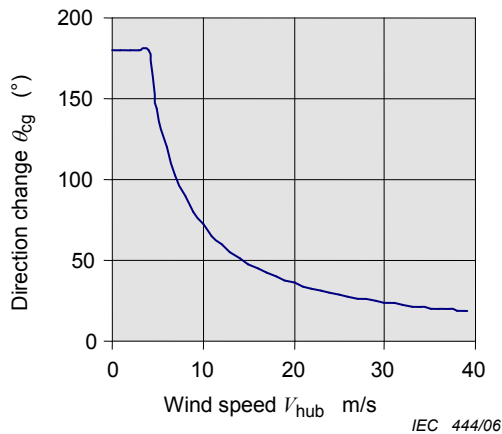


Figure 9 – The direction change for ECD

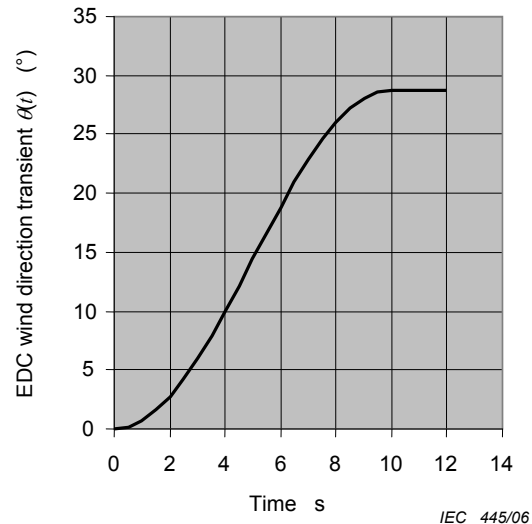


Figure 10 – Time development of direction change for $V_{hub} = 25 \text{ m/s}$

The simultaneous direction change is then given by:

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t \leq 0 \\ \pm 0,5 \theta_{cg}(1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ \pm \theta_{cg} & \text{for } t \geq T \end{cases} \quad (18)$$

6.4 Other environmental conditions

6.4.1 General

Environmental (climatic) conditions other than wind can affect the integrity and safety of the SWT, by thermal, photochemical, corrosive, mechanical, electrical or other physical action. Moreover, combinations of the climatic parameters given may increase their effect. At least the following other environmental conditions shall be taken into account and the action taken stated in the design documentation (see Annex J for further information):

- 1) temperature;
- 2) humidity;
- 3) air density;
- 4) solar radiation;
- 5) rain, hail, snow and ice;
- 6) chemically active substances;
- 7) mechanically active particles (e.g. sand and dust particles);
- 8) lightning;
- 9) earthquakes; and
- 10) marine environment - corrosion.

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

Variations in the climatic conditions within the normal limits, which correspond to a one-year recurrence period shall not interfere with the designed normal operation of a SWT. Unless correlation exists, other extreme environmental conditions according to 6.4.3 shall be combined with the normal wind conditions according to 6.3.2.

6.4.2 Other normal environmental conditions

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

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

When the designer specifies additional external condition parameters, these parameters and their values shall be stated in the design documentation and shall conform to the requirements of IEC 60721-2-1.

6.4.3 Other extreme environmental conditions

6.4.3.1 General

Other extreme environmental conditions, which shall be considered for SWT design, are temperature, lightning, ice and earthquakes.

6.4.3.2 Temperature

The design values for the extreme temperature range shall be at least -20 °C to $+50\text{ °C}$ for the standard SWT classes.

6.4.3.3 Lightning

The provisions of lightning protection required in 9.5 may be considered as adequate for wind turbines in the standard SWT classes.

6.4.3.4 Ice

No ice requirements are given for the standard SWT classes.

In case the manufacturer wants to include ice loading in their design load estimation, a minimum of 30 mm layer of ice with a density of 900 kg/m^3 on all exposed areas is recommended. This static ice load would then be combined with the drag loads on the parked turbine system at $3 \times V_{ave}$. Ice loads on the support structure including guy wires should be considered in the design loads of the support structure.

6.4.3.5 Earthquakes

No minimum earthquake requirements are given for the standard SWT classes.

6.5 Controlled test conditions

Room temperature is +10 °C to +35 °C. For tests under controlled test conditions the controlled room temperature shall always be in the range of +18 °C to +28 °C (+23 ± 5) °C).

6.6 Electrical load conditions

6.6.1 General

The electrical conditions which need to be considered in the design depend on the application of the turbine.

6.6.2 For turbines connected to the electrical power network

6.6.2.1 Normal electrical conditions

The normal conditions at the wind turbine terminals to be considered in design are listed below. Normal electrical power network conditions apply when the following parameters fall within the ranges stated below:

- Voltage
Nominal value (according to IEC 60038) ± 10 %;
- Frequency
Nominal value ± 2 %;
- Voltage imbalance
The ratio of the negative-sequence component of voltage to the positive-sequence component will not exceed 2 %;
- Auto-reclosing cycles
Auto-reclosing cycle periods of 0,2 s to 5,0 s for the first reclosure and 10 s to 90 s for a second reclosure; and
- Outages
Electrical network outages shall be assumed to occur 20 times per year. An outage of up to 24 h shall be considered a normal condition.

6.6.2.2 Extreme electrical conditions

At least the following extreme electrical power network conditions at the wind turbine terminals shall be considered in the design:

- voltage – deviations from nominal value of ± 20 %;
- frequency – nominal value ± 10 %;
- voltage imbalances of 15 %;
- symmetrical and unsymmetrical faults; and
- outages – an outage of up to 1 week shall be considered an extreme condition.

6.6.3 For turbines not connected to the electrical power network

6.6.3.1 Battery-charging turbine

The turbine shall be able to operate over the full range of battery voltages listed below:

- voltage range –15 % or +30 % of nominal voltage (example 12 V, 24 V, 36 V, etc.); or
- 5 % beyond upper and lower settings of charge controller.

6.6.3.2 Local-grid

Turbines connected to a local grid thus not connected to a large electrical network will be expected to encounter larger variations in voltage and frequency. The turbine system shall be able to operate within the following constraints:

- voltage: deviation from nominal values of $\pm 15\%$; and
- frequency: nominal ± 5 Hz.

7 Structural design

7.1 General

Wind turbine system structural design shall be based on verification of the structural integrity of the components in the critical load paths from the rotor blades to the foundation. The ultimate and fatigue strength of all structural members (for example: rotor blade, rotor hub, rotor shaft, nacelle, yaw shaft, tower, connections) shall be verified by calculations or tests, or a combination of both, to determine the structural integrity of a SWT with the appropriate safety level. The scope of verification is the same regardless of the design methodology chosen (7.2).

The structural analysis shall be based on ISO 2394 or equivalent, where applicable.

7.2 Design methodology

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

There are three ways given to determine the design loads for the turbine which are described in 5.2 as being:

- 1) simplified loads methodology;
- 2) simulation model;
- 3) full scale load measurement.

7.3 Loads and load cases

7.3.1 General

The types of loads described in 7.3.2 to 7.3.6 shall be considered.

7.3.2 Vibration, inertial and gravitational loads

Inertial and gravitational loads are static and dynamic loads acting on the SWT resulting from inertia, gyroscopic, vibration, rotation, gravity and seismic activity or motion of the support structure such as boats, etc.

A resonance analysis, such as provided by a Campbell diagram, shall be provided for the main structural components of the wind turbine system (see Annex I).

7.3.3 Aerodynamic loads

Aerodynamic loads are static and dynamic loads, which are caused by the airflow and its interaction with the stationary and moving parts of the SWT. The airflow shall be considered to be dependent upon the rotational speed of the rotor, the wind speed across the rotor plane, turbulence, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including aero-elastic effects.

7.3.4 Operational loads

Operational loads result from the operation and control of the turbine system. Operational loads can be caused by yawing, braking, furling, pitching, grid connection, etc.

7.3.5 Other loads

All loads that may occur due to special operating environments specified by the manufacturer shall also be considered (e.g. wave loads, wake loads, ice loads, transport, assembly, maintenance and repair loads, etc.).

7.3.6 Load cases

For design purposes, the life of a SWT can be represented by a set of design situations covering the most significant conditions which the turbine system may experience.

The load cases shall be determined from the combination of specific assembly, erection, maintenance, and operational modes or design situations 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.

Generally the design load cases used to determine the structural integrity of a SWT may be calculated from the following combinations:

- turbine operation without fault and with normal external conditions;
- turbine operation without fault and with extreme external conditions;
- turbine operation with fault and appropriate external conditions; and
- transportation, installation and maintenance design situations and appropriate external conditions (see also 10.6).

If a significant 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 to verify the structural integrity of SWT components. As a minimum the design load cases in Table 2 or Table 4 shall be considered. In those tables, the design load cases are specified for each design situation by the description of the wind, electrical and other external conditions.

Where the control and protection system does not monitor and limit certain turbine parameters, this shall be taken into account in the load cases. Examples of such parameters are:

- cable twist;
- vibrations;
- rotor speed; and
- flutter.

7.4 Simplified loads methodology

7.4.1 General

For certain turbine configurations the loads can be derived using simple, conservative equations for a limited set of load cases. Annex F provides background information for these equations. If the turbine configuration does not meet those configuration requirements the simplified loads methodology cannot be used, instead the alternative simulation modelling (7.5) or load measurements shall be used (7.6).

The turbine configurations that are able to use the simplified loads methodology shall meet all of the following requirements:

- horizontal axis;
- 2 or more bladed propeller-type rotor;
- cantilever blades;
- coordinated blade movement (not independent and uncoordinated pitching, coning, etc.); and
- rigid hub (not teetering or hinged hub).

The turbine configuration may use an upwind or downwind rotor; it may operate at either variable or constant speed; it may have an active or passive pitch mechanism (provided that the pitch mechanism coordinates all blades simultaneously), as well as fixed pitch; and it may furl about vertical, horizontal, or intermediate axes, as well as not furling.

The simplified load methodology uses input parameters which shall be determined as described in 13.2, noting especially the clause regarding yaw 13.2.3. These parameters are:

- design rotational speed, n_{design} ;
- design wind speed, V_{design} ;
- design shaft torque, Q_{design} ;
- maximum yaw rate, $\omega_{\text{yaw,max}}$; and
- maximum rotational speed, n_{max} .

Further the design tip speed ratio is defined as:

$$\lambda = \frac{V_{\text{tip}}}{V_{\text{hub}}} = \frac{\omega R}{V_{\text{hub}}} \Rightarrow \lambda_{\text{design}} = \frac{R}{V_{\text{design}}} \frac{\pi n_{\text{design}}}{30} \quad (19)$$

$$\omega_n = \frac{2\pi n}{60} = \frac{\pi n}{30} \quad (20)$$

The load cases for the simplified load methodology are summarised in Table 2. The load components for the simplified load methodology are found in each clause discussing the load case.

For each design situation, 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 such as analysis of exceeding the maximum material strength, analysis of tip deflection, and stability analysis.

Table 2 – Design load cases for the simplified load calculation method

Design situation	Load cases		Wind inflow	Type of analysis	Remarks
Power production	A	Normal operation		F	
	B	Yawing	$V_{hub}=V_{design}$	U	
	C	Yaw error	$V_{hub}=V_{design}$	U	
	D	Maximum thrust	$V_{hub}=2,5 V_{ave}$	U	Rotor spinning but could be furling or fluttering
Power production plus occurrence of fault	E	Maximum rotational speed		U	
	F	Short at load connection	$V_{hub}=V_{design}$	U	Maximum short-circuit generator torque
Shutdown	G	Shutdown (Braking)	$V_{hub}=V_{design}$	U	
Extreme wind Loading	H	Extreme wind loading	$V_{hub}=V_{e50}$	U	The turbine may be parked (idling or standstill) or governing. No manual intervention has occurred.
Parked and fault conditions	I	Parked wind loading, maximum exposure	$V_{hub}=V_{ref}$	U	Turbine is loaded with most unfavourable exposure
Transport, assembly, maintenance and repair	J	To be stated by manufacturer		U	
Key F analysis of fatigue loads U analysis of ultimate loads					

Other design load cases relevant for safety shall be considered, if required by the specific SWT design.

7.4.2 Load case A: normal operation

The design load for “normal operation” is a fatigue load. The load case assumes constant range fatigue loading for the blade and shaft, these ranges are given below. The ranges are to be considered in the fatigue assessment as peak-to-peak values. The mean values of the load ranges can be ignored.

NOTE See Clause F.3.

Blade loads:

$$\Delta F_{zB} = 2m_B R_{cog} \omega_{n,design}^2 \quad (21)$$

$$\Delta M_{xB} = \frac{Q_{design}}{B} + 2m_B g R_{cog} \quad (22)$$

$$\Delta M_{yB} = \frac{\lambda_{design} Q_{design}}{B} \quad (23)$$

The fatigue loading on the blade would be considered to occur at the airfoil – root junction or at the root – hub junction, whichever is determined to have the lowest ultimate strength. The calculated stresses are the combination of the centrifugal loading (F_{zB}) and the bending moments (M_{xB} and M_{yB}).

Shaft loads:

$$\Delta F_{x\text{-shaft}} = \frac{3}{2} \frac{\lambda_{\text{design}} Q_{\text{design}}}{R} \quad (24)$$

$$\Delta M_{x\text{-shaft}} = Q_{\text{design}} + 2 m_r g e_r \quad (25)$$

$$\Delta M_{\text{shaft}} = 2 m_r g L_{rb} + \frac{R}{6} \Delta F_{x\text{-shaft}} \quad (26)$$

where $e_r = 0,005R$, unless through design documents it can be proven that a lower value is reasonable.

The fatigue load on the rotor shaft shall be considered at the rotor shaft at the first bearing (nearest to the rotor). The range of the stress shall be calculated from the combination of the thrust loading ($F_{x\text{-shaft}}$), the torsion moment ($M_{x\text{-shaft}}$) and the bending moment (M_{shaft}).

7.4.3 Load case B: yawing

For this load case, the ultimate loads (gyroscopic forces and moments) shall be calculated assuming the maximum yaw speed $\omega_{\text{yaw,max}}$ occurring with n_{design} .

For a passive yaw system, the maximum yaw rate is given by the following equation:

$$\omega_{\text{yaw,max}} = 3 - 0,01 \times (\pi R^2 - 2) \quad (27)$$

For all turbines with a swept rotor area of less than 2 m², the maximum yaw rate shall be 3 rad/s.

For an active yaw system the maximum yaw rate shall be determined by measurement in calm winds. If the maximum yaw rate is expected to occur under special conditions such as emergency yawing at higher rate, the active yaw rate shall be measured under those conditions.

The loads due to the bending moment M_{yB} on the blade and the shaft bending moment M_{shaft} shall be calculated using the following equations:

$$M_{yB} = m_B \omega_{\text{yaw,max}}^2 L_{rt} R_{\text{cog}} + 2 \omega_{\text{yaw,max}} I_B \omega_{n,\text{design}} + \frac{R}{9} \Delta F_{x\text{-shaft}} \quad (28)$$

where $\Delta F_{x\text{-shaft}}$ is given by Equation (24).

For the shaft, the loads are dependent on the number of blades.

For a two bladed rotor:

$$M_{\text{shaft}} = 4 \omega_{\text{yaw,max}} \omega_{n,\text{design}} I_B + m_r g L_{rb} + \frac{R}{6} \Delta F_{x\text{-shaft}} \quad (29)$$

For a three or more bladed rotor:

$$M_{\text{shaft}} = B \omega_{\text{yaw,max}} \omega_{n,\text{design}} I_B + m_r g L_{rb} + \frac{R}{6} \Delta F_{x\text{-shaft}} \quad (30)$$

7.4.4 Load case C: yaw error

All turbines operate with a certain yaw error. In this load case a yaw error of 30° is assumed. The flapwise bending moment caused by the yaw error is given by Equation (31)

$$M_{yB} = \frac{1}{8} \rho A_{\text{proj},B} C_{l,\text{max}} R^3 \omega_{n,\text{design}}^2 \left[1 + \frac{4}{3\lambda_{\text{design}}} + \frac{1}{2} \left(\frac{1}{\lambda_{\text{design}}} \right)^2 \right] \quad (31)$$

If no data is available on the maximum lift coefficient, $C_{l,\text{max}}$, a value of 2,0 shall be used.

7.4.5 Load case D: maximum thrust

The SWT can be exposed to high thrust loads on the rotor. The thrust load acts parallel to the rotor shaft and has a maximum value given by:

NOTE See Clause F.3.

$$F_{x\text{-shaft}} = C_T 0,5 \rho (2,5 \times V_{\text{ave}})^2 \pi R^2 \quad (32)$$

where C_T is the thrust coefficient, equal to 0,5. However, caution should be exercised with wind turbines that operate at high rotational speeds at 2,5 V_{ave} , where a C_T of 8/9 may be more appropriate.

7.4.6 Load case E: maximum rotational speed

The centrifugal load in the blade root s_{zB} and the shaft bending moment M_{shaft} due to centrifugal load and rotor unbalance shall be calculated from equations below. The maximum possible rotor speed $\omega_{n,\text{max}} = (\pi/30) n_{\text{max}}$ shall be derived by measurements as described in 13.2.4.

$$F_{zB} = m_B \omega_{n,\text{max}}^2 R_{\text{cog}} \quad (33)$$

$$M_{\text{shaft}} = m_r g L_{\text{rb}} + m_r e_r \omega_{n,\text{max}}^2 L_{\text{rb}} \quad (33')$$

7.4.7 Load case F: short at load connection

In the case of a direct electrical short at the output of the SWT or internal short in the generator, a high moment is created about the rotor shaft due to the short circuit torque of the alternator. In the absence of any proven more accurate values, two times the Q_{design} is to be taken as the short circuit torque acting on the generator shaft.

$$M_{x\text{-shaft}} = G Q_{\text{design}} \quad (34)$$

In the absence of any proven more accurate values, G shall be 2,0.

$$M_{xB} = \frac{M_{x\text{-shaft}}}{B} + m_B g R_{\text{cog}} \quad (35)$$

7.4.8 Load case G: shutdown (braking)

In the case of wind turbines with a mechanical or electrical braking system in the drive train, the braking moment can be greater than the maximum driving moment. In these cases, the braking moment M_{brake} , derived from testing or calculations, shall be used in the design calculations of the SWT. The maximum shaft torque is assumed to be equal to the brake plus

the design torque (thus assuming that the brake is applied while the generator still delivers design torque).

$$M_{x\text{-shaft}} = M_{\text{brake}} + Q_{\text{design}} \quad (36)$$

The brake torque shall be multiplied by the gearbox ratio to yield M_{brake} if the brake is on the high speed shaft.

The blade load during shutdown is assumed to be determined by the shaft torque and blade mass. Thus being:

$$M_{xB} = \frac{M_{x\text{-shaft}}}{B} + m_B g R_{\text{cog}} \quad (37)$$

where $M_{x\text{-shaft}}$ is the shaft torque as calculated in Equation (36).

In case the turbine has a gearbox and a high-speed shaft brake, the shaft torque calculated in Equation (36) should be increased to account for drive train dynamics. In the absence of any proven more accurate values the shaft torque shall be multiplied by a factor of two.

7.4.9 Load case H: extreme wind loading

In this load case, the wind turbine is functioning as per the design intent during extreme wind speeds. The loads on the exposed parts of the SWT shall be calculated assuming wind speed of V_{e50} found in 6.3.3.2.

NOTE See Clause F.3.

If the spinning rotor is controlled to a very low speed then the higher thrust given by Equation (40) shall be used instead of the lower thrust given by Equation (41).

For turbines which will be parked, the out of plane blade root bending moment is dominated by drag and thus defined as:

$$M_{yB} = C_d \frac{1}{4} \rho V_{e50}^2 A_{\text{proj},B} R \quad (38)$$

where

C_d is the drag coefficient and shall be taken as 1,5; and

$A_{\text{proj},B}$ is the planform area of the blade.

For turbines that have their rotor spinning at V_{e50} , it is expected that, at some location on the rotor $C_{l,\text{max}}$ will occur on one of the blades due to variations in wind direction. Thus the blade root bending moment is:

$$M_{yB} = C_{l,\text{max}} \frac{1}{6} \rho V_{e50}^2 A_{\text{proj},B} R \quad (39)$$

If no data is available on $C_{l,\text{max}}$ a value of 2,0 shall be used.

For the thrust load:

For a parked rotor the shaft thrust load is calculated as given by Equation (40).

$$F_{x\text{-shaft}} = B C_d \frac{1}{2} \rho V_{e50}^2 A_{\text{proj},B} \quad (40)$$

For a spinning rotor the thrust force is given by:

$$F_{x\text{-shaft}} = 0,17 B A_{\text{proj},B} \lambda_{e50}^2 \rho V_{e50}^2 \quad (41)$$

where λ_{e50} is the tip speed ratio at V_{e50} , which if not known can be estimated by:

$$\lambda_{e50} = \frac{n_{\text{max}} \pi R}{30 V_{e50}} \quad (42)$$

The maximum tower bending moment shall be calculated using the thrust force calculated with either Equation (40) or (41) (depending on the turbine design). The drag or lift force on the tower and nacelle need to be taken into account as well. Equation (43) shall be used to calculate those forces. For free standing towers the maximum bending moment will occur at the tower base. For guyed towers the maximum bending moment will occur at the upper guy wire attachment.

The load for each component is given by:

$$F = C_f \frac{1}{2} \rho V_{e50}^2 A_{\text{proj}} \quad (43)$$

where

- C_f is the force coefficient (see Table 3); and
- A_{proj} is the component area projected on to a plane perpendicular to the wind direction.

From the loads on the individual components the blade, shaft and tower loads need to be calculated.

7.4.10 Load case I: parked wind loading, maximum exposure

In the case of a failure in the yaw mechanism, the SWT can be exposed to the wind from all directions. Thus, for design purposes, the forces on the SWT blades, nacelle, tower, and tail (if applicable) shall be calculated for all possible exposures including winds from the front, side or rear of the rotor.

The load on each component is given by:

$$F = C_f \frac{1}{2} \rho V_{\text{ref}}^2 A_{\text{proj}} \quad (44)$$

where

- C_f is the force coefficient, which may result from lift or drag; and
- A_{proj} is the component area (in its most unfavourable position) that is appropriate for the force coefficient. For blunt (or bluff) bodies (e.g. nacelle covers and tower sections) the area shall be the projected area on a plane perpendicular to the wind direction. For airfoil shapes the area shall be the planform area.

Table 3 – Force coefficients (C_f)

For all cross sections wind direction is from left to right							
Characteristic length ^a < 0,1 m		1,3	1,3	1,5	1,5	1,5	2,0
Characteristic length ^a > 0,1 m		0,7	1,2	1,5	1,5	1,5	2,0
^a Characteristic length is the top to bottom dimension (perpendicular to the flow) as illustrated here except in the case of the oblique aerofoil for which an aerofoil data book should be consulted.							

7.4.11 Load case J: transportation, assembly, maintenance and repair

The manufacturer shall consider loads on the turbine system caused by the transportation, assembly, installation, and maintenance and repair of the system. Examples of such loads are:

- gravity loads on turbine during transportation in other than upright position;
- loads caused by special installation tools;
- wind loads during installation or maintenance;
- loads introduced by hoisting the turbine onto the foundation;
- loads on a tilt up tower during erection; and
- load on a support structure from climbing it.

As an example the equation to calculate loads during tower tilt up are given below.

$$M_{\text{tower}} = 2\left(m_{\text{tower top}} + \frac{m_{\text{overhang}}}{2}\right) \times g L_{\text{lt}} \quad (45)$$

where

- M_{tower} is the bending moment of the tower at the lifting point attachment [Nm];
- $m_{\text{tower top}}$ is the mass of the nacelle and rotor combined [kg];
- m_{overhang} is the mass of the tower between the lifting point and the tower top [kg]; and
- L_{lt} is the distance between the lifting point and the top of the tower [m].

Equation (45) is based on the following assumptions:

- dynamic amplification factor is 2;
- centre of gravity of turbine is along the rotor axis; and
- the rotor is parked; and
- maximum bending moment occurs when tower is horizontal.

7.5 Simulation modelling

7.5.1 General

In case the design loads are determined by simulation (aero-elastic) modelling the load cases in this subclause 7.5 shall be considered. A minimum set of design load cases (DLC) is given in Table 4. In Table 4 the design load cases are specified for each design situation by the description of the wind, electrical and other external conditions. In load cases evaluated where a wind speed range is given, the load case shall be evaluated over the entire wind speed range to ensure the worst load is identified.

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

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

Table 4 – Minimum set of design load cases (DLC) for simulation by aero-elastic models

Design situation	DLC	Wind condition	Other conditions	Type of analysis
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$ or $3 \times V_{ave}$		F, U
	1.2	ECD $V_{hub} < V_{design}$		U
	1.3	EOG ₅₀ $V_{in} < V_{hub} < V_{out}$ or $3 \times V_{ave}$		U
	1.4	EDC ₅₀ $V_{in} < V_{hub} < V_{out}$ or $3 \times V_{ave}$		U
	1.5	ECG $V_{hub} = V_{design}$		U
2) Power production plus occurrence of fault	2.1	NWP $V_{hub} = V_{design}$ or V_{out} or $2,5 \times V_{ave}$	Control system fault	U
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Control or protection system fault	F, U
	2.3	EOG ₁ $V_{in} < V_{out}$ or $2,5 \times V_{ave}$	Loss of electrical connection	U
3) Normal shutdown	3.1	NTM $V_{in} < V_{hub} < V_{out}$		F
	3.2	EOG ₁ $V_{hub} = V_{out}$ or $V_{max, shutdown}$		U
4) Emergency or manual shutdown	4.1	NTM To be stated by the manufacturer		U
5) Extreme wind loading (standing still or idling; or spinning)	5.1	EWM $V_{hub} = V_{e50}$	Possible loss of electrical power network	U
	5.2	NTM $V_{hub} < 0,7 V_{ref}$		F
6) Parked and fault condition	6.1	EWM $V_{hub} = V_{e1}$		U
7) Transport, assembly, maintenance and repair	7.1	To be stated by the manufacturer		U
Key F analysis of fatigue loads U analysis of ultimate loads				

7.5.2 Power production (DLC 1.1 to 1.5)

In these load cases, 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 manufacturing the rotor 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.