Design Load Basis Guidance for Distributed Wind Turbines

R. Damiani and D. Davis

RRD Engineering

NREL Technical Monitor: Brent Summerville

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List of Acronyms

ACP	American Clean Power
DFMEA	design failure mode and effect analysis
DLC	design load case
dWAM	Distributed Wind Aeroelastic Modeling
ECD	extreme coherent gust with directional change
ECG	extreme coherent gust
EDC	extreme directional change
EOG	extreme operating gust
EOG_1, EOG_{50}	EOG with 1- and 50-year return period
ETM	extreme turbulence model
EWM	extreme wind speed model
EWS	extreme wind shear
FLS	fatigue limit state(s)
HAWC2	Horizontal Axis Wind turbine simulation Code 2nd generation
HAWT	horizontal-axis wind turbine
IEC	International Electrotechnical Commission
IECRE	IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications
NREL	National Renewable Energy Laboratory
NTM	normal turbulence model
NWP	normal wind profile model
O&M	operations and maintenance
OEM	original equipment manufacturer
PSF	partial safety factor
RRD	RRD Engineering, LLC
SLS	service limit state(s)
ULS	ultimate limit state(s)
VAWT	vertical-axis wind turbine
V&V	verification and validation
WTG	wind turbine generator

Math Symbols

A	Weibull scale parameter
F_k	generic characteristic load
k	Weibull shape parameter
I_{ETM}	ETM turbulence intensity
$P_E(F_k)$	probability of exceedance of F_k
p_0	reference atmospheric pressure
T_{ECD}	transient duration for ECD
T_{EDC}	transient duration for EDC
T_{EWS}	transient duration for extreme wind shear (EWS)
T_{gust}	gust duration for EOG

v_{ave}	annual average wind speed (10-minute [min] average) at hub height
v_{ECD}	ECD wind speed increase
v_{EWS}	EWS wind speed difference between top and bottom of the rotor
v_{e50}	50-year (yr) return period 3-second gust wind speed at hub height
v_{gust1}	1-yr return period gust wind speed at hub height for deterministic DLCs (EOG1)
v_{gust50}	50-yr return period gust wind speed at hub height for deterministic DLCs (EOG50)
v_{hub}	hub-height wind speed
v_{in}	cut-in wind speed (10-min average) at hub height
v_{out}	cut-out wind speed (10-min average) at hub height
v_r or v_{rated}	rated wind speed (10-min average) at hub height
v_{ref}	reference wind speed (10-min average) at hub height
v_1	1-yr return period mean wind speed (10-min average) at hub height
v_{50}	50-yr return period mean wind speed (10-min average) at hub height

Greek Symbols

1P, 2P...nP	one time, two times ...n-times the rotor revolution speed
α	power law exponent
γ_f	load PSF
γ_m	material PSF
γ_n	consequence of failure (importance) PSF
ρ_{air}	air density
σ_1	longitudinal component of the wind velocity standard deviation (ETM)
ν_{air}	air kinematic viscosity
Θ_{EDC}	EDC wind direction change magnitude
Θ_{ECD}	ECD wind direction change magnitude

Executive Summary

Aeroelastic modeling is the primary methodology for structural and performance assessment of any wind turbine. Nonetheless, its use in the distributed wind industry sector is limited due to several challenges (Damiani and Davis 2022). One of these challenges is the perceived complexity of generating a proper set of numerical simulations to extract and process the key outputs for component design and verification, and, ultimately, achieve certification. This perceived complexity makes it difficult to reliably predict the structural and performance response of small wind turbines. From the investigation conducted in (Damiani and Davis 2022), it is apparent that many stakeholders in this sector believe that a comprehensive guide for developing a design load basis for distributed wind turbines is necessary.

This report addresses this need, by providing:

- Scope of the design load basis and connections to the parent design basis document
- A detailed breakdown and description of the various sections that make up a design load basis
- References to the basic distributed wind design standards and to additional standards, which, although directly addressing larger turbines, provide the necessary guidance and fill in the gaps that exist in the basic standards
- A real-life example of a design load basis for a downwind horizontal-axis wind turbine (HAWT), including its load case table, that can be directly used as a template for other distributed wind HAWTs
- Methods to postprocess results including determining the ultimate limit state (ULS) and fatigue limit state (FLS) load levels
- Additional elements that overlap between design control, certification, conformity assessment, alternatives to aeroelastic modeling, and verification and validation.

The design load basis provides the basis for the structural design of a wind turbine's rotor nacelle assembly and tower and, based on the safety class (International Electrotechnical Commission [IEC] 2019), describes the methods and parameters applied to the loads analysis and its postprocessing for assessing the structural limit states. It contains the key environmental parameters used in the aeroelastic modeling simulations, a description of the numerical model, the load case table, and an interpretation of how the final load level is determined. Together with the parent design basis, the design load basis is a live document, which can be updated during the project to guide the conceptual through detail design phases and possibly operations and maintenance (O&M).

This report only covers the key structural components and does not address all the aspects that may be covered by a more thorough design load basis. This limitation is primarily driven by the fact that the main design and certification standards for the United States (American Clean Power [ACP] 2021; IEC 2013) allow for simplifying or deferring the associated requirements.

Although no specific prescription exists for a design load basis document, this report provides guidance for both the design and certification of a distributed wind turbine. To help create a template design load basis, the authors provide examples of the various design load basis sections based on a downwind HAWT that was recently developed.

One of the main contributions of this report is the detailed description of the inputs and parameters that are needed for the various design load case setups, including a detailed load case table and the details of fault simulations, which are required components of the design load basis in pursuit of certification.

This report also discusses in detail the handling of ULS and FLS verification, which is largely missing or vague in the main reference design standard (IEC 2013). In particular, a rigorous but practical framework for the lifetime fatigue analysis is offered with step-by-step guidance on the postprocessing of the aeroelastic modeling results from multiple numerical realizations and different design load cases.

Other items that complement the design load basis related to design and type certification are also discussed, among which are the design procedure, design control management, and verification and validation. Understanding, documenting, and systematically controlling the design steps not only creates a roadmap for the product development, but can be required by the certification body for conformity assessment and certification in addition to the design load basis and design reports. Finally, the design load basis can support verification and validation activities to augment and quantify confidence in the aeroelastic modeling results.

The conclusion provides next steps in this research work, which include the process of creating packages (design load basis and load reports) for reference wind turbines.

The recommendations outlined in this study aim to enhance the value and user-friendliness of aeroelastic modeling. By implementing these suggestions, the industry can effectively leverage this currently underutilized tool, leading to improved design efficiency, simplified certification, and the production of high-quality wind turbine products that are widely accessible, certifiable, and dependable.

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1 Introduction

Aeroelastic modeling is the primary methodology for assessing structural loading and performance of any wind turbine, thereby providing an understanding of the impact of design parameters on its loading and power performance before witnessing it in the field. Despite these advantages, the use of aeroelastic modeling in the distributed wind energy technology sector is limited, especially for less-established manufacturers. As highlighted in Damiani and Davis (2022), several challenges impede broader adoption. These challenges include the complexity of generating Campbell diagrams for analyzing resonances and aeroelastic instabilities of wind turbine systems, lack of aeroelastic codes for vertical-axis wind turbines (VAWTs), lack of capabilities in the current codes to correctly simulate yaw dynamics of passively yawing turbines, and a lack of verification and validation (V&V) data. An additional significant need lies in the perceived complexity of generating a proper set of numerical simulations to extract and process the key outputs for component design and verification, and, ultimately, achieve certification. The associated uncertainties in the needed V&V strategy can reduce confidence in reliably predicting the structural and performance response of small wind turbines.

This technical report is the tenth deliverable in a series of research and development efforts conducted by RRD Engineering, LLC (RRD) within the National Renewable Energy Laboratory's (NREL's) Distributed-wind Aeroelastic Modeling (dWAM) project.

NREL contracted RRD for support and guidance on the use of aero-servo-elastic codes (e.g., OpenFAST) for the distributed wind energy sector. In particular, RRD was tasked with identifying the strengths and weaknesses of current standards (e.g., IEC 61400-2 IEC 2013), supporting the augmentation of aeroelastic tools, and developing a plan to exercise and validate specific wind turbine aeroelastic models, thereby improving aeroelastic modeling codes, tools, and user experience to increase the adoption of these simulation tools in the distributed wind industry. The goal is to assist NREL in devising, developing, and implementing a research methodology aimed at enhancing national and international standards for the advancement of distributed wind energy technology.

These deliverables address several of the research priorities and objectives identified in Damiani and Davis (2022) for the aeroelastic code advancement in the distributed wind community. Among the other challenges listed in Damiani and Davis (2022) is the difficulty, which is perceived by many stakeholders, of interpreting and adhering to the design standards' aeroelastic modeling prescriptions. For example, uncertainties exist on the number and input variation types of numerical realizations needed for fault cases, or on how to properly simulate drivetrain and rotor imbalances. Overspeed is perceived as a "lurking" threat for distributed wind turbines, yet there is wavering confidence in both the capability of aeroelastic modeling to capture overspeed worst-case loading scenarios and in the standard's guidance for fault cases that may lead to them. More advice on selecting critical vs. non-design-driving load cases is also needed, and when faced with a new configuration, it becomes essential. The scope of the output channels that should be monitored and investigated is also somewhat ambiguous. Uncertainties also lie in the necessary postprocessing of the aeroelastic modeling results, and how to handle both ultimate and fatigue limit state (ULS and FLS) verifications.

Overall, from the investigation conducted in Damiani and Davis (2022), it is apparent that many believe that a comprehensive guide for developing a design load basis for distributed wind turbines, similar to the one by Hansen, Thomsen, Natarajan, and Barlas (2015), is necessary.

In this document, we provide basic guidance that could be used to supplement the American Clean Power (ACP) 101 (ACP 2021) and International Electrotechnical Commission (IEC) 61400-2 (IEC 2013) design standards for setting up and processing design load cases (DLCs) via aero-servo-elastic modeling. The document can also be used as a reference for V&V efforts associated with developing new aeroelastic modeling capabilities in OpenFAST (RRD Engineering, LLC 2023d), and to generate template load and performance reports and aeroelastic modeling tutorials that can be used for certifying new wind turbines based on reference turbine models (RRD Engineering, LLC 2024a, 2023f, 2024b). Refer to Spossey (2024) for guidance on the certification process for distributed wind turbines, the IEC System for Certification to Standards Relating to Equipment for Use in Renewable Energy Applications (IECRE) OD-501 series and OD-554 operational documents, and the Independent System Operator (ISO)/IEC 17000 standard (IECRE 2022, 2024, 2021; ISO 2020) for the complete definition and list of requirements for design, component, type, and project certification schemes, and the related conformity assessments.

Significant effort and documentation go into a certification package, and many of its elements are not considered here; for example, electrical loads and associated documentation, as well as the type testing. Additionally, because attention is primarily placed on ACP certification.

The remainder of this document is structured as follows. Section 2 gives an overview of the role of the design basis and design load basis within the design and certification activities. Section 3 offers the actual guidance for issuing a design load basis document for a typical distributed wind horizontal-axis wind turbine (HAWT). Additional considerations that overlap the certification and V&V efforts are discussed in Section 4. A few final remarks are presented in Section 5.

2 The Role of the Design Basis and Design Load Basis

The design basis document provides the safety levels, boundaries of applicability, parameters, key assumptions, methods, principles, and constraints used for the design and certification of a wind turbine or wind power plant (see also IECRE [2021]). It also contains the environmental conditions, performance criteria, material requirements, standards, and code hierarchy to be followed in the various phases of design. The list of standards may include those for the certification process (IECRE 2022, 2024, 2021), component design, quality and design control (GL and ISO [2015]), performance, interaction with the electrical network (Underwriters Laboratories [UL] 2023, 2024, 2022), and specific verification items (e.g., fatigue treatment of the welds [International Institute of Welding 2008; British Standard Institution 2005]).

The design basis must also provide at least an overview of the control and protection system strategy, as well as foundation interface specifications (e.g., the acceptable foundation stiffness values). Component purchase specifications and quality control procedures, transportation requirements, installation and commissioning procedures and checklists (e.g., interface points, tooling, and safety measures), and maintenance processes (e.g., inspection and tooling) should also be described or reference the relevant documentation and standards provided. Personnel safety instructions and references to appropriate manuals and other pertinent documents should also be included. The design report usually contains a design failure mode and effect analysis (DFMEA), in which different faults that can occur are listed including their causes, detection, and prevention methodologies. The design basis may provide a general overview (e.g., providing a list of components to be assessed for faults, fault severity ratings, and frequencies of occurrence) of what will be delivered as far as fault analysis in the design report. More information on the monitoring sensors and de-rating, protection, or shutdown mechanisms can be found in those documents.

For larger deployment projects, the design basis can comprise multiple documents, identifying environmental conditions (e.g., meteorological ocean conditions for nearshore and offshore plants), soil conditions, load calculations, installation, operation, and decommissioning requirements. Note that it is not a structural design report or a certification report per se, but, as the name implies, a guide to achieve permitting and certification. As such, the design basis is alive document that can be updated during the project to guide the conceptual through detail design phases and possibly operations and maintenance (O&M). Examples of later project phases addressed in the design basis are assembly torque instructions for bolted connections, inspection scope and frequency, crane setup and approach to wind turbine component replacement, and associated accidental load calculations due to unexpected impacts.

Particularly in the distributed wind energy industry, where multiple variants of the same turbine (e.g., marine vs. telecommunication version, 50 hertz [Hz] vs. 60 Hz) may be developed simultaneously, the design basis may include multiple wind turbine versions to be analyzed.

A type certification (IEC 2010; IECRE 2022, 2021) is a comprehensive process that requires a thorough evaluation of the design basis as well as the design itself, in addition to other key aspects such as manufacturing and testing. The purpose of type certification is to ensure that a specific type of product, such as a wind turbine, conforms to predefined standards. In many cases, a single conformity statement can be issued to cover both the evaluation of the design basis and the design, which simplifies the documentation and certification process. In a broader sense, certification extends beyond evaluating just the design or design basis. It can encompass various aspects of compliance, such as quality management systems (e.g., ISO 9001), safety protocols, or environmental management (e.g., ISO 14001). Although type certification is specifically focused on ensuring that a particular product type meets technical and performance standards, general certification may involve a wider range of factors, covering additional elements of an organization's processes or systems.

The U.S. Department of Energy defines a design basis as "Information which identifies the specific functions to be performed by a structure, system, or component of a facility, and the specific values or range of values chosen for controlling parameters as reference bounds of design. These values may be (1) restraints derived from generally accepted "state of the art" practices for achieving functional goals, or (2) requirements derived from analyses (based on calculations and/or experiments) of the effects of a postulated accident for which a structure, system, or component must meet its functional goals." (Code of Federal Regulations 2024).

In summary, the design basis frames a project and its entire life cycle within environmental, regulation, engineering, and safety bounds. Within it, technical guidance is provided to calculate loads in the various limit states (e.g., ultimate, fatigue, service, and accidental limit states). We refer to this "child document" of the design basis as the design load basis.

2.1 Scope of the Design Load Basis

The design load basis contains specific details that relate to the load calculations and possibly the structural verification of distributed wind turbine components (e.g., blades, hub, shaft, mainframe, tower). Note that, similarly to the structural analysis, a subdocument to address the electrical components (e.g., generator, slip ring, transformer, inverter, batteries, lightning protection) may be generated depending on the complexity of the machine and the requests of the certification body.

The design load basis document can guide the design process and verification of load calculations via load testing, but also support the assessment of the wind turbine site-suitability of a design for a specific site and therefore the certification of a specific wind turbine installation (this is called "project certification" within IECRE). The latter is more frequently applied when new hub heights are sought and therefore new tower models are developed and installed.

In the simplest settings, the design load basis refers to the appropriate design standards [e.g., (IEC 2013, 2019; DNV 2024)]. In general, however, coordinate systems are defined, and units, sign conventions, and symbols are identified for the reporting of the loads, and the loads analysis methodology is discussed (e.g., the aeroelastic model to be used or any other method that would be acceptable by the certifying agent). Furthermore, the exposure and safety class (DNV 2024; IEC 2019) are stated together with the limit states of interest and the associated probabilities of load exceedance. It is also common practice to identify the lifetime of the wind turbine and to state how binning of the fatigue loads and load extrapolations are computed and processed.

In some cases, the turbine configurations and design specifics may require clear instructions on what DLC may apply, details on how to handle faults, as well as the range of wind speeds to be considered for the specific class and design, load partial safety factors (PSFs), material PSFs, and so on. It is worth emphasizing that the design basis and design load basis should address aspects of safety, in particular, the designers should have a clear understanding of the safety class for their wind turbine and have it vetted by the certification body, as that determines any potential deviations on standards' PSFs or DLCs to be applicable. Safety requirements may be determined by local regulations on a project-specific basis.

Although there is no rigid prescription for a design load basis, it is customary to agree on an outline with the parties involved (e.g., certification body, permitting authority, engineering of record) to pave the way to certification or guarantee approvals for deployment. As mentioned earlier, the dynamic nature of the design basis allows for updates and modifications to the design load basis as the project progresses. IECRE (2024) provides clear indications on the design basis evaluation and minimum requirements on the design basis documentation that include components that are more relevant to the load calculation. In particular, IECRE (2024) states that the combined information given in the design basis and design documentation enables the certification body to perform an independent evaluation of loads and DLCs within the design evaluation. That statement can help decide what must be included in the design load basis (subdocument of the design basis).

A list of typical components of a design load basis is provided in Table 1

Table 1. List of Typical Components of a Design Load Basis

Component	Description
Project description	A succinct description of the goals of the project and specifications of the product and geographical/environmental settings as applicable
Purpose of the document	Scope of the design load basis, including parties involved and respective responsibilities (e.g., original equipment manufacturer responsibility, professional engineer responsibility, certification body responsibility)
Standards of reference	Design standards and all regulatory material that should be addressed and/or referenced in the design process and the final design report to be used for assessing the project, including certification and/or deployment and installation
System of units	• International System of Units (SI) • Imperial
Coordinate systems and conventions	• Global and component-local reference frame • Sign convention for rotations, actions, and reactions
Design procedure	• Design process and design control (Independent System Operator 2015) • Design iterations
Numerical model description	• Software • Discretization of the components • Soil/foundation • Damping • Aerodynamic assumptions • Controller specifics • Rotor-nacelle-assembly specifics
Environmental conditions	Wind distribution and key design parameters (e.g., as found in Annex A of International Electrotechnical Commission [IEC] 61400-1 or Annex B of IEC 61400-2)
Load case table	• Matrix of design load cases (DLCs) including key environmental conditions (e.g., mean wind speed, configuration parameters (e.g., yaw errors), number of seeds, duration of simulations, load partial safety factors (PSFs)

Component	Description
Load levels assessment and analysis method	• Limit states, probabilities of exceedance, and PSFs • Stochastic DLCs • Deterministic DLCs • Isolated events • Boundary conditions and influence of adjacent components • Service limit state(s) methods and postprocessing • Ultimate limit state(s) averaging and postprocessing • Damage equivalent loads and fatigue limit state methods • Material requirements and PSFs • Permissible stresses
Reporting requirements	Required documentation
Third-party requirements, certification requirements, and so on	Required documentation

A design load basis that follows the current design standards can help achieve a conformity evaluation within the certification process besides offering guidance in the design of a new wind turbine. Furthermore, the use of a full design load basis can improve and increase the feedback from the end user (turbine original equipment manufacturer [OEM]) to the international design standard committees.

In the utility-scale sector, the design load basis is part of the package that includes the design basis and the design report that must be evaluated under the design evaluation for (type) certification. Whereas IECRE (2022) contains a checklist for needed documentation, the engineer in charge of certification should consult with the certification body to validate the list. For distributed wind turbines, this checklist may be a lesser requirement, and IECRE provides dedicated guidance in OD-554 (IECRE 2021), though this should be verified with the certification body.

2.2 How To Use the Remainder of This Guide

The remainder of this document is structured as a template. The various sections provide both a discussion of what each should contain and an example of design load basis elements for a downwind turbine with passive yaw. The text containing the example turbine design load basis is italicized. It is important to note that the example wind turbine uses guidance from both the IEC 61400-1 and IEC 61400-2 standards, as it falls below the 150-kW threshold but has a rotor swept area exceeding 200 square meters (m^2). The inclusion of IEC 61400-1 guidance is conservative and should result in a more robust design, offering enhanced safety and reliability for a wind turbine of this size.

This guide aids the aeroelastic modeling user in creating a document that would direct the loads analysis methodology and yield a procedure to assess the final design load levels for the various turbine components. The guide can also be used to produce a document in support of certification; however, the presented tables, symbols, and graphics are examples of what could be used in a design load basis, but are not to be interpreted as prescriptive. The design standards and the interpretation by the certification body, in fact, will always take precedence when pursuing certification.

We emphasize that the underlying assumption of this design load basis document is that it is for the aeroelastic modeling (no simplified loads method or direct load measurement) of a three-bladed HAWT and for evaluating its strength and safety. IECRE (2021) can be used as a guide for assessing type certification conformity.

3 Design Load Basis for a Typical Horizontal-Axis Wind Turbine

3.1 Project Description

In this section, general specifications, safety class, and characteristics of the wind turbine that are relevant to the loads analysis should be provided. Alternatively, these details and additional information on the turbine system may be contained in the design basis and therefore a reference to the pertinent section of the design basis should be made in that case. This is also a good place for a general introduction to the contents of the design load basis, and to address, at a high level, any deviations from the general design standards and guidelines.

This design load basis comprises the basis for the structural design (and code checks) of the key component of the turbine (rotor nacelle assembly and tower) and describes the method behind the loads analysis and output data postprocessing for assessing the structural limit states. No special safety class is foreseen for this project, and the design load cases in International Electrotechnical Commission (IEC) 61400-2 IEC (2013) will be applied with slight modifications (per IEC 61400-1 IEC [2019] to account for turbulent realizations and fault events as discussed in subsequent sections. The design load basis contains the key environmental parameters used in the aeroelastic modeling simulations, a description of the numerical model, the load case table, and an interpretation of how the final design loads are determined. Note that foundation stiffness requirements are also provided, but no assessment of foundation loads is performed. The wind turbine generator (WTG) design is to be performed according to state-of-the-art methods and interpretations of the governing standards, rules, and guidelines indicated in the design basis and as needed in the design load basis sections.

3.1.1 Wind Turbine Generator Description

Recommended items to be covered by the wind turbine description include the following:

- Drawings with key dimensions of the components
- Mass schedule
- Blade chord, thickness, and twist distributions
- Airfoil shapes and polars
- Details of the drivetrain, electrical system, one-line diagrams, and characteristic quantities of the generators that are important for the dynamic response of the wind turbine
- A discussion of the control philosophy and mechanics (e.g., pitch, furling, mechanical brakes)
- Reference to controller documentation and version
- A description of the vibration-dampening device, if applicable, including tower-tuned mass dampers or active dampers
- A resonance diagram (Campbell diagram) (see Section 3.4.5)
- Reference to documents for transportation and installation or a description of fixtures and processes together with acceptable wind speeds for installation and accelerations for transport.

The wind turbine is the WTG 22-60, a downwind, three-bladed HAWT (Figure 2) based on an induction generator and a redundant full-span pitch overspeed protection system. The power regulation occurs through aerodynamic stall of the rotor blades. A mechanical brake is present on the high-speed shaft, but it is only used to keep the rotor from spinning in parked conditions and after a shutdown once the turbine starts idling. The key information for the turbine is given in Table 2 and the power curve is shown in Figure 1.

Table 2. Turbine Specifications Relevant to the Design Load Basis

Parameter	Value	Unit
Turbine IEC class	II	
Hub height	30	meter (m)
Cut-in wind speed	4	meter per second (m/s)
Cut-out wind speed	24	m/s
Rated wind speed	11	m/s
Rated power	60	kilowatts
Power regulation	Stall/pitch	
Rotor diameter	20.1	m
Rotor swept area	317	square meter (m^2)
Rotor rotational speed range	38	revolutions per minute (RPM)
Rotor mass	1,785	kilogram (kg)
Generator mass and center of mass coordinates (CM) in local reference frame	330 (0.4, 0, 0)	kg, m
Gearbox details and mass	Three-stage planetary, 663	kg
Nacelle mass and CM (w.r.t. the tower-top reference frame)	2,202; (0.15, 0.4, 0.04)	kg, m
Rotor nacelle assembly mass	5,035	kg
Rotor nacelle assembly CM (w.r.t. the tower-top reference frame)	(0.502, 0.4, 0.499)	m
Rotor nacelle assembly Ixx, Iyy, Izz (w.r.t. CM)	14,454; 12,430; 11,410	$kg*m^2$
Protection strategy	Full-span pitch to stall and mechanical brake	
High-speed-shaft mechanical brake max torque	1,100	N*m
Design lifetime	20	year
Installation period	1	week

Parameter	Value	Unit
Foundation	Concrete spread footing or pier foundation	
Tower length and outer diameter at base	29.7/1.5	m
1p acceptable range	<RPM/60%–5% >RPM/60%+5%	hertz (Hz)
3p acceptable range		Hz

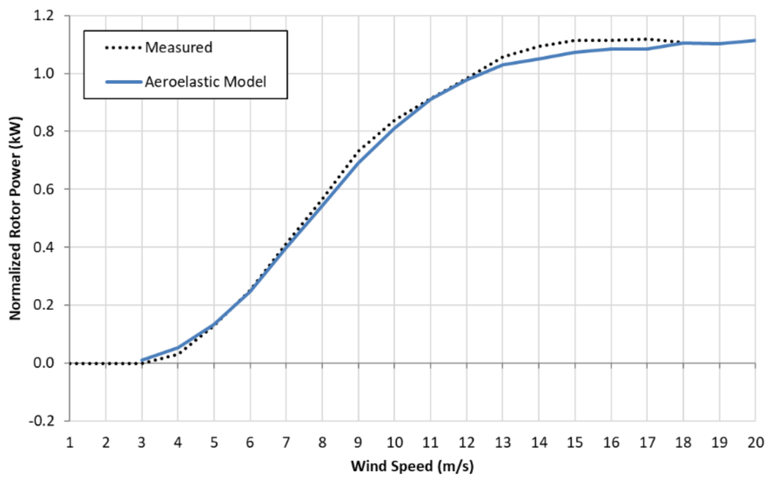

Figure 1. Calculated power curve from modeling.

Note: kW = kilowatts, m/s = meters per second.

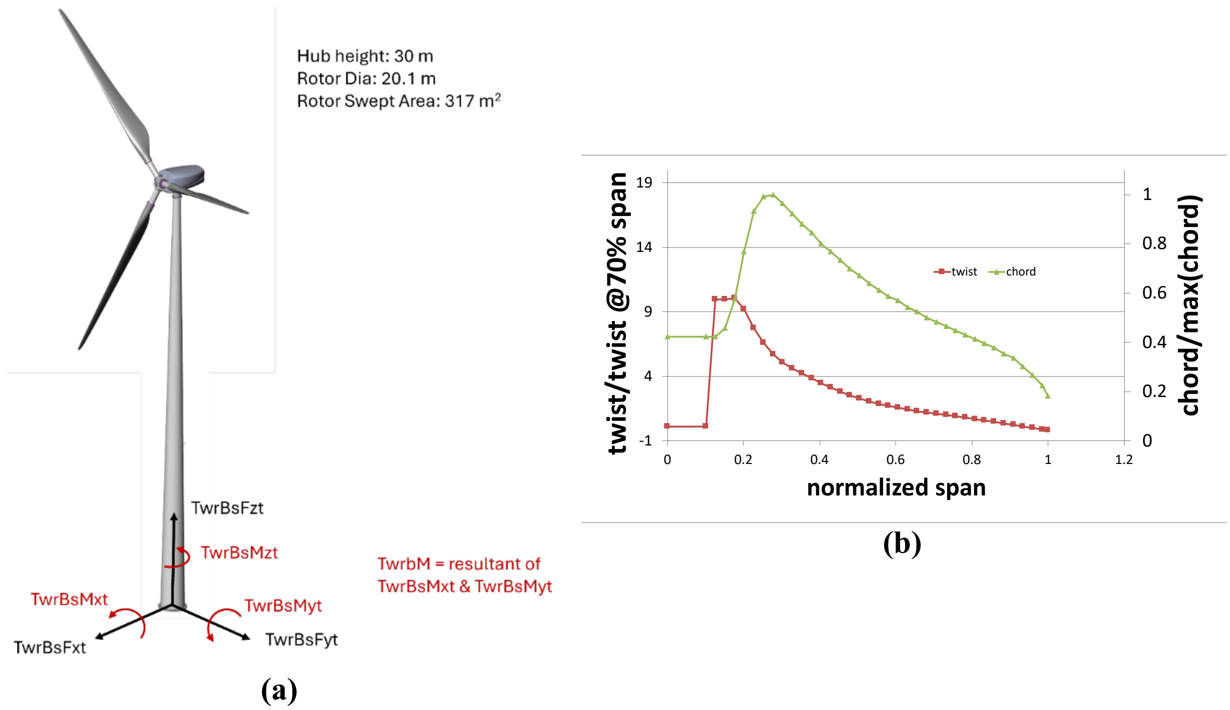

Figure 2. Rendering of the WTG 22-60 with key dimensions (a); twist and chord distribution (b).

Note: m = meters, m^2 = square meters

The blades are transported in a container within a specifically designed rack. The not-to-exceed accelerations are 3g[1] in all axes. The nacelle is transported in shrink wrap on a flatbed truck. The not-to-exceed accelerations are 3g in all axes. Blades are mounted with the help of a local crane after tower erection and nacelle mounting. For the installation, the maximum allowable wind speed is 6 m/s (13.4 miles per hour). More details on transportation and installation are provided in the "Transportation and Installation (T&I) manual.

3.1.2 References to Codes and Standards Specific for Loads Analysis

This section provides references to design and certification codes and standards that may have specific relevance for the aeroelastic modeling of the wind turbine, the assumptions made, and the verification of its components. These standards might have been mentioned in the parent design basis document, in which case explicit reference to the relevant design basis sections may be provided.

- *ACP 101 (ACP 2021): for general instructions on which components to evaluate for strength and safety (the blade, blade-to-hub connection, hub, main shaft, bearings, yaw shaft, connection to the tower, critical safety/protection systems and components, and nacelle mainframe). Furthermore, this standard provides indications on how to handle the tower coupling to the wind turbine and its design.*

[1] 1g = 9.81 m/s^2

- *IEC 61400-1 (IEC 2019), IEC 61400-2 (IEC 2013): for prescriptions in terms of design load cases, PSFs, and aeroelastic modeling requirements.*
- *EN1993-1-9 (European Committee for Standardization 2005): for weld details and fatigue verification.*
- *"Guidelines for the certification of wind turbines" (DNV-GL 2010) for material properties for welded steel (Q345E, A572), alloy steel (4340,4140, 34CrNiMo6,42CrMo6), glass-fiber-reinforced plastic, and adhesives.*
- *ISO 90001 (ISO 2015): for a general quality management system.*
- *IEC 61400-4 (ISO 2012): for gearbox design requirements.*
- *ISO 76 and 281 (ISO 2006, 2007): for roller bearings.*
- *ISO 3010 (ISO 2017): for seismic actions.*

3.1.3 Coordinate Systems

Coordinate systems, symbols, and sign conventions to be employed in the design and verification documents, specifically those that are used for the output of aeroelastic modeling channels, should be indicated in this section. The IEC 61400 standard series provides general reference frames (e.g., inertial, tower, shaft) that are internationally adopted by the industry and therefore should be employed to the maximum extent possible. However, different software and in-house conventions may require modifications to the IEC coordinate systems.

The system of units used in this design load basis is the SI system of units unless stated otherwise (e.g., kg, m, s, N).

Reference is made to the IEC main coordinate system and conventions (Section 4.3 [IEC 2013]) used throughout the design documents. For site-specific applications, reference to an earth-based coordinate system is made to assess tower fatigue loads.

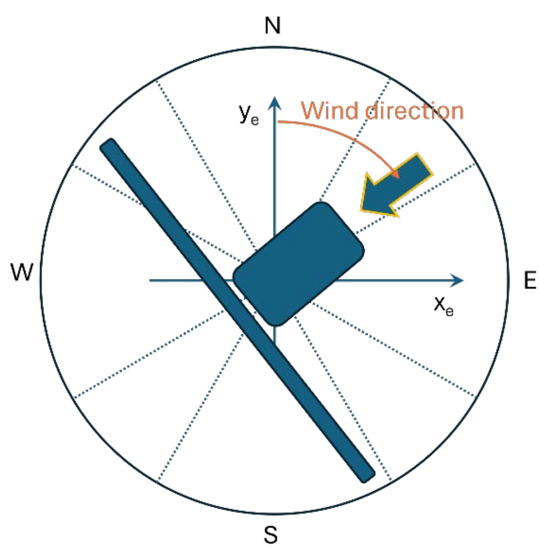

Figure 3. Earth-fixed reference frame for tower fatigue load assessments in site-specific calculations

Additionally, Figure 4 shows the nomenclature for force and moment channels and their orientation for both the blade root and blade extender. Furthermore, the nomenclature to be used in the design and verification of the components is given in Table 3.

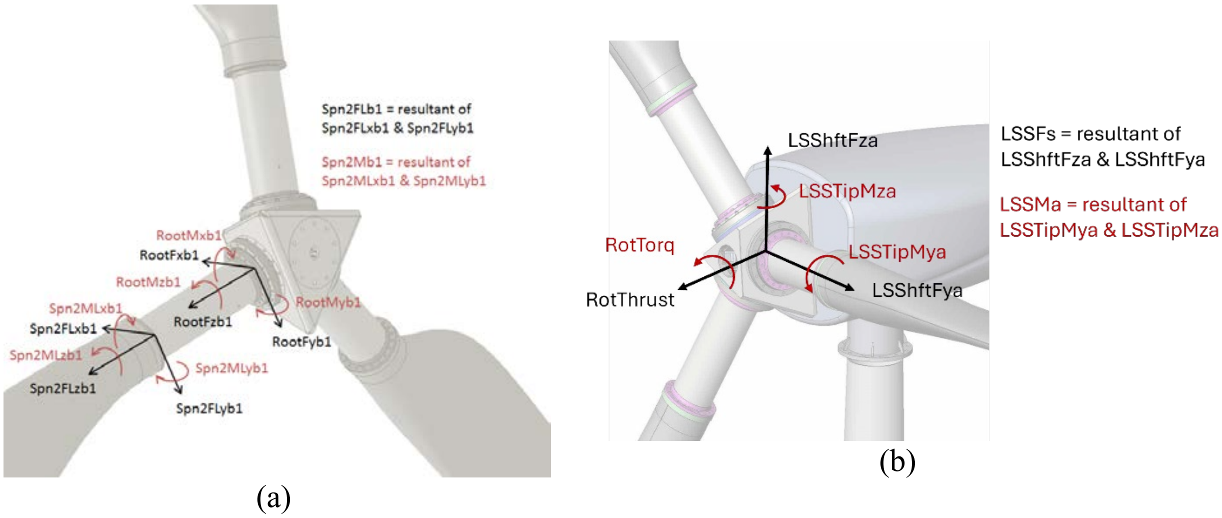

Figure 4. (a) Extended-blade root and extender root force and moment channels and orientation (both pitching with the blade). Spn2 denotes the location of the computational node 2 along the extended blade, which is set at the physical blade root. Therefore, Spn2FLxb1[-yb1,-zb1] and Spn2MLxb1[-yb1,-zb1] indicate loads at the root of the blade in the extended configuration to be compared with the baseline blade root loads. (b) Shaft forces and moment channels used for the shaft verification.

Table 3. Symbols Used for the Key Load Channels for Design and Verification

Symbol	Meaning
OoPDefl1-3	Tip out-of-plane deflection of blades 1–3
IPDefl1-3	Tip in-plane deflection of blades 1–3
TipClrnc1-3	Distance between blade tip and tower axis for blades 1–3
YawBrTDxt	Fore-aft deflection at tower top
YawBrTDyt	Side-side deflection at tower top
RotThrust, RotTorq	Rotor thrust and torque
RootM1–3	Blade-root bending moment resultant for blades 1–3
RootFxb1-zb1	Blade-1 root shear and axial loads
RootMxb1-zb1	Blade-1 root bending and torsional moments
YawBrFxp-zp	Fore-aft, side-side shear, and axial force at the tower top
YawBrMxp-zp	Side-side bending, fore-aft bending, and torsional moment at tower top
YawBrMxn-zn	Side-side bending, fore-aft bending, and torsional moment at tower top in a reference frame yawing with the nacelle
RotThrust, LSShftFya-za	Forces on the shaft in a reference frame rotating with the shaft
RotTorq, LSSTipMya-za	Moments on the shaft in a reference frame rotating with the shaft
TwrBsFx-zt	Fore-aft, side-side shear, and axial force at the tower base
TwrBsMx-zt	Side-side bending, fore-aft bending, and torsional moment at the tower base

3.1.4 Control System and Protection System and Faults

This section provides an overview of the power regulation strategy, the main actuation, and the main protection system of the wind turbine. Furthermore, the faults that will be considered in the loads analysis and aeroelastic simulations should be listed. Diagrams may simplify the understanding of the various modes of operation and the setup of simulations with faults. A description of the condition and remote monitoring and inspection program can help justify why certain choices in the simulations were made.

The wind turbine uses aerodynamic stall as a form of power regulation. The protection system comprises a full-span, independent blade pitch-to-stall, and a mechanical brake. The independent pitch system brakes the rotor to an idle (<5 RPM) under either high winds (above cut-out), a grid fault or any other fault condition that may otherwise trigger an overspeed, or a manual shutdown. The mechanical brake engages once the rotor is at idle.

Yaw is passively controlled, and yaw motion is limited by a yaw damper, therefore no explicit yaw-error case will be simulated.

The faults in the control system will include a stuck pitch actuator and leaving one blade at the fine pitch (run configuration).

Other faults that will be simulated are:

- *A drop in the grid connection*
- *A generator short circuit; because of the induction nature of the generator, this fault results in the same effect as a grid connection failure.*

Because the mechanical brake has the function of keeping the rotor parked for maintenance, and during high-wind events when the blades have already pitched to stall, a failure in the mechanical brake is not simulated. The machine has sensors that monitor the positions of the actuators; if a fault is recorded, the turbine will not be allowed to restart after a stop. The mechanical brake is normally applied, therefore following an electrical grid drop would remain applied. The brake pads are designed to last the life of the wind turbine, but the biannual inspection would guarantee their integrity. The yaw system is passive and therefore considered fail-safe.

3.2 Environmental Conditions, Turbine Class, Lifetime

This section describes any variations from the standard wind turbine class and/or compliance with design standards requirements. It should also indicate the expected lifetime of the turbine and whether periods without the rotor nacelle assembly (during installation) are foreseen for tower fatigue calculation purposes, although this may not be within the scope of the certification. Additionally, a description of the assumed wind speed distribution (e.g., Weibull scale (A) and shape parameters (κ)) and extreme wind speeds at return periods of 1 and 50 years should be provided.

Special attention should be given to turbines that will be certified for colder climates, where icing can cause a rotor mass imbalance, or marine environments or seismic regions. In some situations, additional special parameters should be provided for special classes (class S), (e.g., for a cold climate environment, a minimum of 30 millimeters of ice accretion with a density of 900 kg/cubic meter (m^3) (IEC 2010) on all exposed surfaces of the wind turbine and support structure must be considered and the associated drag should be accounted for in extreme events by considering extreme wind speeds of $3*v_{ave}$. Parameters for normal and extreme electrical conditions are described in the standards (IEC 2013) for both battery-charging and grid-connected wind turbines.

Finally, for calculating fatigue in elements like the tower or foundation, the probability distribution of wind direction should be provided.

This wind turbine was designed for lower wind speed sites, and an IEC 61400-2 Class II IEC (2013) *was selected with TI15=20% per* ACP (2021)*. The wind profile's power law exponent is set at 0.2. The Weibull's parameters are reduced to a simpler Rayleigh per* IEC (2013)*, and the wind direction probability distribution is shown in* Table 4 *and* Figure 5.

Table 4. The Wind Direction Probability Density Function Used for Fatigue Calculations

Sector Bin Center [°]	Sector Range [°]	Probability [%]
0	345–15	9.30
30	15-45	10.00
60	45–75	7.10
90	75-105	4.60
120	105–135	3.80
150	135-165	5.30
180	165–195	10.20
210	195-225	15.50
240	225–255	10.60
270	255-285	5.70
300	285–315	7.70
330	315-345	10.20

The wind turbine's cut-in to cut-out range is indicated in Section 3.1. Because of the passive yaw nature of the wind turbine, no yaw offset (error) is simulated. Wind velocity inclinations of 0° and +8° are simulated. Other environmental parameters are shown in Table 5.

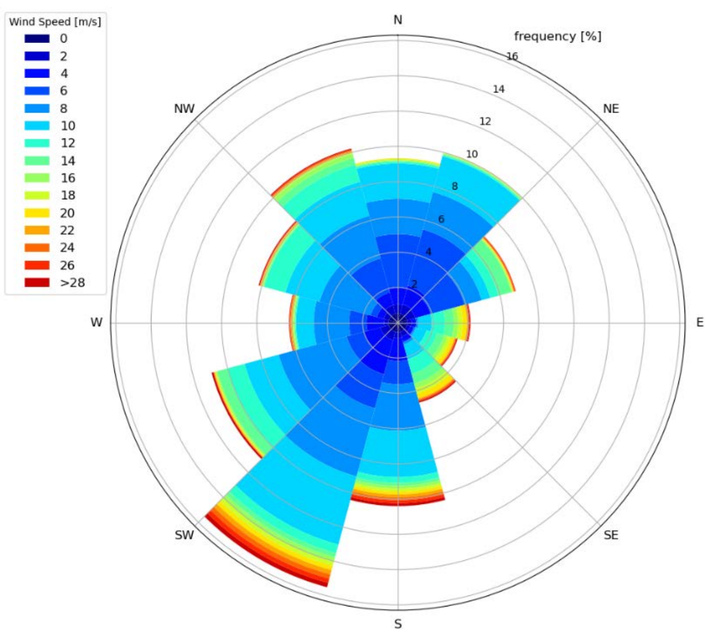

Figure 5. The wind direction probability density function used for fatigue calculations

Table 5. Assumed Environmental Conditions

Condition	Item (Referenced to Hub Height)	Unit	Value
Operational	Wind climate		IEC 61400-2
	IEC class		IIB
	Air density	kg/m^3	1.225
	Air viscosity	Pascal-second (Pa*s)	1.789×10^{-5}
	Weibull A	m/s	8.5
	Weibull k		2
	a (wind shear exponent)		0.2
	I15 (70% quantile TI at 15 m/s)		0.2
Extreme Wind, Parked Cases	Air density	kg/m^3	1.225
	v_{ref} (50-year [yr] return period 10-minute [min] average wind speed)	m/s	42.5
	v_{1ref} (50-yr return period, 10-min average wind speed)	m/s	34
	v_{e50} (50-yr return period, 3-s gust speed)	m/s	59.5
	v_{e1} (50-yr return period, 3-s gust speed)	m/s	44.625
	a (wind shear exponent)		0.2

Only ambient turbulence is considered (single installation) and the IEC turbulence intensity function with hub-height wind speed is applied following the B class for the normal turbulence model (Figure 6).

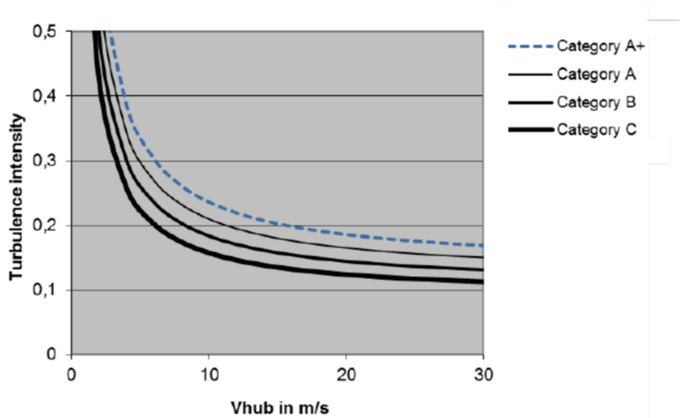

Figure 6. Turbulence intensity as a function of hub-height wind speed. Image from IEC (2019)

For the extreme turbulence model (ETM) turbulence intensity, the prescribed standard deviation for the longitudinal component of wind velocity is used (IEC 2019):

$$\sigma_1 = 2 * I_{ref}\left(0.072 * \left(\frac{V_{ave}}{2} + 3\right) * \left(\frac{V_{hub}}{2} - 4\right) + 10\right) \quad (1)$$

with V_{ave}=0.2*$V_{ref} = 21.25 m/s$ *for Class II.*

The deterministic cases were set by following the prescriptions of IEC (2019) *for Class II (*Figure 7 *and* Table 6*).*

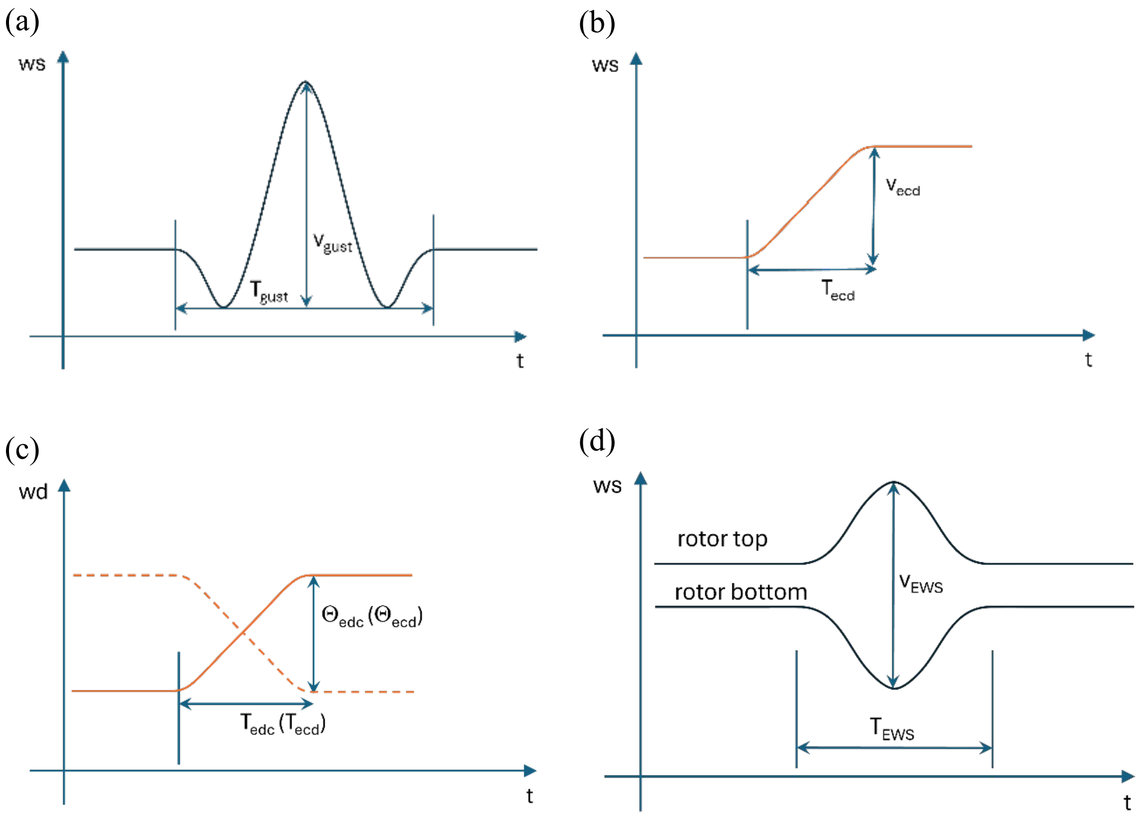

Figure 7. Time profiles of gust speeds (WS) and directions (WD) for deterministic cases: (a) extreme operating gust, (b) extreme coherent gust with direction change [ECD], (c) extreme direction change [EDC], (d) extreme wind shear [EWS]. More details in the list of symbols and IEC (2019, 2013).

Table 6. Extreme Turbulence Model Parameters, and Deterministic DLC Environmental Key Parameters. Symbol Meanings Provided in IEC (2013, 2019).

		ETM	EOG1	EOG50	EDC	ECD	EWS
Wind Speed	s_1	I_{ETM}	v_{gust1}	v_{gust50}	Q_{EDC}	Q_{ECD}	v_{EWS}
3	1.260	1.043	5.482	7.309	1.907	180.000	4.126
4	1.380	0.806	6.004	8.005	1.690	180.000	4.281
5	1.500	0.664	6.526	8.701	1.542	144.000	4.436
6	1.620	0.569	7.048	9.397	1.435	120.000	4.591
7	1.740	0.501	7.570	10.093	1.354	102.857	4.745
8	1.860	0.450	8.092	10.789	1.290	90.000	4.900
9	1.980	0.410	8.614	11.485	1.239	80.000	5.055
10	2.100	0.379	9.136	12.182	1.196	72.000	5.210
11	2.220	0.353	9.658	12.878	1.161	65.455	5.365
12	2.340	0.331	10.180	13.574	1.131	60.000	5.520
13	2.460	0.313	10.702	14.270	1.105	55.385	5.674
14	2.580	0.297	11.224	14.966	1.083	51.429	5.829
15	2.700	0.284	11.747	15.662	1.063	48.000	5.984
16	2.820	0.272	12.269	16.358	1.046	45.000	6.139
17	2.940	0.262	12.791	17.054	1.030	42.353	6.294
18	3.060	0.252	13.313	17.750	1.017	40.000	6.449
19	3.180	0.244	13.835	18.446	1.004	37.895	6.604
20	3.300	0.236	14.357	19.142	0.993	36.000	6.758
21	3.420	0.230	14.879	19.839	0.982	34.286	6.913
22	3.540	0.223	15.401	20.535	0.973	32.727	7.068
23	3.660	0.218	15.923	21.231	0.964	31.304	7.223
24	3.780	0.213	16.445	21.927	0.957	30.000	7.378
25	3.900	0.208	16.967	22.623	0.949	28.800	7.533

No ice loading is considered for this wind turbine.

3.3 Design Load Cases and Aeroelastic Modeling Setup

The DLCs should follow those requested for analysis in the standards of reference. Here, IEC 61400-2 (IEC 2013) (small wind turbines) is assumed to be the standard of record for DLCs, but extensions to -1 may be provided as needed.

In the general setup of the aeroelastic modeling simulations, at a minimum, the following items should be discussed:

- The mass schedule and structural parameters if differences between measurements and the model exist. In particular, the mass and inertia of the nacelle (drivetrain and bedplate) should be as close as possible to the as-built ones. The same applies to the tower.
- The wind speed range for normal operation, including:

    - Typical cut-in to cut-out range (e.g., 4:2:26 m/s to indicate simulations with mean wind speeds of 4 to 26 m/s with 2 m/s bins)
    - Modified wind-speed range if the turbine can operate in power boost or high-wind ride-through modes; these modes should be indicated together with the resolution in the wind speed array.

- Basic wind shear for the mean wind speed profile (e.g., $\alpha = 0.2$ for certification to IEC 61400-2)
- Wind direction management. In cases where the support structure is not axial-symmetric, the wind direction is important because the stresses and strains in the support structure will vary due to diverse moments of inertia along different axes. Note that this accounting of the wind direction is in addition to the handling of the yaw errors.
- Air density used for normal power production cases and parked or idling extreme wind events (e.g., $\rho_{air} = 1.225$ kg/m3)
- Rotor mass and pitch imbalance
    - Typically, the aerodynamic imbalance can be achieved by modifying the fine pitch of two of the three blades by +/-0.5°. Alternatively, the twist of two blades can be modified by the same amount. Other values can be negotiated with the certification body based on evidence provided by the OEM. It is important to specify what the expected pitch setting (fine pitch) is in the absence of any imbalance.
    - The rotor mass imbalance is achieved by modifying the total mass of two of the three blades (e.g., by -0.2 – +0.5% of the total blade mass). Alternatively, or in conjunction with the mass value modification, the center of mass of the blade along the span can be modified. The details of the mass imbalance are selected by the OEM based on their manufacturing and testing experience and should be approved by the certification body.

- Pitch rates used if applicable (e.g., 5°/s normal operation, 8°/s emergency shutdown)
- Tower verticality tolerance. Specify if the model includes any deviations from verticality, justify the exclusion of these effects in the model calculations if applicable, and explain how the tower verification process addresses this. Note that gravity loads and associated PSFs can be referenced from Section 7.6.2.1 of IEC (2019).
- Yaw misalignment. DLC 1.1 (1.2), 1.3, 1.5, 1.6, and 1.7 require a nominal yaw error based on the expected control system's tracking error. In the absence of OEM-specific data (+-8°) can be used for these DLCs.
- Faults. How the faults mentioned in Section 3.1.4 are modeled in the simulations. For example, how the generator short is simulated with respect to gust profile and rotor azimuth position.
- Seismic response approach. Whereas earthquake-resistance requirements are not present in the IEC standard wind turbine classes, it should be stated whether the effects of ground acceleration, when combined with frequently occurring operational loads, can be neglected to assess the structural integrity of the turbine. Alternatively, in cases where local ordinances require an assessment of the seismic integrity, the

numerical approach to account for the seismic forcing on the turbine response should be described, and the following guidelines could be employed:

  - Ground accelerations with a return period of 475 years (yr)
  - Load PSF of 1.0
  - The calculated seismic loading should be directly added (in the most unfavorable way) to the mean loads from normal operation at rated wind speed (v_r) or emergency shutdown loads at v_r, whichever is larger.
  - Annex D in IEC (2019).

- Treatment of transients. Normally, a segment of the time series resulting from the typical aeroelastic modeling simulation is removed from the analysis to account for transient and computation ramp-ups.
- Control system algorithm or dynamically linked library and associated version, including any specific parameters.
- Damping settings. For example, the structural damping for the tower and blades, and if an external damper is used (e.g., tuned mass damper), how that is incorporated in the model and the version associated with the algorithm and/or dynamically linked library.

Any other assumptions used in the model to approximate the turbine dynamic response (e.g., degrees of freedom enabled or excluded) should be listed in this section, highlighting the known limitations.

The following situations were considered:

- *Power production cases*
- *Power production cases with faults in the generator, in the grid connection, and/or in the pitch braking system*
- *Parked cases. The mechanical brake is engaged in these simulations: DLC 5.1, 5.2, 6.1, 7.1.*
- *Transport*
- *Installation.*

*Standard sea-level atmospheric properties are assumed (ρ_{air} = 1.225 kg/m^3, p_0=101,325Pa, ν_{air} = 1.48*10^{-5} m^2/s) and a wind speed power law profile is employed with α = 0.2. A heavier and a lighter blade mass (+0.5% and -0.5% of the expected typical blade mass) with a fine pitch of -0.5° and -1.5°, respectively. The correct pitch setting is -1° assigned to the blade with the correct mass.*

For the cases when a shutdown occurs, a 10°/s pitch rate is applied consistent with the brake-pitch actuation design and specifications.

Given the limited hub height (<40 m) and the possibility of adjusting the alignment at the tower base through leveling at the anchor bolts and grouting, the expected out-of-verticality is less than 0.5°. No provision is made in the aeroelastic modeling code setup for this maximum tolerance and no adjustment to the postprocessing results is envisioned. For the design of the tower and foundation, however, the effect associated with out-of-verticality will be included, adding the additional gravity load to the unfavorable load (PSF 1.1).

Because the downwind turbine is self-aligning, and because we do not expect any possible failure in the yaw bearing within the prescribed lifetime, yaw error simulations are limited to nominal -8°:0°:+8° from field experience.

The control system faults, discussed in Section 3.1.4, are simulated by considering one blade stuck in the RUN pitch setting during shutdown events and high-wind speed parked cases. The "grid-drop" will be simulated at different instants during an extreme gust event for DLCs simulating extreme operating gust (EOG).

No special provisions are made for seismic loading in this certification round. The wind turbine will be evaluated case by case for deployment in significant seismic loading risk in site suitability assessments.

Stochastic simulations are run for 700 seconds (s), removing the first 100 s from the postprocessing of the data to remove spurious transients.

The control system relies on an induction generator (i.e., a nominal constant generator speed). The protection system acts on the blade pitch when a shutdown is required (e.g., grid fault, generator fault, control fault, or wind speeds exceeding cut-out). These events are simulated as isolated events and no specific control DLL is required for the simulations. Monitoring system details, including setpoints, and types of shutdowns are provided in the design document.

A 1% structural damping at all frequencies is included in the model for both tower and blades based on previous experience and measurements.

The yaw damper constant is set at 144,000 newton meters (Nm)/(rad/s) constant, from a manufacturer's manual, whereas the drivetrain equivalent torsional spring and damping constant are set at 961,930 Nm/rad and 858 Nm/(rad/s), respectively, which were obtained from decay tests conducted in the lab and whose details are provided in the design report.

3.3.1 Dynamic Software Description

This design load basis guidance refers to the aeroelastic modeling of distributed wind turbines, therefore, no extensions for the simplified load method are included. To certify the turbine, the certification body will require that the aeroelastic modeling software be certified or validated by a third party. This section of the design load basis should detail the efforts involved in selecting and accurately operating the software. For example, if a proprietary aeroelastic modeling code is used, a description of the V&V efforts is required. The certification body may indicate the approach to follow if a noncertified code is used to design the turbine components, or if multiple codes are used. For example, they may provide acceptable errors (e.g., 10%) between the output of their standard aeroelastic modeling software and the OEM's proprietary one.

Among the various key parameters for the aeroelastic modeling software to discuss are:

- General structural approach (e.g., modal reduction, finite element model, lumped mass)
- Aerodynamics approach (e.g., blade-element-momentum theory vs. the free-wake vortex method, three-dimensional effects on airfoil aerodynamics, unsteady

aerodynamics, aerodynamic losses treatment, tower shadow) and turbulence handling (e.g., full-field turbulent wind files with a Mann or Kaimal spectrum and respective coherence model functions)

- Number and description of degrees of freedom
- Stiffness, mass, and damping handling in the various components
- Handling of the soil-structure interaction
- Material and/or geometric nonlinearities captured or ignored by the software
- Comparison of test data and analytical solution for canonical cases
- Benchmarking cases.

The standards specify time-series simulations, so no provision is made for the frequency domain approach. If the software used is already approved by the certification body, the description can be limited to mentioning the software version used.

The aeroelastic modeling software used to evaluate loads on the wind turbine is OpenFAST v3.5.3 (https://github.com/OpenFAST/openfast), which is well-known in the industry and regularly maintained and benchmarked against other software programs (e.g., HAWC2, Bladed) already established in the certification process. OpenFAST is a modal-based model that can account for nonlinearities (e.g., centrifugal stiffening associated with rotor blade rotational velocity, and bending in the tower associated with tower-top deflection). The aerodynamics are modeled via a blade-element-momentum theory algorithm, which accounts for wake induction and unsteady aerodynamics and dynamic stall, tower shadow, and tip and hub losses. The airfoil polars were calculated via XFoil (https://web.mit.edu/drela/Public/web/xfoil/) and further modified for rotational augmentation corrections for three-dimensional delayed stall (Du's [Du and Selig 1998] and Eggers' [Eggers, Chaney, and Digumarthi 2003] methods). The airfoil polars are shared with the certification body in the blade design report. Structural damping is included as a fraction of critical for the first two bending modes of the blades and tower, and as damping constants for the drivetrain and yaw mechanism, respectively. The wind files are created based on a Kaimal spectrum and exponential coherence model as given in IEC (2019) via Turbsim. The tower is supposed to be clamped to a rigid foundation; thus, no soil-foundation stiffness effects are accounted for in the calculations. This hypothesis has been validated in field tests that showed negligible effects of the soil characteristics, foundation mass, stiffness, and damping on the measured natural modes of vibration.

3.3.2 Design Load Case Description and Recommended Parameters

Here, a readable description of the prescribed DLCs in IEC (2013) is provided, similar to what was done in Hansen, Thomsen, Natarajan, and Barlas (2015) for the DLCs in IEC (2019).

The aeroelastic modeling end user may use this DLC guide to complement what is in IEC (2013) to set up and process the numerical simulations. Section 3.3.3 presents the load case table, which is what the user must generate to both direct the aeroelastic modeling in support of the design and to incorporate in the design load basis to submit to the certification body together with all the other documents for certification. This section is a guide to generating the appropriate load case table, which will be different depending on machine characteristics, control strategy, and wind turbine class.

The IEC (2013) DLC scope includes normal power production, shutdown, control and grid failures, parked and idling states, and yaw error situations. The goal of the DLCs is to address ultimate limit state(s), serviceability limit state(s) (SLS), and fatigue limit state(s). Wind fields are prescribed as vertically sheared (through a power law) either turbulent or deterministic time series. Full-field turbulence wind files are recommended in situations where IEC (2013) allows for a choice of either deterministic or stochastic wind fields, as the latter renders a more realistic response. Wind fields are based on a mean wind speed at hub height, which is conventionally based on a 10-min average; the frequency of occurrence for a given wind speed follows a Rayleigh distribution per IEC (2013).

IEC (2013) is coarse and unclear when describing some of the DLCs, and in other cases, the choice of wind speeds may be questionable, and multiple options are provided. Here, we propose a conservative set of choices that are valid for (IEC 2013) and would be accepted by a certification body. At times, the more thorough prescriptions from (IEC 2019) are recommended, including the number of realizations with turbulent wind seeds. The OEMs may elect to adhere entirely to IEC (2019) for the choices of DLCs, tweaking environmental parameters (e.g., turbulence intensity) as needed after the certification body's approval.

The nomenclature used in Tables 8 through 22 pertains to IEC (2013) unless otherwise indicated. Indicated wind speeds are hub-height wind speeds, and when stochastic wind fields are used (normal turbulence model), the 10-min mean wind speed is indicated. The tables can be used to set up the DLC simulations and postprocessing for ULS and FLS. Though not explicitly stated, IEC (2013) still requires SLS verification through analyzing critical deflections (in particular, tower and blade tip deflections) to guarantee wind turbine safety. IEC (2013) considers deflection checks as part of ULS verification. For specific situations, it may be appropriate to differentiate between ULS and SLS, with the use of reduced PSFs and therefore probability of load/deflection exceedance. However, in Tables 8 through 22, no specific distinction is made between ULS and SLS.

The typical DLC setup will have as aeroelastic modeling output channels, the loads, accelerations, and deflections pertinent to the structural verification of the various components. They vary depending on the type of machine and software used, but, at a minimum, blade-root bending moments and shears; low-speed shaft torque; tower-top and tower-bottom bending moments; and shears are required.

It is important to note that many users of this document will focus on the design and certification of small wind turbines following the guidelines of IEC (2013) and ACP (2021). However, there are instances where it may be necessary to apply the more stringent DLC guidelines from IEC (2019). This is especially relevant when analyzing turbines with a rated power under 150 kW but with a rotor swept area exceeding 200 m^2. In our example, the turbine has a rotor swept area of 317 m^2 and a rated power of 60 kW, making this consideration applicable.

A summary of the external conditions to be evaluated based on the IEC 61400-1 or -2 standards can be found in Table 7.

Table 7. External Condition Summary From IEC 61400-1 and IEC 61400-2

External Conditions	IEC 61400-1 IEC (2019)	IEC 61400-2 IEC (2013)
Wind turbine class	I, II, III, S	I, II, III, IV, S
I_{ref}	A+ (0.18), A (0.18), B (0.14), C (0.12)	All (0.18)
Normal wind profile model (NWP)	YES	YES
Normal turbulence model (NTM)	YES	YES
Extreme wind speed model (EWM)	YES	YES
Extreme operating gust (EOG)	YES	YES
Extreme turbulence model (ETM)	YES	NO
Extreme direction change (EDC)	YES	YES
Extreme coherent gust (ECG)	NO	YES
Extreme coherent gust with direction change (ECD)	YES	YES
Extreme wind shear (EWS)	YES	NO

Table 8. DLC 1.1a and DLC 1.1b (Normal Power Production)

DLC 1.1a and DLC 1.1b	Normal Power Production
Detailed Description	Simulation of power production throughout the wind power curve envelope with no faults. The turbulence model is indicated by IEC 61400-2 (IEC 2013) and it is common to all the wind turbine classes. Typical expected yaw errors shall be included during normal operation based on OEM's design and experience. Although IEC (2013) does not contain details in this regard, IEC (2019) recommends a minimum of six realization (different turbulent seeds) per wind speed. The DLC is divided into two (DLC1.1a and DLC1.1b), wherein the difference is in the postprocessing, ULS+SLS (DLC1.1a) vs. FLS (DLC1.1b).
Limit State Applicable	ULS (SLS) and FLS PSF: γ_f =1.35 (ULS) γ_f =1.1 (SLS) γ_f =1.0 (FLS) If following IEC (2019): γ_f =1.25 (if load extrapolation) or 1.5 (ULS)
Simulation Parameters	• Simulation length: 600 s (10-min minimum length of usable data) • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: v_{in} to v_{out} with a maximum bin step of 2 m/s • Turbulence: ○ Model and TI15: normal turbulence model (NTM) with TI15=0.18 (IEC 2013) or 0.2 if ACP (2021) is used for certification ○ Power-law shear exponent: 0.2 ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 6 • Flow inclination: [0°,+8°] • Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with certification body) • Faults: None
Expected Number of Simulations	• 432 typical (no. of wind speeds * no. of yaw errors * no. of seeds* no. of flow inclinations)
Postprocessing	• ULS/SLS: ○ Average peaks from various realizations, extract contemporaneous loads by selecting the event that renders the closest (but on the conservative side) load to the averaged peak value ○ If following IEC (2019): perform load extrapolation (Graf, Damiani, Dykes, and Jonkman 2017; IEC 2019) for (at a minimum) blade root moments and tip deflection, and use reduced γ_f =1.25 (ULS), alternatively use γ_f =1.5 (ULS) • FLS: For each output file, rainflow count the cycles. Combine results based on a weighting scheme (see Section 3.4.2), expected availability, and wind speed probability density function, to arrive at lifetime fatigue characteristics and design loads from this DLC.

Table 9. DLC 1.2 (ECD: Extreme Coherence Gust With Directional Change)

DLC 1.2	ECD: Extreme Coherence Gust With Directional Change		
Detailed Description	DLC simulating power production with a deterministic wind field featuring a simultaneous rise in wind speed (described by ECD, see also Section 3.2) and a direction change in about 10 s. IEC (2013) prescribes that the analysis be performed on wind speeds $<v_{design}=1.4v_{ave}$. IEC (2019) recommends investigating results for three wind-speed bins centered about rated wind speeds.		
Limit State Applicable	ULS	PSF: γ_f =1.35 (ULS)	
Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: v_{in} to v_{design} with a maximum bin step of 2 m/s • Turbulence: not applicable (N/A) • Power-law shear exponent: 0.2 • Recommended yaw offsets: 0° • Flow inclination: [0°,+8°] • Faults: None		
Expected Number of Simulations	• 6 typical (no. of wind speeds * no. of flow inclinations)		
Postprocessing	ULS: Extract maximum (minimum) of all peaks as characteristic load. ULS PSF applies.		

Table 10. DLC 1.3 (EOG_{50}: Extreme Operating Gust; 50-yr Return Period)

DLC 1.3	EOG_{50}: Extreme Operating Gust; 50-yr Return Period		
Detailed Description	DLC simulating power production with a deterministic wind field featuring a rise and a drop in wind speed (described by EOG, see also Section 3.2) with a return period of 50 years in about 14 s. IEC (2013) prescribes that the analysis be performed on wind speeds in [v_{in},v_{out}]. IEC (2019) recommends investigating results for three wind-speed bins centered at rated wind speed, including bins at v_{in} and v_{out}.		
Limit State Applicable	ULS	PSF: γ_f =1.35	
Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: v_{in} to v_{out} with a maximum bin step of 2 m/s • Turbulence: N/A • Power-law shear exponent: 0.2 • Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with certification body) • Flow inclination: [0°,+8°] • Faults: None		
Expected Number of Simulations	• 72 typical (no. of wind speeds * no. of yaw errors * no. of flow inclinations)		
Postprocessing	ULS: Extract maximum (minimum) of all peaks as characteristic load. ULS PSF applies.		

Table 11. DLC 1.4 (EDC_{50}: Extreme Direction Change; 50-yr Return Period)

DLC 1.4	**EDC_{50}: Extreme Direction Change; 50-yr Return Period**		
Detailed Description	DLC simulating power production with a deterministic wind field featuring an extreme wind directional change during about 6 s (as described by EDC, see also Section 3.2) with a return period of 50 years. IEC (2013) prescribes that the analysis be performed on wind speeds in [v_{in},v_{out}]. IEC (2019) recommends investigating results for three wind-speed bins centered at rated wind speed, including bins at v_{in} and v_{out}.		
Limit State Applicable	ULS	PSF: γ_f =1.35	
Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: v_{in} to v_{out} with a maximum bin step of 2 m/s • Turbulence: N/A • Power-law shear exponent: 0.2 • Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with certification body) • Flow inclination: [0°,+8°] • Faults: None		
Expected Number of Simulations	• 72 typical (no. of wind speeds * 2 (positive and negative directional changes) * no. of yaw errors * no. of flow inclinations)		
Postprocessing	ULS: Extract maximum (minimum) of all peaks as characteristic load. ULS PSF applies.		

Table 12. DLC 1.5 (ECG: Extreme Coherent Gust)

DLC 1.5	ECG: Extreme Coherent Gust	
Detailed Description	DLC simulating power production with a deterministic wind field featuring a rise in wind speed during about 10 s (as described by ECG, see also Section 3.2). IEC (2013) prescribes that the analysis be performed at $v = v_{design}$.	
Limit State Applicable	ULS	PSF: γ_f =1.35 (ULS)
Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: v_{design} • Turbulence: N/A • Power-law shear exponent: 0.2 • Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with certification body) • Flow inclination: [0°,+8°] • Faults: None	
Expected Number of Simulations	• 6 typical (no. of wind speeds * no. of yaw errors * no. of flow inclinations)	
Postprocessing	ULS: Extract maximum (minimum) of all peaks as characteristic load. ULS PSF applies.	

Table 13. DLC 2.1 (Power Production and Fault Leading to Shutdown)

DLC 2.1	Power Production and Fault Leading to Shutdown		
Detailed Description	DLC simulating power production with a deterministic wind field and a control system fault that brings to a shutdown. IEC (2013) prescribes that the analysis be performed at $v = v_{design}$, or v_{out}, or $2.5v_{ave}$. IEC (2019) recommends using NTM and the entire [v_{in}, v_{out}] range, and that is preferable and recommended here.		
Limit State Applicable	ULS	PSF: γ_f =1.35	

Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) or 600 s if following NTM
	• Recommended transient length (to remove from the beginning of time series): 60 s
	• Wind speed range: v_{design}, or v_{out}, or $2.5v_{ave}$ per IEC (2013); [v_{in}:2: v_{out}] per IEC (2019).
	• Turbulence: N/A per IEC (2013); or IEC (2019) (recommended):
	  ○ Model and TI15: Normal turbulence model (NTM) with TI15= 0.2
	  ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 12
	• Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with certification body)
	• Flow inclination: [0°,+8°]
	• Power-law shear exponent: 0.2
	• Faults: grid connection loss (loss of load/torque), generator short (resistive torque spike), pitch runaway (one blade to fine pitch at max pitch rate), stuck pitch:
	  ○ Fault applied within 1 min after initial transients (onset of fault may be set based on wind speed rise to capture worst cases)
	  ○ The shutdown procedure uses the rates (braking torque and blade pitch rates) that are prescribed for normal shutdowns.		

Expected Number of Simulations	• Depends on the number of faults simulated and thus on the machine type
	• Assuming all faults mentioned apply:
	  ○ 24 (IEC 2013) (no. of wind speeds * no. of faults * no. of yaw errors * no. of flow inclinations * no. of realizations)
	  ○ 3,456 (IEC 2019) (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations)		

Postprocessing	ULS: • Extract the maximum (minimum) of all peaks as characteristic load (IEC 2013) • If following IEC (2019), use instead the average of the upper (worst) half of the peaks extracted from all the realizations (recommended). ULS PSF applies.		

Table 14. DLC 2.2 (Power Production Under Faulted Condition [No Shutdown])

DLC 2.2	Power Production Under Faulted Condition (No Shutdown)	
Detailed Description	DLC simulating power production with a turbulent wind field and a control system fault that does not bring the wind turbine to a shutdown. IEC (2013) prescribes that the analysis be performed across the entire [v_{in}, v_{out}] range with NTM.	
Limit State Applicable	ULS (SLS) and FLS	PSF: γ_f =1.35 (ULS) γ_f =1.1 (SLS) γ_f =1.0 (FLS)
Simulation Parameters	• Simulation length: 600 s (minimum length of usable data) • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: [v_{in}, v_{out}] with a maximum bin step of 2 m/s • Turbulence: ○ Model and TI15: normal turbulence model (NTM) with TI15=0.18 (IEC 2013) or 0.2 if ACP (2021) is used for certification ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 12 or 6 for yaw-control fault • Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with certification body) for faults other than yaw control; 0°:15°:350° for yaw-control fault • Flow inclination: [0°,+8°] • Power-law shear exponent: 0.2 • Faults: yaw-control fault (for active yaw machines), pitch runaway (one blade to fine pitch at max pitch rate), pitch stuck	
Expected Number of Simulations	• Depends on the number of faults simulated and thus on the machine type • Assuming all faults mentioned apply: ○ 1,728 (all but yaw-control faults) and 3,312 (yaw-control fault) (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations)	
Postprocessing	• ULS (SLS): ○ Average peaks of all realizations at each wind speed, then extract the worst-case values (maxima of maxima and minima of minima) (IEC 2013) ○ If following IEC (2019), use the average of the upper (worst) half of the peaks extracted from all the realizations. ULS PSF applies. • FLS (SLS): For each fault type (see also Section 3.4.3): ○ Select the number of faults per year, $N_{f,yr}$: $N_{f,yr} * 10'$ should amount to a minimum of 1 day (24 hours). Other values may be justifiable by OEM and acceptable by the certification body. ○ Rainflow count all simulation output datasets ○ Weight the realizations and aeroelastic modeling based on Rayleigh distribution for the class ○ Determine lifetime damage based on component S-N, weighted cycle counts, and material and consequence-of-failure PSFs.	

Table 15. DLC 2.3 (EOG1: Extreme Operating Gust; 1-yr Return Period)

DLC 2.3	EOG_1: Extreme Operating Gust; 1-yr Return Period		
Detailed Description	DLC simulating power production with a deterministic wind field featuring a 1-yr return period extreme gust and a loss of electrical load (e.g., grid loss). IEC (2013) prescribes that the analysis be performed at v = min (v_{out}, 2.5v_{ave}). IEC (2019) prescribes [v_{rated}-2m/s, vrated+2m/s, v_{out}], which is what is recommended here.		
Limit State Applicable	ULS	PSF: γ_f =1.35(ULS)	

Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) or 600 s if following NTM
	• Recommended transient length (to remove from the beginning of time series): 60 s
	• Wind speed range: min(v_{out},2.5v_{ave}) per IEC (2013); [v_{rated}-2m/s, v_{rated}+2m/s, v_{out}] per IEC (2019) (recommended)
	• Turbulence: N/A
	• Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with the certification body)
	• Flow inclination: [0°,+8°]
	• Power-law shear exponent: 0.2
	• Faults: grid connection loss (loss of load)
	  ○ Fault applied at three different instances along the EOG profile to capture the worst-case scenario
	  ○ The shutdown procedure uses the rates (braking torque and blade pitch) that are prescribed for normal shutdowns		

Expected Number of Simulations	• 18 (IEC 2013) (no. of wind speeds * no. of fault realizations * no. of yaw errors * no. of flow inclinations) • 54 (IEC 2019) (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations)		
Postprocessing	ULS: extract maximum (minimum) of all peaks as characteristic load (IEC 2013). ULS PSF applies.		

Table 16. DLC 3.1 (Normal Shutdown)

DLC 3.1	Normal Shutdown		
Detailed Description	DLC simulating power production with a turbulent (NTM) wind field and a normal shutdown. IEC (2013) prescribes that the analysis be performed across the entire [v_{in}, v_{out}] range with NTM.		
Limit State Applicable	FLS	PSF: γ_f =1.0	

Simulation Parameters	• Simulation length: 600 s (minimum length of usable data)
	• Recommended transient length (to remove from the beginning of the time series): 60 s
	• Wind speed range: [v_{in}, v_{out}] with a maximum bin step of 2 m/s
	• Turbulence:
	  ○ Model and TI15: normal turbulence model (NTM) with TI15=0.18 (IEC 2013) or 0.2 if ACP (2021) is used for certification
	  ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 6
	• Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with the certification body)
	• Flow inclination: [0°,+8°]
	• Power-law shear exponent: 0.2
	• Faults: N/A
	• The shutdown procedure uses the rates (braking torque and blade pitch rates) that are prescribed for normal shutdowns		

Expected Number of Simulations	432 (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations)		

Postprocessing	• FLS (see also Section 3.4.3):
	  ○ Select the number of shutdowns per year, $N_{s,yr}$: $N_{s,yr} * 10'$ should amount to a minimum of 7 days; other values may be justifiable by OEM and acceptable by the certification body
	  ○ Rainflow count all simulation output datasets
	  ○ Weight the realizations and aeroelastic modeling based on the Rayleigh distribution for the class
	  ○ Determine lifetime damage based on component S-N, weighted cycle counts, and the material and consequence-of-failure PSFs.		

Table 17. DLC 3.2 (Normal Shutdown in EOG1: Extreme Operating Gust; 1-yr Return Period)

DLC 3.2	Normal Shutdown in EOG_1: Extreme Operating Gust; 1-yr Return Period		
Detailed Description	DLC simulating power production with a deterministic wind field featuring a 1-yr return period extreme gust and a normal shutdown. IEC (2013) prescribes that the analysis be performed at v = v_{out}, ($v_{maxshutdown}$ for turbines without a clear cutout). IEC (2019) prescribes [v_{rated}-2m/s, vrated+2m/s, v_{out}], which is what is recommended here.		
Limit State Applicable	ULS (SLS)	PSF: γ_f =1.35 (ULS)	
Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) or 600 s if following the normal turbulence model • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: v_{out}, (or $v_{max,shutdown}$) per IEC (2013); [v_{rated}-2m/s, vrated+2m/s, v_{out}] per IEC (2019) (recommended) • Turbulence: N/A • Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with certification body); • Flow inclination: [0°,+8°] • Power-law shear exponent: 0.2 • Faults: N/A • Shutdown applied at three different instances along the extreme operating gust (EOG) profile to capture the worst case. The shutdown procedure uses the rates (braking torque and blade pitch rates) that are prescribed for normal shutdowns.		
Expected Number of Simulations	○ 18 (IEC 2013) (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations) ○ 54 (IEC 2019) (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations)		
Postprocessing	ULS (SLS): • If following IEC (2013), extract maximum (minimum) of all peaks as characteristic load. • If following IEC (2019), group average peaks from various realizations per yaw offset. Select the worst case among averaged values as the characteristic load. Extract contemporaneous loads by selecting the event that renders the closest (but on the conservative side) load to the selected peak value. ULS (SLS) PSF applies.		

Table 18. DLC 4.1 (Emergency Shutdown)

DLC 4.1	Emergency Shutdown		
Detailed Description	DLC simulating power production with a turbulent (NTM) wind field and an emergency shutdown. IEC (2013) prescribes that the analysis be performed at a hub-height wind speed prescribed by the OEM. IEC (2019) prescribes [v_{rated}-2m/s, v_{rated} +2m/s, v_{out}], which is what is recommended here.		
Limit State Applicable	ULS (SLS)	PSF: γ_f =1.35 (ULS)	

Simulation Parameters	• Simulation length: 600 s (minimum length of usable data)
	• Recommended transient length (to remove from the beginning of the time series): 60 s
	• Wind speed range: [v_{rated}-2m/s, v_{rated}+2m/s, v_{out}] per IEC (2019) (recommended)
	• Turbulence:
	  ○ Model and TI15: normal turbulence model (NTM) with TI15=0.18 (IEC 2013) or 0.2 if ACP (2021) is used for certification
	  ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 6 [(IEC 2019) requires 12, but assuming yaw offsets, 6 seeds are adequate to capture worst-case load levels]
	• Recommended yaw offsets: -10°, 0°, 10° (to be specified and justifiable by OEM and agreed upon with the certification body)
	• Flow inclination: [0°,+8°]
	• Power-law shear exponent: 0.2
	• Faults: N/A
	• Shutdown:
	  ○ Applied after initial transients; the time of occurrence is to be selected by OEM; number of seeds and yaw offsets allow to capture the worst case for various component loads
	  ○ The shutdown procedure uses the rates (braking torque and blade pitch) that are prescribed for emergency shutdowns		

Expected Number of Simulations	• 108 (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations)		
Postprocessing	ULS (SLS): Average peaks from various realizations grouped per yaw offset. Select the worst case among averaged values as the characteristic load. Extract contemporaneous loads by selecting the event that renders the closest (but on the conservative side) load to the selected peak value. ULS (SLS) PSF applies.		

Table 19. DLC 5.1 (Parked/Idling in Extreme Wind – Steady)

DLC 5.1	**Parked/Idling in Extreme Wind - Steady**	
Detailed Description	DLC simulating a deterministic wind field featuring a 50-yr return period extreme gust (v_{e50}) and a reduced shear. IEC (2013) prescribes that the analysis be performed at v = 1.4 v_{ref}.	
Limit State Applicable	ULS (FLS)	PSF: γ_f =1.35(ULS)
Simulation Parameters	• Simulation length: 100 s (minimum length of usable data) • Recommended transient length (to remove from the beginning of time series): 60 s • Wind speed range: v = 1.4 v_{ref} =v_{e50} • Turbulence: N/A • Recommended yaw offsets: -15°, 0°, 15° ;(if active yaw and grid fault, consider extreme yaw errors) • Flow inclination: [0°,+8°] • Power-law shear exponent: 0.11 • Faults: ○ Loss of electrical load (e.g., electrical grid drop): for active yaw turbines, this may cause extreme yaw errors.	
Expected Number of Simulations (typical)	• 6 (IEC 2013) (no. of wind speeds * no. of yaw errors * no. of flow inclinations)	
Postprocessing	ULS: Extract maximum (minimum) of all peaks as characteristic load (IEC 2013). ULS PSF applies.	

Table 20. DLC 5.2 (Parked/Idling in Extreme Wind – Turbulent)

DLC 5.2	Parked/Idling in Extreme Wind – Turbulent		
Detailed Description	DLC simulating parked or idling (depending on machine control system) with a turbulent (normal turbulence model) wind field and gusts close to v_{e50}. IEC (2013) prescribes that the analysis be performed at a hub wind speeds <0.7v_{ref}.		
Limit State Applicable	FLS	PSF: γ_f =1.0	

Simulation Parameters	• Simulation length: 600 s (minimum length of usable data)
	• Recommended transient length (to remove from the beginning of the time series): 60 s
	• Wind speed range: v_{out} to 0.7v_{ref} (IEC 2013) with a maximum bin step of 2 m/s
	• Turbulence:
	  ○ Model and TI15: normal turbulence model with TI15=0.18 (IEC 2013) or 0.2 if ACP (2021) is used for certification.
	  ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 6
	• Recommended yaw offsets: -15°, 0°, 15°
	• Flow inclination: [0°,+8°]
	• Power-law shear exponent: 0.11
	• Faults: N/A		

Expected Number of Simulations	• 108 (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations)		
Postprocessing	FLS: For each output file, rainflow count the cycles. Combine results based on a weighting scheme (see Section 3.4.2), expected un-availability for v≤ v_{in}, and wind speed probability density function, to arrive at lifetime fatigue characteristics and design loads from this DLC. The probability of wind speeds below v_{in} can be added to the bin containing v_{in}.		

Table 21. DLC 6.1 (Parked/Idling Under Faulted Conditions in Extreme Wind – Steady)

DLC 6.1	**Parked/Idling Under Faulted Conditions in Extreme Wind - Steady**		
Detailed Description	DLC simulating a steady (extreme wind speed model, EWM) or turbulent (normal turbulence model, NTM) wind field featuring a 1-yr return period extreme gust and a reduced shear, and under faulted conditions. IEC (2013) prescribes that the analysis be performed at a hub wind speed of v_{e1}=0.75*v_{e50} (3-s gust value); however, it is recommended that a turbulent wind field be used and that the mean wind speed be calculated as 0.8*v_{ref} per IEC (2019).		
Limit State Applicable	ULS (SLS)	PSF: γ_f =1.35(ULS)	

Simulation Parameters	• Simulation length: 600 s (minimum length of usable data)
	• Recommended transient length (to remove from the beginning of the time series): 60 s
	• Wind speed range: v =0.8*v_{ref} =v_1
	• Turbulence:
	  ○ Model and TI15: normal turbulence model (NTM) with TI=0.11v_1 (IEC 2019)
	  ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 6
	• Recommended yaw offsets: -15°, 0°, 15° for faults other than yaw control; 0°:15°:345°[2] for the yaw-control fault
	• Flow inclination: [0°,+8°]
	• Power-law shear exponent: 0.11
	• Faults: Grid connection loss (loss of load/torque), pitch stuck (one blade stuck in run), extreme yaw error (for machines with active yaw)
	  ○ Fault applied since the start of the simulation		

Expected Number of Simulations	• Assuming all faults mentioned apply:
	  ○ 72 (no. of wind speeds * no. of faults * no. of yaw errors * no. of flow inclinations * no. of realizations) for non-yaw-control faults
	  ○ 272 (no. of wind speeds * no. of yaw errors * no. of flow inclinations * no. of realizations) for yaw-control faults		

Postprocessing	ULS: Average peaks from various realizations per type of fault, select largest (worst) value, and extract contemporaneous loads by selecting the event that renders the closest (but on the conservative side) load to the selected peak value. ULS PSF applies.		

[2] Here and elsewhere a range indicated as xx:yy:zz indicates: xx starting sector, yy directional bin-width, and end sector zz.

Table 22. DLC 7.1 (Transportation/Installation/Maintenance/Repair)

DLC 7.1	Transportation/Installation/Maintenance/Repair		
Detailed Description	Loads due to transportation may be calculated based on expected acceleration along the three axes for each component. Installation loads may be due to extreme inclinations of parts, sling reactions, and wind drag. These can usually be estimated conservatively by manual engineering calculations that result in satisfied ULS (SLS) levels. Caution should be exerted for loads on the tower if tilt-up towers are used with the rotor nacelle assembly preassembled. For maintenance and repair, a parked rotor should be analyzed that may not have been under DLC 6.1. Repeat those DLCs with rotor lock as applicable and under maximum wind speed for maintenance.		
Limit State Applicable	ULS (FLS)	PSF: γ_f =1.35(ULS)	

Simulation Parameters	• Simulation length: 600 s (minimum length of usable data)
	• Recommended transient length (to remove from the beginning of the time series): 60 s
	• Wind speed range: v =v_{mtn}
	• Turbulence:
	  ○ Model and TI15: normal turbulence model (NTM) with TI15=0.2.
	  ○ Minimum number of realizations per wind speed (turbulence seeds for 10-min simulations): 6
	• Recommended yaw offsets: 0°:15°:345°
	• Flow inclination: [0°,+8°]
	• Power-law shear exponent: 0.11
	• Faults: none and pitch stuck (one blade stuck in run)
	  ○ Fault applied since the start of the simulation
	  ○ Rotor lock is enabled		

Expected Number of Simulations	• Assuming all faults mentioned apply: ○ 432 (no. of wind speeds * no. of faults * no. of yaw errors * no. of flow inclinations * no. of realizations)		
Postprocessing	ULS: Average peaks from various realizations, extract contemporaneous loads by selecting the event that renders the closest (but on the conservative side) load to the averaged peak value. ULS PSF applies.		

3.3.3 Load Case Table

The load case table is an efficient tool to list the DLCs of relevance for the design and verification of the wind turbine components, and an instrument to effectively communicate with the certification body and achieve approval before the loads analysis is performed and results processed. Guidance for the presentation of the load cases can be found in (DNV 2024) Appendix C, but the following list provides the key simulation parameters to include:

- The DLC with reference to the standard followed (e.g., IEC 61400-1 or -2, to be agreed upon with the certification body)
- Wind speeds, directions, and turbulence model simulated
- Simulation length
- Minimum simulation length (not accounting for transients) is 10 min for all stochastic DLCs
- Number of turbulence seeds
- Note that DLC 2.1, 2.2, 5.1 (IEC 2019) require a minimum of 12 seeds, and all other stochastic DLCs require a minimum of 6 seeds
- Number of simulations
- Transient interval to be discarded
- Type of analysis (e.g., ULS, SLS, FLS)
- Load PSF
- Additional information regarding the turbulence model and/or fault simulated
- Additional multipliers for the number of simulations and details to explain the difference in the simulations (e.g., positive and negative direction change in an extreme coherent gust with directional change (ECD) case, and different azimuthal positions for the onset of a fault).

A detailed description of each DLC is given in Table 8–Table 22 along with guidance on how to postprocess the results of the aeroelastic modeling analyses to obtain the design load tables.

The discussion of faults to be analyzed is a critical one and the certification body has to agree that those simulated faults are sufficient to guarantee a full characterization of the ULS and FLS loading levels.

The DLCs were mostly selected by following IEC (2013)*, except in the choices of wind speeds and turbulence for a few cases extracted from the prescriptions in* (IEC 2019) *as discussed with the certification body in previous communications. The considered faults and total number of faults per year (*$N_{f,yr}$) *are:*

- *Grid fault (including generator faults that result in a grid fault);* $N_{f,yr} = 144$
- *One blade pitch stuck in "run";* $N_{f,yr} = 10$
- *One blade pitch runaway to "park";* $N_{f,yr} = 10$

In the aeroelastic modeling simulations, faults are introduced either from the beginning of the simulations (e.g., in DLC 6.1), or after initial transients have settled (DLC 2.1). For deterministic DLCs with an occurrence of gusts, multiple timings were set with respect to the gust time profile (e.g., DLC 2.3) to capture the worst-case loading.

The expected wind turbine availability is 95%. The number of normal shutdowns are approximated at $N_{s,yr} = 1{,}000$. Faults and normal shutdowns are distributed following the assumed Rayleigh wind speed distribution.

Transportation accelerations were assumed to be 2 g. A maximum installation and maintenance mean wind speed of 10 m/s at hub height is indicated. The load case table is given in Table 23. *Given the passive yaw design, no imposed yaw offsets were preset except for DLC 7.1 to account for possible conditions during installation and maintenance. Utilized number of realizations, as well as PSFs, are also shown.*

The output channels of the aeroelastic modeling include:

- *Environment: time stamp, wind velocity components at hub apex*
- *Turbine state: rotor and generator RPM, blade pitch, yaw angle, generator torque, and generator power*
- *Turbine performance: rotor torque, thrust, and power*
- *Loads:*
    - *Blade-bending moments and shears (flap- and edgewise) and normal force along 10 span locations*
    - *The shaft torque and bending moments at the hub connection and location of the main bearing, both fixed and rotating with the shaft*
    - *Yaw-bearing shears and bending moments along all three axes both fixed with the tower and rotating with the nacelle*
    - *Tower-base shears and bending moments along all three axes fixed to the base.*
- *Deflections:*
    - *In-plane and out-of-plane blade-tip deflections (translational and rotational)*
    - *Tower-top deflections (translational and rotational).*

Table 23. Example Load Case Table.

Note: U = Ultimate; F = Fatigue

Design Situation	Design Load Case	Standard	Description	Wind Speed – V_{hub} [m/s][3]	Turbulence Model Turbulence Intensity (TI)/Shear exponent α	Imposed Yaw Error [°]	Wind Direction [°]	Other Conditions	Number of Seeds	Additional Multiplier	Description of Additional Multiplier	No. of Simulations	Simulation Length [s]	Transient Length [s]	Type of Analysis	Partial Safety Factor	Notes
Power Production	1.1	IEC 61400-1&2	NTM	4:2:26	TI15 = 0.2, α = 0.2	N/A	0°	Load extrapolation	6	2	flow inclination	144	660	60	U	1.35	1.25 PSF with load extrapolation
	1.1b	IEC 61400-2 for PSF	As 1.1, but for FLS processing	4:2:26	"	N/A	wind rose for tower; else 0°		6	2	flow inclination	144	660	60	F	1	
	1.2	IEC 61400-2	ECD	11.9	TI15 = 0.0, α = 0.2	N/A	per ECD from 0°		N/A	4	positive and negative directions (2) and flow inclination (2)	12	160	60	U	1.35	
	1.3	"	EOG50	4:2:26	"	N/A	0°		N/A	2	flow inclination	24	160	60	U	1.35	
	1.4	"	EDC50	4:2:26	"	N/A	per EDC		N/A	4	positive and negative directions	48	160	60	U	1.35	

[3] "4:2:26" is a sequence notation indicating a start at 4 m/s, increasing by 2-m/s increments (bin widths) up to 26 m/s (e.g., 4, 6, 8, … 26).

Design Situation	Design Load Case	Standard	Description	Wind Speed – V_{hub} [m/s][3]	Turbulence Model Turbulence Intensity (TI)/Shear exponent α	Imposed Yaw Error [°]	Wind Direction [°]	Other Conditions	Number of Seeds	Additional Multiplier	Description of Additional Multiplier	No. of Simulations	Simulation Length [s]	Transient Length [s]	Type of Analysis	Partial Safety Factor	Notes
											(2) and flow inclination (2)						
	1.5	“	ECG	11.9	“	N/A	0°		N/A	2	flow inclination	6	160	60	U	1.35	
Power Production + Fault	2.1	“	NWP	26	TI15 = 0.0, α = 0.2	N/A	0°	Pitch fault (runaway), generator fault, grid fault	N/A	2	flow inclination	6	160	60	U	1.35	Runaway blade, generator short, and grid disconnect
	2.2	IEC 61400-2 (-1 provides number of seeds)	NTM	4:2:26	TI15 = 0.2, α = 0.2	N/A	Wind rose for tower; else 0°	Pitch fault (runaway)	12	2	flow inclination	6	660	60	F/U	1;1.35	One blade to other than run pitch
	2.3	IEC 61400-2	EOG1	26	TI15 = 0.0, α = 0.2	N/A	0°	Grid fault		2	flow inclination	6	160	60	U	1.35	
Normal Shutdown	3.1	“	NTM	4:2:26	TI15 = 0.2, α = 0.2	N/A	Wind rose for tower; else 0°		6	2	flow inclination	144	660	60	F	1	
	3.2	“	EOG1	26	TI15 = 0.0, α = 0.2	N/A	0°			6	different timing of fault w.r.t. gust (3) and flow	6	160	60	U	1.35	

Design Situation	Design Load Case	Standard	Description	Wind Speed – V_{hub} [m/s]³	Turbulence Model Turbulence Intensity (TI)/Shear exponent α	Imposed Yaw Error [°]	Wind Direction [°]	Other Conditions	Number of Seeds	Additional Multiplier	Description of Additional Multiplier	No. of Simulations	Simulation Length [s]	Transient Length [s]	Type of Analysis	Partial Safety Factor	Notes
											inclination (2)						
Emergency Shutdown	4.1	“	NTM	9, 11, 13	TI15 = 0.2, α = 0.2	N/A	0°		12	2	flow inclination	72	660	60	U	1.35	
Extreme Wind	5.1	IEC 61400-2	EWM50	59.5	TI15 = 0.0, α= 0.11	N/A	0°	Grid fault		4	with and w/o grid fault (2) and flow inclination (2)	4	160	60	U	1.35	Mechanical brake engaged
	5.2	“	NTM	4:2:30	I15 = 0.2, α = 0.2	N/A	Wind rose for tower; else 0°		6	2	flow inclination	336	660	60	F	1	Mechanical brake engaged; results to be weighted via Weibull wind speed distribution and number of events

Design Situation	Design Load Case	Standard	Description	Wind Speed – V_{hub} [m/s][3]	Turbulence Model Turbulence Intensity (TI)/Shear exponent α	Imposed Yaw Error [°]	Wind Direction [°]	Other Conditions	Number of Seeds	Additional Multiplier	Description of Additional Multiplier	No. of Simulations	Simulation Length [s]	Transient Length [s]	Type of Analysis	Partial Safety Factor	Notes
Parked With Fault	6.1	“	NTM	34	TI15 = 0.11, α = 0.11	N/A	0°	Pitch fault (one blade stuck in run)	6	2	flow inclination	12	160	60	U	1.35	Mechanical brake engaged
Transport/ Install	7.1	“	NTM	10	TI15 = 0.2, α = 0.2	N/A	0°		6	2	+1 transport case (1), and flow inclination (2)	218	660	60	U	1.35	Assessment of components and transportation fixtures due to accelerations; erection of turbine on tower/maintenance with yaw and rotor lock

3.4 Postprocessing

Postprocessing involves manipulating the raw aeroelastic modeling time-series output to extract the driving loads for the various components and load channels. Furthermore, the end goal of this process is to verify the limit states and assess the potential for resonances or instabilities. The output loads should be presented with the component sizing in mind, thus grouped by wind turbine part and cross section within each part, and listing the driving load components first (e.g., bending moments for tower and blade cross sections).

The verification of the various parts should be included in the design report, but the design load basis should mention the methodology followed. For example, the cross-verification of shaft and tower may be carried out analytically, the hub, given its complicated shape and stress state, via finite element analysis, and to verify a complex structural layup of a composite part, structural tests may be performed. Additionally, the design load basis should mention the approach to handle finite element analysis hot spots, whether the yield or ultimate strength of the material will be utilized, and the critical deflections that will need to be verified. In particular, the process to qualify the blade-tip critical deflection (DNV 2024; IEC 2019; DNV-GL 2015) should be stated (see also Section 3.4.2).

Load and resistance factor design is used in IEC (2019) with PSFs to account for uncertainties in the load levels, material resistance, and the importance of structural components with respect to the consequence of failure. Section 7 in IEC (2019) provides values of γ_m (consequence of failure PSF).

The main limit states discussed in the design standards are:

- ULS. In these limit states, the extreme loads, stresses, and strains are calculated to ultimate strength and buckling of the various components.
- FLS. These limit states are related to the possibility of failure due to repeated, cycling loading.
- SLS. These limit states address criteria related to normal use and durability, focusing on deformations that exceed tolerances without surpassing the load-carrying capacity.
- Accidental limit states (ALS).
    - These limit states refer to damage to components due to an accidental event or operational failure.
    - For a distributed wind turbine, these limit states are not formally prescribed. However, because of the proximity of distributed wind turbines to the public, evaluating whether and which accidental loads could occur can help guarantee safety and provide a low risk as a consequence of failure.

The relevant output channels of aeroelastic modeling simulations are selected by the OEM, but it is good practice to share a table of key channels with the certification body. Besides loads, other important output variables are deflections and/or strains. The deflections, in particular, are important to verify SLS (e.g., blade-tip deflection, tower-top deflection), and strains are important to verify the strength of composite parts for FLS and ULS.

Finite-element-analysis-derived transfer functions may be used to arrive at strains and stresses from load values (the common output of aeroelastic modeling codes) for complicated structural arrangements (e.g., the anisotropic composite cross sections of a rotor blade), whereas in other instances, analytical formulas can be used. Design standards and appropriate references can be used for this task (e.g., IEC [2013]; Young and Budynas [2002]).

The raw data from the numerical simulations should be appropriately processed to extract overall maxima, minima, and other statistical quantities of interest, as well as to perform rainflow cycle counting (Downing and Socie 1982).

The DLC description (e.g., Section 3.3.2) also contains a short description of how the simulation results will be postprocessed to obtain the tables of extreme and fatigue loads for the main components.

3.4.1 Extreme (Ultimate Limit State)

The ULS verification is called ultimate strength analysis in IEC (2013). Although no formal description of the load and resistance factor design procedure is provided in IEC (2013), and no connections to statistical extrapolation and probabilities of load exceedances are given, a more thorough treatment of ULS is recommended. IEC (2019), DNV-GL (2010), DNV (2024), and Damiani (2018) provide in-depth explanations for the reliability levels in the load and resistance factor design approach.

IEC (2019) assumes a $5*10^{-4}$ probability of failure, and the design approach, including the PSFs, length of simulations, and the concept of load extrapolation, have all been calibrated to guarantee this reliability level. IEC (2019) further states how many turbulent seeds per wind speed should be used for stochastic wind field simulations. This guidance can help with processing data and for aeroelastic modeling simulations following IEC (2013).

The averaging of the peaks from multiple realizations is also not discussed in IEC (2013), and we recommend following IEC (2019) for both the number of turbulent seeds to use per DLC and per wind speed, and for the averaging of the peaks from the various simulation output datasets. Specifically:

- For stochastic DLCs (i.e., turbulent wind, with or without faults) the exceedance probability for the characteristic load shall be calculated considering the wind speed probability distribution.
- For DLC 1.1, the characteristic value of the load (F_k) shall be determined by a statistical load extrapolation (Graf, Damiani, Dykes, and Jonkman 2017) to an exceedance probability $P_E(F_k) \leq 3.8*10^{-7}$, (i.e., a 50-year recurrence period). Associated with this extrapolated value, the ULS load PSF can be reduced to $\gamma_f = 1.25$. The standard also allows for an approximation to this characteristic value that can be calculated by multiplying the largest of the means (from multiple realizations at each wind speed) of the peak load by an extrapolation factor of $\gamma_f = 1.5$.
- For all other stochastic wind field DLCs, the characteristic load is taken as the worst-case value of the mean values of the peaks from the various realizations at each wind speed. However, for power-production DLC 2.1, 2.2, and emergency shutdown DLC 5.1 (4.1 for [IEC 2013]), the characteristic load value is taken as the mean of the upper half of the maximum loads.

- For deterministic wind field DLCs, the characteristic load value is taken as the worst-case computed transient value.

An effective presentation of the ULS loads requires the concept of contemporaneous loads (DNV 2024). A contemporaneous load table reports the maximum and minimum values of each load channel of relevance with all the other load channel values occurring at the time of maximum or minimum. The maxima and minima are shown along the diagonal, the other load channel values are read along rows, and in specific columns information on the load PSF, relevant DLC, time stamp, and environmental conditions (e.g., wind speed, yaw error), where control outputs (such as blade pitch and yaw position) may also be provided. Note that because of the averaging scheme discussed earlier, the assumed extreme may need to be associated with the closest relevant time step to determine the contemporaneous loads.

For example, for the blade-root verification, a dedicated table of contemporaneous loads would present the blade-root flapwise and edgewise bending moment minima and maxima, and all the associated loads occurring simultaneously to these peak values (see also Table 24). Alternatively, the loads can be reported along sectors (e.g., for a minimum of twelve 30° sectors).

Table 24. Example of a Contemporaneous Load Table for Blade Root Loads.

Note the calculated extreme column shows the load value for the time instance that returns the closest relevant value to the averaged one.

Parameter	Type	File Name	DLC Name	Calculated Extreme	RootFxb1 (kN)	RootFyb1 (kN)	RootF1 (kN)	RootFzb1 (kN)	RootMxb1 (kN-m)	RootMyb1 (kN-m)	RootM1 (kNm)	RootMzb1 (kN-m)	Time (s)	WS (m/s)	NacYaw (deg)	YawErr (deg)	BldPitch1 (deg)	BldPitch2 (deg)	γf
RootFxb1	**Minimum**	**D:/RRD_ENG**	DLC1.3	- 6.0714E+00	**- 6.1465E+00**	- 7.2880E-01	6.1896E+00	1.7910E+01	2.4897E+00	- 2.8030E+01	2.8141E+01	- 1.5935E-02	6.5858E+02	2.4878E+00	- 2.3430E+01	1.2678E+02	- 1.0000E+00	- 1.0000E+00	1.35
RootFxb1	**Maximum**	**D:/RRD_ENG**	DLC7.1	1.4184E+01	**1.4561E+01**	- 4.8120E+00	1.5336E+01	- 1.9830E+00	1.6980E+01	6.9355E+01	7.1403E+01	- 3.3020E+00	3.5946E+02	5.3836E+01	2.6200E+01	2.4506E+01	- 1.0000E+00	- 9.0000E+01	1.1
RootFyb1	**Minimum**	**D:/RRD_ENG**	DLC2.2	- 8.0840E+00	1.8480E+00	**- 8.3620E+00**	8.5638E+00	2.1650E+01	3.5281E+01	1.5130E+01	3.8389E+01	- 1.2120E+00	1.0932E+02	3.3124E+01	- 4.1880E+00	- 1.2582E+00	- 1.0000E+00	- 4.5100E+01	1.1
RootFyb1	**Maximum**	**D:/RRD_ENG**	DLC2.1	4.3002E+00	- 1.3930E-01	**4.3044E+00**	4.3067E+00	3.2710E+01	- 1.3613E+01	5.7880E+00	1.4793E+01	- 6.5500E-01	5.3710E+02	1.9025E+01	- 1.0990E+01	- 1.2008E+01	- 1.6000E+01	- 1.6000E+01	1.35
RootF1	**Minimum**	**D:/RRD_ENG**	DLC2.2	4.7479E-03	- 3.2820E-03	- 1.2780E-04	**3.2845E-03**	2.9590E+00	1.6750E-01	1.3340E+00	1.3445E+00	- 1.3280E-01	1.0840E+02	1.6906E+01	- 4.7600E+00	- 9.1660E+00	- 1.0000E+00	- 9.0000E+01	1.1
RootF1	**Maximum**	**D:/RRD_ENG**	DLC7.1	1.4642E+01	1.4610E+01	- 3.6990E+00	**1.5071E+01**	3.7539E+00	1.2870E+01	7.7170E+01	7.8236E+01	- 3.1350E+00	3.8192E+02	5.0794E+01	- 1.9400E+01	- 1.8960E+01	- 1.0000E+00	- 9.0000E+01	1.1
RootFzb1	**Minimum**	**D:/RRD_ENG**	DLC2.2	- 2.9671E+00	3.1240E+00	- 7.6303E-01	3.2158E+00	**- 2.9673E+00**	2.6663E+00	1.4070E+01	1.4320E+01	- 4.9860E-01	1.9384E+02	2.8919E+01	- 6.5380E+00	- 2.8980E+00	- 1.0000E+00	- 9.0000E+01	1.1
RootFzb1	**Maximum**	**D:/RRD_ENG**	DLC2.2	3.8117E+01	1.7562E+00	- 3.7060E+00	4.1011E+00	**3.8142E+01**	1.9140E+01	2.2290E+01	2.9380E+01	- 8.7407E-01	4.1104E+02	2.5841E+01	7.9510E+00	1.1505E+01	- 1.0000E+00	- 2.6200E+01	1.1
RootMxb1	**Minimum**	**D:/RRD_ENG**	DLC2.3	- 1.3672E+01	5.2652E-01	4.1400E+00	4.1734E+00	1.7850E+01	**- 1.3672E+01**	7.4646E+00	1.5577E+01	- 5.2600E-01	4.3120E+01	2.3140E+01	- 8.7870E-01	- 8.7870E-01	- 1.0000E+00	- 1.0000E+00	1.1
RootMxb1	**Maximum**	**D:/RRD_ENG**	DLC2.2	3.3267E+01	1.8480E+00	- 8.3620E+00	8.5638E+00	2.1650E+01	**3.5281E+01**	1.5130E+01	3.8389E+01	- 1.2120E+00	1.0932E+02	3.3124E+01	- 4.1880E+00	- 1.2582E+00	- 1.0000E+00	- 4.5100E+01	1.1
RootMyb1	**Minimum**	**D:/RRD_ENG**	DLC1.3	- 2.7841E+01	- 6.1465E+00	- 7.2880E-01	6.1896E+00	1.7910E+01	2.4897E+00	**- 2.8030E+01**	2.8141E+01	- 1.5935E-02	6.5858E+02	2.4878E+00	- 2.3430E+01	1.2678E+02	- 1.0000E+00	- 1.0000E+00	1.35
RootMyb1	**Maximum**	**D:/RRD_ENG**	DLC7.1	7.1916E+01	1.4906E+01	- 3.2420E+00	1.5254E+01	2.9640E+00	1.1560E+01	**7.6610E+01**	7.7477E+01	- 3.2030E+00	1.3920E+02	5.3242E+01	- 9.7200E+00	- 9.9234E+00	- 1.0000E+00	- 9.0000E+01	1.1
RootM1	**Minimum**	**D:/RRD_ENG**	DLC2.2	1.5077E-02	- 2.2100E-01	3.1654E-02	2.2326E-01	2.8980E+00	8.6810E-03	1.2130E-02	**1.4916E-02**	- 8.6130E-02	7.2622E+02	1.3415E+01	1.1790E+01	9.7452E-01	- 1.0000E+00	- 9.0000E+01	1.1
RootM1	**Maximum**	**D:/RRD_ENG**	DLC7.1	7.3038E+01	1.4906E+01	- 3.2420E+00	1.5254E+01	2.9640E+00	1.1560E+01	7.6610E+01	**7.7477E+01**	- 3.2030E+00	1.3920E+02	5.3242E+01	- 9.7200E+00	- 9.9234E+00	- 1.0000E+00	- 9.0000E+01	1.1
RootMzb1	**Minimum**	**D:/RRD_ENG**	DLC7.1	- 3.3485E+00	1.3020E+01	- 4.0628E+00	1.3639E+01	4.3410E+00	1.4990E+01	6.5880E+01	6.7564E+01	**- 3.3945E+00**	3.3706E+02	5.2402E+01	- 1.8140E+01	- 1.5024E+01	- 1.0000E+00	- 9.0000E+01	1.1
RootMzb1	**Maximum**	**D:/RRD_ENG**	DLC6.1	5.0137E-01	- 3.5882E-01	- 1.8110E+00	1.8462E+00	- 2.3602E+00	4.8960E+00	- 3.3252E+00	5.9184E+00	**5.8817E-01**	3.2420E+02	3.9753E+01	- 1.6950E-01	2.7757E+00	- 9.0000E+01	- 9.0000E+01	1.35

3.4.2 Service Limit State

IEC (2013) prescribes that the deflections in the wind turbine structure and support structure should be verified for unnecessary or significant failures. Typically, the load levels to be used in the SLS are those associated with the probability of exceedance of $10^{-4} – 10^{-2}$ (DNV 2024), especially for the support structure.

The tip deflection and tower-clearance check are generally considered part of the SLS, though the minimum tower clearance can be seen as a ULS. IEC (2013) does not provide details on how to perform these checks, and DNV (2024), IEC (2019), and DNV-GL (2015) are recommended for guidance. DNV-GL (2015), for example, requires that the worst-case deflections of the tower and blade shall not reduce the tower-blade clearance by more than 70% of its value at rest.

The design load basis should discuss what deflections will be considered in the analyses for SLS verification. Tower-top deflections and blade-tip deflections are two obvious variables that should be checked for the possibility of tower or guy wire strikes in the case of a guyed tower.

3.4.3 Fatigue Limit State

IEC (2013) mandates that all fatigue load cases must be combined to evaluate lifetime fatigue damage. When verifying FLS, several details must be considered, though a comprehensive explanation of fatigue treatment for wind turbines is beyond the scope of this document. For more information on FLS processing, refer to the key standards (IEC 2013, 2019; DNV 2024; DNV-GL 2010, 2015), and references (Sutherland 1999; Downing and Socie 1982; International Institute of Welding 2008; Mandell et al. 2019).

Here, we discuss items that should be mentioned in the design load basis, including a description of the considered FLS situations, the methodology for presenting the results of the numerical simulations, and the verification procedure.

The fatigue loads can be reported in terms of load spectra (number of cycles as a function of load range levels) and Markov matrices (Figure 8–Figure 9); however, damage equivalent loads are often used.

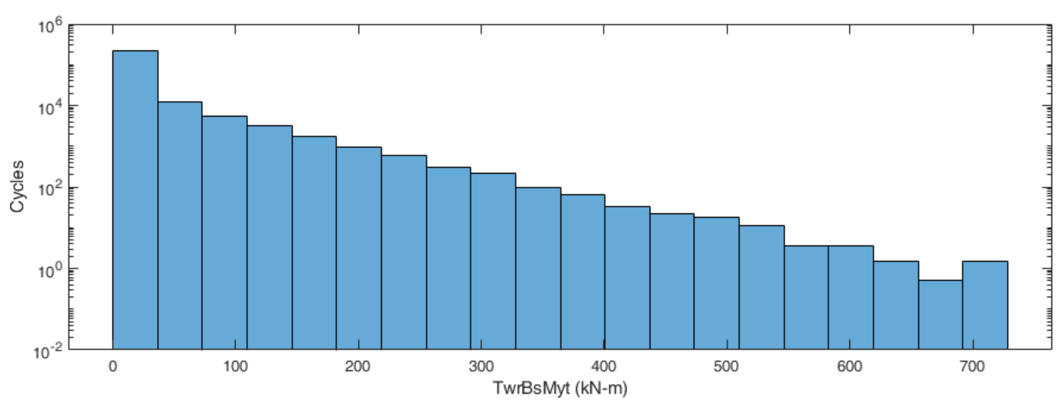

Figure 8. Example of a fatigue load spectrum

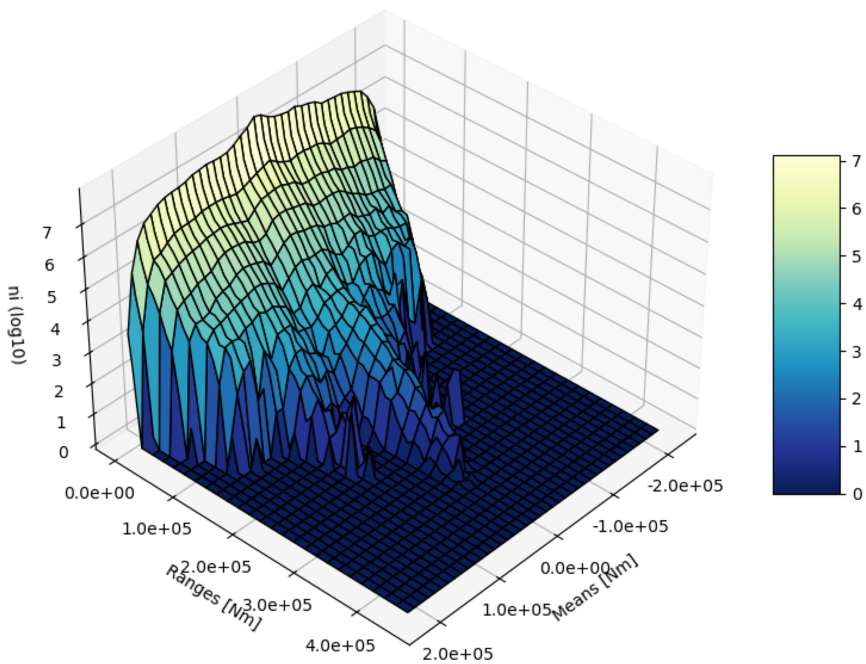

Figure 9. Example of a Markov matrix for bending loads near the tower base

Equation 2 is a simple formulation for the DEL if the S-N curve has a single slope, m_1, where n_{eq} is the reference number of cycles (usually equal to the lifetime in seconds for a 1-Hz cycle frequency), n_i is the number of cycles associated with the load range level, S_i.

$$DEL = \left(\frac{1}{n_{eq}} \sum_i n_i S_i^{m_1} \right)^{1/m_1} \qquad (2)$$

More complicated expressions can be derived to account for mean loads and for S-N curves with two slopes, with knowledge of the ultimate strength of the component detail under examination and S-N reference (curve knee) values (Figure 10).

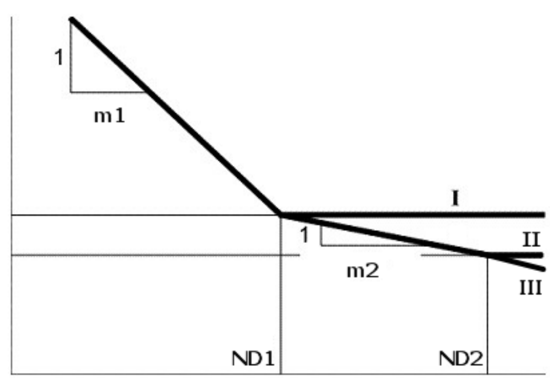

Figure 10. Example S-N curve with two slopes (m1 and m2)

Before arriving at Markov matrices and DELs, however, the results of the fatigue DLC simulations must be organized (weighted) according to the probability of occurrence of the various load situations (e.g., environmental conditions, faults, and start-up/shutdown events). A method must be devised to extrapolate the rainflow counted cycles for the various load channels to the entire lifetime of the distributed wind turbine. In the sample design load basis presented in (Table 25), we offer a possible procedure to determine the weighting to assign to the simulations based on the distribution of lifetime across the various fatigue limit state DLCs (Figure 11).

The procedure that will be employed to postprocess the fatigue limit state DLCs is documented in Figure 11 and Table 26. S-N curves and additional details will be provided in the design report document, including the finite element analysis used to verify the individual components starting from the determined driving load levels and DELs.

Table 25. Distribution of Lifetime Across DLCs Following IEC 61400-2

Fraction of Lifetime	V [m/s] 0	V_{in} – V_{rated} – V_{out}	$0.7V_{ref}$	State
A_v* T_{life}		DLC1.1b		running
(1- A_v)* T_{life}	Add to lowest bin →	DLC5.2		Idling or Parked
T_{life}			DLC5.2	Idling or Parked
N_{syr}*10'		N(v_j) shutdown DLC3.1		run/shutdown
N_{fyr}*10'		N(v_j) shutdown DLC2.2		run/shutdown

Table 26. FLS DLC output post-processing approach

Step	Description
1	Assign availability value A_v (OEM's best experience)
2	Simulate fatigue limit state DLCs per Section 3.3 and catalog all the output files from the numerical aeroelastic modeling simulations
3	Calculate the weighting factor to extrapolate the cycle count for the **power-production (DLC1.1b)** output file associated with the *j*-th wind speed bin (centered on $v_j \in [v_{in}, v_{out}]$) and the *s*-th turbulence seed (realization): $$W_j = \frac{T_{life}}{\sum_{s=1}^{n_s} T_{j,s}} A_v p(v_j) \quad (3)$$ where T_{life} is the design lifetime of the wind turbine in seconds, $T_{j,s}$ is the time elapsed in the time series (output file) in seconds, n_s is the number of realizations at that v_j, and $p(v_j)$ is the probability that the mean wind speed lies within the *j*-th wind speed bin as in Eq. 4 for a Rayleigh distribution:

Step	Description
	$$p(v_j) = e^{-\left(\frac{v_j - b_w/2}{\lambda}\right)^2} - e^{-\left(\frac{v_j + b_w/2}{\lambda}\right)^2} \quad (4)$$
4.	Calculate the weighting factor to extrapolate the cycle count for the **power production with fault (DLC 2.2)** output file associated with the *k*-th wind speed bin (centered on $v_k \in [v_{in}, v_{out}]$) and the *s*-th turbulence seed (realization): $$W_k = \frac{T_{life}}{\sum_{s=1}^{n_s} T_{k,s}} N_f(v_k) p(v_k) \quad (5)$$ $$N_f(v_k) = \frac{N_{f,yr}}{\sum_k p(v_k)} p(v_k) \quad (6)$$ where $T_{k,s}$ is the time elapsed in the time series (output file) in seconds; $p(v_k)$ is the probability that the mean wind speed lies within the *k*-th wind speed bin (same as in Eq. 4; $N_f(v_k)$ is the estimated number of faults per year within the *m*-th wind speed bin (weighted by the wind speed distribution) out of the total number of expected faults per year, $N_{f,yr}$.
5.	Calculate the weighting factor to extrapolate the cycle count for the **extreme wind (DLC 5.2)** output file associated with the *l*-th wind speed bin (centered on $v_l \in (0, 0.7 v_{ref}]$) and the *s*-th turbulence seed (realization): $$W_l = \begin{cases} \frac{T_{life}}{\sum_{s=1}^{n_s} T_{l,s}} p(v_l) \; if \; v_l \geq v_{out} \\ \frac{T_{life}}{\sum_{s=1}^{n_s} T_{l,s}} (1 - A_v) p(v_l) \; otherwise \end{cases} \quad (7)$$ where $T_{l,s}$ is the time elapsed in the time series (output file) in seconds, and $p(v_l)$ is the probability that the mean wind speed lies within the *l*-th wind speed bin (same as in Eq. 4. Note that, conservatively, the probability of $p(v_l < v_{in})$ can be added to that of the first bin centered on v_{in}.
6.	Calculate the weighting factor to extrapolate the cycle count for the **normal shutdown (DLC 3.1) (discrete)** output file associated with the *m*-th wind speed bin (centered on $v_m \in [v_{in}, v_{out}]$) and the *s*-th turbulence seed (realization): $$W_m = \frac{T_{life}}{\sum_{s=1}^{n_s} T_{m,s}} N_s(v_m) \quad (8)$$

Step	Description
	$$\mathrm{N_s(v_m)} = \frac{\mathrm{N_{s,yr}}}{\sum_{\mathrm{m}} \mathrm{p(v_m)}} \mathrm{p(v_m)} \quad (9)$$ where $N_s(v_m)$ is the estimated number of shutdowns per year within the m-th wind speed bin (weighted by the wind speed distribution) out of the total number of expected shutdowns per year, $N_{s,yr}$; $T_{m,s}$ is the time elapsed in the time series (output file) in seconds.
7.	Calculate the lifetime damage, D, based on all the time-series-scaled cycle counts following Miner's rule: $$D = \sum_i \sum_o \frac{W_o n_{i,o}}{N_i} \quad (10)$$ where $n_{i,o}$ is the number of cycles at the *i*-th load-range level from the *o*-th time series, and N_i is the number of cycles to failure associated with the factored ($\gamma_f \gamma_m \sigma_i$) stress range, which can also account for mean stress effects (Goodman, Gerber, or Soderberg corrections).

It is important to note the absence of fatigue loading considerations during transportation or installation in IEC (2013), as it assumes these phases are short in duration, which is in contrast to utility-scale wind energy installations.

In the previous steps, the wind speed probability is given by a Rayleigh distribution in alignment with IEC (2013). For components that do not rotate with the nacelle, such as the tower, the yaw bearing (lower race), and foundation, the assumptions that the load cycles are direction invariant render a conservative design for those components. Although excluded from certification to ACP (2021), the tower and foundation components could be designed and/or verified for specific site and wind regimes. In this case, the previously mentioned damage can then be redistributed in different directions (e.g., along sectors at the tower base) based on $p(\theta_q; v_o)$ (i.e., is the probability that, at the given wind speed v_o, the wind direction lies within the bin that is centered on θ_q).

For each wind directional sector, a damage, $D_{\theta,}$ can be calculated as in Eq. 11, where the new weighting factors, $W_{o,\theta}$, are calculated as in Eq. 3 but with $p(v_o)p(\theta_q; v_o)$ replacing the $p(v_o)$ terms:

$$D_\theta = \sum_i \sum_o \frac{W_{o,\theta} n_{i,o}}{N_i} \quad (11)$$

Finally, the procedure illustrated earlier assumes knowledge of the appropriate S-N curve for the component under examination and a determination of the stress range from the load range usually returned by the aeroelastic modeling simulations. That transfer function can be determined using simple analytical equations in some cases (IEC 2013), but for complicated parts (e.g., hub, mainframe, blade airfoil section) a finite element analysis may be required.

Together with the items mentioned earlier, it may be advisable, though not strictly required until the design evaluation phase, to share in the design load basis the assumed S-N curves and references for the certification body to review and approve.

3.4.4 Partial Safety Factors

PSFs account for uncertainties in the load assessment, the severity of the consequence of failure, and the material design resistance [see also Sorensen and Toft (2014) for a discussion on PSFs in the IEC 61400-1 design standard].

Generally speaking, the verification of limit states within a load and resistance factor design approach requires satisfying Eq. 12:

$$\gamma_f F_k \leq \frac{f_k}{\gamma_m \gamma_n} \tag{12}$$

where F_k is the characteristic load, f_k is the characteristic resistance, γ_f is the load PSF, γ_m is the material PSF, and γ_n is the consequence of failure PSF. For more details, refer to IEC (2019).

The design load basis should state what PSFs are utilized for the verification phase, and approval from the certification body should be received. Alternatively, a reference to appropriate design documents should be provided.

The load PSFs are indicated in IEC (2013) as γ_f=1.0 and 1.35 for the FLS and ULS, respectively. For dead loads that are well-known, a γ_f=1.0 can be used for the ULS. Aeroelastic-modeling-derived loads, however, usually include aeroelastic, inertial, and gravity loads, and separating the contribution is critical.

IEC (2013) also provides guidance for the FLS material PSFs for both composite and metal materials. In particular, "total factors" that are applied to the static ultimate material strength for glass-fiber-reinforced plastic and carbon-fiber-reinforced plastic (accounting for fatigue, environmental, reliability, and size effects) are provided in Annex E. This treatment, however, is less rigorous than following fatigue standards and references for composites and materials (e.g., CEN [2005]; Maniaci and Naughton [2019]; International Institute of Welding [2008]).

A more thorough treatment of PSFs is given in IEC (2019), where for ULS a distinction is made between the normal vs. abnormal situations, and between favorable and unfavorable loads. Additionally, separate PSFs for the consequence of failure (aka, importance factors, 0.9–1.3) are provided as a function of the type of component (e.g., "fail-safe" vs. "nonfail-safe" components). Considering ULS, IEC (2019) offers general material safety factors ($\gamma_m \geq 1.1$ generally applied to metal yield strength, or 1.2 for global buckling, or 1.3 for ultimate rupture). For FLS, a series of PSFs (loads (γ_f=1.0), consequence of failure (γ_n=1.0 – 1.3), and materials ($\gamma_m \geq 1.1$ – 1.7) are also provided.

Although it must be agreed upon by the certification body, it may make more sense to follow the more rigorous PSF treatment found in IEC (2019), and, for the choice of material PSFs, the best practice is to use appropriate recognized standards.

The load PSFs for our postprocessing are indicated in the load case table. The design report will show additional PSFs (i.e., material and consequence-of-failure PSFs) employed for the structural verification of the various parts.

3.4.5 Campbell Diagram

IEC (2013) requires that the main natural frequencies of a wind turbine be evaluated by conducting a modal analysis culminating in a "resonance diagram," also known as a Campbell diagram (Figure 11). The diagram must contain the natural frequencies of the system as a multicomponent assembly (e.g., rotor blade, drivetrain, and support structure [tower and guy wires as applicable]), which vary with the operational state (mainly rotor RPM), and the relevant excitations (e.g. rotor speed and multiples, 1P, 3P, 6P and so on for three-bladed rotors). The calculation of the natural frequencies is usually achieved through the eigenanalysis of a linearized and periodic solution of the model about a given state (e.g., RPM, blade pitch, yaw setting, generator torque). The aeroelastic modeling software manual can provide guidance on the eigenfrequency extraction (Larsen and Hansen 2019). Campbell diagrams can also be expressed in terms of natural frequencies and damping ratios as a function of mean hub-height wind speed, based on the expected operating point (e.g., rotational speed, blade pitch) at each wind speed. In this rendition, the diagram accounts for the full effect of the aerodynamics on the rotor blades and actual pitch settings, therefore it matches the reality of the wind turbine dynamics more closely.

Attention should be paid to avoid the occurrence of resonances in the operating speed range of the wind turbine. Furthermore, a discussion of the acceptance ranges for the support structure design should be provided to achieve certification. This discussion/documentation may contain a description of the vibration monitoring system, and alert, alarm, and avoidance triggering values, in case operation is sought within a resonance range.

For example, efforts toward avoiding resonance in tower fore-aft and side-side and blade flapwise and edgewise first bending modes should be discussed. Variable-speed distributed wind turbines may not necessarily suffer from resonance when the rotor speed intersects these mode frequencies due to the unsteady nature of the wind and limited rotor inertia. Nonetheless, if the possibilities of overlap between forcing and natural frequencies exist, any load amplifications shall be considered in the design of the structure. In some cases, it may be worth implementing a "frequency-hop" control function to skip resonance frequencies.

Given the quasi-constant speed nature of the machine, the tower's first natural frequency must lie above or below the 1P (0.63 Hz), with a 10% margin.

The calculated Campbell diagram is given in Figure 12*. No overlap between natural modes and forcing below 9P is expected at the rated (and constant for this induction machine) RPM. Below rated, the turbine will not be affected by resonance because it will be accelerating or decelerating toward rated or idling, respectively.*

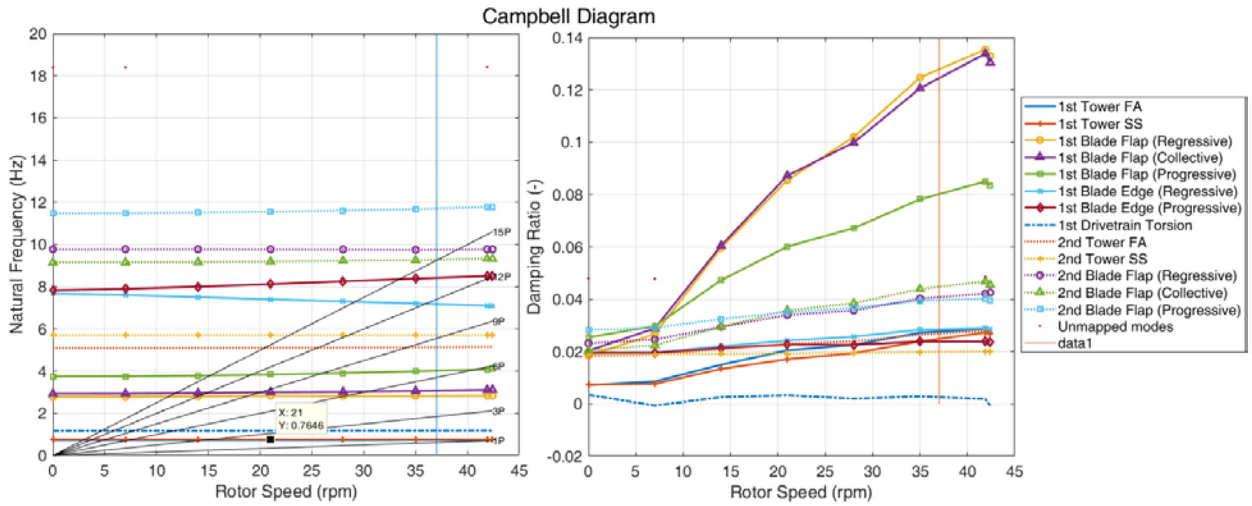

Figure 12. Campbell diagram, with the vertical line representing the rated RPM

4 Additional Items Toward Design Basis and Design Evaluation

In this section, we mention other aspects that will be required in addition to the design load basis for conformity assessment and certification and that are tied to the design load basis development and control.

As already discussed, the control and protection system should be mentioned in the design load basis and design basis, in terms of version and key characteristics, but the details can be left to the actual design report and its evaluation by the certification body. Other items are discussed next.

4.1 Design Procedure

The structural loads are to be assessed via integrated simulations of wind, aerodynamics, and structural dynamics on the WTG for several load cases. The simulations are performed with an aeroelastic code as described in Section 3.3.

A detailed description of the numerical model is typically given in the WTG type approval or certification documentation. The wind turbine design shall also be accompanied by a tower and foundation design (e.g., Table 27).

Table 27. Typical Design Process Including Tower and Foundation Assessment

Step	Description	Responsible Party
1. Turbine Preliminary Design	Preliminary sizing of blades, hub, shaft, gearbox, generator, bearings,	Turbine OEM
2. Modal Analysis	Generate a Campbell diagram, identify potential issues for resonances or instabilities and solutions	Turbine OEM
3. DLC and Environmental Conditions Selection	Generate wind files and set up simulation batch files	Turbine OEM
4. Aeroelastic Simulations and WTG Verification	Generate ULS, FLS, SLS, and ALS tables with driving loads	Turbine OEM
5. WTG Detailed Design	Finalize design of various components and repeat step 4	Turbine OEM
6. Assess Tower Design	Verify design and in case modify and regenerate aeroelastic modeling results (step 4)	Contractor, professional engineer, wind turbine OEM
7. Evaluate Foundation	Verify foundation stiffness (sensitivity analysis) for exemplary soil conditions; if insufficient, modify tower design	Contractor, professional engineer, wind turbine OEM

Note: ALS = accidental limit states

The design iterations for the WTG described in Table 26 are executed until:

- The blades, drivetrain, and bedplate are verified to withstand ultimate, fatigue, service, and accidental limit states.

The tower and foundation design iterations are executed until:

- The WTG's first eigenmodes (usually two) are within the required bandwidth
- The foundation and tower designs can withstand the assessed ultimate and fatigue load levels.

4.2 Design Control Management

Design control management is an important item to arrive at a certified product. The certification body will be able to verify the quality management process that includes design control management and the evolution of the design that reduces overall risk to the product and consumers.

If the wind turbine OEM already implements a quality management system, then the design control management is inherently applied and the certification body does not need to review it. However, in other cases, it is important to satisfy the certification body's requirements for document control. IEC (2010) mentions that the design control management should comply with ISO 9001 (ISO 2015) guidelines and that all related design documents should include revision status for the benefit of all parties. This includes control of the design basis and design load basis documents. Clause 7.3 in ISO (2015) demands that an entity control the design process by ensuring that customer requirements are met and the resulting products are reliable, safe, and meet applicable legal and regulatory requirements. This step entails a systematic approach to the design, including identifying design objectives, creating design and development plans, selecting appropriate methods and tools, and reviewing, verifying, and validating the design outputs.

It is recommended that, at a minimum, the OEM prepare the design basis and design load basis with some version control system and that drawings, spreadsheets, and other related documents be tagged and linked to a reciprocal identification and logging code system.

4.3 Design Failure Mode and Effect Analysis

Although not strictly needed for certification to IEC (2013), a design failure mode and effect analysis (DFMEA) is recommended for the design evaluation and type certification.

The fault analysis in the design basis usually includes a DFMEA matrix, in which all possible faults are listed together with their causes, detection, and monitoring devices, consequence of failure, and expected frequency of occurrence. This matrix allows us to quantify the total risk and identify possible prevention methodologies. Although it is not needed for the design load basis, it may be useful in understanding how to set up the aeroelastic modeling simulations; therefore, it can be an effective tool for the actual design. For example, the various faults can be identified in the DFMEA matrix and appropriate simulation parameters can be chosen to include the worst-case scenarios.

The DFMEA matrix helps assess whether the design of the new turbine is safe or new modifications are needed. It is normally used to identify potential failure modes and their impact on reliability, thereby establishing a ranking based on the risk priority number.

An example DFMEA is given in Table 31. The severity of the fault is assigned based on Table 28, whereas the values for probability of failure and detectability of the fault are based on Table 29 and Table 30. These are guidelines, but the certification body may recommend alternatives.

Table 28. Values for the Severity of Effects Associated With a Failure Mode; To Be Used in the Design Failure Mode and Effect Analysis

Effect	Severity of Effect	Ranking
Hazardous without	Very high severity ranking when a potential failure mode affects safe system operation without warning	10
Hazardous with warning	Very high severity ranking when a potential failure mode affects safe system operation with warning	9
Very high	System inoperable with destructive failure without compromising safety	8
High	System inoperable with equipment damage	7
Moderate	System inoperable with minor damage	6
Low	System inoperable without damage	5
Very low	System operable with significant degradation of performance	4
Minor	System operable with some degradation of performance	3
Very minor	System operable with minimal interference	2
None	No effect	1

Table 29. Values for the Probability of Occurrence Associated With a Failure Mode; To Be Used in the Design Failure Mode and Effect Analysis

Probability of Failure	Failure Prob	Ranking
Very high: Failure is almost inevitable	> 1 in 2	10
	1 in 3	9
High: Repeated failures	1 in 8	8
	1 in 20	7
Moderate: Occasional failures	1 in 80	6
	1 in 400	5
	1 in 2,000	4
Low: Relatively few failures	1 In 15.000	3
	1 in 150.000	2
Remote: Failure is unlikely	in 1,500.000	1

Table 30. Detectability Values Associated With a Failure Mode; To Be Used in the Design Failure Mode and Effect Analysis

Detection	Likelihood of Detection by Design Control	Ranking
Absolute uncertainty	Design control cannot detect potential cause/mechanism and subsequent failure mode	10
Very remote	Very remote chance the design control will detect potential cause/mechanism and subsequent failure mode	9
Remote	Remote chance the design control will detect potential cause/mechanism and subsequent failure mode	8
Very low	Very low chance the design control will detect potential cause/mechanism and subsequent failure mode	7
Low		6
Moderate	Moderate chance the design control will detect potential cause/mechanism and subsequent failure mode	5
Moderately high	Moderately high chance the design control will detect potential cause/mechanism and subsequent failure mode	4
High	High chance the design control will detect potential cause/mechanism and subsequent failure mode	3
Very high	Very high chance the design control will detect potential cause/mechanism and subsequent failure mode	2
Almost certain	The design control will detect potential cause/mechanism and subsequent failure mode	1

Table 31. Example of Design Failure Mode and Effect Analysis Matrix

Item/ Function	Failure Mode	Effect of Failure	Severity	Cause/ Mechanism of Failure	Probability	Current Design Controls	Detectability	Risk Priority #	Aeroelastic Modeling Notes
Pitch Actuators	All three actuators seize due to compressor/ reservoir leak under PARK	No power production, but safe configuration	5	Leak in the compressor/ reservoir line	3	Pressure sensor + no power production/RPM recorded while wind is above cut-in; locking pin will be engaged holding the blades in PARK	1	15	DLC 7.1 (61400-1) or 5.1 (61400-2)
	One or two actuators stuck in PARK	Turbine cannot run	5	Leak in the lines or reservoirs of individual blades/stuck pins	4	Same as above	1	20	DLC 7.1 (61400-1) or 5.1 (61400-2)
	One or two actuator tanks lose pressure during RUN	Slow stop	5	Air leaks	4	Checked loads with simulations	5	100	DLC 2.1-2.3, 2.4 (61400-1) or DLC 2.1-2.2-2.3 (61400-2)
	Three actuator tanks lose pressure while in RUN, generator is down, and no other brake	Turbine cannot stop—overspeed	10	Air leaks, grid failure	1	Very low probability of occurrence, three check valves need to fail while all tanks or hoses fail	10	100	DLC 2.2, 2.3, 2.4 (61400-1) or DLC 2.1, 2.2, 2.3 (61400-2)
	One to two actuator tanks lose pressure while in RUN, gen is down, and no other brake	Slow stopping	5	Air leaks, grid failure	3	Similar to above cell	1	15	DLC 2.1-2.3, 2.4 (61400-1) or DLC 2.1-2.2-2.3 (61400-2)

Item/ Function	Failure Mode	Effect of Failure	Severity	Cause/ Mechanism of Failure	Probability	Current Design Controls	Detectability	Risk Priority #	Aeroelastic Modeling Notes
Pitch Actuators	One to three actuator tanks lose pressure while in RUN, generator is ON, and brake available	Slow stopping/wear of brake	3	Air leaks	7	Pressure sensor	1	21	DLC 2.2, 2.3, 2.4 (61400-1) or DLC 2.1, 2.2, 2.3 (61400-2)
Pitch Actuators	One actuator shaft failure or extender pitch-plate failure	No pitch control on one blade, one blade stuck at RUN, slow stopping/no start	5	Poor quality assurance/quality control of actuator	2	Pressure sensor+ no power production/RPM recorded while wind is above cut-in	1	10	DLC 2.1-2.3,2.4, 6.4,7.1 (61400-1) or DLC 2.1, 2.2, 2.3, 6.1 (61400-2)
	Compressor failure	Wind turbine not running	5		6	Low pressure detected	1	30	DLC 7.1 (61400-1) or 5.1 (61400-2)
	Freezing in one line from the tank reservoir to valve	Cannot pitch one blade to PARK (see actuator failure)	5	Failure of drainage	5	This is a double failure so the P is calculated as P1*P2, the rank is calculated as mean (P1r, P2r)	1	25	(See actuator failure)

Item/ Function	Failure Mode	Effect of Failure	Severity	Cause/ Mechanism of Failure	Probability	Current Design Controls	Detectability	Risk Priority #	Aeroelastic Modeling Notes
Other Pneumatic Failures	Dump valve stuck closed	Blade stuck in RUN, slow stopping	5	Wear/grit accumulation	5	Pitch sensor detection, redundancy	1	25	DLC 2.1-2.3, 2.4 (61400-1) or DLC 2.1-2.2-2.3 (61400-2)
Other Pneumatic Failures	Dump valve stuck open	Blade cannot be put into RUN, turbine will not operate	5	Wear/grit accumulation	4	Pitch sensor detection, redundancy	1	20	DLC 7.1 (61400-1) or 5.1 (61400-2)
Pitch Bearing	Seize of one bearing in RUN or close to RUN	Slow stopping	5	Lack of lubrication, and so on	3	Pitch sensor detection	10	150	DLC 2.1-2.3, 2.4, 6.4, 7.1 (61400-1) or DLC 2.1, 2.2, 2.3, 6.1 (61400-2)
	Seize of one bearing in PARK	Blade cannot be pitched to RUN, turbine will not operate	3	Lack of lubrication, and so on	3	Pitch sensor detection	1	9	DLC 7.1 (61400-1) or 5.1 (61400-2)
	Catastrophic failure	Blade thrown	10	Fatigue of bearing race – under-designed bearing	1	SKF engineering review of the loads	10	100	N/A

Item/ Function	Failure Mode	Effect of Failure	Severity	Cause/ Mechanism of Failure	Probability	Current Design Controls	Detectability	Risk Priority #	Aeroelastic Modeling Notes
Mechanical Brake	Failure to apply during startup	Rotor might spin backward, no serious gearbox damage, slow start	3	Pads very worn	3		10	90	DLC 3.1-3.3 (61400-1)
	Failure to release from PARK	Wind turbine will not run	6	Pneumatic failure	5	Wind is greater than cut-in and no power	1	30	DLC 6.1-6.4 (61400-1) or 6.1 (61400-2)
	Failure during emergency (see actuators)								(See actuators)
Slip Ring	Failure to conduct	Pressure sensors offline, turbine will shutdown	5	Wear, or electrical open circuit	4	Pressure sensor warning	1	20	DLC 4.1, 4.2, 5.1 (61400-1) or DLC 3.1, 3.2, 4.1 (61400-1)
	Failure to conduct	Valves lose power, turbine will shut down	5	Wear, or electrical open circuit	4	Pitch sensor detection, redundancy	5	100	DLC 4.1, 4.2, 5.1 (61400-1) or DLC 3.1, 3.2, 4.1 (61400-1)
Slip Ring	Valves always powered, blade cannot be placed in PARK	Slow stopping assuming only one blade is affected	5	Electrical short	4	Pitch sensor detection, redundancy	1	20	DLC 2.1-2.3, 2.4 (61400-1) or DLC 2.1, 2.2, 2.3 (61400-2)
Yaw system	Seizes in high winds	Possible high loads if left with yaw	9	Lack of lubrication	1	Field experience does not show this to be a problem, yaw error should be detected	6	54	DLC 2.1-2.3, 2.4, 6.3 (61400-1) or DLC 2.1, 2.2, 2.3, 5.1 (61400-2)

Item/ Function	Failure Mode	Effect of Failure	Severity	Cause/ Mechanism of Failure	Probability	Current Design Controls	Detectability	Risk Priority #	Aeroelastic Modeling Notes
		error under extreme winds							
	Seizes in low winds	Turbine won't produce electricity and suffer more fatigue	4	Lack of lubrication	2	Limited power production due to yaw errors, yaw error should be detected	6	48	DLC 2.4, 6.4 (61400-1) or DLC 2.2 (61400-2)

4.4 Conformity Assessment

The design load basis is only one of the documents that must be provided to the certification body in support of the type certification, but the certification body would not issue any statement with respect to design evaluation conformity until all required documents are submitted. To reach full compliance for the design evaluation, IEC (2019) and IECRE (2022) must be followed thoroughly. The conformity statements are issued upon successful completion of the design evaluation of specific certification modules (IECRE 2022) and accompany the final evaluation report. Relevant conformity statements are issued following the successful evaluation of the design basis, the design documents, manufacturing, and type testing. Normally, a certification body issues either a type certificate or a component certificate. For certification to ACP (2021), a type certificate for the rotor nacelle assembly is issued but not a full type certificate, which usually covers the tower and foundation requirements as well.

Furthermore, ACP (2021) provides the technical requirements for conformity assessment as a function of wind turbine peak power based on structural design and type testing.

This report was developed to help create the design load basis and design basis, and support the design process and issuing of design documents for the design evaluation and issue of conformity statements and certification by the certification body.

4.5 Discussion of Simplified Loads Methodology and Direct Load Measurements

ACP (2021) requires (at a minimum) that the strength evaluation include the blade, blade root to hub connection, hub, main shaft, bearings, yaw shaft, connection to the tower, critical safety/protection systems and components, and nacelle frame. ACP (2021) further states that the rest of the structure must be checked to verify that sound engineering practices have been employed in the design to maintain the normal operation of the wind turbine and for preventing any potential hazards. IEC (2013) more widely states that the ultimate and fatigue strength of all structural members (including the tower) must be verified by calculations or tests, or a combination of both, to determine the structural integrity of a small wind turbine with the appropriate safety level. To determine the design loads, IEC (2013) allows three ways: simplified loads methodology, aeroelastic modeling, and full-scale load measurements (IEC 2015). The simplified loads methodology can only be applied to HAWTs with rigid hubs and uses a set of simple equations to determine loads in key DLCs based on predetermined design values (e.g., design rotor speed, wind speed, and maximum yaw rate).

ACP (2021) allows wind turbine OEMs to use the simplified loads methodology for turbines seeking certification if their peak power is less than 30 kW, though this methodology is discouraged above a peak power of 10 kW. The simplified loads methodology uses simple equations for key load components (e.g., the blade-root flapwise bending moment), but there is some room for interpretation on how to verify the various parts when the other load components are not prescribed (e.g., blade-root shear and edgewise bending) in the same DLC. Engineers should use their best judgment to include all the load components conservatively. Because of these drawbacks and other underlying uncertainties, such as determining the appropriate partial PSFs for the simplified loads methodology when valid experimental evidence suggests lower PSF values, a design load basis for the simplified loads methodology may also be issued and shared for evaluation by the certification body. In general, these difficulties and the lack of guidance in the design load basis for the simplified loads methodology encourage turbine manufacturers to rely on aeroelastic modeling, which can also take advantage of lower PSFs for a more cost-effective design.

Direct load measurements are to be taken under conditions as close as possible to the aeroelastic modeling DLCs described in Section 3.3 and extrapolation performed to IEC (2015). Load measurements should be performed at or under the guidance of an accredited laboratory and personnel, and it is an undertaking not easily handled by distributed wind turbine OEMs. For this reason, we recommend that load measurements be pursued for aeroelastic modeling V&V rather than to achieve direct measurements for load assessment, component verification, and certification.

Finally, it is worth noting that ACP (2021) does allow microturbines (peak power less than 1 kW) to be certified without any modeling (simplified loads methodology or aeroelastic modeling) or load measurements but still requires three of the five typical type tests to be performed: power performance, safety and function, and duration.

4.6 Verification and Validation Plan

To conclude this discussion on items of the design basis and design evaluation that relate to the design load basis, we must mention V&V efforts. The use of modeling to support the design of wind energy systems can reduce the number of design, build, and test cycles. However, experimental testing in support of model development and model assessment is critical. When using aeroelastic modeling to calculate design loads and arrive at component verification, quantifiable confidence in the results of the analysis should be demonstrated to achieve certification.

Code verification is performed to determine whether the computational model fits the mathematical description, whereas code validation determines whether the model accurately represents the real-world application.

Associated with V&V, uncertainty quantification is conducted to determine how variations in the numerical and physical parameters affect simulation outcomes. Several resources (American Society of Mechanical Engineers 2009, 2012; Maniaci and Naughton 2019; American Institute of Aeronautics and Astronautics 1998; Hills, Maniaci, and Naughton, 2015) can be leveraged to establish a program of V&V to provide confidence in the aeroelastic modeling results. Generally speaking, a V&V framework emphasizes collaboration between modelers, experimentalists, and third-party subject matter experts to plan and implement the required procedures, but guidance from the certification body should be requested and have priority in the program to ensure a clear path to certification.

The design load basis might include a framework for V&V, especially in the case of innovative components and modeling features.

IEC is currently working on new standards that outline V&V requirements for loads calculations, and NREL's dWAM program will be investigating this topic further in the next phase of the project. More guidance on these aspects for the design load basis will become available through the publications resulting from these research efforts.

5 Conclusions and Final Remarks

This document presents the key elements of the design load basis, an integral part of the design and certification of a distributed wind turbine. This effort was conducted in response to the many aeroelastic modeling challenges and uncertainties that face stakeholders in the distributed wind energy industry (Damiani and Davis 2022) and that are being tackled by NREL's dWAM project.

The design load basis provides the foundation for the structural design of a wind turbine's rotor nacelle assembly and tower and describes the methods applied to the loads analysis and its postprocessing for assessing the structural limit states. It contains the key environmental parameters used in the aeroelastic modeling simulations, a description of the numerical model, the load case table, and an interpretation of how the final load level is determined. Together with the parent design basis, the design load basis is a live document that can be updated during the project to serve conceptual through detail design phases and possibly O&M. Because one of the goals of the design and certification standards is to guarantee a high level of safety, it is not surprising that the design basis/design load basis package should address aspects of human safety, in particular, the designers should have a clear understanding of the safety class for their wind turbine, and have it validated by the certification body, as that determines any potential deviations/exceptions on PSFs or DLCs to be applicable.

This document only covers the key structural components and does not address all the aspects that may be covered by a design load basis; in particular, there was no detailed discussion on the electrical and interconnection requirements and loading, or the verification of electrical components (e.g., generator, inverter, electrical coupling and slip rings, lightning protection). Additionally, there are some specific aspects of the structural design that are not fully covered in this guidance. This is driven by the fact that the design and certification standards allow for a simplification or deferral of the associated requirements. For example, the verification of the foundation design and its interface with the tower, which should be carefully addressed in the design phase, are not a requisite for certification, and only acceptable rotational stiffness ranges can be provided to satisfy the standards prescriptions.

Although no specific prescription exists for a design load basis document, this document provides a Table of Contents that can be followed for both the design and certification of a distributed wind turbine. Reference has been made to the most relevant design standards for U.S. certification (ACP 2021; IEC 2013), but other standards were mentioned especially for situations and load cases wherein the main two lacked information and guidance. Moreover, this document can be used as a template for creating a new design load basis for typical distributed wind HAWTs. Examples of the various design load basis sections were provided based on a downwind HAWT that we recently developed.

One of the main contributions of this document is the detailed description of the inputs and parameters that are needed for the various DLC setups, including the details of fault simulations. The aeroelastic modeling end user may make use of this DLC guide to complement what is in IEC (2013) to set up and process the numerical simulations. Furthermore, we provided an example of a load case table, a required component of the design load basis in pursuit of certification.

Details of ULS and FLS verification, which are largely missing or vague in the primary reference design standard (IEC 2013) were clarified. In particular, we presented a framework for the FLS analysis that allows for the interpretation and postprocessing of the aeroelastic modeling results from multiple numerical realizations and different DLCs within the lifetime of the wind turbine.

Finally, we discussed other items that complement the design load basis toward design and type certification, among which V&V and DFMEA. When using aeroelastic modeling to calculate design loads, quantifiable confidence in the results of the analysis should be demonstrated to achieve certification. The design load basis can support V&V activities lending confidence in the results. Although not strictly required for certification under IEC (2013), a DFMEA is recommended for design evaluation and type certification. A DFMEA helps quantify the overall project risk and can guide the setup of aeroelastic modeling simulations by identifying potential failure modes and determining appropriate simulation parameters to address worst-case scenarios.

Within the continued efforts in the dWAM project, this document could be used to create a package encompassing:

- A reference wind turbine model
- A design basis/design load basis
- A loads and performance report containing:
    - Detailed modal (Campbell diagrams) information
    - Load information (ULS and FLS loads on all major components, blade, hub, shaft, tower top, and base at a minimum for all the relevant DLCs in the design standards (IEC 2013)
    - Performance information (e.g., rotor and generator power, torque, and rotor thrust at a minimum)
- A verification and validation report against available and recently collected data at NREL.

As outlined in RRD Engineering, LLC (2023d), the package would synergistically augment V&V efforts within dWAM by generating "template" reports as discussed in (Damiani and Davis 2022). This future effort would significantly help the industry toward both the building and troubleshooting of a new model as well as the numerical model validation.

In addition, as this document is used in practice, we anticipated that areas for improvement and refinement will become evident. The application of the methodologies and guidelines outlined here will likely uncover opportunities to enhance clarity, fill in gaps, and address emerging challenges. Feedback from stakeholders and practical experiences will play a crucial role in evolving this document, ensuring it remains a relevant, robust, and invaluable tool for future design and certification processes.

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