



TECHNICAL SPECIFICATION

Corrected version
2026-04

**Wind energy generation systems -
Part 4-1: Reliability assessment of drivetrain components in wind turbines**

Sample Document

get full document from standards.iteh.ai



THIS PUBLICATION IS COPYRIGHT PROTECTED
Copyright © 2026 IEC, Geneva, Switzerland

All rights reserved. Unless otherwise specified, no part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying and microfilm, without permission in writing from either IEC or IEC's member National Committee in the country of the requester. If you have any questions about IEC copyright or have an enquiry about obtaining additional rights to this publication, please contact the address below or your local IEC member National Committee for further information.

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

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

About the IEC

The International Electrotechnical Commission (IEC) is the leading global organization that prepares and publishes International Standards for all electrical, electronic and related technologies.

About IEC publications

The technical content of IEC publications is kept under constant review by the IEC. Please make sure that you have the latest edition, a corrigendum or an amendment might have been published.

IEC publications search -

webstore.iec.ch/advsearchform

The advanced search enables to find IEC publications by a variety of criteria (reference number, text, technical committee, ...). It also gives information on projects, replaced and withdrawn publications.

IEC Just Published - webstore.iec.ch/justpublished

Stay up to date on all new IEC publications. Just Published details all new publications released. Available online and once a month by email.

IEC Customer Service Centre - webstore.iec.ch/csc

If you wish to give us your feedback on this publication or need further assistance, please contact the Customer Service Centre: sales@iec.ch.

IEC Products & Services Portal - products.iec.ch

Discover our powerful search engine and read freely all the publications previews, graphical symbols and the glossary. With a subscription you will always have access to up to date content tailored to your needs.

Electropedia - www.electropedia.org

The world's leading online dictionary on electrotechnology, containing more than 22 500 terminological entries in English and French, with equivalent terms in 25 additional languages. Also known as the International Electrotechnical Vocabulary (IEV) online.

Warning! Make sure that you obtained this publication from an authorized distributor.

CONTENTS

FOREWORD	3
INTRODUCTION	5
1 Scope	6
2 Normative references	6
3 Terms, definitions, abbreviated terms, units and conventions	7
3.1 Terms and definitions	7
3.2 Abbreviated terms and units	8
4 System reliability analysis model	10
4.1 General	10
4.2 Failure mode identification, classification, and system element assignment	10
5 Component reliability analysis models	12
5.1 Individual failure modes	12
5.2 Gear reliability calculation	12
5.2.1 General	12
5.2.2 Estimation of service life for defined failure probabilities	12
5.2.3 Extrapolation of failure probabilities to the design life	16
5.3 Rolling bearing reliability calculation	17
5.4 Shaft reliability calculation	18
Annex A (informative) Example reliability calculations	20
A.1 General	20
A.2 Example system reliability model	20
A.2.1 Identification of components	20
A.2.2 Identification of system elements	20
A.2.3 Classification and selection of system elements	21
A.2.4 Arrangement of reliability model and calculation of system reliability	21
A.2.5 Example system assumptions	21
A.3 Example gear tooth surface durability (pitting) reliability calculation	22
A.3.1 Example gear assumptions	22
A.3.2 Estimation of service life for defined failure probabilities	22
A.3.3 Extrapolation of failure probabilities to the design life	25
A.4 Example gear tooth bending strength reliability calculation	26
A.4.1 Example gear assumptions	26
A.4.2 Estimation of service life for defined failure probabilities	26
A.4.3 Extrapolation of failure probabilities to the design life	28
A.5 Example rolling bearing contact fatigue reliability calculation	29
A.6 Example shaft fatigue fracture reliability calculation	29
A.6.1 Example shaft assumptions	29
A.6.2 Estimation of life for the nominal failure probability	29
A.6.3 Extrapolation of service life for 10% failure probability	30
A.7 Example system reliability calculation	31
Annex B (informative) Application of the Weibull distribution to rolling bearing fatigue life	32
Bibliography	35
Figure 1 – Calculated design versus apparent failure probability	5
Figure 2 – Example of a system elements tree	11

Figure 3 – Service-life calculation for a 50 % failure probability (top) from a scaled LRD (bottom)	13
Figure 4 – S-N curve for different failure probabilities (Hein et al. 2018).....	15
Figure A.1 – Functional elements	20
Figure A.2 – System elements	21
Figure A.3 – Service-life calculation with 1 % failure probability S-N curve (bottom) and failure probability (top)	24
Figure A.4 – Lognormal fit for gear pitting failure probability.....	25
Figure A.5 – Lognormal fit for gear bending failure probability	28
Figure B.1 – Evaluation of identical data by 2- and 3-parameter Weibull distributions	32
Figure B.2 – Estimation of Weibull parameter γ by 3-parameter Weibull evaluation.....	33
Figure B.3 – Evaluation of identical data by five test scenarios.....	34
Table 1 – Failure probability conversion factors for permissible gear stresses.....	15
Table A.1 – Simplified LRD.....	22
Table A.2 – Contact stress for each load bin	22
Table A.3 – Number of cycles for each load bin	23
Table A.4 – Number of cycles for each load bin	23
Table A.5 – Damage for each load bin	24
Table A.6 – Damage sum, lifetime margin factor, and lifetime	24
Table A.7 – Bending stress for each load bin.....	26
Table A.8 – Number of cycles for each load bin	27
Table A.9 – Number of cycles for each load bin	27
Table A.10 – Damage for each load bin	27
Table A.11 – Damage sum, lifetime margin factor, and lifetime.....	27
Table A.12 – Torsional stress for each load bin	29
Table A.13 – Number of cycles for each load bin	30
Table B.1 – Effect of test scenario on L_{10} and Weibull parameters β and η	34

INTERNATIONAL ELECTROTECHNICAL COMMISSION

**Wind energy generation systems -
Part 4-1: Reliability assessment of drivetrain components in 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 61400-4-1 has been prepared by IEC technical committee 88: Wind energy generation systems, in co-operation with ISO technical committee 60: Gears. It is a Technical Specification.

It is published as a dual logo technical specification.

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

Draft	Report on voting
88/1124/DTS	88/1147/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, published 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.

This corrected version of IEC TS 61400-4-1:2026 incorporates the following correction:

- addition in the foreword that this is a double logo technical specification prepared in cooperation with ISO/TC 60

Sample Document

get full document from standards.iteh.ai

INTRODUCTION

Gearboxes historically have been and still are a large contributor to wind turbine operating expenses and downtime. IEC 61400-4 describes requirements for the specification, design, and verification of gearboxes in wind turbines. This Technical Specification (TS) accompanies IEC 61400-4 and describes a method for the calculation of the design reliability of gearboxes for wind turbines.

The method enables comparison of the calculated reliability of gearbox designs as a function of time. It allows gearbox suppliers, wind turbine manufacturers, wind plant owners, and others to compare different gearbox designs on equal terms. For example, the design reliability can be compared between different gearbox designs for the same load conditions or for the same gearbox in different load conditions. Wind turbine manufacturers and operators can also use the information for defining field service and repair strategies.

Currently, that occur in the field have a standardized or generally accepted calculation method (Hovgaard 2015). Therefore, as illustrated in Figure 1, there is a difference between the calculated failure probability and apparent failure probability observed in the field.

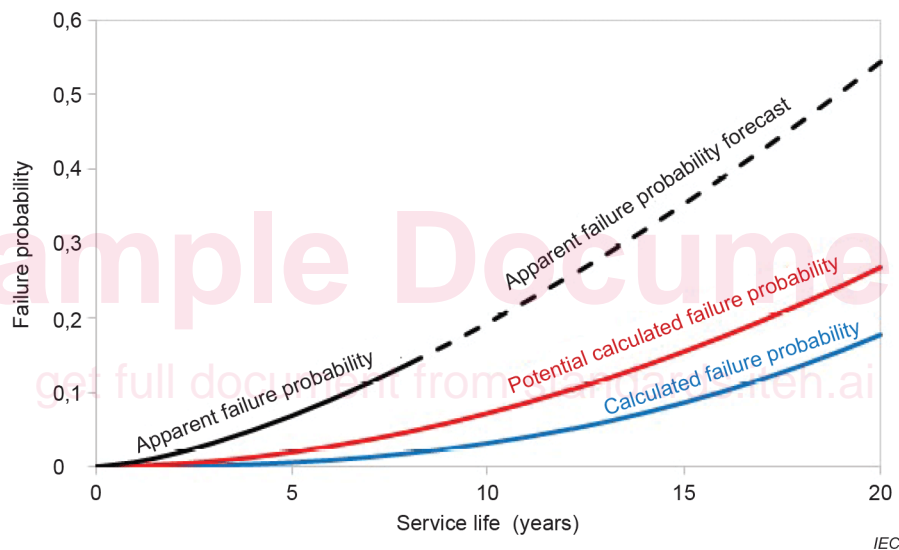


Figure 1 – Calculated design versus apparent failure probability

The method described in this document can accommodate additional failure modes in the future, as long as these modes are calculable according to a standardized method and are time related. Figure 1 also indicates how the inclusion of additional failure modes might reduce the gap between calculated and apparent failure probability in the future. Further information can be found in Strasser et al. (2015).

1 Scope

This part of IEC 61400 specifies a method to calculate the design reliability of wind turbines gearboxes covered by IEC 61400-4, based upon failure modes where standardized calculation methods are publicly available.

Currently, not all failure mechanisms that occur in the field have accepted theoretical models. Therefore, the method only provides a quantitative assessment method of the failure mechanisms that can be described with accepted mathematical models for the complete gearbox, stages (functional units), field replaceable units, and individual components.

For the calculable failure mechanisms, it is possible to compare the reliability between different gearbox designs within the limitations of the theoretical models. The use of field-based statistical parameters can improve the accuracy of the calculated reliability.

The calculated design reliability can provide information for the lifecycle management strategy. However, this document does not provide trade-off decisions between higher design reliability and maintenance strategies (e.g. preventive or predictive maintenance). This document does not consider repairable system analysis.

Due to the lack of accepted theoretical models for some failure modes, the model can currently not predict the apparent failure probability in the field.

Neither this document nor IEC 61400-4 specify a minimum value of design reliability.

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

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

ISO 6336-2:2019, *Calculation of load capacity of spur and helical gears - Part 2: Calculation of surface durability (pitting)*

ISO 6336-3:2019, *Calculation of load capacity of spur and helical gears - Part 3: Calculation of tooth bending strength*

ISO 6336-5:2016, *Calculation of load capacity of spur and helical gears - Part 5: Strength and quality of materials*

ISO 6336-6, *Calculation of load capacity of spur and helical gears - Part 6: Calculation of service life under variable load*

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

DIN 743 (all parts), *Shafts and axles, calculations of load capacity*

3 Terms, definitions, abbreviated terms, units and conventions

3.1 Terms and definitions

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

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at <http://www.electropedia.org/>
- ISO Online browsing platform: available at <http://www.iso.org/obp>

3.1.1

apparent failure probability

failure probability observed in the field, including all failure modes, whether they are considered in the calculated system reliability as described in this document or not

3.1.2

component

part in the gearbox system comprising one or more functional elements

EXAMPLE Gear wheel.

3.1.3

failure mode

manner in which a failure occurs

EXAMPLE Gear tooth root bending fatigue fracture.

3.1.4

failure probability

$F(t)$

unreliability function

probability that the time to failure is lower or equal to the time, t

3.1.5

failure probability density function

derivative of the distribution function, which describes the amount of failures as a function of time

3.1.6

field replaceable unit

individual component or gearbox subassembly that can be replaced with relatively low cost and effort, considerably less so than a complete gearbox replacement

EXAMPLE In typical wind turbine gearboxes, the high-speed shaft and bearings are considered as field replaceable units.

3.1.7

functional element

element of a component providing a specific function

EXAMPLE Gear tooth.

Note 1 to entry: A component can have several functional elements.

3.1.8 reliability

probability that a product does not fail during a defined period of time under given functional and environmental conditions

Note 1 to entry: The term probability takes into consideration that various failure events can be caused by coincidental, stochastically distributed causes and that the probability can only be described quantitatively. See Bertsche (2008).

3.1.9 reliability function

$R(t)$

survival probability

probability of survival until time, t

3.1.10 system element

unique combination of a failure mode with a functional element of a component

EXAMPLE Gear tooth root bending fatigue fracture of the sun pinion.

3.1.11 system element reliability function

$R_{SE}(t)$

failure behaviour of a system element

3.1.12 system reliability function

$R_S(t)$

failure behaviour of the complete system, calculated from the system element failure behaviours and Boolean system theory

3.2 Abbreviated terms and units

This document uses equations and relationships from several engineering specialties. As a result, there are, in some cases, conflicting definitions for the same symbol. All the symbols used in the document are nevertheless listed, but, if there is ambiguity, the specific definition is presented in the clause where they are used in equations, graphs, or text.

$F(t)$	failure probability	%
f_{F1}	conversion factor for tooth root bending strength for failure probability, F	–
f_{H1}	conversion factor for pitting strength for failure probability, F	–
f_{tB}	failure free time factor	–
i	load bin index	–
j	system element index	–
L_F	lifetime where failure of F % of the elements is expected	h
L_{10}	bearing rating life for 10 % failure probability (i.e. 90 % reliability)	h
L_{10mr}	bearing combined modified reference rating life for 10 % failure probability (i.e. 90 % reliability)	h
N_D	number of shaft load cycles for endurance strength according to DIN 743 series	–
$N_{L\text{ ref}}$	number of gear load cycles for endurance limit according to ISO 6336-6	–

$N_{FF,i}$	allowable number of load cycles for tooth root bending strength for failure probability, F , and load bin, i	–
$N_{HF,i}$	allowable number of load cycles for pitting strength for failure probability, F , and load bin, i	–
$N_{SF,i}$	allowable number of load cycles for shaft fatigue fracture for failure probability, F , and load bin, i	–
n_i	number of cycles for load bin, i	–
n_R	shaft rotational speed	r/min
$n_{rel,i}$	relative shaft rotational speed for load bin, i	–
p	material S-N curve slope exponent	–
$R(t)$	reliability function	–
$R_{SE,j}(t)$	system element reliability function for element, j	–
$R_S(t)$	system reliability function	–
S_{LFF}	lifetime margin factor for bending strength for failure probability, F	–
S_{LHF}	lifetime margin factor for pitting strength for failure probability, F	–
S_{F50} %	relative standard distribution for bending strength for failure probability, F	%
S_{H50} %	relative standard distribution for pitting strength for failure probability, F	%
$T_{rel,i}$	relative torque for load bin, i	–
t	time	h
t_d	design life, typically 175 000 h for a 20-year design life	h
t_{sF}	tooth root bending strength service life	h
t_{sH}	pitting strength service life	h
$t_{rel,i}$	relative time for load bin, i	%
U_{crit}	critical damage sum	–
U_{FF}	damage sum for gear tooth root bending strength for failure probability, F	–
$U_{FF,i}$	damage for gear tooth root bending strength for failure probability, F , and for load bin, i	–
U_{HF}	damage sum for gear pitting strength for failure probability, F	–
$U_{HF,i}$	damage for gear pitting strength for failure probability, F , and for load bin, i	–
U_{SF}	damage sum for shaft fatigue fracture for failure probability, F	–
Z_F	quantile of the standard normal distribution for failure probability, F	–
β	Weibull shape parameter	–
γ	Weibull location parameter	h
η	Weibull characteristic life or scale parameter	h
σ	lognormal distribution standard deviation	h
σ_{ADK}	shaft endurance strength according to DIN 743 series	MPa
$\sigma_{ANK,i}$	shaft fatigue strength for each load bin	MPa
$\sigma_{F,i}$	gear tooth root stress for load bin, i	MPa

σ_{FPF}	gear tooth root bending stress limit for failure probability, F	MPa
$\sigma_{H,i}$	gear tooth contact stress for load bin, i	MPa
σ_{HPF}	gear tooth pitting stress limit for failure probability, F	MPa

DIN	Deutsches Institut für Normung
FVA	Forschungsvereinigung Antriebstechnik
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
LRD	load revolution distribution
VDMA	Verband Deutscher Maschinen- und Anlagenbau

4 System reliability analysis model

4.1 General

This document specifies a Boolean approximation for calculating the system reliability function, $R_S(t)$, of the gearbox. The gearbox elements are represented as a series of blocks, each of them representing the probability of a gearbox element failing in one calculable failure mode.

The approach makes the following assumptions:

- The gear elements currently considered in the model do not have any redundancies. Therefore, the reliability elements are arranged in sequential blocks. This indicates that the model considers the gearbox as failed if any of the individual elements fail. In particular, the individual elements of a planetary gear system are not considered redundant or have parallel paths.
- All individual elements within the gearbox are assumed to be independent.

NOTE Several other approaches for reliability analysis exist. Standardizing one method for wind turbine drivetrains improves the opportunities to share data between different stakeholders (e.g., operators, manufacturers of wind turbines or gearboxes) and thereby accelerates the validation of the analysis against field data and enriches the model with empirical data.

Within these assumptions, the system reliability function, $R_S(t)$, is calculated as the product of the system element reliability functions, $R_{SE_j}(t)$

$$R_S(t) = \prod_{\forall j} R_{SE_j}(t) \quad (1)$$

If a system is comprised of multiple identical components, the reliability of each component shall be considered in Formula (1).

An example of a system reliability calculation is described in Annex A.

4.2 Failure mode identification, classification, and system element assignment

For analysing system reliability, the gearbox system is structured according to its sub-systems, components, functional elements, and failure modes. A system element is a unique combination of a failure mode of a functional element of a component. The structured system can be illustrated as a system element tree as outlined with dashed lines in Figure 2, with an example system element "pitting on sun pinion gear teeth".