A Revised International Standard for Gearboxes in Wind Turbine Systems

Preprint

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Presented at the Conference for Wind Power Drives
Aachen, Germany
March 21–22, 2023

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Conference Paper
NREL/CP-5000-85224
April 2023

This report is available at no cost from the National Renewable Energy Laboratory (NREL) at www.nrel.gov/publications.

Contract No. DE-AC36-08GO28308

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Suggested Citation
McNiff, Brian, Jonathan Keller, Alfredo Fernandez-Sison, Jens Demtröder. 2023. A *Revised International Standard for Gearboxes in Wind Turbine Systems: Preprint*. Golden, CO: National Renewable Energy Laboratory. NREL/CP-5000-85224. https://www.nrel.gov/docs/fy23osti/85224.pdf.

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National Renewable Energy Laboratory
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Golden, CO 80401
303-275-3000 • www.nrel.gov

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A Revised International Standard for Gearboxes in Wind Turbine Systems

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Keywords: *gearbox, wind turbine, standards, testing*

Abstract: Gearbox and wind turbine design and application standards have contributed significantly to improvements in reliability over the past two decades. The International Electrotechnical Commission (IEC) 61400-4 standard for wind turbine gearbox design is currently being revised by a joint working group of experts in IEC Technical Committee (TC) 88 (wind energy generation systems) and International Organization for Standardization (ISO) TC60 (gears) to further that effort. Experts from ISO TC4 (rolling bearings) and ISO TC28 (lubricants) have actively participated. This revision has implemented lessons learned from industry use of Edition 1 since its publication in 2012.

The main document, IEC 61400-4, was pared down to essential design requirements and application-specific recommendations along with a design verification framework. The joint working group leveraged concurrent development of other standards, such as IEC 61400-8 on wind turbine structures, to replace Edition 1 content. These updates are described along with how the standard relates to the IEC Renewable Energy certification scheme for wind turbines.

The joint working group recognized the interest in maintaining informative parts of Edition 1, including annexes on wind turbine architecture and loads, bearing and gear arrangements, bearing selection, lubrication system descriptions, and lubricant performance recommendations. This information was retained in two technical reports: IEC/TR 61400-4-2 Lubrication and IEC/TR 61400-4-3 Explanatory Notes. Additionally, a technical specification, IEC/TS 61400-4-1, was drafted to provide a reliability calculation method for comparing different design options or conditions. Salient elements of these documents are described.

All four documents were recently distributed for IEC/ISO review, ballot, and comment. Publication is expected in 2023.

1 Introduction

International Electrotechnical Commission (IEC) 61400-4, a design standard for wind turbine gearboxes, was published in 2012 as part of the IEC Technical Committee (TC) 88 wind turbine standards under a high-level cooperation with International Organization for Standardization (ISO) TC60 (gears). This standard provides requirements for the design of all gearbox elements including gears, bearings, shafts, and substructures—more specifically, how to use the extant standards for those elements in this unique application. Guidance is also included for bearing selection, lubrication properties, and system operation and maintenance. A description of the wind turbine operating environment and loading is also provided.

Feedback from various sources have called for an update to Edition 1 for a number of reasons:

- American Gear Manufacturers Association (AGMA) standard 6006, the U.S. national standard on wind turbine gearboxes, was updated by narrowing the main text to only requirements and removing informative content and guidance. A basic reliability model was also included.
- The German VDMA issued a specification document proposing text for system reliability modelling (VDMA 23904) and another addressing plain bearings (VDMA 23903).
- The recently developed IEC Renewable Energy (IECRE; https://www.iecre.org) certification system recommended that Edition 2 revise testing requirements to be directly coupled to design requirements.

As a result, the joint working group (JWG) started development of Edition 2 of IEC 61400-4 in 2017. The starting point was to pare down the main document to essential design requirements and application-specific recommendations along with a verification framework. The JWG also took advantage of concurrent development of other standards, such as IEC 61400-8 on wind turbine structures and ISO 6336-22 on micropitting, to improve or replace Edition 1 content by directly referencing those documents.

The JWG recognized the interest in maintaining the informative parts of Edition 1, including annexes on wind turbine architecture and loads, bearing and gear arrangements, bearing selection, lubrication system descriptions, and lubricant performance recommendations. Some of this information was retained in two technical reports, IEC/TR 61400-4-2: "Lubrication of drivetrain components in wind turbines" and IEC/TR 61400-4-3: "Explanatory Notes on IEC 61400-4." Additionally, a technical specification was created, IEC/TS 61400-4-1: "Reliability assessment of drivetrain components in wind turbines," to provide a reliability calculation method for comparing different design options or conditions.

This document provides an overview of the pertinent changes and some details on design requirement and verification changes.

2 Edition 2 design requirement changes

2.1 Overview

Initially, it was expected that the design requirements for the major elements would not change from Edition 1 of IEC 61400-4, but fundamental design standards for wind turbines and gearbox elements—gears, bearings, shafts, and lubricants—have since been updated and changed, and some new standards have been published. These changes were accommodated into Edition 2 as noted in Table 1 and Table 2. These will be described further in this section, along with rearranging and extracting informative parts into two technical reports and one technical specification.

2.2 Gears

2.2.1 Gear design life analysis

The only significant change to the gear design requirements in the standard was to account for differences from updates to ISO 6336-2 (pitting) and ISO 6336-3 (tooth bending), as noted in

Table 2. Wind turbine original equipment manufacturers (OEMs), gearbox manufacturers, and the FZG at the Technical University of Munich participated in estimating gear design life for different arrangements and gear types to assess and quantify the differences between the 2006 and 2019 editions of the pitting and tooth bending standards.

The safety factors for pitting resistance didn't change between editions of ISO 6336-2, but in some arrangements the safety factors for tooth bending strength according to ISO 6336-3 did change. The limits of these factors in IEC 61400-4 Edition 2 were adjusted to account for those differences. The important outcome was that the JWG experts maintained the same "absolute" safety level despite some changes in calculated life factors. The rationale for this change, including the results of the comparative analysis between editions, is included in IEC/TR 61400-4-3 Explanatory Notes.

Table 1 IEC TC88 wind turbine standards influencing modifications to Edition 2

Standard	Title/ subject	JWG modifications to Edition 2
IEC 61400-1:2019	Part 1: Design requirements	some partial safety factors on materials and loads change in Edition 4
IEC 61400-3-1	Part 3-1: Design requirements for fixed offshore wind turbines	supplemental reference to IEC 61400-1, component designers should recognize more complex loading and environment
IEC/TS 61400-3-2	Part 3-2: Design requirements for floating offshore wind turbines	supplemental reference to IEC 61400-1, designers should recognize added floating degrees of freedom
IEC CDV 61400-8	Part 8: Design of wind turbine structural components	removed structures design clause and informative Annex, replace with reference to 61400-8

Table 2 ISO TC60 gear standards influencing modifications to Edition 2

Standard	Title/ subject	JWG modifications to Edition 2
ISO 6336-2:2019	Part 2: Calculation of surface durability (pitting)	revisit minimum safety factors compared to 2006
ISO 6336-3:2019	Part 3: Calculation of tooth bending strength	revisit minimum safety factors compared to 2006
ISO/TS 6336-4:2019	Part 4: Calculation of tooth flank fracture load capacity	added new tooth flank fracture (TFF) risk recommendations

2.2.2 Scuffing

Edition 2 includes reference to methods under development for the evaluation of gear scuffing risk: ISO/TS 6336-20 and ISO/TS 6336-21. Some guidance is also provided for minimum safety factors determined using these methods.

2.2.3 Tooth flank fracture

Tooth flank fracture (TFF) is a fatigue failure of the gear flank characterized by complete or partial tooth fracture originating beneath the hardened layer. These have been occurring (rarely) in wind turbine gears. Currently, there is no standardized method available for determining the risk of TFF. However, Edition 2 refers the designer to ISO/TS 6336-4 to review parameters influencing TFF.

2.3 Bearings

No fundamental changes in rolling bearing design requirements and considerations are included in Edition 2. However, some clarifications were provided for use of ISO/TS 16281 on rolling bearing life estimation. Some of the informative parts of Edition 1 were maintained in the annexes, but the bearing selection tables were removed.

However, considerations and requirements for utilizing plain bearings in wind turbine gearboxes are new to Edition 2. Although there is not a lot of field experience with plain bearings in wind turbines, many current turbines include these bearing options. Much of the new content identifies useful standards and analysis methodologies. The fundamental risks to plain bearings are lack of lubrication in various operating scenarios and overload, as shown in Figure 1. These risks and some mitigation strategies are included in Edition 2.

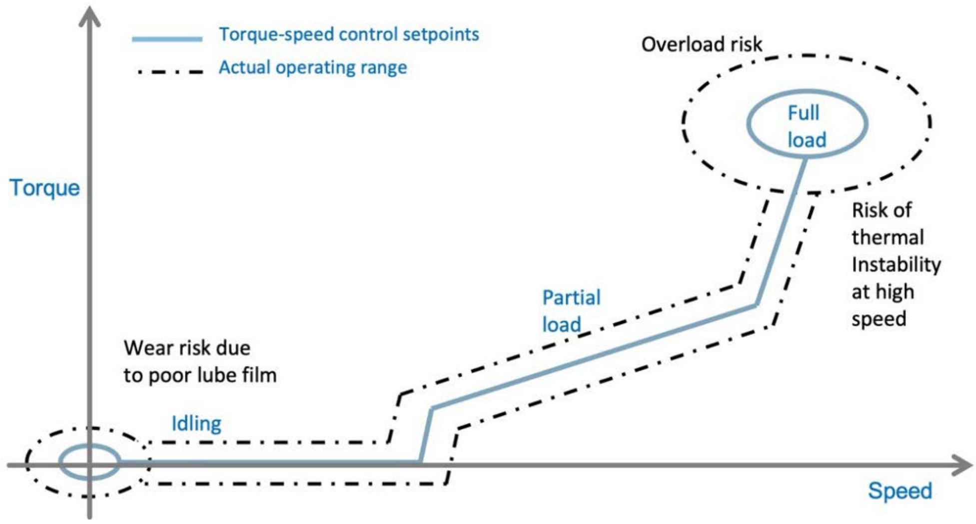

Figure 1: Relevant operational regions for plain bearings

2.4 Structures

Edition 1 included requirements for the design of gearbox substructures, such as planet carriers and housings, along with an explanatory annex. It was agreed by the JWG that the existing requirements (and the informative content) were available in many standard textbooks and handbooks with some variations on approach. Fortunately, IEC TC88 Project Team 8 (PT 61400-8) has been concurrently developing an international standard specific to wind turbine nacelle structures. Some JWG experts participated in PT 61400-8 and acted as liaison to the JWG to help align efforts. Structures requirements were therefore reduced to referencing IEC 61400-8 (currently a committee draft for vote (CDV)) in the main document and deleting the informative annex.

2.5 Lubrication

In Edition 2, the requirements for the lubricant and lubrication system are included in the main document in a concise, well-contained clause connected to the gearbox element design requirements. The informative parts of this from Edition 1 were spread between the main body lubrication clause and an annex. As noted above, this has been updated to the current state of the art and used to develop a new technical report—IEC/TR 61400-4-2. This TR contains a very useful collection of explanations of the components of the lubricant and additives, the functional parts of the lubricant system, and some guidance on interpreting lubricant properties (viscosity, acid content, etc.) and parameters (cleanliness, water content, etc.) for effective monitoring of the lubricant condition over time. This also includes guidance on effective monitoring methodologies and oil change intervals/criteria.

2.6 Explanatory notes

As noted above, the JWG decided to keep some Edition 1 informative content, including guidance on preliminary bearing selection and basic bearing life rating, rationales for where some of the gear and bearing design requirements evolved from, and some useful explanations of common wind turbine loading descriptions and summaries. These items are included in the technical report, IEC/TR 61400-4-3.

2.7 Reliability model

As a completely new part of the revision of Edition 2, the JWG drafted a wind turbine gearbox reliability modelling method in a separate technical specification, IEC/TS 61400-4-1, *Wind energy generation systems—Part 4-1: Reliability assessment of drivetrain components in wind turbines.* The JWG derived some of this from the previously updated AGMA 6006 standard and from the concurrently drafted VDMA specification 23904.The method described is suitable for comparing the calculated design reliability between gearboxes based only on failure modes where standardized calculation methods are publicly available, including:

- Gear tooth bending strength (as per ISO 6336-3)
- Gear tooth surface durability (pitting, as per ISO 6336-2)
- Modified reference bearing life (as per ISO/TR 16281)
- Shaft fatigue fracture (as per DIN 743 or IEC/CDV 61400-8).

The methodology described could be expanded to include additional unique failure modes that demonstrate a similarly standardized life calculation or are supported by empirical data.

It should be noted that not all failure modes observed in the field have a standardized calculation method. Therefore, there is a difference between the apparent reliability observed by owners and that calculated with the model, as characterized in Figure 2.

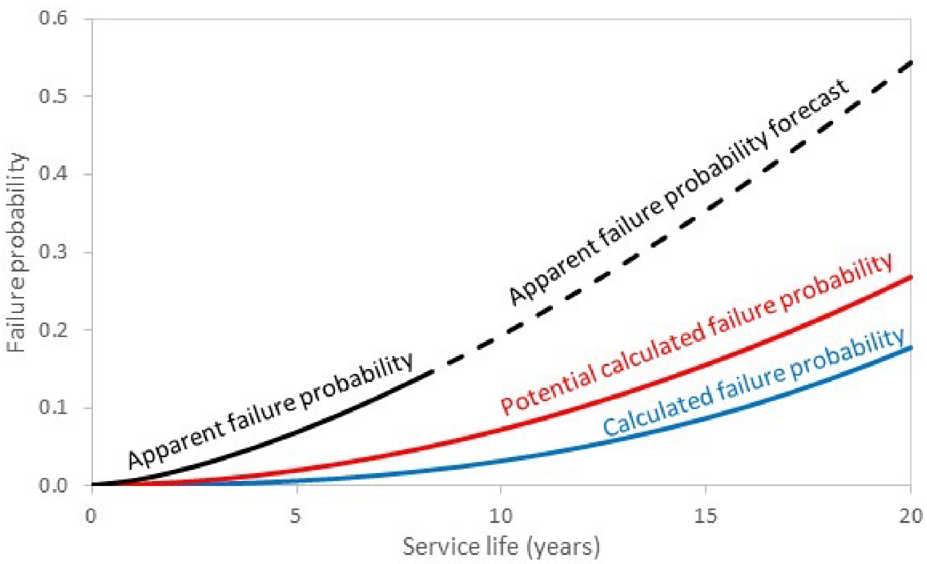

Figure 2: Apparent and calculated reliability

3 Verification and validation

3.1 Overview

In Edition 1 of IEC 61400-4, the design verification requirements were a set of prescriptive tests for prototype and serial manufacture that were considered "good practice" but lacked any useful evaluation of the test outcomes compared to the design requirements. This included a required overload or "robustness" test at some elevated, fixed load for a period of time that was not connected to any design requirements or outcomes. Similarly, serial production testing was required for all production units without the outcomes being directly connected back to design assumptions. In use, this was found to be an incomplete way to assess the design for the application. Also, the new IECRE certification system—developed since the publication of Edition 1—strongly recommended that the revision address a significant improvement in gearbox testing.

To fill the perceived gap, wind turbine OEMs and gearbox designers augmented these requirements with internally developed testing methodologies. For instance, Siemens Gamesa developed their SALT (Smart Accelerated Life Testing) methodology, which implemented a failure risk-based approach (even for observed failure modes that lack calculable life estimations) using testing with several levels of integration from testing a gearbox element to field testing on the complete wind turbine. Also, ZF's DORoTe approach (Design Operational Robustness Test) included more complex loading (e.g., dynamic loading, start/stops) in the tests [VER15]. The intent was to apply loads experienced in-field by the whole system. Both of these were an improvement over fixed-load tests because a wind turbine gearbox is a complex, multi-element system, and each of these elements (gears, bearings, shafts, etc.) is subject to differing failure risks and causality mechanisms. This makes it difficult to apply meaningful proof overload testing or design-life equivalent fatigue testing of the complete system.

Based on this, the JWG proposed a failure-mode-focused process of design verification as a fundamental change in Edition 2 of IEC 61400-4. This process assures that the gearbox complies with the design requirements; confirms the design assumptions used in bearing, gear, and structural analytical and design tools; and, to the maximum extent possible, reduces the risk of known failures.

3.2 Failure mode risk-based approach

During the design process, failure risks are to be identified using a design failure mode and effects analysis (FMEA) or equivalent, along with the expected mechanisms. The FMEA connects the required verification evidence to each of the risks.

Calculable damage or design life models for different elements and risks can be directly verified by measuring some variables in physical testing. Of course, not all of the identified failure modes have broadly accepted calculable models for operating life. However, techniques are available to leverage design and field experience to reduce uncertainty and verify application design factors.

A summary of the failure mode categories is provided in Table 3. Basically, A1 failure modes have a validated and broadly acceptable analytical methodology for estimating application lifetime. Category A2, B, and C failure modes lack a lifetime calculation model defined in a recognized design code or standard. It is expected that some form of direct measurement can be used to verify the A1 design calculation parameters or model input assumptions.

Table 3 Failure mode categorization

	Failure mode category			
	A1	A2	B	C
Load/ stressor profile	Deterministic (loaded by defined stress)	Deterministic (loaded by defined stress)	Stochastic (loaded by friction, abrasion, extreme temperature, dirt corrosion, etc.)	Stochastic (randomly loaded by impacts, friction, abrasion, etc.)
Assessment/ calculation	Validated models available	Validated models not available	Some models available	No models available
Type	Cumulative	Cumulative	Non-cumulative	Cumulative/non-cumulative
Failure mode examples	Tooth bending, bearing rolling contact fatigue	Tooth flank fracture, bearing WEC	Scuffing	Debris damage, fluting
Note: The categorization of the example failure modes reflects the current state of the art and can change (e.g., when a calculation model for an A2 failure mode gets validated and recognized).				

A verification plan should include all design requirements included in the standard along with expected failure modes identified in the FMEA, and guidance on how to objectively verify them. In addition to design verification by physical testing, options for verification by similarity with previous designs and simulation of some design elements are included. The verification and validation matrix for gear elements is shown as an example in Table 4.

Table 4 Verification matrix for failure risks in gear elements

Failure mode or design feature	Type	Detection requirement	Verification or validation method			Acceptance criteria
			Simulation	Similarity	Testing	
Load distribution for planetary stages	F	Load distribution magnitudes	Y		T1 or T4	Measured $K_{H\beta}$ and $K_V K_\gamma$ load factors less than or equal to requirement
Load distribution - parallel stages	F	Visual inspection	Y		T1 or T4	Contact area within ±10% of simulated area
Surface durability	A1	Visual inspection		Y	T2	No pitting as per ISO 10825-1
Tooth root fatigue fracture	A1	Visual inspection		Y	T2	No tooth breakage or initial cracks as per ISO 10825-1
Scuffing	B	Visual inspection		Y	T2	No scuffing as per ISO 14635-1:2000
Micropitting	B	Visual inspection		Y	T2	No micropitting as per ISO 10825-1
Tooth flank fracture	A2	Visual inspection	essentially A1	Y	T2	No fracture as per ISO 10825-1
Tooth rim fracture	A2	Visual inspection		Y	T2	No surface crack
Note: F - fatigue analysis used, Y- the verification method is allowed for other types (see Table 3).						

3.3 Verification methods

3.3.1 Physical testing

The JWG prescribed four different tests that ranged from just the gearbox as a single component (T1) to a more complete integration into the wind turbine (T4), as listed in Table 5. Physical tests are different from Edition 1 in that the test outcomes are connected to verifying selected design requirements and informing specific failure risks as identified in, for example, Table 4.

Table 5 Physical tests prescribed in Edition 2

Test	Type	Outcomes	Applied loads and configurations
T1	Functional tests	K-factors, deflection, temperature stability, dynamics	performed in a gearbox-only test environment, apply min 120% of reference torque min 1 hour, speed sweeps, torque steps
T2	Robustness test	non-calculable failure modes	various levels of drivetrain integration
T3	Climate tests	temperature, lubricant, bearings	extreme climatic conditions
T4	Integrated system test	influences from whole system integration	complete turbine in-field or full nacelle in test rigs, start-up, shutdown, e-stops, grid events, low load, electrical events

3.3.2 Simulation

As a new approach allowed in Edition 2, verification and validation by simulation may be used based on calculation and analytical models specific to the identified failure modes and risks as long as the system operates within the defined boundary conditions of the models.

3.3.3 Similarity

Verification and validation by similarity may be used to show that a previously certified, existing series production gearbox is comparable to the new gearbox as defined in Edition 2. Most wind turbine types are offered in multiple variants to account for variations in operating conditions, wind regime, grid frequency, rotor diameters, or power ratings. Different gearbox variants can have different reference speed, gear ratio, or reference torque. These gearbox variants are of the same gearbox type if all of the following criteria are fulfilled:

- All variants share the same design basis, use the same concepts and technologies, and share the same manufacturing processes
- The design of the variant adheres to the minimum calculated safety factors and rating life requirements, and the risk assessment does not indicate any new failure modes
- All design and operating parameters are within the ranges specified.

Variants of the same gearbox type will typically share components or modules (e.g., a complete planetary stage). Variants within a gearbox type may be verified by similarity as described if at least one variant of the type is verified by testing.

4 Certification

4.1 IEC Renewable Energy certification system

The IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications is referred to as the IECRE. The wind energy sector of this system (IECRE-WE) certification scheme constitutes a complete third-party conformity assessment of any wind turbine type or wind turbine component type. IECRE operational documents (OD) have been developed that specify procedures for all elements of the type certification scheme to systematically confirm that a wind turbine or component type has been designed, tested, manufactured, and documented in conformity with design assumptions, specific standards, and other internationally accepted technical requirements.

It should be noted that normative requirements (for design, verification, manufacturing, etc.) are developed in the international standards, not in these ODs. These ODs are instead rules and procedures for carrying out the third-party conformity assessment in a consistent, inclusive manner. ODs have been developed for all the standardized competency areas (e.g., blade structural testing, power performance testing, electrical system testing) to describe the use of the standards in evaluation, pertinent design documentation and required test reports. ODs have also been written to guide the assessment of third-party test labs (and certification bodies) in the IECRE scheme to assure these entities meet the specific competency requirements and are independent and trustworthy throughout the IECRE system.

This internationally developed and accepted approach allows test reports, design assessments, type tests, and component-focused analysis/tests to be accepted throughout the system no matter where they are carried out, as long as they are performed by IECRE-assessed test labs (RETL) and certification bodies (RECB). The final products are globally accepted certificates from the certification bodies for a turbine or component type that result from a readily reviewable and transparent scheme. Now that Edition 2 of IEC 61400-4 is soon to be completed, the IECRE ODs for applying it in the IECRE certification system need to be updated.

4.2 Pertinent IECRE operational documents

4.2.1 IECRE website

Some explanation of pertinent ODs is provided in this clause. Wind Energy sector ODs (WE uses the numbering "OD 5xx" to discern it from other RE sectors) can be found at the Rules and OD section at https://www.iecre.org/documents/refdocs/.

4.2.2 OD 501

IECRE System, Operational Document OD 501: *Type and component certification scheme (for wind turbines)*

This OD describes procedures for conformity assessment relating to the design, testing, and manufacturing of a wind turbine and/or components. This is the overarching document used by RECBs that integrates the complete WE type certification process.

4.2.3 OD 501-2

IECRE System, Operational Document OD 501-2: *Conformity assessment and certification of wind turbine gearboxes by RECB*

The main objective of this operational document is to describe the evaluation method and procedure for the certification of wind turbine gearboxes as a module to OD 501. For the most part, design documentation and test reports for adhering to IEC 61400-4 (as well as upstream standards) are required to be supplied for this evaluation. As a key element, it also includes a manufacturing evaluation to assess that a specific gearbox is manufactured in conformity with the design documentation verified during the design evaluation. It requires manufacturing of at least one representative specimen of the type under certification.

4.2.4 OD 551-yy

IECRE System, Operational Document OD 551-yy: *Assessment of competency of RETLs or RECTFs for wind turbine gearboxes testing*

This (unpublished) operational document was drafted to be used as a guide to assess the competency of IECRE third-party test laboratories (RETL) or IECRE customer test facilities (RECTF)—usually an OEM or gearbox vendor—under IECRE for gearbox verification testing. After completion of the final version of IEC 61400-4, this OD will be updated and submitted to IECRE member bodies for approval and publication for use in the IECRE system.

One of the main reasons this OD was drafted during the revision of IEC 61400-4 is that gearbox testing is commonly performed by wind turbine OEMs and/or gearbox manufacturers for various reasons. These are called "customer test facilities" in other IEC certification schemes, and they require a layer of observation or witnessing by a certification body to provide independent review. This is accommodated in the OD.

5 Summary

The IEC 61400-4 standard for wind turbine gearbox design is currently being revised by a group of experts in IEC TC 88 (wind energy generation systems) and ISO TC60 (gears). Experts from ISO TC4 (rolling bearings) and ISO TC28 (lubricants) have also actively participated. This revision has implemented lessons learned from industry use of Edition 1 since its publication in 2012.

The main document, IEC 61400-4, was pared down to essential design requirements and application-specific recommendations along with a design verification framework. All of this was updated to the current state of the art from revised wind energy and gear industry standards and research. Lessons learned from the use of Edition 1 over the past decade were also included. The experts leveraged concurrent development of other standards, such as IEC 61400-8 on wind turbine structures, to replace Edition 1 content.

The key changes in Edition 2 were described along with informative parts published in technical reports on lubrication and explanatory notes, and a technical specification on a reliability model.

Finally, a brief summary was given of how the IECRE conformity assessment system will be used with the revised standard in the wind turbine certification process.

6 Acknowledgments

This work was authored in part by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Wind Energy Technologies Office. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

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Conference for Wind Power Drives, Aachen, Germany, 2015

Note: The following standards are discussed as they pertain to the revision of IEC 61400-4. It was decided to list these instead of direct reference.

7.1 Wind energy standards

IEC 61400-1:2019, Wind energy generation systems — Part 1: Design requirements

IEC 61400-3-1:2019, Wind energy generation systems — Part 3-1: Design requirements for fixed offshore wind turbines

IEC/TS 61400-3-2:2019, Wind energy generation systems — Part 3-2: Design requirements for floating offshore wind turbines

IEC 61400-4:2012, Wind turbines — Part 4: Design requirements for wind turbine gearboxes

7.2 Unpublished standards (in final stages)

IEC/CDV 61400-4:2023, Wind energy generation systems — Part 4: Design requirements for wind turbine gearboxes

IEC/CDV 61400-8:2022, Wind energy generation systems — Part 8: Design of wind turbine structural components

IEC/DTS 61400-4-1, Wind energy generation systems — Part 4-1: Reliability assessment of drivetrain components in wind turbines

IEC/DTR 61400-4-2, Wind energy generation systems — Part 4-2: Lubrication of drivetrain components in wind turbines

IEC/DTR 61400-4-3, Wind energy generation systems — Part 4-3: Explanatory notes on IEC 61400-4 – Supportive information for wind turbine gearbox design

7.3 Gear standards

ANSI/AGMA 6006-B20, Standard for design and specification of gearboxes for wind turbines, AGMA, Alexandria, VA 2020

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

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

ISO/TS 6336-4:2019, Calculation of load capacity of spur and helical gears — Part 4: Calculation of tooth flank fracture load capacity, ISO, Geneva, 2019

ISO/TS 6336-20:2022, Calculation of load capacity of spur and helical gears — Part 20: Calculation of scuffing load capacity — Flash temperature method, ISO, Geneva, 2022

ISO/TS 6336-21:2022, Calculation of load capacity of spur and helical gears — Part 21: Calculation of scuffing load capacity — Integral temperature method, ISO, Geneva, 2022

ISO/TS 6336-22:2018, Calculation of load capacity of spur and helical gears — Part 22: Calculation of micropitting load capacity, ISO, Geneva, 2018

VDMA Specification 23903, Basic design requirements for plain bearings in main gearboxes of wind turbines, VDMA Frankfurt, 2020

VDMA Specification 23904, Reliability assessment for wind energy gearboxes, VDMA Frankfurt, 2020