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TITLE:

Wind energy generation systems – Part 9: Probabilistic design measures for wind turbines

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WIND ENERGY GENERATION SYSTEMS

Part 9: Probabilistic design measures for wind turbines

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The text of this Technical Specification is based on the following documents:

Draft	Report on voting
XX/XX/DTS	XX/XX/RVDTS

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

The language used for the development of this Technical Specification is English.

This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available

at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at <http://www.iec.ch/standardsdev/publications>.

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- replaced by a revised edition, or
- amended.

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INTRODUCTION

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WIND ENERGY GENERATION SYSTEMS

Part 9: Probabilistic design measures for wind turbines

1 Scope

This Technical Specification sets out minimum requirements to the use of probabilistic design measures in order to ensure the structural and mechanical integrity of wind turbines. The TS shall be based on the general approach in ISO 2394, which also forms the basis for IEC 61400-1. In 61400-1 the design verification approach is based on deterministic design using safety factors. However, edition 4 opens for introduction of probabilistic design in an informative annex specifying requirements to the calibration of structural material safety factors and structural design assisted by testing. This TS provides appropriate methodologies and requirements for full probabilistic design by taking into account specific uncertainties on not only material properties but also on environmental conditions, design models and the degree of validation.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 61400-1, *Wind energy generation systems - Part 1: Design requirements*

IEC 61400-2, *Wind energy generation systems – Part 2: Design requirements for small wind turbines*

IEC 61400-3-1, *Wind energy generation systems – Part 3-1: Design requirements for offshore wind turbines*

IEC 61400-3-2, *Wind energy generation systems – Part 3-2: Design requirements for floating offshore wind turbines*

IEC 61400-4, *Wind energy generation systems - Part 4: Design requirements for wind turbine gearboxes*

IEC 61400-6, *Wind energy generation systems - Part 6: Tower and foundation design requirements*

IEC 61400-8, *Wind energy generation systems - Part 8: Design of wind turbine structural components* (CDV version)

IEC 61400-12-1, *Wind energy generation systems - Part 12-1: Power performance measurements of electricity producing wind turbines*

IEC 61400-13, *Wind energy generation systems – Part 13: Measurement of mechanical loads*

IEC TS 61400-31, *Wind energy generation systems – Part 31: Siting Risk Assessment* (DTS version)

IEC 61400-50-1, *Wind energy generation systems – Part 50-1: Wind measurement – Application of meteorological mast, nacelle and spinner mounted instruments*

ISO 2394, *General principles on reliability for structures, 2015.*

3 Terms and definitions

3.1

limit states

state of a structure beyond which the structure no longer satisfies the design criteria

[SOURCE: ISO 2394]

3.2

parked wind turbine

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

[SOURCE: IEC 61400-1]

3.3

reference wind speed

V_{ref}

basic parameter for wind speed used for defining wind turbine classes

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

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

[SOURCE: IEC 61400-1]

3.4

site data

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

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

[SOURCE: IEC 61400-1]

3.5

standstill

condition of a wind turbine that is stopped

[SOURCE: IEC 61400-1]

3.6

support structure

part of a wind turbine comprising the tower and foundation

[SOURCE: IEC 61400-1]

3.7

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

[SOURCE: IEC 61400-1]

3.8

wind turbine site

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

[SOURCE: IEC 61400-1]

3.9

component class

classification of the wind turbine structural components according to redundancy and safety requirements

Note 1 to entry: Refer to IEC 61400-1.

[SOURCE: IEC 61400-6]

3.10

reliability class

class of structures or structural members for which a particular specified degree of reliability is required

3.11

design situations

sets of physical conditions representing the real conditions occurring during a certain time interval for which the design will demonstrate that relevant limit states are not exceeded

[SOURCE: IEC 61400-6]

3.12

effect of actions

effect of actions (or action effect) on structural members or on the whole structure

Note 1 to entry: Internal force, moment, stress and strain are examples of action effect on structural members. Deflection and rotation are examples of action effect on the whole structure.

[SOURCE: IEC 61400-6]

3.13

fatigue limit state

structural failure due to damage accumulation under effects of repeated loading

[SOURCE: IEC 61400-6]

3.14

serviceability limit state

state which corresponds to conditions beyond which specified service requirements for a structure or structural element are no longer met

[SOURCE: IEC 61400-6]

3.15

ultimate limit state

limit states which generally correspond to the maximum load bearing capacity

Note 1 to entry: This generally corresponds to the maximum load-carrying resistance of a structure or structural element but in some cases to a strain or deformation limit.

[SOURCE: IEC 61400-6]

3.16**reliability**

ability of a structure or structural member to fulfil the specified requirements, during the working life, for which it has been designed.

Note 1 to entry: Reliability is often expressed in terms of probability.

Note 2 to entry: Reliability covers safety, serviceability, and durability of a structure.

[SOURCE: ISO 2394]

3.17**structural safety**

ability (of a structure or structural member) to avoid exceedance of ultimate limit states, including the effects of specified accidental phenomena, with a specified level of reliability, during a specified period of time

[SOURCE: ISO 2394]

3.18**reliability-based design**

design procedure that is subjected to prescribed reliability level of the structure

[SOURCE: ISO 2394]

3.19**member reliability**

reliability of a single structural member which has one single dominating failure mode

[SOURCE: ISO 2394]

3.20**system reliability**

reliability of a system of more than one relevant structural member or a structural member which has more than one relevant failure mode

[SOURCE: ISO 2394]

3.21**resistance**

ability of a structure (or a part of it) to withstand actions without failure

[SOURCE: ISO 2394]

3.22**target reliability**

specified average acceptable failure probability that is to be reached as close as possible

Note 1 to entry: Reliability targets are generally model dependent and need to be set for each case considered based on the models used.

[SOURCE: ISO 2394]

3.23

reliability-based design

A design procedure that is subjected to prescribed reliability level of the structure.

[SOURCE: ISO 2394]

3.24

risk-informed design

design optimized with due consideration of the total risks, including loss of lives and injuries, damages to the qualities of the environment, and monetary losses

Note 1 to entry: Risk-based design is presently not generally accepted by all national standards and codes.

[SOURCE: ISO 2394]

3.25

robustness

ability of a structure to withstand adverse and unforeseen events (like fire, explosion, impact) or consequences of human errors without being damaged to an extent disproportionate to the original cause

[SOURCE: ISO 2394]

3.26

hazard

unusual and severe threat, e.g. a possible abnormal action or environmental influence, insufficient strength or stiffness, or excessive detrimental deviation from intended dimensions

[SOURCE: ISO 2394]

3.27

limit state

state beyond which a structure no longer satisfies the design criteria

[SOURCE: ISO 2394]

3.28

serviceability limit states

limit state concerning the criteria governing the functionalities related to normal use

[SOURCE: ISO 2394]

3.29

limit state function

function $g(X_1, X_2, \dots, X_n)$ of the basic variables, which characterizes a limit state when $g(X_1, X_2, \dots, X_n) = 0$

[SOURCE: ISO 2394]

3.30

basic variables

variables representing physical quantities which characterize actions and environmental influences, material and soil properties, and geometrical quantities

204 [SOURCE: ISO 2394]

205 **3.31**

206 **design service life**

207 assumed period for which a structure or a structural member is to be used for its intended
208 purpose with anticipated maintenance, but without substantial repair being necessary

209 [SOURCE: ISO 2394]

210 **3.32**

211 **model uncertainty**

212 basic variable related to the accuracy of physical or statistical models

213 [SOURCE: ISO 2394]

214 **3.33**

215 **aleatory uncertainty**

216 inherent variability typically associated with the loading environment, the geometry of the
217 structure, and the material properties

218 [SOURCE: ISO 2394]

219 **3.34**

220 **epistemic uncertainty**

221 lack of knowledge that, in principle, can be reduced by measurements or improved theories

222 Note 1 to entry: The exact borderline between aleatory and epistemic is not always unambiguous.

223 [SOURCE: ISO 2394]

224 **3.35**

225 **hierarchical modelling of uncertainty**

226 random variable is a function of other random variables

227 [SOURCE: ISO 2394]

228 **3.36**

229 **probabilistic methods**

230 verification methods in which the relevant basic variables are treated as random variables,
231 random processes, and random fields, discrete or continuous

232 [SOURCE: ISO 2394]

233 **3.37**

234 **reliability index**

235 β

236 substitute for the failure probability $\beta = \Phi^{-1}(P_f)$ where Φ^{-1} is the inverse standardized normal
237 distribution

238 [SOURCE: ISO 2394]

239 **3.38**

240 **structural model**

241 idealisation of the structure, physical, mathematical, or numerical, used for the purposes of
242 analysis, design, and verification

243 [SOURCE: ISO 2394]

244 **3.39**

245 **First/Second Order Reliability Methods - FORM/SORM**

246 numerical methods used for determination of the reliability index β

247 [SOURCE: ISO 2394]

248 **3.40**

249 **reference period**

250 period of time used as a basis for assessing the design value of variable and/or accidental
251 actions

252 [SOURCE: ISO 2394]

253 **3.41**

254 **load effect**

255 effect of actions (loads) is a result of actions on a structural member (e.g. internal force,
256 moment, stress, strain) or on the whole structure (e.g. deflection, rotation)

257 [SOURCE: based on ISO 2394]

258

259

260

261 **4 Symbols and abbreviations**

262 **4.1 Symbols and units**

263 **TO BE COMPLETED FOR THE FINAL VERSION OF THE TEXT**

C	scale parameter of the Weibull distribution function	[m/s]
c	environmental conditions	[-]
D	rotor diameter	[m]
D_{adm}	admissible damage level	[-]
$D(t)$	accumulated damage at time t	[-]
E	event	[m]
I_{ref}	reference value of the turbulence intensity corresponding to the 70 % quantile at 15 m/s	[-]
I_{eff}	effective turbulence intensity	[-]
k	shape parameter of the Weibull distribution function	[-]
m	Wöhler curve exponent	[-]
n_i	counted number of fatigue cycles in load bin i	[-]
$N(.)$	number of cycles to failure as a function of the stress (or strain) indicated by the argument (i.e. the characteristic S-N curve)	[-]
N	return period for extreme situations	[years]

p	air pressure	[N/m ²]
$P(-)$	probability	[-]
P_f	probability of failure	[-]
ΔP_f	annual probability of failure	[-]
$P_{f E}$	probability of failure conditional on event E	[-]
$P_{f E,v,c}$	probability of failure conditional on an event E , mean wind speed v and specific wind conditions c	[-]
$g(\cdot)$	limit state equation	[-]
$F_X(x)$	probability distribution function for a stochastic variable X	[-]
$f_X(x)$	probability density function for a stochastic variable X	[-]
X	stochastic variable	[-]
K	material parameter of the SN-curve	[-]
θ	statistical parameters in probability distribution functions $F_X(x \theta)$	[-]
Y	stochastic variable in hierarchical stochastic model	[-]
P_s	survival probability	[-]
S	load effect	[-]
L	load effect	[-]
N_{ref}	reference number of cycles for the equivalent load	[-]
L_E	is the extreme load effect during event E	[-]
R	resistance	[-]
R	stress ratio	[-]
T_L	design lifetime	[y]
v	mean wind speed	[-]
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]
V	wind speed	[m/s]
$V(z)$	wind speed at height z	[m/s]
V_{ave}	annual average wind speed at hub height	[m/s]
V_{cg}	extreme coherent gust magnitude over the whole rotor swept area	[m/s]
V_{eN}	expected extreme wind speed (averaged over three seconds), with a recurrence time interval of N years. V_{e1} and V_{e50} for 1 year and 50 years, respectively	[m/s]
V_{gust}	largest gust magnitude with an expected return period of 50 years	[m/s]
V_{hub}	wind speed at hub height	[m/s]
V_{in}	cut-in wind speed	[m/s]
V_{50}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 50 years	[m/s]

V_{100}	extreme wind speed (averaged over 10 minutes) with a recurrence interval of 100 years	[m/s]
V_{out}	cut-out wind speed	[m/s]
V_r	rated wind speed	[m/s]
V_{ref}	reference wind speed	[m/s]
$V_{\text{ref,T}}$	reference wind speed for tropical-like conditions	[m/s]
$V(y,z,t)$	longitudinal wind velocity component to describe transient horizontal wind shear	[m/s]
X_M	random variable representing a model uncertainty for M	[-]
W_X	random variable representing an environmental parameter X	[-]
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	[-]
β	Reliability index	[-]
γ_f	partial safety factor for loads	[-]
Δ	Uncertainty on the Palmgren-Miner damage summation model	[-]
γ_M, γ_R	partial safety factor for resistances	[-]
λ_F	annual failure rate	
λ_E	rate of events	
$\theta(t)$	wind direction change transient	[deg]
θ_{cg}	angle of maximum deviation from the direction of the average wind speed under gust conditions	[deg]
θ_{eN}	extreme direction change with a return period of N years	[deg]
Λ_1	turbulence scale parameter defined as the wavelength where the non-dimensional, longitudinal power spectral density, $fS_1(f)/\sigma_1^2$, is equal to 0,05	[m]
ρ	air density	[kg/m ³]
σ_1	hub-height longitudinal wind velocity standard deviation	[m/s]
Φ	standardized normal probability distribution function	[-]
φ	standardized normal probability density function	[-]
σ_{lim}	Component capacity (e.g. yield strength, tensile strength) in terms of limiting stress level	MPa
σ_m	Mean stress	MPa
σ_R	stress range	MPa
S_u	ultimate limit strength	MPa

σ_Y yield strength of the material

MPa

4.2 Abbreviated terms

COV	coefficient of variation
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
FMEA	failure mode and effect analysis
FORM	First Order reliability Method
FRT	fault ride through
IFORM	Inverse First-Order Reliability Method
SORM	Second Order reliability Method
NWP	normal wind profile model
NTM	normal turbulence model
ULS	ultimate limit state
FEM	Finite Element Method
LSE	Limit State Equation
LVRT	Low Voltage Ride Through
PSF	Partial Safety Factor
RNA	Rotor Nacelle Assembly
S-N	Stress- Cycle Curve for fatigue of materials
PSHA	probabilistic seismic hazard analyses

5 Principal elements

5.1 General

The following clauses specify essential requirements to the use of probabilistic design measures in order to ensure the structural and mechanical integrity of wind turbines. The specification of requirements applies to the design, siting and reassessment of a wind turbine system and its components, accounting for validated influences of the manufacturing, operations, and maintenance, and site-specific environmental conditions.

This document provides appropriate methodologies, probabilistic models, and requirements for probabilistic assessment of components in line with IEC61400-1. Probabilistic assessment is an alternative to the semi-probabilistic (deterministic) assessment procedures given in IEC 61400-1. The reliability assessment is performed for individual components and failure modes, and the resulting system reliability is implicitly accepted. The designer may select components and failure modes for probabilistic assessment, while the remaining failure modes shall be verified using traditional semi-probabilistic methods. It is allowed to do a full probabilistic analysis, or use probabilistic methods to calibrate specific partial safety factors for use in semi-probabilistic assessment. Specific partial safety factors for a subset of limit states should be calibrated such that the average reliability over the subset is as close to the target reliability as possible. In IEC 61400-1, the same partial safety factors are applied for a range of load cases, components, and environmental conditions, and as a result the obtained reliability level may deviate from the target reliability specified in this document. Deviations from the methodologies, probabilistic models, and requirements are allowed if properly justified.

The main steps in a reliability assessment for a selected component and failure mode are the following:

- a) Determine appropriate consequence class and target annual reliability index (see 5.2)
- b) Model specification
 - i) Formulate limit state equations (see 7)
 - ii) Develop appropriate probabilistic models for the variables in the limit state equations (see 6 and additionally 9 for siting)
- c) Reliability analysis
 - i) Perform a reliability analysis and compute the annual reliability index (see 8)
 - ii) Assess the accuracy of the computation and perform sensitivity studies (see 8)
- d) Assessment
 - i) For design situations: Perform a design optimization loop over steps b)-c) until a design is found where the target reliability is reached or exceeded in all years of the planned lifetime.
 - ii) For siting: The component has sufficient reliability on a site if the target reliability is reached or exceeded in all years of the planned lifetime.
 - iii) For reassessment: The component has sufficient reliability for continued operation for as many years as the target reliability is reached or exceeded.

The reliability model and assessment procedure should undergo verification by comparing the results of the reliability analysis with the result of a deterministic analysis for a baseline model.

5.2 Target Reliability Level and Component Classes

In Table 1 target reliability levels are given dependent on the consequence of failure (component class)¹ for ultimate limit states. The target reliability level may be achieved through a combination of design, prescribed scheduled maintenance and parts replacement, and health monitoring. For fatigue limit states, the target is given for the annual reliability index in the last year of the design lifetime. For limit states related to the ultimate strength, the target is given for the year with the largest annual failure probability, typically the first year of operation. Exceptions to these target reliabilities should be permitted if justified based on ISO 2394². Reliability targets for serviceability limit states should be defined based on their consequences, see ISO 2394 and JCSS PMC. Target reliabilities for special safety class wind turbines should be agreed between the manufacturer, customer and relevant authorities.

Table 1 – Target reliability levels.

Component class	Annual target probability of failure	Annual target reliability index
Component class 1	$2 \cdot 10^{-3}$	2.9
Component class 2	$5 \cdot 10^{-4}$	3.3
Component class 3	$5 \cdot 10^{-5}$	3.9

5.3 Limit States

For the failure modes selected for probabilistic assessment, limit state equations should be formulated based on the deterministic design equation, representing variables by their probability distributions, instead of using characteristic values and partial safety factors. Uncertainties related to external conditions, load assessment, and resistance (as described further in chapter 6) should be included either directly (e.g. the input variable is represented directly as a random variable in the limit state equation) or indirectly (e.g. the effect of uncertainty on one or more variables is represented as a model uncertainty multiplied on the load effect) in the limit state equation.

Reliability assessments may be performed for ultimate and serviceability limit states such as:

- Exceedance of the ultimate strength
- Fatigue failure
- Static Instability
- Dynamic Instability
- Component interference due to deformation
- Extreme vibrations
- Loss of control functionality
- Permanent deformations

5.4 Data Validity

Probabilistic models for physical quantities should be based on representative data, and model uncertainties should be assessed to the degree possible through a combination of tests and measurements such as:

- Material tests
- Test of sub-components / scaled components

¹ If human health and/or environment is at risk, a site-specific risk assessment with failure modes of tower collapse and throwing parts is to be performed, as defined in IEC TS 61400-31.

² Changes to the target reliability for specific cases can be motivated by e.g. the consequence of failure, cost of safety measure, or the level of uncertainties.

- 367 – Full-scale component tests
- 368 – Load measurement campaigns (e.g. prototype testing)
- 369 – Environmental data (e.g. met-mast data)
- 370 – Operational data
- 371 The availability of data depends on whether the reliability assessment is made in relation to
- 372 design, siting, or reassessment. Examples of typical situations and available data are:
- 373 – Design of RNA components for an IEC class or class S turbine (tests on material and sub-
- 374 components, data from other wind turbine models)
- 375 – Site-specific design of tower, sub-structure and/or foundations, or site assessment of an
- 376 IEC class or class S turbine for a specific site (tests on material and components, load
- 377 measurement campaigns, environmental data)
- 378 – Re-assessment of a wind turbine during or near the end of the operational phase (tests on
- 379 material and components, load measurement campaigns, environmental data, operational
- 380 data, condition
- 381 – monitoring data)
- 382 – The possible influence of the following sources of uncertainty should be included in the
- 383 analysis where relevant: Deviation in raw material quality
- 384 – Nonconformity of finished parts to quality control specifications
- 385 – Unknown part defects outside the scope of QC specifications (i.e., incomplete CTQ
- 386 specifications due to incomplete knowledge)
- 387 – Nonconformity of installation procedures to specifications
- 388 – Site environmental conditions
- 389 – Variability in operational practices, including controller issues
- 390 – Variability in maintenance practices
- 391 – Nonconformity of component repairs with specifications or standard industry practice.

392
393

6 Uncertainty representation and modelling

6.1 General

The uncertainties associated with the external conditions, load assessment, structural resistance and electrical / mechanical component reliability related to wind turbine control or safety system should be modelled for the wind turbine lifetime as part of a reliability analysis.

6.1.1 Types of uncertainty

Various sources of uncertainty as for example natural / physical variability, statistical uncertainties, measurement uncertainties and model uncertainties exist.

The natural / physical uncertainties are typically uncertainties related to the external conditions, the geometry of the structure and the material properties and are often referred to as aleatory uncertainties.

The statistical uncertainties originate from limited information and data about external conditions, material properties, load validation etc. and are often referred to as epistemic uncertainties.

The measurement uncertainties originate from uncertainty in measurement setup, equipment, calibration or analysis of tests and are often referred to as epistemic uncertainties. The list of contributions to measurements uncertainty should be as complete as reasonable for the application and reflect the information available about accuracy.

The model uncertainties originate from idealizations and imperfections associated with describing a physical phenomenon using mathematical models. This includes the formulation of the models (M), that attempt to represent the real world (Y) based on a given input (X), as well as the parameters (θ) of the model that are subject to uncertainty, see Figure 1. Model uncertainty is e.g. associated with aeroelastic models, finite element models, reduced-order representations, simplifications in failure criteria definitions and are often referred to as epistemic uncertainties.

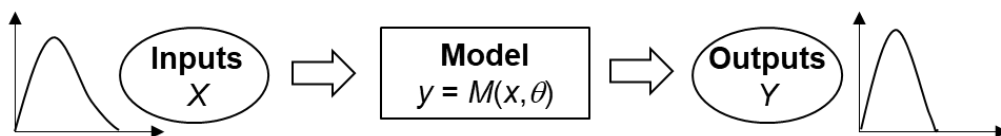


Figure 1 – Application of a mathematical model to estimate an output based on a given input.

Uncertainties can be aleatory or epistemic and can change nature in different phases of the lifetime of a wind turbine. For example, a material property can be considered as aleatory before the manufacturing of a wind turbine, once the wind turbine is manufactured, it can be considered as an epistemic uncertainty.

6.1.2 Interpretation of probability and treatment of uncertainty

In structural reliability analysis, the Bayesian interpretation of probability should be considered as the most adequate basis for the consistent representation of uncertainties, independent of their sources. It facilitates the joint consideration of analytically assessed uncertainties, evidence as obtained through observations and subjectively assessed uncertainties (expert knowledge).

Subjective information can e.g. be used to quantify the expected variation for a very limited test sample based on previous test samples or to quantify physical or model uncertainties which either cannot or are not practically possible to measure. However, subjectively assessed uncertainties should be used with caution and the information used should be documented and preferable obtained through a structured process as e.g. Cooke (1991).

In Bayesian probability theory, the values for probabilities are estimated based on an adequate combination of data, theoretical arguments, and judgment. There is no distinction in the treatment between aleatory and epistemic uncertainty. If large amounts of data are available, the Bayesian interpretation coincides with the frequentist one.

Considering the probabilistic modelling of a random basic variable X , the principle in Bayesian probability analysis is to model one or more of the parameters θ (e.g. the mean and standard deviation) of the probabilistic model (e.g. the probability distribution function) as random variables themselves. The frequentist or subjective information available about X can then be used in the probabilistic modelling of θ .

All uncertainties that are of importance for the reliability analysis of a wind turbine or parts thereof should be considered in the analysis using the theory of probability. A systematic approach based on a hierarchy of uncertainties can support the identification of contributions to uncertainty.

6.1.3 Probabilistic model

Depending on the nature of the reliability problem, basic variables can be represented as random variables, random processes and random fields, discrete as well as continuous.

The probabilistic models should describe the uncertainties of individual random basic variables, but also accommodate the consideration of the dependencies among them.

Dependencies often arise due to causality, spatial and/or temporal correlations and/or ergodic states of underlying phenomena, as well as statistical and/or model uncertainties that commonly affect the uncertainties of the individual variables.

The uncertainty in the basic variables and the dependencies among them can normally be modelled by probability distribution functions $f_X(X|\theta)$ and correlation coefficients ρ focussing on the application of interest (e.g. extreme values).

A dependent or hierarchical modelling is recommended, where applicable. The dependent or hierarchical model assumes that a random quantity Y can be written as a function of several variables, each one representing a specific type of variability:

$$Y_{ijk} = f(X_i, X_{ij}, X_{ijk}) \quad (1)$$

The variables X_i , X_{ij} , X_{ijk} represent various origins, time scales of fluctuation, or spatial scales of fluctuation. This modelling approach is for example relevant for the wind conditions, where the wind speed standard deviation σ_1 (turbulence) is dependent on e.g. the 10min mean wind speed V_{hub} and terrain roughness.

The probabilistic models should when relevant also accommodate the updating of the models by additional information, which can become available with, for example, experiments, tests, inspections, and monitoring. The Bayesian updating formula provides the operational basis for this.

The description of uncertain quantities by probabilistic models should correspond to well-defined outcome spaces (or populations) and the results of the reliability analysis are only valid for the same sets.

The probabilistic models can be determined based on information from different e.g. wind turbine types, design concepts or site conditions. In these cases, it should be justified that the probabilistic model is representative and potential residual uncertainty should be covered by model uncertainty.

6.1.4 Uncertainties for wind turbines

The typical flow chart and uncertainties which should be considered in probabilistic design for wind turbines are shown in Figure 2 and the principles for assessment of the individual uncertainties are described in the following sub-sections.

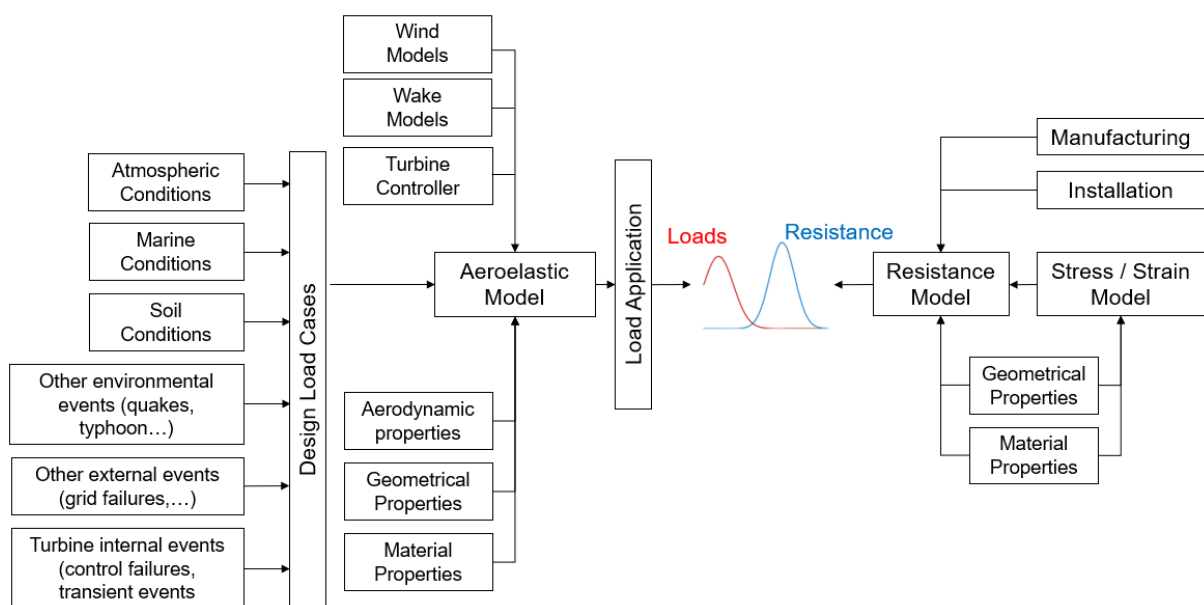


Figure 2 – Typical flow chart and uncertainties to be considered in probabilistic design of wind turbine components.

The *design load cases* defined in IEC 61400-1, IEC 61400-3-1 and IEC 61400-3-2 specify the minimum number of design situations which should be considered. The uncertain input to the design load cases is listed in the following:

- *Atmospheric conditions* represent the uncertainty in e.g. mean wind speed, extreme wind speed (incl. tropical cyclones), turbulence, wind shear, air density and gust events.
- *Marine conditions* represent the uncertainty in e.g. wave conditions, current, tides and storm surge.
- *Other environmental events* represent the uncertainty in e.g. temperature, lightning, ice conditions and earthquakes.
- *Other external events* represent the uncertainty in e.g. grid fault, loss of electrical network, low voltage ride through.
- *Turbine internal events* represent the uncertainty in e.g. controller failures (primary and secondary layer protection functions), overspeed, actuators and braking systems.

499 The *aeroelastic model* is normally relying on a number of sub-models:

- 500 • *Wind models* represent the uncertainty in e.g. the Mann or Kaimal turbulence models.
- 501 • *Wake models* represent the uncertainty in e.g. the added wake turbulence method or
- 502 dynamic wake meandering model.
- 503 • *Turbine controller* represents the uncertainty in e.g. a simplified controller
- 504 implementation.

505 Additionally, the *aeroelastic model* is based on some input parameters which normally are

506 constant for the different design load cases:

- 507 • *Aerodynamic properties* represent the uncertainty in e.g. lift and drag coefficients.
- 508 • *Geometrical properties* represent the uncertainty in e.g. thickness and length.
- 509 • *Soil / Material properties* represent the uncertainty in e.g. stiffness.

510 The aero-elastic simulations are normally post-processed in order to determine the input to the

511 resistance model:

- 512 • *Load application* represent the uncertainty in e.g. extrapolation, contemporaneous
- 513 loads, rainflow cycle counting and Miner's rule.

514 The *resistance model* or failure criteria is based on the following input parameters:

- 515 • *Manufacturing* represents the uncertainty in e.g. the manufacturing quality.
- 516 • *Installation* represents the uncertainty in e.g. the installation process and quality.
- 517 • *Geometrical properties* represent the uncertainty in e.g. thickness and length.
- 518 • *Material properties* represent the uncertainty in e.g. stiffness and strength.

519 Additionally, the resistance model is often dependent on a sub-model

- 520 • *Stress / Strain model* represent the uncertainty in stress and strain assessment for a
- 521 load application e.g. through a finite-element model.

522 The individual physical, model, measurement and statistical uncertainties can be quantified

523 directly and propagated through the flow chart in order to determine the resulting uncertainty in

524 the load or resistance. Alternatively, the resulting uncertainty on load or resistance can be

525 determined directly by other means.

526 **6.2 External condition uncertainty modelling**

527 **6.2.1 General**

528 The external conditions refer to the environmental and electrical conditions which affect the

529 wind turbine or parts thereof. Environmental conditions can in general be separated into wind,

530 marine, soil and other conditions.

The individual environmental conditions should be modelled by stochastic models established based on the standard conditions used for IEC class verification as defined in IEC 61400-1, IEC 61400-3-1 and IEC 61400-3-2 or representative measurements for the quantity and application of interest. The term “representative” should be considered in relationship to the measurements available and expert knowledge used for defining the standard conditions used for IEC class verification.

The standard conditions cover along with the design load cases in IEC 61400-1, IEC 61400-3-1 and IEC 61400-3-2 the relevant design situations for a wind turbine for which stochastic models may be established.

Uncertainty representation and modelling for site specific conditions are described in chapter 9.

6.2.2 Wind conditions

The atmospheric conditions can in general be separated into the standard wind conditions and other conditions defined in IEC 61400-1. The standard wind conditions are generally established by determining a characteristic value (typically 50 year value) for a single wind parameter or wind event e.g. turbulence or gust. The potential interaction of the individual wind conditions and non-linear interaction of the wind turbine controller can influence the wind turbine response and should if relevant be considered when the stochastic models are established.

Probabilistic models established for IEC class type certification (I-III & A+-C) should be based on the probabilistic models defined in IEC 61400-1 when available. Other wind conditions may be modelled by probabilistic models when these are in alignment with the general design philosophy in IEC 61400-1. As an example, the air density can be modelled by a probabilistic model with mean value equal to 1.225 kg/m^3 as specified in IEC 61400-1 and other parameters determined based on a few reference sites. Probabilistic models established for IEC class “S” should be specified by the designer.

Alternatively, probabilistic models may be established based on representative wind or turbine measurements from a few reference sites. The probabilistic models may be developed by identifying the standard wind conditions (e.g. gusts or wind direction changes) from IEC 61400

-1 in wind or turbine measurements with a sufficient resolution to cover the spatial and time fluctuations. The probabilistic models should beyond the physical uncertainty in the wind conditions also represent the measurement and statistical uncertainty in the wind measurements used to establish them.

The turbulence model describes the spatial and time variation in the wind velocity field established through longitudinal, lateral and upward vector components, generally consistent with a specified 10-min average wind speed at hub height and reference turbulence intensity, see IEC 61400-1 Annex C. The model and statistical uncertainty related to the turbulence model should be quantified e.g. as part of the load uncertainty modelling, see section 6.3.

6.2.2.1 Normal wind conditions

The normal wind conditions are represented by the mean wind speed distribution, the Normal Wind Profile (NWP) and the Normal Turbulence Model (NTM) in IEC 61400-1.

The mean wind speed distribution $F_{V_{hub}}(V_{hub})$ for the wind speed at hub height V_{hub} (10min reference period) is according to IEC 61400-1 defined as a Rayleigh distribution for the different IEC classes.

$$F_{V_{hub}}(V_{hub}) = 1 - \exp \left[-\pi \left(\frac{V_{hub}}{2 V_{ave}} \right)^2 \right] \quad (2)$$

where V_{ave} is the annual average wind speed. The Rayleigh distribution is a special case of the more general Weibull distribution which normally is used to characterize the mean wind speed distribution in probabilistic models.

$$F_{V_{hub}}(V_{hub}) = 1 - \exp \left[- \left(\frac{V_{hub}}{A} \right)^k \right] \quad (3)$$

where A and k are the scale and shape parameter. The NWP represent a deterministic wind profile (no turbulence) modelling the variation of mean wind speed over the rotor using average (near-neutral boundary layer) conditions for wind shear and air density. The NWP is used in combination with specific controller actions like start-up or shutdown and serves as the basis upon which other wind events are added. Uncertainty modelling for the NWP is therefore normally not relevant or replaced by other specific wind conditions as e.g. the NTM model.

The NTM represent normal stochastic wind (turbulence) conditions using a distribution for the turbulence and average conditions for wind shear and air density to model normal operating conditions. The stochastic representation of the NTM should according to IEC 61400-1 be based on a Weibull distribution $F_{\sigma_1}(\sigma_1)$ for the wind speed standard deviation σ_1 (10min reference period) for IEC class verification.

$$F_{\sigma_1}(\sigma_1) = 1 - \exp \left(- \left(\frac{\sigma_1}{C} \right)^k \right) \quad (4)$$

$$k = 0.27 \cdot V_{hub}(\text{s/m}) + 1.4 \quad (5)$$

$$C = I_{ref}(0.75 \cdot V_{hub} + 3.3\text{m/s}) \quad (6)$$

where C and k are the scale and shape parameter and I_{ref} is the reference turbulence intensity according to IEC 61400-1. The uncertainty modelling for the NTM should cover the natural variation of mean wind speed and turbulence. Additionally, the uncertainty modelling may cover variations in wind shear, air density and wind direction along with the potential dependence / correlation between these due to different atmospheric stability conditions.

6.2.2.2 Extreme wind conditions

The extreme wind conditions are in IEC 61400-1 represented by the Extreme Wind Model (EWM), Extreme Operation Gust (EOG), Extreme Turbulence Model (ETM), Extreme Direction Change (EDC), Extreme Coherent gust with Direction change (ECD) and Extreme Wind Shear (EWS). These events are defined to cover all relevant extreme wind conditions for a wind turbine and are defined by extrapolation of a single wind parameter or wind event. The events should therefore in general not be combined with variations in other wind conditions.

The stochastic models for the extreme wind conditions should correspond to an annual reference period when combined with specific operational states e.g. grid-loss, start-up or shutdown. This ensures consistency with the target reliability level specified in 5.

The EWM represents conditions with extreme wind speeds. The EWM is in IEC 61400-1 defined by the maximum 10min mean wind speed with a return period of 1 year and 50 years, which represent the characteristic value.

$$V_{50} = V_{ref} \quad (7)$$

The uncertainty modelling for the EWM should represent the physical uncertainty in the annual maximum wind speed which for extratropical storms can be modelled by a Gumbel distribution with a typical coefficient of variation equal to 12% for IEC class verification.

The EOG represents the extreme gust which occurs together with a specific operation event such as a start-up, shut-down or electrical fault to give a combined return period of 50 years. The EOG can according to IEC 61400-1 be replaced with the NTM model for DLC 2.3 and by the ETM model for DLC 3.2 and 4.2 offering an easier combination with specific operational states.

The EOG is in IEC 61400-1 defined by a gust profile expressed in space over the event duration and described by the gust magnitude V_{gust} (which for current wind turbine design is defined by the second term in equation (9)) and duration T .

$$V_{gust} = \beta \left(\frac{\sigma_1}{1 + 0.1 \left(\frac{D}{\Lambda_1} \right)} \right) \quad (8)$$

$$V(z, t) = \begin{cases} V(z) - 0.37 V_{gust} \sin(3\pi t/T) (1 - \cos(2\pi t/T)) & \text{for } 0 \leq t \leq T \\ V(z) & \text{otherwise} \end{cases} \quad (9)$$

The uncertainty modelling for the EOG should represent the uncertainty in the annual maximum gust magnitude and duration. The gust profile can be considered deterministic along with the parameters Λ_1 , D and σ_1 (90% quantile). The gust magnitude and duration can be assumed fully correlated and can be modelled by a Gumbel distribution based on the return periods defined in Table 2. A simplified uncertainty model for the EOG can be obtained by only modelling the gust magnitude probabilistically, while assuming the duration is deterministic ($T=10.5s$).

Table 2 – EOG parameters for different return periods.

Return Period	Gust Magnitude (V_{gust})	Duration (T)
IEC 61400-1 Ed.4	$\beta = 3.3$	$T = 10.5s$
1 year	$\beta = 4.8$	$T = 10.5s$
50 year	$\beta = 6.4$	$T = 14.0s$

The ETM represents the 50 year extreme turbulence conditions at a given mean wind speed V_{hub} , based on the Inverse First Order Reliability Method (IFORM) using the models for the normal wind conditions in 6.2.2.1, see Annex B. Alternatively, the uncertainty model for the ETM can be represented by the conditional distribution for the annual extreme turbulence at a given mean wind speed.

The EDC represent the extreme direction change which occur together with a specific operation event such as a start-up with a return period of 50 years. The EDC is in IEC 61400-1 defined by a wind direction variation, expressed over the event duration, which is described by the extreme direction change magnitude θ_e and duration T .

$$\theta_e = \pm \beta \arctan \left(\frac{\sigma_1}{V_{hub} \left(1 + 0.1 \left(\frac{D}{A_1} \right) \right)} \right) \quad (10)$$

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0.5 \theta_e (1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ \theta_e & \text{for } t > T \end{cases} \quad (11)$$

634 The uncertainty modelling for the EDC should represent the uncertainty in the annual extreme
635 wind direction change. The wind direction profile and duration can be considered deterministic
636 along with the parameters Λ_1 , D and σ_1 (90% quantile). The extreme wind direction change can
637 be modelled by a Gumbel distribution based on the return periods defined in Table 3.

638 **Table 3 – EDC parameters for different return periods.**

Return Period	Extreme Direction Change (θ_e)	Duration (T)
IEC 61400-1 Ed. 4	$\beta = 4.0$	T = 6s
1 year	$\beta = 4.8$	T = 6s
50 year	$\beta = 6.4$	T = 6s

639 The ECD represents the 50 year extreme coherent gust with direction change occurring during
640 normal operating conditions. The ECD is in IEC 61400-1 defined by a gust and wind direction
641 variation, expressed over the event duration, which is described by the coherent gust magnitude
642 V_{cg} , wind direction change magnitude θ_{cg} and duration T.

$$V(z, t) = \begin{cases} V(z) & \text{for } t < 0 \\ V(z) \pm 0.5 V_{cg} (1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ V(z) + V_{cg} & \text{for } t > T \end{cases} \quad (12)$$

$$\theta_{cg} = \begin{cases} 180^\circ & \text{for } V_{hub} < 4 \text{ m/s} \\ \frac{720^\circ}{V_{hub}} & \text{for } 4 \text{ m/s} < V_{hub} < V_{ref} \end{cases} \quad (13)$$

$$\theta(t) = \begin{cases} 0^\circ & \text{for } t < 0 \\ \pm 0.5 \theta_{cg} (1 - \cos(\pi t/T)) & \text{for } 0 \leq t \leq T \\ \pm \theta_{cg} & \text{for } t > T \end{cases} \quad (14)$$

643 The uncertainty modelling for the ECD should represent the uncertainty in the annual extreme
644 coherent gust and wind direction change. The gust profile, wind direction profile and duration
645 (T=10s) can be considered deterministic. The annual extreme coherent gust magnitude and
646 wind direction change can be assumed fully correlated and can be modelled by a Gumbel
647 distribution with a coefficient of variation of 10%.

648 The EWS represents the 50 year extreme transient events with horizontal and vertical wind
649 shear. The EWS is in IEC 61400-1 defined by a wind speed profile for the event duration, which
650 is described by the wind shear magnitude parameter β and duration T.

651 Transient (positive and negative) vertical shear: