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MINISTRY OF DEVELOPMENT

PROcedures for TESTing and measuring wind energy systems (PROTEST)

Template for the specification of loads necessary for designing drive train systems

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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 e.g. [32], [33], [34]). 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. [35] and discussions with turbine manufacturers, component suppliers, and certification bodies [36] 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 among others in [35] and expert discussions [36] 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 (PROcedures for TESTing 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. For gearboxes in common wind turbine architectures the special interfaces and load specification are explained in [1], Annex B.

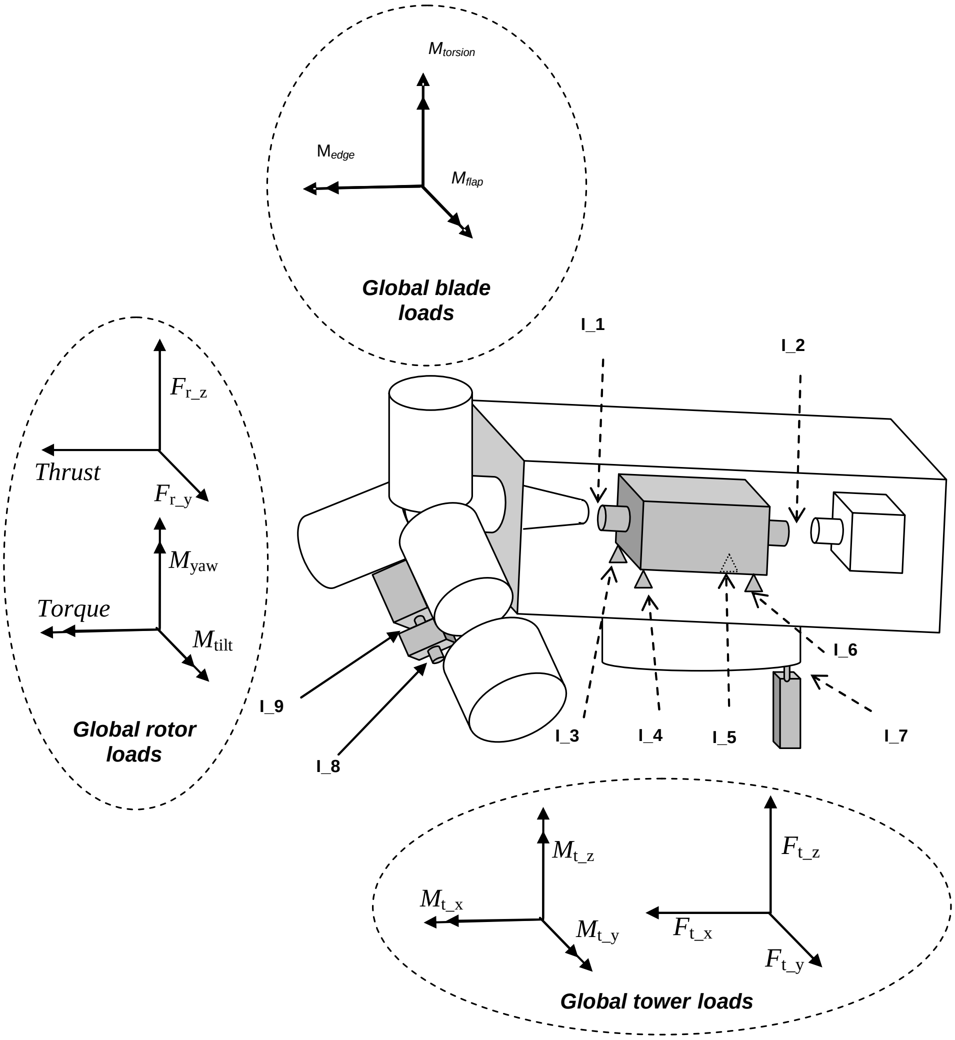

Figure 1 Schematic presentation of transforming "global turbine loads" to "local components loads" at nine interfaces, (gearbox, pitch system and yaw system)

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 drive train in complex terrain conditions**: 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 August 2010.

1.2. Work Package 3: Determination of loads at interfaces

In this report the findings in work package 3 will be discussed regarding the drive train system of the wind turbine. Therefore first the objective and background of this work package within the PROTEST project will be discussed, followed by the scope of this report.

1.2.1 Objective and background

The main objective of work package 3: “Determination of loads at interfaces” is to determine procedures for the selected components, among them the drive train and the gearbox, that describe how the loads at the interconnection points should be defined, taking into account the load cases specified in work package 2.

To this end, the specification of the interfaces of the selected wind turbine mechanical systems, more specifically for the drive train and the gearbox, is required. That includes isolating the gearbox and the drive train from the overall wind turbine structure and creating an adequate description of the sectional loads at the interfaces at which the overall wind turbine loads need to be transferred to design parameters. An assessment should follow regarding which knowledge of loading (i.e. torques, bending moments, accelerations, motions, deformations etc.) is considered as a valuable improvement over the current state-of-the-art.

Within the PROTEST project an overview of the up to date procedures regarding the modelling, the measurements and the certification of wind turbine mechanical systems, including the gearbox and the drive train, was presented in [37]. The design load cases and design drivers for the wind turbine components that should be considered for the load specification on the drive train were presented in the frame of work package 2 of the PROTEST project in [38].

These results, [37]-[38], will be further developed within WP3 to define the procedure for determining the loads at the interfaces of the considered components. The relevant issues of the wind turbine gearbox are discussed in the working draft IEC 61400-4 [1]. This document was used within WP3 as a starting point on the topic of the gearbox and the drive train to determine what kind of information is necessary at the interfaces for designing the mechanical components of the drive train.

1.2.2 Scope of the report

This document is prepared within the frame of WP3. The report is aiming to serve as a template for the specification of loads (spectra, figures, time-at-level, displacements, etc.) necessary for designing the drive-train of a wind turbine.

This report starts with the system and component definition following the results from WP2 of the PROTEST project. The relevant standards and results from literature survey are listed in section 3. In section 4 issues concerning the design and modelling of drive-train system components are discussed. This leads to the interface definition and the specification of the loads across these interfaces (section 5). Finally a format for the description and presentation of the loads is proposed in section 6.

2. Component definition

Clarification of the system is an essential step, in order to identify the interconnection points necessary for the design of each component. This is also necessary for defining the load (input – output) conditions of the components/subsystems of the wind turbine drive train under investigation. The break down of the drive train system into sub-systems/components presented in this section closely follows the results of WP2 of the PROTEST project [38].

In modern wind turbines, various alternative configurations of the drive train to produce electric power through the turning rotor are encountered (drive train with gearbox and high speed generator, gearless direct-drive and hybrid systems). Results of WP2 show that the interest of the PROTEST project partners is mainly on wind turbines having a drive train comprising a gearbox and a high speed generator. Thus the focus on the definition of interconnection points for load estimation will be put on these configurations. Assigning the gearbox as a point of interest within the drive train, according to IEC 61400-4 (draft) [1] (Table 22, Annex B) and taking into account the results of WP2 of the PROTEST project, the drive train comprises the following sub-systems/components:

- Rotor
- Rotor Hub
- Main (rotor) shaft (Low speed shaft)
- Main shaft bearing
- 2nd main shaft bearing (if applicable)
- Gearbox
- Torsion supports (left and right) (so called “torque arms”)
- Damper element
- Brake Disk
- High speed shaft Coupling
- High speed shaft (not mentioned in the IEC 61400-4 [1])
- Generator including following features:
  - Bearings/bushings
  - Electrical system

According to the decision taken within the PROTEST project the electrical system will not be treated with the project, however, for completeness it is recorded under the generator sub-system. Additionally, the gearbox, as well as the (internal) interfaces of the gearbox are very important part of the specification and will be separately discussed.

In Figure 2 a schematic layout of the drive train with two main bearings is shown as an example of the different configurations of the drive train encountered in modern wind turbines. From this figure it is clear that the structural part of the wind turbine, which is used to support the drive train, should also undertake the loads that will be eventually transferred to the wind turbine tower.

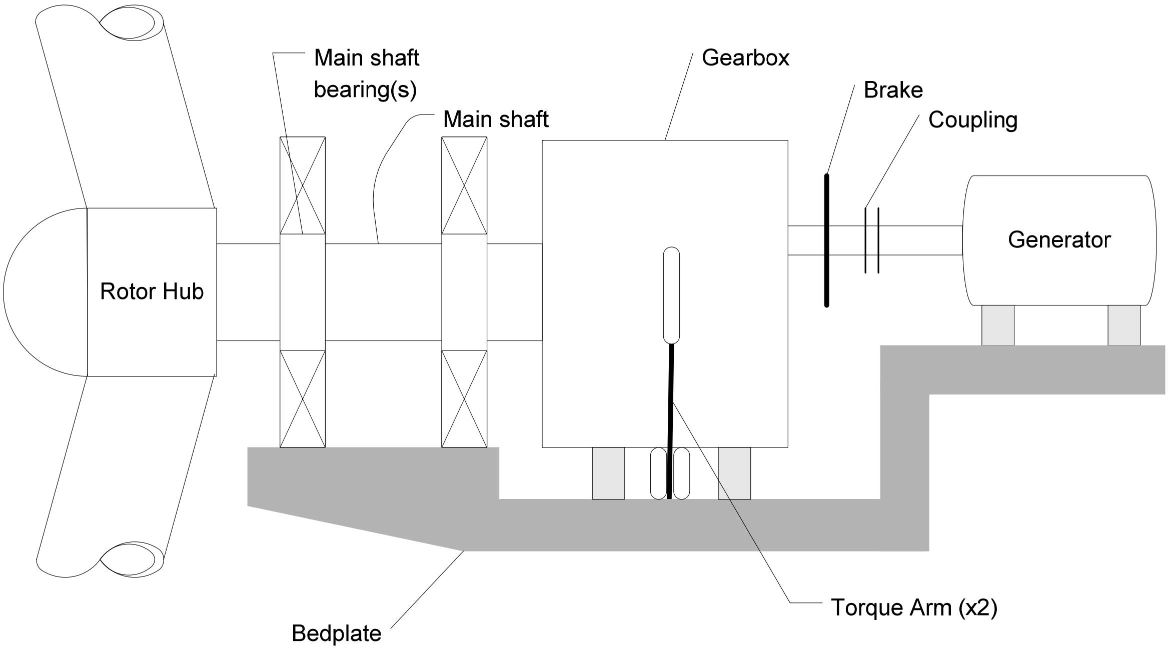

Figure 2 Schematic of nacelle layout with two main bearings

3. Survey of standards and relevant specification literature

Starting from the design guidelines (standards, regulations) for the components/systems a review of the relevant standards is performed in this section with focus on the load definition necessary for designing the drive train system of the wind turbine. Where applicable the reference standard for the design of a component of the system under investigation is mentioned. Additional standards (guidelines, specifications) that cover testing and certification procedures are also addressed.

3.1. Baseline standards

- **IEC 61400-1** [3] is the baseline standard covering the design of the whole wind turbine.

  In this document the design load cases for all the wind turbine components are defined. It is also specified, which load cases will be taken into account within a fatigue analysis and which for an ultimate (extreme) analysis. Normal Turbulence Model and Normal Wind Profile model are cases treated in fatigue analysis, including start-up, shut down events and parked conditions (for wind speed <0.7 V_{ref}). Wind speed distribution is prescribed.

- **IEC 61400-4** [1] (Currently ISO 81400-4:2005 [2]): is the baseline standard covering the design of the gearbox of the wind turbine.

  Through this document, the user is directed to IEC 61400-1 [3] for the definition of design load cases. However, a more detailed analysis is described in Annex B (ISO 81400-4:2005 [2]) regarding the load spectra, including both normal loads and transient events. Especially for the transient events, the wind turbine manufacturer is required to provide an estimation of the number of probable occurrences over the life time of the wind turbine, but these numbers are site dependant (e.g. driven by the reliability of the grid). In IEC 61400-4 [1] apart from reference to the IEC 61400-1 [3], it is stated that in the required specification at least the following should be provided:

(1) a description of the DLC relevant for transmission design,

(2) the frequency of occurrence,

(3) the probability of occurrence e.g. abnormal or normal load case,

(4) the duration of occurrence,

(5) information on load calculation model including transmission model and transmission model and

(6) a reference to DLC, or identification or relevant partial safety factor for loads, with clear information whether these are already included, or need to be added.

Design Loads should be given at the Interface (Interconnection Points). Great emphasis is given in this aspect in the IEC 61400-4 [1] document, including the definition of these points.

The current work will be limited to defining the load cases required according to the abovementioned documents. This is due to the fact that the standards for the design of the subcomponents are beyond the scope of this project. However, the relevant standards will be mentioned, including short descriptions.

- **ISO 6336(-1,-3,-5, -6):** are the standards covering load capacity of spur & helical gears [4]-[8]. In particular ISO 6336-6 deals with the calculation of service life under variable load [8].
- **DIN 3990:** is the standard to be followed for the fatigue rating of gears according to GL – Guidelines for the certification of WTs [9].
- **DIN 743:** is the standard for shafts & axles [10]
- **ISO 76 & ISO 281:** are the standards covering rolling bearings. ISO 76 covers the static loading [11] and ISO 281 the dynamic loading [12].

Additional standards/documents that provide important information for the performance of the scheduled work are the following:

- **IEC WT01:** is the baseline standard covering the certification procedure of the wind turbine (including components) [13].
- **IEC/TS 61400-13:** is the baseline standard covering load measurements on components of the wind turbine (field measurements) [14].
- **GL Guidelines for the certification of WTs** [9]**:** This document includes a description on what procedures to follow (including references to relevant standards) during the design of gearboxes, but also a description on how to verify the gearbox design models (e.g. a verification testing according to ISO 8579-2). Moreover, it is clearly stated in the document that for these components, not only the average values of the fatigue loads are necessary, but also the Load Duration Distribution (LDD) should be specified. Additionally, there are directions on how to combine the Design Load Cases for the fatigue analysis, including an estimation of the yaw operation.
- **ISO 8579-2:** Acceptance testing for gears – vibration level [15].
- **DIN 45667:** is the standard covering the load duration distribution procedure [16].
- **GL Guideline for the certification of Condition Monitoring System for WTs** [17]**:** In this document additional information is provided on the measurements required to monitor the condition of the gearbox.

- **Specification of manufacturers:** e.g. INA catalogue [18] and Rothe Erde technical document [19] covering slewing rings and FAG publication [20] covering the design of rolling bearing mountings.

NOTE 1: American Equivalents (e.g. ANSI/AGMA, ASTM) of the abovementioned standards are not referenced in the current document.

NOTE 2: Standards that are referenced and should be followed when applying the referenced standards of the current document, but which refer to special design methodologies (material & lubrication specifications, etc.) are not referenced in the current document.

4. Modeling of components during wind turbine design

The process of designing a wind turbine can be divided into two stages. One stage involves the extraction of loads and estimation of the wind turbine behaviour due to the stochastic wind loading and the other stage involves the detailed analysis of each component/system. During the design of a new wind turbine a loop is necessary for exchanging information between these two stages. In other words, using wind turbine nominal data (e.g. gross dimensions, reference values for cut-in, rated and cut-out wind speed, etc.) and employing assumptions, as the final design specifications are not at hand (at this stage), the first dimensioning loads are estimated through aerodynamic simulations. These are distributed to the designers of the basic WT components, i.e. blades, gearbox, tower, generator, etc. After the initial dimensioning of the components the designer of each component provides details regarding the component for the initial aero-elastic analysis of the wind turbine. The scope of performing an aero-elastic simulation at this stage is to derive as accurately as possible the induced loads on the various wind turbine components, as well as to evaluate the overall behaviour of the wind turbine under the influence of the wind conditions. Multiple loops of the process result in the final load estimations and the detailed design of each component/system.

4.1. Aero-elastic simulation of the wind turbine

A review of state of the art aerodynamic and aero-elastic simulation procedures is given in [21]. In this work, a description of the structural modelling of the wind turbine is given: “The main components of a wind turbine are the blades, the drive train and the tower. They are all modelled as beam structures and typically the structural properties are assumed for each component to continuously vary along the corresponding elastic axis. However, localized properties can be added in the form of concentrated masses, dampers, or springs. The gearbox (if present), the generator, the hub are usually added in this way. The involvement of different body motions for each component in combination with the connections where loads and displacements are communicated for one component to the other, calls for a global formulation of the dynamic problem. To this end most works adopt a multi-body approach, which consists of considering each component separately subject to appropriate boundary conditions, which fit the different components into the complete configuration”.

Obviously for all systems/components the 3D structure is reduced to fit in the aeroelastic simulation. For example, the 3D structure of a multi-layered composite material blade is modelled as a beam likewise the 3D structure of the tower.

4.1.1 Gearbox

For the complex system of the gearbox the minimum information required to perform an aero-elastic simulation is following according to IEC 61400-4 [1]:

- Transmission ratio (of the gearbox)

- Mass of the gearbox
- Centre of gravity of the gearbox (e.g. coordinates relatively to the tower top)
- Mass moments of inertia Jx,y,z
- Stiffness (torsional stiffness)
- Damping properties

These are usually provided for the initial phases of the simulation.

The data required for the modelling of the gearbox depends strongly on the intended level of detail and the demand towards the frequency range of the analysis.

The possible level of detail for such a model ranges from simple torsional mass-spring-damper-systems with only a few rotational degrees of freedom to very complex systems containing flexible bodies and super-elements representing housings and foundations.

For a basic representation, the gearbox can be described as a single equivalent inertia and torsional stiffness. This reduces the gearbox to a single degree of freedom system. The system can be adapted to match the first torsional eigenfrequency of the structure. Being a single Degree of Freedom (DoF) system, this model is not capable of representing the dynamic behaviour of the structure for frequencies higher than the first eigenfrequency.

Following discussions with PROTEST partners, this is the case for the available aero-elastic simulation codes BLADED, Flex 5 and Phatas. For the modelling of the gearbox these codes require only the gearbox ratio, while the other properties of the gearbox (torsion stiffness and inertia of the rotating parts) are incorporated in the model in the gross parameters requested for the drive train definition (see section 4.1.4 of the current document). As an exception to this, Phatas requires in addition to the gearbox ratio the constant loss, the proportional loss and the gearbox inertia. Moreover, in BLADED an external DLL containing the model of the gearbox can be connected to the code.

The aero-elastic simulation tool TURBU allows for a more detailed description of the gearbox requiring following input parameters:

- Transmission ratio (of the gearbox)
- Mass of the gearbox (given independently for the rotating parts (gears) and the non-rotating parts (gearbox house) of the gearbox)
- Mass moments of inertia Jx,y,z (given independently for the rotating parts (gears) and the non-rotating parts (gearbox house) of the gearbox)

However, for a more detailed analysis and not simply treating the system as “black box” additional information can be modelled with currently available aero-elastic simulation tools developed specifically for the wind energy sector. To this end, the gearbox can be modelled using beams, masses, mass moments of inertia and gear ratios to represent the stages within the gearbox (shafts and gears) provided that the information is available for the aero-elastic simulation.

In parallel, information on the support points of the gearbox should be provided along with the adequate stiffness and damping for the support points.

If additional torsional or translational DoFs are to be covered in the model, the level of detail has to be increased. Additional rotational DoFs can be introduced by means of a higher discretisation of the shafts in the gearbox. This can be done using multiple masses connected by spring-damper elements for each shaft. The same can be achieved using beam elements. For the consideration of shear effects and bending modes Timoshenko beam elements should be the first choice. The use of solid elements requires a reduction of the mass and stiffness matrices, e.g. Guyan-Method or Craig-Bampton-Method [22].

Using MATLAB, Simpack or Adams, for example, the internal dynamics of the gearbox can be considered by modelling the gearbox elements as shown in Figure 3 and by them, connecting the model with available aero-elastic wind turbine simulation tools [23].

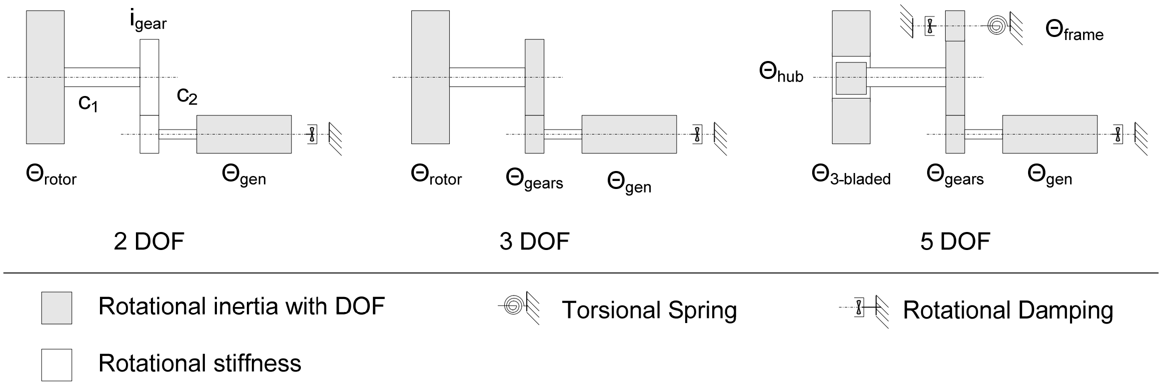

Figure 3 Examples of simplified gearbox models

Besides the description of the gearboxes shafts, the modelling of the gears meshing is of major importance towards the dynamic behaviour of the model under investigation. The codes currently available for the analysis of the drive-train dynamics allow two approaches for the modelling of meshing gears:

- Gear constraint with force element
- Purpose-built, time variant force element

The first approach combines a constrained equation for the speed ratio of two shafts with a force element. The force element represents a constant value for the meshing stiffness.

The purpose-built force element allows the more realistic modelling mechanisms which are present during the gear contact. Here, the meshing stiffness is derived from the geometric data and the material properties of the gears. The influence of a variation in the gears centre and axial distance is included and has not to be modelled additionally.

This approach is commonly used if additional degrees of freedom are present in the model. This might be translational DoFs representing the bearing and housing stiffness.

On the other hand, current practice indicates that the aero-elastic simulations are performed with a time step adequate to cover up to about 20Hz (or lower for the modern multi-MW class wind turbines), which is possible using a time step in the order of 0.006s during simulations. This time step leads to a sampling frequency of about 80Hz, which corresponds to 4 times the 20Hz frequency and is considered as the minimum sampling frequency to capture the phenomena up to 20Hz. The frequency region covered using aero-elastic simulations is driven by the selected time step and vice versa. In order to accelerate the simulation solution the time step might be increased, with the penalty of reducing the frequencies covered by the analysis. As wind turbines become larger, the natural frequencies are getting lower and thus, the simulation time step can be increased to optimize the simulation time in this sense.

It is understood, that this sampling frequency is lower than what is usually employed in multi-body simulations, since the latter are usually used to capture phenomena acting faster. These multi-body simulations (using smaller time steps) are specifically targeted for the identification of dynamic problems, i.e. verify the avoidance of severe resonances. In that case, the analysis is limited to the derivation of the Frequency Response Function of the system and verification of the systems response for specific load cases of interest and not aiming to capture the various load cases as defined in IEC 61400-1.

Currently available aero-elastic simulation tools derive the loading on the major components of the wind turbine by using the abovementioned minimum time-step for capturing phenomena up to 20Hz (or lower for modern multi-MW Wind turbines). In order to capture phenomena anticipated acting faster than this, a clear indication of the highest frequency involved should be provided.

As an output of the model, sophisticated aero-elastic simulation tools provide the following information, relative to the gearbox, which is derived through simplified modelling of the entire drive train, as pointed out in [22]:

- Three forces and moments on the gearbox input node (low speed side)
- Three forces and moments on the gearbox output node (high speed side) if basic information is provided for the gearbox

Depending on the information available similar output could be provided for support positions of the gearbox. For example in TURBU the coaxial rotation of the gearbox house relative to the nacelle is provided. Moreover, if information on the individual stages of the gearbox is available, the output will be given on the modelled points in terms of both displacements and forces.

4.1.2 Drive train

Information required for the complex system of the drive-train (except the gearbox) to perform an aero-elastic simulation is the following according to IEC 61400-4 [1]:

- Shaft (Main shaft & High speed shaft)
    - Mass
    - Centre of gravity
    - Stiffness
    - Mass moments of inertia Jx,y,z
- Main shaft bearing & 2nd main shaft bearing (if applicable)
    - Mass
    - Centre of gravity
    - Stiffness
    - Mass moments of inertia Jx,y,z
- Torsion supports (left & right)
    - Stiffness
    - Damping
- Generator
    - Mass
    - Centre of gravity
    - Mass moments of inertia Jx,y,z
- High speed shaft Coupling
    - Stiffness
    - Damping

Details of (mis)-alignment affecting load calculations should be documented according to IEC 61400-4 [1].

Although these input parameters are specified as necessary for the aero-elastic simulations, discussions with PROTEST partners [23], [24] revealed that the actual required input of various commercially available and/or in-house developed aero-elastic codes is following (excluding gearbox data):

- Main shaft
    - Mass: TURBU
    - Centre of gravity: TURBU
    - Stiffness: BLADED (torsional only), Phatas (torsional only), TURBU (bending & torsion)
    - Damping (torsional only): BLADED
    - Mass moments of inertia Jx,y,z: Phatas, TURBU
- High speed shaft
    - Stiffness (torsional only): BLADED, Phatas, TURBU
    - Damping (torsional only): BLADED, TURBU
    - Mass moments of inertia Jx,y,z: BLADED, Phatas, TURBU
- Main shaft bearing & 2nd main shaft bearing (if applicable)
    - Location: TURBU
- Torsion supports (left & right)
    - Stiffness: Phatas, TURBU
    - Damping: Phatas (Viscous), TURBU
- Generator
    - Mass moments of inertia Jx,y,z: BLADED, TURBU
    - Torque – Speed relation: Phatas
- Whole Drive Train
    - Stiffness (torsional): Flex 5 (may be non-linear)
    - Damping (torsional): Flex 5

BLADED and Flex 5 allow for external DLLs to simulate the dynamic behaviour of the whole drive train (FLEX 5) or individually for gearbox only or gearbox & high speed shaft & generator rotor (BLADED).

As an output of the model, sophisticated aero-elastic simulation tools provide the following information on nodes of the drive train, which are derived through simplified modelling of the entire drive train, as pointed out in [22], the moments and forces and the displacements. The output of course depends on the availability of details for employment within the aero-elastic model.

Thus, following the required input as set up above and according to discussions, the output of the available commercial and/or in-house developed tools for the time domain simulations of the dynamic response of the wind turbine are following:

- Generator torque: Flex 5, Phatas, TURBU

- Rotor Torque: Flex 5, Phatas, TURBU
- Gearbox Torque: BLADED
- Rotational Speed of Main shaft & high speed shaft
- Three forces and moments on the drive train nodes (low speed side)
- Three forces and moments on the drive train nodes (high speed side) if basic information is provided for the gearbox

It is noted that output relative to the gearbox has been discussed in previous section.

As a result of the simplification of the drive train model in the traditional design codes, for the design of the drive train, the simulated output needs to be further processed to loads on the individual components, such as gears, bearings and shafts [22]. This approach is only valid when the drive train's internal components contribute by any means only negligibly to the dynamics of interest [22]. Therefore, a clear input should be also provided for the aero-elastic analysis for the highest dynamics of interest.

On the other hand, although the simulation tools are available, as also pointed out in [26], the following is a list of limitations in current simulation approaches:

- Aero-elastic simulation of the entire wind turbine to extract the entire set of load cases is time consuming. Personal discussions with aero-elastic analysts indicated a time-frame of one week is needed for the extraction of the complete set of load cases described in the IEC 61400-1, however, using a simple model of the drive train. When using a more detailed model for the drive train, as in [27] the simulation of an "emergency stop" transient load case, of about 150s (2.5 minutes) "real time", takes about 35 minutes CPU time on a Pentium IV computer! As also recognized in IEC 61400-4 both simplified aero-elastic simulations of the entire wind turbine as well as detailed analysis of the gearbox are required for a comprehensive design.
- Although the transformation of the details of the 3D structure of the blades and the tower into a 1D structure, which is usually used during the aero-elastic simulation, is well documented and straightforward, the documentation of transforming the 3D structure/system of the drive train and the yaw and pitch mechanisms into suitable information to be used in aero-elastic simulations of the wind turbine is not publicly available. The reasons behind this are twofold: On the one hand the sophisticated aero-elastic simulation tools employ a very simplistic modeling of the drive-train, while when more sophisticated simulation tools for the drive train are used then the aero-elastic input part of the structure is oversimplified, due to cost and time required for each of the two analysis types. On the other hand, as pointed out in [26], the data transfer between parties, especially regarding the gearbox and bearings could be problematic.
- A lack of understanding of which are the important parameters of the drive-train (which is usually treated as a "black box" during the simulation of the whole wind turbine), in combination with the cost of the analysis and the fact that the analysis is only a "simulation" which might not capture the actual load cases the wind turbine will face during its operation" may prevent a decision on repeating simulation runs after design modifications.
- The most important limitation is that, although the simulation runs are available and explicitly defined the proportion of each load case in the entire life of the wind turbine is not. For critical load cases for the drive train such as starts and stops, parked conditions, generator switching's etc., there is no clear description of how many are expected during the life of the wind turbine (since these are strongly site dependent) and depend on controller settings that are easily modified (especially for the yaw and pitch systems). Only GL – Regulation for the certification of Wind Turbines [9] provide some guidance on

that aspect. In other words, aero-elastic simulations provide the load time-series that should be taken into account, but the description of the life spectra, which is formed of these time-series, is lacking.

4.2. Wind Turbine Components modeling

Taking as input the loads provided by the aero-elastic simulation tools, a detailed analysis of the wind turbine components is performed by the designer of the component/system. To this end, finite element methods or multi-body simulations are usually employed with a varying modelling detail reaching up to the modelling of each bearing or gear-tooth (depending on each case). In cases where the detailed analysis is performed for the design of components it involves proprietary information by the manufacturer/designer (e.g. Leaflet of SKF for pitch/yaw bearings [28]).

Much effort is put to verify the modelling tools, in terms of assessing whether the model predicts the behaviour of the system accurately, e.g. [27] dealing with the drive train, [29] addressing the modelling of pitch bearing of a wind turbine.

But still no matter how detailed the analysis is performed, no matter how accurately the response of the system is predicted, if the estimation for the loads during the operational life of the system is not accurate, the estimation of the operating life will be subject to uncertainties.

4.2.1 Gearbox

In IEC 61400-4 [1] it is specified that the following information should be available at each interconnection point, relevant to the drive train and gearbox:

- Forces and moments
- Rotational speed
- Motions/Accelerations
- Deflections
- Temperatures
- Lubricant flow, -temperature & -pressure
- Misalignment or alignment allowances

The load data should be presented as a function of time for the relevant DLC's. Using the distribution of these DLC's over the wind turbine's life span, the loads required for the estimation of the operating life of the gearbox and its components can be generated and analyzed.

However, it is also recognized that most of this information will only be available after the (almost) complete design of the wind turbine and the gearbox. This requires an iterative design approach in which the simulated load data and updated model parameters are exchanged to converge to accurate load predictions yielding accurate estimation of the operating life of the gearbox and its components.

4.2.2 Drive train

The drive train is a system comprising several subsystems and components as described in Section 2.4 of the current document. Therefore, for the design of the complete drive train system an interaction between teams performing the detailed design on the major components of the drive train (e.g. hub, main shaft, gearbox, etc.), as well as the team performing the assessment of the complete drive train is necessary through the whole design/development phase. Current practice involves the dimensioning of generally standardized lay-outs of the wind turbine.

In general to initiate the design process of the individual subsystems of the drive train one needs the geometrical specifications, as well as the loading (at least an initial estimation). Fatigue and extreme (static) loading should be considered. The initial estimation of the loading conditions is delivered to the designer of the drive train subsystem as an output of simulation tasks performed. Fatigue loads are provided in the form of Markov matrices and LDDs calculated for the desired lifetime of the wind turbine (usually 20 years).

In [30] it is recognized that the load estimation on the various components of the drive train is performed through simulations using a simplified model of the drive train components. To compensate for neglecting the dynamic properties of the components a resonance analysis is described as essential. This analysis is used for comparing the behaviour of the simplified model used during simulations for extracting loads with the global behaviour of a more detailed drive train model.

4.3. Conclusions – modeling

A lot of effort is currently being put into the complete aero-elastic simulation of the wind turbine, including detailed information on all systems of the turbine. Ongoing work is performed especially for the drive train components in this field, e.g. within the project UPWIND WP 1B2 (Contract No. SES6-019945). Therefore, as a step forward not only the time series of each loading case needs to be measured (estimated) but also the contribution of the various load cases to the expected life of the component system in order to improve estimation of operating life of the component. Especially the load cases that are benign to the other components of the wind turbine, that is the blades and the tower, and which are usually ignored, seem to play an important role in the design (and operation) of components involving bearings and gears. For example, the case “Wind turbine parked (standing still or idling)” is estimated, however, no indication is given as to the duration of this condition, which plays an important role in bearings. In other words, it is different if the machine is parked for a long period of time, e.g. 600 hours continuously during one year, or if these 600 hours are spread over the year. Moreover, a realistic approach should be given for the transient load cases. It does not suffice to define the cut-in and cut-out wind speeds, if one does not estimate the normal starts and stops that the wind turbine will endure during its service life, irrespective of whether these are due to wind conditions, decisions of authorities in the power supply lines for the interconnected wind turbines, or simply due to a weak grid. The GL–regulations for the certification of wind turbines [9] recommendations could provide a starting point in this aspect, which should be verified with experimental data or other statistics.

5. Load definition at interconnection points

5.1. Definition of interconnection points

According to IEC 61400-4 the first step is to define the interconnection points (interfaces) for the design. It should be noted that the definition of interconnection points (interfaces) follows the definition of Interfaces of IEC 61400-4 [1], adequately modified to cover the needs of the systems addressed in the PROTEST project. That is, the interconnection points (interfaces) are defined as: a defined boundary of the specific system that is either a physical mount to another wind turbine subcomponent or a path of exchange such as control signals, hydraulic fluid, or lubricant. Additionally, instead of the word “interfaces” the phrase “interconnection point” is used herein to connect with the potentials of simulation tools used in the wind energy sector, which provide the output data (displacements, forces, moments, etc.), on “nodes” of the modelled components of the wind turbine. For example the high speed shaft interconnection point with the gearbox during simulation is the node connecting the high speed shaft element with the gearbox element and is given certain freedoms and constraints.

As already noted, due to the importance of the gearbox as a wind turbine component, this system will be treated separately from the drive train. This approach will lead to identification of the gearbox interfaces, which when the gearbox is considered as a component of the entire drive train are internal interfaces of the larger system.

5.1.1 Gearbox

Based on the definition of the gearbox system, as presented in previous section of the current document the interfaces of the system are described in this section. For the gearbox, IEC 61400-4 [1] identifies the following interconnection points (interfaces), commonly applied in modern wind turbine designs:

- The low speed shaft to the gearbox (specifically the gearbox 1st stage entrance)
- The high speed shaft to the gearbox (specifically the gearbox last stage - output)
- The mounting positions of the gearbox on the nacelle main frame typical via torque arm to the gearbox (specifically the gearbox housing)
- The mechanical break typically connected to the high speed shaft
- Other major interfaces, depending on whether additional systems of the wind turbine are directly mounted on the gearbox, may include:
    - the generator to the gearbox (if the high speed shaft is part of the gearbox housing)
    - the pitch system to the gearbox (if the pitch system is mounted on the gearbox housing)
    - the yaw system to the gearbox (if the yaw system is mounted on the gearbox housing)
    - the brake system to the gearbox (if the system is mounted on the gearbox housing)
- Other interfaces including (interfaces for sensors, lifting points, etc.)

Depending on the arrangement of the wind turbine the following sketch shows the relevant interconnection points (interfaces) relevant to the gearbox only. In the configuration shown in Figure 4 it is supposed that the gearbox does not support other systems (i.e. that no additional systems are directly mounted on the gearbox). Accordingly, following interfaces can be identified for this configuration:

1. The low speed shaft to the gearbox (specifically the gearbox entrance stage)
2. The high speed shaft to the gearbox (specifically the gearbox output stage)
3. The nacelle main frame through the supporting positions of the gearbox to the gearbox (specifically the gearbox housing)
4. The mounting positions of the gearbox on the nacelle main frame via torque arms to the gearbox (specifically the gearbox housing)

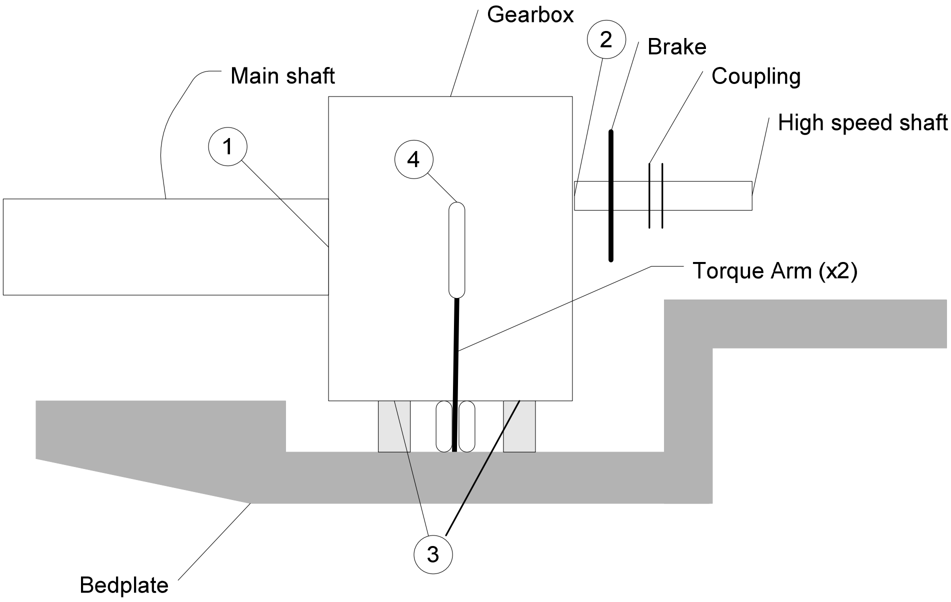

Figure 4 Schematic of the gearbox layout without supported systems

5.1.2 Drive train

Depending on the wind turbine layout, and following the definition of the drive train presented in the previous section and IEC-61400-4 [1] the following interconnection points (interfaces) are identified:

- The rotor hub to the drive train (specifically on the low speed – main shaft)
- The generator to the drive train (specifically on the high speed shaft). Note, that within the PROTEST project, it was decided that the focus will be on the mechanical loads transferred through the components of the wind turbine. Thus, the actual interface in this case is internal to the generator.
- The nacelle main frame (through the support points of the gearbox and main shaft) to the drive train (the support points depend on the configuration, but usually these are on the main shaft and the gearbox housing)
- Blade control transfer mechanisms (if pitch system is attached to the drive train)
- The mechanical brake

Specifically, for the configuration using a modular drive train with two main bearings, as shown in Figure 5, the following interfaces (interconnection points) can be identified:

1. The rotor hub to the drive train (on the low speed – main shaft)
2. The 1st main bearing of the drive train (on the low speed shaft) to the nacelle main frame
3. The 2nd main bearing of the drive train (on the low speed shaft) to the nacelle main frame
4. The torque arm on the gearbox to the nacelle main frame
5. The nacelle main frame to the support points of the gearbox
6. The nacelle main frame to the support points of the generator
7. The generator to the drive train (on the high speed shaft) – internal interface of the drive train
8. The mechanical brake to the drive train (on the high speed shaft) – internal interface of the drive train
9. The coupling on the high speed shaft of the drive train – internal interface of the drive train
10. Other (e.g. interfaces for lubrication systems, sensors) – not shown in Figure 5

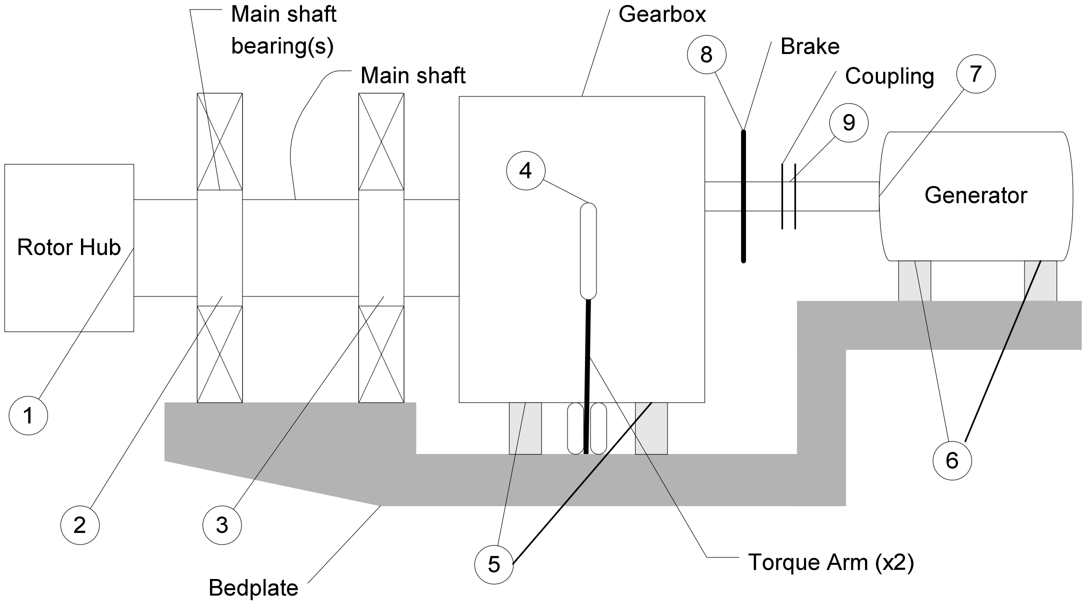

Figure 5 Schematic of nacelle layout with two main bearings (interfaces)

For the configuration using a modular drive train with a 3-point suspension, as shown in Figure 6, the following interfaces (interconnection points) can be identified:

1. The rotor hub to the drive train (on the low speed – main shaft)
2. The Main bearing of the drive train (on the low speed shaft) to the nacelle main frame
3. The torque arm on the gearbox to the nacelle main frame
4. The nacelle main frame to the support points of the gearbox of the drive train
5. The nacelle main frame to the support points of the generator of the drive train
6. The generator (on the high speed shaft) to the drive train – internal interface of the drive train
7. The mechanical brake to the drive train (on the high speed shaft) – internal interface of the drive train
8. The coupling on the high speed shaft of the drive train - internal interface of the drive train
9. Other (e.g. interfaces for lubrication systems, sensors) – Not shown in Figure 6

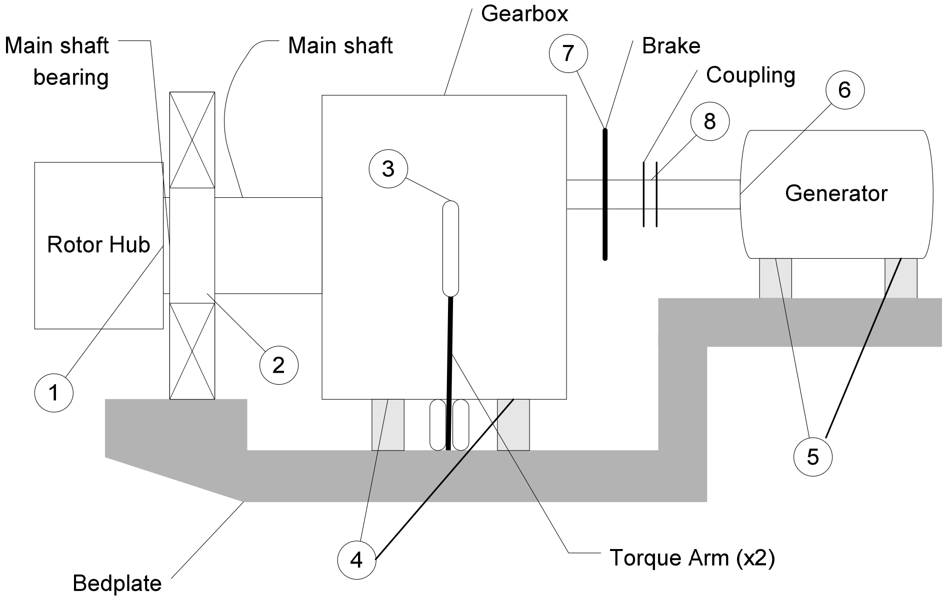

Figure 6 Schematic of nacelle layout with Triple-point suspension (interfaces)

Finally, for the configuration using an integrated drive train, as shown in Figure 7, the following interfaces (interconnection points) can be identified:

1. The rotor hub to the drive train (on the low speed – main shaft)
2. The torque arm on the gearbox housing of the drive train to the nacelle main frame
3. The nacelle main frame to the support points of the gearbox housing of the drive train
4. The nacelle main frame to the support points of the generator
5. The generator (on the high speed shaft) to the drive train – internal interface of the drive train
6. The mechanical brake on the high speed shaft of the drive train – internal interface of the drive train
7. The coupling on the high speed shaft of the drive train – internal interface of the drive train
8. Other (e.g. interfaces for lubrication systems, sensors) – not shown in Figure 7

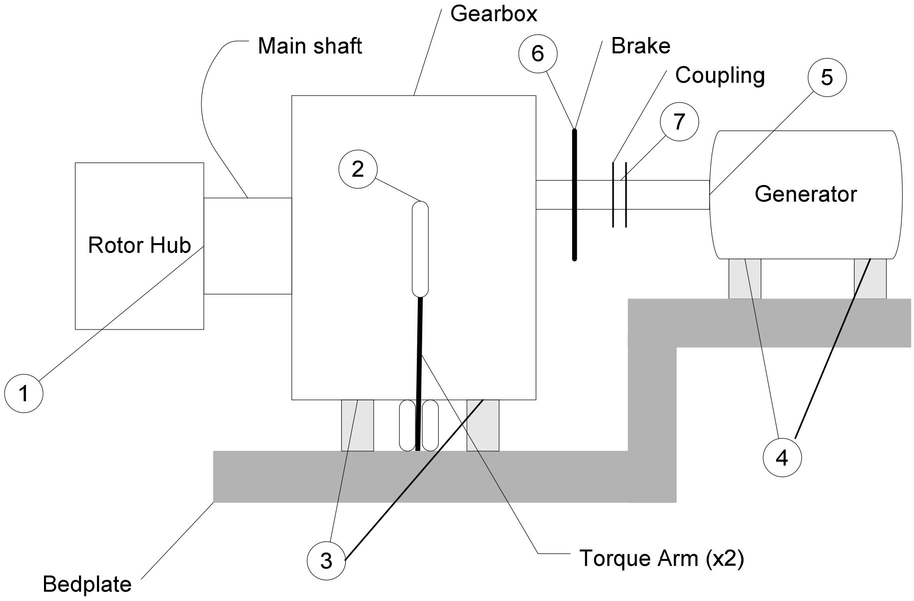

Figure 7 Schematic of nacelle layout with integrated drive-train (interfaces)

It should be noted that following current practice in wind turbine and drive train simulations the main shaft is treated as a system by itself. Therefore in a comprehensive analysis covering all systems of the wind turbine the interfaces of the main shaft should be clearly defined. In such a case, the interfaces of the main (low speed) shaft that should be investigated are shown in Figure 8, including:

1. The rotor hub to the main shaft
2. The 1st main bearing (if any, depending on the lay-out of the drive train) to the main shaft
3. The 2nd main bearing (if any, depending on the lay-out of the drive train) to the main shaft
4. The gearbox to the main shaft

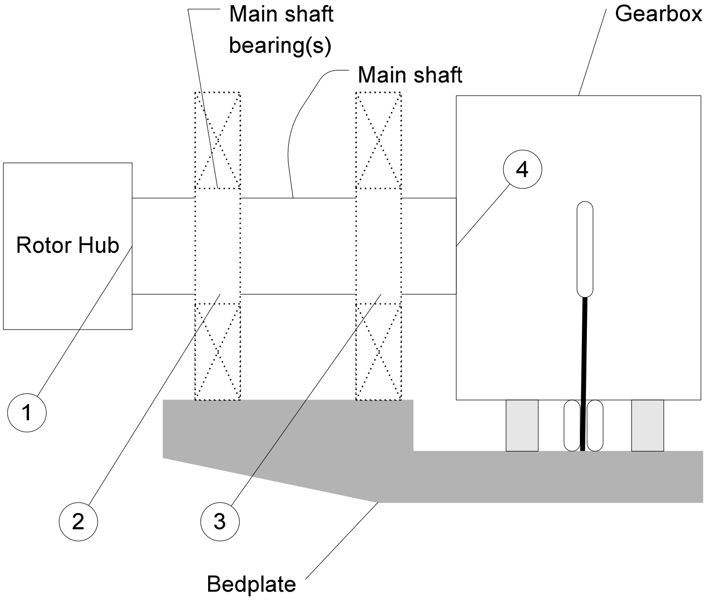

Figure 8 Interfaces of the main shaft

The same is applicable to other parts of the drive train, i.e. the Main bearing, the brake, the high speed shaft and the coupling.

Nevertheless, in the current project these are treated as components of the entire drive train, as defined within WP2 of PROTEST.

5.2. Definition of loads transferred across the interfaces

A clear definition of the loads, motions and processes that are transferred across the above defined interconnection points should be provided.

Specifically for the gearbox (for the drive train as well) there are two distinct load cases: 1) The case where the mechanical break is not active (and the rotor is free to rotate) and 2) the case where the mechanical break is active. These two cases should be clearly discerned and connected with wind flow conditions and conditions of the wind turbine.

The following conditions can be identified: Depending on the various wind inflow conditions, the mechanical break can be either active or non-active (with the rotor free to rotate). The case where the mechanical break is active (i.e. braking the rotor) refers to transient cases with the rotor being brought to a standstill as well as in cases where the rotor is kept at standstill. For these two cases (with the break active) loads are also affected by the condition of the yaw system (whether the wind turbine is active or not), as well as other cases, which are wind turbine dependent and not shown in the figure (such as whether aerodynamic breaks are active or not). For the case where the mechanical break is not active, the wind turbine could be either rotating and connected to the generator or could be idling, while also a transient case (that of a start up from idling to rotation with power production) should be treated independently. A schematic representation of the various conditions is shown in Figure 9. There are also other wind turbine conditions that reserve special treatment (e.g. the case of two speed wind turbines involving generator or generator winding switches), but as these depend on the wind turbine configuration these are not shown in the figure. Covering all the wind inflow and wind turbine conditions and including conditions of faults, transport, assembly, maintenance and repair will form the complete set of design load cases as required by IEC 61400-1. Special consideration should be given to load cases described in IEC 61400-4.

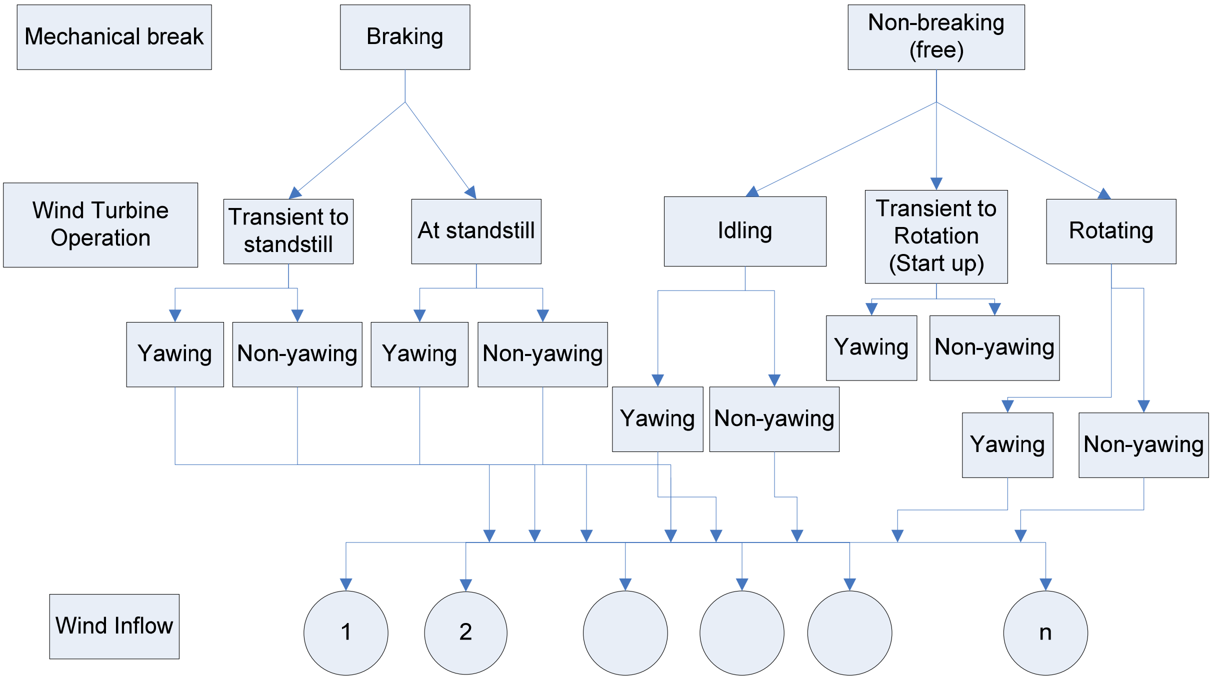

Figure 9 Various load cases for the drive-train (and gearbox) system

5.2.1 Loads transferred across the gearbox system

Loads transferred across the gearbox system, depend on the configuration of the wind turbine. Therefore, detailed analysis would have to be based on detailed configurations. In an ideal situation the purpose of the gearbox would be to transmit the torque and the rotation (revolutions) of the rotor to the generator through the high speed shaft, counter-acting all other loads arriving at the gearbox from the rotor through the low speed part of the drive train. To this end, the torque arms of the gearbox are used to counter-act the torque reaction of the gearbox from the rotor. The forces and bending moments are either counter-acted through the main bearing(s) of the main shaft or (depending on the configuration) through bearings of the gearbox. Bending moments and torsion (torque) are usually measured on the main shaft during conventional load measurement campaigns (as specified in IEC/TS 61400-13). The force measurements, however, are not required and usually these measurements are not performed. The forces (and moments) on the main shaft can be estimated through aero-elastic simulations. But to obtain the forces and moments on the high speed shaft or the forces on the torque arms through aero-elastic simulation detailed information on the gearbox and the drive train is necessary.

For the gearbox system there are two discrete cases that should be considered: 1) the loads to the gearbox system coming only from the rotor, while the system at the back of the gearbox maintains its state (e.g. no braking applied, generator connected, etc.) and 2) loads to the gearbox system coming from the rotor, while the system at the back of the gearbox introduces additional loading (e.g. application of mechanical brakes, disconnection of generator, etc.)

Classifying the general loads transferred across the interfaces of the gearbox as loads, kinematics and dynamics, the following parameters should be defined.

Loads:

- Axial and shear loads, bending moments and torsion of the low speed shaft (at the gearbox interface).
- Axial and shear loads, bending moments and torsion of the high speed shaft (at the gearbox interface).
- Forces at the torque arms.

Kinematics:

- Position (including angle, rotational speed and axial displacement) of the low speed shaft (at the gearbox interface)
- Position (including angle, rotational speed and axial displacement) of the high speed shaft
- Displacement of the torque arms.

Dynamics:

- Accelerations

Furthermore, synchronization of the general loading conditions is required with the wind turbine operational parameters, such as status, rotor revolution speed, power production, azimuth position.

A summary of the recommended measurements during an experimental campaign specifically designated on the gearbox is presented on the following table:

Table 1 Recommended measurements during an experimental campaign

Interconnection point	Loads	Synchronicity	Analysis
Main shaft & gearbox	Loads: [Main shaft Axial and Shear forces][*], Bending moments and Torsion (Torque) Kinematics: main shaft angle & speed, axial displacement Dynamics:	WT status WT operational magnitudes (Power, RPM) Azimuth position Wind inflow (Wind speed & Wind direction)	Mean loads Fatigue loads (RFC, LDDs)
High speed shaft & gearbox	Loads: [Axial & Shear forces, Bending Moments][†] and torsion (torque) Kinematics: High speed shaft angle & speed, axial displacement Dynamics:	..	Mean loads Fatigue loads (RFC, LDDs)
Torque arms & gearbox	Loads: Kinematics: Axial, Vertical & tangential Displacement Dynamics:	..	
Gearbox housing	Accelerations on bearings	..	
Additional measurements (internal to the gearbox system)	Lubrication temperature on Gearbox bearings, gear meshes or overall volume temperature	..	

5.2.2 Loads transferred across the drive train

Loads transferred across the drive train on specific interface points, depend on the configuration of the wind turbine. Similar to the case for the gearbox, detailed analysis of the loads transferred through each component of the drive train would have to be based on the specific configuration of the wind turbine. In an ideal situation the purpose of the drive train would be to transmit the torque and the rotation (revolutions) of the rotor to the generator, counteracting all other loads of the rotor through the interfaces with the nacelle bed. Therefore, all axial and shear forces and the bending moments of the rotor will have to be transferred to the nacelle bed (and from there to the tower top), while the rotor torque should pass through the drive train to the generator, leaving the torque reactions of the gearbox on the nacelle bed.

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[*] These loads are not usually measured but are estimated during aero-elastic simulations

[†] These loads are not usually measured and are estimated during aero-elastic simulations only when adequate data are provided for the gearbox

Classifying the general loads transferred across the interfaces of the drive train as loads, kinematics and dynamics, the following parameters should be defined for the drive train.

Loads:

- Axial and shear loads, bending moments and torsion of the low speed shaft (at the rotor interface).
- Axial and shear loads, bending moments and torsion of the high speed shaft (at the generator interface).
- Forces at the torque arms of the gearbox.
- Forces at the main bearing(s) on their interfaces on the nacelle main frame (if applicable)

Kinematics:

- Displacements at the supports
- Positions (angle, speed of rotation and axial displacement) of moving (rotating) elements (e.g. shafts)

Dynamics:

- Accelerations

Furthermore, synchronization of the general loading conditions is required with the wind turbine operational parameters, such as status, rotor revolution speed, power production, azimuth position.

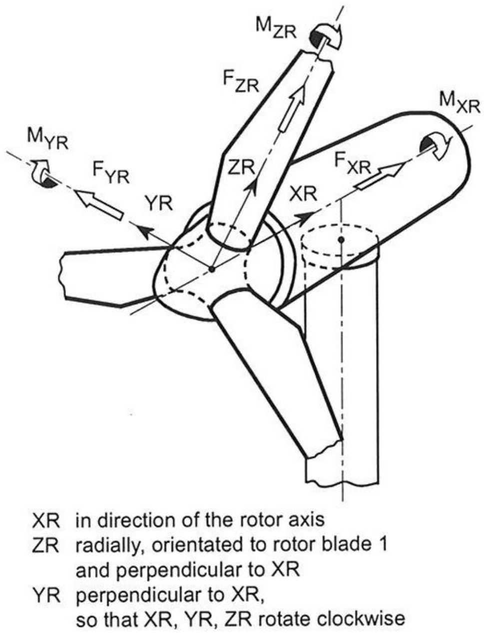
Table 1 can be used as the basis of the recommended measurements during an experimental campaign specifically designated on the drive train.

5.2.2.1 Loads transferred across the main shaft

In this section a simplistic analysis is presented for the loads transferred across the main shaft. This type of analysis would only be applied during an initial assessment of the gross loads transferred across the main shaft. But it could not replace the need of a detailed aero-elastic analysis.

Depending on the main shaft arrangement, as well as the main bearings axial (thrust) forces might be counteracted at the main bearing or the gearbox.

The coordinate system (the rotor coordinate system) for the analysis is shown in Figure 10 and it rotates with the rotor.



XR in direction of the rotor axis
ZR radially, orientated to rotor blade 1
and perpendicular to XR
YR perpendicular to XR,
so that XR, YR, ZR rotate clockwise

Figure 10 Rotor coordinate system taken from GL [9]

From a simple static load analysis the loads transferred across the main shaft interfaces are shown in Figure 11, while the free body sketch of the main shaft is shown in Figure 12:

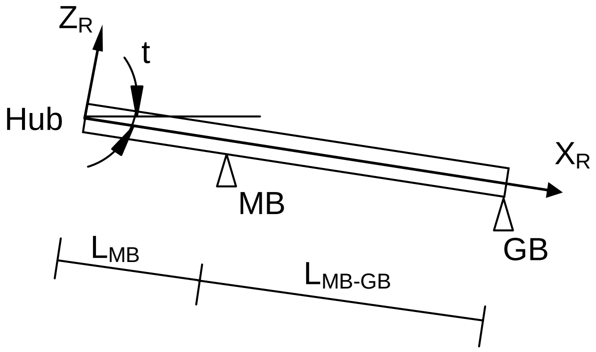


Figure 11 Sketch of main shaft

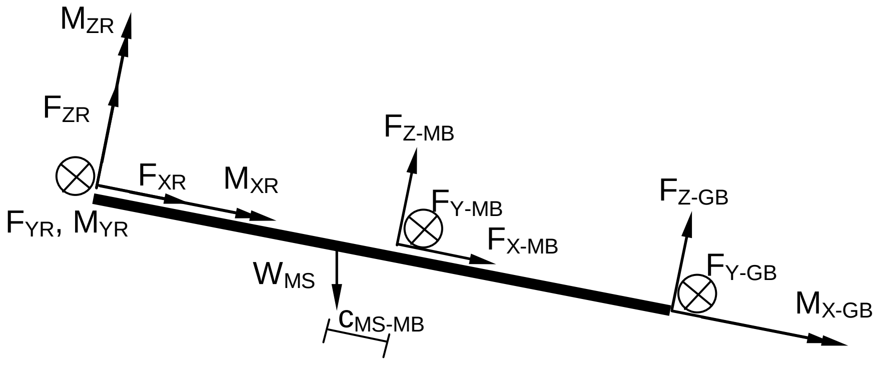


Figure 12 Free body diagram of the shaft

The loads on the shaft from the hub centre are counteracted through reactions on the main bearing (MB) and the gearbox (GB), assuming a triple-point suspension system (see Figure 6) and a tilt angle (t). Again assuming that the axial load (thrust), i.e. the force F_{XR} on the rotor coordinate system is counteracted by the main bearing and that both the main bearing and the entrance bearing of the gearbox cannot sustain bending moments, following equations apply for the reactions at the main bearing (MB) and the gearbox entrance (GB):

$F_{X\text{-}MB} = -F_{XR} - W_{ms}\sin(t)$

$$F_{Y-MB} = \frac{M_{ZR}}{L_{MB-GB}} - F_{YR}\left(1 + \frac{L_{MB}}{L_{MB-GB}}\right) + W_{MS}\sin\alpha\cos t\left(1 + \frac{c_{MS-MB}}{L_{MB-GB}}\right)$$

$$F_{Z-MB} = -\frac{M_{YR}}{L_{MB-GB}} - F_{ZR}\left(1 + \frac{L_{MB}}{L_{MB-GB}}\right) + W_{MS}\cos\alpha\cos t\left(1 + \frac{c_{MS-MB}}{L_{MB-GB}}\right)$$

$M_{X\text{-}MB} = M_{Y\text{-}MB} = M_{Z\text{-}MB} = 0$

$F_{X\text{-}GB} = 0$

$$F_{Y-GB} = -\frac{M_{ZR}}{L_{MB-GB}} + F_{YR}\left(\frac{L_{MB}}{L_{MB-GB}}\right) - W_{MS}\sin\alpha\cos t\left(\frac{c_{MS-MB}}{L_{MB-GB}}\right)$$

$$F_{Z-GB} = \frac{M_{YR}}{L_{MB-GB}} + F_{ZR}\left(\frac{L_{MB}}{L_{MB-GB}}\right) - W_{MS}\cos\alpha\cos t\left(\frac{c_{MS-MB}}{L_{MB-GB}}\right)$$

$M_{X\text{-}GB} = -M_{XR}$

$M_{Y\text{-}GB} = M_{Z\text{-}GB} = 0$

where α is the azimuth angle, W_{MS} is the weight of the main shaft and $c_{MS\text{-}MB}$ is the distance of the centre of gravity of the main shaft with respect to the main bearing.

In these equations following variables entering in equations are measured during a conventional load measurement campaign: the azimuth angle (α), the bending moments and torsion on the main shaft, M_{XR}, M_{YR} and M_{ZR}, the distances $L_{MB\text{-}GB}$ and L_{MB}. Following data are usually provided by the wind turbine manufacturer: the weight of the main shaft, W_{MS} and the centre of gravity $c_{MS\text{-}MB}$. The rotor thrust, F_{XR}, is indirectly estimated through measurements on the tower bottom (bending moments) and the root of the blade(s), while F_{YR} and F_{ZR} are assumed to be zero (or negligibly small). However, for the forces, $F_{XR,}$ F_{YR} and F_{ZR} there are a number of assumptions involved, leading to corresponding uncertainties, the effect of which has not been estimated. This might be especially important for individual pitch controlled wind turbines, where an aerodynamic symmetry of the rotor cannot be maintained if for example the blades have momentarily different pitch angles.

On the other hand the three forces and moments are provided as output by aero-elastic simulation codes if appropriately modeled.

The kinematics include position (both rotating and axial position), rotational speed of the shaft, as well as deflections.

5.2.2.2 Loads transferred across the main bearing

These can be directly deduced by the reaction loads of the main shaft, $F_{X\text{-}MB}$, $F_{Y\text{-}MB}$, $F_{Z\text{-}MB}$, assuming that no bending ($M_{Y\text{-}MB}$, $M_{Z\text{-}MB}$) and torsion ($M_{X\text{-}MB}$) moments are supported by the main bearing and then transformed to axial load (thrust), equal to $F_{X\text{-}MB,}$ and radial loads equal to $\sqrt{F_{Y-MB}^2 + F_{Z-MB}^2}$. However, for more accurate calculations also the loss in torque due to friction of the bearing should be accounted for.

For the transformation of the loads on the non-rotating nacelle system for further analysis of the support of the main bearing on the nacelle main frame, then following transformation matrix should be applied, with α the azimuth angle of the rotor:

$$\begin{Bmatrix} F_{X-MB,N} \\ F_{Y-MB,N} \\ F_{Z-MB,N} \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix} \begin{Bmatrix} F_{X-MB,R} \\ F_{Y-MB,R} \\ F_{Z-MB,R} \end{Bmatrix}$$

6. Description/Presentation of Loads

Irrespective of whether the loads at the interconnection points are the result of a simulation or a measurement, these come in the form of a time series. For a detailed specification of the presentation of loads at the interfaces required for the design of a wind turbine system, such as the drive train or the gearbox, the reader is referred to IEC 61400-4. In summary, the output of the simulation runs, for each Design Load Case (DLC) should include the following information according to IEC 61400-4:

- Description of the DLC relevant for transmission design. But the relevancy should be decided by the component designer, therefore, all prescribed DLCs should be provided.
- Frequency of occurrence
- Probability of occurrence e.g. abnormal or normal load case
- Duration of occurrence
- Information on load calculation model including transmission model
- Reference to DLC, or identification or relevant partial safety factor for loads, with clear information whether these are already included, or need to be added

IEC 61400-4 also describes that the loads should be documented including:

- Time series presentation
- Rain-flow count tables including information on
    - Which design load cases (DLCs) have been considered
    - The frequency of occurrence for each DLC considered
    - Information on safety factors already applied or to be applied
- Load Duration Distribution (LDD) expressed as time at level
    - Which design load cases (DLCs) have been considered
    - The frequency of occurrence for each DLC considered
    - Information on safety factors already applied or to be applied
    - Nominal torque
    - Nominal rotational speed

However, it should be mentioned that the relevant standards for the component analysis (e.g. ISO 6336-6), use Palmgren-Miner cumulative damage calculation principle, which is based on number of cycles at Load Level (torque level).

In the following section a method for the presentation of loads when measured in the field is proposed. It is noted that a major difference from how the loads are presented in a measurement report up to now is the Load Duration Distribution. For the analysis of the time series measured during a wind turbine load measurement campaign, IEC/TS 61400-13 prescribes that analysis includes the estimation of rain-flow matrices (through application of the rain-flow counting method), the definition of the load spectra (through combination of the rain-flow matrices) and the calculation of equivalent loads at a given frequency (usually at 1Hz).

6.1. Proposal for the presentation of load measurements

IEC/TS 61400-13 [14] should be followed wherever possible. However, in order to better illuminate the load cases that affect the components/systems under study the following presentation/analysis should be added for the load measurements regarding the drive train and the gearbox of the wind turbine.

- A selection of measurement cases that can be used for the validation of wind turbine design models should be made, assuring the atmospheric conditions and the specific turbine characteristics, as described in IEC 61400-4. This is necessary for enabling the accurate reproduction of the as-measured response using data from the field tests.
- Analysis specifically intended for the verification of design assumptions for the gearbox, including torsional vibration, combined structural response and reaction at the gearbox supports and interfaces, as described in IEC 61400-4.
- Analysis regarding the drive train resonances including vibration levels at representative locations (possible corresponding to work shop testing locations), following IEC 61400-4
- Measurements and analysis regarding the lubrication delivery/cooling system effectiveness including temperatures as described in IEC 61400-4

According to IEC 61400-4 in addition to load measurements prescribed in the IEC/TS 61400-13 the torque on the low and the high speed shaft should be measured in experimental campaigns requiring the verification of the gearbox and the drive train. Additionally, the shaft speed should be also measured. Both measurements are foreseen in Table 1. According to IEC 61400-4 additional load measurements for forces and bending moments may be required for the evaluation of the gearbox interface loads and design assumptions. These however, are also foreseen in Table 1, such as the bending moments and forces on the two shafts (main shaft and high speed shaft).

Following IEC 61400-4 sampling rate should be adequately selected (in cooperation with the gearbox manufacturer) for each application, higher than 3 to 5 times the relevant vibration frequency.

Measured load cases (MLC's) shall be represented as time series including as a minimum the MLC's shown in Table 2, following the presentation of measurement load cases as per IEC/TS 61400-13.

Table 2 MLCs targeted for the gearbox and drive train

MLC number[‡]	Gearbox MLC	Short description	Target wind speed[§]	Notes
1.1	1.1.1	Power Production	$v_{in} < v_{hub} < v_{out}$[**]	Designated run-up in IEC 61400-4
1.3	1.3.1	Idling	$v_{in} < v_{hub} < 0.75v_{e1}$	
	1.3.2	Backwind Idling	$v_{in} < v_{hub} < 0.75v_{e1}$	
2.1	2.1.1	Start-up	v_{in} and $>v_r$+2m/s	Designated cut-in in IEC 61400-4
2.2	2.2.1	Normal shut-down	v_{in}, v_r and $>v_r$+2m/s	Designated shut-down in IEC 61400-4
2.3	2.3.1	Emergency shut-down	v_{in} and $>v_r$+2m/s	Designated emergency stop in IEC 61400-4
2.4	2.4.1	Grid failure	v_r and $>v_r$+2m/s	Designated Electrical events in IEC 61400-4
	2.4.2			Other possible electrical events
xxx.1[††]	xxx.1.1	Brake application	v_{in}, v_r	Defined in IEC 61400-4, however, without any details it is not clear what the case means, e.g. case where the WT is stopped only by applying the mechanical break, a normal stop or an emergency shut down.

Additionally, following IEC 61400-4 a Campbell diagram (plot of system forcing and response frequencies) should be provided through the complete operating speed range to evaluate resonance risk.

Finally, measured temperatures at specified locations on the gearbox and lubrication system should be reported with emphasis on maximum temperatures and maximum temperature durations.

If applicable, during the measurement campaign lubricant analysis shall also be performed and reported.

[‡] As per IEC/TS 61400-13

[§] Target wind speed as per IEC/TS 61400-13

[**] Has to be further divided into wind speed bins and turbulence bins

[††] MLC described in IEC 61400-4 but without direct correspondence to IEC/TS 61400-13

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