ΚΑΠΕ CRES | CENTRE FOR RENEWABLE ENERGY SOURCES AND SAVING

Building a competitive Greece
MINISTRY OF DEVELOPMENT

PROcedures for TESTing and measuring wind energy systems (PROTEST)

Template for the specification of loads necessary for designing yaw 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. [1], [2], [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. [4] and discussions with turbine manufacturers, component suppliers, and certification bodies [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 among others in [4] and expert discussions [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 (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 [6], Annex B.

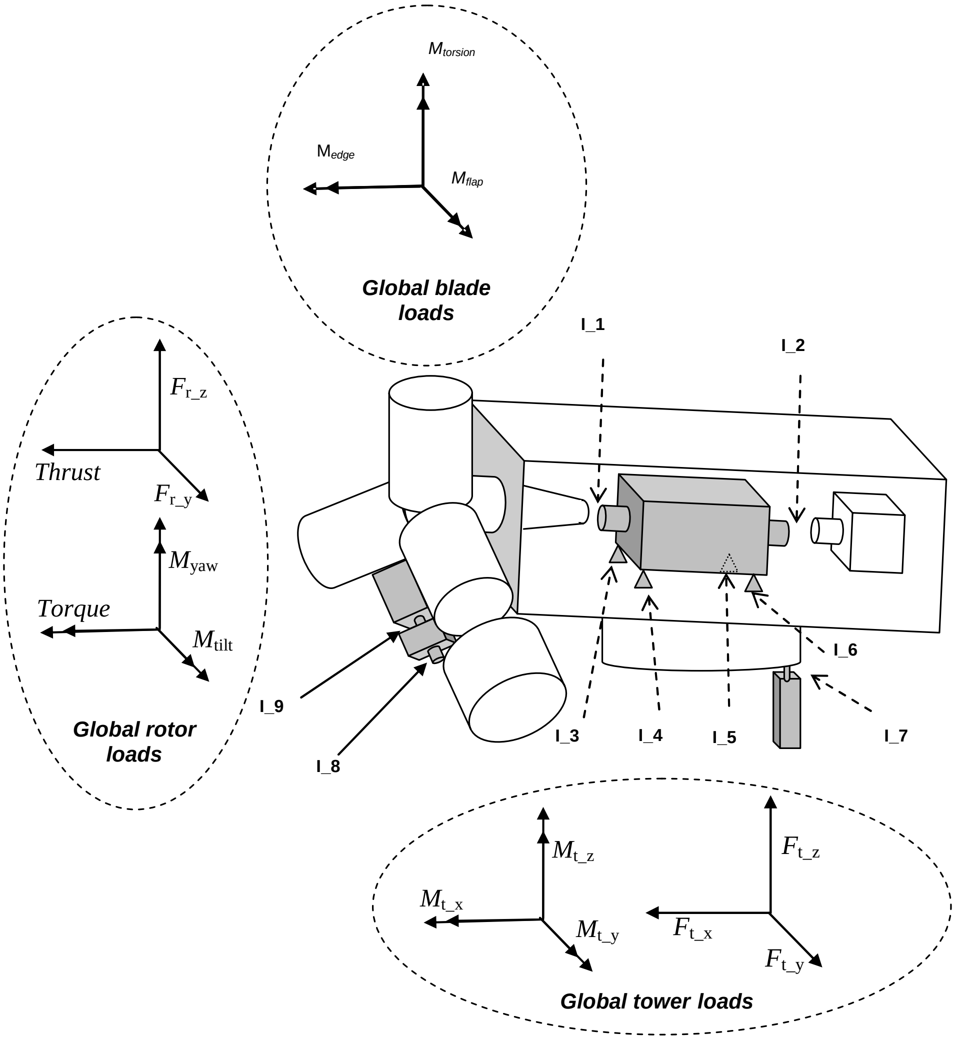

Figure 1 Schematic presentation of transforming "global turbine loads" to "local components loads" at nine interfaces, (gearbox, pitch system and yaw system)

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 yaw 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 the procedures for the selected components, among them the yaw system, 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 yaw system, is required. That includes isolation of the yaw system from the overall wind turbine structure and further building on the adequate description of the sectional loads at the interconnection points (interfaces) 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 yaw systems, was presented in [7].

Within WP3 the results presented in [7] as well as the findings of work package 2 of the PROTEST project reported in [8] regarding the design load cases and design drivers for the wind turbine components that should be considered will be further developed to define the procedure for determining the loads at the interfaces of the considered components. On the topic of the yaw system the working draft IEC 61400-4 [6] where the relevant issues of the wind turbine gearbox are discussed, was used as a starting point to determine what kind of information are necessary at the interfaces for designing the mechanical components of the yaw system.

1.3. *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 yaw system 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 yaw 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 loads (input – output) conditions of the components/systems of the wind turbine yaw under investigation. Therefore, in this section the components are defined as identified within WP2 of the PROTEST project [8]. The break down of the yaw system into sub-systems/components presented in this section closely follows the results of WP2.

The yaw system allows the relative rotation of the nacelle with respect to the tower to orientate the rotor toward the direction of the in-flowing wind. In case the in-flowing wind has a constant direction, then the yaw system is employed to maintain the orientation position of the nacelle with respect to that direction. Moreover, the loads from the nacelle are transmitted to the tower through the yaw system. The yaw system is also employed to unwind cables passing from the nacelle to the tower if needed, as well as during maintenance operations to position the nacelle in pre-defined orientations.

Although various configurations exist for the yaw system especially for the load sharing between sub-systems to allow rotation of the nacelle, while restraining radial motion, for most of the applications the yaw system can be divided in following main components:

- Yaw bearing: which transmits all loads from the nacelle to the tower and guide the rotation of the nacelle during orientation (only rotation is allowed). Usually the yaw bearing is a roller bearing or sliding plate. Static and load dependent bearing friction provides partially retention torque.
- Yaw actuator/driver: which provides the required driving torque to rotate the nacelle and might provide retention torque to keep the nacelle in the required orientation
- Yaw transmission systems/components: (e.g. gears) which provide incremental motion or fix the yaw position (orientation) of the nacelle when the yaw system is inactive
- Yaw brake: which fixes the yaw position of the nacelle when the yaw system is inactive or provides damping during yaw activity
- Other components, e.g. sensors

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 yaw 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) cover testing and certification procedures are also addressed.

- **IEC 61400-1** [10]: Is the baseline standard covering the design of the whole wind turbine.

  In this document the design load cases for all 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** [6] (Currently ISO 81400-4:2005 [9]): Is the baseline standard covering the design of the gearbox of the wind turbine.

Although this document is not directly addressing the design of the yaw system, it provides useful directions for the design of this wind turbine component (i.e. the yaw system). Through this document, the user is directed to IEC 61400-1 [10] for the definition of design load cases. However, a more detailed analysis is described in Annex B (ISO 81400-4:2005 [9]) 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 [6] apart from reference to the IEC 61400-1 [10], 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

(6) a reference to DLC, identification of 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 on this aspect in the IEC 61400-4 [6] 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 [11]-[15]. In particular ISO 6336-6 deals with the calculation of service life under variable load [15].
- **DIN 3990:** Is the standard to be followed for the fatigue rating of gears according to GL – Guidelines for the certification of WTs [16].
- **DIN 743:** Is the standard for shafts & axles [17]
- **ISO 76 & ISO 281:** Are the standards covering rolling bearings. ISO 76 covers the static loading [18] and ISO 281 the dynamic loading [19].

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) [20], will be replaced by IEC61400-22.
- **IEC/TS 61400-13:** Is the baseline standard covering load measurements on components of the wind turbine (field measurements) [21].
- **GL Guidelines for the certification of WTs** [16]**:** This document includes a description on what procedures to follow (including references to relevant standards) during the design of the yaw system. Moreover, it gives guidance for the simulation of global loads at the yaw system's interfaces and the strength analysis of the yaw system using extreme and fatigue loads (e.g. Load Duration Distribution LDD). 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 [22].

- **DIN 45667:** Is the standard covering the load duration distribution procedure [23].
- **GL Guideline for the certification of Condition Monitoring System for WTs** [24]**:** In this document additional information is provided on the measurements required to monitor the condition of the gearbox. These might be also applicable to the yaw system comprising a transmission system (gearbox) and bearing.
- **Specification of manufacturers:** e.g. INA catalogue [25] and Rothe Erde technical document [26] covering slewing rings and FAG publication [27] 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. Modelling of components during Wind Turbine design

The process of designing a wind turbine can be divided into two stages. One stage involves the calculation 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 aeroelastic analysis of the wind turbine. Multiple loops of the process result in the final load estimations and the detailed design of each component/system.

The current state of aeroelastic simulations of wind turbines will be shortly discussed next, including the current limitations that are relevant to the yaw system. Next the modelling of the yaw system will be treated, followed by the main conclusions of this chapter.

4.1. Aeroelastic simulation of the Wind Turbine

A review of state of the art aerodynamic and aeroelastic simulation procedures is given in [28]. In the mentioned 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. Other examples are the flexibility or damping characteristics of the yaw bearing or the pitch mechanism. The involvement of different body motions for each component in combination with the connections where loads and displacements are communicated from 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.

Specifically the information required for the yaw system to perform an aeroelastic simulation is:

- Nacelle mass (including mass of rotor, hub, nacelle, etc.)
- Nacelle centre of gravity (taking into account rotor, hub, nacelle, etc.)
- Nacelle yaw inertia (inertia of nacelle about yaw axis)
- Yaw bearing mass
- Static and load dependent yaw bearing friction
- Gyroscopic torque of Rotor about yaw (tower) axis
- Yaw stiffness (as a torsion spring)
- Yaw damping (damping ratio about yaw axis)
- Parameters of the controller, including yaw (angular) rate

As an output of the model, sophisticated aeroelastic simulation tools provide the following information for the yaw system:

- Tower top displacements X, Y, Z
- Tower top loads Fx, Fy, Fz
- Tower top bending moments
- Tower top torsion (torsion about yaw axis applied by e.g. wind loading)
- Yaw torque (torque transmitted through yaw bearing)

For a more elaborate analysis of the yaw system more detailed knowledge of the system response is necessary. For example, elasticity of the yaw system could also be modelled. In this case the transient response of the wind turbine (at the points of interest, interfaces modelled) can be captured more accurately and in turn the loads used during the design phase.

Since the yaw system is not modelled in detail, additionally, solutions could be provided depending on where you define the input and output of the yaw system. In other words, one can obtain a solution when modelling the input *to* the wind turbine system *of* the yaw system (i.e. when applying a load from the yaw system that leads to rotation of the nacelle) and another solution when modelling the input *of* the wind turbine system *to* the yaw system (i.e. the loading on the yaw gear(s)). These can form different load cases specifically designed for the yaw system.

On the other hand, although the simulation tools are available, as also pointed out in [30] the following is a list of limitations in current simulation approaches:

- Aeroelastic simulation of the entire wind turbine to extract the entire set of load cases is time consuming. Personal discussions with aeroelastic 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 and other wind turbine systems. A detailed model of the yaw system including the bearing interface with the nacelle, would necessitate to run simulations of the loading using a detailed model of the nacelle bed and a detailed model of the tower, to include effects of deformations on the yaw bearing for example, which cannot be captured through the currently employed models. Nevertheless, such transient analysis methods require CPU time that is a multiple of the actual (event) time.

- 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 aeroelastic simulation, is well documented and straight forward, the documentation of transforming the 3D structure/system of the yaw 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 aeroelastic simulation tools employ a very simplistic modelling of the yaw system, while when more sophisticated simulation tools for the yaw system are used then the aeroelastic 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 [30], the data transfer between parties, especially regarding the gearbox and bearings could be problematic.
- Yet, the most important 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 yaw system such as starts and stops, parked conditions, manoeuvres etc., there is no clear description of how many occurrences are expected during the life of the wind turbine, since these depend strongly on the site and on controller settings that are easily modified (especially for the yaw system). Only GL – Regulation for the certification of Wind Turbines [16] provides some guidance on that aspect. In other words, aeroelastic 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.
- In addition to the previous limitation, according to the standard approach for fatigue load calculation a set of load time series is calculated and afterwards rain-flow counted to determine the fatigue load level. The set of time series may comprise the simulation of special yaw manoeuvres as transient load cases. It also comprises time series of usually 10 minutes length for each wind speed bin investigated with a chosen mean wind speed and mean angle of wind direction. During the time series the angle of wind direction may vary around the chosen average. Depending on the controller yaw algorithm this may lead to some yaw system activity. But this approach does not model real wind direction changes over time leading to associated yaw system activity and fatigue loading. If a hysteresis is applied in the algorithm before starting the motors, the yaw system activity and fatigue loading may as a result be very small.

4.2. Wind Turbine Components modelling

Taking as input the loads provided by the aeroelastic 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 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 [32]).

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. [31] dealing with the drive train and [33] 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.

In this section some design requirements will be discussed for the main components of a yaw system. The intention is not to cover all aspects of the component design, but to provide a basis for the selection of important force components and signals to be specified in the interfaces and measurement campaign.

4.2.1 Yaw bearing

A recent report [34] provides guidance for the design of yaw (and pitch) bearings following ISO 76 [18] and ISO 281 [19] and the respective American Standards.

The required information, for the detailed design of the **yaw bearing system** can be summarized in the following (e.g. Rothe Erde GmbH KD 100 Questionnaire [26]):

- Bearing diameter
- Axis of rotation (for the yaw system = vertical)
- Bearing under compression, tension or compression and tension[*] (for the yaw system = compression)
- Gear position (depends on application, for yaw system usually internal)
- Movement type (for yaw system = Positioning only or intermittent rotation)
- APPLIED LOADS: Divided in Maximum Working Load, Maximum Test Load & Extreme Load
    - Axial Loads
    - Radial Loads
    - Bending Moments
- COLLECTIVE LOADS WITH RESPECTIVE TIME PERCENTAGES
- CIRCUMFERANTIAL FORCES to be transmitted by the GEAR
    - Tangential Force per drive
        - Normal
        - Maximum
    - Number of Drives
        - Position (In angle degrees specifying distance between them)
- Speed of rotation or number of movements and angle per unit time together with relating collective loads
    - Normal
    - Maximum
- Pinion data for checking the meshing geometry of the gears
- Condensed stiffness data of the upper structure (i.e. nacelle) (However, no clear data are given: Axial stiffness, bending stiffness, etc.)
- Condensed stiffness data for the lower companion structure (i.e. tower) (However, no clear data are given: Axial stiffness, bending stiffness, etc.)
- Other operating Conditions

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[*] For bearings it is important to know if the system will be under tension (e.g. to drive a hanging system-mass), under compression (e.g. to drive masses on top), or alternating under compression & tension (as in the case of the blade pitch bearing)

  - Operating temperatures
  - Temperature differences between the outer and inner ring

4.2.2 Yaw transmission system

The yaw transmission system (gearbox) is used to convert the power of the yaw driver into speed and torque. The pinion mounted on the output shaft of the yaw transmission system meshes with the teeth of the yaw bearing. Clearly, the design of the yaw transmission system should follow the relevant standards applicable for gearboxes (e.g. ISO 6336 [11]-[15] for gears and ISO 281 [19] for bearings).

Information required for the selection/design of a gearbox can be summarized in the following:

- Required output torque
- Output speed
- Input speed (connected to the yaw driver)
- Radial force applied on the output shaft
- Radial (Overhang) load distance from shoulder of output shaft
- Axial thrust on output shaft
- Lifetime expectancy (estimation of accumulated operating hours)
- Ambient temperature

For the gearbox an important parameter is the service factor representing the severity of the application. This factor depends on the type of load the gearbox operates with (e.g. uniform load, shock load), the specific duty (characterized by number of starts per hour) and the operating daily hours to form the accumulated operating hours.

An additional constraint is the thermal capacity of the gearbox. This is again related to the duty cycle of the yaw system (i.e. the operating time under load to the total cycle time including the time at rest) and the ambient temperature.

Finally, the momentary peak torque and the starting torque present constraints and should be available for the design of the yaw transmission system.

4.2.3 Yaw actuator/driver

The yaw actuator (driver) is used to convert the electrical power to drive the yaw transmission system (gearbox).

Information required for the selection/design of a yaw actuator can be summarized in the following:

- Rated Power
- Motor voltage
- Number of poles
- Frequency
- Duty type
- Starts per hour

Additional information are required if there are also specifications for motor in-build brake system. These include:

- Brake voltage

- Brake torque

Within the PROTEST project the focus is on the transmission of loads and therefore the electrical and electronic parts of the systems studied are considered out of the scope. Depending on the requirements electrical parts will be briefly discussed, as for example the case of measuring the power consumption of the yaw actuator (electrical motor) to estimate the torque of the yaw transmission system (gear).

An illustrative work on the requirements for the design verification of pitch systems for the wind turbines, which is also applicable (with proper adaptation) to the design of the yaw transmission system in combination with the yaw driver is [35]. The mentioned document stresses the importance of including the frictional moment on the bearing to calculate effectively the thermal loading of the pitch drive motor. Similar results are expected for the yaw drive motor also.

4.3. Conclusions – modelling

A lot of effort is currently being put into the complete aeroelastic 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). As a step forward the time series of each loading case (DLC) needs to be measured (estimated) including the wind inflow as detailed as possible, so as to enable the model verification, as proposed within the PROTEST project. On the other hand, the contribution of the various load cases to the expected life of the component system, needs to be measured (estimated) under a statistical framework, where occurrence of events is recorded. This would improve estimation of operating life of the component, since the statistical data would be taken into account during fatigue estimations. Especially the load cases that are benign to the other components of the wind turbine, i.e. 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. A similar concept should be applied for the yaw movement. 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 recommendations in the GL–regulations for the certification of wind turbines [16] could provide a starting point in this aspect, which should be verified with experimental data or other statistics. It is recognized, however, that in the general case a lot of boundary conditions determine the loads of transient events a wind turbine experiences. These stem from the special wind turbine design (e.g. control system, component configuration), maintenance procedures (e.g. how often the emergency button is pressed per year for testing), frequency of occurrence of load relevant faults (e.g. fault in pitch system) or site conditions (e.g. grid quality, grid codes). Therefore, it would be difficult or even impossible to define minimum requirements on the extent and number of transient load cases for load calculation that is appropriate for all manufacturers and sites.

Nevertheless, proper statistical based information taking into account an expected range of site conditions in relation to controller parameters, would lead to an improved initial estimation of the occurrence and duration of the transient events, relevant to the wind turbine system under consideration. In a second stage failure statistics might be added in order to further improve the estimated number of occurrence and duration of the relevant transient events, important for the fatigue calculations.

5. Load definition at interface points

5.1. *Definition of interface 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 [6], adequately modified to cover the needs of the yaw system 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 pitch system during simulation is the node connecting the blade root to the hub of the wind turbine and is given certain freedoms and constraints.

In the following, when defining the interfaces of the yaw system the identification of the system is left out of the nomenclature. For example the interface between the yaw system and the nacelle, when addressing the interconnection points (interfaces) of the yaw system is called: The nacelle interface to the yaw system.

Specifically for the yaw system the interconnection points (interfaces) are:

1. The interface between the Tower Top to the yaw system (specifically the yaw bearing)
2. The interface between the Nacelle to the yaw system (specifically the yaw bearing)
3. The interface of the yaw transmission system, i.e. the yaw gear(s), where a tangential force is introduced to the system to rotate the nacelle relative to the tower
4. The (electrical) interface of the wind turbine controller to the yaw system (specifically the yaw actuator/driver)

An oversimplified sketch of the yaw system and the relevant interfaces is shown in Figure 2.

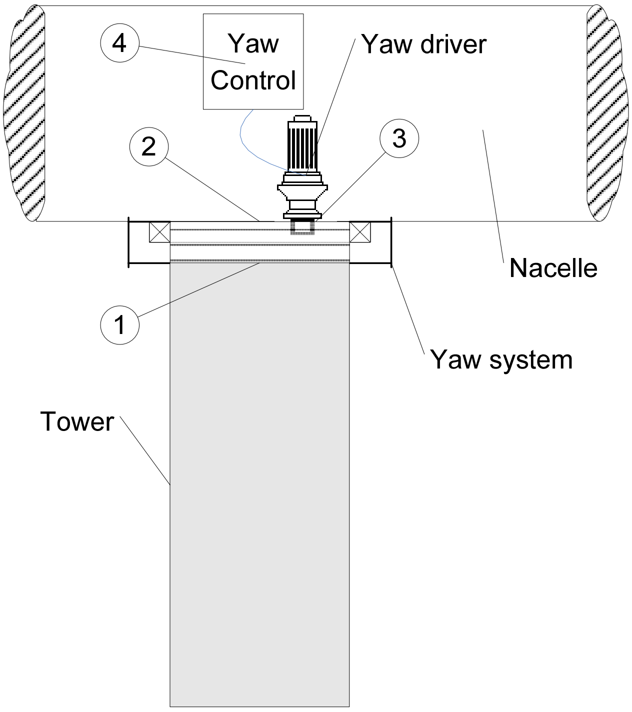


Figure 2: Simplified sketch of yaw system showing interfaces

In addition to the interconnection points (interfaces) described above, internal interconnection points of a system can be introduced by dividing a system into its sub-systems.

The yaw system can be divided into a set of sub-components as follows:

Table 1: Sub-Systems Level 0-4 for Yaw System (Example showing one branch)

0	Yaw System					
1	Tower Connection	Nacelle Connection	Slewing unit (Yaw Bearing)			
2			…	Slewing Ring Wheel	Gearbox	
3					First Gear Stage	…
4					Pinion	…

This approach leads to a set of systems on different detail levels which are connected by interconnection points. At each interface, the 6 fundamental loads can be defined. Additionally, characterising values for each load can be added (e.g. rotational speeds).

This leads to a matrix of interconnection loads. Each interconnection load has to be assessed with respect to the individual importance of the value towards the overall result as well as the effort required for the determination of the value. This evaluation enables a structured ranking of interconnection loads from which the required load sets are selected. The resulting list of selected values will differ for each assessed system since the evaluation of the individual relevance will vary due to factors like analysis approach, experience, available data and others.

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 yaw system there are two distinct cases: 1) the loads transferred while the yaw system is used to keep the nacelle position at a pre-defined position, i.e. Non-yawing (as defined by the controller) and 2) the loads transferred while the yaw system is active and used to bring the nacelle into the required position, i.e. yawing. The two load cases should be clearly distinguished 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 yaw system can be either Yawing the nacelle or Non-yawing (at standstill), while the wind turbine might be in normal operation or non-rotating (at stand-still), could be in pitching motion or could be non-pitching. The latter depends also on whether the machine is pitch- or stall controlled, therefore, this distinction could be regarded as normal operation and classification for pitch controlled wind turbines in pitching operation or constant pitch, might not be needed for the design of the yaw system. Taking this into account, a schematic representation of the various conditions is shown in Figure 3. 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.

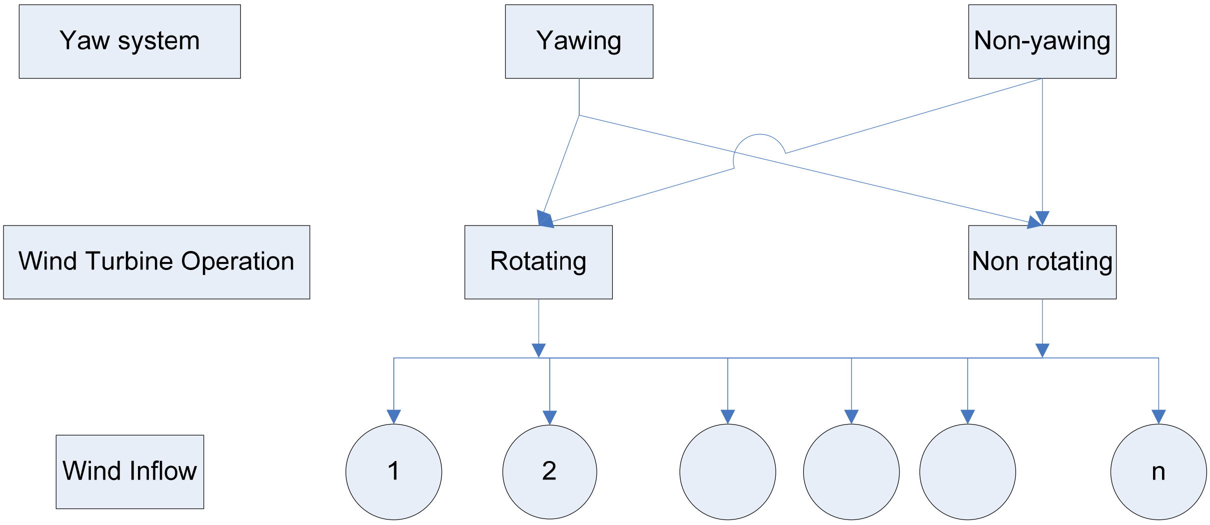


Figure 3: Various load cases for the yaw system

For the loads to be transferred while the yaw system is used to keep the nacelle at a defined orientation angle, i.e. **non-yawing**, all loads acting on the nacelle end should be transferred to the tower. That is the yaw system should be used to have axial and shear forces, bending moment and torsion transferred from the nacelle to the tower. These are already estimated through aeroelastic simulations. Tower top bending moments and torsion can be measured during conventional load measurement campaigns.

Torsional motion of the yaw system (while the system is maintaining nacelle position), i.e. non-yawing, could be measured on an operating wind turbine with vibration sensors positioned at the nacelle part of the yaw system, measuring possible small torsional vibrations (motion and acceleration).

For the loads to be transferred while the yaw system is operating (driving the nacelle to the requested nacelle position), i.e. **yawing**, the loads to be transferred through the yaw system are again all axial and shear forces, as well as bending moments acting on the tower top, while torsion will be transferred to the tower distorted through the action of the yaw actuator (driver).

Using the coordinate system that has its origin at the intersection of the tower axis and the lower edge of the nacelle and rotates with the nacelle, shown in Figure 4 and following [35] for the meshing torque, M_M, acting on the yaw gear teeth, the following relationship can be applied:

$$M_M = M_{ZNT} + \text{sign}(\dot{\alpha}_y) M_R + J_{NR}\ddot{\alpha}_y = i_y M_{yD} - i_y^2 J_{yD}\ddot{\alpha}_y \tag{1}$$

Where M_{ZNT} the yaw moment on the nacelle, α_y the yaw angle, J_{NR} the nacelle yaw inertia, J_{yD} the inertia of the yaw driver and the yaw transmission system (as one system), i_y the gear ratio of the entire yaw system (including the gear ratio of the yaw gearbox and the gear ratio of the yaw bearing and the drive pinion and M_R is the frictional moment of the yaw bearing. For the load dependent frictional moment several practical estimates are available. In [35] the general form is given:

$$M_R = D_{bearing}\left(\mu_{Bend}\frac{M_{Bend}}{D_{bearing}} + \mu_{Axial}F_{Axial} + \mu_{Radial}F_{Radial}\right) + M_{R0} \tag{2}$$

Where M_{Bend} is the bending moment on the bearing, which for the yaw bearing equals: $M_{Bend} = \sqrt{M_{XNT}^2 + M_{YNT}^2}$, F_{Axial} the axial force on the bearing, which for the yaw bearing is equal to F_{ZNT} and F_{Radial} is the radial force acting on the bearing, which for the yaw system is given by: $F_{Radial} = \sqrt{F_{XNT}^2 + F_{YNT}^2}$

In [34] the running friction torque depending on the friction coefficient, μ, for different types of ball bearings is given by:

$$M_R = \mu D_{bearing}\left(\frac{4.4}{2}\frac{M_{Bend}}{D_{bearing}} + \frac{1}{2}F_{Axial} + \frac{2.2}{2}F_{Radial}\right) \tag{3}$$

where μ takes values between 0.003 & 0.004 depending on the bearing type.

In [26] the starting friction torque for ball bearings is given by:

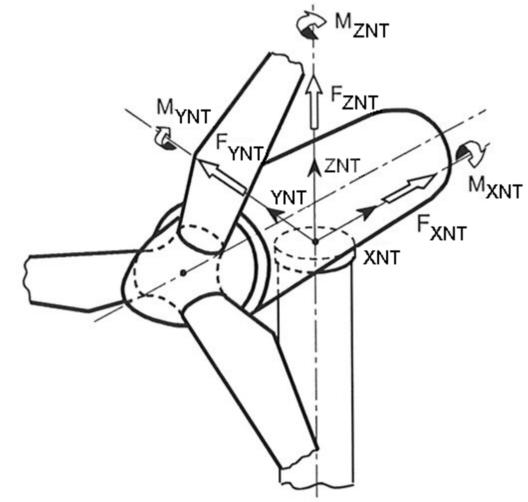
$$M_R = \mu D_{bearing}\left(\frac{4.4}{2}\frac{M_{Bend}}{D_{bearing}} + \frac{1}{2}F_{Axial} + \frac{2.2}{2}F_{Radial}1.73\right) \tag{4}$$

While for the roller bearing the corresponding empirical relationship is given by:

$$M_R = \mu D_{bearing}\left(\frac{4.1}{2}\frac{M_{Bend}}{D_{bearing}} + \frac{1}{2}F_{Axial} + \frac{2.05}{2}F_{Radial}\right) \tag{5}$$

with μ taking values between 0.003 and 0.008 depending on the specific bearing type.

In [26] it also stated that the abovementioned approximations allow the estimation of the starting torque to within ±25%.



XNT horizontal in direction of rotor axis, rotating with nacelle
ZNT vertically upwards
YNT horizontally sideways, so that XNT, YNT, ZNT, rotate clockwise

Figure 4 Coordinate system modified from GL [16]

During the aeroelastic simulations for the torsion the equations to be solved in the time domain are [36]:

$$J_{NR}\ddot{\alpha}_y + \mathrm{YawDamp}\cdot\dot{\alpha}_y + \mathrm{YawSpr}\cdot\alpha_y = \mathrm{YawDamp}\cdot\mathrm{YawRateNeut} + \mathrm{YawSpr}\cdot\mathrm{YawNeut} + M_{ZNT}$$

$$M_M = \mathrm{YawSpr}\cdot\left(\alpha_y - \mathrm{YawNeut}\right) + \mathrm{YawDamp}\cdot\left(\dot{\alpha}_y - \mathrm{YawRateNeut}\right)$$

Where J_{NR} is the instantaneous inertia of nacelle, rotor, etc. about yaw axis, M_{ZNT} is the torque about the yaw axis applied by (e.g.) wind loading, M_M is the torque transmitted through the yaw bearing, *YawSpr* and *YawDamp* are the spring constants and the damping of the yaw bearing, α_y is the current nacelle position (yaw angle) and *YawNeut* is the commanded nacelle position.

Similar to the case where the yaw system is inactive (holding the nacelle under defined yaw angle) , i.e. non-yawing, the axial and shear forces as well as the bending moments are an output of the aeroelastic simulation. The torsion and torque are also an output of the aero-elastic simulation if the model includes information of the yaw system and in particular the yaw controller. Tower top bending moments and torsion are measured during conventional load measurement campaigns, as well as nacelle position (yaw angle).

The measurement of torque (Load) on the yaw system could be indirectly measured through measuring the power of the yaw drivers. This will be investigated within WP7 of the PROTEST project.

The yaw position is also measured during conventional load measurement campaigns, which could also provide the acceleration and/or rate of yawing. Excitation of torsional vibrations of the nacelle, during yawing and their measurement should be investigated within WP7 of the PROTEST project.

Additional measurements of the temperature of the yaw base and frictional parts is recommended, in case temperature affects the kinematics and therefore, also the loads of the yaw system during operation.

A summary table with the recommended quantities to be measured during an experimental campaign is presented in the following:

Table 2: Recommended measurements during an experimental campaign

Interconnection point	Loads	Synchronicity	Analysis
Tower top & YS	Loads: Tower top Axial & Shear forces, Bending moments and Torsion Kinematics: (measured at nacelle) Dynamics: (measured at nacelle)	WT status WT operational magnitudes (Power, RPM) Wind inflow (speed & direction)	Mean loads Fatigue loads (LDDs)
Nacelle & YS	Loads: (measured at tower top) Kinematics: Nacelle yaw position & speed Dynamics: acceleration on nacelle bearing in two perpendicular directions	..	..
Yaw transmission system (gear) & YS	Loads: Torque (Pressure) Kinematics: (measured at nacelle) Dynamics: (measured at nacelle)	..	Uneven torque distribution
WT controller & YS	Yaw system power consumption Command	..	..
Yaw bearing & YS (internal system measurements)	Additional measurements: Temperature at yaw base and frictional parts	..	..

Specifically for the yaw system components, the following measurements are recommended:

- For the yaw actuator: P_{yD} (power consumption) as measured, M_{YD} calculated from measurements using Eq.(1)
- For the yaw transmission system: M_M as measured during yaw motion
- For the yaw bearing: Tower top axial & shear forces, Bending moments and Torsion, as measured
- Estimation of the frictional torque through application of Eq.(3)-(5) during yaw motion.

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 yaw system, 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 the Palmgren-Miner cumulative damage calculation principle, which is based on number of cycles at Load Level (torque level).

In the following 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 [21] should be followed wherever possible. However, in order to better illuminate the load cases that affect the components/systems under study following presentation/analysis should be added for the load measurements regarding the yaw system.

In addition to the loads described in the IEC/TS 61400-13 (i.e. bending moments and torsion) also the axial load and the shear loads will be measured at the tower top, since for the design of the yaw system axial, radial and tilting moment loads are necessary. It is recognized that the measurement of the axial and shear forces is not straight forward. Thus, the issues involved regarding the instrumentation and the adequate calibrations will be the further investigated within WP4 of the PROTEST project.

The measured load components will be provided in the usual lay-out followed for the presentation of loads according to IEC/TS 61400-13. However, also LDD analysis will be performed (at least to the tower top torsion). The time variation of these (extra) load components is expected to be similar to the tower top loads usually measured according to IEC 61400-13. Therefore, the same sampling ratio will be used.

Additional presentation of loads with respect to the nacelle position (similar to the presentation of loads with respect to azimuthal position of the rotor) will be performed. This will cover the loads measured at the tower top.

Capture matrices for both normal power production and transient events (including parked conditions, grid failures, etc.) should be divided in cases with yaw motion and cases without.

Sample record measurement and analysis should be performed for cases of yaw operation (yawing) and cases without yaw operation (non-yawing) independently.

Since it is anticipated that the yaw operation (yawing) will not cover the 10minute file, special treatment of these captured files should be foreseen. These should be considered as transient load cases. The yaw system operation (yawing) is strongly related to the wind inflow and the controller settings.

However, a discussion is necessary to define yaw operation (yawing), relevant to the motion with respect to the teeth of the yaw system. In this aspect a more extensive analysis should be performed, covering more than one data set (10minute file), since it is likely that during the campaign analysis the nacelle position will not cover the 360°. Following the presentation of measurement load cases as per IEC/TS 61400-13 a presentation of the relevant cases for the yaw system is shown in following table.

Table 3: MLCs targeted for the yaw system

MLC number[*]	Yaw MLC	Short description	Target wind speed[†]	Notes
1.1	1.1.1	Power Production (yawing)	$v_{in} < v_{hub} < v_{out}$[‡]	Referring to normal operation (if yaw system is active then the file is recorded under this classification)
	1.1.2	Power Production (non-yawing)	$v_{in} < v_{hub} < v_{out}$	Referring to normal operation (if yaw system is in-active then the file is recorded under this classification)
1.2	1.2.1	Power Production plus occurrence of fault	$v_{in} < v_{hub} < v_{out}$	If necessary split to yawing and non-yawing condition
1.3	1.3.1	Parked, idling, non-yawing	$v_{in} < v_{hub} < 0.75v_{e1}$	(if possible include yaw misalignment)
	1.3.2	Parked, idling, yawing	$v_{in} < v_{hub} < 0.75v_{e1}$	
2.1	2.1.1	Start-up non-yawing	v_{in} and $>v_r$+2m/s	
	2.1.2	Start up yawing	v_{in} and $>v_r$+2m/s	
2.2	2.2.1	Normal shut-down non-yawing	v_{in}, v_r and $>v_r$+2m/s	
	2.2.2	Normal shut-down yawing	v_{in}, v_r and $>v_r$+2m/s	
2.3	2.3.1	Emergency shut-down	v_{in} and $>v_r$+2m/s	If necessary split to yawing and non-yawing condition
2.4	2.4.1	Grid failure	v_r and $>v_r$+2m/s	
2.5	2.5.1	Over-speed activation of the protection system	$>v_r$+2m/s	

It should be noted that for transient load cases 2.1-2.5 ideally the measurements should be taken at v_{out}, following the recommendations of IEC/TS 61400-13.

In contrast to the recommendation of IEC/TS 61400-13 it might be useful not to exclude any directional sections due to shadowing effects, etc. (as performed during measurements following IEC/TS 61400-13, or IEC 61400-12, where measurements affected by obstacle shadowing are characterised as invalid and therefore rejected), to cover the “real” loading of the yaw system, irrespective of whether the wind speed is measured with the required accuracy or not. These affected measurements by obstacle shadowing should be kept and analysed in comparison to the valid measurements and treated as special conditions. As a

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[*] 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

minimum the analysis of these captured time series should involve a comparison of the minimum and maximum values in combination with the standard deviation calculated within the respective 10-min file.

Specifically for yaw components following presentation of measurements should be included in the report:

- For the Yaw Actuator: M_{yD} time series & Root mean square (RMS) per wind condition
- For the Yaw Transmission system: M_M time series & Rain-flow-counting matrix (RFC) per wind condition
- For the Yaw bearing:
    - Loads (F, M) time series & RFC per wind condition
    - Kinematics (α_y mean/amplitude/speed) per wind condition
    - Temperature (if available) in relation to other measurements
    - Acceleration PSD per wind condition

Additional information in statistical terms per wind condition (wind speed, turbulence) and wind turbine condition (normal operation or standstill) should be provided regarding yaw operation. These for example can be

- Starts within 10-min captured file, time of operation, time duration up to next start
- Average angle of rotation for each single operation & speed

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