DNV·GL

RECOMMENDED PRACTICE

DNVGL-RP-0363 Edition April 2016

Extreme temperature conditions for wind turbines

DNV GL AS

FOREWORD

DNV GL recommended practices contain sound engineering practice and guidance.

Any comments may be sent by e-mail to *rules@dnvgl.com*

CHANGES – CURRENT

General

This is a new document.

CONTENTS

Contents

SECTION 1 INTRODUCTION

1.1 Preamble

This DNV GL recommended practice (RP) provides principles and technical requirements for wind turbines in extreme temperature conditions – both onshore and offshore.

This DNV GL RP can be applied as part of the technical basis for carrying out type certification of wind turbines, or component certification, or project certification.

Guidance note:
The present DNV GL RP will cover the technical requirements to be applied for the DNV GL certification schemes. It is also intended for application in connection with IEC 61400-22 related certification schemes.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

This DNV GL RP is intended to be applied in its entirety. Nevertheless, certain parts of it may be omitted if the applied certification scheme allows for such reduction in scope, and provided this is properly documented as a part of the certification process.

All requirements specified in this RP shall be fulfilled. Deviations from these requirements, or the application of alternative means of complying with these requirements, may be acceptable after consultation and agreement with the certification body, provided that an equivalent level of safety and reliability can be demonstrated.

1.2 General

This RP provides principles, technical requirements, and guidance for design, and documentation of wind turbines in extreme temperatures. The RP may be used for the design of on- and offshore wind turbines in extreme tempeartures, which are outside the normal temperature range requirements in the present codes and standards such as /1/, /2/, /3/. Further, ice accumulation is outside the scope of this RP.

1.3 Objectives

The objectives of this RP are to:

— provide an internationally acceptable level of safety, reliability, and durability by defining minimum requirements for wind turbines in extreme temperatures (in combination with referenced standards, recommended practices, guidelines, etc.,)
— provide guidance for determination of loads and advice the analysis methods as relevant for operational (FLS and SLS) and extreme (ULS) conditions, however, not accidental conditions (ALS) implicated by the extreme temperatures
— serve as a guideline for designers, suppliers, purchasers, and regulators
— serve as basis for the design of wind turbines exposed to extreme temperatures.

1.4 Scope and application

This RP is applicable to all types of wind turbines intended for installation in sites with extreme temperatures. The RP is also applicable to the design of components for the wind turbines in extreme temperatures.

This RP cover the following topics:

— external conditions
— design loads
— control and protection system
— manuals
— rotor blades
— mechanical components
— electrical components
— support structures – steel and concrete.

1.5 Certification

Certification principles and procedures related to certification services for wind turbines are specified in relevant DNV GL service specifications /7/, /8/, or GL guidelines /2/, /3/.

1.6 Testing

If testing is done to demonstrate any function or property of an equipment or material, all such tests shall be in compliance with the requirements set out in the corresponding certification scheme.

Guidance note:

A test plan should be established, which contains the following information as a minimum:

- precise description of the tests to be performed including boundary and test conditions
- measurement parameters to be recorded along with the planned resolution of the measurement data
- expected test results and success criteria.

The test results should be documented in a test report, which should include the following as a minimum:

- documentation on measurement set-up
- documentation on component types used and serial numbers (for example, hydraulic aggregate, motor, accumulator, etc.,)
- calibration information of the measuring equipment
- test results (plots of measurement parameters), its evaluation and a final conclusion.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

1.7 References

The following references constitute type and project certification of wind turbines:

Table 1-1 References

/1/	IEC 61400-1, Wind turbines – Part 1: Design requirements.
/2/	GL Rules and Guidelines – IV Industrial Services – Part 1 – Guideline for the certification of wind turbines, Edition 2010.
/3/	GL Rules and Guidelines – IV Industrial Services – Part 2 – Guideline for the certification of offshore wind turbines, Edition 2012.
/4/	IEC 61400-3, Wind turbines – Part 3: Design requirements for offshore wind turbines.
/5/	IEC 61400-22, Wind turbines – Part 22: Conformity testing and certification.
/6/	IEC 61400-2, Wind turbines – Part 2: Design requirements for small wind turbines.
/7/	DNVGL-SE-0074, Type and component certification of wind turbines according to IEC 61400-22, December 2014.
/8/	DNVGL-SE-0073, Project certification of wind farms according to IEC 61400-22, December 2014.
/9/	DNVGL-SE-0077, Certification of fire protection systems for wind turbines, March 2015.
/10/	DNVGL-ST-0376, Rotor blades for wind turbines, December 2015.
/11/	DNVGL-ST-0126 Design of wind turbine support structures.
/12/	DNVGL-OS-C101, Design of offshore steel structures, general – LRFD method, July 2015.
/13/	ISO 75-2, Plastics – determination of temperature of deflection under load – Part 2: plastics and ebonite.
/14/	ISO 6721-1, Plastics – determination of dynamic mechanical properties – Part 1: general principles.
/15/	EN 1993-1-10, Eurocode 3: Design of steel structures – Part 1-10: Material toughness and through-thickness properties.
/16/	ISO 898-1, Mechanical properties of fasteners made of carbon steel and alloy steel – Part 1: Bolts, screws and studs with specified property class – coarse thread and fine pitch thread.
/17/	IEC 60529, Degrees of protection provided by enclosures (IP code).
/18/	IEC 60068-2, Environmental testing Part 2: Tests.
/19/	DNVGL-SE-0124, Certification of grid code compliance, March 2016.

1.8 Definitions

1.8.1 Verbal forms

Table 1-2 Definitions of verbal form

Term	*Definition*
shall	verbal form used to indicate requirements strictly to be followed in order to conform to this document
should	verbal form used to indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required
may	verbal form used to indicate course of action permissible within the limits of the document

1.8.2 Terms

Table 1-3 Definitions of terms

Term	*Explanation*
high temperature (HT)	the wind turbine is designed for operation at ambient temperature above +40°C and corresponding extreme temperature above +50°C
low temperature (LT)	the wind turbine is designed for operation at ambient temperature below -10°C and corresponding extreme temperature below -20°C
normal temperature (NT)	the wind turbine is designed for operation at ambient temperatures in the range of -10°C to +40°C and corresponding extreme temperature range of -20°C to +50°C

1.9 Acronyms, abbreviations, and symbols

Table 1-4 Definitions list

Term	*Definition*
IEC	International Electrotechnical Commission
$\theta_{mean,year}$	annual average ambient temperature (hourly mean value) [°C]
$\theta_{min,operation}$	minimum allowable ambient temperature for wind turbine operation (instantaneous value) [°C]
$\theta_{max,operation}$	maximum allowable ambient temperature for wind turbine operation (instantaneous value) [°C]
$\theta_{1year,min}$	minimum ambient temperature to be expected in hourly average [°C] (recurrence period 1 year)
$\theta_{1year,max}$	maximum ambient temperature to be expected in hourly average [°C] (recurrence period 1 year)
$\rho(\theta_{mean,year})$	air density for annual average ambient temperature $\theta_{mean,year}$ [kg/m^3]
$\rho(\theta_{min,operation})$	air density for low temperature design load cases at minimum allowable ambient temperature for wind turbine operation $\theta_{min,operation}$ [kg/m^3]
$\rho(\theta_{1year,min})$	air density for low temperature design load cases at minimum ambient temperature to be expected in hourly average $\theta_{1year,min}$ [kg/m^3]
$\theta_{min,area}$	minimum allowable internal survival temperature for a component within the named area (instantaneous value) during an ambient temperature outside the wind turbine of $\theta_{1year,min}$ [°C]
$\theta_{max,area}$	maximum allowable internal survival temperature for a component within the named area (instantaneous value) during an ambient temperature outside the wind turbine of $\theta_{1year,max}$ [°C]
$\theta_{min,area,operation}$	minimum allowable internal temperature for the operation of a component / device within the named area (instantaneous value) during the operation of the wind turbine at an ambient temperature outside the wind turbine of $\theta_{min,operation}$ [°C]
$\theta_{max,area,operation}$	maximum allowable internal temperature for the operation of a component / device within the named area (instantaneous value) during the operation of the wind turbine at an ambient temperature outside the wind turbine of $\theta_{max,operation}$ [°C]
$\Delta\theta_{area}$	the temperature difference between the prescribed area of the component and its surroundings [°C]
$\Delta\theta_{area,operation}$	the temperature difference between the prescribed area of the component and its surroundings during the operation of the wind turbine [°C]
ALS	accidental limit states
DLC	design load case
ECD	extreme coherence gust with direction change

Table 1-4 Definitions list (Continued)

Term	*Definition*
EDC	extreme direction change
EOG	extreme operating gust
ETM	extreme turbulence model
EWM	extreme wind speed model
EWM1	extreme wind speed model with recurrence period of 1 year
EWS	extreme wind shear
FLS	fatigue limit states
HT	high temperature
LT	low temperature
NT	normal temperature
NTM	normal turbulence model
NWP	normal wind profile
PMG	permanent magnet generator
SLS	serviceability limit states
ULS	ultimate limit states

SECTION 2 EXTERNAL CONDITIONS

2.1 General

The external conditions to be considered for the design are dependent on the intended site or site type (low / high temperature) for a wind turbine installation.

If minimum temperatures below -20°C have been observed during long term measurements (preferably ten years or more) on an average of more than nine days a year, the site is defined as a Low Temperature site. The nine-day criteria is fulfilled if the temperature at the site remains below -20°C for one hour or more on the respective days. In this case, special requirements for the wind turbine and its support structure shall be observed and both shall be designed for Low Temperature.

Similarly, if maximum temperatures above +50°C have been observed during long term measurements (preferably ten years or more) on an average of more than nine days a year, the site is defined as a High Temperature site. The nine-day criteria is fulfilled if the temperature at the site remains above +50°C for one hour or more on the respective days. In this case, special requirements for the wind turbine and its support structure shall be observed and both shall be designed for High Temperature.

For low or high temperature conditions, the designer needs to specify appropriate normal and extreme temperatures along with corresponding air density. If necessary, allowable operating temperature ranges for all or relevant wind turbine components including electrical cabinets and transformers need to be specified/documented. The following ambient temperatures and air densities shall be specified as a minimum:

$\theta_{mean,year}$	annual average ambient temperature (hourly mean value) [°C]
$\theta_{min,operation}$	minimum allowable ambient temperature for wind turbine operation (instantaneous value) [°C]
$\theta_{max,operation}$	maximum allowable ambient temperature for wind turbine operation (instantaneous value) [°C]
$\theta_{1year,min}$	minimum ambient temperature to be expected in hourly average (recurrence period 1 year) (minimum value) [°C]
$\theta_{1year,max}$	maximum ambient temperature to be expected in hourly average (recurrence period 1 year) (maximum value) [°C]
$\rho(\theta_{mean,year})$	air density at $\theta_{mean,year}$ [kg/m^3]
$\rho(\theta_{1year,min})$	air density at $\theta_{1year,min}$ [kg/m^3]
$\rho(\theta_{min,operation})$	air density at $\theta_{min,operation}$ [kg/m^3]

For LT, the air density used for load calculation and in the determination of the power curve shall be calculated by applying the ideal gas law and the standard air pressure of 101325 N/m^2 (at sea level).

The temperature value $\theta_{1year,min}$ can be set to $\theta_{1year,min}$ +35°C and $\theta_{min,operation}$ can be set to $\theta_{min,operation}$ +25°C for determining the air density accordingly. The increase by 35°C and 25°C respectively is equivalent to definitions of the normal temperature conditions (NT). The standard air density for normal temperature conditions is 1.225 kg/m^3 referring to +15°C. The ambient temperature range for normal temperature condition is -10°C to +40°C, being +15°C ± 25°C. The extreme temperature range for normal temperature condition is -20°C to +50°C, being +15°C ±35°C. The $\theta_{mean,year}$ remains unchanged.

The following equation shall be used to calculate temperature-dependent air density:

$$\rho(\theta) = \frac{p}{R \times \theta}$$

where,

p = 101325 N/m^2, atmospheric pressure at sea level

R = 287 J/(kg · K), universal gas constant

θ = $\theta_{1year,min}$ + 35°C to calculate $\rho(\theta_{1year,min})$, the temperature value used shall be in Kelvin

θ = $\theta_{min,operation}$ + 25°C to calculate $\rho(\theta_{min,operation})$, the temperature value used shall be in Kelvin

While using the above equation, please note that as the universal gas constant is expressed in terms of Kelvin, the corresponding temperature values need to be converted to the consistent unit (Kelvin).

Corrections for different altitudes may be applied.

SECTION 3 DESIGN LOADS

3.1 Influence of extreme temperature

The following shall be considered for load calculations:

The air density shall be corrected in relation to the corresponding air temperature for each load case and the altitude at the site. The corrected air density should be considered in the load calculation and in the determination of the power curve.

The mechanical properties of the materials used shall be selected according to the ambient temperatures. Especially the temperature dependent influence of elastomer on the spring and damping characteristics of the drive train and adjacent components should be taken into account (see also Sec.6).

Operation at extreme temperature (low and high) conditions may have an impact on drive train losses, damping, and pitch system response. These shall be taken into account, if found applicable. If a correlation between extreme wind and temperature conditions exists, the respective combinations shall be considered for the appropriate load cases.

Strongly differentiated thermal expansion as a consequence of different thermal expansion coefficients and / or major temperature gradients may change the system rigidity e.g. by means of modification of the bearing pre-load, bolt pretension etc. Resulting significant additional loads for single components are to be considered in the design.

3.2 Load cases

The load calculation shall consider the modified temperature range. The loads are primarily affected by the change in air density.

Guidance note:
The altered air density resulting to a shift in turbine operational point may result to:

- changes in the power curve
- unfavourable turbine controller behaviour
- increase in start-stop cycles for turbines with/without de-icing systems
- premature and unwanted stall behaviour of turbine blades.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

3.2.1 High temperatures

Regarding high temperature conditions, as the air density decreases in higher ambient temperature, the loads are not expected to increase. If relevant, further considerations similar to low temperature conditions may be carried out.

3.2.2 Low temperatures

Calculation of the loads for fatigue analysis should be performed at $\theta_{mean,year}$ (at the air density value of $\rho\ (\theta_{mean,year})$).

For the determination of extreme loads, the extreme temperature (1 year recurrence period), $\theta_{min,operation}$, shall be combined with normal external conditions (normal turbulence model (NTM), normal wind profile (NWP)).

The conditions after occurrence of a fault (DLC 7.1, applying the extreme wind speed model with recurrence period of 1 year (EWM1)) shall be combined with the extreme temperature, $\theta_{1year,min}$, with a recurrence period of 1 year.

Extreme external conditions with a recurrence period of 50 years (extreme turbulence model (ETM), extreme wind shear (EWS), extreme wind speed model (EWM), extreme operating gust (EOG), extreme coherent gust with direction change (ECD), and extreme direction change (EDC)) shall be combined with the mean temperature $\theta_{mean,year}$. If wind conditions and temperatures at the site can be correlated, this correlation shall be taken into account.

For DLC 8.x, an extreme temperature for transport, erection, maintenance, and repair may be defined and this temperature may be used as an alternative to the extreme temperature, $\theta_{1year,min}$. This has to be considered in the manuals.

Extreme conditions due to low temperatures and earthquake may not be considered at the same time. Load cases with earthquake conditions applied should be combined with $\theta_{mean,year.}$

3.3 Load analysis

Load analysis shall be carried out according to the standards / guidelines under consideration, e.g.: /1/, /2/, /3/ etc.

3.3.1 Low temperatures

For further evaluation of the gear box, the extreme loads in the hub coordinate system N (e.g. for designing the torque arm) and in the rotor coordinate system R (e.g. for designing the planetary gear carrier) shall be stated separately:

— for all load cases with wind turbine in production operation and
— for all other load cases.

Additionally, the extreme loads in the rotor coordinate system R shall be stated separately:

— for all load cases with temperature $\theta_{mean,year}$
— for all load cases with temperature $\theta_{min,operation}$ and
— for all load cases with temperature $\theta_{1year,min}$.

SECTION 4 CONTROL AND PROTECTION SYSTEM

4.1 Design documentation

The design documentation should include information about what has to be included additionally to the wind turbine type with respect to handling of extreme low and high temperature conditions, for example:

— description of the operation control, when an ambient temperature of $\theta_{min,operation}$ or $\theta_{max,operation}$ is exceeded / fallen short of (e.g. start-up and stop procedures, temperature dependent automatic measures such as opening / closing of the mechanical brake, on / off of heating / cooling systems)

— description of temperature dependent interferences in the wind turbine control (e.g. temperature dependent start-up and stop procedures, temperature dependent power control)

— exact specification of all used ambient temperature values $\theta_{1year,min/max}$, $\theta_{mean,year}$, $\theta_{min/max,operation}$, etc., which were used in the design as well as the lowest / highest temperature, which is assumed, when grid failure occurs

— description of changes / amendments for control and protection system

— description of the points of measurements, sensors, and measuring instruments, which are used for the registration of the used temperatures (e.g.: ambient temperatures, inside temperatures, and component temperatures)

— descriptions and data sheets of the control and protection related relays, sensors, actuators and, if applicable, measuring transducers showing the suitability to work at the required temperature range

— the design documentation should also be documented experience from existing turbines in sites with identical conditions.

4.2 Systematic consideration of possible faults

Possible failures on e.g. heating / cooling systems or temperature measurements may influence the protection functions of the wind turbine negatively. This should be considered in the design of the control and protection system as well as for fault load cases.

4.3 Control and protection functions

The considerations are to be supplemented to cover the whole range of possible ambient temperatures.

4.4 Braking systems

It is to be shown that the braking systems (including their possibly existing energy storage) remain functional in the temperature range between $\theta_{min,operation}$ and $\theta_{max,operation}$.

A test of the pitch system for extreme low temperature conditions may be required (see [7.4.3]) and the respective requirements in the following should be taken into account:

The test shall ensure and show that the pitch system is capable to run all blades into feathered position in an appropriate time under assumption of appropriate loading. This test is required whenever a braking system is designed as pitch system.

The test shall ensure the operability of the pitch system. All parts of the pitch system (e.g. including accumulator, pitch drive / cylinder, valves, controller, pipes and cables, pitch gearboxes, pitch converter) shall be tested. Pitch bearings may be excluded from the test when the manufacturer states their suitability. Mainly it shall be shown that the required pitch rate can be reached when slow movement of pitch drive / cylinder and break-loose moment of the bearing are taken into account.

4.5 Measurement devices for wind speed and direction

The effectiveness of a possibly existing heating system is to be shown up to $\theta_{min,operation}$.

4.6 Turbine behaviour at grid return after grid failure

The start-up procedure is to be described at $\theta_{min/max,operation}$. In doing so, the respective measured component temperatures and the allowable temperatures for the components (e.g. gearbox, generator, transformer, and electrical cabinets) are to be considered. See also [7.4.8].

If the ambient temperature is lower than -5°C on grid return, the following should be applied:

A successful accumulator test run should be performed prior to turbine's re-start in case electric energy storage is used for a braking system. A sufficient charging procedure should be performed in addition to the test run.

4.7 Yaw system

Functionality of the yaw system at $\theta_{1year,min/max}$ is to be shown, preferably by tests.

4.8 Turbine behaviour, when the wind turbine is operating at low/high temperature

The control functions and respectively the procedures implemented in the control system depending on the temperature are to be described down/up to $\theta_{min/max,operation}$. In doing so, the corresponding measured component temperatures and the inputs of the component suppliers (e.g. gearbox, generator, transformer, electrical cabinets) are to be considered.

4.9 Overheating protection on heating/cooling systems

All heating / cooling systems should be designed to prevent overheating. The type of overheating protection and the set values are to be described. If external heating/cooling is necessary, it should be shown by e.g. datasheet of the cooling liquid and datasheet of the heating/cooling unit, that no damage to the cooling liquid and to its isolating function will occur due to hot spot heating.

In the case of fire protection system in the wind turbine, /9/ may be complied.

4.10 Supervision of heating/cooling systems

The control system should supervise, whether important heating/cooling systems are functioning and all machinery components and electrical components are inside the temperature range specified by the component's supplier for operation. If the heating/cooling and possible other measures do not succeed in keeping the component's temperatures in allowable temperature ranges, the turbine should go to safe mode. The relevant procedures are to be described.

At braking or for safety systems, this supervision can be a safety relevant component and is to be treated as such.

SECTION 5 MANUALS

5.1 Installation manual

The allowable temperatures for installation activities are to be specified. Activities that cannot be carried out for certain temperature intervals shall be specified.

Guidance note:
Among others, the following activities can be affected:

- concrete pouring
- assembly of bolted connections
- bonds, welding
- paint work
- handling of operating materials (e.g. oil and grease).

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

5.2 Commissioning manual

The allowable temperatures for commissioning are to be specified.

The additional working steps for the wind turbine type for extreme temperatures, which are to be accomplished during commissioning, are to be specified. These are e.g.:

- inspections of the control parameters for heating / cooling systems as well as the control system at wind turbines for extreme temperatures
- tests and inspections of the components, which exist due to the extreme temperatures (heating / cooling systems, insulating materials etc.).

5.3 Operating manual

The necessary information for operation of the wind turbine type in extreme temperatures is to be stated.

5.4 Maintenance manual

The additional working steps for the wind turbine type for extreme temperatures, which are to be accomplished during maintenance, are to be specified. These are e.g.:

- inspections of the control parameters for heating / cooling systems as well as the control system at wind turbines for extreme temperatures
- tests and inspections of the components, which exist due to the extreme temperatures (heating / cooling systems, insulating materials etc.).

Maintenance activities affected by temperature conditions should be specified in the manual.

SECTION 6 ROTOR BLADES

6.1 General

The rotor blade of a wind turbine is generally subject to high structural loads both during production and during standstill or idling. Therefore, the most severe temperatures expected to be encountered by the blade structure should be considered for structural design, regardless whether it is supposed to be operating or not at these temperatures. The same severe temperature consideration should be applicable for nacelle cover and spinner.

When estimating* $\theta_{min,area,operation}$ and $\theta_{max,area,operation}$, the following factors should be taken into account:

— ambient temperatures ($\theta_{1year,min}$ and $\theta_{1year,max}$)
— solar radiation
— blade colours
— heat capacity and conductivity of the blade structure
— blade heating systems for de-icing / anti-icing.

Without further justification, the material and testing requirements in connection with the design verifications and associated reduction factors from either /2/ or /3/ or /10/, may be considered sufficient to cover a temperature range from $-30°C \leq \theta_{1year,min}$ to $\theta_{1year,max} \leq +50°C$. This temperature range should cover the range of estimated $\theta_{min,area,operation}$ and $\theta_{max,area,operation}$.

If the temperatures specified above are exceeded, further material testing and structural verification shall be carried out for extreme blade temperatures, in order to demonstrate that the blade structure at a given extreme temperature can withstand all relevant design loads. The relevant design loads in this context shall be the extreme load envelope including the tower clearance load case; or, alternatively, specific load cases for a given extreme temperature to be reported as part of the design basis.

Only if a significant fraction of the design fatigue load spectrum is expected to occur at temperatures exceeding the ones specified above, additional justification (i.e. further material testing and structural verification potentially affected by extreme temperatures) with regard to fatigue may be required.

* Note: For estimating the body temperature, a conservative approach shall be followed as long as body temperature measurements are not available along the blade.

6.2 Specific requirements for high temperature conditions

Thermal stability of matrix and adhesive resins should be proven with regard to the ambient temperature range for which the rotor blade is designed. If the glass transition temperature (Tg), heat deflection temperature (HDT, according to /13/), or a similar material characteristic, exceeds $\theta_{1year,max}$ by at least 15°C, no further proof is required.

For all structural properties that are susceptible to change at the given $\theta_{max,area,operation}$, further material testing at the given $\theta_{max,area,operation}$ should be carried out, at least including:

— elastic and strength properties of foam cores
— laminate compressive strength in fibre direction
— adhesive bonded joints strength, including bonded root inserts.

In addition, the face sheet adhesion strength of composite constructions should be considered.

If the testing reveals changed material properties at the given $\theta_{max,area,operation}$ as compared to the ones used as a basis for the blade design, additional structural verification analyses should be carried out in conformance with the applicable requirements from /2/ or /3/ or /10/, at least including:

— buckling analysis, in case of changed elastic and strength properties of foam cores
— laminate fibre failure analysis, in case of changed compressive strength in fibre direction
— bonded joints analyses, in case of changed adhesive bonded joints strength, including bonded root inserts.

Evidence should be provided that the global mechanical characteristics of the blade at the given $\theta_{max,area,operation}$ are not expected to change beyond accepted tolerances, in order to maintain consistency with the load cases. An assessment of the blade deflection and the clearance to the tower shell at the given $\theta_{max,area,operation}$ shall be provided.

When the blade temperature is approaching the glass transition temperature, T_g, creep will/may be critical.

6.3 Specific requirements for low temperature conditions

Through DMA (dynamic mechanical analysis, e.g. as in /14/) with a starting temperature of $\leq \theta_{1year,min}$ – 10°C, it should be ensured that no transitions of any nature occur at temperatures below $\theta_{1year,min}$ that could affect the structural properties of lamination and adhesive resins.

For all structural properties that are susceptible to change at the given $\theta_{min,area,operation}$, further material testing at the given $\theta_{min,area,operation}$ should be carried out, at least including:

— elastic and strength properties of foam cores
— laminate tensile strength perpendicular to the fibre direction (σ_{22}); and laminate in-plane shear strength (τ_{12})
— adhesive bonded joints strength, including bonded root inserts
— brittleness for plastic materials.

In addition, the face sheet adhesion strength of composite constructions should be considered.

If the testing reveals changed material properties at the given $\theta_{min,area,operation}$ as compared to the ones used as a basis for the blade design, additional structural verification analyses shall be carried out in conformance with the applicable requirements from /2/ or /3/ or /10/, at least including:

— buckling analysis, in case of changed elastic and strength properties of foam cores
— laminate inter-fibre failure analysis, in case of changed σ_{22} or changed τ_{12}
— bonded joints analyses, in case of changed adhesive bonded joints strength, including bonded root inserts
— effect of damping on loads.

Evidence should be provided that the global mechanical characteristics of the blade at the given $\theta_{min,area,operation}$ are not expected to change beyond accepted tolerances, in order to maintain consistency with the load assumptions, for example, damping properties.

SECTION 7 MECHANICAL COMPONENTS

7.1 Introduction

This section provides requirements and information for mechanical and structural components of wind turbines in extreme (low/high) temperature conditions.

Precondition for the applicability of this chapter is that the mechanical and structural components have already obtained/in the process of obtaining certification according to a certification scheme, for example, as described in /7/ or /8/, for the normal temperature ranges.

7.2 General

Adaptation of the wind turbine mechanical and structural components to extreme temperature conditions should be appropriately demonstrated by the wind turbine and/or the component manufacturers. The manufacturer shall submit appropriate documentation to describe the modifications introduced with the extreme temperature application, e.g. heating/cooling systems and ventilation strategies in nacelle and hub. For components such as bearings, yaw system, gear box, etc., the component manufacturer shall state that the respective part is suitable for the intended temperature range.

The wind turbine manufacturer shall specify the temperature ranges which mechanical and structural components may be used within. Distinction shall be made between usability during operation, standstill, and idling states of the wind turbines.

All strength verifications (fatigue and extreme) shall be considered for $\theta_{min,operation}$ except for loads derived from DLC 7.1, 8.x, which should be considered with $\theta_{1year,min}$.

Alternatively, the minimum temperature for DLC 8.x may also be defined by the manufacturer. In case of heated components, the wind turbine manufacturer shall specify:

- which component is heated
- where and how the component is heated
- which temperature the component is heated to.

In such case, all strength verifications (fatigue and extreme), with the exception of loads derived from DLC 6.2, 7.1, 8.x, may be considered for the temperature for which the component is heated to.

The wind turbine manufacturer shall also submit design documentation of the heating and cooling systems and specifications of the heating and cooling systems' control logic. The position of the temperature sensors of the single component should be specified.

The design calculation of the heating / cooling systems as well as the thermal balance of the heated / cooled components should be submitted.

7.3 Material characterisation

Materials for hub and nacelle mechanical components may include metallic materials such as various steel and cast iron grades and aluminum alloys, as well as composite and polymer materials.

If the operating temperature defined for the component is outside the minimum level specified according to the respective material standard, the wind turbine manufacturer shall verify and submit the material certificate, which documents the mechanical properties of the materials under the relevant temperature conditions.

If the material properties relevant for the component function diverge from the nominal standard values in design temperature and / or operation temperature, additional requirements shall be appropriately applied on the product documentation, e.g. drawings or specifications.

Temperature-dependent material properties which should be appropriately characterized at the operating temperatures of the wind turbine may include:

- ultimate strength
- fatigue strength

- fracture toughness
- impact toughness
- modulus of elasticity
- coefficient of thermal expansion
- friction coefficient.

7.3.1 Ductility requirements for metallic materials in low temperatures

Wind turbine and / or component manufacturers should provide evidence that the selected metallic material does not exhibit brittle behaviour at the operating and standstill temperatures. Such evidence may include e.g. results from Charpy V-notched bar impact tests and/or fracture toughness tests executed at $\theta_{1year,min}$.

In such case, the resulting mean impact energy or fracture toughness shall fulfil the material requirements given in the relevant material standard for the extreme minimum temperature under normal conditions, i.e. -20°C.

If a sufficient fracture toughness of the material cannot be confirmed by testing, an analytical verification of the component may be performed confirming sufficient material toughness with respect to ULS, SLS or FLS loads.

Guidance note:

If the material of a component possesses a substantial decrease of elongation at fracture or fracture toughness at $\theta_{1year,min}$ or a low elongation at fracture or fracture toughness in general, the static load capacity verification is to be extended to ensure the integrity of the structure, e.g. by means of a strength assessment with fracture mechanics. The assessment should consider the calculated final flaw size at the end of turbine lifetime, if crack growth is expected due to fatigue loads. The initial flaw sizes on the component should be assumed under consideration of the specified quality level for non-destructive testing. The fracture mechanics properties of the material have to be verified by material tests.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

Special requirements:

For EN 10025 steel structures, the methodology described in /15/, may be applied to verify that the structure has a sufficient fracture toughness. In case of welded structures, welding consumables should also be assessed.

For forged, cast and stainless steel grades, if no fracture toughness value at $\theta_{1year,min}$ is available in the corresponding material standards, a Charpy V-notched bar impact test can be performed at $\theta_{1year,min}$. In such case, KV at $\theta_{1year,min}$ may not be less than 27 J.

7.4 Component specific requirements

7.4.1 General

For all wind turbine components described below, the component manufacturer shall submit a confirmation that the components or the operating resources (e.g. oils and greases) may be used in the specified temperature ranges. Further component specific requirements are hereunder described.

7.4.2 Bearings

The supply of sufficient amounts of lubricant for all relevant bearing points has to be ensured during operation and especially during the start-up procedure for the whole range of operating temperatures. In some cases, this may need to be ensured by means of preheating before beginning of operation.

The operability of the bearing sealing should be guaranteed over the whole temperature range to ensure the required lubricant cleanliness. The lubricant should not lose its corrosion protection characteristics over the complete temperature range.

The temperature-dependent behaviour of the used lubricants' viscosity should be considered when determining the component loads as well as concerning the system behaviour of the wind turbine. This may be done by calculations or measurements. The friction rates in the bearing at low temperatures may be considered in the load calculation and design.

7.4.3 Yaw and pitch system

If the pitch and yaw systems are part of the wind turbine's operation and safety strategy, the operability and start-up (e.g. brakeaway torques) of the pitch and yaw system over the whole range of temperatures shall be documented (see [4.4]). The documentation shall also confirm that the pitch and yaw systems are capable of providing the required output speeds over the whole range of temperatures. The documentation should also consider the interaction of the pitch and yaw systems with the other components. In case of automated lubrication systems, the documentation should also demonstrate the conveyability of the lubricant over the whole temperature range.

When designing the drives, the temperature dependency of the losses of nacelle and blade bearings as well as gear boxes has to be considered.

For yaw and blade bearings, the bearing manufacturer should specify the expected load dependent and load independent bearing friction torques over the operating temperature range as well as the brakeaway torque. These may be considered in the wind turbine aeroelastic load calculations.

7.4.4 Main gearbox

The gearbox manufacturer should define operating limit values for the gearbox based on the temperatures of the oil sump and gearbox bearings. The limit values should be reflected in the wind turbine control system strategy, which may lead to limiting power or respectively torque transmitted by the gearbox.

Due to the very high lubrication viscosity, at low temperatures the internal gearbox losses may be significantly higher than under normal operating conditions. Due to the bad lubrication, the gearbox should only be allowed to idle in these conditions. In case of low oil sump temperatures or failure of the oil heating system, a sufficient lubricant supply is necessary to enable idling operation of the gearbox in this situation.

The functionality of the gearbox lubrication system during start-up at extreme temperatures should be described and verified by means of climate chamber test. The test should reproduce the real ambient conditions. Torque and oil temperature should be monitored during the whole test. Such a test is typically done in that way that a gearbox is cooled down to -40°C for at least 24 hours. After the gearbox is cooled down the heaters and the electrical oil pump can be switched on. As soon as the oil temperature in the oil sump is reaching -30°C, the gearbox can be set into the idling mode (approximately 3 rpm at the input shaft). When the oil temperature within the gearbox in all the stages reaches at least -10°C without visual damages, the test is passed. The test conditions, the monitored values and the test results shall be documented and submitted.

Guidance note:

Test rig experiences show that the dynamic behaviour of the gearbox in the drive train at $\theta_{1year,min}$ is characterised by a brakeaway torque (ca. 10~20% of the nominal torque) and a friction torque (ca. 5~10% of the nominal torque). The exact values are highly dependent on the lubricant temperature.

---e-n-d---of---g-u-i-d-a-n-c-e---n-o-t-e---

The influence of the thermal expansion concerning bearing clearance and bearing pre-stress are to be considered in the design. For cast components of the main gearbox, the requirements of [7.3] shall be fulfilled. In selected cases, a material qualification procedure may have to be performed. The scope of this procedure shall be agreed with the certification body in advance.

7.4.5 Brakes

The temperature dependence of the friction coefficient of the pads is to be considered in the design.

If the safety concept requires that the turbine remains in parked conditions at extreme temperatures, the value of the friction coefficient of the pads should be verified for this temperature as well.

7.4.6 Energy storages

The function of the hydraulic, mechanical, and electrical energy storages, which are part of the safety system, has to be ensured at the specified design and operating temperature. In this sense, the increased friction losses at low temperatures should be considered when designing the energy storages.

The energy storages should be included in the low temperature start-up tests. During testing, the following values should be measured for electrical storage if applicable: voltage, current, speed and temperature of hottest points at motor and frequency converter.

7.4.7 Bolted connections

The materials used for structural bolted connections should be in compliance with /16/. If the design and operating temperature are outside the temperature ranges specified in /16/, applicability of the material used for bolted connections shall be verified. The procedure shall be agreed with the certification body.

The ambient conditions for assembly of bolted connections, e.g. friction coefficient and assembly temperature, should be in compliance with the specifications by the bolt manufacturer. The different thermal expansion behaviour of the clamped components (especially in case of different materials or temperature distribution) as well as the temperature dependent friction coefficients at the head and at the thread of the bolt should be considered in the design.

If friction coefficients for the designated assembly temperature are not available, assembly tests with suitable bolt assembly pre-load measurement devices should be performed to determine suitable bolt assembly parameters. Alternatively, suitable load controlled (friction independent) assembly methods may be applied.

The allowable temperature range to assemble the bolted connection should be specified e.g. in the installation manuals.

7.4.8 Low temperature start-up procedure after grid failure

After an enduring grid failure, in which the complete wind turbine including the nacelle, hub with rotor blades and tower is entirely cooled down to the lowest operating temperature or lower, a low temperature start-up procedure implemented in the control system of the wind turbine should be executed. The procedure should be capable of re-establishing the operating state of the wind turbine, when the grid connection is restored. If any alternative method is available, documentation for the same shall be submitted along with justification. See also [4.6].

The wind turbine manufacturer shall provide a description of the procedure including:

— switch-on time of the components
— heating time
— equilibrium temperatures.

The functionality of the low temperature start procedure should be explained and verified for main gearbox, yaw and pitch drives and gearboxes as well as for other components, if needed. Also during low temperature start-up procedure, the wind turbine should only be allowed to idle. Power generation may start after the whole gearbox is heated up to the allowable minimum gearbox temperature. This temperature has to be specified by the gearbox manufacturer or alternatively minimum gearbox temperature of +10°C may be used.

SECTION 8 ELECTRICAL COMPONENTS

8.1 Introduction

This section provides requirements and information for electrical components of wind turbines in extreme (low/high) temperature environment. If grid code compliance is planned it is described in /19/.

8.2 General

8.2.1 Heating/cooling systems

It is to be specified which wind turbine components are heated/cooled.

It is to be specified where and how the components are heated/cooled and which temperature rises/sinks are reached due to the heating/cooling. The design calculation of the heating/cooling systems as well as the thermal balance of the heated/cooled components and operating resources (e.g. lubrication system) are to be submitted. Verification can be done by measurements.

Criteria for the operation of the heating/cooling are to be specified. For all heating/cooling systems data may be stated in the following way:

Table 8-1 Criteria for the operation of heating

heating element manufacturer / type	*heating output*	*place of installation*	*place of measurement*	*principle of function*	*start at t [°C]*	*stop at t [°C]*

Table 8-2 Criteria for the operation of cooling

cooling element manufacturer / type	*cooling output*	*place of installation*	*place of measurement*	*principle of function*	*start at t [°C]*	*stop at t [°C]*

For documentation on heating also refer to [8.2.9].

8.2.2 Start up procedure of wind turbine after long stand still during grid failure

A complete start up procedure concerning heating up or cooling down to operational temperature range should be given for the complete wind turbine after grid failure. The procedure should contain the measures for heating/cooling without grid power where necessary (e.g. for heating up the generator or main power transformer before switching on). The electrical installations (transformer, generator, converter and control cabinets etc.) are to be included in the procedure.

8.2.3 Temperatures

Electrical installations and components have to withstand the temperatures of the internal areas and locations in which they are installed. It shall be shown with test reports or data sheets.

8.2.4 Design documents

The following information should be implemented and submitted together with the other documentation mentioned:

1) Temperature assumptions considered for the design of electrical installations for wind turbines.
2) Documentation proving, that calculations for thermal strength and current carrying capacity of cables and bus bars are still valid for changed ambient conditions (see [8.2.8] and [8.2.9]) temperatures.
3) Data sheet of the component manufacturer according to [8.2.8] and [8.2.9]. For each electrical cabinet or space, the following information are required: $\theta_{min,area}$, $\theta_{\mathrm{min,area,operation}}$ for low temperature conditions, $\theta_{max,area}$, $\theta_{max,area,operation}$ for high temperature conditions and $\Delta\theta_{area}$, $\Delta\theta_{area,operation}$.

4) Especially for the power cable in the tower, which are twisted during the yaw operation, additional data for low temperature condition should be given (see [8.2.8]).
5) A confirmation of the generator manufacturer should be given for the temperature range within which switching on voltage is allowable (normal production operation), as well as the temperature range within which no damage will occur while the generator is switched off. Manufacturer should take into account low/high temperature capability for generator elements like windings, bearings, structural steel, shaft, cooling motors, bearings lubrication systems, and electronics (e.g. encoder) during operation as well as during grid failure.
6) A confirmation of the transformer manufacturer should be given for the temperature range within which normal production operation is allowable, the temperature range within which no damage will occur when the transformer is switched off, and the minimum or maximum allowable temperature for powering the transformer as well as allowable speed of temperature rise when heated and / or powered (in low temperature condition).
7) Wherever relevant, calculations or test reports including the temperature rises should be given.
8) If other documentation such as long term operational experience is available for the intended temperature conditions, the above documentation may be substituted by providing justification.

8.2.5 Rotating electrical machines

8.2.5.1 Windings

1) The motors and the generator should not be under voltage, when the measured winding temperature is below the minimum or above the maximum allowable temperature given by the manufacturer of the corresponding rotating electrical machine. Cooling air or liquid should be considered as well. Before switching on, sufficient heating/cooling should be provided.
2) The manufacturer of the generator should agree on the design and the power required for necessary heating/cooling.
3) In addition to the design calculation of the heating/cooling systems, the performance of the heating of the generator should be tested within prototype testing of the generator without reaching unacceptable hot spot temperatures. As a minimum, the manufacturer of the generator has to confirm, that the generator heating/cooling procedure implemented in the wind turbine does not reduce generator lifetime nor isolating capability.
4) In the case of permanent magnet generator (PMG), the maximum operational temperature of the magnets should be declared taking into account demagnetization during short circuit on generator output at maximum operational temperature conditions.

8.2.5.2 Slip ring for power transmission to the rotor

Material of the slip ring should be defined, together with the accepted temperature range and minimum air humidity demands for operation with design wear. The degree of protection of the slip ring against dust in high temperature environment should be at least IP5X or maybe IP6X according to /17/.

8.2.6 Transformers

8.2.6.1 General

If external heating or cooling of the transformer is necessary before switching on (see [8.2.2] and [8.2.3]), measures have to be described, how this can be achieved, or sufficient back-up power should be provided. Energy calculations should be submitted.

8.2.6.2 Liquid cooled transformers

The start-up procedure of the transformer after cool-out or heat-up should be designed by the wind turbine manufacturer in accordance with the corresponding requirements of the transformer manufacturer. This may be shown by a manufacturer declaration of the transformer manufacturer.

8.2.6.3 Heating/cooling

1) The transformers, especially the medium voltage transformer, should not be under voltage, when the measured winding temperature is below the minimum or above the maximum allowable temperature

given by the transformer manufacturer. Cooling air or liquid should be considered as well. Before switching on, sufficient heating/cooling should be provided. The manufacturer of the transformer should agree on the design and the power required for necessary heating.

2) In addition to the design calculation of the heating/cooling systems, the performance of the heating/cooling of the transformer should be tested within prototype testing.

8.2.7 Installation and operation of energy storage devices

Allowable temperature ranges, stated by the original equipment manufacturer, should be kept at the location of installation. Electrical energy storage devices, used for the supply of emergency safety systems, shall be in their operational temperature range before the wind turbine is started. Sufficient cooling or heating should be provided (see [8.2.9]). Derating of battery capacity caused by low temperatures should be taken into account for battery calculations.

8.2.8 Selection of cables and lines

1) The maximum allowable torsion of the power cable needs to be specified. If the power cable is twisted by the yaw operation at the place of installation, the length of free hanging cable should be given. The ability of the cable to fulfill this specification under extreme temperature conditions should be proved by the cable manufacturer.
2) For cable design, the corresponding derating factor according to environmental temperature conditions should be considered.

8.2.9 Electrical cabinets and other electrical equipment

1) For each cabinet or other electrical equipment being in scope, a thermal area should be defined.
2) For definition of thermal area, allowable operational temperature ranges, in the design phase, all items mounted inside the cabinet should be reviewed concerning their thermal resistance during operation and during grid failure (see [8.2.4] (2)). For low temperature conditions, the item with the lowest allowable operational temperature defines the minimum operational temperature of the thermal area $\theta_{min,area,operation}$. This item and the resulting temperature definition for the thermal area in this cabinet should be documented (only one data sheet per cabinet, the one with the most critical temperature specifications). For high temperature conditions, the item with the highest allowable operational temperature defines the maximum operational temperature of the thermal area $\theta_{max,area,operation}$. This item and the resulting temperature definition for the thermal area in this cabinet should be documented (only one data sheet per cabinet, the one with the most critical temperature specifications).
3) The same should be done concerning the minimum/maximum survival temperatures in a switched off mode, resulting in $\theta_{min,area}$ / $\theta_{max,area}$. For electrical equipment not mounted inside cabinets and not mentioned in other sections, the outer surface of the equipment should be considered as the border between "area" and "surrounding area".
4) The heating of the cabinet should be designed in such a way that the minimum temperature defined for this cabinet is reached, even at minimum design temperature $\theta_{1year,min}$. For cooling of the cabinet, the maximum temperature should be reached even at $\theta_{1year,max}$. This may be shown either by analysis or by testing.
5) If testing is chosen, $\Delta\theta_{area,operation}$ should be measured in a situation similar to "waiting for wind" during a time, long enough to reach thermal stability inside the cabinet. For testing $\Delta\theta_{area}$, a situation similar to "long black-out" should be used for measurement.
6) Starting of the wind turbine after grid disconnection should not be possible before all thermal areas have reached their operational temperature range $\theta_{min,operation}$ or $\theta_{max,operation}$.
7) Assessment has to be made, whether the strength calculation or test of bus bars for short-circuit current stress are valid for the corresponding thermal area temperature $\theta_{min,area,operation}$ / $\theta_{max,area,operation}$, and if the bus bars will maintain the required clearance and creepage distances relative to other voltage-carrying or earthed components.
8) Cabinet doors should be sealed and air inlets should be protected with filters if deemed necessary.
9) Depending on the turbine and component design, additional environmental tests according to IEC 60068, /18/, might be necessary.

SECTION 9 SUPPORT STRUCTURES – STEEL AND CONCRETE

9.1 Introduction

This section provides requirements and information for design of wind turbine support structures in extreme (low/high) temperature conditions.

Regarding the foundations, part of the soil connected to the geotechnical design of the foundation may be frozen all time or for a part of the year. In warmer conditions, the soil on the surface may freeze and thaw up to a certain depth, while in permafrost areas, the soil is permanently frozen into the depth and may thaw and freeze from the surface downwards to a certain depth. The freeze and thaw action changes the soil's qualities. This has to be taken into account in the geotechnical design, as the attendant changes in soil qualities may cause movements of the foundation or a reduction of bearing strength and stiffness. For this, regulations set out in the local building codes shall be complied.

9.2 Low temperature conditions

1) For design of support structures, the minimum temperature which is expected at the site, $\theta_{1year,min}$, has to form the basis for the design. However, for structures below the lowest astronomical tide, appropriate section in the standard /12/ ([3.2.3.2]) may be taken into account.
2) The materials used have to comply with the requirements according to the governing set of standard. If the design temperature $\theta_{1year,min}$ of a support structure component is below the temperature limit specified in the relevant material standard, the usability of the material is to be verified by additional tests, e.g. Charpy-V test for impact toughness. These additional requirements are to be stated on the respective drawings or specification in relation to the material definition.
3) For fasteners, corrosion protection systems or other materials, which are relevant for the resilience and durability of the support structures, for which no minimum temperature limit is specified, the usability for the intended temperature range for use is to be confirmed by the manufacturer of the material or by tests.
4) The toughness requirements (imact toughness – Charpy – V and fracture toughness – CTOD) for steel structures e.g. for the support structure, shall be in accordance with the governing material standard.
5) The material used for bolted connections shall fulfil the requirements of /16/, or other relevant standards. If design and operational temperature are outside the temperature ranges specified in /16/ (or similar), verification for applicability of the material used for bolted connections is required. The ambient conditions for assembly of bolted connections have to be in compliance with the specification by the bolt manufacturer (e.g. friction coefficient, assembly temperature).
6) In the case of materials used for grouted connections, requirements in the appropriate regulations / standards shall be complied.
7) The chosen corrosion protection system shall be applicable for the specified design and operating and survival temperature of the support structure.
8) Welding on sites in low temperature conditions is not allowed.
9) Exposure class for the concrete and the concrete mixture shall be specified in accordance with the amount of water saturation and the presence of de-icing agents or salt water at the site.
10) For in-situ cast concrete structures, the ambient temperature has to be above +5°C in the construction phase. If the ambient temperature is below that value in the construction phase, special measures have to be taken to ensure that the fresh concrete has a temperature above +5°C for all phases of construction (transport, casting, hardening, curing etc.) in order to ensure sufficient hardening of the concrete. Alternatively, other measures have to be taken. In addition, appropriate requirements on the relative humidity shall be taken into account.
11) Special measures for construction of concrete structures at low temperatures have to be described on the drawings or in construction specifications.

9.3 High temperature conditions

1) It has to be checked if the temperature gradients for calculating the heat influences on support structures according to the governing design standard apply to the temperature conditions at the specific site.
2) Welding on sites in high temperature conditions is not allowed.
3) The temperature in reinforced and prestressed concrete structures due to solar radiation shall be prevented from exceeding +100°C in general. If this requirement cannot be met, measures have to be taken in order to secure that the structure is not damaged.
4) For in-situ cast concrete structures, the temperature of fresh concrete has to be below +30°C in the construction phase. If the ambient temperature is above that value in the construction phase, special measures have to be taken to ensure that the higher temperature is not harmful to the concrete. In addition, appropriate requirements on the relative humidity shall be taken into account.
5) In the case of materials used for grouted connections, requirements in the appropriate regulations / standards shall be complied.
6) Special measures for construction of concrete structures at high temperatures have to be described on the drawings or in construction specifications.