IEC TS 61400-9

Edition 1.0 2025-07

TECHNICAL SPECIFICATION

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

ICS 27.180

ISBN 978-2-8327-0494-3

IEC TS 61400-9:2025-07(en)

CONTENTS

FOREWORD 5
1 Scope 7
2 Normative references 7
3 Terms, definitions, symbols and abbreviated terms 7
3.1 Terms and definitions 7
3.2 Symbols and abbreviated terms 10
3.2.1 Symbols 10
3.2.2 Abbreviated terms 12
4 Principal elements 13
4.1 General 13
4.2 Minimum reliability level and component classes 14
4.3 Limit states 14
4.4 Data validity 15
5 Uncertainty representation and modelling 16
5.1 General 16
5.1.1 Uncertainties 16
5.1.2 Types of uncertainty 16
5.1.3 Interpretation of probability and treatment of uncertainty 16
5.1.4 Probabilistic model 17
5.1.5 Uncertainties for wind turbines 18
5.2 External condition uncertainty modelling 19
5.2.1 General 19
5.2.2 Wind conditions 19
5.2.3 Normal wind conditions 20
5.2.4 Other conditions 21
5.2.5 Electrical network conditions 22
5.3 Load uncertainty modelling 23
5.3.1 General 23
5.3.2 Aeroelastic model 23
5.3.3 Extreme loads 24
5.3.4 Fatigue loads 25
5.4 Structural resistance uncertainty modelling 25
5.4.1 General 25
5.4.2 Geometrical properties 25
5.4.3 Material properties 25
5.4.4 Resistance models 26
5.4.5 Fatigue strength and damage accumulation 26
6 Performance modelling 26
6.1 General 26
6.2 Structural performance of primary structures 26
6.2.1 General 26
6.2.2 Load performance calibration for ultimate limit states 27
6.2.3 Evaluation of serviceability limit states 30
6.3 Performance of primary mechanical and electrical components 30
6.3.1 General 30
6.3.2 Requirements for mechanical components 31

6.3.3 Serviceability limit states for mechanical components 31
6.3.4 Requirements for electrical components and control and protection systems 31
6.4 Robustness 32
7 Assessment of reliability 32
7.1 Overview 32
7.1.1 General 32
7.1.2 Reliability measures 32
7.1.4 Accuracy requirements 34
7.1.5 Sensitivity analysis 34
7.2 Reliability-based method 35
7.2.1 General 35
7.2.2 Probability of failure for extreme design situations 35
7.2.3 Probability of failure for fatigue design situations 35
7.2.4 Updating probability of failure using test or inspection data 36
7.3 Semi-probabilistic method 36
7.3.1 General 36
7.3.2 Representative and characteristic values 36
7.3.3 Partial factor method for extreme and fatigue design situations 37
7.3.4 Reliability-based calibration of partial safety factors 37
8 Site suitability analysis 37
8.1 General approach and scope 37
8.2 Reliability models for site suitability analysis 38
8.2.1 General 38
8.2.2 Load models for site suitability assessment 39
8.2.3 Resistance model for site suitability assessment 40
8.2.4 Structural performance on site specific conditions 41
8.3 Site specific uncertainty modelling 41
8.3.1 General 41
8.3.2 Quantification of site-specific uncertainties 45
8.4 Reliability assessment 46
Annex A (informative) Uncertainty quantification 47
A.1 General 47
A.2 Bayesian methods 47
A.2.1 General 47
A.2.2 Closed form solutions for parameter estimation 48
A.2.3 Exact inference for continuous parameters 51
A.2.4 Sampling-based inference 51
A.2.5 Exact inference for discretized parameters 51
A.3 Maximum likelihood 51
A.4 Model uncertainties 52
A.4.1 General 52
A.4.2 Example: Model uncertainty quantification 54
Annex B (informative) Inverse FORM 63
Annex C (informative) Example calculations for reliability assessment 67
C.1 General 67
C.2 Ultimate limit state 67
C.2.1 Design equation 67

C.2.2 Limit state equation 67
C.2.3 Reliability assessment 68
C.2.4 Direct reliability-based design 69
C.2.5 Reliability-based calibration of partial safety factors 69
C.2.6 Assess the accuracy of the computation and perform sensitivity studies 70
C.3 Fatigue limit state 71
C.3.1 General 71
C.3.2 Limit state equation 72
C.3.3 Reliability-based calibration of partial safety factors 74
Annex D (informative) Formulation of event driven design load cases 76
D.1 General 76
D.2 Formulation of wind conditions with conditional events (Example DLC 2.3) 76
D.3 Probability of failure for independent events (Example DLC 2.1) 77
Annex E (informative) Updating of distributions based on evidence 79
E.1 Updating of distributions for basic variables 79
E.2 Event updating 80
Annex F (informative) Example of the relative approach to site suitability assessment 81
Annex G (informative) Uncertainty scenarios for site specific wind assessment 83
Bibliography 87

Figure 1 – Application of a mathematical model to estimate an output based on a given input 16
Figure 2 – Typical flow chart and uncertainties to be considered in probabilistic design of wind turbine components 18
Figure 3 – Typical split between uncertainties which should be propagated through the aeroelastic model (shaded) and those which should be represented by model uncertainty 24
Figure 4 – Measures of reliability computation of failure probability 33
Figure 5 – Highlight of relevant uncertainties related to site suitability assessment 42
Figure A.1 – Graphical representation of the structure for estimation of a) the mean value of X when the population variance is known and b) the mean value and the variance of X 48
Figure A.2 – Plot for estimation of model uncertainty 53
Figure A.3 – Experiment value Y as function of theoretical value $h(x)$ 55
Figure A.4 – Cumulative distribution and probability density functions for the predictive distribution, the estimated lognormal distribution and the predictive distribution for n = 5 57
Figure A.5 – Various approaches for MCMC models for model uncertainty quantification 58
Figure A.6 – Probability density function for each method 61
Figure A.7 – Cumulative distribution function for each method 61
Figure A.8 – Lower tail of the cumulative distribution function for each method 62
Figure A.9 – Lower tail of the cumulative distribution function for each method for a sample size n = 50 62
Figure B.1 – Contour line for ETM in the u-space and the linear approximation used in IFORM 65
Figure B.2 – Contour lines for ETM, linear approximation (in the u-space), and the characteristic values defined in IEC 61400-1 66

Figure C.1 – Yearly (conditional) probability of failure for the calibration example with COV_{gen} = 20,0 % and γ_R = 1,35 75

Figure C.2 – Yearly (conditional) reliability index for the calibration example with COV_{gen} = 20,0 % and γ_R = 1,35 75

Table 1 – Minimum reliability requirements 14

Table A.1 – Theoretical and experimental values 54

Table A.2 – Stochastic model 58

Table A.3 – Parameters and moments estimated using each method 60

Table A.4 – Selected quantiles for the predictive distribution (including statistical/parameter uncertainty) and the fitted lognormal distribution (not including statistical/parameter uncertainty) using each method 60

Table C.1 – Baseline stochastic variables for load and resistance model 68

Table C.2 – Annual reliability index for different main wind turbine components (tower) and design situations (DLC 1.3 and 6.1) 69

Table C.3 – Resulting reliability index for different values of design parameter for simplified example 69

Table C.4 – Resulting reliability for different partial safety factor for loads (given γ_M = 1,2) 70

Table C.5 – Assessment of reliability index convergence with number of draws in Monte Carlo simulations 70

Table C.6 – Sensitivities of the reliability index with respect to each random variable in the limit state equation 71

Table C.7 – Baseline stochastic model for the fatigue limit state analysis 73

Table C.8 – Results for safety factor calibration exercise under different assumptions of COV_{gen} 74

Table F.1 – Stochastic model 81

Table G.1 – Uncertainty scenarios for anemometer calibration 83

Table G.2 – Uncertainty scenarios for mounting effects of anemometers 83

Table G.3 – Uncertainty scenarios for measurement heights 83

Table G.4 – Uncertainty scenarios for amount of available data 84

Table G.5 – Uncertainty scenarios for long-term wind speed distribution 84

Table G.6 – Uncertainty scenarios for extreme wind speed events 84

Table G.7 – Uncertainty scenarios for terrain map quality 84

Table G.8 – Uncertainty scenarios for wind shear modelling 85

Table G.9 – Uncertainty scenarios for terrain complexity 85

Table G.10 – Uncertainty scenarios for distance from measurement point to position of interest 85

Table G.11 – Uncertainty scenarios for wake models 85

Table G.12 – Representative values of COV of wind parameters for normal scenario 86

INTERNATIONAL ELECTROTECHNICAL COMMISSION

_____

Wind energy generation systems – Part 9: probabilistic design measures for 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.
2) The formal decisions or agreements of IEC on technical matters express, as nearly as possible, an international consensus of opinion on the relevant subjects since each technical committee has representation from all interested IEC National Committees.
3) IEC Publications have the form of recommendations for international use and are accepted by IEC National Committees in that sense. While all reasonable efforts are made to ensure that the technical content of IEC Publications is accurate, IEC cannot be held responsible for the way in which they are used or for any misinterpretation by any end user.
4) In order to promote international uniformity, IEC National Committees undertake to apply IEC Publications transparently to the maximum extent possible in their national and regional publications. Any divergence between any IEC Publication and the corresponding national or regional publication shall be clearly indicated in the latter.
5) IEC itself does not provide any attestation of conformity. Independent certification bodies provide conformity assessment services and, in some areas, access to IEC marks of conformity. IEC is not responsible for any services carried out by independent certification bodies.
6) All users should ensure that they have the latest edition of this publication.
7) No liability shall attach to IEC or its directors, employees, servants or agents including individual experts and members of its technical committees and IEC National Committees for any personal injury, property damage or other damage of any nature whatsoever, whether direct or indirect, or for costs (including legal fees) and expenses arising out of the publication, use of, or reliance upon, this IEC Publication or any other IEC Publications.
8) Attention is drawn to the Normative references cited in this publication. Use of the referenced publications is indispensable for the correct application of this publication.
9) IEC draws attention to the possibility that the implementation of this document may involve the use of (a) patent(s). IEC takes no position concerning the evidence, validity or applicability of any claimed patent rights in respect thereof. As of the date of publication of this document, IEC had not received notice of (a) patent(s), which may be required to implement this document. However, implementers are cautioned that this may not represent the latest information, which may be obtained from the patent database available at https://patents.iec.ch. IEC shall not be held responsible for identifying any or all such patent rights.

IEC TS 61400-9 has been prepared by IEC technical committee 88: Wind energy generation systems. It is a Technical Specification.

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

Draft	Report on voting
88/1063/DTS	88/1102/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 www.iec.ch/publications.

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

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

- reconfirmed,
- withdrawn, or
- revised.

1 Scope

The part of IEC 61400, which is a 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 document is 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 of IEC 61400-1:2019 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. IEC 61400-1 is the governing standard. This document 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. This document also provides provisions for semi-probabilistic design, including reliability-based calibration of partial safety factors and assessment of existing wind turbines. The probabilistic methods in this document are formulated generically and can be applied to structural and mechanical failure modes where a limit state equation can be formulated.

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 61400-1:2019, *Wind energy generation systems – Part 1: Design requirements*

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

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

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

IEC 61400-13, *Wind turbines – Part 13: Measurement of mechanical loads*

IEC TS 61400-31, *Wind energy generation systems – Part 31: Siting risk assessment*

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

EN 1990, *Eurocode – Basis of structural design*