PROTEST

Determination of Load Cases and Critical Design Variables

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ECN-E--10-007 Jan 2010

Acknowledgement/Preface

This report has been written as part of the EU project "PROTEST", which in fact is a pre-normative project that should result in uniform procedures to better specify and verify the local component loads acting on mechanical systems in wind turbines.

This project is partly funded by the European Commission (EC) under the FP7 program and partly by ECN.

EC contract nr. : 212825
ECN project nr. : 7.9530

The contributions of all project partners are greatly appreciated.

Grant Agreement no.: **212825**

Project acronym: **PROTEST**

Project title:
PROcedures for TESTing and measuring wind energy systems

Instrument: Collaborative Project

Thematic Priority: **FP7-ENERGY-2007-1-RTD**

Deliverable D2:
Determination of Load Cases and Critical Design Variables

Date of preparation: January 2010

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WP Leader: Holierhoek, J.G..

Start date of project: 01.03.2008 Duration: 30 months

Organisation name of lead contractor for this deliverable: ECN

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)

Dissemination level

PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Abstract

An overview of systems for which the Critical Design Variables (CDV's) and a minimum set of Design Load Cases (DLC's) should be specified is given. At least drive train, pitch system and yaw system should be considered, but the possibility of adding other components if required existed, however the above mentioned three systems were sufficient. For each system the different components have been specified that need to be considered in more detail with respect to design loads than is currently the case in the standards and guidelines.

A specification of the CDV's for these selected systems is discussed as well as the specification of the (international) standards currently used. A minimum set of DLC's for the selected systems is also specified. For this purpose it has been determined whether the already specified DLC's in standards like IEC61400-1, GL guidelines for the Certification of Wind Turbines, and IEC61400-4 cover these design load cases so that in case the design load is covered, the corresponding DLC's are identified; in case the design load is not covered, new DLC's are proposed. Only three new DLC's are proposed, with the marginal note that strictly speaking they are not new DLC's, they more illustrate the lack in modelling possibilities in current tools. These new DLC's concern the misalignment, resonance and LVRT (Low Voltage Ride Through). Over all the DLC's are well covered by the current standards and guidelines.

Contents

Terms and Definitions 6

1. Introduction 7
   1.1 PROTEST project 7
   1.2 Work package 2: Load cases and design drivers 10
      1.2.1 Objective and background 10
      1.2.2 Approach 11
   1.3 Scope of the report 11

2. Background information on standards and guidelines 12
   2.1 IEC 61400-1 12
   2.2 GL guidelines 14
   2.3 IEC 61400-4 15

3. Load Cases and Critical Design Variables 16
   3.1 Overview systems 16
   3.2 Design loads and design load cases 17
   3.3 Specification of relevant design load cases 19
      3.3.1 Proposal for new DLC 19
      3.3.2 Treatment of existing DLC's 20

4. References 21

Appendix A Format questionnaire 22
   A.1 Selection of components 22
   A.2 Characteristic design loads 23
   A.3 Simulation models 23

Appendix B Results questionnaire 24
   B.1 Selection of components 24
      B.1.1 Gearbox 25
      B.1.2 Drivetrain apart from gearbox 25
      B.1.3 Pitch system 26
      B.1.4 Yaw system 27
   B.2 Characteristic design loads 27
      B.2.1 General 27
      B.2.2 Gearbox 28
      B.2.3 Drive train apart from gearbox 31
      B.2.4 Pitch system 32
      B.2.5 Yaw system 33
   B.3 Simulation models 34

Terms and Definitions

DLC	Design Load Case; the combination of operational modes or other design situations, such as specific assembly, erection or maintenance conditions, with the external conditions [Ref.6].
Design Load	The load for which the strength of any component has to be documented. It generally consists of the so-called characteristic load multiplied with the appropriate partial safety factors for loads and consequence of failure, see also IEC 61400-1 and clause 6 [Ref. 8]
Limit State	The state of a structure and the loads acting upon it, beyond which the structure no longer satisfies the design requirement [ISO 2394, modified] (*NOTE The purpose of design calculations (i.e. the design requirement for the limit state) is to keep the probability of a limit state being reached below a certain value prescribed for the type of structure in question (see ISO 2394).)* [Ref.6].
CDV	Critical Design Variable; a design variable that from experience is expected to strongly affect the design.
Failure Mode	The mode of failure. Passing over a specific limit state described by a single equation could lead to different failure modes depending on the vector followed when passing from the safe state to the failure state.

1. Introduction

1.1 PROTEST project

High reliability of wind turbines and their components is one of the pre-requisites for an economic exploitation of wind farms. For offshore wind farms under harsh conditions, the demand for reliable turbines is even more relevant since the costs for repair and replacement are very high. Unfortunately, present day wind turbines still show failure rates between 2 to 5 failures per year that need visits from technicians (derived from i.e. [Ref. 1], [Ref. 2], [Ref. 1Ref. 3]). Although electrical components and control systems fail more often, the costs related to repair of failed mechanical systems (drive train, pitch and yaw systems and bearings) are dominating the O&M costs and downtime.

In-depth studies, e.g. [Ref. 4] and discussions with turbine manufacturers, component suppliers, and certification bodies [Ref. 5] revealed that one of the major causes of failures of mechanical systems is insufficient knowledge of the loads acting on these components. This lack is a result of the shortcomings in load simulation models and in load measurement procedures on the level of the components. Due to the rapid increase of wind turbines in size and power as a response to the market demands, suppliers of components are forced to (1) come up with new designs very often and (2) produce them in large numbers immediately. The time needed to check whether the components are not loaded beyond the load limits used in the design and to improve the design procedures is often not available or transparent to the component supplier. This leads to the unwanted situation that a large number of new turbines are equipped with components that have not really exceeded the prototype phase.

It was also concluded from a.o. [Ref. 4] and expert discussions [Ref. 5] that at present, the procedures for designing rotor blades and towers of wind turbines are much more specific than the procedures for designing other mechanical components such as drive trains, pitch and yaw systems, or main bearings. The design procedures for blades and towers are clearly documented in various standards and technical specifications. The reason for having extensive design standards for blades and towers is that these components are critical for safety: failures may lead to unsafe situations and designing safe turbines did have (and should have) the highest priority in the early days of wind energy. Parallel to the development of design standards, the wind energy community has developed advanced design tools and measurement procedures to determine the global turbine loads acting on the rotor and the tower. At present however, it is no longer acceptable to focus on safety only and neglect the economic losses. Lacking of clear procedures for designing mechanical components and specifying the loads on these components should no longer be the reason for early failures.

In 2007, ECN (NL) together with Suzlon Energy GmbH (DE), DEWI (DE), Germanischer Lloyd (DE), Hansen Transmissions International (BE), University of Stuttgart (DE), and CRES (GR) decided to define the **PROTEST** project (**PRO**cedures for **TEST**ing and measuring wind energy systems) within the FP7 framework of the EU. The PROTEST project in fact is a pre-normative project that should result in uniform procedures to better specify and verify the local component loads acting on mechanical systems in wind turbines. The local component loads should be specified at the interfaces of the components. The relationship between global turbine loads acting on the rotor and tower and local component loads action on the interface of components is visualised in Figure 1-1. For gearboxes in common wind turbine architectures the special interfaces and load specification are explained in [Ref. 8, Annex B].

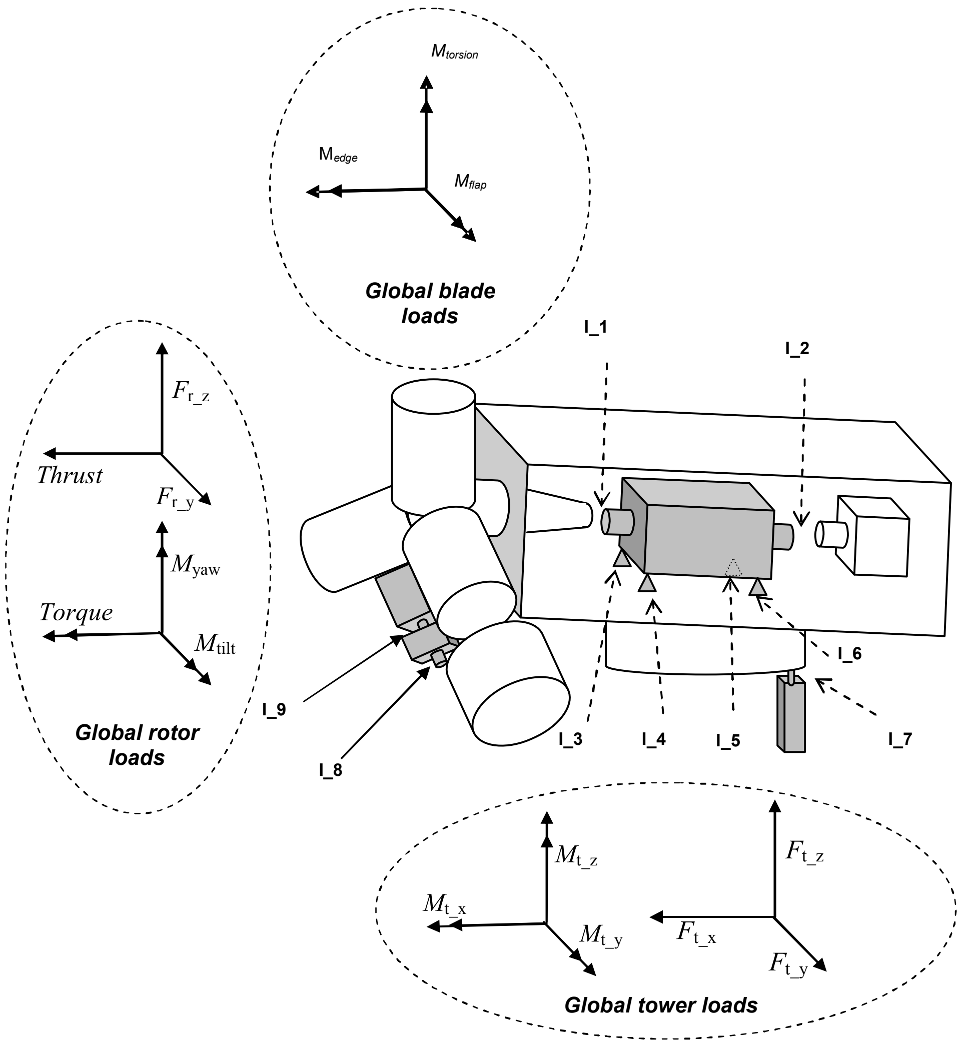

Figure 1-1: *Schematic presentation of transforming "global turbine loads" to "local components loads" at nine interfaces, (gearbox, pitch system and yaw system)*

The term "loads" should be considered broadly in this respect. It comprises not only forces and moments, but also all other phenomena that may lead to degradation of the components such as accelerations, displacements, frequency of occurrence, time at level, or temperatures. Within the PROTEST project initially the components drive train, pitch system and yaw system have been selected for detailed investigation.

The uniform procedures to better specify and verify the local component loads should include:

(1) A method to unambiguously specify the interfaces and the loads at the interfaces where the component can be "isolated" from the entire wind turbine structure, and
(2) A recommended practice to assess the actual occurring loads by means of prototype measurements.

The following questions will be answered:

- How should the loads at the interfaces be derived from the global turbine loads?
- Which design load cases should be considered and measured and are relevant for the different components?
- Which signals should be measured during prototype testing (including sample frequency, accuracy, duration)?
- How should the loads at the interfaces be reported and communicated between turbine manufacturer and component supplier?
- How can design loads be compared with measured loads?

- Are the current practices of evaluating the experimental data in relation to their use for model tuning accurate?
- Do the assumptions in the model input yield to uncertainties which are higher than the ones achieved during the load measurements?
- What are the criteria to assess whether the measured loads are more benign than the calculated loads?
- Are the current practices of assessing the measured loads and the data post processing results adequate?

To develop the procedures and to carry out the work within the PROTEST project, both analytical work and experimental work are foreseen. The analytical work is needed to determine the relevant load cases and to develop procedures to derive local component loads from global turbine loads during the design. The experimental work is needed to develop and verify new procedures for prototype measurements. In total nine work packages are foreseen.

1. State of the art report: An inventory will be made of the present day practice on turbine and component design and testing, including ongoing standardisation work and identification of areas for improvement.
2. Load cases and design drivers: For the selected components, it will be determined which load cases and design driving factors (external, operational or design inherent) should be considered.
3. Loads at interfaces: For the selected components, it will be specified how the loads at the design points should be documented with the aim of being a meaningful improvement over the current state-of-the-art (reporting format, time series incl. synchronisation and minimum frequencies, statistics, spectra, time-at-level, etc.)
4. Prototype measurements definition: For each component, a recommended measurement campaign will be defined taking into account the following aspects: load cases, signals (torques, bending moments, forces, motions, accelerations, and decelerations), sensors, measurement frequencies, processing, uncertainties and inherent scatter, reporting.

Experimental verification is planned for the three components involved in the project. This work is defined in the Work Packages 5, 6, and 7.

5. Drive train: Suzlon S82 turbine in India with gearbox of Hansen Transmissions.
6. Pitch system: Nordex N80 turbine owned and operated by ECN at flat terrain.
7. Yaw system and complex terrain effects: NM 750 turbine in Greece in complex terrain.

In these three case studies, the initial procedures developed in task 1 through 4 will be applied. The initial design loads at the interfaces will be determined with state-of-the-art design methods and the measurement campaign will be executed to verify these design loads.

8. Evaluation and reporting: Based on the results of the design study and the measurement results, the procedures of task 2, 3, and 4 will be evaluated and if necessary improved.
9. Management, Dissemination and Exploitation

As mentioned previously, The PROTEST project in fact is a pre-normative project that should result in uniform procedures to better specify and verify the local component loads acting on mechanical systems in wind turbines. Ultimately, the procedures generated in this project should be brought at the same level as the state-of-the-art procedures for designing rotor blades and towers. If appropriate, the results of this project will be submitted to the (international) standardisation committees.

The project runs from March 2008 until mid 2010.

1.2 Work package 2: Load cases and design drivers

In this report the findings in work package 2 will be discussed. Therefore first the objective and background of this work package within the PROTEST project will be discussed, followed by an explanation of the approach that has been used. Finally the scope of this report is given.

1.2.1 Objective and background

As stated in the project proposal of PROTEST the main objective of WP2 "Determination of load cases and design drivers" is to define the design drivers and a minimum set of design load cases (DLC's) for at least the following systems: drive train, pitch system and yaw system. However it should be considered whether other systems have to be included in this overview also. Once started on the work in this work package it was realised that there was not a clear definition for 'design drivers' and that this term was confusing, different views existed on what design driver meant. Therefore it has been decided to change the terminology and determine the Critical Design Variables (CDV's) of the three systems, where a CDV has been defined as 'a design variable that from experience is expected to strongly affect the design'.

The following results should be obtained within this WP.

1. Overview of systems for which the CDV's and a minimum set of DLC's should be specified (at least drive train, pitch system and yaw system should be considered, but other components may be added if required).
2. Specification of the CDV's for the selected systems and specification of the (international) standards used.
3. Specification of a minimum set of DLC's for the selected systems. For this purpose it will be determined whether the already specified DLC's in standards like IEC61400-1 [Ref. 6], GL guidelines for the Certification of Wind Turbines [Ref. 7], and IEC61400-4 [Ref. 8] cover these design load cases so that:
    - in case the design load is covered, the corresponding DLC's are identified;
    - in case the design load is not covered, new DLC's are proposed.

In IEC-61400-1 and the GL guidelines a minimum set of loads is described that shall be considered for the design calculations of a wind turbine. Additional requirements for gearboxes are described in IEC-61400-4. So the results of this WP are especially meant to provide input for further refinement and further specification of these wind energy standards (IEC 61400-1, GL guidelines and IEC 61400-4). In practice these wind energy standards are used in connection with more detailed design standards. A good illustration for this is given in the wind energy newsletter of GL [Ref. 10] where the interplay between IEC61400-4 and standards such as ISO 6336 (calculation of load capacity of spur and helical gears) and ISO 281 (Rolling bearings – dynamic load ratings and rating life) is presented and it is shown that the wind energy standards are not used instead of these detailed standards, but on the contrary the wind energy standards:

- specify the internal and external loads to be considered (f.i. in IEC61400-1 a minimum set of loads is defined, whereas in IEC61400-4 additional loads specific for wind turbines gearboxes are defined);
- provide specific requirements w.r.t the application of the more detailed standards (f.i. target values for some safety factors);
- provide additional demands for aspects not covered elsewhere.

It should be emphasised that this work package aims at the specification of a minimum set of loads (DLC's) to be considered for each of the selected structural systems, which should cover the external loadings to be considered in the more specific standards such as ISO 6336 and ISO 281 for gearboxes.

1.2.2 Approach

To define the CDV's and a minimum set of design load cases (DLC's) for the structural systems (drive train, pitch system and yaw system) the following steps are carried out:

1. Initially the knowledge and experience within the PROTEST project team is collected. For this purpose a questionnaire has been set up based on the above mentioned wind energy standards (IEC-61400-1, GL Guidelines, IEC-61400-4), with the objective to make an overview of (1) the knowledge and experience available and (2) the point of view for improvement of each partner.
2. The results of the questionnaire were processed and structured. Based on the results of the questionnaire together with the outcome of work package 1 (state of the art report) [Ref. 9], a draft proposal for the CDV's and DLC's has been developed. This proposal is presented to several specialists (wind turbine manufacturers, suppliers of components, etc.) not involved in the PROTEST project, and these specialists were asked to review this proposal.
3. With the feedback from the specialist the final proposal has been drawn up.

1.3 Scope of the report

In the current report a draft proposal is given for the design drivers and a minimum set of design load cases (DLC's) for the structural systems (drive train, pitch system and yaw system). This draft proposal is based mainly on the knowledge and experience within the PROTEST project team, which has been collected on the one hand by means of a questionnaire set up for this work package and on the other hand on the state of the art report compiled as part of work package 1.

The wind energy standards (IEC-61400-1, GL Guidelines, IEC-61400-4) have been used to set up this questionnaire. To provide some background information on these standards, in Chapter 2 a brief outline is given with emphasis on the definition of the loads and specification of the DLC's. The questionnaire as submitted to the partners is part of Appendix A. The information provided by means of these questionnaires has been joined together in Appendix B.

Based on the results of the questionnaires (Appendix B) and based on the results of the SOAR of work package 1 [Ref. 9], a proposal has been set up for the Critical Design Variables and design load cases. This proposal is given in Chapter 3, where three main topics are addressed. First the structural systems to be considered are specified together with a structural breakdown. Next the characteristic design loads for these systems are given based on the CDV's that have been determined and finally a proposal is drafted for additional DLC's required to cover the characteristic design loads.

2. Background information on standards and guidelines

For designing wind turbines use is made of wind energy standards and/or guidelines, like the IEC-61400-1 [Ref. 6] and the GL Guidelines for the Certification of Wind Turbines [Ref. 7]. In these standards a number of Design Load Cases (DLC's) are specified which have to be analysed. DLC's for wind turbines are the combination of the design situations of a wind turbine (both operational modes and transient modes) with wind conditions (gusts) and other external conditions (e.g. grid failures and lightning). In these standards the procedures for designing wind turbine rotor blades and towers are much more specific and well documented compared to the design procedures of other mechanical systems, such as the drive train, pitch system, and yaw system. This problem has been recognised for the gearbox and an IEC working group has been established which is preparing the new standard IEC 61400-4 "Wind Turbine Generator Systems – Part 4: Design and specification of gearboxes" [Ref. 8].

So to define the critical design variables and a minimum set of DLC's for all relevant mechanical systems, these standards should obviously used as a starting point. In the following sections, the DLCs mentioned in the wind turbine standards will be discussed, together with their scope and limitations. During the discussions of the DLCs, the objectives of the PROTEST project will be kept in mind, meaning that the usefulness of the DLCs for the design of the drive train, yaw system, pitch system and other mechanical systems will be assessed.

2.1 IEC 61400-1

IEC61400-1 3rd edition 2005-08; "Wind Turbines – part 1: Design requirements".

This document specifies essential design requirements to ensure the engineering integrity of wind turbines. As a minimum the design load cases described in section 7.4 of this IEC document shall be considered; see Table 2.1. From this table it is clear that only external loading conditions mainly due to wind or electrical conditions are considered.

In Chapter 9 of this IEC document additional demands are given for the mechanical systems[1], such as gearbox, yaw system, pitch system and rolling bearings. These additional demands mainly consist of references to ISO standards and of specification of safety factors. No additional information w.r.t. design load cases is given in this chapter.

[1] A mechanical system for the purposes of this standard is any system, which does not consist solely of static structural components, or electrical components, but uses or transmits relative motion through a combination of shafts, links, bearings, slides, gears and/or other devices. Within a wind turbine, these systems may include elements of the drive train such as gearboxes, shafts and couplings, and auxiliary items such as brakes, blade pitch controls, yaw drives. Auxiliary items may be driven by electrical, hydraulic or pneumatic means.

Table 2 – Design load cases

Design situation	DLC	Wind condition	Other conditions	Type of analysis	Partial safety factors
1) Power production	1.1	NTM $V_{in} < V_{hub} < V_{out}$	For extrapolation of extreme events	U	N
	1.2	NTM $V_{in} < V_{hub} < V_{out}$		F	*
	1.3	ETM $V_{in} < V_{hub} < V_{out}$		U	N
	1.4	ECD $V_{hub} = V_r - 2$ m/s, V_r, $V_r + 2$ m/s		U	N
	1.5	EWS $V_{in} < V_{hub} < V_{out}$		U	N
2) Power production plus occurrence of fault	2.1	NTM $V_{in} < V_{hub} < V_{out}$	Control system fault or loss of electrical network	U	N
	2.2	NTM $V_{in} < V_{hub} < V_{out}$	Protection system or preceding internal electrical fault	U	A
	2.3	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}	External or internal electrical fault including loss of electrical network	U	A
	2.4	NTM $V_{in} < V_{hub} < V_{out}$	Control, protection, or electrical system faults including loss of electrical network	F	*
3) Start up	3.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	3.2	EOG $V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
	3.3	EDC $V_{hub} = V_{in}$, $V_r \pm 2$ m/s and V_{out}		U	N
4) Normal shut down	4.1	NWP $V_{in} < V_{hub} < V_{out}$		F	*
	4.2	EOG $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
5) Emergency shut down	5.1	NTM $V_{hub} = V_r \pm 2$ m/s and V_{out}		U	N
6) Parked (standing still or idling)	6.1	EWM 50-year recurrence period		U	N
	6.2	EWM 50-year recurrence period	Loss of electrical network connection	U	A
	6.3	EWM 1-year recurrence period	Extreme yaw misalignment	U	N
	6.4	NTM $V_{hub} < 0{,}7\ V_{ref}$		F	*
7) Parked and fault conditions	7.1	EWM 1-year recurrence period		U	A
8) Transport, assembly, maintenance and repair	8.1	NTM V_{maint} to be stated by the manufacturer		U	T
	8.2	EWM 1-year recurrence period		U	A

Table 2.1: *Overview of design load cases [Ref. 6]*

The following abbreviations are used in Table 2:	
DLC	Design load case
ECD	Extreme coherent gust with direction change (see 6.3.2.5)
EDC	Extreme direction change (see 6.3.2.4)
EOG	Extreme operating gust (see 6.3.2.2)
EWM	Extreme wind speed model (see 6.3.2.1)
EWS	Extreme wind shear (see 6.3.2.6)
NTM	Normal turbulence model (see 6.3.1.3)
ETM	Extreme turbulence model (see 6.3.2.3)
NWP	Normal wind profile model (see 6.3.1.2)
V_r±2 m/s	Sensitivity to all wind speeds in the range shall be analysed
F	Fatigue (see 7.6.3)
U	Ultimate strength (see 7.6.2)
N	Normal
A	Abnormal
T	Transport and erection
*	Partial safety for fatigue (see 7.6.3)

Table 2.2: *Overview of abbreviations used in Table 2.1 [Ref. 6]*

2.2 GL guidelines

IV Rules and Guidelines Industrial Services - Part 1: Guidelines for the certification of Wind Turbines, Edition 2003, Germanischer Lloyd

Similar to IEC 61400-1 requirements for determination the loads to be considered are given in Chapter 4 of this GL guideline. The minimum number of DLC's can be found in section 4.3 of the GL guideline (table is not copied into this document). Comparing the DLC's of both guidelines it can be concluded that design situations do agree, although in GL guideline for some design situations a number of additional DLC's have been specified and less DLC's require the application of the normal (extreme) turbulence model.

In part 2 "Guidelines for the certification of OffshoreWind Turbines, Edition 2003", also the wave loading is considered, resulting in a more extensive list of DLC's.

In Chapter 7 of the GL guideline additional demands are given for machinery components, such as blade pitch system, bearings, gearboxes, yaw system etc. Similar to IEC 61400-1 no additional DLC's are specified. For some components it is stated in general terms that some loads (mostly caused by the geometry) should be included. For the generator bearing and the gearbox bearing at the outgoing high speed shaft loads due to misalignment between gearbox and generator should be considered. For the gearbox it is mentioned that, depending on the drive train concept, additional loads may be introduced at the gearbox input and output shaft. However in both cases no further details are given.

2.3 IEC 61400-4

Document N135 – IEC 61400-4 WD3 2008-06: “Design requirements for Wind Turbine Gearboxes”.

Chapter 6 of IEC 61400-4 aims at the drive train loads and amongst others the following aspects are addressed:

- guidance on the definition of the interfaces between the gearbox and the connected components (section 6.2.1 and Annex B);
- information which needs to be defined for describing the pertinent operating conditions and reactions at each of these interfaces, forces, moments, displacements etc. (section 6.2.2)
- wind turbine load calculations (section 6.2.3)
- drive train dynamic simulations using a detailed drive train model should be used to study the torsion resonance behaviour within the operating speed range (section 6.5).

According to section 6.2.3 of IEC 61400-4, the pertinent operating conditions at each of the agreed interfaces shall be determined in accordance with IEC 61400-1, which defines a minimum set of design loads cases (DLC). However, it may be necessary to include additional design load cases that may become relevant for the gearbox and its components. In IEC 61400-4 the following examples are given:

- DLC resulting in axial motions at low loads
- DLC including generator switch operations, for example for 2-speed generators
- DLC resulting in torque reversals
- DLC resulting in acceleration and deceleration of the drive train (e.g. high speed side caused by brake events or grid loss)
- DLC at reduced rated power possibly resulting in torque reversals (e.g. noise reduction operation, block control operation)
- DLC at wind speeds below cut-in (e.g. idling pendulum and braked)
- DLC caused by asymmetric loads from mechanical brake (normal, fault)
- DLC resulting from actions at periodic maintenance (e.g. emergency stop system tests)

This gives an overview of the currently available guidelines and the new guidelines that are being prepared concerning wind turbines. Specific guidelines for the pitch system and yaw system are at this moment not being developed or available, but the large difference between level of specification of the design standards for the blades and tower compared to other components in the wind turbine is being assessed.

3. Load Cases and Critical Design Variables

3.1 Overview systems

In addition to the components already covered sufficiently in the existing wind energy standards like IEC-61400 and the GL guidelines (f.i. blades and tower), at least the structural systems given in Table 3.1 should be considered in more detail with respect to design loads. Because of the specific problems with gearboxes nowadays it is obvious that the gearbox should be treated separately from the other drive train systems. To determine the "loads" on the whole drive train properly it should be emphasized that the dynamics that may be introduced by the machine frame and by the generator support structure should be taken into account in the simulation models as well.

To enable the specification of the Critical Design Variables for the systems given in Table 3.1 use is made of the breakdowns given in Table 3.2 - Table 3.5. It should be noted that these breakdowns are limited to those components or subsystems which are relevant for the structural integrity and therefore should be aimed at when specifying CDV's and design loads. Further details concerning the selection of the components in the breakdown are given in Appendix B.1.

Although not a structural component and not directly linked with "loads", there is a strong argument to include lubrication in the breakdown of the gearbox. Lubrication is of great importance for the structural reliability of the gearbox, while the efficiency of the lubrication system may be strongly dependent on the external conditions, e.g. also during a cold start up the lubrication system should work properly, which may depend upon specific control strategies. Hence for the designer of a gearbox it is of importance that the minimum set of DLC's provided by the wind turbine manufacturer does cover the reliable working of the lubrication system also.

In general the components mentioned in Table 3.3 are present in a drive train. However, the exact drive train architecture should be considered to asses whether this list is still covering the actual design.

Table 3.1: *Structural systems*

- Gearbox
- Drive train apart from gearbox
- Pitch system
- Yaw system

Table 3.2: *Breakdown of gearbox*

- Gears
- Bearings
- Shafts and shaft-hub connections
- Structural elements
  - Torque arm
  - Planet carrier
  - Any other structural components transferring major loads
- Lubrication

Table 3.3: *Breakdown of drive train apart from gearbox*

- Main bearing
- Main shaft
- Main shaft – gearbox connection
- High speed shaft
- High speed shaft – mechanical break coupling
- High speed shaft – generator coupling
- Generator

Table 3.4: *Breakdown of pitch system*

- Pitch bearing
- Pitch gearbox
- Pitch drives
- Actuator gear

Table 3.5: *Breakdown of yaw system*

- Yaw bearing
- Yaw brake
- Yaw drives
- Yaw gear

3.2 Design loads and design load cases

The relevant Critical Design Variables (CDV's) for the structural systems in Table 3.1 are elaborated in detail in Appendix B.2. The corresponding design loads are given below in Table 3.6 - Table 3.9. Beside the specification of the design loads, it is indicated whether the external condition introducing these design loads are covered by an existing design load case (DLC) in IEC-61400-1. For the relation with the GL guidelines, one is referred to section 2.2.

Table 3.6: *Design loads for gearbox*

General		
Name	**Type of load**	**Covered by DLC**
Rotor torque (Note 1)	Ultimate strength and fatigue	Yes: Note 2
Torque reversals	Ultimate strength, fatigue, and Hertzian stresses	Yes: Note 2
Relative displacements (axial, radial and angular) of: • main shaft – main bearing; • HSS - gearbox flange	Ultimate strength and fatigue	Yes: Note 2
Misalignment in drive train		No
External or internal electrical fault	Ultimate strength and fatigue	Yes: DLC 2.1, 2.2, 2.3, 2.4, 6.
LVRT (Low Voltage Ride Through)	Ultimate strength and fatigue	Yes: DLC 2.3, 2.4: Note 3
Gears		
Name	**Type of load**	**Covered by DLC**
Gear Rating • Pitting and bending stress • Scuffing • Micro pitting • Static strength	IEC-61400-4 WD3 – section 7.2.2	Yes: Note 2
Operation at overload	Ultimate strength and fatigue	Yes: Note 2
Bearing		
Name	**Type of load**	**Covered by DLC**
General design consideration • Subsurface initiated fatigue • Surface initiated fatigue • Adhesive wear	IEC-61400-4 WD3 – section 7.3	Yes: Note 2

• Frictional corrosion		
• Overload		
Relative displacement shafts/bearings	Ultimate strength and fatigue	Yes: Note 2
Temperature differences in the bearing	Ultimate strength and fatigue	Yes: Note 2

Note 1: Special attention should be given to the efficiency of the lubrication system

Note 2: All typical wind turbine operation modes are covered in the guidelines, so the external condition(s) introducing this design load is captured.

Note 3: LVRT is a complex situation which can contain many different DLC's, the current representation of this in the guidelines is too limited. The current tools are also not able to perform the necessary detailed analysis.

It is currently assessed that, when the above mentioned DLC's will be considered for gears and bearings, they will also include the relevant CDV's with sufficient detail for the shafts, shaft-hub connections and structural element (and possibly the lubrication system).

Table 3.7: *Design loads for drive train apart from gearbox*

Name	**Type of load**	**Covered by DLC**
Torque and bending moments acting on main shaft, high speed shaft, couplings, bearings, etc.	Ultimate strength and fatigue	Yes, Note 1
Resonance	Different components interference	No
Torque oscillations with load reversals of high speed shaft	Fatigue	Yes, Note 1
Relative displacements (axial, radial and angular) of: • main shaft – main bearing; • HSS – generator flange	Ultimate strength and fatigue	Yes, Note 1

Note 1: All typical wind turbine operation modes are covered in the guidelines, so the external condition(s) introducing this design load is captured.

Table 3.8: *Design loads for pitch system*

Name	**Type of load**	**Covered by DLC**
Drive torque for pitching	Ultimate strength and fatigue	Yes, Note 1
Drive torque for positioning	Ultimate strength	Yes, Note 1
Grid loss and gust	Ultimate strength	DLC 1.5
Deformation of hub - blade joint	Constraining forces and moments in pitch bearing	Yes, Note 1
Dynamic oscillating torque in pitch drive train	Fatigue and Hertzian stresses in the gears	Yes, Note 1

Note 1: All typical wind turbine operation modes are covered in the guidelines, so the external condition(s) introducing this design load is captured.

Table 3.9: *Design loads for yaw system*

Name	**Type of load**	**Covered by DLC**
Drive torque for yawing	Ultimate strength and fatigue; Wear of yaw brake and yaw gear	Yes, Note 1
Drive torque for braking (position holding)	Ultimate strength	Yes, Note 1
Deformation of the tower top flange or nacelle main frame	Constraining forces and moments on yaw bearing	Yes, Note 1

Note 1: All typical wind turbine operation modes are covered in the guidelines, so the external condition(s) introducing this design load is captured.

It appears that that for almost all design loads the external conditions introducing these design loads are covered by existing DLC's. The following two design loads are not covered: (1) loads in gearbox due to misalignment in the drive train, and (2) loads due to resonance in the drive train. In section 3.3 further details are given for specifying two new DLC's. The fact that the external conditions are covered by existing DLC's does not mean that that these DLC's can be applied straightforward in the design process of the structural systems, mainly due to the fact that the traditional wind turbine simulation tools are limited in modelling the structural systems with sufficient detail. Application of other type of simulation tools (like multi body simulation) may provide the possibility to solve the problem of the lack of detail, however at the cost of increased computation time, so then the problem arises that not all required DLC's can be analysed in a reasonable time period anymore. This problem will also be addressed in section 3.3.

3.3 Specification of relevant design load cases

3.3.1 Proposal for new DLC

For the design of the gearbox and the drive train the following three causes for higher loads should possibly be taken into account in the guidelines prescribed by IEC-61400-1 or the GL guidelines.

- DLC – Misalignment

  Misalignment of the drive train may cause constraining forces in the gearbox. To analyse these constraining forces it should be prescribed to what extend misalignment in the drive train should be considered. However, no clear information is available about the magnitude of drive train misalignment in practical situations. Therefore it is advised that the aspect of drive train misalignment should be discussed between the wind turbine designers, gearbox suppliers, and bearing suppliers, with the aim to specify a target value for drive train misalignment that should be used in the design for the gearbox.

  A complicating factor to analyse drive train misalignment is that in the traditional wind turbine simulation tools in general a simplified model is used for the drive train with only a limited number of degrees of freedom, so that misalignment can not be analysed with these models. This implies that for the design of the gearbox the constraining forces have to be specified on the interfaces. The consequences of prescribing loads at the interfaces are discussed in section 3.3.2.

- DLC – Resonance

  The drive train consists of a number of dynamic structures, which may show interference. This interference may lead to unexpected dynamic behaviour and therefore a resonance analysis has to be performed with models and tools that can be used within different frequency ranges in order to check the confidence levels that will be better at low frequencies than at higher frequencies. The current tools are not yet accurate enough to enable these analyses. An example of frequency ranges could be. [0 – 5 Hz] [5 – 50 Hz], [50 – 200 Hz], [200-500 Hz], [500-2000Hz].

- DLC –LVRT

  Fault or loss of the electrical network connection is included in DLC's 2.3 and 2.4, however in practise the tools are not yet good enough to completely analyse these DLC's. The LVRT should be described in more detail, many different shapes of the low voltage can be specified and have different effect on the turbine. The different grid codes that exist in different countries further complicate this DLC. This combination deems it impossible to prescribe the LVRT DLC's in detail. It is clear that it will also be very hard to find the most critical cases for a specific turbine. Combined with wind speed, a detailed approach of LVRT can result in a large number of DLC's to be analysed. The details of this process can therefore not be specified during this project. The LVRT DLC's are however of significant of importance for both fatigue and ultimate strength.

Strictly speaking especially the first two cases are **not** new DLC's; a maximum misalignment should be taken into account in the analysis and the real misalignment should not exceed the assumed maximum. A violation of the tolerance criterion cannot be accounted for in the DLC's, it must be assumed that a turbine is constructed according to the prescriptions. Resonance should automatically show up during the analysis. However, many of the currently used tools do not take the misalignment into account and the resonance could occur for frequencies that are much higher than can be analysed or are practically feasible in current tools. They could also not show up due to the limitations of the models used. Therefore it seems appropriate to specify new DLC's where these aspects are taken into account, but not put the same demands on all simulations of existing DLC's. Loss or faults of the electrical network are already described in the DLC's, however this process is at this moment too complex for the state of the art tools to enable detailed enough analysis. Also a lot of different possible cases could be defined for LVRT and the most critical cases are not easily determined, they can even depend on the country due to the different grid codes in place.

3.3.2 Treatment of existing DLC's

A general conclusion with respect to the characteristic design loads is that for almost all design loads the external conditions are covered by the DLC's already specified in IEC-61400-1 and the GL guidelines. This means that in principle all loads acting on the structural components (gearbox, drive train, pitch system, and yaw system) can be determined. However, in practice it is more complicated due the fact that the traditional wind turbine simulation tools are not able to model the structural components in sufficient detail, f.i.:

- insufficient modelling of the drive train deformation and of the deflections of gearbox interior components making some underlying assumptions for the calculations invalid (load transmission lines in the gears may change to load transmission points under angular displacement of gears);
- insufficient modelling of the systems by omitting flexibilities and deformations in the wind turbine main frame that lead to constraining forces and moments at the system joints to the adjacent structural system/component.

Therefore the suppliers generally use special purpose tools for the design of their components and for this purpose the relevant loads acting at the interfaces have to be made available by the wind turbine manufacturer. For this reason a set of relevant loads has to be specified at the interfaces, which can be used for the design by the component supplier. For the calculation of this load set traditional wind turbine simulation tools are used.

For the specification of a set of relevant loads acting at the interfaces the following aspects have to be addressed.

- Definition of load set at interface

  The DLC's relevant for the design of the structural component have to be selected. One of the objectives of the ProTest project is to provide guidelines for this selection, where the input from wind turbine designers and the designer of the structural components should be leading. As the case studies defined in the work packages 5 – 7 comprise measurements and analyses on existing wind turbines, the feedback from these case studies will be used to set up a proposal for such a guideline.

- Modelling of structural component in simulation tool

  To determine the relevant loads at the interfaces, all relevant DLC's should be simulated with the traditional wind simulation tools, where the modelling of the structural components is done with sufficient detail. As part of the current work package a study is carried out by the University of Stuttgart in which the minimum number of degrees of freedom required for the structural components is determined [Ref. 11].

- Determination of loads at interfaces

  Once the relevant DLC's have been analysed in sufficient detail with a traditional wind turbine simulation tool the loads acting at the interfaces have to be determined. A procedure for this will be developed with work package 3 of the ProTest project.

4. References

Ref. 1 M. Durstewitz et.al., Wind Energy Report Germany 2001; Annual Evaluation of WMEP, ISET, Germany 2002

Ref. 2 Energie- og Miljødata (EMD), database with energy production figures, incidents and accidents.

Ref. 3 BTM Consult: International Wind Energy Development; World Market Update 2005, Denmark, March 2006.

Ref. 4 Wiggelinkhuizen, E. et. al., "CONMOW: Condition Monitoring Offshore Wind Turbines", EWEC 2007.

Ref. 5 Dutch Wind Work Shops, held at ECN 11&12 October 2006

Ref. 6 IEC-61400-1, "Wind turbines – part1: Design requirements", third edition 2005-08

Ref. 7 Germanischer Lloyd, "IV Rules and Guidelines Industrial Services – 1. Guideline for the Certification of Wind Turbines", Edition 2003

Ref. 8 IEC 61400-4 WD3 2008-06, "Design requirements for Wind Turbine Gearboxes", committee draft

Ref. 9 Stefan Hauptmann et al., "ProTest - State of the Art Report", 2009

Ref. 10 Dipl-Ing. R. Gryzybowski and Dipl-Ing. K. Steingrőver, "Gearboxes for Wind Turbines in the Light of National and International standards", Beaufort6, Edition 1/2008.

Ref. 11. Stefan Hauptmann, under construction

Appendix A Format questionnaire

In this questionnaire you are asked to provide information (as far as possible) concerning the load assumption of a number of structural systems. For this purpose a number of tables have to be filled out. The information required is explained in *italic text*, and sometimes an example is given just for illustration. The italic text inside the tables can be skipped or deleted when filling out these tables.

A.1 Selection of components

According to the project proposal at least the following structural systems should be considered, drive train, pitch system and yaw system, however other structural systems should be added when of importance. Each of these systems is composed of sub-systems c.q components, f.i. when looking at the drive train one can think about subsystems/components such as the generator, gearbox, main bearing etc. and for the pitch system components such as the pitch bearing, pitch gearbox, etc.

Please complete table below by filling out the structural systems other than drive train, pitch system and yaw system to be included.

Table: structural systems to be considered within ProTest project

Name of system	Explanation
Drive train	Proposal
Pitch system	Proposal
Yaw system	Proposal
(name of additional system)	*(reason for adding this system)*
(name of additional system)	*(reason for adding this system)*

Please complete table below for each system by filling out the subsystems and or components at which should be aimed when specifying design drivers and probably design load cases (DLC) later on.

Table: Break down of structural system into subsystems and or components

Name of system	
(fill out name of system for which information is provided, f.i. drive train/pitch/system/yaw system/name of new system)	
Subsystem / component	**Remark**
(name of subsystem or component)	*(if possible, reason why this subsystem or component should be aimed at)*

Please copy above table to fill out information for another system.

A.2 Characteristic design loads

This section is meant to collect information about the load assumptions applicable for the (sub)systems and components specified in the previous section.

Probably several guidelines, codes or standards are already used in the design process of these (sub)systems and components. Next to the wind turbine design codes such as the IEC 61400 standards and the GL guidelines one can think about more specific standards like the ISO standards.

Once the design drivers have been specified, it has to be determined whether these design drivers are covered already with existing DLC's as described in the IEC-guidelines or the GL-guidelines. In case a design driver is not covered yet with an existing DLC it should be determined which kind of load assumptions should be made to cover this design driver, and if possible a DLC should be specified. As a guideline for this section the examples[2] given for the gearbox could be considered.

Please complete the table below for each (sub)system or component

Table: Load assumption for (sub)systems/components

Name of (sub)system or component

Codes or standards applicable

Name of guideline, code or standard *(f.i. IEC61400-1 or ISO 281)*	Description *(brief outline of the objective of the standard)*

Design drivers

Name *(identification of design driver)*	Description *(brief description of design driver)*	Covered by DLC *(Determination if design driver is covered with existing DLC and if applicable the number of the DLC, possibly in combination with recommendations in other standards, e.g. ISO, AGMA, etc.)*	Requirements for new DLC *(brief description of load assumptions to cover the design driver)*

Please copy above table to fill out information for another (sub)system or component.

A.3 Simulation models

To analyse the DLC's specifically addressed for the structural (sub)systems and components it is probably necessary to perform more complex analyses than currently possible with wind turbine simulation tools such as HawC, FLEX and BLADED (f.i. SIMPACK for dynamic analysis of gearbox).

To get an overview of these more complex analysis tools you are asked to fill out the table below.

Table: Simulation tools

Name of (sub)system or component

Simulation tools

Name of tool *(f.i. SIMPACK for dynamic analysis of gearbox)*	Description *(brief outline of capabilities, limitations, and application of tool)*

[2] See section 2.3 of current report

Appendix B Results questionnaire

B.1 Selection of components

According to the project proposal at least the following structural systems should be considered, drive train, pitch system and yaw system. Although the gearbox is part of the drive train, it was proposed to treat the gearbox separately and to focus in more detail on the relevant components of the gearbox also.

Furthermore the following structural systems may be of importance because of their impact on the overall dynamic behaviour of the wind turbine and consequently on the loading of the structural components.

- Machine frame, generator support structure.
  Insufficient stiffness causes unexpected deformations; such may lead to extra loads in the above mentioned structural systems. No explicit guidance is given in the wind turbine standards as of what shall be tested to validate the subsystem's integrity. Although, there may be specifications in the detailed design standards.
- Soft/soft tower structure.
  Soft/soft tower design has important implications for the turbine's overall dynamic behaviour.

When considering the ProTest project proposal, it is most likely impossible to broaden the technical content and to treat these two latter systems (frame and tower) similar to the gearbox, drive train etc. Nevertheless the implications the frame and tower may have on the structural systems of the original project scope should be addressed.

Summarizing, the scope of ProTest project will comprise the structural systems given in Table B.1, where the dynamic loads induced by frame and tower will be addressed.

Table B.1: *Structural systems*

• Gearbox
• Drive train apart from gearbox
• Pitch system
• Yaw system

Below, for each of the structural systems given in Table B.1, a breakdown in subsystems/components is made. These breakdowns are not comprehensive, but are limited to those subsystems and/or components which should be aimed at later on when specifying design drivers and design loads cases.

B.1.1 Gearbox

Based on chapter 7 of IEC 61400-4 WD3 the components summarised in table B.2 are selected for the gearbox

Table B.2: *Breakdown of gearbox*

GEARBOX

Subsystem / component	**Remark**
Gears	The gears cause a large number of gearbox failures.
Bearings	The gearbox bearings cause a majority of the gearbox failures: • Axial dof of shafts • Sliding of bearings. • Bearing stiffness.
Shafts and shaft-hub connections	The flexibility of the gearbox shafts is important for interactions of other components with the gearbox (low frequency), but also for interactions inside the gearbox subcomponents (higher frequency)
Structural elements	At least the following components should be considered: • Torque arm • Planet carrier (gear misalignment may be caused by deformation of planet carrier cage sidewalls) • Any other structural component transferring major loads
Lubrication	Lubrication is mentioned for reasons of consistency and is not directly linked with "loads" as such, however, it may be relevant to keep it because of relevant specification of "external conditions" => e.g. a lubrication system should work in a reliable way also during cold start conditions => this may depend upon specific control strategies

B.1.2 Drivetrain apart from gearbox

. In Annex B of IEC 61400-4 three common drive train architectures are presented, viz.:

- modular drive train with two main bearings
- modular drive train with 3-point suspension
- integrated drive train

Although the arrangement of the drive train will be dependent on the drive train architecture, in general the components summarised in table B.3 can be distinguished. It should be noted that the loading and the dynamic behaviour of these components may strongly depend on the whole drive train architecture.

Table B.3: *Breakdown of gearbox*

DRIVE TRAIN APART FROM GEARBOX

Subsystem / component	**Remark**
Main bearing(s) (including bushing)	The behaviour of the main bearing and its bushing may cause additional loading for the gearbox
Main shaft (MS)	Major component, can be massive shaft carrying bending and torque, can be divided into bending tube and torque shaft, can be a wide diameter conical tube of very short length.
Main shaft / gearbox joint	Depending on the type of joint alignment can be a sensitive parameter. Also tolerance to axial and radial motion or even inclination can be relevant.
High speed shaft (HSS)	Dynamics of the HSS arrangement can be important; alignment, tolerance to axial and radial motion or even inclination can be relevant.
HSS / mechanical brake coupling	Dynamics of the mechanical brake/coupling in the HSS arrangement can be important; alignment, tolerance to axial and radial motion or even inclination can be relevant.
HSS / generator coupling	The principal task of the coupling is (1) to compensate for misalignment of gearbox and generator and (2) to absorb extreme load peaks. Hence, the interactions of the gearbox and the generator are very much depending on the dynamic behaviour of the coupling. In this context it is of interest to what extend the coupling is able to actually meet these demands during operation of the wind turbine, where amongst others the failures from the electrical side should be considered.
Generator: bearings, electrical system, bushing	Dynamics of the HSS arrangement can be important; alignment, tolerance to axial and radial motion or even inclination can be relevant. Current leaking through HSS to gearbox may create problems in the lubrication of the gears.
If applicable: hydraulic pitch actuation system	A main hydraulic piston working through a hollow main shaft can cause static over-determination of the mechanical system.

B.1.3 Pitch system

Table B.4: *Breakdown of pitch system*

PITCH SYSTEM

Subsystem / component	**Remark**
Pitch bearing	Friction of the pitch bearing caused by deformation (ovalisation) is one of the main loads for the pitch drive train. Bearing clearance or play must compensate for deformation of the blade or hub. Specific aspects are: (1) The rollers and races are not all loaded equally as the wind turbine is operated most of the times at a small range of pitch angles (0 - 30° in full load operation), so this holds for the wear of the rollers and races also. (2) Lightning current through the bearings may cause damage of the rollers
Pitch gearbox	Possible resonances of gearbox stages with the rotor blade torsion natural frequencies may cause additional pitch drive train loads
Pitch drives (electric or hydraulic)	Provides required driving torque
Actuator gear / rod	Play in joints or delay times in the control can cause unfavourable control actions

B.1.4 Yaw system

Table B.5: *Breakdown of yaw system*

YAW SYSTEM

Subsystem / component	**Remark**
Yaw bearing	The yaw bearing passes on all loads from the nacelle to the tower. Insufficient stiffness in the tower top flange or nacelle main frame structure can lead to unfavourable loads
Yaw brake	Provides damping during yaw activity or fixes yaw position of nacelle when yaw system is inactive
Yaw gear	Provides incremental motion or fixes yaw position of nacelle when yaw system is inactive. Wear may become relevant when the yaw system provides damping to a free yaw concept. Frequent loading occurs when turbine is operating in wind regimes with frequent changes of wind direction
Electrical yaw drives	Provides required driving torque and damping during yaw system activity. Frequent loading occurs when turbine is operating in wind regimes with frequent changes of wind direction
Hydraulic yaw drives	Provides required driving torque and damping during yaw system activity. Frequent loading when turbine is operating in wind regimes with frequent changes of wind direction

B.2 Characteristic design loads

B.2.1 General

A general conclusion with respect to the characteristic design loads is that a large number of the design drivers is covered by the DLC's already specified in IEC-61400-1 and the GL guidelines, in particular those dealing with the operational loads of the wind turbine. Nevertheless the results of the structural analyses for these DLC's may have its limitations because the traditional wind simulation tools are limited in detail, f.i.:

- insufficient modelling of the drive train deformation and of the deflections of gearbox interior components making some underlying assumptions for the calculations invalid (load transmission lines in the gears may change to load transmission points under angular displacement of gears);
- insufficient modelling of the systems by omitting flexibilities and deformations in the wind turbine main frame that lead to constraining forces and moments at the system joints to the adjacent structural system/component.

Hence as a general requirement it should be stated that all relevant DLC's should be simulated with sufficient detail, *where it should be a task of the current ProTest project to specify the required level of detail.*

Although it is expected that most DLC are covered already, in the following section the design drivers are considered and it is determined whether these design drivers are covered by a DLC specified already or a new DLC has to be defined.

B.2.2 Gearbox

Table B.6: *Design drivers for gearbox*

GEARBOX

Codes or standards applicable

Name of guideline, code or standard	**Description**
IEC61400-1	Wind turbine design requirements
GL 2003	Wind turbine design requirements Assessment of structural components
IEC61400-4 WD3, including all standards mentioned in chapter 2 (normative references) and in section 7.2	Wind turbine gearbox design requirements
AGMA 2006	Standard for Design and Specification of Gearboxes for Wind Turbines

Design drivers: general

Name	**Description**	**Covered by DLC**	**Additional requirements**
Rotor torque	Extreme and fatigue	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	
Torque reversals	Oscillations in the drive train with load reversals can cause peaked loads, oscillating axial loading and excessive Hertzian stresses	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	Is covered by DLCs, but local phenomenon is not resolved by current model detailing.
Relative displacements (axial, radial and angular) of: • main shaft – main bearing; • HSS - gearbox flange or generator flange	Large relative displacements exceeding the tolerances may cause constraining forces and moments	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	Is not possible with current simulation models, need assessment of relevance.
Misalignment in drive train		No	Is not possible with current simulation models, need assessment of relevance.
External or internal electrical fault	Fatigue analysis with a number of occurrences per year	DLC 2.3	
LVRT (Low Voltage Ride Trough)	May cause high torques in drive train	DLC 1.4	Is covered by DLC, but current wind turbine simulation models are not able to cover high frequency dynamics caused by generator.
Site specific loads	Fatigue analysis of: wind farm wake and increased turbulence intensity and yaw misalignment	DLC 2.3	

Design drivers: gears

Name	Description	Covered by DLC	Additional requirements
Gear Rating • Pitting and bending stress • Scuffing • Micro itting • Static strength	cf. IEC-61400-4 WD3 – section 7.2.2	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	Although these design drivers are covered by existing DLC's they are not resolved properly in the current wind turbine simulation models. Hence relevant DLC's have to be selected, and the results of these DLC;'s have to be passed on to the gearbox designer. two main problems may arise in this process : • The selection of the relevant DLC's • The determination of the loads at the interfaces. Both aspects are subject of the ProTest project.
Operation at overload	Due to drive train oscillations the LDD could develop gear loads larger than rated loading with higher occurrence frequency as expected	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	

Design drivers: bearing

Name	Description	Covered by DLC	Additional requirements
General design consideration • Subsurface initiated fatigue • Surface initiated fatigue • Adhesive wear • Frictional corrosion • Overload	cf. IEC-61400-4 WD3 – section 7.3	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there	Although these design drivers are covered by existing DLC's they are not resolved properly in the current wind turbine simulation models. Hence relevant DLC's have to be selected, and the results of these DLC;'s have to be passed on to the gearbox designer. Two main problems may arise in this process : • The selection of the relevant DLC's • The determination of the loads at the interfaces. Especially DLC's during which a bearing is loaded under its minimum design load are of great importance.
Relative displacement shafts/bearings	Large relative displacements may cause constraining forces and moment, and changes in transmission line size	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there	
Temperature differences in the bearing	Rapid temperature changes (especially in the fast rotating bearings) may lead to constraining forces on the rollers and races when the bearing heats up faster than the engulfing gearbox housing	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	Quick change in bearing temperature with large gradient between inner and outer race

It is currently assessed that when the above mentioned DLC's will be considered for gears and bearings, they will also include the relevant design drivers with sufficient detail for the shafts, shaft-hub connections and structural element (and possible the lubrication system).

Important reasons for failing are related to:
Although not a DLC, the following points should be addressed also.

- Neglecting issues related to lubrication like: (1) water accretion in the lubricant, (2) electrical current sent through the lubricant decomposing the oil and disabling lubrication.
- With increasing size of the gear wheels the uncertainty increases in (1) gear shape, (2) gear dimensions, and (3) load distribution. Furthermore it may occur that one gear of a planetary stage has to carry the entire load. Although this is not a DLC it has be considered during the design.
- With increasing size of rollers and races the uncertainty increases in (1) bearing/roller dimensions, and (2) clearance. Although this is not a DLC it has be considered during the design.

B.2.3 Drive train apart from gearbox

Table B.7: *Design drivers for drive train apart from gearbox*

Name of (sub)system or component

DRIVE TRAIN APART FROM GEARBOX

Codes or standards applicable

Name of guideline, code or standard	**Description**
IEC61400-1	Wind turbine design requirements
GL 2003	Wind turbine design requirements
GL	Assessment of machinery components

Design drivers

Name	**Description**	**Covered by DLC**	**Additional requirements**
Extreme load	Max bending main shaft; Max torque main shaft, HSS, Generator coupling, etc.; Max. bearing forces	Yes, maximum from already prescribed DLC's	Torque does not include high-frequency parts of load spectrum. Extreme loads for (sub)components have to be determined by suitable model
Fatigue		Yes, load spectrum specified by already prescribed DLC's	Load of geared components taken in gear ratio only, high frequency elements ignored,
Resonance	Different components interference	NO	Resonance analysis has to be performed by detailed model of drive train. Relatively coarse model, not accurate for higher frequency elements
Torque oscillations with load reversals	Forced or resonant oscillation of high speed shaft torque	Yes, as all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	Operation should be modelled/analysed carefully by suitable model throughout the power output range
Relative displacements (axial, radial and angular) of: • main shaft – main bearing; • HSS - gearbox flange / generator flange	Large relative displacements may cause constraining forces and moment	Yes, as all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	

B.2.4 Pitch system

Table B.8: *Design drivers for pitch system*

PITCH SYSTEM

Codes or standards applicable

Name of guideline, code or standard	**Description**
IEC61400-1	Wind turbine design requirements
GL 2003	Wind turbine design requirements

Design drivers

Name	**Description**	**Covered by DLC**	**Additional requirements**
Drive torque for pitching	Max Torque while pitching	Yes, maximum from all DLCs in GL guidelines	Complex load scenario not covered by analysis tools,
Drive torque for positioning	Max Torque for holding position	Yes, aximum from all DLCs in GL guidelines	Support by friction not known, some dynamics of rotating hub and blade bearings not modelled
Drive Fatigue	Fatigue spectrum on pitch drive	Yes, Fatigue spectrum from all fatigue relevant DLCs in GL guidelines	Dynamics with non-linearity (clearance, non-linear friction etc) and high-frequency components should be taken into account in the model used to analyse the design driver.
Grid loss and gust		DLC 1.5	
Constraining forces moments in pitch bearing	Deformation of hub/blade joint	Yes: all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	Possible deformation shall be modelled/analysed carefully throughout the power output range with suitable model
Hertzian stress in the gears	Hertzian stress may go beyond acceptable limits	Yes, as all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there	Acceptable limits for Herzian stress in a gear pair may be exceeded due to static or dynamic (torque) loading of the pitch drive train. Current simulation models due not resolve this level of detail, might not even in future be possible.
Dynamic oscillating torque in pitch drive train	Excessive play in the actuators (gears / joints / rods) may cause controller induced oscillations	Yes, as all typical wind turbine operation modes are covered in the guidelines. If applicable the design driver is captured there.	Realistic play and delay times of hardware shall be modelled and the effects analysed carefully throughout the power output range

B.2.5 Yaw system

Table B.9: *Design drivers for yaw system*

YAW SYSTEM

Codes or standards applicable

Name of guideline, code or standard	**Description**
IEC61400-1	Wind turbine design requirements
GL 2003	Wind turbine design requirements

Design drivers

Name	**Description**	**Covered by DLC**	**Additional requirements**
Drive torque for yawing	Providing required driving torque during yaw system activity, frequent loading when turbine is operating in wind regimes with frequent changes of wind direction	Yes	Although load is covered by existing DLC's, the complex load scenario may not be treated well by analysis tools, as friction values not known (mean and deviation)
Drive torque for braking (position holding)	Providing required driving torque for fixing yaw position	Yes	Support by friction not clear
Wear of yaw brake	Yaw break provides damping during yaw activity or fixing yaw position of nacelle when yaw system inactive. Excessive use may cause excessive wear on the yaw brake system	Yes	Excessive use should be modelled/analysed carefully throughout the power output range.
Drive fatigue	Fatigue spectrum for yaw loads	Yes,	Dynamics with non-linearity (clearance, non-linear friction etc) and high-frequency components should be taken into account in the model used to analyse the design driver.
Fatigue and wear of yaw gear	Providing incremental motion / damping when yawing or fixing yaw position of nacelle when yaw system inactive, wear/fatigue may become relevant when the yaw system provides damping to a free yaw concept, frequent loading when turbine is operating in wind regimes with frequent changes of wind direction,	Yes	Must be thoroughly analysed carefully throughout the power output range
Constraining forces and moments on yaw bearing	Insufficient stiffness in the tower top flange or nacelle main frame structure can lead to constraining loads	Yes	To be modelled/analysed carefully throughout the power output range with suitable model

B.3 Simulation models

To analyse the structural (sub)systems and components in sufficient detail, the special purpose computer tools given in Table B.10 are used in addition to the wind turbine simulation tools such as HawC, FLEX and BLADED[3].

Table B.10: *Special purpose computer tools*

Name of tool	Description	Used by
SIMPACK	Multi body simulation code that is used for different applications: • Dynamic analysis of gearbox and pitch drive train • Interaction of different components in an entire turbine with high level of detail • Aeroelastic calculations using detailed component models. For aeroelastic calculations including models with higher level of details than used in Bladed, Flex5, etc. the Rotor Aerodynamics Tool Aerodyn (BEM and GDW) is used by UStutt in conjunction with SIMPACK. For considering the rotor aerodynamics in more detail, the AWSM code is used by Ustutt in conjunction with SIMPACK to capture the influence of the BEM simplifications to DLC simulations e.g. when dealing with yawed inflow. SIMPACK includes a simple FE tool for the generation of non-linear elastic models that is constrained to beam elements. A possibility to include more advanced FE models, generated with other codes like ABAQUS is given. SIMPACK provides high flexibility in modelling, requires implementation of robust aero-elastic model, is relatively slow, and finally is too detailed for coverage of all DLCs at current level	Hansen Ustutt ECN GL Suzlon
ABAQUS	FE code: Used for generation of advanced flexible bodies. The use of ABAQUS is suggested, because it is extremely reliable when dealing with large deformations.	Ustutt
DRESP	Detailed dynamic drive train analysis with good sub-models for gears, couplings and bearings, limited to torsional degree of freedom only. RWTH Aachen, IME, Institut für Maschinenelemente, Prof. Peter W. Gold	Suzlon DEWI
KISSsoft	KISSsoft AG, Switzerland	DEWI
S4WT, Samcef for Wind Turbines,	Computer Aided Engineering software, using Finite Element Method and Optimization techniques , A. Heege, Samtech Iberia	DEWI
3-D Simulation von Windenergieanlagen	Professor Dr. Friedrich Baumjohann, Fachhochschule Bielefeld, Fachbereich Mathematik und Technik	DEWI

[3] An elaborate review of drive train related tools is given by J. Peeters. *Simulation of dynamic drive train loads in a wind turbine*. PhD dissertation, K.U.Leuven, Department of Mechanical Engineering, Division PMA, Leuven (Heverlee), Belgium, 2006. available online: http://hdl.handle.net/1979/344. In addition to the list given in this dissertation, the following other software packages could today also be included in this list:

- SimulationX (company ITI, Dresden, Germany)
- Recurdyn (company Functionbay, Korea)
- Alaska (Institut für Mechatronik, Chemnitz, Germany)